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THE HIE-ISOLDE REPORT

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ABSTRACT

The ISOLDE facility at CERN has a long and successful tradition of continuous development and growth in order to meet the scientific requests from the user community. The current situation continues this habit and several projects to increase the scientific scope of the facility by technical developments are underway or envisaged within the mid-term future planning. These developments will result in a transformed facility with the label HIE (High Intensity and Energy)-ISOLDE where the intensity, quality and the energy range attainable of the secondary beams will be substantially improved. They are largely in line with necessary technical developments towards the future EURISOL facility. This report summarizes these development projects, together with specific scientific cases that will benefit or become feasible.

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1 Introduction and Executive Summary

The ISOLDE facility exists as a concept since four decades, after the decision in 1964 by the CERN management to construct the first Radioactive Beam facility at CERN. Throughout its various apparitions, the facility has been steadily increasing its scientific scope and user basis, and has been one of the emblematic installations leading to the current general recognition of the potential of research with radioactive beams. The last incarnation of the ISOLDE facility commissioned in 1992, PSB-ISOLDE, was largely motivated by the possibility of post-accelerated radioactive beams. Since 2001, this has been achieved through the addition of the REX-ISOLDE post-accelerator.
It has been highlighted by several science planning organs [1][2][3] that radioactive beam physics opens unprecedented possibilities in nuclear structure and astrophysics research, and that new and developed experimental facilities are needed to exploit these possibilities. In the European context, two complementary facilities are recommended by NuPECC to be constructed [4]; FAIR-NUSTAR[5] and EURISOL[6], using the techniques of in-flight separation and ISOL-method, respectively. The EURISOL facility is slated to be a considerably upgraded version of the CERN-ISOLDE facility, able to deliver radioactive beams of 2-3 orders of magnitude higher intensity than today. This necessitates a proton driver accelerator capable of delivering 1-2 GeV protons with a beam power of 5 MW. The planned SPL LINAC[7], which is a prerequisite for LHC luminosity upgrades but also for neutrino superbeams, "beta-beams" or the muon neutrino factory, has the optimal parameters for an advanced ISOL facility. Several sites are suited to host EURISOL, but due to the evident technical and scientific synergies, CERN might thus emerge as the obvious choice.

However, as also recommended by NUPECC, the realization of EURISOL is still to be seen in a long-term perspective and exploitation and further developments of the existing RIB facilities are required. In the case of ISOLDE, a vigorous upgrade programme is planned that will transform the facility into HIE (High Intensity and Energy)-ISOLDE where the secondary beam intensities and the energy range attainable will be substantially improved. These developments are largely in line with necessary technical developments towards EURISOL. Thus, to further exploit the potential of the existing facility, the "Standing Group for Upgrade of the ISOLDE facility" was formed in 2002, based on a mandate from the then CERN Directors of Fixed-target physics and Accelerators. This group oversees and prioritizes the various technical developments, and the current report is meant as a tool in this process. The report is subdivided into two parts, the first (Chapter 2-10) dealing with facility upgrades and the second (Chapter 11-13) with new experimental possibilities made possible by these upgrades, including corresponding experiment-specific developments.

It is clearly recognized that user-demand driven facility developments have historically been the main key to the success of ISOLDE, and that this has to be a continuous process. The continuously improved beams have attracted an increasing user community over the years. However, there is not only one sole parameter that is requested by the experimental collaborations, but several, and partly even contradicting. The requests concern higher intensity, new isotopes/elements, beam purity, beam emittance, time structure, charge state, higher and lower beam energy, and the routes to these improvements are manifold.

The available intensity of a radioactive to an experiment depends on a large number of factors (production cross-section, decay losses, diffusion and effusion constants in the production target, ion source efficiency and ion beam transmission), for a post-accelerated beam in REX-ISOLDE, further losses have to be taken into account (efficiency and decay losses in the trapping and charge breeding phases, intensity in the chosen charge state, transmission), that vary strongly from element to element and the various isotopes. Increased intensity of a specific element does not only mean that the measurements can be performed in less time or to a higher statistical precision, but also that further, more exotic isotopes can become within reach for the experiments.

1.1 Increasing intensity, purity and number of available radioactive beams

The most straightforward route to higher secondary beam intensities is to increase the primary proton beam intensity. The ISOLDE facility is currently coupled to the PS Booster synchrotron which can deliver a maximum beam current of 4 μA on the production targets. During operation until 2005, the effective current delivered to ISOLDE has been 1.92 μA due to sharing with other programmes. The prospects for proton beam availability in the coming years and increasing the proton intensities along the full injector chain at CERN has recently been reviewed by the High Intensity Proton (HIP) working group within the AB Department. Chapter 2 contains ISOLDE-relevant excerpts of their report, where the two main paths for increasing the average beam current available for ISOLDE are faster cycling of the PSB and the addition of a new injector, LINAC-4.

The target and ion source system is a key link in the production of radioisotopes, and Chapter 3 sketches necessary R&D in order to handle increased primary beam intensities and to further increase the production yield and reach new elements and/or isotopes through tailored engineering. Increasing primary beam intensities implies new challenges concerning radioprotection and chapter 0 summarizes the necessary actions to this respect.

The Resonant Ionisation LASER Ion Source (RILIS) has proven to be an outstanding tool in selectively ionising the desired element with, in most cases, the highest efficiency attainable. However, the set-up, optimization and running of the RILIS is still complex, and constitutes an “experiment within the experiment”. Chapter 4 describes the perspectives of upgrading the system in order to improve its scope while facilitating its operation.

The mass separation and the beam transport efficiency to the experiment are further crucial factors in achieving maximum beam intensity and purity. Ideas for improving the mass selectivity of the separators and the throughput by modifications of the beam transport system are described in Chapter 7.

Chapter 9 describes the envisaged developments concerning cooling, bunching and charge breeding of ions before post-acceleration.

1.2 Improving beam characteristics

The low-energy radioactive beams from ISOLDE are, due to the production method, pseudo-continuous and have a relatively large emittance, moreover, the ions are singly charged. These circumstances can pose severe limitations on the possible experiments. The ISCOOL radiofrequency cooler and buncher described in Chapter 8 will provide low-emittance low-energy beams to a large range of experiments.

Collinear LASER spectroscopy with completely new precision will be possible by the small energy spread and time-tagged decay studies, improving the signal-to-noise ratio can be performed using bunched beams of the most exotic species. By utilizing the highly charged ions from REXEBIS as outlined in Chapter 11 would push the precision frontier of the existing mass measurement set-up ISOLTRAP.

1.3 Increasing the beam energy range

The first-generation experiments performed at REX-ISOLDE have demonstrated the potential of reactions around the Coulomb barrier using radioactive beams. However, the scientific scope can be drastically enlarged if the energy range is increased. With increasing energy, heavier nuclei and further classes of reactions can be utilized (see Figure 1.1). Furthermore, enlarged dynamic energy range permits optimizations for each case with respect to cross-section and open reaction channels, e.g. Coulomb excitation experiments can be performed at the highest "safe" energy still below the Coulomb barrier.

The energy range between the pure ISOL beam (60 keV) and the lowest possible extractable beam energy from REX-ISOLDE (300 keV/u) is also of major interest for astrophysically relevant reactions and condensed matter research as described in Chapter 12. Here, combining highly-charged ions from a charge-breeder ion sources like the existing REXEBIS and PHOENIX ECRIS described in Chapter 9 with a moderate post-acceleration by electrostatic means or a small RFQ structure would yield high-intensity beams in this energy domain.

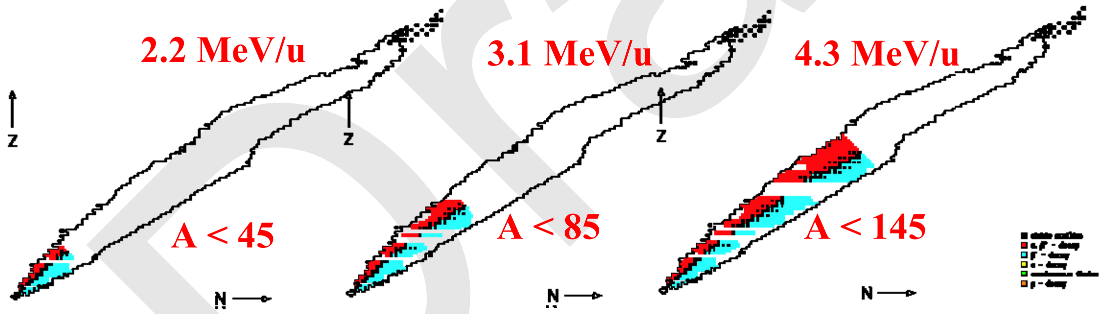

Figure 1.1 The attainable range of isotopes at REX-ISOLDE reaching the Coulomb barrier for symmetric reactions.

[1] NuPECC Report "NuPECC Long Range Plan 2004: Perspectives for Nuclear Physics Research in Europe in the Coming Decade and Beyond" (2004), http://www.nupecc.org/pub/lrp03/long_range_plan_2004.pdf

[2] The OECD Megascience Forum, Report of the Working Group on Nuclear Physics, 1999, http://www.oecd.org/dataoecd/23/62/2102613.pdf

[3] The DOE/NSF Nuclear Science Advisory Committee "OPPORTUNITIES IN NUCLEAR SCIENCE - A Long-Range Plan for the Next Decade", 2002, http://www.sc.doe.gov/henp/np/nsac/docs/LRP_5547_FINAL.pdf

[4] Roadmap for Construction of Nuclear Physics Research Infrastructures in Europe, 2005, http://www.nupecc.org/pub/NuPECC_Roadmap.pdf

[5] An International Accelerator Facility for Beams of Ions and Antiprotons - Conceptual Design Report, GSI 2003, http://www.gsi.de/GSI-Future/cdr/

[6] The EURISOL Report, ed. J. Cornell, GANIL 2003, http://www.ganil.fr/eurisol/Final_Report.html

[7] R. Garoby, "*A New Proton Injector at CERN*", AB-Note-2003-048 (SPL), Geneva, 2003.

2 Perspectives for increased proton intensity for ISOLDE – HIP report excerpts

The High Intensity Proton working group (HIP) within the AB department was formed in order to *"collect the needs of the various user communities, evaluate the benefits of the possible improvements and elaborate a preferred long-term scenario of the CERN accelerator complex. Short-term first priority steps had to be proposed, in line and consistent with the long-term scenario."* The group has recently summarized its conclusions in the report CERN-AB-2004-022 OP/RF [1], edited by M. Benedikt and R. Garoby and here only excerpts of the report, relevant for ISOLDE, will be repeated. Except for minor rewritings to obtain language cohesion, no changes to the text have been undertaken.

2.1 Physics request

2.1.1 ISOLDE (short term)

… ISOLDE operation does not generally interfere with high energy physics, using PSB cycles that cannot be exploited by the PS (case of PS cycle longer than one basic period). The nominal request is for 50% of the PSB cycles, which corresponds to an average of 1350 cycles/hour. At the maximum intensity of 3.2×10^{13} protons per pulse (ppp), the average beam current delivered to ISOLDE is then 1.92 μA.

2.1.2 ISOLDE (medium term)

… The user community is expected to get larger and the proton flux has to grow and be brought as close as possible to the technical limit of 10 μA of the present experimental zone.

2.2 Performance of the accelerator complex

The only direct physics client of the PSB is the ISOLDE facility. The figure of merit for ISOLDE operation is the average number of available PSB cycles and the official request amounts to a minimum of 50% of the yearly cycles. This corresponds to an average of 1350 PSB cycles/hour of PSB operation for ISOLDE. Table 2.1 compares requested and available cycles for ISOLDE for the period 2006 to 2010.

Table 2.1 PSB cycles for ISOLDE operation in 2006, 2007 and 2010.

Year	PSB physics operation [hours]	PSB cycles to ISOLDE		PSB cycles requested	
		[%]	[cycles/h]	[%]	[cycles/h]
2006	4500	48 %	1296	50%	1350
2007	5400	45 %	1215	50%	1350
2010	5400	47 %	1269	50%	1350

As can be seen from Table 2.1, the ISOLDE physics request can be nearly fulfilled in the period 2006 to 2010. However, this is not fully satisfying, especially since the ongoing ISOLDE upgrade programs will eventually lead to an increase of the request by a factor of five.
The overall conclusion is that the CERN accelerator complex, with the already ongoing improvements, cannot provide all the requested beams in the period 2006 to 2010 in the assumed operational scenario. ... With the present capabilities of the accelerator complex, any wishes for higher beam availability or upgrading of CNGS

and ISOLDE performance cannot be fulfilled. The production of the ultimate LHC beam is also not feasible with the presently used scheme.

2.3 Upgrades for Radioactive Ion Beams

2.3.1 Present status and upgrade planning of the ISOLDE facility

… The intensity limit for the present ISOLDE facility is determined by the radioprotection for target stations, and estimated at 10 μA [2], [3].
The production of the 1.4 GeV proton beam for ISOLDE involves only the Linac2 and the PSB machines. The present CERN commitment towards ISOLDE is based on a number of "shifts" per year, corresponding to about 50% of the total number of PSB cycles and was usually fulfilled during the last years. With the PSB repetition time of 1.2 s and considering 90% beam availability this translates to 1350 pulses/hour. Multiplying this figure by the nominal PSB ISOLDE intensity of 3.2×10^{13} ppp gives an average current of 1.92 μA usually available for ISOLDE [4].
The demand coming from the ISOLDE community for the period 2006-10 is for an increase of this figure up to the target limit of 10 μA, i.e. a factor of ~5. The present limitation in average current comes from both the maximum proton intensity that can be produced and the number of PSB pulses that are available for ISOLDE. These two points are therefore the key issues for an upgrade analysis.

2.3.2 Beam intensity limitations and improvement scenarios

The main limiting factor for the proton beam intensity that can be provided by Linac2 and PSB is the excessive incoherent space charge tune shift that occurs at 50 MeV injection into the PSB. With an intensity of around 1×10^{13} protons per PSB ring, the vertical space charge tune spread during RF capture exceeds 0.5 and the combination of several techniques is required to avoid large beam losses and to make high intensity operation possible.
A horizontal multi-turn scheme (10-13 turns) is used to inject the Linac2 beam into the PSB. To make full use of the available aperture, coupling of the transverse planes is applied during injection in order to transfer some of the horizontal oscillation into the vertical plane. Already during the injection process, the main magnetic field is ramped to accelerate the beam out of the space charge regime as quickly as possible. A dual harmonic (h=1 and h=2 in anti-phase) RF system is employed to flatten the bunches during the capture process and the early acceleration phase to improve the bunching factor hereby reducing the incoherent space charge tune spread of the beam. Nevertheless a sophisticated resonance compensation scheme is needed to avoid the destructive effect of transverse betatron resonances up to third order. All these techniques have been studied and optimized over the last years. Very little margin is left for further improvements and no significant increase in beam intensity can be expected with the present operation conditions.
The only straightforward way to significantly improve the PSB beam intensity is to attack the problem directly at its roots, i.e. to reduce the space charge tune spread at injection by increasing the injection energy. The space charge tune shift is inversely proportional to $\beta\gamma^2$, and the experience of other laboratories having increased their linac energy confirms that the final accumulated intensity is roughly proportional to $\beta\gamma^2$ at injection. The Fermilab linac upgrade (1993, 200 to 400 MeV corresponding to a factor 1.7 in $\beta\gamma^2$) opened the way for an increase of the booster intensity from 3×10^{12} to 5.5×10^{12} protons per pulse [5].

Taking the requirement to make the LHC beam in a single batch as the final goal, the PSB intensity has to be increased by a factor two. This improvement should be obtained by increasing $\beta\gamma^2$ at injection by a factor two, i.e. by increasing the linac energy from the present 50 MeV up to 160 MeV. If the linac is upgraded, then it is almost mandatory to change at the same time the particle type from protons to H^-. This means to strongly modify the PSB injection area, but the advantages of a modern charge-exchange injection in terms of beam loss reduction, phase space painting options and emittance control clearly justify the investment. Simulations of 160 MeV H^- injection and accumulation in the PSB are in progress, and present results confirm the expected gain in intensity [6][7].

The option of increasing the energy of Linac2 has been considered but finally discarded due to the limited energy achievable in the available space at the end of the linac, about 20 m. Using standard tanks at 202 MHz, only 80 MeV could be reached, at a cost of about 30 MCHF (P+M). The limited increase in PSB intensity would present only a minor interest for ISOLDE, and no significant advantages for the other users [8]. Higher gradients could be achieved by linac tanks at double frequency (405 MHz), allowing to reach about 100 MeV. However, the cost would be higher, due to the completely new RF system to be designed and built, and the gain still marginal. Structures at higher frequency and gradient can not be used due to the low transfer energy.

The preferable solution is to build a new linac injector. Being the fourth linac to be built at CERN, the latter would be naturally called Linac4. This option has been recently studied with a certain detail as an outcome of the SPL study. The energy of the original SPL room-temperature injector has been increased from 120 to 160 MeV, and its design can be directly used for the Linac4 [9]. The new linac would be housed in the PS South Hall, where the required 100 m space and the infrastructure (water, electricity, etc.) are largely available, and its beam would go to the PSB in a line parallel to the existing LEIR transfer line. Another factor contributing to lowering the construction cost is that most of the Linac4 makes use of 352 MHz RF equipment recuperated from the LEP machine. Moreover, an RFQ injector that can be used for Linac4 will be given to CERN by the "Injecteur de Protons de Haute Intensité" (IPHI) collaboration (CEA and IN2P3), at the end of their testing period in 2006. It must also be taken into consideration the fact that a modern linac would profit of technologies, like low energy chopping and collimation, intended to minimize beam losses and reduce the environmental impact of high intensity operation. The target value of

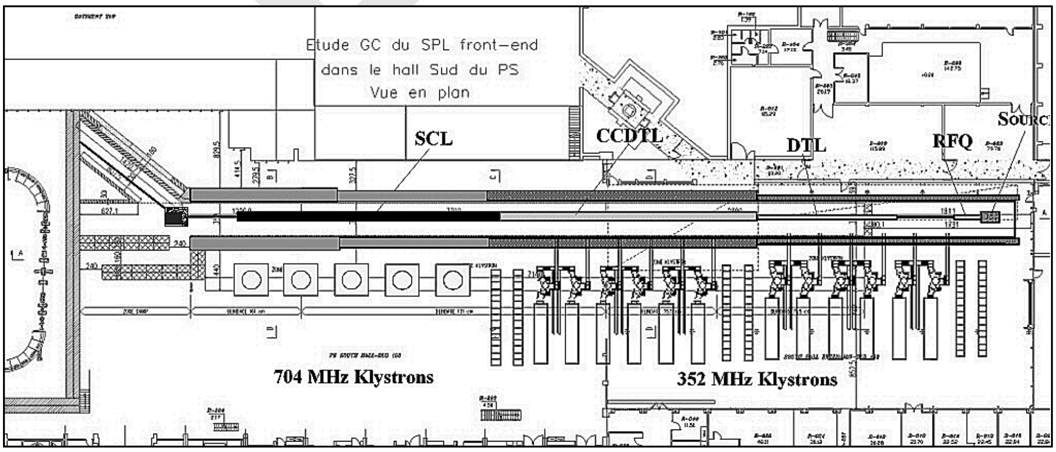

Figure 2.1 Layout of Linac4 in the PS South Hall

6.4×10^{13} ppp in the PSB (factor two with respect to present peak intensity) could be reached with a linac delivering 30 mA H^- current during pulses of up to 500 μs length. The overall cost of a 160 MeV Linac4 in the PS South Hall, including the modification to PSB and the transfer line, has been estimated at 70 MCHF (P+M). shows a schematic layout of Linac4 in the South Hall.

2.3.3 Increasing the number of PSB cycles available for ISOLDE

Presently, on average, around 50% of the PSB cycles are made available for ISOLDE and the remaining 50% correspond to beams that are sent to the PS for the various other physics programmes on PS and SPS. Since this ratio will not significantly change in the short and medium-term future, no changes for ISOLDE can be expected with the present operating conditions (see 2.4).

To increase the number of available PSB cycles for ISOLDE, in a transparent way for the other physics users, the total (yearly) number of cycles has to be increased. There are two approaches: either prolonging the PSB operation period or increasing the PSB repetition frequency. With the latter option in mind several machine developments and studies were performed in 2001 and 2002 to investigate the feasibility of decreasing the PSB repetition time (and also the Linac2 repetition time) from the standard 1.2 s to 0.6 s [10]. The choice of 0.6 s was motivated by the fact that the PSB main power supply, after major upgrading in the framework of the "PS for LHC project", just allows to perform a 1.4 GeV magnetic cycle within 0.6 s.

The outcome of the investigations was that a repetition time of 0.6 s is feasible for Linac2 with only minor modifications (the machine was initially designed for 2 Hz operation) but too demanding for the PSB, pushing several essential machine systems towards or beyond their limits. Even though all physics beams could be produced on short 0.6 s cycles with nominal performance, several systems of the PSB would not support 24 h operation with 0.6 s cycling. Especially the main power supply transformers (rms current limited), the first and second harmonics RF systems (rms power and cooling limited) and the main magnets cooling circuit would require major upgrade or replacement. In addition, several power converters in the transfer lines PSB - PS and PSB - ISOLDE would also need replacement so that the total cost for reducing the PSB repetition time to 0.6 s would be in the order of 10 MCHF and require significant manpower investment.

The situation is fundamentally different when analysing a reduction of the repetition time to 0.9 s. In this case, all PSB systems can operate within specifications, only a single transfer line power converter needs replacement and a few others some upgrade work. The overall cost can be roughly estimated to around 1-2 MCHF and accordingly less manpower is required so that a reduction of the PSB repetition time can be considered a valid short-term upgrade possibility.

The potential gain for ISOLDE is still important. With 0.9 s repetition time instead of 1.2 s, the number of PSB cycles in a given period increases by 33%. Assuming (to first order) that the 33% additional cycles are made available for ISOLDE (i.e. the number of cycles for other users remains unchanged) the gain factor is $(50 + 33)/50 = 1.66$ so that instead of 1350 cycles, as presently, around 2240 cycles would be available per hour for ISOLDE.

Obviously 0.6 s repetition time would be significantly more beneficial for ISOLDE (with assumptions as above the gain factor is $(50 + 100)/50 = 3.0$) but it requires ten times more investment than the 0.9 s option and does not benefit other CERN users in a way comparable to e.g. the Linac4 option.

Results of detailed calculations are given in 2.4.

2.3.4 *Estimate of short and medium-term ISOLDE performance*

The effect of the two potential upgrades on the performance of the ISOLDE facility is analysed below. The decrease of the PSB repetition time from 1.2 s to 0.9 s is considered a short-term option that could already be effective in 2006. The intensity increase by a factor two, expected from a new Linac4 is a medium-term option and could be achieved at the earliest by 2010. Combining the two options, the overall gain for ISOLDE would be 2 × 1.66 = 3.32, i.e. the average current to ISOLDE can be estimated to reach ~6.4 μA.

The different scenarios are summarized in Table 7.1. The number of cycles available for ISOLDE is compatible with all other physics requirements and especially the assumed LHC and SPS operation modes (see Chapter 3). The assumed intensities per PSB pulse are 3.2×10^{13} ppp with Linac2, and twice more, 6.4×10^{13} ppp with Linac4. The "gain factor" is the ratio of the expected average current and the present average current of 1.92 μA (Section 2.3.1). In the case of Linac4 upgrade, it is assumed that the LHC beam will be produced with single batch filling of the PS instead of the presently used double batch operation, hereby freeing some more cycles for ISOLDE during periods with LHC beam requests.

Scenario	**2006**		**2007**[1]		**2010**			
	1.2 s Linac2	**0.9 s** Linac2	1.2 s Linac2	**0.9 s** Linac2	1.2 s Linac2	**0.9 s** Linac2	1.2 s **Linac4**	**0.9 s Linac4**
PSB cycles/hour	1300	2250	1210	2110	1270	2200	1290	2240
% of PSB cycles	48	63	45	59	47	61	48	62
Protons/pulse [$\times 10^{13}$]	3.2	3.2	3.2	3.2	3.2	3.2	6.4	6.4
Protons/hour [$\times 10^{16}$]	4.2	7.1	3.9	6.7	4.1	7.0	8.3	14.1
Av. current [μA]	1.9	3.2	1.7	3.0	1.8	3.1	3.7	6.4
Gain factor	0.97	1.64	0.90	1.55	0.94	1.61	1.91	3.28

Table 2.2 Expected ISOLDE performance under various upgrade scenarios.

The final conclusion is that reducing the PSB repetition time from 1.2 to 0.9 s is an important, cost-effective short-term option that provides a significant gain of ~60% increase in average current (via the number of available cycles) for ISOLDE. In the medium term, another important gain of ~100% increase in average current (via peak current per pulse) can then be achieved with Linac4. Combining the two options will result in an increase of the average current by a factor ~3.3 as compared to the present situation.

2.4 *Effect of upgrades on proton beam availability*

The effects of some of the proposed accelerator complex upgrades on the proton beam availability for the period 2006 to 2010 are analysed in this chapter. The upgrades considered in detail are:

(i) Reduction of the basic period (and the Linac2 and PS Booster repetition time) from the present 1.2 s to 0.9 s or 0.6 s. Consequently the number of available PSB cycles is increased by either 33% (0.9 s) or 100% (0.6 s). A change of the basic period length also implies modifications of most of the PS and SPS cycles. The effect is however

[1] The figures for 2007 assume only proton operation in the SPS. In the case of ion commissioning (see Section 3.1.1), ISOLDE would benefit from periods when the SPS request (only) ions.

rather small on the SPS since the length of the SPS cycles is usually determined by the time required for the cycling and not by the injection flat bottom. More details on the effect of reduced basic period on PS and SPS cycles can be found in [11]. The beam characteristic (intensity, emittance, etc.) for all users is assumed to be independent of the basic period length.

(ii) Increase of the CNGS intensity from 4.4×10^{13} to 7.0×10^{13} protons per SPS cycle. For this option it is assumed that PS and SPS high intensity performance can be pushed by around 60% as compared to the nominal CNGS scenario. The higher intensity in the PS is achieved by using two consecutive injections from the PSB (double batch filling), similar to LHC operation [12]. Production and characteristic of the beams for all other physics users are to first order identical to the nominal scenario. The main impact of this option is therefore the increased number (factor 2) of PSB cycles required for CNGS operation.

(iii) A new Linac4 (160 MeV, H^-) as injector for the PSB [9]. In this scenario it is assumed that the increased injection energy allows doubling the beam brightness in the PSB. Therefore the nominal (and also the ultimate) LHC beam can be produced with a single PSB pulse in contrast to the presently used double batch scheme, thus reducing the number of required PSB cycles by a factor of two. A similar argument applies to CNGS operation, where the higher intensity (7.0×10^{13}) can be achieved with a single PSB batch for the PS, avoiding the disadvantageous double batch filling required for option (ii). As discussed above, it is assumed that PS and SPS can handle the 60% increase in intensity. Finally it is expected that the PSB intensity for ISOLDE can be doubled from the nominal 3.2×10^{13} to 6.4×10^{13} ppp. All other physics beams will be produced like in the nominal scenario.

The comparison of the various upgrades is based on the operation conditions and guidelines that were defined for the performance analysis of Chapter 3 in [1]. The same supercycle compositions, user priorities and beam requests were assumed. Table 2.3 to Table 2.11 summarize the beam availability for all physics users for 2006, 2007 and 2010 for the following three scenarios:

- Present operational beam characteristics (“standard operation”).
- Increased CNGS intensity of 7.0×10^{13} per SPS cycle (“CNGS double batch”).
- 160 MeV H^- injection into the PSB (“Linac4”).

Table 2.3 to Table 2.5 are for the present Linac2 and PSB repetition time of 1.2 s, Table 2.6 to Table 2.8 assume 0.9 s and Table 2.9 to Table 2.11are for 0.6 s.

…

ISOLDE performance is quoted in three different ways: pulses per hour, average percentage of PSB cycles and average current. This is because the present way of quantifying ISOLDE performance by quoting either PSB pulses or percentage of cycles makes little sense when changing the PSB repetition time.

It should be noted that Linac4 is considered a medium-term option that will be available by 2010 at the earliest. Nevertheless performance figures for this option are quoted for 2006 and 2007 for comparison.

	Request	**Standard operation**	**CNGS high intensity**	***Linac4***
CNGS [× 10^{19} pot/year]	4.5	4.4	6.3 (4.5)	*7.0 (4.5)*
FT [× 10^{5} spills/year]	7.2	3.3	3.0 (4.5)	*3.3 (5.1)*
East Area [× 10^{6} spills/year]	1.3	1.3	1.2	*1.3*
nTOF [× 10^{19} pot/year]	1.0-1.5	1.4	1.3	*1.4*
ISOLDE [pulses/hour] Average current [μA]	1350 (50%) 1.9	1300 (48%) 1.9	930 (34%) 1.3	*1300 (48%)* *3.7*

Table 2.3 Beam availability in 2006 with 1.2 s PSB repetition time.

	Request	**Standard operation**	**CNGS double batch**	***Linac4***
CNGS [× 10^{19} pot/year]	4.5	4.4	6.3 (4.5)	*7.0 (4.5)*
FT [× 10^{5} spills/year]	7.2	1.9	1.8 (3.3)	*1.9 (3.7)*
East Area [× 10^{6} spills/year]	1.3	1.5	1.4	*1.6*
nTOF [× 10^{19} pot/year]	1.0-1.5	1.7	1.5	*1.7*
ISOLDE [pulses/hour] Average current [μA]	1350 (50%) 1.9	1210 (45%) 1.7	890 (33%) 1.3	1260 (47%) 1.8
SPS LHC filling cycle [s]	-	21.6	21.6	*18.0*
SPS LHC pilot cycle [s]	-	22.8	25.2	*22.8*

Table 2.4 Beam availability in 2007 with 1.2 s PSB repetition time.

	Request	**Standard operation**	**CNGS double batch**	**Linac4**
CNGS [× 10^{19} pot/year]	4.5	4.9 (4.5)	7.0 (4.5)	7.8 (4.5)
FT [× 10^{5} spills/year]	7.2	3.3 (3.8)	3.0 (5.1)	3.3 (5.7)
East Area [× 10^{6} spills/year]	1.3	1.5	1.4	1.5
nTOF [× 10^{19} pot/year]	1.0-1.5	1.7	1.5	1.7
ISOLDE [pulses/hour] Average current [μA]	1350 (50%) 1.9	1270 (47%) 1.8	920 (34%) 1.3	1290 (48%) 3.7
SPS LHC filling cycle [s]	-	21.6	21.6	18.0
SPS LHC pilot cycle [s]	-	22.8	25.2	22.8

Table 2.5 Beam availability in 2010 with 1.2 s PSB repetition time.

	Request	**Standard operation**	**CNGS double batch**	***Linac4***
CNGS [× 10^{19} pot/year]	4.5	4.2	6.3 (4.5)	*6.7 (4.5)*
FT [× 10^{5} spills/year]	7.2	3.2	3.0 (4.5)	*3.2 (4.8)*
East Area [× 10^{6} spills/year]	1.3	1.2	1.1	*1.2*
nTOF [× 10^{19} pot/year]	1.0-1.5	1.3	1.3	*1.3*
ISOLDE [pulses/hour] Average current [μA]	1350 (50%) 1.9	2250 (63%) 3.2	1850 (51%) 2.6	*2250 (63%)* *6.4*

Table 2.6 Beam availability in 2006 with 0.9 s PSB repetition time.

	Request	Standard operation	CNGS double batch	*Linac4*
CNGS [$\times 10^{19}$ pot/year]	4.5	4.3	6.3 (4.5)	*6.8 (4.5)*
FT [$\times 10^{5}$ spills/year]	7.2	1.9	1.8 (3.3)	*1.9 (3.6)*
East Area [$\times 10^{6}$ spills/year]	1.3	1.5	1.4	*1.5*
nTOF [$\times 10^{19}$ pot/year]	1.0-1.5	1.7	1.6	*1.7*
ISOLDE [pulses/hour] Average current [μA]	1350 (50%) 1.9	2110 (59%) 3.0	1760 (49%) 2.5	*2210 (61%)* *3.2*
SPS LHC filling cycle [s]	-	18.9	18.9	*18.9*
SPS LHC pilot cycle [s]	-	23.4	25.2	*23.4*

Table 2.7 Beam availability in 2007 with 0.9 s PSB repetition time.

	Request	Standard operation	CNGS double batch	Linac4
CNGS [$\times 10^{19}$ pot/year]	4.5	4.7 (4.5)	7.0 (4.5)	7.5 (4.5)
FT [$\times 10^{5}$ spills/year]	7.2	3.2 (3.4)	3.0 (5.1)	3.3 (5.6)
East Area [$\times 10^{6}$ spills/year]	1.3	1.5	1.4	1.5
nTOF [$\times 10^{19}$ pot/year]	1.0-1.5	1.6	1.5	1.6
ISOLDE [pulses/hour] Average current [μA]	1350 (50%) 1.9	2200 (61%) 3.1	1810 (50%) 2.6	2240 (62%) 6.4
SPS LHC filling cycle [s]	-	18.9	18.9	18.9
SPS LHC pilot cycle [s]	-	23.4	25.2	23.4

Table 2.8 Beam availability in 2010 with 0.9 s PSB repetition time.

	Request	Standard operation	CNGS double batch	*Linac4*
CNGS [$\times 10^{19}$ pot/year]	4.5	4.4	6.6 (4.5)	*6.9 (4.5)*
FT [$\times 10^{5}$ spills/year]	7.2	3.3	3.1 (4.7)	*3.3 (5.0)*
East Area [$\times 10^{6}$ spills/year]	1.3	1.3	1.2	*1.3*
nTOF [$\times 10^{19}$ pot/year]	1.0-1.5	1.4	1.3	*1.4*
ISOLDE [pulses/hour] Average current [μA]	1350 (50%) 1.9	4000 (74%) 5.7	3540 (66%) 5.0	*4000 (74%)* *11.4*

Table 2.9 Beam availability in 2006 with 0.6 s PSB repetition time.

	Request	Standard operation	CNGS double batch	*Linac4*
CNGS [$\times 10^{19}$ pot/year]	4.5	4.4	6.6 (4.5)	*7.0 (4.5)*
FT [$\times 10^{5}$ spills/year]	7.2	1.9	1.9 (3.5)	*1.9 (3.7)*
East Area [$\times 10^{6}$ spills/year]	1.3	1.6	1.5	*1.6*
nTOF [$\times 10^{19}$ pot/year]	1.0-1.5	1.7	1.6	*1.7*
ISOLDE [pulses/hour] Average current [μA]	1350 (50%) 1.9	3880 (72%) 5.5	3490 (65%) 5.0	*3960 (73%)* *11.3*
SPS LHC filling cycle [s]	-	19.8	19.8	*18.0*
SPS LHC pilot cycle [s]	-	22.8	24.0	*22.8*

Table 2.10 Beam availability in 2007 with 0.6 s PSB repetition time.

	Request	Standard operation	CNGS double batch	Linac4
CNGS [× 10^{19} pot/year]	4.5	4.9 (4.5)	7.4 (4.5)	7.8 (4.5)
FT [× 10^{5} spills/year]	7.2	3.3 (3.8)	3.1 (5.4)	3.3 (5.7)
East Area [× 10^{6} spills/year]	1.3	1.5	1.5	1.5
nTOF [× 10^{19} pot/year]	1.0-1.5	1.7	1.6	1.7
ISOLDE [pulses/hour] Average current [μA]	1350 (50%) 1.9	3960 (73%) 5.6	3520 (65%) 5.0	3990 (74%) 11.4
SPS LHC filling cycle [s]	-	19.8	19.8	18.0
SPS LHC pilot cycle [s]	-	22.8	24.0	22.8

Table 2.11 Beam availability in 2010 with 0.6 s PSB repetition time.

2.4.1 Conclusions

…

The comparison between upgrades highlights that a significant increase of the SPS intensity per pulse for CNGS is a very effective way of improving the performance for CNGS and/or FT, whereas the choice of the basic period length and the PSB repetition time has no important influence on these physics users. A potential way of achieving this is to fill the PS with two consecutive PSB cycles (double batch operation) and to improve on high intensity operation of PS and SPS. This has unfortunately the detrimental effect of reducing the number of PSB cycles available to other users. With the present PSB repetition time of 1.2 s, ISOLDE operation would seriously suffer, as can be seen in Table 2.3 to Table 2.5, whereas for the PS (East Area, nTOF, AD) no shortage of cycles or beam availability is anticipated. The straightforward way of improving ISOLDE performance is to decrease the PSB repetition time. For a repetition time of 0.9 s (Table 2.6 to Table 2.8), ISOLDE performance will still be ~30% above request when double batch operation is used for CNGS. A further decrease of the repetition time to 0.6 s profits again mainly ISOLDE that will then reach 2 or even 2.5 times the requested performance.

The installation of Linac4, as injector for the PSB, will significantly increase the proton flux for ISOLDE (~×2), and to a lesser extent, for CNGS and FT (~×1.1). For LHC, Linac4 is also very valuable for the twice higher brightness that can be achieved in the PSB. Moreover, PSB cycles are freed for other users because LHC nominal and ultimate beams and also very high intensity CNGS type beams can be produced with single PSB batches. When combined with a shorter basic period of 0.9 or 0.6 s, Linac4 will bring the flux to ISOLDE to 3.4 or even 6 times the nominal request.

2.5 Summary of the recommendations

In the short term, to define in 2004 and start in 2005 the 3 following projects:

- New multi-turn ejection for the PS.
- Increased intensity in the SPS for CNGS (implications in all machines).
- 0.9 s PSB repetition time.

In the medium term, to work on the design of Linac4, to prepare for a decision of construction at the end of 2006.

In the long term, to prepare for a decision concerning the optimum future accelerator by pursuing the study of a Superconducting Proton Linac and by exploring alternative scenarios for the LHC upgrade.

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3 HIE ISOLDE Targetry

The ISOLDE facility traditionally develops new radioactive ion beams, the R&D priorities on ion-sources, new target material or new beam purification methods are commonly set by the technical group and representatives of the users, the ISOLDE collaboration often contributes to this effort.
The life time of ISOLDE target at the PS-booster is of the order of a million proton pulses which corresponds to few 10^{19} protons. The proton beam pulsed structure limits the target lifetime via thermal shocks induced material sintering that eventually drops the release efficiency by one order of magnitude. Independently, for high Z target materials (U, Th, Pb and Ta), the integrated radiation dose generated by few 10^{19} GeV protons reaches the radiation hardness limit of the vacuum vessel O-rings sealing.
The average proton-beam intensity upgrade from 2 µA to 10 µA would not impact the above defined target life time but proportionally increase the frequency of target changes. Beside the associated increase in operation costs, the setting up time (3-6 days) of a target unit would be larger that the RIB production period and therefore would become the limiting factor. The target handling is done via industrial robots, however, the hands on maintenance of the facility requires a throughout revision in order to fulfil the principle of minimization of radiation doses on collaborators and radioactive waste. The R&D on the various components towards targets dedicated to a pulsed 10 µA HIE ISOLDE facility is briefly described below. The EURISOL-DS targetry tasks will develop targets for 100 kW and 4 MW close to dc proton beam power over the next four years. Evident synergies on design of ion-sources, effusion modelling and radiation hardness will be exploited. The required actions are listed in Table 14.1.

3.1 Front-ends

The so-called "front-end" is composed of 2 vacuum vessel sections; the electrostatic acceleration section consist of a moveable electrode and two pairs of electrostatic deflectors and the beam optics section containing an electrostatic quadrupole triplet. The modelling of the ion-beam optics in view of the removal of the moveable extraction electrode movement will be studied. Indeed, a fixed electrode is an asset as all mechanical items are subject to hands on maintenance or quick exchange. The alignment of the front-end is now done once for all as both sections are mechanically aligned and only the first section needs to be modified to adapt to any new standard.

3.2 Vacuum vessel

The installation of metallic sealing on all feed trough implies an increase in the sealing pressure and non reusability of the sealing. A deep modification of the standard geometrical arrangement with repercussions on the front-end coupling is unavoidable. The engineering study should clarify within 2 years the constraints of a metallic and ceramics based vacuum vessel on the front-end.

3.3 Targets

The PS-booster provides proton pulses of up to 3×10^{13} protons within 2 µs. The quasi instantaneous heating generates thermal shocks that lead to the destruction of the target Ta-oven and to rapid sintering of the target material. By keeping the same irradiation parameters, the target lifetime of typically 7 days would become shorter with increased intensity. A campaign of measurement was started to investigate this phenomenon, proportional increase of the target diameter and proton- beam size leading to quadratic reduction of the temperature jump but increased target volume (and increased effusion time) may be unavoidable.

3.4 Transfer line, oven and effusion

Once the target material arrangement is optimized, the desorption enthalpies are defining the residence time of chemicals on substrates and therefore the effusion time. For some of the slowly released elements, the choice of i.e. rhenium or carbon instead of tantalum as construction material for the transfer line and oven would considerably speed up the effusion process. Systematic studies of desorption enthalpies were published by Eichler and Gaeggeler and are now investigated for RIB production by the TARGISOL EU-project.

3.5 Beam purification

Suppression of easily ionized alkali isobaric contamination is an important key to the success of experiments. Internal drift fields for Ta-targets and micro bunching increased the signal to noise ration up to a factor 5. Despite a reduction of the RILIS efficiency by at least a facto hundred, orders of magnitude improved signal to noise are expected from electrostatic suppression of surface ionized ions. On-line test are pending. Chemical separation of alkali elements in a quartz transfer line is a promising purification method. On line tests should demonstrate if the quartz surface keeps its properties while coupled to an outgassing high temperature container.

3.6 Ion Sources

ECR ion-sources for gaseous elements and RILIS dedicated ionization schemes for new elements such as mercury and gold will be developed. Systematic modelling of the plasma and beam-optics properties of existing ion-sources will be undertaken. The planned measurements of emittances and efficiencies are the observables that will validate the simulation. Eventually, a multi stage extraction will be investigated. The new extraction should aim at suppressing or further reducing the internal extraction electrode movement while keeping the space required by the radioelement confining shutter and vacuum valve.

3.7 Radioactive waste characterization

The estimation of the produced radioactive waste resulting from high energy accelerators and facilities is an obligation stated in CERN’s radioprotection manual. A program is being written to follow up the irradiation of ISOLDE targets and the decay of the produced radio-nuclei over decades. The release parameters, the ionisation efficiency and the chemical form of the released elements will be integrated to identify the final destination (target, vacuum system, separator or experiments) of specific radio-elements. The description of the full process is complex and rather than high precision, the model should aim at a better understanding of the various transport mechanism opening the path for specific optimizations.

3.8 Radioactive waste transport and intermediate storage

The transport of irradiated targets between the class A laboratory and the intermediate storage requires dedicated shielded equipment and standard transport confinement (i.e. 200 l barrel). The intermediate storage requires an upgrade that includes dedicated aerosol monitoring system and access control. The preconditioning of the waste prior to its transport to intermediate storage consists in separation of Al from other materials. This operation is planned in the class A laboratory and should be followed by compaction.

4 ISOLDE Laser Ion Source - Status and Development

4.1 Introduction

The proposal IP50 “Development of a laser ion source” has been approved by the ISOLDE Committee in 1988. The collaboration consisting of the University of Mainz, Institute of Spectroscopy (Troitsk, USSR) and the ISOLDE Collaboration proposed to use the ISOLDE off-line separator for tests of appropriate target ion source configuration with respect to efficiency and purity. At that time collaborators from the Institute of Spectroscopy already had imported a set of copper vapour lasers (CVL) and dye lasers for the approved earlier experiment IS82 “Multiphoton ionization detection in collinear laser spectroscopy”. The off-line tests were performed in 1989. Following on-line test experiments at the SC ISOLDE-3 (1990-1991) successfully demonstrated that resonant multi-photon excitation and final ionization by pulsed lasers is an efficient tool for the production of isobarically pure ion beams.
During the migration of ISOLDE facility to the PS-Booster the laser setup was shipped to Germany, where the RILIS technique has been applied for study of short-lived Sn isotopes at GSI Darmstadt.
The installation of a permanent laser ion-source at the PS-BOOSTER ISOLDE was proposed in 1993 by the CERN-Daresbury-Leuven-Mainz-Oslo-Troitzk Collaboration as “Request for implementation and further development of the ISOLDE laser ion-source” (ISC/P47). The laser equipment was supplied from Troitsk as their contribution to the ISOLDE programme. It included three CVL operating in the Master Oscillator – Power Amplifier (MOPA) mode, three dye lasers, and a set of optical and mechanical components for laser beam control and focusing. The market cost for equivalent commercial equipment was estimated as 971 kDM at that time.
First physics run with the use of RILIS has been carried out in 1994 (IS333:

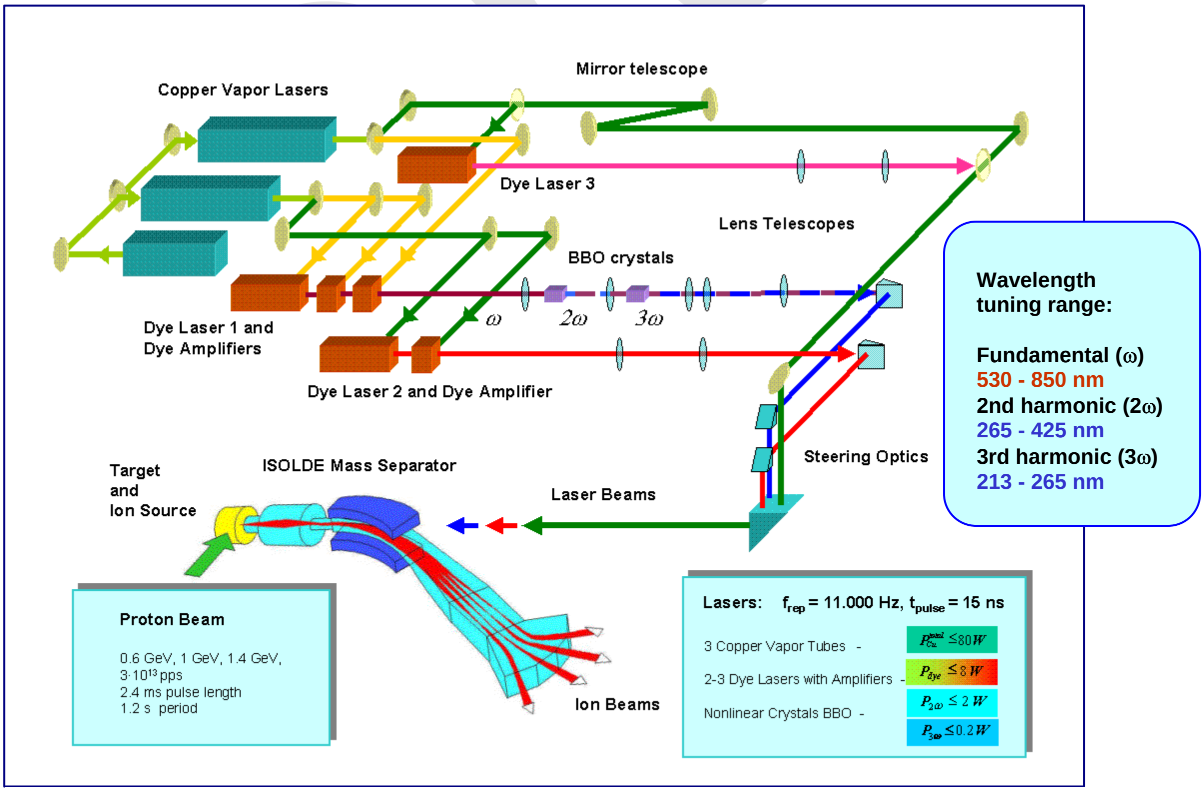

Figure 4.2 Simplified scheme of the ISOLDE RILIS

“Neutron-rich silver isotopes produced by a chemically selective laser ion-source: test of the r-process "Waiting-Point" concept”). The development program of RILIS was defined by the approval of the experiments proposed for the laser ion source. It consisted of testing the ionization scheme of the requested element as well as determination of the ionization efficiency, the selectivity and other operational parameters in an off-line mode. Ion beams of 20 chemical elements have been produced with RILIS at ISOLDE in the period of 1994-2002. During that time the output MOPA power increased from 40 W up to 80 W, the wavelength tuning range was extended due to an implementation of new dyes as well as by generating the second and third harmonics beams (Figure 4.2).
The laser ion source became the most requested type of the ion source within ISOLDE community. Experiments carried out with the use of RILIS are shown in .Data on evolution of the RILIS annual operation time together with the indication of ionized elements are presented by the diagram in

Table 4.1 Involvement of RILIS in the ISOLDE program

1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004
IS333	IS333	IS335	IS304	IS333	IS335	IS333	IS333	IS302	IS335	IS333
IS335	IS335	IS359	IS333	IS335	IS345	IS335	IS335	IS333	IS348	IS366
	IS345		IS335	IS345	IS358	IS345	IS363	IS343	IS359	IS368
			IS345	IS358	IS359	IS358	IS368	IS345	IS368	IS369
			IS353	IS359	IS364	IS359	IS369	IS359	IS369	IS378
			IS358	IS365	IS368	IS365	IS373	IS360	IS375	IS396
			IS359	IS366	IS369	IS368	IS374	IS368	IS387	IS401
						IS369	IS387	IS369	IS396	IS406
						IS374	IS393	IS378	IS401	IS409
						IS378	IS403	IS381	IS402	IS410
						IS387	IS406	IS387	IS403	IS411
							I33	IS390	IS406	IS412
								IS391	IS407	IS413
								IS393	IS410	IS418
								IS396	IS412	IS421
								IS401	IS413	IS426
								IS403		IS427
								IS404		
								IS406		
								IS410		

The development and operation of the RILIS was provided exclusively by resources of ISOLDE Collaboration until 01.04.2000. After the transfer of the technical part of ISOLDE to PS division, the RILIS system became a CERN operated setup. Running the laser ion source requires a particular expertise; consequently, a new post of applied engineer was open, which implied 33% of working time for ISOLDE RILIS. For the round-the-clock operation of RILIS much more manpower is needed. During the physics runs on-shift service of external specialists usually is supported by ISOLDE Collaboration.

Technically the RILIS laser system is quite old. The basic equipment – CVL and dye lasers – was manufactured 15 years ago. Some improvement of the safety and operation conditions of RILIS has been reached during last years in particular due to the realization of ISOLDE Consolidation Project (ICP). This work was going on in following directions:

- Laser hut extension – done, 2001
- Remote controlled beam tuning – done, 2002
- Laser beam diagnostics – done, 2003
- Automated beam positioning – in progress
- Automated laser power monitoring – in progress

Figure 4.3 Annual operation time of the RILIS laser setup and produced ion beams

The stability of CVL operation has been recently improved due to the replacement of old DC high voltage power supplies by contemporary stabilized arc-protected power sources. The CVL oscillator is totally replaced by a new laser. More reliable laser operation is expected in 2005 due to utilizing demineralised water for laser cooling. For that a dedicated laser chiller will be installed during the shutdown 2004.
The stable performance of the RILIS setup is of great importance for ISOLDE facility, therefore all possibilities for upgrading the RILIS lasers are to be considered in order to define an optimal way. Several scenarios for that are under discussions among the experts in the field of laser techniques:

4.2 Replacement of the old CVL by new CVL available on the market.

There are very few producers of copper vapour lasers in the world. We have contacted with "Oxford Lasers ltd.", manufacturer of CVL systems for industrial applications. The discussions of RILIS requirements with the managing director of this company were followed by the "Proposal for a high power master oscillator, power amplifier laser system" accompanied by the commercial offer. The average output power of this system is specified to 80 W at the pulse repetition rate of 10 kHz, which corresponds to the current CVL system. Its maintenance seems less time consuming and the beam quality (divergence) is better. But the pulse duration is by a factor of 1.4 longer (25 ns vs. 18 ns), which means less peak power of the laser pulses. Consequently, the efficiency of UV light generation in non-linear crystals will be reduced. Assuming a reproduction of the dye laser efficiency and an absence of the saturation in the frequency multiplication process, the expected power reduction factors are 2 for frequency doubling and 2.8 for frequency tripling processes. The ionization efficiency of some elements is directly proportional to the power of frequency-doubled UV beam (Be, Cu). Thus, for these elements such CVL replacement is not favourable. On the other hand, the ionization efficiency for many other elements probably will gain as far as more CVL power can be delivered to the ion source cavity due to the lower laser beam divergence.

4.3 Replacement of the CVL by solid-state lasers.

The dye lasers can be pumped by the solid state lasers (SSL) instead of CVL. Since the wavelengths of second harmonic generation of a Nd:YAG laser (532 nm) or Nd:YLF laser (524 nm) are close to the wavelength 511 nm of CVL, most of the currently used ionization schemes can be applied after such replacement. In addition, a broader choice of ionization schemes will be provided by making use of the SSL fundamental frequency, third and forth harmonics beams.

In the aspects of operation and maintenance SSL would be preferential as well: they do not require long-time preheating, the power supply control is relatively simple, the level of electromagnetic noise is much lower with respect to CVL, and the life-time of active elements can exceed 20000 hours.

Presently the world laser market is dominated by the SSL (24310 units sold in 2002[1]), in particular due to the growing applications for materials processing and medical therapeutics. The SSL technology is developing and its average pricing is reducing. Still most commercially available SSL have either too low repetition rates, or too long pulse duration or too low average power.

Therefore, an inquiry concerning the capability to produce a laser source specified for ISOLDE RILIS was sent to leading SSL producers. It is imperative for this replacement to keep the capability to produce a broad range of ion beams at the same or higher level of ionization efficiency as with existing CVL system. Therefore, requirements to SSL are formulated as follows:

Mode of operation	pulsed
Wavelength	532/527 nm, optionally also fundamental, 3rd and 4th harmonics
Pulse repetition rate	8-15 kHz
Pulse duration	15-20 ns
Output pulse timing jitter	< 3 ns
Average output power (532nm)	80 W or 40+40 W (two beams)
Power stability	+/- 5% over 24 hours
Beam divergence	0.1 mrad after expanding to 20 mm diameter
Beam pointing stability	0.02 mrad after expanding to 20 mm diameter

By present time 10 replies are received. There are few propositions of lasers with specifications very close to the requested ones. A call for tender can be announced as soon as funding for this replacement has been defined.

[1] K. Kincade and S.G. Anderson, Laser Focus World, 39, No.1, p.143 (2003).

4.4 Creating a new fully solid-state laser system.

It is now possible to construct all solid state tuneable laser systems, which will access the wavelengths of interest. Such a system would comprise a SSL laser followed by a number of optical parametric oscillators (OPO) or Ti:sapphire lasers which would then be frequency multiplied to the desired wavelength. This is an attractive long-term option. However in the short to medium term there are a number of major problems with this route that make it very unattractive for the ISOLDE facility at this time. These include:

- The need for very high powers compared to the state of the art for these types of laser.
- The need to generate high powers in the UV which will require frequency multiplication from the IR.
- The reliability of such a system would be questionable given the powers required and the number of state of the art units used.

The use of lasers of this type would probably require the ionization routes to be re-optimized as it is unlikely that the attractive wavelengths for the all solid state system would correspond to those currently obtained from the dye system.
The combined requirement for laser development and spectroscopic studies mean that a tremendous amount of R&D work needs to be undertaken before such a source could be fitted to a facility on which so much other work relies.

To some extent the R&D work on the development of all solid state laser system for RILIS application is included into the program of the joint research activity “**LAS**er techniques for **E**xotic nuclei **R**esearch” (**LASER**) in the frame of EU-funded project EURONS.

4.5 RILIS Upgrade Program.

The status of RILIS was reported to ISOLDE Collaboration Committee on 25.02.2003. At that time the RILIS laser system did not provide reliable operation. A necessity of RILIS upgrade was evident and the following program of laser upgrade has been presented:

1. Short term – improvement of the actual setup in order to provide as far as possible the conditions for reliable RILIS operation (2003).
2. Middle term – supporting the installation in reliable operational conditions until the appropriate solid state lasers will become available on the market (2004-2006).
3. Long term – replacement the laser setup by the new system which will be delivered in a result of the R&D in the frame of JRA LASER (2006-2008).

At present, the measures covering the short term and partially the middle term stages are implemented.
Development of ionization schemes for new elements and optimization of schemes for available RILIS elements requires carrying out dedicated laser spectroscopy research. To this purpose a build-up of separated laser installation is started at CERN within LP section of AB/ATB group. It will include two low pulse repetition rate SSL-OPO systems recuperated from CEA Saclay. The research work using this installation is expected to carry out as part of JRA LASER.
The next step requires an investment of the order of 500 kUSD for purchase of solid state pumping lasers for RILIS setup. The availability of the SSL at ISOLDE RILIS

setup will provide a possibility to apply it for pumping the dye lasers as well as for OPO and Ti:sapphire lasers.

The advantage of transition to a full solid state laser system is not obvious at present time. Due to the different wavelength range dye lasers provide more efficient ionization for some elements, while Ti:sapphire lasers can be used efficiently for some other elements. Therefore, a universal RILIS would include different types of tuneable lasers with accordingly optimized pumping lasers.

5 Radiation Protection Issues for a Beam Power upgrade of the ISOLDE facility

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5.1 Introduction

In the ISOLDE facility, radioactive isotopes are produced by proton bombardment of a thick target. The products are ionised, accelerated to an energy E = 60 keV, mass-separated and transported to experimental stations.
At present, the production target is bombarded by a protons with E = 1.4 GeV. The beam is extracted from the PS Booster PSB in pulses, each containing up to 3 10^{13} protons. The PSB can deliver one pulse every 1.2 seconds, half of which are dedicated for filling the Proton Synchrotron PS. The average proton beam current on the target is therefore 2.0 μA at the energy of 1.4 GeV, resulting in an average power dissipation of 2.8 kW in the target and on the following beam dump.
A recent proposal from the ISOLDE Group envisages to increase the average particle current to 10 μA, partly by making use of a faster cycling rate of the PSB, but mostly by the availability of higher currents of low-energy protons than today from a potential new linear accelerator, LINAC 4. This note highlights the different radiation protection issues resulting from the increased particle current in the projected facility, which is called High Intensity and Energy (HIE) ISOLDE.
In the chapter 0, the shielding of the target area with respect to the experimental area and to the zones accessible to the public around the facility against stray radiation from the target is described. Chapter 0 assesses the activation of the targets and the target area and the resulting radiation dose to personnel. Chapter 0 addresses protection against radioactive contamination. Chapter 0 treats gaseous and aqueous releases from ISOLDE into the environment and chapter 0 reviews the situation with respect to radioactive waste from ISOLDE.
The aim of this report is to point to the areas where the present provisions for radiation protection are insufficient for operation of HIE ISOLDE and where investment in technical solutions and manpower are required. The report is partly based on a Technical Note from the year 2000 [3], which came to similar conclusions.

5.2 Shielding of the target area

The purpose of the shielding around the target area is to protect members of the public outside of the facility and personnel working in the facility from stray radiation. It is designed such that the dose limits applicable to these groups of persons cannot be exceeded under normal operation conditions and in case of accidents.
The shielding must guarantee that the dose rate in spaces accessible to the public does not exceed 0.5 μSv h^{-1}, or 2.5 μSv h^{-1} in places without permanent occupancy (parking spaces, corridors, staircases, toilets...). In a supervised radiation area[1], such as the ISOLDE experimental area, the ambient dose equivalent rate is limited to 10 μSv h^{-1}. Only locally, at inaccessible positions, higher values can be tolerated, but they must not affect the global average over the hall.

[1] In the next revision of Safety Code F, « Protection against Ionising Radiation », the naming of designated radiation areas follows the conventions in France and other E.U. countries. The characteristics of the « supervised area » correpond largely to those of the presently defined «simple controlled radiation area ».

Line-of-sight shielding models [5] give a first, conservative estimate of expected dose equivalent H from the collision of high-energy protons with matter behind a shielding. Such models are based on a source term depending on proton beam energy and angle of radiation incidence $H_0(E, \theta)$, a - geometrical attenuation with total distance r and an exponential taking into account the radiation attenuation in a composite shield employing n different materials with thickness d_i and radiation mean free path lengths λ_i:

The source term is calculated for an energy of E=1.4 GeV and a target for one mean free path length in which 63% of the protons will react. This choice is conservative even for the densest targets employing lead. It does not take into account the additional neutrons emitted from fission in U-C and Th-C targets.

Before 1990, all shielding were designed under the assumption that the average beam intensity at ISOLDE is 10^{13} protons s^{-1} at an energy of 1 GeV [4]. This corresponds to a current of 1.6 μA and a power of 1.6 kW, lower than presently used beam parameters. The ISOLDE target area has been shielded with concrete walls and earth shielding against areas accessible to the public (the parking spaces and the Route Democrite). The thickness of this shielding, resulting from the 1990 estimations, is equivalent to 8 m of earth. The weakest point of the shielding is situated at the emergency exit from Bat. 179 to Route Democrite, where ambient dose equivalent rates can temporarily exceed the guidance value of 2.5 μSv h^{-1} at present proton beam intensities.
Between the target area and the separator areas are approximately 4 m of earth shielding, reinforced by 0.8 – 1.2 m of iron. The separator areas are shielded against the experimental area by concrete blocks, with a thickness between 1 and 3 metres. Access mazes with a width of passage of 1 metre lead from the experimental area to the separator areas.

For the proposed HIE-ISOLDE beam with a current of 10 μA, the concrete and earth shielding around the target area becomes insufficient for protecting the public: in 10 m distance behind an earth shield of 8 m thickness, the expected ambient dose rate is 14 μSv h^{-1}, exceeding the relevant dose rate guidance value by a factor of 6.
For places in the experimental hall close to the shielding of the separator areas, ambient dose rates may reach 30 μSv h^{-1} (access door to HRS separator area) or 80 μSv h^{-1} (at the GHM or GLM beam line). These values exceed the guidance value for supervised radiation area by a factor of up to 8.
It is well known that neutrons stream from the target area into the High Voltage room and from there into the experimental hall. The HV room has been equipped with an access control system to protect personnel from the significant dose rates prevailing therein when uranium- or thorium targets are used. Today, the "sea" of neutrons in the experimental hall creates an ambient dose rate of 1 – 2 μSv h^{-1}, measured with the radiation monitors on the wall opposite the target area. A five-fold increase in beam power would increase the ambient dose rate to 10 μSv h^{-1} for the whole hall, leaving no margin for the extraction of radioactive beams into the experimental area.

In the controlled separator areas and the High-Voltage Room, radiation monitors are included in the interlock chain of the access control system. Access to the High-Voltage room is only authorised when the ambient dose rate there is lower than 100 μSv h^{-1}. At present beam intensities, this occurs during operation with U-C or Th-C targets on the HRS separator.
Once the proton beam is turned off, authorised personnel can access the separator areas when the ambient dose equivalent rate in these areas has dropped significantly below that of a high radiation area (2 mSv h^{-1}). Even then, careful planning of the work and optimisation of the radiation exposure are mandatory.

5.3 Activation in the Target Area and Dose to personnel

The personal dose limit at CERN is 20 mSv, but for the reason of ensuring the legally required optimisation of exposure, an action level of 6 mSv in one year has been set. This value of annual personal dose may only be exceeded in exceptional cases with a special authorisation. Installations at CERN must be planned and operated in such a way that a foreseeable excess of the action level under routine operation conditions is excluded.

The secondary particle cascade from the impact of the proton beam on the ISOLDE target is activating all materials in the target area. Radioactive contamination in and around the front-end constitutes an additional radiation source and exposed the personal to a contamination risk.
Today, the dose equivalent rate in the Faraday cages around the two production targets is typically $H^*(10) \approx 4 \ldots 5$ mSv h^{-1}. This ambient dose equivalent rate puts severe constraints on so-called “hands-on” maintenance of the target and the front-ends. Each intervention is carefully planned and closely monitored by RP personnel. Interventions in the target area are deferred towards the end of the annual shutdown in order to benefit from radioactive decay. These protective measures result in an annual collective dose for the ISOLDE target- and separator between 15 and 25 man-mSv. Today, annual personal doses to a few specialised individuals are in the range between 4 – 6 mSv and therefore very close to the action level. The procedure of exchanging a whole front-end, which is required whenever a major breakdown occurs, leads to a collective dose of 3 man-mSv.

Activation and contamination and thus the dose equivalent rate resulting from them are proportional to the number of protons hitting the targets. An increase of the number of protons by a factor of 5 would result in an ambient dose rate in the vicinity of the front-ends of up to $H^*(10) \approx 25$ mSv h^{-1}. If one simply scales the annual collective dose at HIE-ISOLDE with the same factor of 5, it would become comparable with that of the entire SPS.
It is obviously not possible to plan for a fivefold increase of activation and contamination and to continue with the present “hands-on” maintenance procedures, because it is foreseeable that the action level for annual personal dose would be exceeded. Consequently, the front-ends and the targets must be constructed in a way that urgent interventions during the running time of HIE-ISOLDE occur only very exceptionally and do not take more than fractions of minutes. Even towards the end of a 6-month long shutdown, ambient dose rates will be so high that maintenance of the whole target-front-end system must be reduced to the absolute minimum. A front-end change, for example, would lead to a collective dose of 15 man-mSv. This implies a

redesign of the present target/front-end system, using manipulators and robots not only for changing targets but also for maintenance by changing whole functional groups of the front-end, when required.

5.4 Protection against Radioactive Contamination

Personnel working at ISOLDE are exposed to external radiation, as everywhere else in designated radiation areas at CERN. In addition, they risk being exposed to internal radiation after contamination with radioisotopes. The annual dose limit of 20 mSv and the action level of 6 mSv are understood as limiting the sum of external and internal exposure.

The isotopes produced in the ISOLDE targets present a risk of widespread contamination in the facility. The vacuum system in the target and separator areas is heavily contaminated. Past the switchyards, the contamination is becoming gradually weaker, but it cannot be neglected when intervening on the vacuum system in the experimental area. Turbo molecular pumps, backed up by oil-filled roughing pumps, maintain the vacuum. Radioactive isotopes are contaminating all vacuum pipes and the interior of the turbo molecular pumps, making standard maintenance impossible. The volatile isotopes are retained in the oil of the roughing pumps. These are installed at various places in the separator areas and the experimental area.
Depending on the type and concentration of isotopes captured in the oil, the pumps can have a significant dose rate (several mSv h^{-1} on contact). The annually required oil change exposes the personnel to a high contamination risk. The oil of the pump on the High Resolution Separator HRS contains 32 MBq of α-emitters (mainly $^{208, 209, 210}Po$). This corresponds to the 16 000-fold of the authorisation limit of these isotopes as defined in the Radiation Safety Code [1] in accordance with [2,6]. Extensive protective measures are required for this operation, which must be performed in a radioactive work sector of the highest protection class A [6].
Finally, the storage, conditioning and elimination of contaminated waste are more complicated and costly than for a comparable volume of activated waste. In the present layout, the HRS separator area (not classified as work sector of class A) houses several roughing pumps for the separators and front-ends. Changes of the layout of the experimental hall may result in installing more vacuum equipment in the separator areas.
In the separator areas, contamination risk occurs whenever the separators, switchyards and other beam line components are opened for maintenance. Due to the high ambient dose rates during operation ($H^*(10)$ > 100 mSv h^{-1}), the separator areas are presently classified as primary accelerator areas. There is no physically tight separation between them and the experimental area, permitting free exchange of air-borne contaminants during maintenance or in case of failure. Some control equipment is installed in one separator area, exposing its maintenance personnel to external and potentially internal radiation.
Interventions in areas with high dose rates with the risk of personnel contamination require thorough job- and dose planning and the close supervision by RP personnel. At present, one RP engineer is delegated for work at ISOLDE, for difficult interventions he receives backup by another engineer. On average, 1.5 FTE of RP personnel are monitoring work at ISOLDE.

While optimisation of radiation protection at the present ISOLDE facility would benefit from a strict separation of the different areas (target-, separator-, vacuum- and experimental), this will become indispensable for the increased contamination risk in HIE-ISOLDE.
With a contamination of α-emitters at the 100000-fold of the authorisation limit, the standard operation of changing the pump oil requires additional protective measures against contamination and external radiation for the maintenance personnel. Other personnel must be protected from external and internal exposure by the vacuum system. All potentially contaminated vacuum equipment, including that from the experimental area, should be grouped in a shielded work sector of class A exclusively reserved for vacuum applications.
The separator areas shall be freed from all indispensable equipment, classified as a radioactive work sector, at least during maintenance operation, and properly isolated from the experimental area.
The ISOLDE (and HIE-ISOLDE) experimental area is provisionally classified as a work sector of class C [6] although the building does not fulfil the required fire resistance requirements for such an area. The activity which can be manipulated in unsealed form in the hall is limited to the 100-fold of the authorisation limit. This limitation allows conducting experiments with reasonable amounts of gamma/beta emitters. Use of short-lived gamma/beta emitters may be limited by the ambient dose rate they create in the experimental hall, and which is limited to 10 μSv h^{-1}. The s availability of unsealed alpha-emitters for experiments is seriously limited by their low authorisation limit. The benefit from an increased production rate will be marginal for experiments relying on collected radioisotopes in unsealed form or on short-lived gamma/beta emitters because of the limitations of the experimental area.
An overall increase of the risk of external and internal irradiation calls for increased efforts of the Radiation Protection Group for monitoring, planning and supervision of work at HIE-ISOLDE.

The increased risk demands also a review of the practice to allow control of the mass separator to CERN users. The around-the-clock presence of operators in a HIE-ISOLDE facility with fivefold increased proton current would greatly benefit operational safety.

5.5 Radioactive Releases from ISOLDE

The annual dose limit for the public from air releases is 300 μSv for the whole of CERN [1]. In Switzerland, no further optimisation efforts are required once members of the public are exposed to less than 10 μSv a^{-1} [1,2]. It is considered good practice at CERN not to exceed this constraint for gaseous releases. For comparison, exposure of the public from releases from nuclear power plants in Switzerland is between 1 and 5 μSv a^{-1}. In 2004, air releases from TT10 contributed 1.3 μSv to the dose to members of the public. This value will increase with the operation of the CNGS beam, a first, conservative estimate for 4.5 10^{19} protons on the CNGS target indicates an annual dose of 5.3 μSv. The unrestricted running of all experimental facilities on the Meyrin site will call for technical solutions to reduce releases and the dose to the public.

For assessing the impact of radioactive releases on the environment and the public, CERN implements the usual approach to estimate the dose to a member of the "critical group" of the public. The critical group is defined such that the impact of releases from CERN is maximised (by age, by the place of residence or work and by living habits). If the dose to the critical group is not exceeding limits and can be shown to be optimised, this will be true for an arbitrary member of the public. The calculation of dose to a member of the critical group follows regulations from the competent authorities in the host states [7].

There are three types of radioactive gaseous releases from ISOLDE:

1. The release of mainly short-lived positron emitters (^{11}C, ^{13}N...) and ^{7}Be. They are produced via the spallation reaction by the secondary particle cascade resulting from the 1.4 GeV proton beam hitting the target. During operation of ISOLDE, these gases are emitted continuously via the ventilation system.
2. The release of spallation products produced in the ISOLDE targets via the vacuum system of the separators and the experimental hall. Tritium and long-lived noble gases (^{42}Ar, ^{85}Kr and ^{127}Xe) are not retained in the roughing pump oil of the vacuum system. These gases are stored in retention tanks and released after allowing for 5 – 12 months for radioactive decay. The retention tanks are placed in the ISOLDE target area and they have become activated, making an assessment of their activity contained in them by an external dose rate measurement impossible. The tanks are filled up to a positive pressure of 2000 hPa, forcing radioactive gases out in case of a leak.
3. The short-term release of $^{219,\,220}$Rn and its decay products $^{211,\,212}$Pb and of iodine isotopes during the change of U-C and Th-C targets.

In a nuclear or accelerator facility it is standard practice to release activated air via a filtered and monitored stack. The filters will retain most aerosols (notably ^{7}Be) and the monitors will allow quantifying the releases and demonstrating that no limits are exceeded and that the operation of the facility is optimised.

The ISOLDE stack constructed in 1990 was too short to allow for complete mixing of the released air and did not permit reliable release measurement. During the shutdown 2004/5, the ISOLDE facility has been equipped with a new, longer stack. This stack guarantees a laminar flow pattern, the prerequisite for an accurate airflow measurement and a representative air sampling. Reliable figures on the release of short-lived β^+-emitters will be available during 2005. Only then it will be possible to estimate the consequence of an increase of beam power by simple scaling.

At constant beam energy, the production of short-lived β^+-emitters from spallation in air will increase proportionally to the beam current. It may become necessary to significantly modify the ventilation and release system to cope with increased air activation.

For the spallation products from the target, the proportionality to release is mitigated by the decay time, but for the long-lived isotopes of noble gases in the retention tanks the final result will remain approximately proportional to beam power.

The impact of the releases from the retention tanks is monitored by streaming the gas through a monitor chamber. There is no sampling bias involved. The calculated dose to the critical group of the public is negligibly small compared to the short-lived β^+ emitters. As long as the retention tanks are sufficiently dimensioned to allow storing radioactive gases for sufficient decay time, releases will not represent a problem. At the increased production rates of radioactive gases at HIE-ISOLDE, the retention tanks should allow external monitoring of the contained activity and they should be inherently safe against leakage, as for example at SPIRAL in GANIL [10].

The Rn-emanations from target and front-end during target changes must be reduced by an appropriate design of new targets and front-ends.

A second pathway of activity releases is water. Rainwater infiltrates the earth shielding over the ISOLDE area, may be activated and contaminated, and reaches the drainage system of CERN or may reach the ground water. Moisture of unknown origin is regularly observed in the target area. The source of the moisture may be in communication with drainage or ground water. Before increasing beam intensity and activation levels, a sampling pit shall be installed in the vicinity of the ISOLDE target area; permitting regular controls the of the water activation. The water from the ISOLDE facility is drained towards the CERN outlet “Car Club” and discharged into the river Nant d’Avril (CH).

5.6 Production and elimination of radioactive waste

Radioactive waste is defined as activated or contaminated material or equipment for which no further use is foreseen and which can be disposed of. Legislation and reglementation in the host states impose a strict control over radioactive waste. Only under well-defined technical and administrative conditions may radioactive waste be released for reuse, for example as scrap metal. CERN disposes of intermediate storage space for radioactive waste. A treatment- and conditioning centre is in preparation. There, radioactive waste will be prepared for the definitive transport to radioactive waste repositories in the host states.
It is CERN policy that the producer of radioactive waste bears the cost of its elimination [1].

In contrast to most radioactive waste from other accelerators at CERN, waste from ISOLDE generally presents a substantial contamination risk. For the risk of external and internal exposure from ISOLDE waste, the same remarks as in chapter 3 and 4 are applicable. At the end of the annual shutdown, about 30 spent targets are transported to a provisional storage area in the ISR, where they await their elimination from CERN. The storage area for targets has 350 places; it is presently saturated and cannot be extended in the foreseeable future. A project has started in AB department and the Safety Commission to define the necessary tools and procedures for characterisation, conditioning and transport of the targets to the Federal Intermediate Storage Centre (Bundeszwischenlager BZL), located at the Paul-Scherrer Institute PSI in Villigen, Switzerland.

The aim of HIE-ISOLDE is an increased production of radioisotopes for research purposes. This will go hand-in-hand with a proportional increase in the production of radioactive waste, in particular spent targets.
After an increase of proton beam current, the total activity declared as waste would increase proportionally. This will have consequences for the tools and procedures for waste conditioning at CERN. It will also have an influence on the price of elimination, which is determined by the volume of the waste. However, the waste volume cannot be reduced arbitrarily (e.g. by super compaction), because of additional limits on total alpha activity per storage container. Two limiting cases can be envisaged:

1. The lifetime of the targets is related to the total number of protons received. The present lifetime limit is approximately 10^{19} protons. If the targets remain unaltered, the proton beam increase would result in an important increase in the volume of waste (up to a factor of 5), with the same activity per target. This amount cannot be handled either in the facilities envisaged for the

department.
2. If the target lifetime would be increased, the result could be the storage of targets containing up to 5 times more activity than at present. This will impose longer waiting times before and improved protective measures during pre-conditioning operations. All installations and procedures envisaged in the project for target elimination should be designed with these consequences from a beam current increase in mind.

In either case, a new provisional storage area with the necessary protective measures against contamination needs to be provided at CERN for ISOLDE targets.
Finally, an increase of proton current will lead to higher activation levels in the whole HIE-ISOLDE facility. Final dismantling, conditioning and storage of parts or the whole of this facility will become more complicated and costly and the necessary funds for this must already be foreseen in the CERN budget.

5.7 Summary and Conclusions

The proposed increase of proton beam current in the HIE-ISOLDE facility will make the current provisions for radiation protection inadequate. Their necessary upgrade will require numerous modifications to the existing facility, new and improved work procedures and additional staff in the areas of

- Shielding and access
- Optimisation of external irradiation
- Protection against contamination
- Optimisation of releases into the environment
- Storage and conditioning of radioactive waste.

All items in this list must be addressed during the planning stage of HIE-ISOLDE in order to define technical and manpower solutions. Only after this evaluation, the approximate financial cost for improvements and additional staff can be reliably estimated.

5.8 Acknowledgements

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[3] Another facility is planned in the framework of the TITAN project at TRIUMF, which is also aiming for high-precision mass measurements on ISOL type produced radionuclides. First TITAN tests are scheduled for 2007.

6 Optimized ISOLDE Operation

U.Köster, T. Nilsson

6.1 *Increased efficiency of the Radioactive beam*

6.1.1 The production target life-cycle

The operation of the ISOLDE facility differs in many respects from other accelerators at CERN, being completely centred on the life cycle of the production target/ion source assembly used. The typical consecutive steps and associated required times are:

1. Mounting on separator front-end (0.5 – 1 days)
2. Pumping, outgassing and heating of target (2 days)
3. Setting up of ion source and separator with stable pilot beam (0.5 day)
4. Setting up beam transport to experimental set-up with stable pilot beam (0.5 -1 days)
5. Optimizing position of proton beam on target, yield determination, target tests (0.5-1 days)
6. Production run for physics (4-12 days)
7. Cooling time for actinide targets (3 days)

From above, it is clear that the inherent duty factor of one target station cannot exceed 40-60% depending on the target type. Furthermore, points 1, 3, 5 are done by AB staff (Engineers in charge) and should, within scheduled operation, be confined to standard working hours which puts severe constraints on the scheduling.

6.1.2 Push-pull mode operation

The availability of the two separators GPS and HRS allows for operation of the two separators in so-called push-pull mode, i.e. that the target set-up and cooling steps on one separator take place in parallel to the physics run on the other separator. This mode has been in practice since 2001 and has helped to maintain or even increase the number of physics shifts delivered at the facility, in spite of a gradually shortened running period.

Preparation of the RILIS ion source (see chapter 4) can normally be done in parallel to the setting up of the target, but some of the necessary hardware is not doubled which prohibits to completely independently set-up of the RILIS when used in two consecutive runs on the both separators. This can to some extent be alleviated by scheduling non-RILIS runs in between, but with the increased usage of the RILIS, this becomes increasingly challenging.

6.1.3 Parallel operation

The PS Booster permits pulse-to-pulse switching between the two separators, ISOHRS and ISOGPS. This opens up the possibility of parallel operation, which has been utilized at ISOLDE to some extent. In addition to the lower intensities for each experiment compared to single-user mode, the ISOLDE beam-line layout constitutes a serious bottleneck for further exploiting this mode. Currently, all beams have to pass the central CA0 section with the exception of the "collection beam-lines" GHM and GLM. Possible technical solutions how to circumvent this is described in 7.2.

1. A real synchronous operation between GPS and HRS is presently hampered by the common central beam line. However, the real bottleneck is only about 3 m long: the CA0 section. More than 70% of the entire ISOLDE beam time is presently

used at the beam ports LA1 & LA2 (nuclear spectroscopy), LA3 (COLLAPS), LA4 (COMPLIS), RA1 (REX) and the monitoring tape station in CA0, i.e. none of them using the CB0 section. Doubling the CA0 section and replacing the "merging switchyard" and the following switchyard by "crossing switchyards" would allow a real synchronous operation of GPS and HRS: while one is fully running the other could be used with stable beam for set-up or with 1 pulse/supercycle for target tests, for the set-up phase with radioactive beam, for nuclear or atomic spectroscopy with less exotic isotopes which require a sufficient decay period with beam off, for collinear laser spectroscopy, tilted foil polarization or NICOLE experiments which profit from "equidistant" pulse conditions, etc. Thus removing the CA0 bottleneck would lead to >50% increase of the effectively available beam time! Multi-user capability is a central point of the EURISOL Design Study. Hence, the modification of the CA0 section would give a perfect "prototype" for EURISOL.

7 Mass separators and beam transport

7.1 HRS (High Resolution Separator) upgrade: improved resolution

High-resolution operation of the HRS is crucial for a large class of experiments where isobaric contamination from more abundantly produced isotopes can disturb the measurements seriously. The requirements for successfully suppressing unwanted contaminants vary from case to case, with a needed relative mass resolution $\Delta M/M$ between 8000 and 30000.

The performance of the HRS is currently limited by 3 factors:

- Emittance of the ion source
- 2nd order distortions in the magnetic dipoles
- Need for improved beam diagnostics and collimation

In order to realise a significant improvement in the HRS resolution, all three of these issues need to be addressed. A modest improvement in performance and ease of operation may be achieved by addressing just the 2nd and 3rd points.
The three points listed above are exactly those which are key requirements to the EURISOL high-resolution separator [1]. An upgrade of the ISOLDE HRS as suggested in this document would at the same time serve as a prototype of the EURISOL HRS.

7.1.1 Emittance of ion source: RFQ-BC

Construction of an RFQ beam-cooler is already underway at ISOLDE as described in Chapter 8. In the first case it will be installed after the HRS, where it will improve beam transport but will not have any effect on HRS performance. Once thoroughly characterised, one may consider installing the RFQ-BC before the 1st HRS magnet. The RFQ-BC is expected to reduce the beam emittance to ~3 π mm mrad, which would make resolutions of > 10 000 attainable. The RFQ would only be beneficial to HRS resolution if beam distortions in the separator magnets are eliminated. And the resolution could only be used if the beam diagnostics are upgraded. The RFQ would also require a pre-separator after the source, probably a Wien-filter, and suitable beam-matching sections. To accommodate the new equipment, major modifications would be needed to the concrete & earth around the HRS. Altogether, this work entails a major rebuild of the HRS.

7.1.2 Optical aberrations in magnetic dipoles

Beam distortion in the HRS may be eliminated by magnetic multipoles in the separator magnets. The existing multipoles have been shown to be ineffective, and it is proposed to modify the magnet pole faces to attain the correct field shape. This technique has not been used before, and an offline test is highly desirable before considering such a major modification to a running machine.
A multipolar separator magnet should be built and tested offline. Essentially a small isotope separator should be built. The prototype magnet could be of the same kind proposed for the EURISOL high-resolution separator, and is expected to cost 200 kCHF including design. Vacuum chambers, beam-matching sections, and beam-diagnostics would also be needed (see below). A "spare" standard ISOLDE front-end could be used as a beam source and part of the beam matching. Once validated offline, the same principles may be applied to the HRS. With suitable preparation the magnet modifications could be done in a shutdown, without eating into the online running period.

7.1.3 Beam diagnostics

The existing slits and scanners are ill-adapted to the extremely narrow beams at the HRS foci. Moreover, they give no clue as how to optimise the beam shape and should be replaced with new slits, scanners and emittance meters. Suitable emittance meters are currently under development at ISOLDE. The existing fixed-needle beam-scanner (FNBS) could be copied and adapted slightly to make suitable scanners. A new development is needed for the slits. A new scanner/slit/emittance-meter box should be installed at the 1st and 3rd foci of the HRS.

7.1.4 Planning

The 3 points listed above are interdependent, and consequently the order in which they are carried out is important. A suggested plan is outlined as follows:

- Install & test RFQ after HRS
- Build & install beam instrumentation boxes at 1st and 3rd foci
- Build & test prototype EURISOL magnet (test of multipole concept)
- Replace HRS pole faces & add correctors if necessary
- Test high-resolution mode using low emittance source & slits in 1st focus
- Major HRS rebuild:
    - Install RFQ before 1st focus
    - Install pre-separator (Wien filter) before RFQ
    - Add beam-matching sections (everything from the 1st focus onwards stays the same)

Figure 7.1 Illustration of a possible sequence of upgrades to the HRS

The theoretical performance would be:

- Resolution of 1700 for 40 pi mm.mrad beam (e.g. plasma ioniser)
- Resolution of 6700 for 10 pi mm.mrad beam (e.g. surface ioniser)
- Resolution of 20000 for 3 pi mm.mrad cooled beam

Currently, a resolution of 4000-6000 from sources with emittances <~10 π mm.mrad (RILIS) can be achieved.

7.2 The CA0 bottleneck: parallel operation of GPS and HRS

The majority of the experimental installations at ISOLDE receive radioactive ions through the central beamline system, into which the beams from both the HRS and the GPS separators are merged. There are two classes of solution to the CA0 bottleneck: building a second parallel beamline, or pulsing the existing beamline.

The first solution is heavily constrained by the existing beamline layout. A matrix-type switchyard, in the style of that proposed for EURISOL is not possible, due to the layout of the existing beamlines: neither the incoming nor the outgoing beamlines can be moved more than a few cm without disrupting the whole layout of the hall. A very complex (and costly!) switchyard could be imagined, but it is extremely difficult to create a design which, in the small space available, maintains efficient beam transmission without sacrificing operational flexibility.

Pulsing the CA0 beamline, on the other hand, would require almost no modifications to the hardware. The tape station would be accessible by either separator, even during parallel operation. The control system already designed to deal with pulsed machines, so the software modifications are not expected to be dramatic. The elements which would need to be pulsed are labelled in red in Figure 7.2.

Figure 7.2 Existing beamline layout around CA0

7.2.1 Modifications

- Two "contexts" created: one for HRS and one for GPS
- Scanner and faraday cup readout needs to be synchronised
- Switching time of the electrostatic supplies improved
- Timing hardware needed
- Synchronisation of the beam gates
- Software control & visualisation of timing

7.2.2 *Limitations*

- Cannot share a single separator amongst two experiments (if required, this could be achieved at the expense of more complicated controls)
- Cannot share beam amongst two experiments in the LA section, or two experiments downstream of CB0 (if this is a serious restriction, we could decide to pulse all ISOLDE beamlines; pulsing CA0 would be just a stepping stone before moving to fully pulsed beam transport)
- In the case of two experiments each using stable-beam or slowly-released, long-lived species, up to 50% of the yield is lost.
- Short time-slices may not give enough time for the beam diagnostics instruments to read out.

Examples of operation

Figure 7.3 shows two examples beam-sharing in CA0. The settings for the CA0 elements are stored in two "contexts". Switching between the contexts may be triggered by timing signals linked to the PSB cycle, or by timeouts. In the first scenario, the CA0-GPS context is loaded n_g ms before an ISOGPS pulse. Likewise the CA0-HRS context is loaded n_g ms before an ISOHRS pulse. In the second scenario the CA0-HRS context is loaded n_h ms before an ISOHRS pulse. t_h ms later a timeout causes a switch back to the CA0-GPS context.

Triggers may be linked to any of the normal PSB signals (including ALL), and are sent a certain number of milliseconds before the proton pulse arrives to give the hardware time to react (does this time need to be adjustable, or can it be fixed?)
Timeouts are adjustable from ***x*** ms to **xx.xxx** s, or set infinite (disabled).
Beam gates should open and close in synch, allowing for hardware reaction times e.g. the HRS beam gate is closed:

- 1 ms before an ISOHRS proton pulse arrives
- 5 ms after an ISOHRS proton pulse arrives
- if the HRS user beam gate signal is low (=closed)
- if the CA0-HRS context is not set

To make things easy to tune, a number of standard timings should be set up for often-used scenarios.

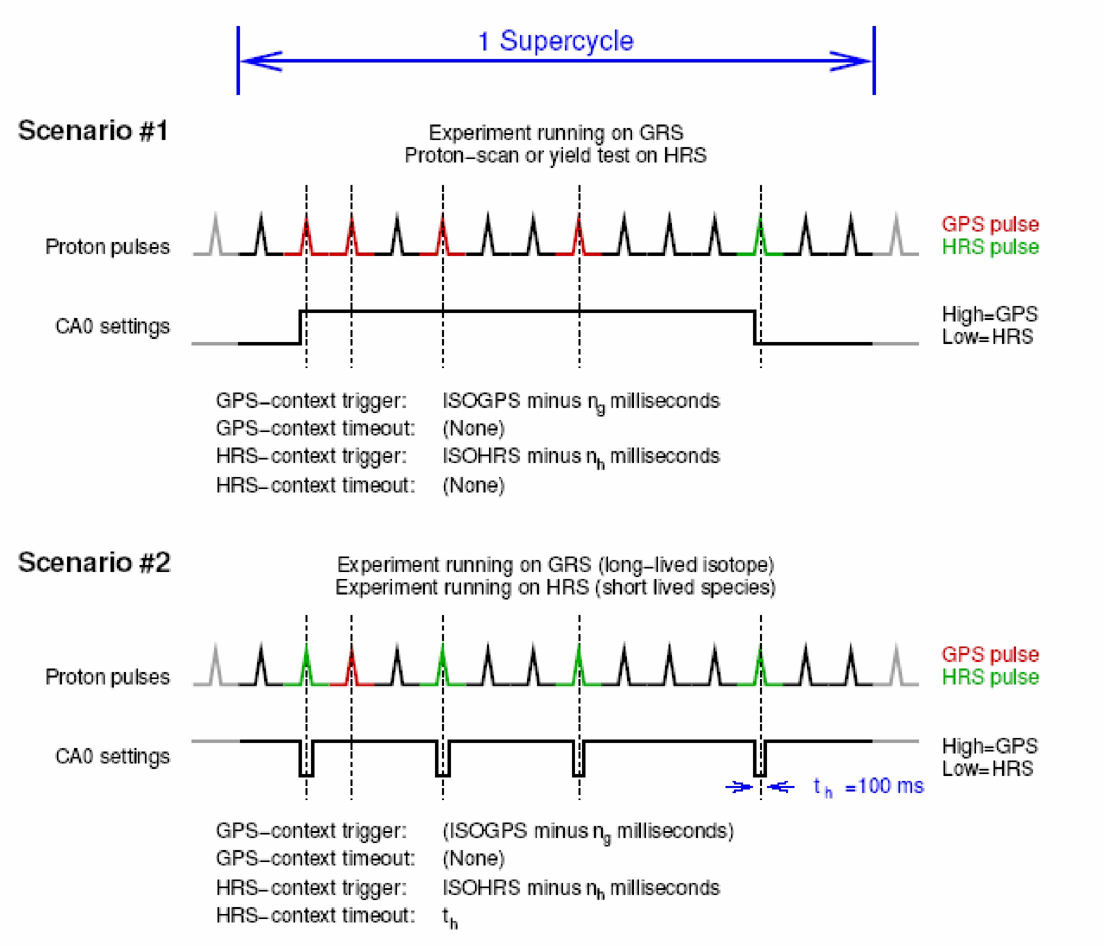

Figure 7.3 **Examples of beam sharing in CA0**

[1] The EURISOL Report, ed. J. Cornell, GANIL 2003, http://www.ganil.fr/eurisol/Final_Report.html

8 ISCOOL project: cooling and bunching RIBs for ISOLDE

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Abstract

As part of the upgrade of the ISOLDE facility, the design and construction of a new Radio Frequency Quadrupole ion Cooler and Buncher (RFQCB) has been carried out to improve the optics properties of the beam that is provided to the experiments. In this contribution an overview of the technical aspects involved in the project are presented, including the location and performances expected, and the design of the different technical systems.

8.1 Introduction

Nuclear physics has been a very productive field in the last decade. The quantity of RIB (Radioactive Ion Beam) facilities has increased and therefore the number of experiments and institutes involved is every time higher.

The main implication is the requirements of the experiments about the optics of the beam provided for the facility are more and more stringent. In particular new experiments propose better beams, with higher intensity, smaller transverse emittances or bunched beams with small longitudinal emittance (energy spread and bunch width). Furthermore each experiment needs different optical properties conditions to assure optimum results.

In this frame new devices have been developed to improve the beam optics parameters of the RIB facilities. At ISOLDE [1], one of the apparatus that have shown a best performance for this task around the world, the RFQCB (Radio Frequency Quadrupole Cooler and Buncher) [7][8][9] was chosen for installation in the ISOLDE beam line to improve the optical properties of the beam, with a maximized efficiency. Such beams will greatly enhance the selectivity of collinear spectroscopy, as exemplified in JYFL [9]. Bunched beam will also simplify the injection of ISOLDE beam to various devices, like ECR or EBIS. In fact, use of an RFQCB can be seen as an alternative injector to REX-EBIS, eventually replacing REXTRAP. Cooled beams will in general improve ion transport through the complex beam line system of ISOLDE. A clear gain is foreseen with those experiments which require beam transport through set of beam defining collimators. An example of such experiment is low-temperature nuclear orientation apparatus NICOLE.

8.2 The ISCOOL project

The ISCOOL (ISolde cooler) project is devoted to the implementation at the ISOLDE beam line of a new RFQCB which will serve most of the users and experiments. The main aim of this project is to adapt the optical properties of ISOLDE RIBs to the present requirements of the experiments, pushing forward the evolution of the research at the facility, e.g. opening the facility to new possible applications as the collinear laser spectroscopy with bunched beams mentioned before [12].

8.2.1 Location and layout of the beam line

Once installed on-line at ISOLDE, ISCOOL will be placed in the beam line section just downstream the HRS (High Resolution Separator), from the final focus of the separator up to the merging switchyard which joins the GPS (General Purpose Separator) and HRS beams [1]. The final emplacement was chosen taking into account space constraints of the building, which make impossible to install the RFQCB elsewhere to be able to improve both GPS and HRS beams.

Figure 8.1Location at ISOLDE: placement of ISCOOL in the layout of the ISOLDE hall (*left view*), layout of the present beam line (*centre view*) and picture of the present appearance of the beam line (*right view*).

A new beam line was designed to replace the existing one (see Figure 7.2), which is made of two quadrupole triplets at centre position. The present project is to remove the present beam line and to replace it for the RFQCB and two new quadrupole triplets, one upstream and another downstream the RFQCB. The first quadrupole serves to focus the beam into the cooler and the last one to focus the beam into the merging switchyard. In addition the RFQCB has been designed as a removable device which allows replacing it for a straight beam line section, permitting ISOLDE to deliver RIBs to the experiments without ISCOOL. Figure 8.2 shows the diagram of the new beam line with the cooler. The new beam line extends between the two vacuum valves (new vacuum section). Figure 8.3 represents the beam line in case ISCOOL has to be removed, e. g. physics with light ion beams. In that case the cooler is replaced by a straight beam pipe and the turbo pump at the injection side is kept in the beam line and pumps down the vacuum section.

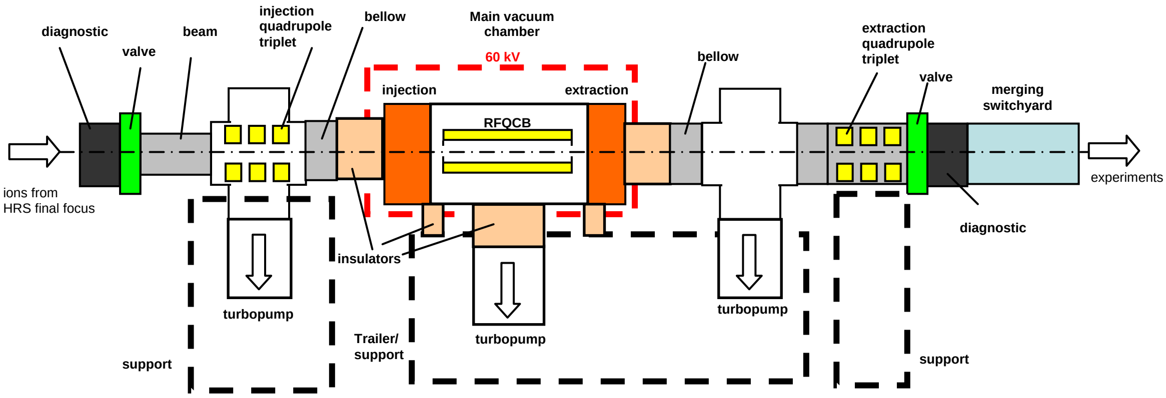

Figure 8.2. Diagram of the new beam line.

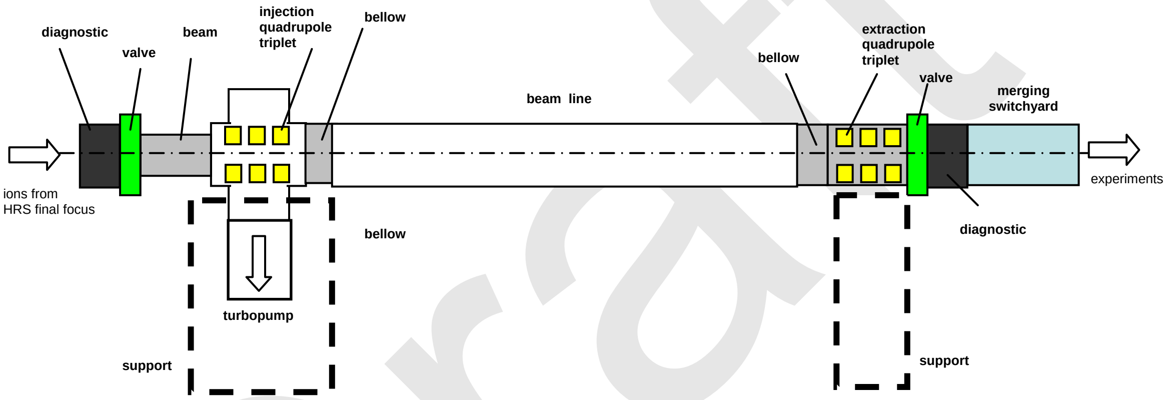

Figure 8.3. Diagram of the new beam line without the RFQCB.

Figure 8.4 illustrates a 3D design of the beam line. A high voltage safety wall encloses the area to avoid people enter inside the high voltage region. The wall has to permit to access the area in any case for intervention in safety conditions (automatic switch off of the high voltage). *Trailer/support* (Figure 8.2) represents the part of the beam line which is removed and placed in another location for modifications or just for temporary store.

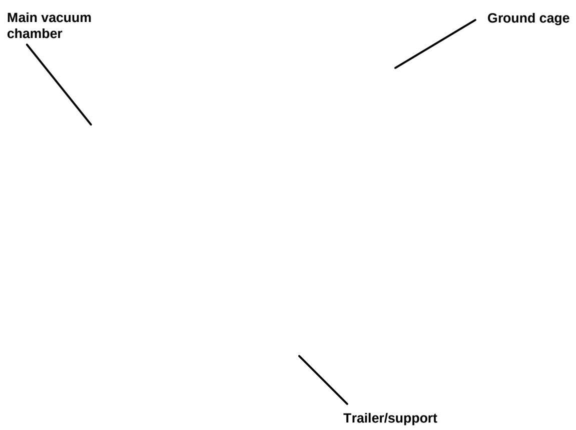

Figure 8.4. 3D layout of the new beam line

8.2.2 Performance of ISCOOL

The main goal of ISCOOL is to cool the beam coming from the HRS (High Resolution Separator). The beam at that point can have a very spread range of optical properties. One of the worst cases is shown in the Figure 8.5. The plot shows the phase space in *(x,x')* coordinates of an ion beam just out of the HRS made of CO (left peak) and N_2 (right peak), both A=28 u. Hence the ion beam has very low optical properties once is out from the HRS, and losses occurs along the way from HRS to the users. ISCOOL has been designed to accept the large transverse emittances provide in some cases by the ion sources, e.g. around 40π mm·mrad at 60 keV for plasma ion sources. ISCOOL will reduce significantly the losses due to the transport along the beam lines up to the experiments thanks to decrease the transverse emittance to values around 1π mm·mrad at 60 keV.

Figure 8.5. Plot of the transverse emittance of a beam out from HRS.

Apart from ion cooling, ISCOOL also bunches the RIB. For a bunched beam either *energy spread* or *bunch width* can be optimized by proper selection of operation parameters in an extraction part, these parameters can be chosen among some range (see Table 8.1).

Mass range	10÷300 u
Operating beam energy	<60 keV
Acceptance	< 40 π mm·mrad
90% Transverse emittance (60 keV)	<3 π mm·mrad
Bunch width	< 10 μs
Energy spread	<1 eV
Maximum space charge density	~10^7 ion/cm^3
Cooling time	10 ms ÷ 10 s
Length quadrupole	800 mm
Radius quadrupole	20 mm

Table 8.1 Main specifications of the RFQCB

8.2.3 Modifications of ISOLDE operation

8.2.3.1 New time structure of the HRS

The implementation of the RFQCB after the HRS will provide a new time structure for ISOLDE. The extraction optics of the RFQCB will become the new starting point of the ISOLDE beam optics. The reason is that the optics of the beam released by ISCOOL, mainly the transverse emittance, is not depending on the type of the beam entering into the cooler. Moreover the capability of ISCOOL to convert the quasi-continuous ISOLDE beam [1] in a bunched beam links the timing of the system to that of the HRS front-end. The new timing at ISOLDE will look much as presented in the Figure 8.6.

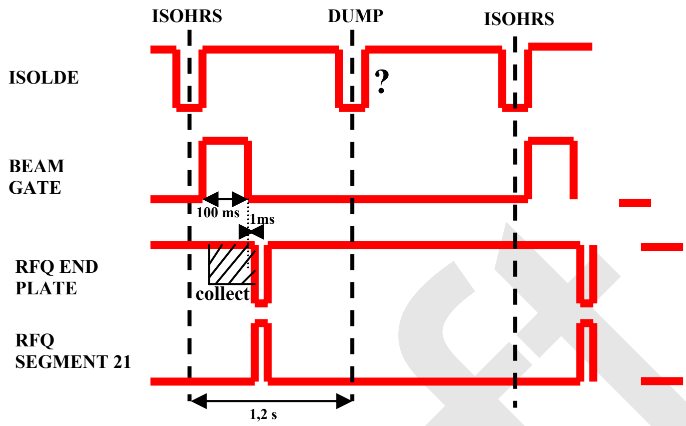

Figure 8.6. New time structure for ISOLDE HRS

ISOLDE HV corresponds to the signal sent to the high voltage power supply of the HRS front-end platform. As explained in [1], the voltage drops just 35 µm before the impact from the PSB (Proton Synchrotron Booster) and comes back to the initial value (normally 60 kV) 5 ms afterwards. Once the beam is produced at the ion source and is accelerated to the corresponding energy, the RIB that will be transported to the users can be selected by using the BEAM GATE signal. With the BEAM GATE is possible to choose the best moment to capture the RIB (Radioactive Ion Beam) and to kick off the beam at any time. In the figure, high values of the signal BEAM GATE indicates the time when the device is opened and beam is thus transported. The BEAM GATE signal transforms the ISOLDE beam in a quasi-continuous beam with bunches of 100 ms width every 1.2 s.

The new capabilities afford by ISCOOL are based in the signals sent to the axial electrodes whose main function is to trap, bunch and extract the beam. The signal RFQ END PLATE corresponds to the potential of the last axial electrode of the trap and determines the time that the beam is collected into the trap. Once the potential of the last electrode is decreased the bunch of ions accumulated is expulsed out and accelerated by the extraction optics up to the desired beam energy. The potential of the last axial electrode is decreased for a period which assures that the bunch is completely released but forbidding not trapped ions exit from the trap, avoiding an increase of the time width of the bunch.

If the time spread of the bunch needs decreasing, one of the axial electrodes placed in the last part of the trap structure can be used to “kick out” the beam (signal RFQ segment 21). The signal RFQ SEGMENT 21 shows the behaviour. Just when the potential of the end plate is switched off, the potential of one of the last segments can be increased provoking a reduction of the time spread of the bunch but also an increase of the energy spread, since the ions that are further from the exit hole in the instant that potential of the end plate is switched off will have more kinetic energy due to the increase in the potential of one of the last segments.

On the other hand, some changes in the present beam gates are to be made. Due to constraints in the length of the beam line, the user's beam gate placed in the ISOLDE beam line has to be removed. Hence only one beam will be left just before the HRS magnets.

8.2.3.2 Remove of the users beam gate

Nowadays at ISOLDE there are two beam gates to stop the beam: one before the mass separators and controlled by the operators and another after the mass separators which can be controlled by the users. The beam section where ISCOOL will be installed (see Figure 8.1) contains the users beam gate. The goal of this device is that the user can block out whenever the RIB released from the separator to the experiment. Due to the installation of ISCOOL and the length constraints, this device has to be removed. Nevertheless the users will still be able to control the beam in the same way than before, although the device that will be controlled will be the beam gate before the mass separators (the only one remaining).

8.3 Technical design of ISCOOL

8.3.1 Optics system

The main goal of the ISCOOL project is to improve the optics of the ISOLDE beam line. The device is considered as a new starting point for the optics of ISOLDE so a lot of care has to be taken for the design of the optical parts. In the following a general description of the deceleration (injection), cooling and bunching, and acceleration (extraction) parts are done.

8.3.1.1 Injection into the RFQCB

The injection of the ion beam into the RFQCB is a crucial point of the device. The objective is to avoid losses due to ions hitting the electrodes or too energetic ions colliding with the buffer gas. The ISOLDE beam is normally transported at 60 keV and the injection energy into the quadrupole has to be around 100 eV, therefore a deceleration system is required. The system that has been chosen is the use of two injection electrodes that, combined with the injection plate of the quadrupole cavity, assure an efficient injection of all the ISOLDE beams. To test the geometry some simulations in SIMION were done by T. Eronen. The simulations show that using the following voltages: 54 kV for the first electrode and 55 kV for the second electrode, the beam can be fully injected into the RFQCB without losses. The voltage of the injection plate of the quadrupole cavity allows to control the injection energy of the ions into the RFQCB, thus placing it at 59.9 kV, the entry energy of the ions into the machine will be 100 eV (design value).

Figure 8.7. Layout of the injection optics for ISCOOL

8.3.1.2 Beam cooling process

The reduction of the emittance due to cooling process inside the RFQCB only depends on the temperature of the buffer gas and not in the kind of beam that is being cooled. Therefore one can say that the beam is “loosing its memory” in the cooler and that the extraction of the beam from ISCOOL becomes the new starting point of the optics at ISOLDE-HRS.

Figure 8.8. Transverse emittance for two ion beams in thermal equilibrium with the buffer gas. Right figure shows a beam with longitudinal velocity component (from [11])

Figure 8.8 shows the action diagram (x,v_x) simulated with SIMION [6] for two ion beams in equilibrium with the buffer gas, which means already cooled. The right figure corresponds to a beam in equilibrium with the buffer gas but with a longitudinal velocity component due to an axial electric field applied along the axe of the quadrupole. The left figure is for an ion beam without axial electric field applied. During the cooling process, it is important a well confinement of the ions in the axe of the quadrupole while they are colliding with the buffer gas. The confinement is done by the RF quadrupole electric field created by the quadrupolar rods. The RF field applied to the rods is controlled by an RF amplifier which can vary the amplitude and the frequency of the RF electric field. The goal is to assure the pseudopotential well and the stability of the collisions. That means to fix the Mathieu parameter *q* around 0.5. The mathematical expression is expressed as:

(1)

Where *Q* is the charge of the ion, is the RF amplitude (0 to peak), *m* the mass of the ion, the characteristic radius of the quadrupole defined as half of the distance between opposite rods, and the RF angular frequency. For different types of RIBs, *q* will change due to the variation in the mass of the ions. Therefore modifications either in or have to be done in order to keep the ion beam motion stable inside the trap. As shown before in Table 8.1, the ranges of operation masses for ISCOOL is from 10 u to 200 u. Table 8.2 shows the values which the RF amplifier is able to keep the *q* value.

Table 8.2. Frequency and voltage amplitude of RF applied to the quadrupole for different ion mass values

In Table 8.2, frequency *f* represents the frequency of RF field ( ). *D* is the so-called pseudopotential well depth, expressed in [V] by

(2)

Figure 8.9 shows the optimized frequency and amplitude of the RF that should be applied to the quadrupole rods for different ion mass values. The optimization values are shown in Table 8.2.

Figure 8.9. Plot of the optimized frequency and voltage amplitude of RF for different ion masses.

Figure 8.10 shows the stop cooling distance depending on the buffer gas pressure and the entry energy of the ions inside the trap. Using this distance it is possible to calculate the length of the quadrupole.

Figure 8.10. Cooling distance of ions inside the RFQCB (from [11]**).** ***E*** **is the entry energy of the ions in the buffer gas,** ***m*** **the ion beam mass and** ***M*** **the buffer gas ion mass.**

8.3.1.3 Bunching and extraction to the ISOLDE beam line

Once the beam has been cooled inside the RFQCB, it has to be bunched (when desired) and accelerated again to 60 keV to be transported to the experiments. As in the case of the injection system, the extraction is made of two electrodes, but their geometry is completely different to that of the injection electrodes, see Figure 8.11.

Figure 8.11. Layout of the extraction optics for ISCOOL

Figure 8.12. Simulation of the emittance extraction at 60 keV with SIMION©. The ellipse encloses 90% of the points.

The bunch process is done before the acceleration using the last axial electrodes of the structure. For an experiment that needs a small time spread (e.g. collinear laser spectroscopy experiments) the bunch can be extracted using the *push-and-pull* procedure (see Figure 8.13). That consists in simultaneously increasing the voltage of one of the last axial electrodes of the RFQCB and decreasing the voltage of the extraction plate. With that procedure the time spread is reduced but the energy spread is increased. If what is needed to optimize is the energy spread a normal extraction procedure, lowering the extraction plate voltage, is used.

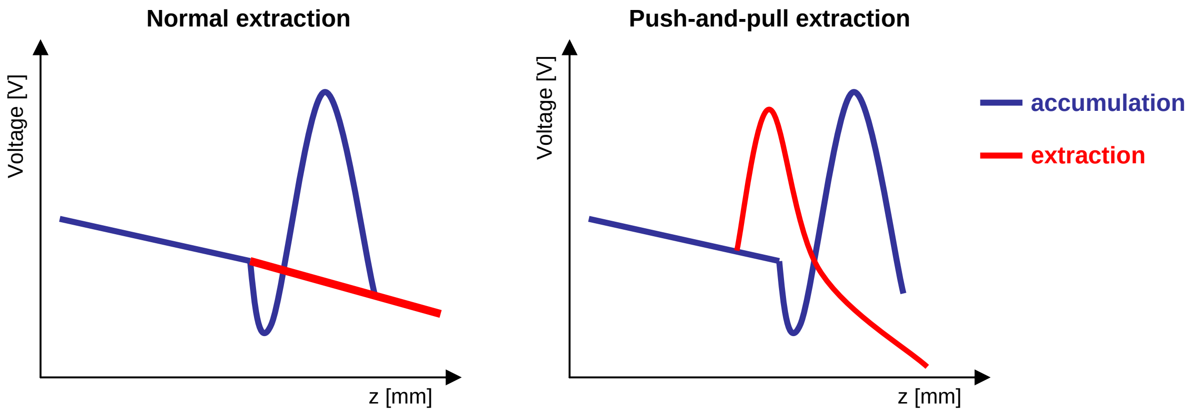

Figure 8.13. Ion extraction procedures from a RFQCB

8.3.2 Mechanical system

The main features of the mechanical design are:

- Separation of the electrodes that create the axial electric field and the quadrupole RF electric field.
- Great flexibility to optimize the axial electric field in a first test phase and during normal operation.
- Easy to set-up and move.
- Bake-out optimized.

Figure 8.14 shows the design structure of the inner structure of the RFQCB. In the figure, half of the quadrupole is presented. The axial electrodes are separated by ceramic insulators. Right part of the figure is the injection side of the cooler. It can be seen that first and last electrodes are more segmented since it is necessary to control better the field in these regions. The structure is made of stacked, variable-depth electrodes that given the axial field separated by electric isolators. The entire package is supported and stiffened by the quadrupole rods and closed by the injection and the extraction plate.

Figure 8.14. Half cut of the mechanical structure of the RFQCB (*left*) and section perpendicular to the optics axis of the quadrupole (*right*)

In Figure 8.15 axial electrodes of different lengths are pictured. Longer ones are placed in the centre region of the quadrupole where the gradient of the potential is smaller. In the injection and above all in the extraction regions, shorter electrodes are used to be able to modify with great precision the potential well in function of the requirements.

Figure 8.15. Axial electrodes of different lengths

All the electrodes (axial and quadrupole rods) are made of stainless steel and electrically isolated by ceramic spacers made of alumina (Al_2O_3). Differential potentials of around 1 kV can be supported. The electrical connections to the electrodes are done by very small plugs which can be easily connected and disconnected.

Two more electrodes in each side, the so-called injection and extraction electrodes are supported by an electrical insulator of the main vacuum chamber. The distances among these electrodes are fixed, but some metallic spacers can be added to vary the distance a few millimetres. In addition ground electrodes in the injection and the extraction side can be moved few millimetres to optimize the optics.

ISCOOL is placed above a trailer that allows an easy removal from the beam line (Figure 8.16). To make changes, the cover of the main chamber can be lifted up with a crane, but a lot of care has to be taken to assure that before all the injection and extraction electrodes have been removed.

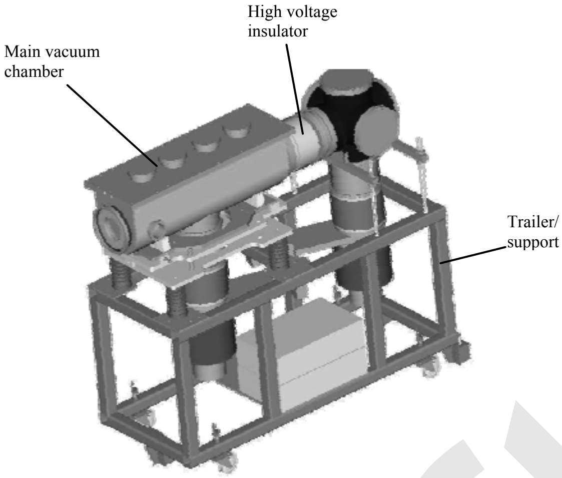

Figure 8.16. Removable part of the ISCOOL project

8.3.3 Vacuum system

The RFQCB works continuously with a flow of buffer gas entering inside the quadrupole chamber. The pressure inside the chamber, around 0.1 mbar for helium, has to be down to 10^{-7} mbar at the ISOLDE beam line. The transition is made through a differential pumping system made of three turbo molecular pumps (see Figure 8.17). The first one is in charge of pumping the main chamber. And the other two are occupied in pumping the injection and extraction parts, respectively. The differential pumping between the three sections is achieved by the use of small holes for the injection and extraction plates of the quadrupole cavity. In this *first step*, the pressure is decreased from the pressure in the quadrupole cavity, around 0.1 mbar, to the pressure in the main chamber, around 10^{-3} mbar. The *second step* is made by the holes of the last injection electrode and the first extraction electrode. The pressure is decreased from 10^{-2} mbar, up to around 10^{-5} mbar either in the extraction or injection regions. Finally, the *last step* to obtain the 10^{-7} mbar standard at the ISOLDE beam line is carried out by the ground injection and extraction electrodes. The turbo molecular pumps used are: a 1600 l/s in the main chamber, and two 1000 l/s, one for the injection and one for the extraction side. When the RFQCB is removed from the beam line and just a straight beam line is placed, only the injection pump remains in place. All the beam line is closed by two main valves at both sides making a new vacuum section.

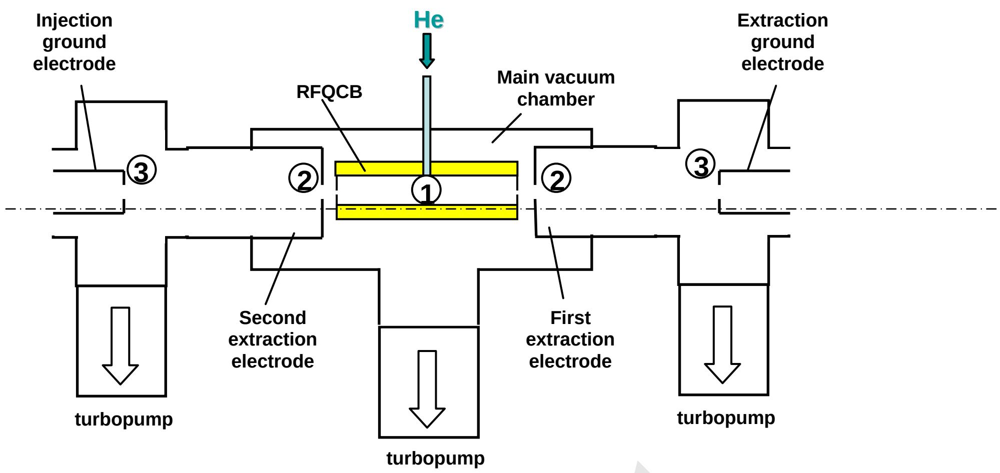

Figure 8.17. Schematic layout of the vacuum system of the RFQCB (only the main components are represented)

8.3.3.1 Buffer gas

To cool the ion beam, the inner chamber is filled up with a buffer gas. The gas chosen must accomplish two main requisites: a high chemical stability and a very low mass (only beams with ions of mass higher than the buffer gas mass can be cooled). Helium fulfils both requirements and looks the best choice. To minimize the losses due to impurities inside the trap [8], helium of maximum purity will be used with a percentage of helium 99.9999% (He grade 6.0). Furthermore a purification system will be added to decrease the impurities down to a level below 10 ppb. The gas flow will be regulated to control the gas pressure inside the chamber. The gas bottle will be placed on a high voltage platform to avoid problems with gas flow along high voltage insulators. The gas will enter into the main chamber through one of the flanges of the top cover using a feedthrough electrically isolated for 1 kV. Inside the chamber a flexible metal pipe will be used as inlet for the RFQCB chamber.
The throughput of ISCOOL was estimated to be around 2÷3 mbar·l/s in function of the diameter of the holes at the injection and extraction plates. The operation time of ISCOOL can be calculated either in a more conservative (and probably realistic) way with the complete running period of ISOLDE (around 30 weeks), or only with the running period of the HRS that is the half of the total time (15 weeks). Therefore the estimated running time of ISCOOL oscillates from 210 days to 105 days of operation per year. If big bottles of helium are used (50 l and 200 bar), the duration of the bottle will vary from 40 days (6 weeks) for a big throughput (3 mbar·l/s) to 65 days (10 weeks) for a low throughput (2 mbar·l/s).

8.3.4 Electronics system

ISCOOL is a high voltage device that has to operate at the same voltage than the HRS front-end. The electronics providing the high voltage is placed at ground in a separate rack. It gives the HV to ISCOOL and to an isolated platform supporting the rack with all the DC and RF electronics for ISCOOL and the gas bottle. The 220 V for the electronics at the HV platform is supplied through an isolation transformer of the same type used in the ISOLDE front-ends to assure the replacement in case of problems.

8.3.4.1 DC electronics

Thanks to the use of the axial electrodes, the electronics to apply the voltage to the electrodes of the RFQCB can be separated: the axial electrodes receive the DC component and the quadrupole rods the RF component. The DC component has to be applied to the whole axial electrodes. The number of these electrodes can be varied but the starting point is 25. The voltages to these electrodes is supplied by standard ISOLDE DC power supplies modified for 1 kV (DC24 - D3500) with an accuracy higher than 0.1%. Last axial electrodes require a fast variation of the voltage to release the bunch inside the trap. To assure a good stabilization of the voltage in so short period (~10-8 s) [7], the voltage for these electrodes is given by two different power supplies and a fast switch controlling which power supply provides the voltage to the electrode. In addition, the voltage of the two injection electrodes (with voltages around 50÷60 kV) are provided by two standard power supplies. The voltage of the first one is provided by a FUG HCN 7E - 20000 NEG (20 kV), and the second one by a FUG HCN 7E - 12500 NEG (12.5 kV). In the extraction part, two other power supplies are used for the extraction electrodes. One ISOLDE standard DC24 - D3500 modified for 1 kV, and another FUG HCN 7E - 20000 NEG, for the second extraction electrode. In all the cases the voltages applied are negative as the power supplies are placed in a high voltage platform at 60 kV. Figure 8.18 shows the electronics scheme of the RFQCB for the DC and RF electronics.

Figure 8.18. Scheme of the DC electronics for the RFQCB

8.3.4.2 RF amplifier

An RF electric field must be applied to the quadrupole rods in order to obtain the alternative quadrupole field which confines the beam. Here the magnitudes (frequency and amplitude) of the electric field are very low and no commercial amplifiers for that purpose are found in the market. The magnitudes required for the ISCOOL RF amplifier can be observed in Table 8.2. In Table 8.3 the frequency and amplitude ranges coming from the magnitudes required are specified.

Frequency range	1 ÷ 0.1 MHz
Amplitude range (0-to-peak)	100 ÷ 250 V

Table 8.3. Magnitudes of the RF amplifier for ISCOOL

8.3.4.3 High voltage

All the RFQCB is working on a high voltage platform that has to be related with the extraction voltage of the HRS front-end. Usually the energy of the RIBs at ISOLDE is 60 keV but this voltage could vary depending on different conditions of the front-end, e.g. vacuum problems can limit the operation voltage to lower voltages. In Figure 8.18 the components placed on the HV platform are indicated: the RF electronics and all the DC applied to the electrodes. The high voltage will be applied through a connector attached to the top flange of the main vacuum chamber. The high voltage is supplied by a power supply *FUG HCN 140-6500*. Two situations can switch off automatically the high voltage power supply (see Figure 8.18):

A problem in the vacuum system (e.g. pressure too high in the beam line or breakdown of some of the pumps) would open a microswitch.

An entry into the ground cage or the electronics cage would open the corresponding microswitch.

8.3.5 Integration in the ISOLDE control system

ISCOOL is fully integrated in the ISOLDE control system, that means can be controlled and optimized from the ISOLDE control room. The parameters that serve to optimize the optics and the cooling and bunching processes can be varied on-line. Moreover the vacuum system is integrated as another vacuum section of ISOLDE. To sum up, the main points to be controlled on-line and modified are:

Control of the HV (scaling all the voltages automatically in consequence).

Control of the parameters of ISCOOL. In two different ways: a first one transparent to the user where modifying the mass required and the bunch extraction parameters the beam is automatically extracted; another way that allows to change more low level parameters such as the frequency and the amplitude of the RF field, or the voltages of all the electrodes creating the DC field.

An easy and fast integration of ISCOOL in the ISOLDE control system is assured thanks to use standard components, most of them already being used at ISOLDE. A more complete description of the present ISOLDE control system can be found in [13].

8.4 Acknowledgements

As a doctoral student at CERN-ISOLDE, I would like to acknowledge my supervisors Ari Jokinen and Mats Lindroos for giving me the opportunity to work in this exciting field, for the help during my stay and for all the support in all the parts of the project. I also thank the ISOLDE target, technical and physics group for the nice work environment and all the support given during the development of the project. Especially, I would like to mention Jacques Pier-Amory and Nicolas Chritin who have made the mechanical design possible. On the other hand, I would like to thank LMU for the support in the mechanical and electronics manufacturing and CSNSM, particularly Dave Lunney and Jean-François Kepinski, for the help in the construction of the test bench and manufacture of ISCOOL. I also acknowledge the support from University of Mainz in the manufacturing phase.

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9 REX-ISOLDE low energy stage

9.1 Introduction

The REX-ISOLDE low energy stage prepares the radioactive ions produced at ISOLDE for acceleration in a compact LINAC to energies up to 3 MeV per nucleon [1]. It consists of a Penning trap (REXTRAP), a charge breeder (REXEBIS) and an achromatic A/q separator of Nier spectrometer type. The charge breeding efficiency depends critically of the quality of injected beam, i.e. its longitudinal and radial emittances. The purpose of the trap is to collect and to cool the radioactive ions delivered by ISOLDE before they are sent in bunches into the EBIS. Within the trapping area the ion motions are damped by the combined effect of collisions with a buffer gas (Ne) and a transverse RF excitation at the ion cyclotron frequency. In the EBIS, the ions are charge bred into charge states fulfilling the requirements of the subsequent injection into the LINAC, i.e. $3 \leq A/q \leq 4.5$. Thereafter the mass separator selects the charge state of interest. The typical cycle time is made up of 20 ms trapping followed by 20 ms charge breeding. For ions heavier than mass 40 longer breeding times can be needed. The longest breeding time used until now with radioactive ions was 150 ms for ^{126}Cd. A detailed description of the beam preparation can be found in the Yellow report describing the REX-ISOLDE facility [2].

Routinely, an overall efficiency for the REX-ISOLDE low energy stage between 1 and 10% is obtained. However, several factors can limit the efficiency of the beam preparation. The main critical issues for the trap and EBIS are:

- High intensity beams (>10 pA) from ISOLDE. Space charge effects can prevent the proper cooling of the ion cloud inside REXTRAP. The injection efficiency into the EBIS then suffers from a lower beam quality. If the current is even larger (>100 pA), the space charge can also inhibit the trapping fields and losses might occur already in the trap.
- Heavy ions. The minimum charge state that has to be reached is $A/q \leq 4.5$ to fulfil the injection requirement of the LINAC. Because of the unfavourable Z/A ratio and the higher number of shells that has to be depleted from electrons for heavier elements, the charge-breeding time becomes longer. If this latter is eventually too long the efficiency decreases due to the heating of the ions by the electron beam. Secondly, the penning trap may become saturated if the bunching time has to be very long. Until now, radioisotopes up to A=126 have efficiently been accelerated.
- Noble gas ions. These ions, for which the ionization energy is quite high, can experience charge exchange with the buffer gas in the trap. In the case of He^+ ions, they neutralize almost immediately after their injection into the trap. For Kr^+, Ar^+ and Xe^+ ions the lifetime is longer than 100 ms.

The purity of the accelerated beam is often a critical issue. After the beam preparation at the trap and EBIS, two types of contaminants may be present. The first one is isobaric isotopes coming from the ISOLDE, not separated away in the ISOLDE mass separator. The second one is the multi-charged ions of similar A/q ratio originating from the residual gas inside the EBIS. The resolving power of the separator, $(A/q)/\Delta(A/q) \approx 150$), give usually the possibility to choose a charge state of interest not superimposed on a residual gas peak in the mass spectrum and thus a pure beam is delivered to the experiment. Nevertheless, in some cases a completely contamination free beam is not attainable, particularly on a sub 0.1 pA level. In worst cases the beam is composed mainly of unwanted species.

To counteract the present limitations and to prepare for coming higher beam intensities from ISOLDE several research and developments tracks are being pursued. Some have already started. The different R&D projects can be regrouped in three categories. Preparation of high intensity beams; increased overall efficiency; beam purity and beam optical improvement. In addition, the development of an alternative charge breeder based on an ECRIS is pursued. A summary of the status and needs of the different projects is given in the following.

9.2 High intensity beam preparation

To overcome the space charge limitation in the Penning trap a new cooling technique, the so-called 'rotating wall' cooling is being evaluated. This method, originating from plasma physics, could be competitive to the currently used 'sideband cooling'. Its principle consists in azimuthally spinning up the ion cloud by means of a resonant radiofrequency excitation of a plasma mode. According to the direction of rotation of the field the resulting Lorentz force is then either compressing or repelling the cloud towards or away from the axis of the trap. During previous tests both dipolar and quadrupolar excitations were applied in the transverse plane of the trap. A (2,1) plasma mode which couples radial to axial motion was successfully excited. The latest efficiency measurements are shown in Figure 9.1 Efficiencies of the different cooling methods as a function of ions per bunch number. They suggest that for these intensities the rotating wall quadrupolar excitation is slightly less efficient than the sideband cooling method. Emittance measurements were carried out in parallel but not conclusive. Nevertheless we intend to complement these tests with new emittance measurements and a careful search for resonant coupling. A new regulation unit for the test ion source should allow a better control of the intensity and allow for higher intensity tests. Lastly, a study of the actual injection efficiency into the EBIS is the most stringent test to decide whether this method is suited or not for the high intensity beams injection into the EBIS.

Figure 9.1 Efficiencies of the different cooling methods as a function of ions per

bunch number

9.3 Improving the overall efficiency of REX-ISOLDE

9.3.1 Improving the trap efficiency

During the design study of REXTRAP, simulations of the ion injection, trapping and cooling processes were undertaken. A trapping efficiency close to 100% was expected. Experimentally less than 50% has been obtained for beams of intensity smaller than 10 pA, even less for higher intensities. Two possible reasons for the limited efficiency have been pointed out. Firstly, the magnetic mirror effect makes the injection from ISOLDE quite difficult, and already at the injection side the ions may be reflected before they enter the trapping region. Secondly, the ion-cooling method may not be strong enough to compress the ion cloud so it can exit the trap through the last collimator without a certain fraction lost. A careful re-analysis of the beam injection conditions and a modification of the internal structure could improve the situation. By varying the beam focussing and the diameter of the entrance and exit diaphragms the losses could perhaps be reduced.

9.3.2 Narrowing the charge state distribution in the EBIS

Within the EURONS JRA Charge Breeding network [3], two different means of narrowing the charge state distribution in the EBIS, and thereby increasing the number of particles in the peak charge state, will be investigated. Presently, a maximum of 25-30% can be obtained in the peak charge state. The first makes use of the large gap in ionisation energy at the shell closure of atomic ions. By adjusting the electron beam energy accurately just below the ionisation potential of a shell closure electron, a large fraction of the ions can end up in a single charge state. This is a specific case, and a suitable A/q-value can not always be found. The second method utilises the dielectronic recombination resonance. The electron beam energy is adjusted to energies which enhance the dielectronic resonance cross section for the dedicated ion species. In that way the recombination rate counteracts the ionisation rate and stops the ionization at a certain charge state. This latter should be first tested at Heidelberg MPI-K before being possibly implemented at REX-ISOLDE. Both methods require an electron beam with a tuneable and in many cases low energy, which makes it cumbersome for the REX-ISOLDE, as the space-charge capacity will be low due to the perveance limit.

9.3.3 New high performance cathode

A crucial issue for the REX-ISOLDE operation is the reliability of the electron cathode in the EBIS. The present cathode type has a short life-time, and requires frequent cumbersome changes stopping the operation for almost two weeks. Moreover, its current density emission does not reach the specification. Alternative cathode types should be investigated, for example the IrCe type, and different manufactures of the LaB6 cathode should be tried out. A complete redesign of the electron gun and the collector would also be beneficial as the design goal of 0.5 A can not be reached with the existing EBIS due to excessive electron beam losses. Complete electron beam simulations are necessary before the design and manufacturing can be carried out. An electron beam current of 0.5 A and current density of 250 A/cm^2, or higher, (so far 0.35 A and 150 A/cm^2 have been reached) would not only increase the acceptance of the EBIS but also boost the space charge capacity. In addition, the higher electron current density would result in shorter breeding times, which reduces the decay losses. Heavier elements can also be charge bred within a shorter time, so the bunching within the trap does not have to be so long that space charge effects start to play a role.

9.4 Beam purity and higher beam quality

9.4.1 Suppressing the isobaric contaminants from ISOLDE

From its intrinsic features the trap can be used as a high resolving mass separator. For example the ISOLTRAP experiment at ISOLDE uses two Penning traps for high accuracy mass measurement. There it has been demonstrated that a resolving power of about 10^5 could be achieved in the preparation trap. In REXTRAP a similar resolving power should be attainable and thereby the isobaric contaminations from ISOLDE could be reduced. However certain limitations inherent to this separation method need to be studied in detail. For instance, the required time of the RF excitation used for the separation is inversely proportional to the resolving power. This becomes a limitation for short-lived nuclides. Secondly, a high resolving power requires a low buffer gas pressure. This may be a limitation for the trap efficiency. A modification of the internal trap structure and an improvement of the differential pumping scheme are most likely required.

9.4.2 Molecular Beams

To suppress known contaminations from the ISOLDE target-ion source unit, it is in certain cases possible to inject into REXTRAP molecules rather than atomic ions. According to their chemical properties, the radioactive elements produced by the proton bombardment can combine with different impurities present in the target-ion source system to a molecule. The radioactive ion of interest is then moved away in the mass spectrum from the contamination. This method, the so-called molecular sideband extraction, has recently been used with $^{70}SeCO^+$ molecules for the Coulomb excitation of Se nuclides. In this way it was possible to suppress the contamination of $^{70}Ge^+$ ions.

Within REXTRAP, according to the voltages applied on the electrodes, the molecules could either be dissociated or kept intact. Figure 2 shows different time-of-flight spectra corresponding to these two schemes. If the molecule is kept intact inside the trap, the breaking occurs inside the EBIS. Systematic testing and efficiency measurements are needed for verifying this method for different molecules, as the optimum trap settings are dependent on for example the electronegativity of the ion.. The optimisation of this method would benefit from radioactive beam identification after the trap (see below). To conclude, in the future the use of molecular beams opens possibility for new contaminants free beams.

Figure 9.2 Time-of-flight spectra of the beam coming out from the trap after injection and cooling of $SeCO^{+}$ molecules

9.4.3 Improvement of the vacuum system

The beam purity at the experimental station after acceleration through REX-ISOLDE is in most cases of outmost importance. An uncontrolled beam contamination distorts the results from Coulomb excitation and neutron transfer. Therefore the suppression of residual gas contamination in the EBIS beam is important, and can be increased by coating the interior of the drift tubes and the electron collector with non-evaporable getter material. The major source of the stable impurities (C, N, and O) is the poor vacuum in the mass separator which has to be addressed. An improved vacuum in this section also reduces the electron recombination; this means the efficiency for heavy highly charged ions is increased. Further improvements involve a complete isolation of the roughing vacuum system for the trap from the rest of the low energy stage beam lines as it has been observed that the buffer gas of the trap can be transmitted to EBIS backwards via the roughing pumping circuit.

9.5 Charge Breeding and cooling techniques

9.5.1 Comparison between Penning trap and RFQ cooler

An RFQ cooler buncher [4] with high capacity will be in the near future at ISOLDE. Its beam cooling performances should then be compared to those of the Penning trap REXTRAP. The space charge limitation, the time needed for beam cooling, and the emittance reduction are of primary interest.

9.5.2 Cooling techniques in charge breeders

Different ion-ion cooling methods are to be studied in the framework of the EURONS charge breeding network. They aim at improving the transverse emittance of the extracted beam from the different charge breeders. In the simplest form some cooling could be achieved by introducing a cooling gas into the EBIS [5]. A more advanced scheme entails injection of positively charged particles in the trapping area of the EBIS and different injection-trapping-extraction schemes. Although the implementation of such techniques is not straightforward with the current REXEBIS setup, it is a future open possibility. A new electrode structure would have to be designed, and a 1^{+} injection source and line added.

9.5.3 ECRIS as charge breeder

At ISOLDE, there exists a second charge breeding device, the PHOENIX ECRIS charge booster [6]. This ECRIS works at 14 GHz radiofrequency, with permanent magnets and normal coils, and is designed to allow ion injection. That means it has the capability to transform lowly charged ions, for instance 1+ ions, to higher charge states, typically A/q>7. Presently it is installed in the experimental hall at the GHM beam line. It has been commissioned and tested, and until now the charge separation is done by a 102 degree magnet after the source. This charge breeding ECRIS could either be used for boosting the ion beam energy for solid state and nuclear astrophysics experiments, or act as an alternative breeder for the REX-ISOLDE LINAC. The two options are described in the section below.

To use DARESBURY/ISOLDE's PHOENIX ECRIS for either of the two alternatives, a few common upgrades are needed. For instance, the vacuum has to be consolidated and standardised, and the control system upgraded. The magnetic separator has to be combined with an energy analyser to suppress the high level of beam contaminations. Moreover, a complete radioactive beam diagnostics system including a tape station and multichannel analyser is desirable. Miscellaneous borrowed power supplies should also be complemented. A local ion source in front of the ECRIS would facilitate the injection tests as one is then not dependent solely on an ion beam delivered from ISOLDE. Finally, the commissioning tests have to be finished and stable working points established.

9.5.4 Charge breeding ECRIS connected to HV platform

For many applications, particularly in solid state or nuclear astrophysics, the beam available directly from the ISOLDE separators are too low in energy and the beams from REX-ISOLDE too high. The lowest beam energy from REX is 300 keV/u and the ISOLDE beam energy is between 20 and 60 keV for 1+ ions. A way to reach the intermediate energy could be to connect the charge breeding ECRIS to a high voltage platform [7]. With a high-voltage platform, operating at a voltage around -300 kV, installed after the ECRIS total ion energies of 360*q keV are reachable. The high space charge capability of the ECRIS makes this particularly suitable for high intensity solid state implantations. The PHOENIX is mainly efficient for slightly heavier elements, that is A>25, and the reachable A/q limits the energy to ~50 keV/u. The existing HV platform could be moved to a position after the GHM and ECRIS, and be located 3 m above the floor to allow for an energy analyzer after the separator magnet. This option presents very little complications, as space at the necessary position is available with little relocation effort. Apart from the general work on the ECRIS already mentioned, a beam line with focusing possibilities to the platform has to be produced.

9.5.5 Beam purification by means of the charge breeding

The ECRIS can be used for improvement of the purity of beams. The charge state will differently develop according to the charge-bred element. By injecting a radioactive mixture of originally the same A/q ratio into the ECRIS, it is then possible to minimize the A/q ratios overlap of the different elements. A subsequent separation of the charge-bred beam improves significantly the beam purity. This has already been proved with neutron-rich argon beams separated from a radioactive krypton contamination [8].

9.5.6 ECRIS as charge breeder injector to the REX LINAC

With HIE-ISOLDE, the proton intensity on the primary target will be increased as well as the radioactive yield production. Then, for some high yield isotopes the space charge limitation inside the Penning trap (and EBIS) may become a limitation. The advantages of an ECRIS charge breeder are its much higher space-charge capacity (some 10^{12} charges of radioactive beam [9] have been already obtained) and its operation without a preparatory buncher/cooler, which would allow for a high throughput.

The PHOENIX ECRIS could be installed on the side of the REXTRAP/REXEBIS system for the injection in parallel into the REX LINAC. For low intensity, high purity beam requests, the EBIS would be used, while for high intensities the ECRIS feeds the LINAC. The ECRIS should be installed at the present position of the solid state experiment ASPIC and be connected to the REX LINAC via a magnetic and electrostatic spectrometer similar to the REX mass separator. Using such a separator mass and energy selections can be preformed and the high rest-gas contamination be suppressed to a large extent. A movable bender directs the beam into the REX beam line. The extracted beam from the ECRIS is smaller than the acceptance of the RFQ. Using afterglow an extraction time of ~5 ms can be achieved. With a confinement time of 70-200 ms, the duty cycle for the LINAC falls within the present specifications (<10%). However, with a reachable A/q<8 inside the ECRIS the REX LINAC needs to be modified as it is designed for mass-to-charge ratio smaller than 4.5. The proposal would be to introduce a stripper foil at the 1.2 MeV/u energy, that is after the IH-structure or even at 2.4 MeV/u for a higher efficiency.

The high A/q inside the RFQ and IH-structure calls for modifications of these accelerating structures. Exchange of the drift tube structures and increased cooling due to a higher acceleration voltage and higher RF power are required. A design similar to the injector to UNILAC at GSI could be used, limiting the effort to production of the structures. The RF frequency can be maintained, but the RFQ, buncher and IH amplifiers have to be upgraded for the higher power level. Also the lenses of the matching section and the inner tank triplet inside the IH-structure have to be upgraded as they are not specified for such a high A/q value. After the IH-structure a box containing a stripper foil unit has to be added. As such an upgrade may entail a shift in axial position of certain LINAC elements as the stripper box is added for example, the upgrade should occur at the same time as the major upgrade of the LINAC to 5.5 MeV/u.

9.5.7 Comparison of EBIS and ECRIS as charge breeders

Even with the PHOENIX ECRIS remaining at its present position after the GHM beam line, a unique possibility to compare the two charge breeding systems TRAP/EBIS and ECRIS is offered at ISOLDE (see Figure 9.3). The performances in terms of breeding efficiency, beam purity, breeding time, space charge limitations, beam acceptance etc can be compared with realistic radioactive beams, for the benefit of future radioactive beam facilities. This is one of the aims of the Charge Breeding network within EURONS.

Figure 9.3 Phoenix ECR ion source (left) and REXEBIS charge breeder (right)

9.6 Miscellaneous

9.6.1 Advanced beam diagnostics

Different beam diagnostics tools such as Faraday cups, beam profile and time-of-flight devices are installed at the trap and EBIS. After REXTRAP it is already possible to measure time-of-flight spectra of the cold extracted beam on a multichannel plate, and the beam composition can be determined to a certain extent. However, the present beam diagnostics system does not allow for a distinction between stable and radioactive beams. In the future a silicon detector placed after the trap could improve the analysis of the composition of a trapped radioactive beam by half-life identification. After the REX mass separator the same identification principle could be applied using a plastic scintillator combined with a photomultiplier. Additional beta energy spectra could also be used for the particle identification. The detectors are already in place, but the installation of suitable electronics and data acquisition remains to be done for both of the detectors, as well as a thorough test of the systems with radioactive beams. Lastly a current sensitive detector or even a particles counter could be foreseen after the mass separator to allow for an efficiency optimisation of the charge breeding inside the EBIS.

9.6.2 Slow extraction of the charge-bred beam

Currently the charge bred ions are extracted in pulses of approximately 50 μs length from the EBIS by means of self-extraction. A short extraction time favours the signal-to-noise ratio in the spectroscopy experiments for low intensity beams, but can become a limitation for higher radioactive beam intensities. Due to the read-out and dead time of the experimental detectors the number of usable event are reduced to a few per pulse. A slower ramping of the EBIS extraction voltage should be implemented to allow for a controlled and slow release of the ions.

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(b)

(a)

<u>**Fig. 1:**</u> Estimated Cross sections and astrophysical S-factors for two typical reactions of astrophysical interest. Assuming a fully stripped RNB beam from a high-charge source (ECR or EBIS) and a High Voltage Platform of ~ -400kV, the maximum energy will be: (a) – $^{7}Be(\alpha,\gamma)^{11}C$, ~1700 keV. (b) – $^{11}C(p,\gamma)^{12}N$, ~ 2500 keV. In both cases, and even assuming a very high yield beam, higher energies are required. This is a typical scenario for astrophysical reactions with RNBs of inverse-kinematics nature.

10 REX-ISOLDE LINAC upgrades

10.1 The IH-9 gap resonator

To use the full range of isotopes from ISOLDE for nuclear physics experiments with Coulomb excitation and transfer reactions, higher beam energies than described above are required at REX. An increased energy of approx. 3 MeV/u allows studies of nuclear reactions up to mass A=85 on deuterium targets. A beam energy above 4.2 MeV/u would be suitable up to mass A=145. Therefore an energy upgrade of the REX-ISOLDE LINAC in order to increase the maximum particle energy at the target has been started. In two steps it is foreseen to raise the beam energy to approx. 5.5 MeV/u by maintaining the beam quality.

A schematic of the REX-ISOLDE LINAC for the first upgrade step is shown in Figure 10.1. . In order to reach 3.0 MeV/u the simplest solution was to include a 9-gap IH-cavity operating at 202.56 MHz. Due to the delay of the final permission to run FRM II, the prototype for the Munich accelerator for Fission Fragments (MAFF) [1] IH-7-Gap resonator was modified to an IH-9-Gap cavity [2]. The resonator has been installed in the REX beam line and it was conditioned successfully to a power level of 90 kW. First stable and radioactive beams with A/q = 3.5 have been accelerated to 3.0 MeV/u [3].

Figure 10.1 Structure of the REX-ISOLDE LINAC of the first upgrade to 3 MeV/u

10.1.1 Modification of a MAFF IH-7gap resonator

For the MAFF-LINAC at the Munich High Flux Reactor FRMII, a more efficient 7-gap structure compared to the split ring resonators of REX-ISOLDE was required for energy variation. Hence the 7-gap structure has been designed as an IH-structure. Due to the higher shunt impedance of IH-structures a higher resonator voltage in combination with a very compact design can be achieved with the same rf-power compared to split ring resonators. Since the resonator is used for acceleration as well as for deceleration, the cell length is kept constant. Based on the fact that the beam energy at MAFF will be varied between 3.7 MeV/u and 5.9 MeV/u a cell length of 74 mm was chosen, which corresponds to a design speed of ß = 0.1. This results in a total length of 518 mm for the seven cells. The inner tank length therefore is 520 mm and the overall outside length is 646 mm.

In the first design for the REX 3MeV/u upgrade, it was foreseen to change the MAFF resonator from a 7-gap to a 9-gap resonator – keeping a constant cell length, corresponding to 2.5 MeV/u synchronous particle energy. Nine gaps were necessary to match the reduced cell length for the lower injection energy of 2.2 MeV/u instead of 3.7 MeV/u. Low level measurements have been carried out to determine Q-values and shunt impedance (Table 10.1) of both, the 7- and 9-gap set-up.

Table 10.1 Specifications of the 7- and 9-gap IH-cavity

	7-gap	**9gap**
cell length [mm]	74	55
gap length [mm]	24	22-26
drift tube length [mm]	50	32
drift tube diameter [mm]	20 / 26	16 / 22
max. A/q	6.3	4.5
synchronous particle ß	0.1	0.073
shunt impedance [MΩ/m] (low level measurements)	129	218
Q (measured)	9800	10100

Before installation at REX, the resonator was tested at the Munich tandem accelerator. At a high energy beam line of the MLL a test bench for high power and beam measurements was installed. Here it was possible to obtain momentum spectra of a dc beam at different amplifier power and spectra for beam pulses at different phases, using a 70° bending magnet positioned behind the resonator tank. The dc-beam spectra from the tandem were used to determine the effective shunt impedance.

A O^{5+}-beam at 2.2, 2.25 and 2.3 MeV/u was used to test the ability of the 9-gap IH-structure to post accelerate at power levels from 5 to 70 kW. An energy spectrum is shown for 70 kW rf-power in Figure 10.2. The tandem peak has been used for energy calibration. The drift tube structure was at that moment adjusted with constant cell lengths of 55 mm.

Figure 10.2 Accelerated beam from the 9-gap resonator with equidistant gaps

The measured effective shunt impedance (Figure 10.3) shows changes with the rf-power level. This corresponds to small values of the TTF below 0.8, which is a result of the constant cell length, designed for 2.5 MeV/u synchronous particle energy. Therefore a higher injection energy led to higher effective shunt impedances also shown in Figure 10.3. However, the curves definitely show saturation at values around 140 MΩ/m, which corresponds to a TTF $\leq$ 0.8. For that reason the drift tube structure had to be installed according to the $\beta\lambda/2$ velocity profile, otherwise the required energy gain for REX-ISOLDE would not have been possible.

Figure 10.3 Effective shunt impedance of the 9-gap resonator for different injection energies

With MAFIA the gap voltage distribution has been calculated for the constant cell length and the adjusted velocity profile (increasing cell length). Taking that distribution shown in Figure 10.4 into account, beam dynamic calculations delivered a TTF of 0.87 and an effective shunt impedance of 165 MΩ/m, which would be sufficient to reach 3.0 MeV/u at REX-ISOLDE at 90 kW rf-power for a beam with A/q = 3.5.

Figure 10.4 Adjustment of the gap voltage distribution

Table 10.2 shows the final geometry of the 9-gap resonator after changing to a βλ/2 structure with a fixed velocity profile. Figure 10.5 shows the power resonator during the installation in the REX-ISOLDE beam line.

Table 10.2 Specifications of the final version of the 9-gap IH-cavity

	IH 9gap
Frequency [MHz]	202.56
Outer tank length [mm]	676
Inner tank length [mm]	520
half shell radius [mm]	145
cell length [mm]	38.5 – 58.5
gap length [mm]	19 – 27
drift tube length [mm]	32
drift tube diameter in./out. [mm]	16 / 22
maximum rf-power [kW]	100
duty cycle [%]	10
Kilpatrick	1.5
shunt impedance (pert.) [MΩ/m]	218
Q_0	10100

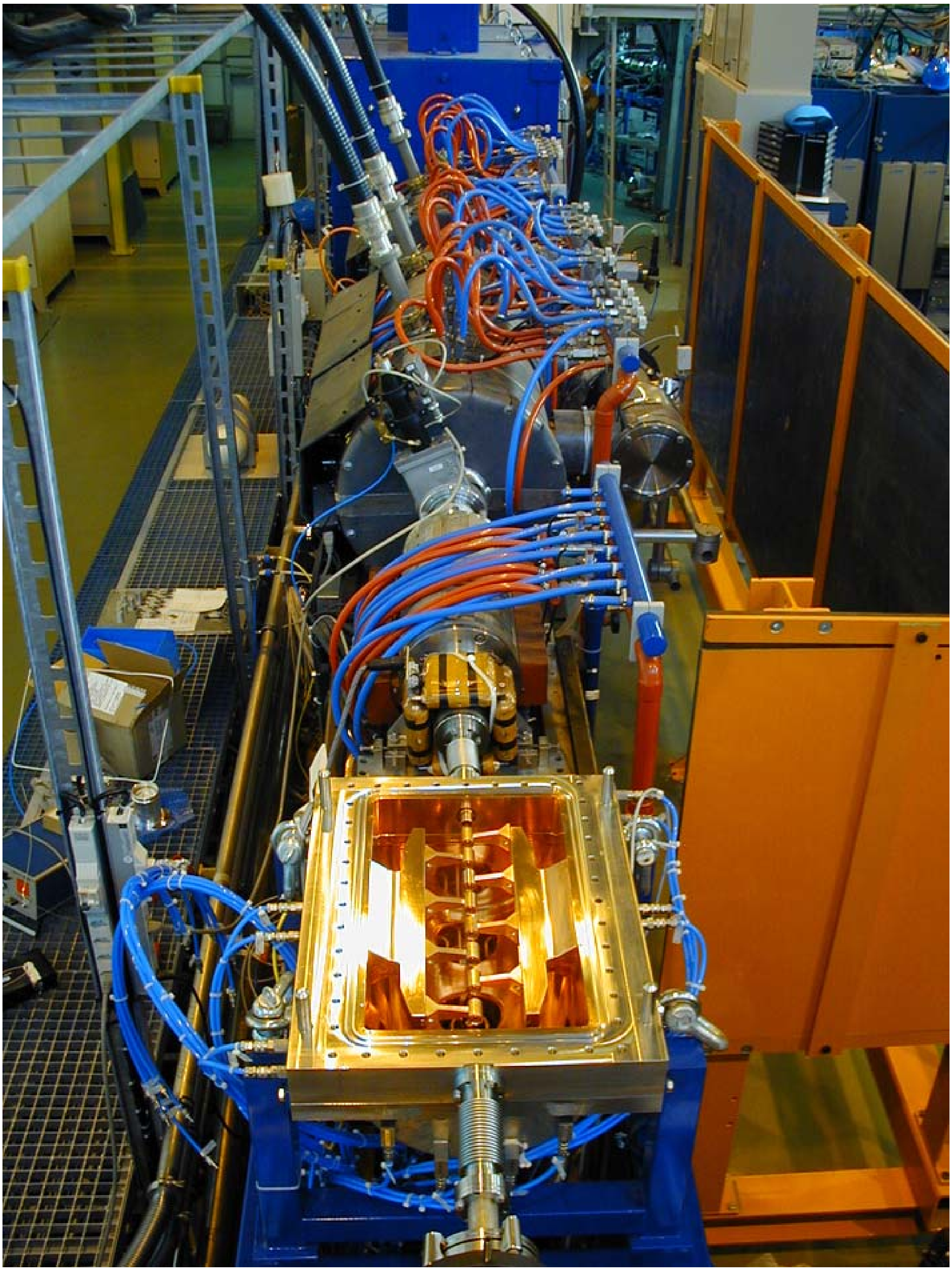

Figure 10.5 Open 202.56 MHz IH 9-gap resonator installed at REX

10.1.2 Particle Dynamics

To compensate for the rf-defocusing in the 9-gap accelerator, a magnetic triplet lens MQT5b was added to the bender section, named – following the above described REX naming scheme – BEN.MQ40 (x-foc.), BEN.MQ50 (y-foc.), BENMQ60 (x-foc.). The lens was placed between the resonator and the diagnostic box 4. It is regarding its gradients, apertures etc. identical to the triplet (IHS.MQ90, IHS.MQ100, IHS.MQ110) behind the IH-structure.

The input for the LORASR simulations was delivered by the original LINAC design calculations for the 7-gap resonators, which were verified in detail during the commissioning phase of REX-ISOLDE [4]. The main goal of the calculations (after having once fixed the drift tube geometry) was to find out to what extend the structure is still energy variable, even if it has a design for a fixed input and output energy. Due to the short length and the small number of gaps as well as the relatively high injection energy, one can expect that the beam quality and transmission after the 9-gap resonator are much less sensitive to changes in the accelerating voltage than it is found in long IH structures at lower energies.

The design injection energy produced by the 7-gap resonators is 2.25 MeV/u at a phase spread of ± 15° (after 1.3m drift) and at an energy spread of ± 0.45 %. Transversely, the beam is injected with an emittance of $\varepsilon_{n,x,y} = 1.4\ \pi$ mm mrad in both planes convergent, whereby only slightly converging beams led to the best transmission. Figure 10.5 shows the in- and output emittances derived from the calculations. The acceptance is – although the drift tube inner diameter had decreased to 16 mm – still two times larger than the emittance of a beam, which fills the full RFQ acceptance.

Figure 10.6 Transverse emittances of the 9-gap resonator from LORASR

To test the energy variation, the resonator voltage was changed in steps according to the measurements at different rf-power levels. The spectra in Figure 10.7 show that the transmission as well as the energy spread stay in a reasonable range down to an output energy of 2.55 MeV/u. With this result (which could be verified during the measurements shown below) the REX accelerator becomes continuously energy-variable over a range from 0.8 MeV/u to 3 MeV/u.

Figure 10.7 Energy spectra at different acceleration voltages

The calculated transit time factors in the fifth gap – which is taken here as a reference - always stay between 0.855 and 0.865. The good flexibility in output energy of the accelerator allows a wider range of mass to charge ratios to be available at energies around 3.0 MeV/u which is only limited by the currently maximum available rf-power. With an rf-power level limited to 90 kW, the maximum A/q at 3.0 MeV/u is A/q = 3.5. Thus, during the first runs with radioactive ions, compromises could be found, like e.g. accelerating $^{76}Zn^{20+}$ ions (A/q = 3.8) at 90kW to ~2.9 MeV/u. Table 10.3 shows the calculated parameters of the 9-gap resonator for regular operation at 3 MeV/u and for the variable energy.

Table 10.3 Design parameters of the 9-gap IH-cavity

	IH 9gap
input energy [MeV/u]	2.2
output energy [MeV/u]	2.55 - 3.0
energy spread [%]	1.0 – 1.6
phase spread [°]	25

transmission [%]	100
TTF on axis in gap No. 5 (2.55 – 3.0 MeV/u)	0.855 – 0.866
maximum A/q (90kW)	3.5
radial acceptance $\alpha_{x,y,norm}$ [π mm mrad]	1.4

From the low level measurements and LORASR calculations for the IH structure an effective shunt impedance of 163 MΩ/m was expected. An energy gain of 0.75 MeV/u requires for ions with A/q = 3.5 an effective acceleration voltage of 2.63 MV, which corresponds at the given shunt impedance and structure length to an rf-power of 85 kW. We therefore performed the tests with a N^{4+} residual gas beam from the REXEBIS. The injected current was in the range of 50 pA in the beginning and went down to ~10 pA because of the slits in front of the energy spectrometer, which were used to reduce the emittance influence on the energy spectra. Figure 10.8 Energy spectra measured with a A/q = 3.5 beam shows the measured spectra.

Figure 10.8 Energy spectra measured with a A/q = 3.5 beam

The measured final energies were in good agreement with the calculations. The decrease of the beam current at higher energies occurs because the beam transport was optimized for a parallel 2.25 MeV/u beam through the spectrometer instead of a convergent injection into the 9-gap. With an optimized injection and a beam transport scaled to the different energies, the transmission was close to 100 %.

The energy peaks at lower power levels show a tail towards the low energy side, which might be the result of a slightly wrong injection phase. However, the FWHM of the peaks correspond remarkably well to the design calculations.

Calculating the effective shunt impedance for an effective acceleration voltage of 2.63 MV at 90kW gives a value of η_{eff} = 154 MΩ/m. With an average transit time factor of 0.865 we derive a shunt impedance of η = 205 MΩ/m. If the decrease of the shunt impedance at higher power levels due to the heating of the resonator is taken into account, this value fits nicely to the η = 218 MΩ/m from perturbation measurements.

10.2 Future Developments and Upgrades

10.2.1 REX-ISOLDE LINAC energy upgrade to 5.4 MeV/u

A major change of the LINAC structure will be required in order to reach energies of 5.4 MeV/u. The three 101.28 MHz 7-gap have to be replaced by an additional 1.85 m IH-cavity at 101.28 MHz, a 202.56 MHz 28-Gap structure and finally three IH 7-gap resonators (of which one is currently operated as a 9-gap resonator).

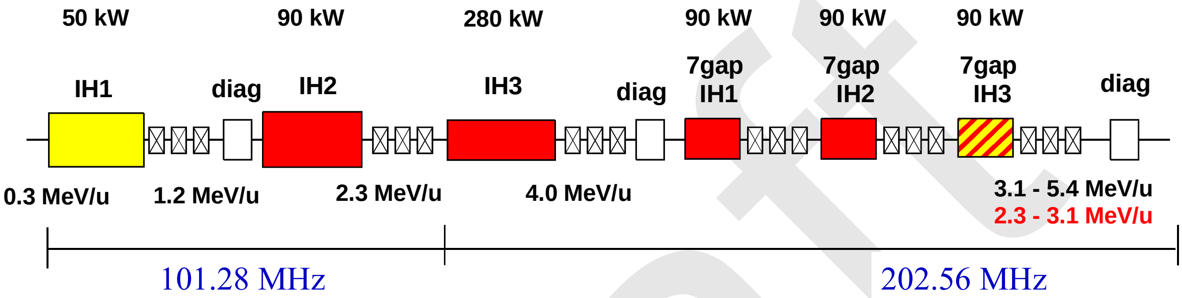

Figure 10.9 Upgrade scenario for REX-ISOLDE for an energy range from 2.3 to 5.4 MeV/u.

The new 101.28 MHz IH structure will inject the beam at 2.3 MeV/u into the 28 gap 202.56 MHz IH-structure. The 28-gap cavity will raise the energy to 4 MeV/u which requires 7.65 MV effective acceleration voltage for ions with A/q = 4.5. With an effective shunt impedance of 160 MΩ/m, an rf-power 280 kW would be sufficient giving enough safety margin for stable operation.

With the following three 202.56 MHz 7-gap resonators of the MAFF type, the beam energy can be varied now in the range between 3.1 – 5.4 MeV/u. For energies below 3.1 MeV/u, one of the IH 7-gap resonators would have to be re-modified to a 9-Gap, switching back to the present conditions after the first upgrade step. Due to the simple mechanical design of the small IH cavities, this modification is not a big effort and should be possible for a dedicated set of experiments at lower energies.

The phase matching of the beam from the new 101.28 MHz IH structure towards the 28-gap resonator is critical and a minimum distance between the two structures has to be guaranteed, otherwise a rebuncher cavity must be installed, which would be anyway advantageous for injection into the 9-gap (energies below 3.1 MeV/u), furthermore a second rebuncher section would allow to install a diagnostic box in front of IH3.

The beam dynamics design of the 28-gap cavity and the beam transport towards the target regions has been completed. The cavity design of the resonator structure is shown in Figure 10.10 Cavity design of the 202.56 MHz 28-gap IH-resonator

Figure 10.10 Cavity design of the 202.56 MHz 28-gap IH-resonator

As pointed out above, the proposed energy upgrade requires production of four new IH cavities. On the amplifier side, the situation is more relaxed. Here the idea is to modify two of the former Spiral 7-Gap amplifiers to 202.56 MHz (for rf-supply of two of the new IH 7-Gap resonators), and to use a spare 1 MW final stage of CERN Linac2 at lower rf-power (280 kW) but increased duty cycle (~3% - 10%, depending on the tube, which can be used) for the 28-gap resonator. Table Y1 shows the rf-requirements at one glance.

IH Tank No.	Frequency (MHz)	Length (m)	η_{eff} MW/m	P_{rf} (kW)	E. Gain (MeV/u)	V_{eff} (MV)	Amplifier
1	101.28	1.5	235	50	0.9	4.1	IH 1
2	101.28	1.85	190	90	1.1	5.0	7 Gap1
3	202.56	1.65	160	280	1.7	7.7	Linac2
4	202.56	0.5	100	90	0.45	2.0	IH 9 Gap
5	202.56	0.5	100	90	0.45	2.0	7Gap2,
6	202.56	0.5	100	90	0.45	2.0	7Gap3,

Table 10.4 Rf-requirements for the 5.4 MeV/u upgrade.

A cost estimation has been worked out for the complete upgrade, listed in 14. The costs are in the range 1.5 M€. Since a lead tunnel and possible rebuncher cavities/amplifiers were not taken into account, 2M€ might be a more realistic value.

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11 High-Precision Mass Measurements of Highly-Charged Exotic Ions with the Mass Spectrometer ISOLTRAP

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and the ISOLTRAP Collaboration

11.1 Physics case

11.1.1 Precision mass spectrometry of short-lived nuclides

High-precision mass values and hence binding energies and *Q*-values of radioactive nuclides allow for important tests of symmetry concepts in nuclear physics and in the search of physics beyond the Standard Model (SM) of particle interaction [10]. Examples are the isospin symmetry, which allows very precise mass predictions using the isobaric-multiplet mass equation IMME, the search for scalar currents that are not predicted in the conventional SM by precision beta-neutrino correlation experiments, and a test of the conserved-vector-current hypothesis, a postulate of the SM. In addition, masses of short-lived radionuclides are important for nuclear structure studies, for testing mass models far from stability and for reliable nucleosynthesis calculations in astrophysics. The relative mass accuracy needed in several of these cases is 10^{-8} or even below, with direct mass measurements only achievable with Penning traps.

Ion traps play an important role not only in high-precision experiments on stable particles but also on exotic nuclei. Besides accurate mass measurements they have recently been introduced to nuclear decay studies and laser spectroscopy as well as to tailoring the properties of radioactive ion beams [9]. This broad usage of trapping devices at accelerator facilities is based on the manifold advantages of a three-dimensional ion confinement in well controlled fields: First, the extended observation time is only limited by the half-life of the radionuclide of interest. Second, the ion beam performance can be improved by, *e.g.*, ion accumulation and bunching, which allows an efficient use of rare species. Third, stored ions can be cooled and manipulated in various ways; even charge breeding of the ions, as performed in REX-EBIS, and polarization are possible.

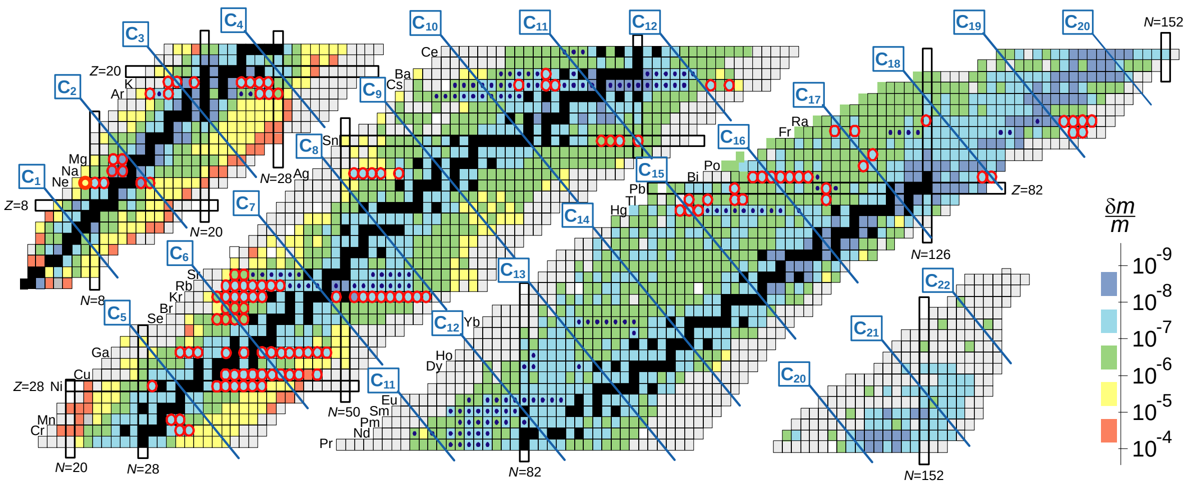

Figure 11.1 Nuclear chart with the relative mass uncertainties δm/m of all known nuclides shown in a colour code (see scale bottom right, stable nuclides are marked in black). Masses of grey-shaded nuclides are estimated from systematic trends [1]. Masses measured with ISOLTRAP since 2002 are marked with red circles, earlier measurements with blue dots. The isobaric lines of the carbon clusters C1 to C22 demonstrate the advantage of using a "carbon cluster mass grid" for calibration purposes.

For on-line mass measurements on short-lived radionuclides the ISOLTRAP Penning trap mass spectrometer installed at ISOLDE/CERN plays a prominent role. Atomic masses are determined with an uncertainty of 10^{-8} for nuclides that are produced with yields as low as a few 100 ions/s and at half-lives well below 100 ms. The scientific highlights include the mass measurements of ^{32}Ar ($T_{1/2}$ = 98 ms) [3], ^{74}Rb ($T_{1/2}$ = 65 ms) [8], and ^{22}Mg [11]. All these results provide important input for fundamental tests of the weak interaction, like test of the conserved vector current (CVC) hypothesis and the unitarity of the Cabibbo-Kobayashi-Maskawa (CKM) matrix.

At ISOLTRAP the mass measurement is carried out via the determination of the cyclotron frequency

(1) $\nu_c = qB/(2\pi m)$

of an ion with a charge-to-mass ratio q/m confined in a strong magnetic field with magnitude B. The magnetic field strength is obtained from the cyclotron frequency $\nu_{c,ref}$ of a well-known reference mass (ideally ^{12}C since the unified atomic mass unit is by definition 1/12 of the mass of that nuclide, see Figure 11.1). For beam purification and subsequent mass measurements ISOLTRAP uses two Penning traps placed in superconducting magnets of 4.7 and 5.9 T field strength, respectively, with a field inhomogeneity of 10^{-7}-10^{-8} in the precision trap [2]. For the determination of the cyclotron frequency, *i.e.* the actual mass determination of the confined ions, a time-of-flight (TOF) method [4] is in use. An overview of all atomic masses measured with ISOLTRAP is given in Figure 11.1**.**

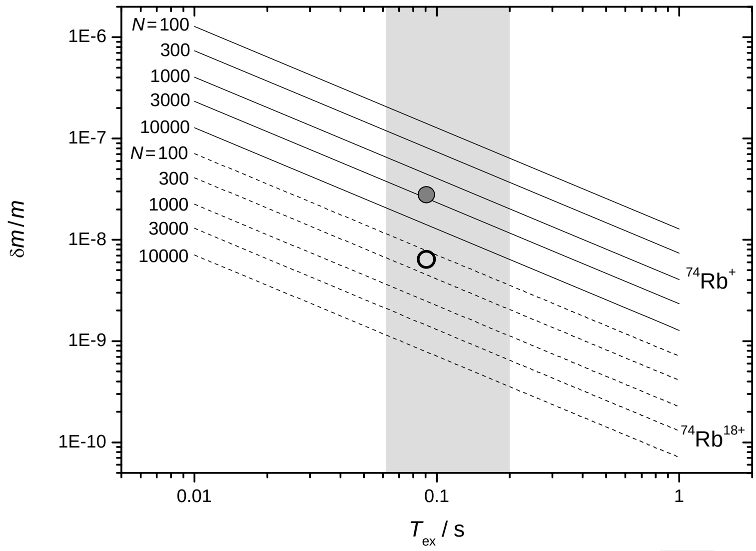

Figure 11.2 Mass uncertainty (see Eq. 1) for ^{74}Rb with a half-life of only $T_{1/2}$ = 65 ms as a function of the excitation time in the Penning trap (B = 5.9 T) for two sets of charge states and different numbers of detected ions. The upper set of curves belongs to singly charged ions, the lower set of curves to ions in the charge state 18+ which can be produced with the REX-EBIS within 20 ms. The grey-shaded area corresponds to an excitation time of about one to three times the half-life (T_{ex} = 60-200 ms). The grey dot gives the present accuracy limit obtained within ~7 radioactive beam shifts with ISOLTRAP in 2003 [8]. The open circle indicates the accuracy limit of ISOLTRAP (δm/m = 8x10^{-9}) [7], which can be reached exploiting highly-charged ions within one to two shifts for $^{74}Rb^+$.

11.1.2 *Highly charged ions for mass spectrometry*

The advantage of using highly charged ions becomes obvious while looking on eq. (1): The cyclotron frequency scales linearly with the charge q of the ion. The resolving power achieved is approximately equal to the product of the cyclotron frequency and the excitation duration T_{ex} and the precision scales with the resolving power. In particular, the relative statistical mass uncertainty is given by

(2) $\delta m/m \approx m / (T_{ex}\, q\, B\, N^{1/2})$

where N is the number of detected ions. In order to obtain a high accuracy, *i.e.* a low mass uncertainty, high cyclotron frequencies due to strong magnetic fields or high charge states, and long interaction times are desirable.

For radioactive ions far from stability the interaction time is limited by the half-life while the number of detected ions is depending on the production yield and the available beam time. Since highly-charged ions have higher cyclotron frequencies the resolving power and the accuracy are increased; or vice versa, a high-precision mass measurement can be performed in a much shorter time as compared to the case of singly-charged ions, which gives access to very short-lived nuclides, *e.g.* to the radionuclide ^{12}Be with $T_{1/2}$ = 21.5 ms. Figure 11.2 shows the advantage of using highly-charged ions with respect to accuracy in the case of ^{74}Rb with charge state 18+ in a 5.9 T magnetic field.

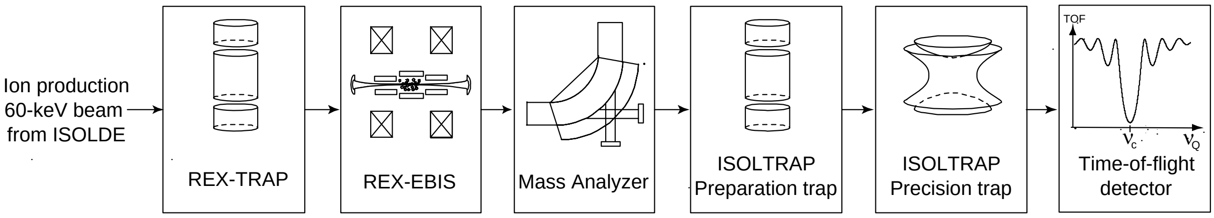

Figure 11.3 Schematic layout of the electron beam ion source (REX-EBIS) and the Penning trap system (ISOLTRAP).

11.2 Proposed technical realization

We propose to combine the existing REX-ISOLDE electron beam ion source (REX-EBIS) and the Penning trap mass spectrometer ISOLTRAP at ISOLDE in order to exploit the advantages of highly-charged ions for high-precision mass measurements. A schematic drawing of the proposed combination is shown in .

Table 11.1 Peak charge-state after 20 ms breeding time

Element	Charge-state
$_{8}$O	7^+
$_{11}$Na	9^+
$_{12}$Mg	9^+
$_{18}$Ar	11^+
$_{19}$K	11^+
$_{20}$Ca	12^+
$_{36}$Kr	16^+
$_{37}$Rb	18^+
$_{51}$Sb	19^+
$_{54}$Xe	21^+

At present the only electron beam ion source trap in operation for charge breeding of short-lived radionuclides is REX-ISOLDE/CERN for post-acceleration experiments[3]. With a 5-keV electron beam and a current of 0.5A a current density of >200 A/cm^2 throughout a 0.8 m long trap region can be obtained in the charge breeder. With these parameters the REX-EBIS trap at ISOLDE/CERN can hold ~6x10^9 charges for an electron-beam charge-compensation of 10% [12]. The most dominant charge states for some typical ions, charge bred for 20 ms in an EBIT with the parameters given above, are listed in Table 11.1. Figure 11.4 shows the breeding time as a function of charge state for some selected elements.

Figure 11.4 Breeding times as a function of the charge state for a current density of 200A/cm^2 (courtesy of F. Wenander [12]).

As for the requirements with respect to ISOLTRAP, for a short storage time of only a few ten to hundred milliseconds a vacuum of $p \leq 10^{-9}$ mbar should be sufficient, which is slightly better than our present vacuum conditions at the precision trap. We plan to improve the vacuum by adding getter pumps to the current ISOLTRAP system. Of course helium buffer gas cooling – at present in use at ISOLTRAP in the radiofrequency cooler and buncher and in the preparation Penning trap – can not be used in the case of highly-charged ions due to charge-exchange losses. Therefore, in a

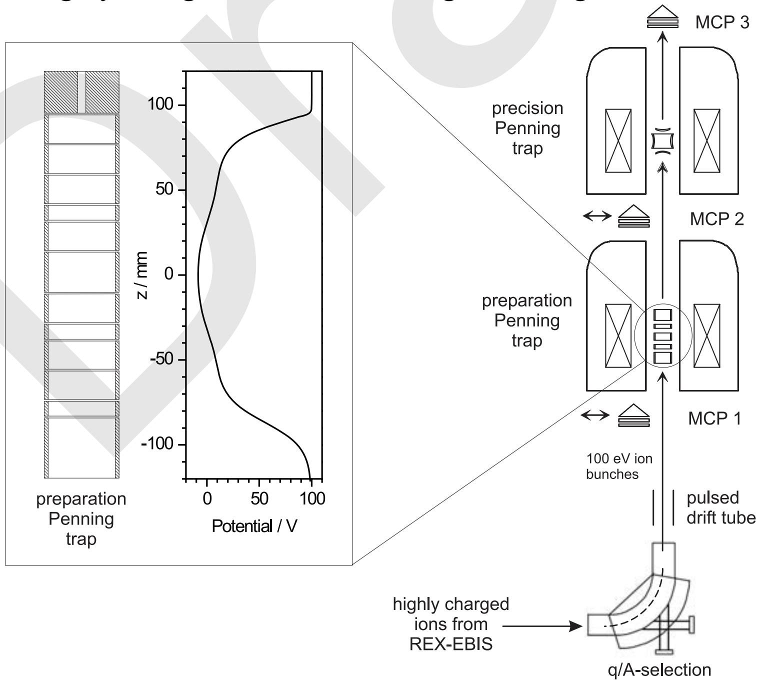

Figure 11.5 Modified experimental setup with a q/A-selection that replaces an electrostatic bender. The inset shows the current electrode configuration of the preparation Penning trap and the applied potential along the axis.

first step we plan to shoot through the buncher and to use evaporative cooling in the preparation trap, *i.e.* throwing away the hottest ions and reducing the overall efficiency by about two orders of magnitude.

However, for high-precision mass measurements the number of ions stored in the precision Penning trap at a given time is reduced to one in order to avoid frequency shifts due to ion-ion interactions. Note that the current cylindrical Penning trap (see inset of) allows the application of evaporative cooling without any change of the electrodes. Only for the lowering of the potential well depth a slight modification of power supplies is necessary.

In a second step the presently achieved efficiency can be re-established by adding electron and resistive cooling (see Figure 11.6) as planned in the HITRAP project at GSI for stable or long-lived isotopes [5]. Also sympathetic cooling with laser-cooled ions might be an efficient way to prepare the ions.

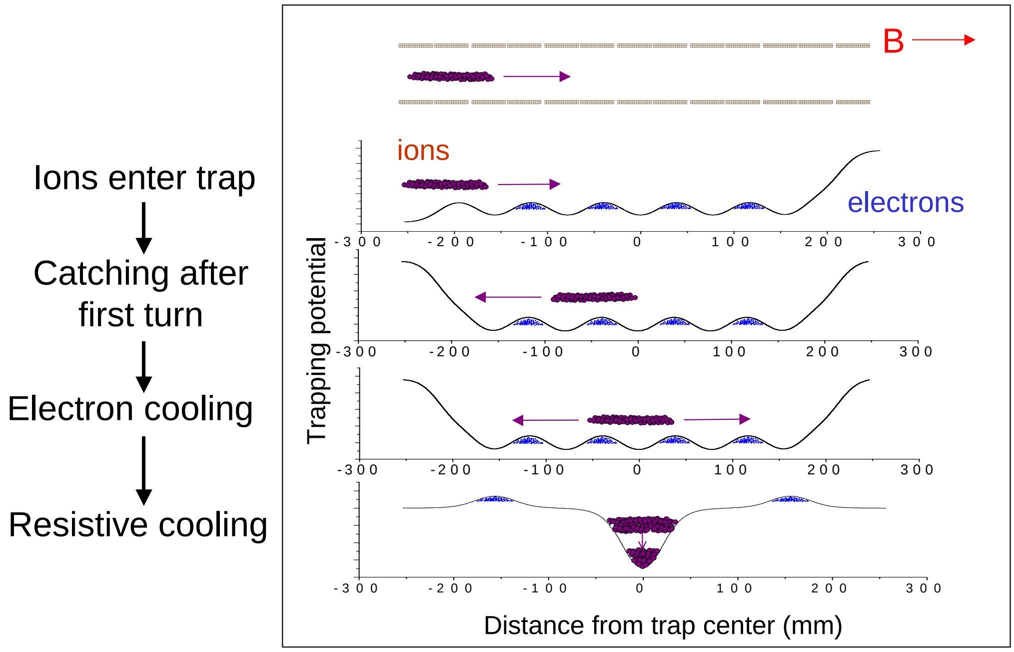

Figure 11.6 Experimental scheme of electron and resistive cooling in a cylindrical Penning trap (courtesy of Wolfgang Quint, GSI).

While the preparation trap is currently also used for purification of the ion ensemble as delivered by ISOLDE, an additional q/A selection step for the ion beam on its way from REX-EBIS to ISOLTRAP is needed and already included in the proposed scheme. The charge breeding at REX-EBIS provides further parameters for the reduction of contaminants. In addition, the selection of appropriate charge states of the ions of interest and the ions for the magnetic-field calibration will lead to closer mass doublets and thus to a further increase of accuracy. As a possible experimental scheme a q/A-selection in front of the preparation Penning trap is shown in .

11.3 Conclusion

In conclusion, the unique combination of an electron beam ion source to produce highly-charged ions and a Penning trap mass spectrometer for high-precision mass measurements installed at ISOLDE/CERN will be the most powerful technique for mass spectrometry on short-lived exotic nuclei. Increased accuracies and a further reduction in the lower limit of the half-lives as compared to the present values are expected.

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12 Solid-state physics with Radioactive Ions

12.1 Physics Case

Radioactive nuclei from various sources have been used for condensed matter investigations for a long time. The earliest application of radiotracers was the investigation of diffusion processes [10]. Nuclei are now being routinely used as probes of their environment in metals and semiconductors via various methods. More recently these techniques have also been applied to the study of complex bio-molecules, surfaces and interfaces. This spin-off of nuclear physics research has been steadily increasing in scope. With the routine availability of high purity radioactive ion beams from isotope separators the possibilities for such investigations have been greatly expanded, permitting technologically ever more demanding experiments. In particular the use of on-line isotope separation at the CERN/ISOLDE facility has demonstrated the great potential for solid state physics research.

During the last 17 years approximately 25 % of the beam time available there has been devoted to condensed matter applications. If we plan a mid-term upgrade of the ISOLDE facility it therefore appears natural that the applications in materials science are going to be an important research field there too. The future user of ISOLDE would be able to utilize the higher beam energies, qualities, and intensities available there.

Figure 12.1Recent research topics of solid-state physics at ISOLDE

In order to give an impression of the wide variety of possible applications, a short summary of the present uses of radioactive ion beams for solid state applications is presented here first, mostly from projects running as part of the ISOLDE program at CERN. More detail on most of the projects may be found in a special volume of the journal Hyperfine Interactions [11]. This is followed by a more detailed description of possible future applications of radioactive ion beams in materials science making use of a mid-term upgrade of the ISOLDE facility.

12.2 Presently possible experiments

Nuclear methods allow the investigation of impurities in condensed matter at a very low concentration, essentially isolated impurity atoms. Crucial for such research is the availability of an isotope with suitable decay characteristics and half-life, but also the clean incorporation into the material to be studied. It is therefore obvious that the use of chemical techniques to produce the samples required from commercially available radioactive isotopes limits the scope of such applications to a few easy cases. Some further cases have been opened up by production of the required sources directly at reactors or accelerators. A considerable simplification was brought by the application of on-line isotope separator implantation for sample production.

Figure 12.2 Possible implantations energies and corresponding implantation depth for ^{111}Cd in Si, today

The major step forward, however, was the use of on-line isotope separators, in particular ISOLDE. This facility has therefore attracted a large number of users from solid state physics. The solid state experiments there take advantage of the wide choice of isotopes available at ISOLDE which can be implanted into the matrix under investigation with the separator energy of 60 keV. Additionally by using a high-voltage (HV) platform as post-accelerator implantation energies up to of 260 keV can be achieved. With REX-ISOLDE the isotopes can be accelerated to 300 keV/u yielding an implantation energy of several MeV. Since this high implantation energy causes an implantation depth of several µm REX-ISOLDE is not useful for many experiments in solid-state physics. At the moment there is a gap of implantation energies between the HV-platform and REX-ISOLDE.

A wide variety of experimental techniques has been introduced for the studies of the implanted samples, briefly summarized below. Many different condensed matter systems are being investigated with these nuclear techniques, in particular semiconductors, metals, surfaces, and interfaces, but also such complex materials as ceramics, high-T_c superconductors, or bio-molecules. In Figure 12.3 the elements that have isotopes used for solid state experiments at ISOLDE are outlined.

Figure 12.3 Elements produced as radioactive beams at ISOLDE (symbols) and used in solid state experiments (circles)

12.2.1 Perturbed angular correlations

Running Experiments: IS325, IS348, IS360, IS368, IS368, IS390, IS391, IS396, IS422, IS425

For the technique of perturbed angular correlations (PAC), isomeric nuclear states in the nanosecond-microsecond time window of the method are needed. These are populated in many radioactive decays, in particular those further away from the stability line. The technique therefore lends itself extremely well to on-line isotope separator implantation. In this way the spectrum of possible isotopes for this method could be greatly extended at ISOLDE, and the full potential has certainly not been exhausted yet. While for laboratory experiments only very few isotopes are suitable (^{111}In, ^{181}Ta, and a few more), the easy availability of short-lived sources has lead to the application of about 25 different source isotopes at ISOLDE. The shortest half-life used up to now is 2 minutes, but for on-line experiments there is in principle no limit, and a few more cases with source half-lives down to seconds wait to be exploited.

In conventional PAC two γ-rays are observed in delayed coincidence. For many decay schemes, however, the detection of the conversion electrons is more favourable. A spectrometer for electron-γ or electron-electron PAC has therefore been installed at ISOLDE [12]. This technique, uniquely suited to implanted systems, has found first promising applications in metal and semiconductor physics.

The PAC experiments have first concentrated on metallic systems, in particular on the electric field gradients extracted from the nuclear quadrupole interaction. This property has then been widely exploited for investigations of semiconductors, surfaces, and bio-molecules. Recently interesting results have been obtained on high-T_c superconductors [13] and colossal magneto-resistance systems (CMR) [14].

12.2.2 Mössbauer spectroscopy

Running Experiments: IS359, IS426

The use of Mössbauer spectroscopy in solid state physics is well established. One major drawback of the technique, however, is the fact that only very few isotopes exist with suitable decay characteristics. For laboratory experiments generally very long-lived source isotopes are needed (e.g. ^{57}Co ($t_{1/2}$ = 272 d), ^{119m}Sn ($t_{1/2}$ = 293 d)). This limitation does of course not exist at an on-line implantation facility.

The Mössbauer measurements conducted in a long series of experiments at ISOLDE have therefore made use of short-lived sources such as ^{57}Mn, ^{119}Sb or ^{119}In. These have been very successfully applied in the studies of implantation behavior in metals and semiconductors. In many cases the results have then led to further studies of the systems investigated by other nuclear techniques like channelling/blocking or perturbed angular correlations. Obviously the combination of different techniques has led to further insight, in particular concerning the lattice site taken up following implantation. Also Mössbauer experiments at ISOLDE were the first to demonstrate site-selective doping of compound semiconductors [15].

12.2.3 Low temperature nuclear orientation

The technique of nuclear orientation (NO) depends on a solid state property, the strong magnetic fields at the nuclei in magnetically ordered solids, metals like Fe, Co, and Ni in particular. The on-line facility NICOLE at ISOLDE routinely makes use of these fields for nuclear spectroscopy studies. Though much of the required solid state information is by now well known and also reasonably well understood, some interesting details are still emerging. Careful experiments with sources from ISOLDE have recently led to a systematic study of spin-orbit-produced electric field gradients in cubic metals, and the first steps towards a quantitative understanding of this phenomenon [16].

12.2.4 Decay labelling

Running Experiments: IS325, IS368, IS391, IS401, IS416

For the physics of semiconductors, and therefore also for their technological application, it is vital to have as much information as possible on the properties of impurity atoms. Various electrical or spectroscopic techniques are routinely used to investigate such problems. One of the major difficulties of these conventional methods is the assignment of an observed signal to a specific impurity element. This is by no means trivial, since the intentionally introduced impurities might be masked by defects or other impurities. It is here where the use of radioactive dopants can be of decisive advantage. With the radioactive decay certain signals can disappear or appear and thus be directly assigned to the incorporated radioactive element. Methods where this approach has been successfully applied at ISOLDE include the Hall-effect, photoluminescence (PL), deep-level transient spectroscopy (DLTS), and electron spin resonance (ESR).

Recently a state-of-the-art PL laboratory, called APRIL, has been set-up near the ISOLDE hall to enable PL experiments with such short-lived isotopes. Thus isotopes with quite short half-life (^{64}Cu ($t_{1/2} = 12.7$ h) and ^{65}Ni ($t_{1/2} = 2.5$ h)) could also be successfully employed [17].

12.2.5 Diffusion studies

Running Experiments: IS368, IS380, IS395

Diffusion of atoms in solids is a fundamental process in condensed matter that has been investigated in great detail. Obviously the first studies concentrated on the self-diffusion of the matrix atoms. Here the marking of the diffusing atom by its decay properties is the most convenient way to follow the depth distribution. Such tracer diffusion studies are also most suitable for investigating the diffusion of impurity atoms, and absolutely essential for systems with low solubility.

Experiments at ISOLDE first concentrated on impurity diffusion in simple metals, later on semiconductors, and finally on complex ceramic materials. For depth profiling different conventional techniques were first employed, followed later by an on-line apparatus using sputtering [18]. Thus isotopes with quite short half-life (^{11}C ($t_{1/2} = 20$ min) and ^{31}Si ($t_{1/2} = 2.6$ h)) could also be successfully employed [19].

12.2.6 Channelling/blocking

Running Experiments: IS360, IS368, IS390

The technique of determining sites of impurity atoms in crystalline solids by measuring the channelling/blocking pattern of the emitted radiation from single crystals lends itself perfectly to isotope-separator produced samples. The typical implantation depth of some 10 nm is just what is required in most cases. The technique also puts no stringent conditions on the decay properties. Charged particles to be used can be α- or β-particles or conversion electrons. Also generally a small source spot is required, to be obtained without much difficulty by focusing the ion beam.

At ISOLDE channelling/blocking has been extensively used in localisation of impurity atoms implanted into semiconductors, but also in some metals. While first experiments were conducted with single detectors, a major improvement was achieved with the use of 2-dimensional position-sensitive devices [20].

12.3 Future possibilities at an upgraded ISOLDE facility

Most of the experimental program in solid state physics running at present has a long-term perspective. It might therefore be envisaged that similar projects would also be launched in this area at an upgraded ISOLDE facility. Obviously the higher intensities of the low energy beams to be available there can facilitate such projects and also possibly widen their scope. Such possible uses will not be further considered here, since they will naturally be follow-ups of the projects presently running at ISOLDE.

There exist several other possible future applications of radioactive ion beams that would be highly interesting, but cannot be performed at the present ISOLDE facility for various technical reasons. Obviously new high-purity isotope beams will, as they have done in the past, also open up new applications in solid state physics. Since such developments are within the scope of the on-going ion source improvement research, they will also not be elaborated upon here. There are, however, three important features of the ion beams of the mid-term upgrading;

i. Higher beam energy
ii. Higher beam quality
iii. Higher beam intensity

Possible projects that would need these features for condensed matter applications are described in detail below.

12.3.1 Deep-level transient spectroscopy

The higher beam energies available at ISOLDE will also open up new perspectives for several measurements performed on semiconductors. The deeper implantation will permit the use of even smaller impurity concentrations than are at present possible. By varying the energy of the ions in the 0.1 to 10 MeV range, homogeneous depth profiles can be produced with a much lower dopant concentration. Also the deeper implantation will help to avoid the sometimes troublesome influence of surface defects and space charge effects.

Clearly the most appealing possibility is the deposition of the radioactive ions at a well-specified depth. This will allow us to reach a specific layer in multi-layered structures, so important in modern device technology. One experiment that could especially profit from this possibility is the technique of deep-level transient spectroscopy (DLTS).

In a DLTS experiment the capacitance change of a diode at different times after voltage switching is measured at variable temperature. Deep energy levels in the band gap of the semiconductor, generally due to impurities or defects, are then thermally populated and depopulated at the different bias voltages. Only levels of atoms in a certain distance from the diode interface contribute to the effect, however. Typically this depth is of order 500 nm, but it can vary widely as a function of the electric properties of the semiconductor.

At present it is of course not possible to implant the radioactive atoms to be studied directly into the specific depth. The DLTS experiments performed up to date at ISOLDE [21] therefore had to resort to diffusion steps to bring the impurities to the required depth. Such thermal diffusion is generally not possible with a complete diode structure, so that the production of the interface had to be done after the thermal diffusion. This complication has greatly restricted the applicability of DLTS with radioactive atoms, and thus the decay labelling of the observed levels to a specific element.

In a recent experiment the possibility of REX-ISOLDE for implanting the radioactive atoms into a specific depth was tested. Since the energy of the radioactive beam of REX-ISOLDE is with 300keV/u too high for the implantation depth needed, the beam will be decelerated by passing through a carbon foil of the right thicknesses. In addition we are going to add the possibility to tilt the foil against the beam direction to change the effective thickness.

The first experiment in 2002 using the radioactive isotope ^{153}Sm implanted in p-type 6H-SiC shows a partial success. The analysis of the DLTS data the decay effects of one deep level in the sample caused by the decaying ^{153}Sm. The setup with the carbon foil as decelerator leads, however, to irreproducible implantation energies. Thus, the signal from the DLTS experiment can not be assigned to an electronic level correctly. Further experiments of ^{156}Eu (IS416) scheduled in may 2004 failed due to the very low yield. Not even a part of a pA of the 28+ charged ions was measurable on our target at the second beam line of REX-ISOLDE. The tiltable carbon-deceleration-foil together with a silicon-detector was intended to control and adjust the exact beam energy. The yield of the REX facility has to be improved for further collections with the proposed technique.

Best collections for the proposed DLTS experiments on (neutron rich) rare earth isotopes might be possible with a HV setup accessible with highly charged ions. Energies in the range of 1 - 6 MeV per ion and a current of at least a few 10 pA, achievable with the proposed ECR setup would be perfect for radiotracer DLTS investigations of a large variety of wide band gap semiconductors. A depth-homogeneous concentration of dopants could be achieved with a tuneable implantation energy by applying a SRIM-simulated energy-dose-program. Applying the mentioned half-life sensitive radiotracer DLTS it is acceptable to have a beam contamination of oxides and isobaric isotopes in the same order of magnitude of the isotope to be investigated if these contaminations have half-lives far from that of the desired isotope.

12.3.2 Local regrowth studies of voluntary induced damage on optoelectronic materials

In most optoelectronic materials the annealing of damage created by ion implantation within few hundreds of nanometers, at the near surface region, has been carefully studied. Quite recent studies, aiming to tune the refraction index of lithium niobate, have been performed using very low doses, $10E^{10}$ - $10E^{13}$ ions/cm^2, of heavy ions with energies between 5 and 30 MeV. In this energy range, damage is created in thick layers that can reach 3 to 10 micrometers. Still the damage introduced with such low doses is enough to significantly change the refraction index of $LiNbO_3$.

Micromachining the interface between implanted and non-implanted regions with ion implantation and annealing led to the formation of a regular modulation in the crystal surface that has been observed with an optical microscope and characterized with AFM.

With the present proposal we aim to use very high-energy stable and radioactive beams to extend these studies to a higher energy range of implantations. By overlapping two (or more) very thin single crystals of LiNbO3, the highly energetic stable ions will create damage in the first crystals only due to the electronic stopping power. In the last crystal both nuclear and electronic damage will be created. Each crystal will now be implanted at selected depths with lower doses of still energetic radioactive nuclei, which are suitable for hyperfine interactions studies using the PAC technique. In this way we aim to follow the reorganization of the damage, layer by layer, and study the basic mechanisms of the annealing.

12.3.3 Diffusion in highly immiscible systems

Diffusion studies with the conventional radioactive tracer technique, whether they are followed up by sectioning of the sample or by some sort of depth sensitive radiation counting, require a certain solubility of the diffusing element for the development of the characteristic diffusion profile. In cases where strong forces keep the impurity atoms at the sample surface these methods are not applicable. It is here where deep implantation of high-energy radioactive ion beams could find a very interesting unique application.

Figure 12.4 Typical range profiles for implantation into solids at various energies. We can expect that a well-defined depth of the order of a few millimetres can be obtained at typically 100 keV/u

Typical implantation profiles for a wide range of implantation energies are shown schematically in Figure 12.4. It may be noted that the degree of localization in a predetermined depth improves with energy on a relative scale, even though the absolute width of the range distribution due to straggling naturally grows with energy.

The system of isolated impurity atoms at a specific depth lends itself perfectly to the investigation of diffusion even for completely immiscible systems. Such systems produced by forced alloying are of increasing technological importance. Their systematic study at high implantation depth and very low concentration could lead to a better understanding of the processes occurring in the materials with practical applications.

12.3.4 Beta-NMR with tilted-foil polarization

Beams of polarized radioactive nuclei open the possibility for interesting applications in various fields. In addition to possible uses in nuclear beta decay studies, such beams would be well suited for β-NMR experiments with short-lived isotopes. The combination of a radioactive ion beam facility with the tilted-multifoil method would allow the production of such nuclei, their subsequent polarization and then measurement of the hyperfine interaction of the nuclear moments with the fields of their surroundings using the β-NMR technique.

If an ion beam is passed through a very thin foil, tilted with respect to the beam direction at an oblique angle, the electronic states of the outgoing ions are polarized. Polarization is initially introduced in the orbital motion of the electrons by the surface interaction on exit of the ion from the foil. During flight in vacuum some of this electron polarization (which is in the direction **n*v**, where **n** is the unit vector perpendicular to the surface of the foil and **v** is the ion velocity vector) is transferred via hyperfine interaction to the nucleus. By a successive passage of several such foils, interspaced with regions of free flight to allow a significant nuclear precession around the total angular momentum F=I+J in flight, the effect can be enhanced. The expectation is that rather sizeable nuclear polarizations can be achieved for a wide variety of elements.

The tilted foil mechanism has already been used to induce in-beam polarization of nuclei at the several percent levels [22]. It has also been applied for the measurement of signs of quadrupole moments of high spin isomers [23] and of parity violation in the $17/2^-$ isomer of ^{93}Tc [24], again a high spin state. In those experiments the ion velocity was generally in the range of 0.01 c to 0.03 c. Conditions relevant to experiments at a radioactive beam facility differ substantially from these earlier experiments. Nuclei of generally lower nuclear spin I are used, requiring only a small number of foils. A lower ion energy in the range of 50 to 100 keV/u should lead to a larger polarization, though this expectation has not been verified by experiments up to now. The smaller size, angular divergence, and energy spread of the radioactive beam, combined with the typically higher count rates, can also make the experiments easier.

Figure 12.5 Schematic representation of the β-NMR setup using the multifoil polarization technique

In a pilot experiment at ISOLDE, making use of a high-voltage platform [25] for a moderate post-acceleration of the ion beam, the feasibility of the proposed experimental project has been demonstrated, and the magnetic moment of the nucleus ^{23}Mg was measured [26].

The quite simple experimental setup is sketched in Figure 12.5. The polarized ions are stopped in a crystal, generally cooled to low temperature in order to increase the spin-lattice relaxation time. A holding magnetic field, best produced by a superconducting magnet, is also applied parallel to the polarization direction. For radioactive nuclei the polarization is most conveniently determined by measuring the angular distribution of the emitted β particles. It has the form $W(\theta) = 1+B_1A_1\cos(\theta)$, where q is the angle with respect to the polarization direction. An RF field is applied to the stopped polarized nuclei and tuned until the polarization (and hence the β-asymmetry) is destroyed. The frequency of this NMR resonance can be measured with high precision.

Beta-NMR has the potential to become a very powerful tool for the investigation of condensed matter. It would complement the other nuclear probe techniques generally used at a radioactive beam facility for studies of the environment of implanted nuclei in solids. Until now only a few probe nuclei have been useful for this method, owing to the difficulty of producing polarized nuclei. The only somewhat universal technique is capture of polarized neutrons. Experiments on ^{8}Li, ^{11}B, ^{20}F and a few others have been successful [27]. The usefulness of this technique for solid state applications, however, is seriously limited by the fact that the samples have to contain a large amount of the element to be studied, thus forbidding the investigation of dilute impurities, otherwise characteristic for the nuclear methods. The exceptions are ^{12}N and ^{12}B, the only nuclei suitably polarized following nuclear reactions [28] and ^{8}Li, that has been used for β-NMR following laser-polarization at ISOLDE [29]. Nevertheless the few applications of the β-NMR method have demonstrated the power of NMR coupled to nuclear detection. Pioneering studies of nuclear relaxation, diffusion, radiation defects, and glass structure have been performed.

With the development of the tilted foil technique the possibility of obtaining polarized ion beams will open up the wide spectrum of isotopes available at ISOLDE for applications of β-NMR spectroscopy. Clearly the strength of the method lies with the lighter elements, where spin-lattice relaxation times are sufficiently long for investigations over a wider temperature range. For these technologically important implants generally no probe atoms suitable for the other nuclear methods like MS or PAC are available. It is difficult, however, to predict which isotopes will be most suitable for condensed matter studies. Exploratory measurements of the β-asymmetries for several of the most interesting cases are necessary before one can discuss a solid state research program with the new technique in detail.

Measurements of the spin-lattice relaxation or Knight shift for light impurities in metals are still very scarce. Together with the hyperfine fields in the few simple ferromagnets they would give direct information on the conduction electron density at the impurity site, one of the few ways to test band structure calculations on a microscopic scale.

The elements of the first two periods are especially important as dopants and impurities in presently used semiconductors, and even more so in diamond and SiC, the semiconductors of the future [30]. Beta-NMR could give direct information about electronic and lattice structure, particularly since the nuclear quadrupole interaction can also be measured with NMR accuracy. The further development of radioactive beams of the reactive light elements (B, C, N, O, and Al, Si, P, S) will be of great significance in this respect. Several of the mirror decays (^{11}C, 1^{3}N, ^{27}Si) should be very suitable for the new technique.

As a representative example of an actual experiment one could consider the investigation of implantation of C and Si into the various forms of SiC by way of the electric field gradients acting on the probe nuclei of ^{11}C and ^{27}Si. For both elements there exists no stable isotope at all that would allow the measurement of nuclear quadrupole coupling constants. One would therefore first test the technique by implantation into non-cubic solids like graphite. Then a series of measurements of the β-NMR pattern at different temperatures could be performed and interpreted to determine the defect configurations present. Later a series of double resonance experiments with the stable nuclei of the matrix could give further details on the lattice site taken up after implantation For example, silicon atoms occupying carbon sites (antisite defects) will show a stronger coupling to the matrix Si spin system than the substitutional atoms. One would probably also investigate a few samples with different doping levels to detect the influence of charged lattice defects. Such a program could typically run for 2-5 years, depending on the suitability of the probe nuclei chosen and the significance of the initial results.

The required beam energies are in the order of 100 keV/u, with a large uncertainty in the present expectations, however. Various test runs to find the optimal conditions for the solid state experiments would certainly have to be made. Intensities of 10^7 ions per second should be largely sufficient.

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13 A Tilted-Foil Setup at the Low-Energy Section of REX-ISOLDE

MAGNETIC MOMENTS ALONG THE N=Z LINE IN PROTON-RICH NUCLEI

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13.1 Introduction

Magnetic moments of nuclei provide an important input to the understanding of nuclear structure since they can provide precise and unique information regarding the single particle nature of the particular nuclear level under study. In the last few years, much focus has been drawn to probing nuclear structure at extreme isospin, using the various new developments in rare-isotope-beam facilities and in ancillary detection systems. In particular, measurements of ground-state magnetic moments in short-lived, proton-rich nuclei can shed much light on the evolution of shell structure as approaching the proton drip line. In the β-NMR method, widely used in such measurements in unstable nuclei, the nuclei are polarized using various possible mechanisms such as reaction polarization, optical pumping and low-temperature orientation [1-3]. The resulting asymmetric distribution of decay β–rays is monitored in the presence of an external static magnetic field and a perturbing rf field. The particular method chosen for polarizing a given nucleus depends mostly upon properties such as life times and atomic structure. For short-lived nuclei in the ms range or for elements not readily amenable to laser techniques, the tilted foil method has a broad potential when combined with the β–NMR technique. In the of tilted foil (TF) geometry, atomic polarization is initially induced in ionic electrons by a surface interaction upon the exit of an ion from a thin foil, tilted at an oblique angle with respect to the ionic beam direction. The atomic polarization (in the direction n **x** V - where n is the unit vector perpendicular to the outgoing surface of the foil and v is the ion velocity vector) is transferred to the nucleus via the hyperfine interaction. The nuclear polarization thus induced can be enhanced, especially for high-spin states, by the use of several foils spaced sufficiently as to allow a significant nuclear precession around the total angular momentum in the flight time between successive foils.

13.2 Experimental Considerations

In our previous experiments at ISOLDE, we have measured the magnetic moments of the ground states of T=1/2 and T=3/2 nuclei in the s-d shell, ^{23}Mg and ^{17}Ne, respectively [4,5], by using the High-Voltage Platform (HVP) at –200 kV. The HVP has been constructed at ISOLDE by our group to boost the initial energy of the 60 keV beams. This boost in energy is essential in order to provide the nuclei under study sufficient energy to traverse one or two carbon foils tilted at 75^{o} to the beam direction. In the first experiment, due to the high yield of ^{23}Mg, it was possible to use the 10 times scarcer 2^{+} charge state in order to obtain a total of 520 keV. However, for nuclei far-from-stability, the beam intensity usually does not allow the use of ions with charge states other than 1^{+}. For ^{17}Ne, due to the lower Z, singly-charged ions were used. However, for ~ Z > 12, much higher energies are needed and we therefore propose to use REX-ISOLDE for this purpose.

The necessary use of the high voltage platform posses several experimental difficulties that the proposed use of REX-ISOLDE for such experiment will alleviate;

i. Even at the 520 keV energy, the multiple scattering in the tilted foils resulted in a loss of more than 50% in the beam reaching the stopper and the rf region, diminishing considerably the accuracy and systematic reliability of the measurement. It is especially important when trying to measure magnetic moments of nuclei in the f shell, with masses in the A=50-70 range, for which the laser ion source at ISOLDE is capable of producing good beams. These nuclei will be the focus of this phase of the research program and provide a complementary method to similar studies using beam-polarization at intermediate energies as now being planned at the NSCL Lab at MSU.
ii. The tilted foil polarization is an atomic effect, depending on the hyperfine interaction of the atomic configurations in the particular charge states emerging from the tilted surface at a given velocity. When using the HVP, this velocity is necessarily fixed at a low value. REX-ISOLDE will provide the opportunity to probe the induced TF polarization at a wide velocity range and thus find the optimum conditions for any particular nucleus, or region of nuclei, under study, greatly enhancing the sensitivity of the method.
iii. Carrying out experiments on the HVP is a complicated and time-consuming procedure as any access to the experimental apparatus is restricted and involves a complicated and elaborate sequence of events. This fact will be automatically remedied in the proposed setup.

With the construction of the new Extension Hall at ISOLDE, several experimental setups such as the MINIBALL array, that need higher REX energies, will move to the new hall. This will facilitate the transfer of the superconducting magnet and the tilted-foil chamber from their present location on the HVP. The needed energies for the tilted-foil polarization may vary in a wide range, from values obtained by using the RFQ device only up to 1-2 MeV/A, and hence can be best obtained at this location.

13.3 The Physics Case

The present commissioning of the REX ISOLDE facility provides radioactive beams with energies from 300 keV/A to 3.2 MeV/a, allowing heavier-mass nuclei to pass through several tilted foils at various charge state and atomic configuration. This will allow a selection of beam energy to obtain possibly higher atomic (and hence, nuclear) polarization. The present results therefore pave the way for future determinations of magnetic moments in, e.g., proton-rich nuclei in the Fe-Ga region of the f shell for which virtually no information exists on magnetic moments of N=Z-1 nuclei and of mirror pairs. As examples we cite the cases of ^{57}Cu that is one-proton removed from the closed ^{58}Ni nucleus and the self-conjugate ^{58}Cu. Another region of much interest are the mirror T=3/2 pairs in the s-d shell such as ^{21}Mg.

13.4 Requirements and Numbers

13.4.1 *Physical space and infrastructure*

The minimum requirements are:

i. A short beam line after the switching magnet behind REX.
ii. A stand to support the superconducting cryostat and the tilted foil chamber.
iii. A return line for He gas.

13.4.2 Beams and yields

From the brief discussion above, the nuclei under consideration are the Z=N+1 isotopes in the f-shell (e.g., ^{57}Cu, ^{53}Fe, etc.) and T=3/2 nuclei in the s-d shell (e.g., ^{21}Mg, ^{33}Ar etc.). The largest unknown when trying to asses the needed yield for a β-NMR measurement is the nuclear polarization in the tilted foil method. This essential quantitative parameter depends on the velocity and charge-state of a given RNB beam and its systematics will become more extensive as experiments progress. For a present rough estimate we can generally follow the results of the previous ^{23}Mg and ^{17}Ne experiments (see Figure 13.1) and assume $A_\gamma \sim$ 1-2%. For these figures, yields of 100-1000 ions/s into the apparatus should be sufficient for a successful determination of a β-NMR resonance. These yields are a realistic goal for the aforementioned beams at REX-ISOLDE.

We would like to note that the determination of quadrupole moments of ground states is also possible using the TF polarization and β-NMR when implanting the polarized RNBs into a non-cubic crystal. Such determination will provide unique and complementary information as to the deformation of the nuclear shape in far-from-stability regions. However, in general a quadruple moment determination is more difficult due to the different frequencies in the β-NMR spectrum as compared to the magnetic case. As a consequence, the quadrupole measurement phase will come only sufficient information is gained about the systematics of the TF polarization.

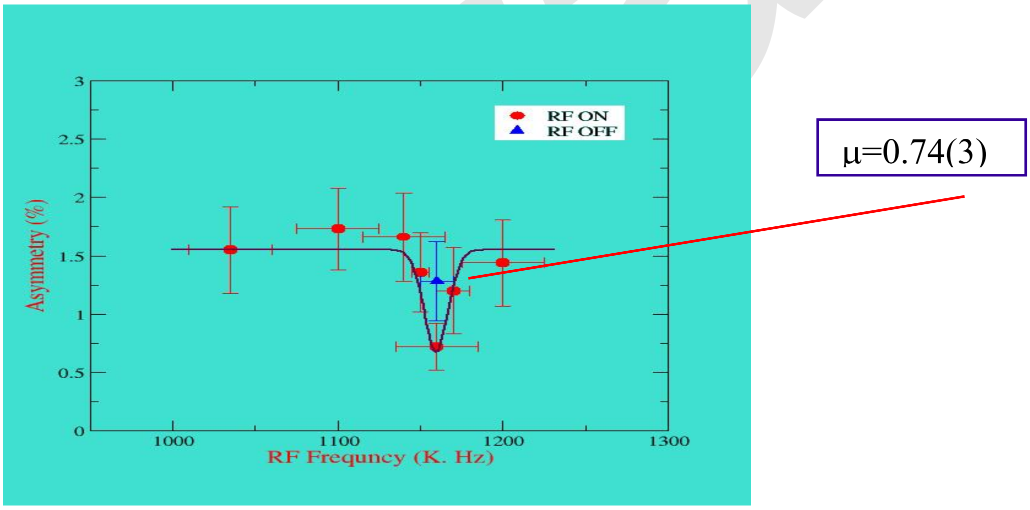

Figure 13.1 β-NMR resonance curve for ^{17}Ne [5]. An asymmetry of $A_\gamma \sim 1.5$ % was obtained.

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14 Appendix – resource estimates

Table 14.1 Costs and approximate scheduling of the HIE upgrade work related to the target irradiation area. The estimation below will be revised after the first milestone (t0 + 9 month) where reports are expected on detailed cost estimation and Fluka simulation of the dose rates and time dependent isodoses matching the new operation mode.

Task	*Deliverables:*		**8.9**	**3,130,000**	
	Project scheduling (~4 years), description and costs within 20%	Eng	0.5		
Detailed Fluka simulation of the ISOLDE target area:					1-Jan-06
	Description of the integrated dose (isodose table). Sullivan's paper describes an "average" ISOLDE year of operation	Phys	0.5		
	Dose rate after irradiation as a function of time for various operation scenarios with the aim of planning repair and shut down activities	Phys	0.5		
	Estimation of the total gaseous release				
	Investigation of the dose rate in the ISOLDE experimental area, including the Laser lab and the HT-room.	Phys	0.5		
Modification of the Target area building					1-Sep-07
	Shielded position for observation equipment (design, purchase) in collaboration with the previous task.	Eng	0.1	100,000	
	Covering the robot trench.	Civil Eng		50,000	
	Shielded areas for the ISOLDE target handling robots	Civil Eng		500,000	
	Modification of the shielding of the intermediate storage of irradiated targets.	Eng			
	Maintenance of the High tension connection “Boris” Tube	Eng	0.4	100,000	
	Modification of the shielding to the Laser laboratory	Civil Eng		20,000	
	Modification (and shielding) of the front end primary pumps	Civil Eng		60,000	
	Modification of the faraday cage		0.4	100,000	
Robots					1-Jul-08
	Investigation of a dedicated target handling robot	Eng	0.5		
	Purchase of a new robot system to be used for the next 15 years. (unless we can demonstrate that the actual one is suitable)		0.3	800,000	
Hands on – maintenance					1-Jul-06
	Define in collaboration with SC new operation procedures (FE exchange, pump maintenance, repair, robot maintenance…) to minimize the foreseeable dose.	Eng	0.6		
	Development of quick coupling for vacuum systems				
Targets and front ends					1-Jan-07
	Development of all metallic-ceramic target vacuum vessels	Eng	1		
	Beam optics of fixed extraction electrodes				
	Response of the resonating HT supply	Eng	0.4		

Production of 2 new target supports (as FE#6 QP-triplet), including a suppression of EEZ movement		1	600,000
Development of all metallic-ceramic front end-coupling	Eng	1	
Production of front-ends adapted to this new standard.		1	600,000
Operation budget increase			
Likely cost increase of the standard target units per year			150,000
Experimental hall classification after the upgrade			
Now class C, Check whereas a Class B is required		0.2	
Safety			
monitoring equipment			50,000

Table 14.2 Technical developments for the next three years needed at the REX-ISOLDE low energy stage.

Goals	Development	Preliminary study	Investment items	Investment cost	Manpower	Time estimate
Improved Efficiencies and higher intensities	New high performance cathode	**• Design study and construction of a new electron gun**	**New cathode, new electron gun mechanical parts**	**50 kCHF**	**2 years of a PhD at CERN**	**2005-2007**
	High intensity beam trapping	**• Tests • Numerical studies**	**New RF excitation generators and amplifiers**	**15kCHF**	**1 year of a PhD student or ½ year of postdoc**	**During 2006**
	Improving the trap efficiency	**• Tests • Numerical studies**	**Idem**		**½ year of a PhD**	**During 2006**
	Improving the differential pumping at the trap	**• Study together with the vacuum group**	**Possibly 2 new turbo pumps 1000 *l* Collimators Gas purifying system**	**50kCHF**	**2 months of a PhD**	**During 2007**
	Narrowing the charge state distribution in the EBIS	**• Shell closures related tests • MPI-K Heidelberg preliminary studies for DR resonances**	**Variable electron energy Requires a new electron gun (see first point above)**	**20kCHF**	**½ year of a postdoc**	**2006-2008**
Higher beam purity	Suppressing the isobaric contaminants from ISOLDE	**• Tests at REXTRAP • Numerical studies**	**Possibly modified RF excitation generators and amplifiers**	**10 kCHF**	**1 year of a PhD student or ½ year of a postdoc**	**2005**
	Molecular beams	**• Possible interesting studies in collaboration with chemists • New beam development tests**	**-**	**-**	**4 months of a postdoc**	**2005-2006**
	Improving the vacuum system of the transfer line	**• Design of the cold trap by the vacuum group**	**Cold trap mechanical parts, new roughing pump**	**20 kCHF**	**1 month of a postdoc**	**2005- 2006**

Better beam emittance	Cooling techniques in charge breeders	• **Preliminary tests and studies by other group in the EURONS network** • **Theoretical/ numerical studies (ion/electron optics)** • **Mechanical design study** • **Tests**	**Positively charged particle source, modification of the current electrode scheme** **Gas injection into the EBIS**	**0 to 70 kCHF** **depending on which method to use**	**1 year of a postdoc**	**2006-2008**
Comparison of Techniques	Beam cooling techniques – Penning trap and RFQ coolers	• **Tests of performances**	**-**	**-**	**½ year of a postdoc**	**2005??-2006**
	EBIS-ECR techniques	• **Tests of performances**	**-**	**-**	**½ year of a postdoc**	**2005-2006**
	Mass separator for the Phoenix-ECR	• **Similar to the TRIUMF one (Rick Baartman's design)**	• **Dipole magnet + electrical bender**	**150kCHF**	**4 months of a postdoc**	**2008**
	Phoenix-ECR consolidation	• **The Phoenix-ECR at REX-ISOLDE**	• **Vacuum system** • **HF** • **Ion source parts**	**800kCHF**	**1½ year of a postdoc**	**2008-2009**
Miscellaneous	Development of beam diagnostics	• **Detector electronics installation** • **Tests with radioactive beam**	**Electronics and MCA**	**20 kCHF**	**2 months PhD**	**2005**
	Slow extraction of the charge bred beam	• **Tests of extraction schemes**	**-**	**-**	**2 weeks of a postdoc**	**2005**