The HIE-ISOLDE Project

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Abstract. The HIE-ISOLDE project is a major upgrade of the existing ISOLDE radioactive ion-beam facility at CERN. The present energy of 3MeV/u for post-accelerated radionuclides will be boosted to up to 10MeV/u which will allow experiments to address all exotic nuclides produced at ISOLDE using, e.g., Coulomb excitation and nucleon transfer reactions. A R&D program on the superconducting linear accelerator is ongoing, including cavity manufacturing with prototype and sputtering tests. Besides the energy upgrade, the beam quality has already been improved and the beam intensity will be increased in the future with the upgrade of the CERN injector chain. An overview of the HIE-ISOLDE project and the present status is given.

1. Introduction
The radioactive ion beam facility ISOLDE [1] at CERN provides a large variety of exotic nuclides, ranging from light isotopes like ⁴He up to heavy isotopes such as ²²⁹Rn [2]. The successful operation over the last 40 years is due to the continuous effort in the development of new beams and better conditions for the experiments and users. In addition to experiments which directly take the 30-60keV ion beam delivered by the ISOLDE ion source, post-accelerated radioactive ion beams can be produced using the REX-ISOLDE system [3]. REX-ISOLDE was the last major upgrade of the ISOLDE facility (2002) and is now used for about 40% of the scheduled beam times. More than 50 different rare isotopes have already been post-accelerated to energies up to 3MeV/u [4].

With the next upgrade, called HIE-ISOLDE (High Intensity and Energy), the beam energy of post-accelerated beams will be increased and the beam quality and intensity improved [5]. The HIE-ISOLDE project was approved by the CERN Research Board in December 2009 and its kick-off occurred in January 2010. Already before that date, part of the beam quality improvement was successfully achieved, for example the installation of a radiofrequency quadrupole cooler and buncher [6] and new pump lasers for the laser ionization source [7]. The outline of the HIE-ISOLDE project is described in the following.

2. Present ISOLDE facility
The ISOLDE radioactive ion-beam facility makes use of thick targets which are irradiated with a pulsed beam of protons at 1.4GeV from the Proton Synchrotron Booster at CERN. At a maximum average current of 2µA the protons initiate fission, spallation, and fragmentation reactions and the produced exotic isotopes diffuse and effuse out of the heated target through a transfer line which is coupled to an ion source. Different types of ion sources are available, e.g. surface ion sources, plasma ion sources, or ionization using lasers. The latter method is element selective and thus offers the possibility to obtain a higher purity of the beam.
Isobaric contamination, mainly due to surface ionization, can be removed by application of mass separators after acceleration to maximal 60 keV.

Many experiments at ISOLDE take the beam directly from the ion source, i.e., at energies of 30-60 keV. With the different setups various properties of radionuclides are probed and measured. For example charge radii and quadrupole moments can be determined using collinear laser spectroscopy [8, 9]. Mass measurements with a Penning trap spectrometer [10] allow one to obtain information for nuclear structure and astrophysics calculations. Decay experiments using sophisticated detection systems measure excited levels in exotic nuclei and search for exotic decay mechanisms [11]. Also solid state physics experiments use short-lived ions to probe lattice structures and to examine the properties of new superconducting materials [12]. All these and many more experiments suffer from isobaric contamination and low production yields, i.e. they would directly profit from a higher intensity of the primary proton beam delivered from CERN and a better purity of the radioactive ion beam.

For REX-ISOLDE experiments not only the production yields and beam purity are important but also the achievable energy after post-acceleration. In the present REX-ISOLDE facility, the RIBs are accelerated with a compact normal conducting linear accelerator, which makes use of a special low-energy preparatory scheme. In Fig. 1 a diagram of the setup is shown. With the buffer-gas filled Penning trap system REXTRAP the incoming ions from ISOLDE are cooled and bunched for subsequent transport to the charge breeder REXEBIS. The ion charge-state is boosted such that the maximum mass-to-charge ratio is always $2.5 < A/q < 4.5$. Before injection into the REXLINAC an $A/q$ selection is performed with an achromatic $A/q$ separator of the Nier spectrometer type. The accelerator is designed with an accelerating voltage for a corresponding maximum $A/q$ of 4.5 and it delivers a final energy of 3 MeV/u for $A/q < 3.5$ and 2.8 MeV/u for $A/q < 4.5$. After charge breeding, the first acceleration stage is provided by a 101.28 MHz 4-rod radiofrequency quadrupole (RFQ) which takes the beam from an energy of 5 keV/u up to 300 keV/u. The beam is then re-bunched into the first 101.28 MHz interdigital drift tube (IH) structure, which increases the energy to 1.2 MeV/u. Three split ring cavities are used to give further acceleration to 2.2 MeV/u and finally a 202.58 MHz 9-gap IH cavity is used to boost and to vary the energy between 2 and 3 MeV/u.

3. Aims of HIE-ISOLDE
3.1. Higher proton beam intensity
Presently, the CERN injector chain starts with the LINAC2 linear accelerator which brings the protons to 50 MeV energy before injecting into the PS Booster for subsequent acceleration to 1.4 GeV. The maximum average current which ISOLDE is allowed to take is 2 $\mu$A. With the installation of the new LINAC4 accelerator at CERN, which is foreseen in 2016, the average current to ISOLDE can be increased up to 6 $\mu$A, i.e. a direct increase by a factor 3 of the
production yields can be envisaged. The present beam energy deposition in the target of about 3kW will increase to about 10kW. The HIE-ISOLDE project will address this increase of intensity with respect to the technical feasibility and safety aspects, i.e. a detailed design study is planned for energy dissipation, target handling, shielding etc. For the low energy part of REX-ISOLDE an upgrade of REXTRAP and the charge breeder REXEBIS is planned to cope with the increased intensity of the rare isotope beams.

3.2. Improved beam quality
The beam quality improvement comprises a better emittance of the beam for better beam transport towards and injection into the various experiments, as well as a higher beam purity to reduce background effects. The beam emittance has already been worked on by installing the buffer-gas filled radiofrequency quadrupole cooler and buncher ISCOOL [6]. This device reduces the beam emittance and can also provide ion bunches of only a few \( \mu \)s and thus allows laser spectroscopy experiments such as COLLAPS [8] or CRIS [9] to gate on the incoming ion bunch and to reduce the background by several orders of magnitude in their measurements [13].

A second major improvement for the beam quality is the installation of new pump lasers for the resonance laser ion source system RILIS [7] at ISOLDE. The formerly used copper-vapor lasers have been replaced with modern Nd:YAG solid state lasers and meanwhile also the subsequent dye lasers have been exchanged with new systems. Since the wavelengths of the pump lasers changed, the ionization schemes had to be adjusted and tested. After the successful operation of the new laser system the copper-vapor lasers have been removed and further improvements are planned, e.g. installation of Ti:Saphire lasers.

Finally, in order to improve the quality of the beam with respect to purity, a new mass separator with higher resolution is required. A design study is planned to examine the replacement or upgrade of the existing high-resolution HRS separator at ISOLDE.

3.3. Higher energy for post-accelerated beams
The envisaged increase of the present energy of post-accelerated beams from about 3MeV/u to 10MeV/u is the main part of the HIE-ISOLDE project. It is planned to replace part of the existing room temperature cavities with superconducting cavities and to add additional ones to reach the higher energy. A R&D program on the superconducting linear accelerator has started in 2008. It is based on superconducting copper cavities of the quarter wave resonators (QWR)

![Figure 2. Beam energy as a function of the number of cavities for various A/q settings.](image-url)
Figure 3. Staging of the installation of the superconducting LINAC modules.

Figure 4. Left: Cavity copper substrate towards final machining steps. Right: Design schematics of a high beta cryo module.

type and makes use of high field superconducting solenoids for the beam focusing. The niobium sputtering technology has been chosen as the baseline technique for the cavity manufacturing and prototype as well as sputtering tests are in an advanced state. In the short term, the new accelerator modules will boost the energy up to 5.5, 8, and 10 MeV/u, while in the longer term, part of present normal conducting linac will be replaced by new superconducting cavities in order to allow the full energy variability between 1.2 and 10 MeV/u as shown in Fig. 2. Figure 3 shows a possible scheme for the staged machine installation.

4. Present status of HIE-ISOLDE

4.1. Beam purity and quality

Besides the successful operation of The RFQ cooler and buncher for many experiments since 2007, a better operation of the laser ion source was achieved with the new RILIS pump lasers [14]. Due to the change in the wavelength, new pumping schemes had to be tested and by use of the off-line test facility LARIS [14] at CERN many auto-ionizing states of several elements could be found. In some cases the higher laser power gave higher ionization efficiencies, i.e. higher yields for the users as was shown for gallium isotopes [14, 15]. The new pump lasers are meanwhile used for all on-line runs using a RILIS for ionization.
4.2. Beam energy
Because of the limited resources available the priority of the HIE-ISOLDE project has been
given to the design and construction of the superconducting linear accelerator. In particular
the R&D effort has focused on the development of the high $\beta$ cavity ($\beta = 10.3\%$), for which
it has been decided to adopt the technology with which niobium is sputtered on a copper
substrate. Other R&D activities are related to the beam dynamics studies which seek to define
a very compact accelerating lattice and consequently the shortest possible machine, a design of
compact superconducting solenoids with limited fringe fields, and the study of the cryomodule
concept.

The superconducting LINAC is designed to deliver an effective accelerating voltage of at least
39.6 MV with an average synchronous phase $\phi_s$ of -20$^\circ$. This is the minimum voltage required
in order to achieve a final energy of at least 10 MeV/u with $A/q = 4.5$. Because of the steep
variation of the ions velocity, at least two cavity geometries are required in order to have an
efficient acceleration throughout the whole energy range. A total number of 32 cavities are
needed to provide the full acceleration voltage. The geometries chosen corresponding to low
($\beta_0 = 6.3\%$) and high ($\beta_0 = 10.3\%$) $\beta$ cavities maintain the fundamental beam frequency
of 101.28 MHz. The design accelerating gradient aims at reaching 6 MV/m with a power
consumption of 7 W per low-$\beta$ cavity and 10 W per high-$\beta$ cavity.

The construction of a high-$\beta$ cavity prototype started in the middle of 2008 and the copper
body which makes the substrate for the niobium sputtering was completed in April 2009. During
the same period a new sputtering chamber was constructed and is now under commissioning.
The critical fabrication steps of the cavity manufacturing process have been identified, which
will require strong quality checks to reduce the risk of faults during the series production. So
far the cavity has been checked also with a series of rf measurements, especially the variation of
the resonance frequency during the several manufacturing steps and all the measurements are
in line with the prediction. The mechanical fabrication of the copper cavity has been completed
and Fig. 4 (left) shows the cavity after the final low water pressure rinsing subsequent to the
chemical polishing.

The cavities will be placed in different so-called cryo modules. These modules are single
vacuum systems with an active thermal shield, which should be serviced and maintained by
CERN personnel, thus the design has to be adapted to fit these considerations. Figure 4 (right)
shows a schematic overview of a high beta cryo module.

5. Infrastructure and new beam lines
The new superconducting LINAC requires the supply with cryogenic liquids and additional
ventilation as well as power supplies. New buildings for this infrastructure are thus planned and
construction will possibly start by mid 2011. Suitable areas have to be found for the construction
of the buildings for the compressor of the liquid helium system, for the helium liquifier with an
associated control room, and also for the other subsystem like the new ventilation unit or the
new electricity distribution panels. For the design of the new beam lines delivering the post-
accelerated beams to the new experiments further information is required. To this end a call was
sent out for Letters of Intent to the ISOLDE and Neutron time-of-flight Experiments Committee
(INTC). In total 35 LOIs were received, from which 29 showed interest to use post-accelerated
beams at higher energy and 5 intend to make use of the intensity upgrade only. An overview of
the requested isotopes is given in Fig. 5.

6. Summary and outlook
The upgrade of the energy for post-accelerated rare isotopes up to 10 MeV/u will open up new
research possibilities at ISOLDE, i.e. Coulomb excitation of higher lying excited states and
nucleon transfer reactions. The recent improvement of the RILIS laser system and the RFQ
buncher and cooler ISCOOL have already shown a major impact on the operation of ISOLDE and the beam quality for experiments. With the staged approach the present ISOLDE facility can continue to operate and deliver beam to the users while the upgrade progresses. With the intermediate step at an energy of 5.5 MeV/u several experiments at, e.g., MINIBALL [16] can profit from the higher energy to go beyond the present limitation for post-accelerated beams. The schedule of the installation of the cryo modules is subject to the upgrade and change in the CERN injector chain for LHC. One crucial step is the commissioning of the LINAC4 and the connection to the PS Booster. It is planned to have the installation of the final cryomodules for the full energy upgrade to 10 MeV/u before the stop of the injector chain before LINAC4 goes into normal operation.

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