Post-accelerated beams at ISOLDE

To cite this article: Y Kadi et al 2017 J. Phys. G: Nucl. Part. Phys. 44 084003

View the article online for updates and enhancements.

Recent citations
- Nuclear-Structure Physics with MINIBALL at HIE-ISOLDE
  P. Reiter and for the? MINIBALL collaboration

Related content
- The European Spallation Source Design
  Roland Garoby, H Danared, I Alonso et al.
- Charge breeding of radioactive ions with EBIS and EBIT
  F Wenander
- SRF acceleration for heavy ions: ATLAS decadal operation and evolution
  P.N. Ostroumov and R.C. Pardo
Post-accelerated beams at ISOLDE*

Y Kadi1, Y Blumenfeld1,2, W Venturini Delsolaro1, M A Fraser1, M Huyse3, A Papageorgiou Koufidou1, J A Rodriguez1 and F Wenander1

1 CERN, CH-1211 Geneva 23, Switzerland
2 Institut de Physique Nucléaire, IN2P3-CNRS, Université de Paris-Sud, Université de Paris-Saclay, F-91406 Orsay Cedex, France
3 KU Leuven, Instituut voor Kern- en Stralingsfysica, B-3001 Leuven, Belgium

E-mail: yacine.kadi@cern.ch

Received 1 February 2017, revised 11 April 2017
Accepted for publication 12 June 2017
Published 29 June 2017

Abstract
This paper presents an overview of the REX-ISOLDE post-accelerator and a detailed description of the high intensity and energy ISOLDE (HIE-ISOLDE) energy upgrade. The status of the HIE-ISOLDE post-accelerator and its performance, including time structure, beam spot size, beam purity, etc. is presented. The high-energy beam transfer line is also described in detail and an overview of present and future instrumentation and plans for further developments is given. Finally, the hardware and beam commissioning is presented.

Keywords: radioactive ion beams, cryomodules, superconducting cavities, high-energy beam transfer lines, superconducting solenoid, beam diagnostics, beam commissioning

(Some figures may appear in colour only in the online journal)

Introduction

Physics with accelerated ion beams reveals interesting facets of nuclear interactions and dynamics and can open up new horizons for nuclear physics and astrophysics. Reaction studies at moderate energies—such as Coulomb excitation, capture and transfer reactions—can shed light to long-standing problems of nuclear structure and stellar nucleosynthesis.

ISOLDE is ideal for experiments with post-accelerated radioactive ion beams, thanks to the wide range of isotopes it can provide; it has produced approximately 1300 nuclei of over 70 elements. The first discussions for post-accelerated beams at ISOLDE began in 1977, however the idea was explored in depth in the late 1980s with the PRIMA proposal [1], which concerned nuclear astrophysics studies of light nuclei at energies of up to 1.4 MeV/u.

* This article belongs to the Focus on Exotic Beams at ISOLDE: A Laboratory Portrait special issue.
Although the proposal was not implemented, it stimulated discussions in the ISOLDE community that eventually led to the REX-ISOLDE (Radioactive beam EXperiment) proposal in 1994 [2]. The REX post-accelerator began operation in 2001 and soon morphed from an experiment into a facility and permanent part of the ISOLDE infrastructure. While the low energy ISOLDE experiments typically use beams of up to 60 keV (total energy) to study decay processes, conduct beam measurements, etc, REX extended the energy range to 3 MeV/\(u\), enabling a variety of reaction studies at moderate energies [3] for all isotopes available at ISOLDE.

The success of REX demonstrated the research potential of post-accelerated radioactive beams and led organically to the next major upgrade of the facility: the HIE-ISOLDE project [4, 5]. HIE-ISOLDE has a threefold goal: to increase the energy reach to 10 MeV/\(u\) with the construction of a new linear accelerator (HIE-linac), to increase the intensity and purity of the beam, and to improve secondary beam characteristics [6]. The energy upgrade is being implemented in three phases to reduce disruptions to the low energy experiments. In September 2016, the first phase of the upgrade was completed, allowing the HIE-linac to accelerate beams to 5.5 MeV/\(u\). The first experiments illustrated the promising potential of the upgraded facility and showcased the physics opportunities that the upgrade opened up. In early 2018, ISOLDE is expected to complete its energy upgrade, reaching 10 MeV/\(u\) and becoming an even more attractive facility for a wide variety of experiments.

### REX-ISOLDE

REX (figure 1) began operation in 2001 and the first experiments were successfully completed in 2002 and 2003 [7]. To accelerate the low energy ISOLDE beam in a universal, cost-effective, fast and efficient way, REX [8, 9] uses a linear accelerator, REX linac, and a novel charge breeding scheme that is based on a Penning trap, REXTRAP and an electron beam ion source, REXEBIS.

The low energy, typically quasi-continuous beam of singly charged ions is delivered to REX with an energy of 30 keV. Its transverse emittance is defined by the type and performance of the ion source, while its time structure is determined by the half-life of a particular isotope in the primary target, as well as this isotope’s diffusion and effusion times inside the target and ion source.
REXTRAP

The continuous ion beam is first accumulated in REXTRAP [10], cooled via buffer gas collisions, and extracted as short bunches. This step is essential, as the Penning trap provides short ion pulses with low emittance, contributing to the high efficiency of the consecutive charge breeder. The REXTRAP setup, designed and built at Mainz University and CERN, comprises a cylindrical gas-filled Penning trap, surrounded by a superconducting solenoid magnet that generates a magnetic field of 3 T, placed on a 30 kV high-voltage platform. Good vacuum in the beam lines leading in and out of the trap is provided by two differential pumping stages [11]. Before the low energy ion beam passes the potential barrier of the trap and enters the high-pressure region, it is electrostatically decelerated. Ions then travel through the cylindrical trap, losing energy in collisions with the buffer gas, which is usually neon or argon. The beam is reflected by a potential wall at the exit of the trap and the ions that have lost energy in the collisions are not able to escape, thus accumulating in the potential minimum of the trap. The ions are then further cooled by the sideband cooling method [12], developed at ISOLDE. After cooling, the potential wall at the extraction side is switched to a low enough value to allow ions to be released in a short pulse and be accelerated towards ground potential. The resulting cold bunches reach close to the initial ISOLDE beam energy. In figure 2, a time-of-flight of a beam extracted from REXTRAP is shown. Apart from the beam of interest, some Ne\(^+\) and/or H\(_2\)O\(^+\) may also be present due to collisions at injection and poor vacuum, respectively. The contamination elements are either rejected by a kicker system or suppressed by the \(A/q\)-selection after REXEBIS.

The longitudinal emittance of the ion beam can be as low as 10 \(\mu\)s eV, depending on the size of the ion cloud. REXTRAP’s efficiency ranges from 25% to 60%, mainly depending on the ion mass. The number of stored and cooled ions is restricted by the Brillouin limit. REXTRAP is capable of fast beam cooling and not designed to perform mass separation, which is difficult at high beam intensities and takes a long time (several 100 ms), even though it has been demonstrated [13]. Notably, the heavier the ion beam is, the faster the cooling.

REXEBIS

After the ions are accumulated and cooled in REXTRAP, they are injected into REXEBIS [14] via an electrostatic achromatic transport line, designed to minimise transmission losses and provide differential pumping in several stages between the Penning trap and the charge breeder. As REXEBIS is located on a platform above the Penning trap, the transport line includes a straight section and two 90° kicker-bender arrangements. REXEBIS, designed and constructed in Sweden by Manne Siegbahn Laboratory and Chalmers University of
Technology, charge breeds ions to multiple charge states via impact with an intense electron beam with an energy of 3–6 keV. The beam is produced by an electron gun and focused by a 1.2 m long solenoid magnet with a magnetic field of 2 T. Radioactive ions are confined in a trapping region and ionised as they collide with electrons. The trapping and confinement region inside REXEBIS has a length of approximately 0.8 m [15].

REXEBIS is capable of producing electron beam currents up to 460 mA and reaching a density of approximately 200 A cm$^{-2}$. During normal operation, 200 mA currents and 100 A cm$^{-2}$ densities are typically used [16]. The charge breeder attains a mass-to-charge ratio typically between 2.5 and 4.5, the higher limit imposed by the normal-conducting part of the linac. The charge breeding time is determined by the mass-to-charge ratio, which in turn depends on the desired isotope. It ranges from approximately 5 ms for very light nuclei with atomic mass number lower than 10 to a few hundreds of milliseconds for heavy mass elements ($A > 200$, see figure 3) [16]. To charge breed heavier elements to higher charge states, it is necessary to increase either the breeding time or the current density. During the charge breeding process, the REXEBIS platform voltage is pulsed from 30 kV at injection to $\sim 20$ kV at extraction, because radioactive ions beams have to be injected to the RFQ of the REX linac with an energy of 5 keV/u to achieve efficient bunching and thus better output emittance of the RFQ [14].

The pulse length of the extracted multiply charged ions can be varied. Light ions leave the breeder within some tens of microseconds, while it takes more than 100 $\mu$s for heavy ions to exit. The ion extraction can be slowed down by modulating the extraction barrier of REXEBIS and pulse lengths in excess of 800 $\mu$s have been demonstrated [16]. The longer
extraction time reduces the instantaneous beam rate at the experiment. The radioactive ion beam intensity is lower than that of the residual gas ions, namely carbon, oxygen, nitrogen, neon (diffusing from REXTRAP) and argon, therefore they have to be separated according to their $A/q$ values in a consecutive mass separator. The mass separator uses a 90° electrostatic deflector and a 90° magnetic bender in a vertical S-shape [18]. Figure 4 shows a mass-over-charge spectrum from REXEBIS with a high-intensity $^{129}$Cs beam being injected into the system.

**REX linac**

The extracted macro-bunches of multiply charged ions can be efficiently accelerated in the compact linear accelerator of REX. The REX linac operates at room temperature, with a duty cycle of up to 10% [9], and was originally built to accelerate beams with $A/q < 4.5$ up to 2.2 MeV/μ, allowing the Coulomb barrier to be reached for isotopes with $A < 50$. It is composed of a range of different radiofrequency (RF) structures and the addition of a 9-gap inter-digital H-type (IH) cavity in 2004 pushed the energy range up to 3.0 MeV/μ for $A/q < 3.5$ and extended the reach of the Coulomb barrier to $A < 85$ [20]. Today the REX linac incorporates a four-rod, $λ/2$ type radiofrequency quadrupole (RFQ) accelerator, followed by a 20-gap IH structure and three 7-gap (7GX) split-ring resonators operating at 101.28 MHz [21]. The radioactive ion beams are accelerated from 5 keV/μ to 0.3 MeV/μ in the RFQ before reaching an energy of 1.2 MeV/μ in the 20-gap IH drift-tube linac structure. A split-ring rebuncher is installed between the RFQ and the 20-gap IH structure to match the longitudinal beam parameters between the two RF structures. After passing through the 20-gap IH structure, ion beams achieve a variable energy of 1.55, 1.88 and 2.2 MeV/μ in each successive 7-gap resonator. Finally, the energy range is boosted to up to 3 MeV/μ in the 202.56 MHz 9-gap (9GP) IH structure. The main RF parameters of each structure are summarised in table 1 and the main characteristics of the beam during acceleration are shown in figure 5.

![Figure 4. $A/q$-spectrum for a typical beam extracted from REXEBIS. In addition to residual gases, externally injected and charge bred caesium (in blue) with a charge state distribution peaking at 30+ is clearly distinguishable. Reproduced with permission from [19].](image-url)
The time structure of the accelerated ion beams at REX depends on a wide range of factors, namely the repetition rate of the primary proton beam, the release profile from the target ion source unit of the desired isotope, the cooling and charge breeding times, the duty cycle of the accelerator and the 101.28 MHz micro time structure of the linac \[3\]. The time structure is shown schematically in figure 6.

Beam instrumentation

The radioactive beam intensity in REX varies between a few 100 to 10^7 ions s^{-1}, although the system can handle higher rates. As many beams have a very low intensity, not detectable by Faraday cups, the setting-up of REX is done with a pilot beam. This is a stable, high-intensity beam, with an \(A/q\) similar to the desired radioactive beam. The system can therefore be tuned using Faraday cups and subsequently be scaled to the \(A/q\) of the radioactive beam. The Faraday cups in use are 25 mm diameter screened cups, capable of measuring averaged currents down to less than 0.1 pA.

For beam profiling, and for detection of very low intensity beams, multichannel plates (MCPs) in combination with phosphor screens are used. The beam is either impinging directly onto the MCP, or on a secondary electron-emitting aluminium plate. Charge-coupled device cameras are used for detecting the light emitted from the phosphor screens. The MCPs can also be used in time-of-flight mode to determine the beam composition after REXTRAP (see figure 2) and the pulse shape after REXEBIS. Note that isotopic separation within an isobar is not achievable.

Finally, using the beam diagnostic system, collimators and stripping foils can be inserted along the beam line. Some of the apertures have attenuation grids to reduce the beam intensity, for example for beam energy measurements using a silicon detector.

REX proved to be a success, thanks to its versatility: it can accelerate a wide variety of ions from light elements, such as \(^6\)He and \(^9\)Li, to heavy mass nuclei, e.g. \(^{225}\)Ra \[3\], and elements from all groups in the periodic table. Isotopes with lifetimes as short as 20 ms \(^{10}\)Be\] have successfully been delivered for experiments. Furthermore, the delivered beam is in most cases very clean from contamination thanks to the excellent vacuum inside REXEBIS. REX is ideal for a large range of experiments, especially those that focus on Coulomb excitation, as

| Parameter | RFQ | ReB | IHS | 7GX | 9GP |
|-----------|-----|-----|-----|-----|-----|
| \(F\) (MHz) | 101.28 | 101.28 | 101.28 | 101.28 | 202.56 |
| No. of gaps/cells | 232 | 3 | 20 | 7 \(\times\) 3 | 9 |
| \(\beta_{\text{in}} \rightarrow \beta_{\text{out}}\) (%) | 0.3 \(\rightarrow\) 2.5 | 2.5 \(\rightarrow\) 2.5 | 2.5 \(\rightarrow\) 5.1 | 5.1 \(\rightarrow\) 6.9^a | 6.9 \(\rightarrow\) 7.8^a |
| \(W_{\text{in}} \rightarrow W_{\text{out}}\) (MeV/u) | 0.005 \(\rightarrow\) 0.3 | 0.3 \(\rightarrow\) 0.3 | 0.3 \(\rightarrow\) 1.2 | 1.2 \(\rightarrow\) 2.2^a | 2.2 \(\rightarrow\) 2.8^a |
| \(E_{\text{acc}}\) (MV m\(^{-1}\)) | 0.44 | 0.36 | 2.7 | \(\sim\) 2.5 | 5.2 |
| \(L_e\) (m) | 3 | 0.2 | 1.5 | \(\sim\) 0.60 | 0.52 |
| \(Z_{\text{eff}} = Z_0 - T_2\) (MΩ m\(^{-1}\))^b | – | 20 | 225 | \(\sim\) 55 | 165 |
| \(Q\) (unloaded) | 4050 | 3700 | 13000 | \(\sim\) 5250 | 1000 |
| \(P\) (kW)^b | 36.3 | 1.6 | 50 | \(\sim\) 75 | 90 |
| \(A/q\) limits | \(\lesssim\) 5.5 | \(\gtrsim\) 2.5 | \(\lesssim\) 4.5 | \(\gtrsim\) 2.5 | \(\gtrsim\) 2.5 |

^a Intermediate energies at entry to 7G2 and 7G3 are 1.55 and 1.88 MeV/u, respectively.

^b Power required for beams with \(A/q = 4.5\).
well as those that investigate transfer reactions and elastic and inelastic scattering in the light mass region. It is equipped with instrumentation for gamma ray and charge particle detection, developed especially for low beam intensities, strong background radiation and low \( \gamma \)-ray multiplicity.

**HIE-linac**

The success of REX’s experimental programme illustrated the need for higher energies, paving the way for the next major upgrade of the facility, the HIE-ISOLDE project. In 2006, an International Advisory Board examined proposals for a normal-conducting and a superconducting linear post-accelerator and concluded that the best option was to base the new design on superconducting quarter-wave resonators. This option presented a significant

---

**Figure 5.** Main beam characteristics during acceleration through the REX-ISOLDE post-accelerator. Multi-particle tracking simulation for \( A/q = 4.5 \). Emittance growth (\( \Delta \varepsilon_{\text{rms}} \)) in all phase space planes (\( \Delta_{\alpha} \)) is observed in the IHS, while a significant increase in longitudinal emittance also occurs in the 9-gap, which is operated at a synchronous phase of \( 0^\circ \) to achieve the requested energy reach of \( 3 \text{MeV}/u \) (\( W_0 \)). Reproduced with permission from [22].
advantage because it provides high gradients, allowing the installation of shorter accelerating structures in the limited space available in the ISOLDE hall. As a result, full energy variability can be achieved without a reduction of beam quality [24]. In line with the 2010 Nuclear Physics European Collaboration Committee recommendations [25], the upgrade significantly enhances the research capabilities of ISOLDE and complements the physics scope and discovery potential of other large-scale nuclear physics facilities, namely SPIRAL2 (Système de Production d’Ions Radioactifs Accélérés en Ligne) and Facility for Antiproton and Ion Research (FAIR). The project comprises an energy upgrade that will increase the energy range from 3 MeV/u to 5.5 and finally to 10 MeV/u and a design study for an intensity upgrade. The energy increase involves the construction of a superconducting linear accelerator (HIE-linac, see figure 7) based on quarter-wave resonators, a high-energy beam transfer line (HEBT) and three experimental beam lines. The design study for the intensity upgrade is necessary to make the best use of the proton beams that will be delivered from Linac4 [26] and the upgraded PSB [27] and includes improvements to the beam and ion source system, mass separators, beam dumps and other components of the facility.

HIE-linac employs technologies that were developed for the LHC ring, such as cryogenics and niobium-on-copper sputtered superconducting RF cavities. The experience gained at other ion beam facilities, such as TRIUMF, ATLAS at Argonne National Laboratory and

Figure 6. Example of time structure of the REX-ISOLDE post-accelerator. (A)—Proton bunches strike the ISOLDE target. (B)—Release of radionuclides from the target is modulated by the proton cycle. (C)—REXTRAP accumulates, bunches and cools the quasi-continuous beam. (D)—REXEBIS breeds synchronously with REXTRAP at e.g. 10 Hz (time of flight between REXTRAP and REXEBIS is a few tens of μs). (E)—Linac is synchronised to the timing of the REXEBIS with a duty cycle permitting an RF pulse of up to 2000 μs at 50 Hz. (F)—Extracted beam from the REXEBIS: Self-extraction—the pulse length is typically 50 μs, with a slower tail. Slow extraction—the pulse length can be as long as the RF pulse, i.e. 2 ms. Reproduced with permission from [23]. Copyright CERN.
Acceleratore Lineare Per Ioni (ALPI) at Legnaro National Laboratories, was also taken into account at the design stage. Six cryomodules, equipped with 32 RF cavities in total, are being installed in the superconducting linear accelerator in three phases. The first phase has already been completed and involved the design, installation and commissioning of two cryomodules, increasing the energy of post-accelerated beams to 5.5 MeV/u. Each cryomodule contains five superconducting high-beta cavities ($\beta_g = 10.3\%$) \cite{17} with a frequency of 101.28 MHz and a superconducting solenoid magnet. In the second phase, thanks to the installation of two additional cryomodules with the same specifications, the energy range of HIE-linac will reach 10 MeV/u for $A/q = 4.5$. One cryomodule has already been assembled and was installed in early 2017 and the second is to be added to the beam line in 2018. In the third and final phase of the high-energy upgrade, the present 7-gap resonators and 9-gap IH structure of REX will be replaced by two cryomodules, each containing six low-beta ($\beta_g = 6.3\%$) cavities and two superconducting solenoid magnets. This will allow the deceleration of radioactive beams to energies below 1.2 MeV/u, an energy range that is presently forbidden due to the fixed velocity profile of the 20-gap IH structure of REX, for nuclear astrophysics studies of light nuclei. The third phase will also likely involve upgrades to the REX post-accelerator, such as the installation of a pre-buncher at a sub-harmonic frequency of the RFQ, which would increase the bunch spacing without major transmission losses and provide significantly smaller longitudinal emittances. The insertion of a beam chopper between the RFQ and the IH structure is contemplated to reduce the background of satellite bunches between the sub-harmonic RFQ frequency.

**Superconducting quarter-wave resonators**

For the manufacture of the superconducting RF cavities, two options for materials were considered: bulk niobium and copper sputter-coated with niobium. RF performance is similar and high gradients can be achieved in both cases. However, the latter option was selected as the most appropriate and cost-effective for the chosen operating temperature (4.5 K) and RF (100 MHz). Copper results in significantly more massive and stiffer cavities than niobium at a lower cost, reduces effects of microphonics and can eliminate electron beam welds. It is also
Insensitive to magnetic flux trapping and thus allows the design of cryomodules without magnetic shields and provides much higher thermal stability against quenches. The pioneering niobium sputter-coating technique was invented at CERN for the accelerating cavities of LEP [28] and the sputtering technology that is needed for this type of geometry was developed at INFN [29]. The coating chamber is an ultra-high vacuum system, allowing base pressures to reach the low 10⁻⁹ mbar range. The cavities are assembled in an ISO5 clean room and special attention has to be paid to reducing dust contamination of the cavity surfaces prior to coating [30]. The specification for the accelerating gradient is 6 MV m⁻¹, with a power dissipation of less than 10 W at 4.5 K. The internal diameter of the high-beta cavities is 300 mm and of the low-beta cavities 180 mm [31].

Table 2. Main design parameters of high-beta cavities.

| Design parameter | Value                      |
|------------------|---------------------------|
| $F_0$ (MHz)      | 101.28                    |
| $\beta_g$ (%)    | 10.3                      |
| $E_{acc}$ (MV m⁻¹) = $V_0/L_a$ | 6                       |
| $L_a$ (m)        | 0.3                       |
| $R_{shunt}/Q_0$ (Ω) | 550                   |
| $E_{peak}/E_{acc}$ | 5.6                    |
| $H_{peak}/E_{acc}$ (G (MV m⁻¹)⁻¹) | 100                  |
| $Q_0$ (at 6 MV m⁻¹, $P = 10$ W) | $5 \times 10^8$       |
| $\Gamma = R_sQ_0$ (Ω) | 31                     |
| $U/E_{acc}^2$ (mJ (MV m⁻¹)⁻²) | 210                   |
| $T$ (K)          | 4.5                       |
Prototypes for the RF cavities, presented in figure 8 along with the design parameters (table 2), were initially fabricated from two rolled copper sheets and included a helium reservoir extended over the whole diameter above the shorting plate of the quarter-wave resonator. This design was used for devising and improving manufacturing and coating techniques. A new optimised design was later developed, improving shape accuracy and repeatability, as well as reducing sensitivity to helium pressure fluctuations. It features inner and outer conductors, made of bulk copper, that are shrink fitted and then electron beam welded from the RF side with only one weld and the beam ports are precision machined rather than deep drawn [32].

For the niobium coating of the superconducting cavities, two methods were initially investigated: DC bias diode sputtering (figure 9) and magnetron sputtering. The first takes advantage of a uniform plasma, as defined by the shape of the cathode, and of high substrate temperatures and negative bias to reduce impurities and increase the mobility of niobium atoms during film growth [33]. In order to optimise the configuration and parameters of diode sputtering, two setups were employed. The first is a cavity with 50 positions for samples placed on the inner and outer conductors, equipped with door access to its interior. This cavity was used to investigate the properties of the superconducting layer as a function of the position on the cavity surface. The second setup is a downscaled test bench used to study the effect of pressure on sputtering yield and film thickness. The sputtering system featured a cylindrical Nb cathode, surrounded with a grid for plasma polarisation and placed inside the cavity. Cathode, grids and cavity are electrically insulated from each other. The cavity can thus be set at a bias voltage while the grids provide the ground reference. Three infrared lamps are mounted outside the cavity, forming the heating system. Each lamp provides 2 kW

Figure 9. DC diode sputtering setup. Reproduced with permission from [34].
of heating power. The whole setup is placed in a vacuum chamber [34]. An ISO5 clean room is used for the assembly of the sputtering setup.

The baseline production workflow for a cavity, presented in figure 10, lasts approximately one month; the main steps are the preparation of the copper cavity substrate, the coating procedure and the RF tests at cryogenic temperatures. First, the surface of the copper substrate undergoes chemical polishing and passivation, it is rinsed with ultrapure water in a cleanroom and preheated in the sputtering chamber at 635–655°C in high vacuum. The cavity is coated by biased diode sputtering at 8 kW discharge power. After dismounting, it is rinsed again with ultrapure water. Finally, RF measurements are performed at liquid helium temperature [34] to characterise the performance of the resonator.

A potential alternative to the diode coating technique could be magnetron sputtering, which has the advantage of high deposition rates at low pressures, thus minimising the final amount of impurities in the Nb layer. Another motivation was that magnetron sputtering is carried out at 150°C, and it was initially believed that diode sputtering at high temperatures would affect the geometric stability of the cavity [33]. For experiments with magnetron, a similar setup as for the diode sputtering was used, the main difference being that a solenoidal coil was added around the vacuum chamber to apply a uniform magnetic field parallel to the cathode axis. A donut ring made of Nb was sometimes positioned on the cathode to increase the cathode surface facing the top part of the resonator. To decrease self-contamination during deposition, hydrogen in the bulk copper is removed as much as possible before the coating procedure by heating up the substrate to 650°C in high vacuum. To achieve uniform layer properties, it is necessary to control the plasma ignition and stability, which presents an additional challenge for the magnetron technique, due to the presence of the magnetic field on top of the complex geometry of the substrate [35].
In the context of the sample studies, the thickness of the niobium film deposited on copper samples was measured by x-ray fluorescence for the diode and magnetron coating methods separately. For both methods, the thickness distribution between the inner and outer conductor of the resonator was dominated by the ratio of the respective surfaces, facing the same cathode surface. This results in higher deposition rates on the inner conductor, which has a four times smaller surface. Film structure, which was analysed by scanning electron microscopy, see figure 11, on the diode coated copper samples was characterised by larger grains in the inner conductor, visible recrystallised copper grains in the inner and outer conductors and uniaxial grains at the tip of the inner conductor. Removing the centre electrode resulted in smoother film with good adhesion in this area, when using the bias diode method. Samples coated with the magnetron method exhibited some voids but no blisters and demonstrated satisfactory adhesion. Finally, the residual resistivity ratio (RRR) was similar for both coating methods, 17 in diode sputtering and 18 in magnetron coating [35, 36]. Figure 12 presents a comparison between the deposition rates of the niobium layer with both methods, as well as the RF magnetic field distribution in the test cavity.

**Beam optics**

A detailed beam dynamics study was conducted with the aim of comprehending and reducing beam emittance dilution. The main source of transverse emittance growth is induced by a coupling between the transverse and longitudinal motions in the cavities of the linac and exacerbated by a resonance phenomenon where the oscillation frequencies in both planes coincide. Secondary causes of emittance growth include the beam steering force in the cavities and the asymmetry (horizontal-vertical) of the RF defocusing force. Measures were taken to overcome these challenges to reduce beam emittance growth during acceleration. An appropriately tuned focusing strength in the linac solenoids was employed to avoid the resonant coupling between the transverse and longitudinal planes, therefore suppressing the dominant source of emittance growth. To improve the symmetry of the transverse defocusing force and minimise acceptance loss, a racetrack-shaped beam port aperture was used in the...
high-beta cavities and an optimisation routine was developed to compute the offset of the beam port aperture required to reduce the steering effect in an optimised way. Detailed information on the beam dynamics studies can be found in [22, 24], see also figure 13.

RF tests

To conduct RF tests at cryogenic temperatures, a dedicated test cryostat was manufactured (figure 14, right), where the cavity can be connected to a helium tank and cooled down in vacuum, surrounded by an actively cooled thermal shield sitting in the same vacuum. The test setup is assembled in an ISO7 clean room, to minimise dust contamination. The cryostat is then pumped, reaching approximately $10^{-5}$ mbar before cooling with liquid helium. Following the cool down of the thermal shield at 50 K and of the cavity at 4.5 K, which lasts around five hours, the pressure reaches $10^{-8}$ mbar [37, 38].

Cavities achieved optimum performance when they were warmed to 30 K and then cooled down again to 4.5 K. This is caused by a reduction in the vertical temperature gradient across the cavity in the second cool down, which in turn decreased the flux trapped in the niobium film in the superconducting transition. The resonance frequency change as a function of temperature was also measured. As this value is connected to the penetration depth in the superconducting state, it allowed the determination of the penetration depth at 0 K and the calculation of the film’s average RRR [33].

Following the necessary preliminary work on samples, test cavities were produced and tested using both methods. After several tests however, and due to time constraints, the development work focused on the diode sputtering method, which was known to have systematically produced usable cavities of the same geometry for the ALPI accelerator at INFN Legnaro.

At the end of the development phase, diode sputtered cavities manufactured at CERN exceeded the demanding design specification of 6 MV m$^{-1}$ field at 10 W power dissipation [33]. As a result, the diode sputtering method was chosen for the series production. Magnetron coating is employed for the cavity tuner plate, using a planar cathode.
Coupler and tuner

The RF cavities are also equipped with a power coupler and a tuning system, both designed at CERN. The RF coupler [39] has the function to supply RF power to sustain the cavity fields at the operational frequency and bandwidth. Its electrical parameters are presented in Table 3. The coupler design adopts a stainless steel external body to reduce the thermal load on the cavity and uses a displacement system with a guidance rail driven from the outside of the cryostat to ensure positioning of the RF antenna in the cryogenic environment. The

Figure 13. Beam dynamics in the HIE-ISOLDE linac, with a schematic layout showing the positions of cavities and solenoids. A minor transverse emittance growth occurs in the first cavity, because of the increased phase spread of the beam after the drift from IHS. The focusing strength is sufficient that the parametric resonance of the transverse motion is suppressed. Normalised rms emittances show an increase of just a few percent and there is noticeable adiabatic damping of the transverse beam size. Longitudinal emittance growth can be observed across the transition region from the low to the high-energy section, however non-linear effects do not grow and are largely cancelled out. Reproduced with permission from [22].
Figure 14. The RF test facilities.

Figure 15. Layout of the HIE-ISOLDE coupler Reproduced with permission from [39]. Copyright CERN.

| Piece | $\varepsilon_r$ | $\tan \delta$ | $\sigma_{in}$ (S m$^{-1}$) | $\sigma_{out}$ (S m$^{-1}$) |
|-------|-----------------|----------------|-----------------------------|-----------------------------|
| 1     | 1               | 0              | $3.5 \times 10^8$           | $3.72 \times 10^7$          |
| 2–4   | 6               | $5 \times 10^{-4}$ | $3.5 \times 10^8$           | $3.72 \times 10^7$          |
| 3     | 1               | 0              | $3.5 \times 10^8$           | $3.72 \times 10^7$          |
| 8     | 9               | $5 \times 10^{-4}$ | $3.5 \times 10^8$           | $3.5 \times 10^8$          |
dissipation of electromagnetic power along the RF line was initially checked on a lumped model of the coaxial cable (see figure 15). The initial operational bandwidth was fixed to 16 Hz, which would allow reaching the nominal accelerating field with RF power of about 200 W. During the 2015 commissioning campaign, a thermal instability, described in [40], was observed in the coupler lines, and the design had to be revisited. A full thermal and electromagnetic analysis was carried out with finite elements codes. Following this, a new antenna was manufactured from copper, which replaced the bronze alloy initially used, and soldered on the inner conductor of the RF line, removing pressure contacts. Another modification was made to the position of thermal anchors and a new anchor was placed adjacent to the coupler.

The HIE-ISOLDE tuner has the function to set the cavity resonance frequency to the Linac master clock at 101.28 MHz and adapt it to changes in frequency, mainly caused by helium pressure and the Lorentz force. It has a tuning range of 40 kHz and can be deformed up to 5 mm. The 0.3 mm thick tuning plate (figure 16) is manufactured from cold rolled copper and coated with a 1.5 μm thick niobium film, using the magnetron sputtering method. An actuator, placed outside the cryomodule at ambient temperature, controls the mechanical deformation. This positioning prevents frictional problems that arise in low temperatures under vacuum and improves tuner reliability. The actuator can be changed if needed without requiring the transport and disassembly of the cryomodule. A lever system, based on knife-edge pivots and a flexural connection, is employed to attach the tuner to the bottom of the cavity; it is designed to be very compact due to space limitations. The tuner has a resolution of 0.1 Hz/step, which is largely sufficient to tune cavities to the right frequency even when operating at bandwidths of a few Hz. More information on the development and design of the HIE-ISOLDE tuning system can be found in [41, 42].

**Superconducting solenoid**

The radioactive ion beam is focused through the cavities of the linac using superconducting solenoids (figure 17), described in [43], located in each cryomodule of the HIE-linac. The choice of the focusing strength is important to avoid emittance growth induced by coupling of the longitudinal and transverse motions in the cavities. Solenoids were used for transverse beam focusing because they could be simply integrated into the cryomodule and as a result, the length of the linac could be minimised and the packing factor increased, consequently
resulting in a higher longitudinal acceptance. Another advantage was the increased tolerance to mismatch and ease to operate, thanks to their single tuning knob [24].

In the high-beta cryomodules, the magnets are located between the second and the third cavity. The low-beta cryomodules will contain two magnets, inserted after the first and after the fifth cavity in order to cope with the increased defocusing of the RF cavities at low beam energy.

A superconducting design was chosen for the solenoid, which is required to be very compact and provide very high fields. The magnets are made of graded coils that consist of enamelled wires. Prototypes were manufactured both with Nb₃Sn and NbTi technologies and, while both performed well, the second option was chosen to optimise cost. The solenoid has a bore diameter of 31 mm and its integrated square field reaches 13.5 T² m over 312 mm magnetic length for a nominal current of 115.5 A at 4.5 K. The peak field at the centre is 7.86 T. See table 4 for a summary of the main parameters of the solenoid. Although there is no quench detection system, the magnets are protected from quenches thanks to the low

Table 4. Main parameters of the solenoid magnets.

| Magnet main parameters                  | Description/value |
|-----------------------------------------|-------------------|
| Bore diameter (mm)                      | 31 ± 0.3          |
| Magnet length (mm)                      | 312               |
| Coil length (mm)                        | 232               |
| Field integral at nominal current (T² m)| 13.5              |
| Peak field at solenoid magnetic centre (T)| 7.86             |
| Stray field at nominal current and at 230 mm from solenoid magnetic centre (T) | <1.8 × 10⁻³ |
| Magnetic remanence at I = 0 and at 230 mm from solenoid magnetic centre (T) | <6.5 × 10⁻⁵ |
| Nominal current (A)                     | 115.5             |
| Operating temperature (K)               | 4.5               |
| He bath operating pressure (MPa)        | 0.13              |
| Inductance (H)                          | 2.37              |
| Stored energy (J)                       | 1.9 × 10⁴         |
| Working point at I_{nom} (% B/Bc)       | 81                |

Figure 17. 3D representation (left) and cross section (right) of the superconducting solenoid. Reproduced with permission from [43]. Copyright CERN.
stored magnetic energy and coil configuration made of parallel diodes and resistors. In the case of a quench, the parallel diodes start to conduct and magnetic energy is dissipated by the resistors, which are located in the helium bath outside the iron yoke.

The presence of the neighbouring superconducting cavities imposes stringent specifications on the remanent magnetisation generated by the magnets, to avoid flux trapping and the stray field at nominal current. The magnetic yoke limits the stray field to below 1.2 mT at a distance of 230 mm from the centre.

The magnets were produced by an external contractor and delivered during 2015–16.

Cryomodule

Owing to space limitations and the need to avoid cold-warm transitions, a design with common beam and insulation vacuum was chosen for the cryomodules. The presence of radioactive ion beams necessitates a fully hermetrical process for the vacuum system that can ensure the controlled discharge of radioactive contaminants to the atmosphere [44]. This design imposes strict requirements on the cleanliness levels and pump-down, venting and cooling procedures, due to the risk of contaminating the superconducting cavities. Stringent cleanliness requirements also prohibited the use of multi-layer insulation, as it might have caused particle release. To prevent dust contamination and guarantee the performance of the superconducting cavities, the cryomodule had to be assembled in a cleanroom environment.

A 130 m² area served as the space where the conditioning, subassemblies and final assembly took place. The area was divided into an ISO5 vertical flux cleanroom, an ISO5/7 horizontal flux clean room and a preparation space between them.

The design created significant logistical challenges for the cryomodule assembly. More than 10 000 parts had to be assembled, varying in size from sub-millimetres to four cubic metres. All components had to be checked, catalogued, cleaned, conditioned and, in some cases, built into subassemblies, before they were moved to the cleanroom and inserted in the cryomodule. The surfaces that would come into contact with vacuum were electro-polished or brushed to reduce the risk of particle release.

The assembly of the first cryomodule was completed in spring 2015, while the second was ready and installed at HIE-linac one year later.

Description

The cryomodule, presented in detail in figure 18, is enclosed in a stainless steel vacuum vessel that weighs 3.5 tonnes. The vacuum vessel comprises a top plate, on which all services connected to the cryomodule are mounted, and a lower box. The two components are fastened together by a double O-ring system. The cryomodule can be pumped to reach a vacuum level of $10^{-10}$ mbar at cold, which is an effect of the cryogenic pumping, and is well below the levels required for thermal insulation and beam transfer.

A cylindrical helium vessel made of stainless steel is installed inside the cryomodule above the cavities. It is fitted with nine ports; five connect it to the cavities, one links it to the solenoid magnet, two to the coolant feed return from the cryomodule support frame and one to the chimney stratification plates. Inside the cylinder, a helium distribution manifold is placed to allow the flow of helium coolant to the cavities and the solenoid. In the two ends of the vessel, diagnostic elements, comprising two temperature sensors, two helium level gauges and two 100 W heaters, are mounted.

A box-shaped thermal shield cooled at 50–75 K is inserted in the vacuum vessel to capture thermal radiation from its walls. It consists of six 2 mm-thick panels connected with
cooling circuits. The panels are made of a copper–silver alloy, chosen because it can tolerate the solder melting temperature of 220 °C without compromising their mechanical properties, and coated with nickel, which results in surfaces that exhibit low emissivity, are free from oxides and less sensitive to handling and air exposure. The circuits are made of copper, chosen because of its high thermal conductivity and are brazed to the shield panels.

The cryomodule components are mounted on a stainless steel frame that is suspended from the top plate of the vacuum vessel via steel rods. This setup allows the active components to be realigned with the nominal beam axis once the operational temperature is reached. The frame is actively cooled with a separate circuit, which is part of the 4.5 K volumes.

More details on the high-beta cryomodule and its assembly can be found in [44, 45].

Cryogenic plant and thermal performance of the cryomodule

The static and dynamic heat loads for one cryomodule operating at steady state conditions were calculated for 75 and 4.5 K temperatures. The results are summarised in table 5; the minimum values do not include contingency, while the maxima allow for uncertainties. The static heat load at 4.5 K is depicted in figure 19.

A helium refrigerator, based on a two-pressure Claude cycle, is used to provide the necessary cooling capacity to the cryomodules for the three main modes of operation: cool down, steady state operation and warm up. It was previously installed in LEP and is now housed in a new building adjacent to the ISOLDE main hall. The refrigerator cold box is rated for a power of 650 W at 4.5 K. The helium is expanded from 1.47 to 0.545 MPa in the two turbines of the cold box, which maintain a discharge temperature of 51 K and 11 K, respectively. Further helium expansion follows in a J–T valve, in which two-phase saturated helium at 0.130 MPa is produced.

A new cryogenic distribution system (figure 20) was also installed in the cryogenics complex. It includes a 30 m transfer line, a 2000 l storage Dewar and six interconnecting valve boxes. The boxes allow the cooling of cryomodules in four stages. First, the thermal...
Figure 19. Static heat load at 4.5 K (boil-off test).

Figure 20. The cryogenics distribution system (left) and the cold box housed in the new building next to the ISOLDE experimental hall (right).

Table 5. Estimated static and dynamic steady state heat loads for one high-beta cryo-module. Reprinted from [44], with the permission of AIP Publishing.

| Source                | Nominal heat load to 75 K (W) | Nominal heat load to 4.5 K (W) |
|-----------------------|-------------------------------|-------------------------------|
| Static heat loads     | Min/Max                       | Min/Max                       |
| Radiation             | 188/347                       | 1.9/2.4                       |
| Conduction            | 127/157                       | 16/25                         |
| Total: static         | 315/504                       | 17.9/27.4                     |
| Dynamic heat loads    |                               |                               |
| Conduction            | 52/52                         | 52/55                         |
| Total: static and    | 367/556                       | 70/83                         |
| dynamic               |                               |                               |
| Liquefaction load     | —                             | 0.025/0.025 g s⁻¹             |
shield is cooled to 75 K from ambient temperature. Then, the horizontal reservoir and the supporting frame are also cooled to 75 K by the shield’s exhaust, which is injected into them. In the third stage, the cavities and the solenoid reach 75 K and finally, liquid helium is directly provided to the reservoir and the frame, which achieve a temperature of 4.5 K [44].

High energy beam transfer lines (HEBT)

The network of HEBT lines was designed and installed to transport the beam accelerated by the HIE-linac to multiple experimental stations over a wide range of energies and mass-to-charge states from 0.3 to 10 MeV/u [46]. The present scope includes three experimental stations side-by-side in the ISOLDE experimental hall, as shown in figure 21, with the option to replace the third station with a transfer line to transport the beam either to a storage ring or another larger experimental station at the back of the hall at a later date. The construction of the HEBT started in 2013 and the installation of the first two beam lines was completed by early 2015. The beam lines to each experimental station have an identical design to facilitate manufacturing, assembly and operation.

The design of the HEBT is based on modular units of doublet cells, achromatic 90° bends and final focusing triplets upstream of the experimental stations. The modularity of the system has eased the staged installation of the HIE-ISOLDE linac, which is progressing one cryomodule at a time, and ensures the upgradability of the HEBT in the future, respecting the demands of the dynamic experimental programme at ISOLDE. The period of the doublet cells has the same length as the cryomodules so that they can be exchanged relatively easily. The critical components of the doublet cells, including quadrupoles, dual-plane trajectory correctors (dipoles) and beam instrumentation boxes, are built into one unit, shown in figure 22, which is appropriately placed through the HEBT lines.

In order to match the beam from the linac into the periodic doublet structure of the HEBT, four quadrupoles are arranged in a quadruplet structure with each magnet equipped with a bi-polar power supply. In the long drift sections of the HEBT, two dipole magnets bend the beam by 90°, leading to each experimental station. The beam is focused into a tight
Figure 22. A doublet unit composed of a beam diagnostics box and trajectory steerer magnet (horizontal and vertical) sandwiched between two quadrupoles.

Figure 23. Isometric view and simplified cross section of the dipole magnets. Reproduced from [47]. CC BY 3.0

Table 6. Design parameters of dipole magnets. Reproduced with permission from [47]. Copyright CERN.

| Parameter                  | Units | Value   |
|----------------------------|-------|---------|
| Number of magnets          |       | 6       |
| Peak field in centre       | T     | 1.2     |
| Allowed integrated field error |       | $\pm 5 \times 10^{-4}$ |
| Magnetic aperture          | mm    | 50      |
| Magnetic length            | mm    | 1414    |
| Bending radius             | M     | 1.8     |
| Bending angle              | deg   | 45      |
| Conductor dimensions       | mm    | $10 \times \sqrt{6}$ |
| Nominal current            | A     | 423     |
| Magnet resistance (20 °C)  | mΩ    | 100     |
| Magnet inductance          | mH    | 113     |
| Cooling flow ($\Delta p = 10$ bars) | 1/min | 23      |
beam spot at the experimental target by a triplet of quadrupole magnets located directly in front of the experimental setup. The design parameters of the beam transfer line magnets for the HEBT presented below are summarised in tables 6–8 and described in detail in [47].

The six dipole magnets, shown in figure 23, have a 1.8 m bending radius and a 45° bending angle, resulting in a 157 mm beam trajectory sagitta. The transverse size of the magnet was decreased by a factor of three thanks to the adoption of a curved structure that follows the sagitta. Considering the switching function required for several of the dipoles, a C-shaped design was chosen for the yoke to avoid the straight vacuum chamber of the non-deflected beam crossing the return yoke. It is not foreseen in the design to simultaneously feed two experiments with the same beam, although the laminated nature of the magnets would permit switching. The pole face rotation of half the bending angle is kept to provide some focusing effect on the beam in the vertical plane, and keep the yoke construction simple. The yoke is made of laminated electrical steel with low silicon content, which has excellent magnetic properties, and is reinforced with iron plates on the sides. Flux density is limited to 1.5 T over the return yoke and the peak magnetic field in the centre is 1.2 T. Small shims have been added to the pole profile ends to improve field quality. An existing 500 A power converter is used to supply the electrical circuit of the dipoles, which consist of six copper conductor racetrack coils. Epoxy resin reinforced with glass fibre is used for insulation. The

| Table 7. Design parameters of quadrupole magnets. Reproduced with permission from [47]. Copyright CERN. |
| Parameter | Units | Value |
| Number of magnets | 24 |
| Peak field gradient in centre | T m⁻¹ | 24 |
| Allowed integrated gradient error | ±1 × 10⁻³ |
| Magnetic aperture diameter | mm | 50 |
| Magnetic length | mm | 209 |
| Conductor dimensions | mm | 6, ø4 |
| Nominal current | A | 142 |
| Magnet resistance (20 °C) | mΩ | 105 |
| Magnet inductance | mH | 30 |
| Cooling flow (Δp = 10 bars) | 1/min | 2.6 |

| Table 8. Design parameters of corrector magnets. Reproduced with permission from [47]. Copyright CERN. |
| Parameter | Units | Value |
| Number of magnets | 15 |
| Integrated field in centre | mT m | 9.1 |
| Allowed integrated field error | % | ±2 |
| Free aperture | mm | 92 × 92 |
| Magnetic length | mm | 258 |
| Conductor dimensions | mm | 4, ø2.5 |
| Nominal current | A | 48 |
| Resistance (per plane, 20 °C) | mΩ | 109 |
| Inductance (per plane) | mH | 10 |
| Cooling flow (Δp = 10 bars) | 1/min | 0.4 |
hydraulic circuit operates at 10 bar, i.e. the differential pressure of the facility’s demineralised water distribution network.

A single quadrupole design covers the requirements of all magnets in the HEBT lattice as shown in figure 24. The beam transfer lines are equipped with a total of 24 quadrupoles, which have 50 mm of aperture (diameter), including 5 mm clearance for the vacuum chamber, and a focusing gradient of up to 24 T m⁻¹. As with the dipoles, the yoke is made of low silicon content laminated steel with pure iron end plates on each side and is square-shaped to enable the insertion of racetrack coils in the poles. The magnet geometry was optimised to bring the field quality within a comfortable margin of the specified integrated field error of ±10⁻³. The cancellation of the integrated dodecapole component was achieved with an end chamfer of 3.5 mm, satisfying the field error requirements. All of the quadrupole magnets are powered independently in order to be able to switch the beam to each experimental target.

The dual-plane trajectory correctors [48] are designed for installation in the confined space between the HIE-linac cryomodules and are also used in the HEBT, as shown in figure 25. The fifteen correctors are placed in every doublet period to efficiently correct for the effect of misalignments of the quadrupoles of \( \sigma = \pm 0.2 \text{ mm} \) at rigidities of up to 2 Tm, where
σ is the standard deviation of the random misalignment of all the quadrupoles in the transfer line from the nominal reference axis. The large integrated field strength of 6 mT m over just 92 mm was met with a window-frame design, in which the coil windings are oriented orthogonally with respect to the longitudinal axis of the magnet. The stray field of the magnet provides most of the field strength due to its large aperture and short length. However, in the HEBT lines some 30% of this stray field is absorbed by the adjacent quadrupoles and the magnet has therefore been designed with a stronger integrated field 9.1 mT m; a water-cooled design was imposed to reach the required current density.

**Beam diagnostics**

Novel beam diagnostic instruments [49] had to be developed to address the needs and challenges of HIE-ISOLDE. The ion beams range in energy from 300 keV/u to 10 MeV/u and in intensity from 1 epA, or even lower for radioactive beams, to several 100 s epA. The diagnostic instruments are contained in specially designed boxes dedicated to measuring the beam properties, namely intensity, transverse profile and position, longitudinal profile and transverse emittance. In phase 1, a total of 13 diagnostic boxes were installed in the HIE-linac, five short ones located between the cryomodules and eight long ones along the beam line and HEBT. Four long diagnostic boxes were added in phase 2 in 2017. In order to maximise the longitudinal acceptance of the accelerator, the linac was designed to be as compact longitudinally as possible. The distance between two cryomodules equals only 37 cm, approximately one quarter of which, i.e. 9 cm, is reserved for the diagnostic boxes, while 12 cm are available for the same purpose in the HEBT. As a result, the boxes are required to have a very compact geometry.

The diagnostic boxes, shown in figure 26, are made of 316 L stainless steel and have a beam pipe aperture of 40 mm. Their octagonal shape allows a six-port design; five ports are used for instruments and one for vacuum pumping. The top and the bottom sides are connected with the alignment system and support devices. Each diagnostic box houses a Faraday cup, a scanning slit and circular and/or vertical collimators. Four boxes contain carbon-based stripping foils, while two house silicon detectors.

The diagnostic requirements for intensity include values between 10 pA and 1 nA measured with an absolute accuracy of 1% for pilot beams of stable ions. Intensity is

---

Figure 26. Visualisation of a short diagnostic box and the instruments it contains.
measured with Faraday cups, whose aperture diameter is 30 mm. The metal parts of the Faraday cups are made of aluminium and their insulators were manufactured with polyimide. Designing and fabricating the short Faraday cups presented a significant challenge because a larger than usual aspect ratio (diameter to depth) was required. Following extensive tests in REX and ISAC-II at TRIUMF with beams similar in energy and composition to those of HIE-ISOLDE, the Faraday cups were able to reach the required accuracy for beam intensity measurements.

Vertical and horizontal collimators help to measure the transverse profile, which is between 1 and 5 mm in dimension, with an accuracy of 10% in beam size measurement and determine the beam position within ±0.1 mm. The collimators are made of an aluminium blade bored with V-shaped slits that move across the face of the Faraday cup, profiling the density of the ion beam in both the vertical and horizontal planes. The blade is 3 mm thick and is installed in one of the diagonal ports of the octagon, moved by stepping motor. The slit width was optimised at 1 mm following simulations of the measurement. The design ensures a high enough signal-to-noise ratio, whilst at the same time avoids distorting the measurement of the beam profile and size.

For measurements of the longitudinal beam characteristics, a resolution of <1% (2σ) is required for the energy spread and <100 ps for the bunch length. Two silicon detectors are positioned to identify the time of arrival of ions at two positions along on the beam transfer line and thus the absolute time of flight can be measured, allowing the calibration of beam velocity or energy per nucleon. They can also determine beam energy variations at different phases of the RF cavities, and thus they can be used to set the amplifiers of the cavities to the correct operational phase [50]. Silicon was the detector of choice, as it allows the best beam spectroscopy performance. The decision to use silicon detectors instead of, for example, the first dipole magnet in the HEBT was motivated by the fact that the former provide a fast procedure for cavity phasing that could eventually be fully automated [49].

Transverse emittance measurements are specified to have an accuracy of ±20% for beam currents that reach 1 nA. A dedicated emittance metre used previously at REX, which employs the slit and grid method, is used to conduct these measurements in the HIE-linac. There is also the option of employing a two-slit technique, using two diagnostic boxes in the HEBT. Several simulations were performed to study beam measurements with additional noise contribution for three different slit widths and 1 mm was determined as the optimal slit width value. The final implementation of such an emittance measurement is still to be realised. A detailed description of the diagnostic boxes and instruments can be found in [51].

**Beam optics**

Detailed beam optics studies were carried out with the aim of understanding and correcting alignment and magnet field errors in the HEBT. Table 9 shows the estimated X-/Y- beam

| Energy (MeV/u) | X-/Y- beam spot sizes (mm) | Average beam loss (%) | Bunch lengthening (ns) |
|----------------|---------------------------|-----------------------|-----------------------|
| 0.3            | 6                         | 0.3                   | 6.3                   |
| 5.9            | 3                         | <0.1                  | 0.6                   |
| 10             | 2.7                       |                       | 0.3                   |
spot sizes (in FWHM) at the target, as well as average beam loss and bunch lengthening until the target of XT01 for various energies [52].

\section*{Experimental Instrumentation}

The layout of the beam lines as they were in 2016 is shown in figure 7. A third beam line was installed in 2017, as illustrated by figure 21. A high-resolution germanium detector array called Miniball [53] is located on the first beam line. Miniball has been in operation for more than ten years and is used in many Coulomb excitation and transfer reaction experiments. It is complemented by three ancillary setups: the CD-type Double sided Silicon Detector, SPEDE (Spectrometer for Electron Detection) [54] for electron conversion studies and T-REX [55], a set of double sided silicon strip detectors. The second beam line transferred the beam to a general-purpose scattering chamber, which was replaced with the ISOLDE Solenoidal Spectrometer in 2017 for transfer reaction studies. Smaller, moveable experimental setups will be installed at the end of the third beam line. An example is the scattering chamber, with different charged particle detector arrays such as CORrelation SETup for quasi-fission measurements. It will have to be removed when Active Target Detector [56] or the optical time projection chamber is installed in its place.

Over thirty experiments have already been approved; two of them have finished data-taking in autumn 2016 and the rest are in the preparation stage. Some of the topics that are proposed for investigation in the upgraded facility are isospin symmetry, collectivity versus single particle structure, magic numbers far from stability, shape coexistence, as well as quadrupole and octupole degrees of freedom.

\section*{Commissioning}

Phase 1 of the ISOLDE high-energy upgrade was completed in 2016 with the installation of two high-beta cryomodules, and phase 2 will finish in 2018, when the fourth high-beta cryomodule is added to HIE-linac, increasing the energy reach to 10 MeV/u for $A/q = 4.5$.

Before the first experiments took place in the new facility, a wide range of tests and measurements were performed as part of the hardware and beam commissioning.

\subsection*{REX commissioning}

In 2015, some parts and systems of REX were replaced or improved in order to enhance the performance of HIE-linac. Upgrades to REX included new water cooling circuits for magnets, cavities and RF amplifiers, thermal sensors for the quadrupoles, as well as two fast Penning gauges and a fast acting valve to avoid damage to the superconducting RF cavities in the event of accidental venting of the beam line. Following the installation of the cooling circuits and thermal sensors, measurements of cooling water flow and temperature rise were conducted to set interlock levels. The cooling fans, power converters and low level radio-frequency of the amplifiers also underwent maintenance [57].

\subsection*{Commissioning 2015}

\textbf{Hardware commissioning.} The hardware commissioning campaign of the HIE-linac before the first physics run in 2015 aimed to establish parameters for its first operation, debug and test controls and find possible limitations of the hardware. The commissioning procedure was
laid out to minimise the risk of damage at first powering of the active elements, taking into account the design constraints and the interrelations among the systems.

In order to avoid dust contamination of the RF cavities during pump-down of the cryomodule, the gas velocity was maintained everywhere below 0.3 m s\(^{-1}\) until the molecular regime was reached, thus restricting particulate movements due to drag forces. Transportation of the vessel to the linac took place under static vacuum. Measurements revealed excellent vacuum performance: pressures in the range of \(10^{-11}\) mbar were reached after cool down at 4.5 K.

The first cryomodule was cooled down in approximately three weeks’ time. The procedure presented challenges because the commissioning of the cryogenics facilities took place over the same period. The permitted temperature gradients in the subsystems of the cryomodule also imposed limitations to the cool down process, as well as the need to avoid excessive cryo-pumping of residual gas on the cavity surfaces. A boil-off technique was used to measure the static heat load, which was found to be in the order of 10 W at 4.5 K, in accordance with the design values.

A new system using optical targets that can be viewed from the exterior of the cryomodule was devised to observe the positions of active elements on the beam line, in particular during cool down. The accelerating cavities and the solenoid magnet were intentionally placed approximately 4 mm lower than the nominal beam line when the cryomodule was manufactured, as the supporting system was expected to move upwards by the same amount during cooling due to thermal shrinkage. All elements were aligned within 0.1 mm from the ideal beam line, well within the design requirement of 0.3 mm and 0.15 mm rms in the case of the cavities and the solenoid, respectively.

The accelerating cavities are controlled by a new digital LLRF system. Besides controlling the couplers and tuning system, it offers the possibility of running the cavities with a self-excited loop for measurement and conditioning. The cavities can also be locked on amplitude and phase set-points for beam operation. In the beginning of commissioning, cavities were set at 101.28 MHz. Conditioning of the multipacting bands up to 60 kV m\(^{-1}\) was carried out during cool down, thanks to the variable couplers and self-excited loop function of the LLRF system. A multipacting band is also present in the superconducting cavities around 1.5 MV m\(^{-1}\). Following conditioning of the cavities, their \(Q\) versus \(E\) was measured accurately in critical coupling. All cavities attained the nominal field free from field emission, except one in which a field emission onset above 5 MV m\(^{-1}\) was observed. Remarkably, it was noted that the RF performance in terms of \(Q\) values of the cavities in the cryomodule was significantly enhanced in comparison to the performance of the separate cavities in vertical tests. Following a thorough investigation, this phenomenon was attributed to the cryomodule’s optimal cooling conditions whereby the temperature gradients across the cavities are minimised during the superconducting transition. To verify that the solenoid stray field did not cause any perturbation on the cavities, both the solenoid and the cavities were powered at nominal fields simultaneously. When measurements of the cavities ended, the couplers were moved to reach the selected bandwidth for beam operation (10 Hz) and the LLRF feedback loops were set up. The design requirements for 0.1% rms stability in amplitude, and 0.2° in phase were amply satisfied, as shown in figure 27.

The superconducting solenoid magnets in the cryomodules were operated at nominal current, as they had already been trained in the factory, without any quenches. To inspect the behaviour of the cryogenic system, one quench was deliberately caused, and the expected small increase in pressure was observed. A minor issue arose when systematic trips of the power converter in current regulation mode operation were observed—caused by the change
of differential impedance when polarity was reversed. This was addressed by using voltage mode to switch polarity.

The RF measurements were verified with the acceleration of a stable beam. Beam energies were measured both with a silicon detector and with a dipole magnet at the HEBT used as spectrometer. Scans of cavity phases were also performed to study the output energy variation. The accelerating voltages obtained via these three methods match within 3%.

A major issue arose when a design flaw was discovered in the RF feed system, that would result in thermal breakdown after some hours of operation. Following the increase in bandwidth and subsequent rise in RF power as the cavities were moved to higher fields, it was noticed that the way the RF signals drifted pointed to the slow expansion of the coupler antenna, an observation verified by additional tests. To address this problem for the 2016 physics run, both cryomodules were equipped with new coupler lines that used an improved design. In order to maintain at least part of the 2015 physics programme, it was determined that the best course of action was to reduce forward power by optimising the operation of the LLRF system and limiting the bandwidth at 3–4 Hz. Cavities operated at 4 MV m$^{-1}$ with 35 W forward power and powering was limited to six hours per day, allowing the RF couplers and lines to cool down between runs.

More details on the first commissioning experience with HIE-ISOLDE can be found in [40].

**Beam commissioning.** Beam commissioning was performed in several stages. First, the REX diagnostics box, located between the RFQ and the buncher, was recommissioned by a 0.3 MeV/$\mu$ beam and all diagnostic elements were found to be in good working order. The commissioning of the first HIE-ISOLDE diagnostic box followed, using a beam with the same energy. Its equipment fulfilled the design requirements. Transverse beam profiles with

![Figure 27. Performance of the LLRF loops at 3 Hz bandwidth. The design requirements for 0.1% rms stability in bandwidth and 0.2° in phase are satisfied by a wide margin [58].](image-url)
intensities of a few epA were measured using the Faraday cups, scanning slits and collimators. Silicon detectors measured the energy and energy spread of beams with low intensity and recognised beam contaminants. Carbon foils were used to alter the mass-to-charge ratio of the ions in order to clean beam contaminants in some experiments. Five of them were tested and the charge state distribution of the resulting beam was measured. The determination of operational settings for the RF amplifiers was necessary, as several of their LLRF components had been replaced and their calibration had changed. The transmission through the RFQ for different RF powers was measured and an operation point with 95% transmission plateau was chosen. Amplitudes and phases of the rest of the RF structures were found using a silicon detector. A 2.85 MeV/u beam was used to commission the rest of the diagnostic boxes and the magnets along HIE-linac and the first HEBT line. Owing to time limitations, beam optics measurements were confined to the absolutely necessary. Beam transmission from separator magnet to the end of experimental lines was found to be ∼75% and alignment of the optical elements was satisfactory. In the last stage, cavities were phased with a silicon detector located at the end of the linac tunnel and the second HEBT line was commissioned. The 2015 beam commissioning in HIE-ISOLDE is described in [57].

Physics run. In October 2015, a five-week run took place at HIE-ISOLDE, which was then equipped with one high-beta cryomodule. The first experiment performed Coulomb excitation of the neutron-rich Zn isotopes. A radioactive beam was accelerated to 4 MeV/u in the new superconducting linac and in the following weeks, different charge states of Zn isotopes were sent to the experimental station. An overview of the physics run can be seen in table 10, while the energy and gamma ray spectrum of the Zn beam is presented in figures 28 and 29.

Commissioning 2016

Hardware commissioning. In preparation for the 2016 physics run, the first cryomodule was removed, vented and equipped with new couplers in the ISO5 clean room. It was installed again in the beam line with the second cryomodule in May 2016. The cool down of the two cryomodules took longer than expected, and highlighted limitations in the management of transients from the cryogenics plant. Active cooling of the two cryomodules was performed in several stages with floating periods in-between and, as a result, passive cooling of cavities and solenoids through radiation on the thermal shields lasted a few weeks. As customary, multipacting levels at a low field were conditioned before reaching the superconducting transition. A spontaneous increase in vacuum pressure was observed in the second cryomodule some days after its temperature reached 4.5 K (see figure 30). Pressure became steady at 10⁻⁹ mbar.

The RF measurements at cold highlighted a degraded performance on the first and the last cavity of the first cryomodule, which had been transported back to the clean room and vented to exchange the RF couplers. All other cavities reached the nominal field of 6 MV m⁻¹, close to the required power dissipation of 10 W, in particular those of the second cryomodule, which was a confirmation of the soundness of the assembly procedure and slow pump-down. As in the first commissioning experiment of 2015, it was found that the RF performance of the cavities in the cryomodule exceeded that shown in the vertical tests.

Owing to the contamination of the first and fifth cavities of the first cryomodule, their maximum fields were limited to below the onset of field emission, i.e. to 2.5 and 3.5 MV m⁻¹, respectively. A suitable optics solution was accordingly found and the requested beams were delivered to the experiments for the 2016 physics campaign. The Q–E curves of all ten cavities can be seen in figure 31. Operational bandwidths varied between 5 and 10 Hz. The
Table 10. Overview of the 2015 operations at the two beam lines.

| Beam | Origin | Energy (MeV/u) | HEBT | Experimental station | Time (h) |
|------|--------|----------------|------|----------------------|----------|
| RIBs | $^{74}\text{Zn}^{25+}$, $^{74}\text{Zn}^{21+}$, $^{76}\text{Zn}^{22+}$ | 2.85/4.0 | GPS target | XT01 | Miniball Spectrometer | 50 |
| Stable | $^{22}\text{Ne}^{7+}$ | 2.85 | EBIS | XT01 | Miniball Spectrometer | 31 |
|       | $^{14}\text{N}^{6+}$ | 2.85/4.0 | EBIS | XT02 | Scattering Chamber | 2 |
|       | $^{12}\text{C}^{4+}$ | 4.0 | EBIS | XT02 | Scattering Chamber | 2 |
|       | $^{133}\text{Cs}^{39+}$ | 2.85/4.0 | Ion source | XT01 | SPEDE | 105 |
LLRF loops were set up individually to achieve the most stable operation possible. Severe perturbations were found to detune all the cavities in a coherent fashion, which made the LLRF work particularly challenging. After a thorough search, the cause of the perturbation was localised in the cryogenics distribution system. The situation was somewhat mitigated by changing the operation point of the cryogenics process. A systematic investigation of the cryogenics performance, as well as all attempts to condition the two cavities with He processing, were postponed until after the physics run.

During the commissioning of the solenoids, short circuit to ground was identified in one of the bus-bars. The circuit could still be powered after securing the connection to ground, which was displaced very close to the earth fault. The operational current was limited to the

Figure 28. Energy spectrum of the beam delivered to the Miniball experimental station. The beam of interest is $^{76}\text{Zn}^{22+}$ and a contaminant $^{38}\text{Ar}^{11+}$ are presented in red. Reproduced from [57]. CC BY 3.0.

Figure 29. Doppler-corrected gamma ray spectrum obtained in the Coulomb excitation of the first radioactive beam delivered at 4.0 MeV/u: $^{76}\text{Zn}$ beam impinges on a $^{196}\text{Pt}$ target (blue) and the equivalent gamma spectrum for 2.8 MeV/u (red). The higher energies of HIE-ISOLDE show an increase of cross section and markedly improve the population of higher-lying states [59] (© SIF, Springer-Verlag Berlin Heidelberg 2016). With permission of Springer.
minimum necessary for good beam transmission, in order to reduce the magnetic stored
energy. The second solenoid underwent a training quench at 60 A and reached the nominal
current of 110 A.

Alignment of active components was monitored and ensured by the MATHILDE system
[60]. Thermal contraction caused an expected 4 mm vertical shift, while lateral movement
was negligible. Figure 32 depicts the horizontal and vertical positions of the cavities and
solenoids during alignment.

After the physics run, He processing was successfully applied in situ to the two cavities
in the first cryomodule, which were affected by field emission from 2.5 and 3 MV m$^{-1}$,
respectively, resulting in recovering of the RF performance up to 5 MV m$^{-1}$ for both cavities
(figure 33).

The 2016 hardware commissioning campaign is presented in [62].
Beam commissioning. Beam commissioning activities at the REX normal-conducting injector were performed simultaneously with hardware commissioning at HIE-linac. A mixture of helium, carbon, oxygen, neon and argon beams with $A/q = 4$ was used for the setup beam. The beam was drifted through the cryomodules into the HEBT lines with REX.

Figure 32. Longitudinal ($Z$) and transversal ($X$) positions of the cavities (in red) and solenoid (in blue) during cryomodule alignment. Reproduced with permission from [61]. Copyright CERN.
energy and was used to commission the diagnostic boxes. Then, the superconducting cavities 
were phased, a process which also verified that the calibration of the gradients was accurate.
The beam energy was measured using the first dipole of the first HEBT line, silicon detectors 
and a time-of-flight system.

Characterising the energy and energy spread of the beam is important for the users of the 
facility. The post-accelerator is equipped with several diagnostic devices that can be used to 
do these measurements that were commissioned during the 2016 campaign:

- Silicon detectors. Four detectors located in different positions along the linac and HEBT 
  lines were used to measure changes in the beam energy and the energy spread of the 
  beam (figure 34).

- Dipole as an energy spectrometer. Slits before and after the first dipole of the first HEBT 
  line were used to collimate the beam and select ions on the beam axis after the focusing 
  and steering optical elements were turned off. The beam current past the dipole was 
  measured for different magnetic fields (figure 35). Both the energy spread and the 
  absolute energy could be determined by this method using the previously measured 
  effective magnetic length of the dipole.

Figure 33. Helium processing in situ for the first and fifth cavity of cryomodule 1 in 
November 2016.

Figure 34. Beam energy spectrum for all cavities.
Time of flight. The time-of-flight information provided by two of the silicon detectors located after the second cryomodule and separated by 7.76 m was also used to measure the energy of the beam. The results of the measurements conducted during the beam commissioning showed that the uncertainty in the beam energy using this method was lower than $\pm 0.5\%$.

Calibration of the RF systems. The energy of the beam can be calculated using the accelerating gradients, the transit time factor of the cavities and the synchronous phases of the beam. The typical uncertainty determining the energy of the beam using this method for a single cavity is $\pm 1\%$.

The transverse profiles of the beam were measured using the scanning slits in several diagnostic boxes. The measurements conducted during the beam commissioning showed that beam profiles could be clearly determined for intensities as low as 10 epA. For example, figure 36 shows three beam profiles measured for a beam with a total intensity of 42 epA. The three profiles correspond to different focusing strengths of a quadrupole located before the diagnostic box.

More details about the 2016 beam commissioning can be found in [63].

Physics run. On 9 September 2016, the first exotic beam marked the start of operations for the upgraded facility. The first experiment investigated excitation states of tin isotopes, using transfer reactions and Coulomb excitation of an $^{110}$Sn$^{26+}$ beam, post-accelerated to 4.5 MeV/u. See table 11 for an overview of the six experiments conducted at HIE-ISOLDE and
**Table 11.** Overview of the six experiments that took place during the 2016 physics run.

| Beam    | Energy (MeV/u) | Origin   | HEBT | Experimental station       | Time (h) |
|---------|----------------|----------|------|-----------------------------|----------|
| RIBs    |                |          |      |                             |          |
| $^{110}\text{Sn}$ $^{26+}$ | 4.5          | GPS target | XT01 | Miniball spectrometer       | 115      |
| $^{142}\text{Xe}$ $^{33+}$ | 4.5          | HRS target | XT01 | Miniball spectrometer       | 100      |
| $^{78}\text{Zn}$ $^{20+}$  | 4.3          | GPS target | XT01 | Miniball spectrometer       | 130      |
| $^{132}\text{Sn}$ $^{31+}$ | 5.5          | HRS target | XT01 | Miniball spectrometer       | 130      |
| $^{9}\text{Li}$ $^{1+}$    | 6.7          | GPS target | XT02 | Scattering chamber          | 70       |
| $^{66}\text{Ni}$ $^{16+}$  | 4.5          | GPS target | XT01 | Miniball spectrometer       | 140      |
| Stable  |                |          |      |                             |          |
| $^{22}\text{Ne}$ $^{5+}$, $^{23}\text{Ne}$ $^{6+}$ | 2.8      | EBIS   | XT01 | Miniball spectrometer       | 60       |
| $^{12}\text{C}$ $^{4+}$    | 6.7          | EBIS   | XT02 | Scattering chamber          | 7        |
| $^{132}\text{Xe}$ $^{32+}$ | 4.5          | GPS target | XT01 | SPEDE                       | 85       |
Conclusion

The HIE-ISOLDE upgrade of the long running ISOLDE facility at CERN aims at broadening the reach of the physics programme through an increase of the post-acceleration energy and of the radioactive beam intensity and quality. This paper has focused on the new post-accelerator. The project was approved in 2009 and the first phase was completed in the fall of 2016. Phase 1 included the R&D, construction, installation and commissioning of two cryomodules bringing the final energy to 5.5 MeV/u and the two associated high-energy beam transport lines. The accelerator has performed according to specifications and a good reliability has been observed, which has already led to the success of several physics experiments. These results validate the choice of a superconducting linear accelerator for such a heavy ion post-accelerator, based on cavities sputtered with niobium on a copper substrate using the DC bias diode sputtering method.

The second phase of the project will be completed by early 2018 with the installation of two additional cryomodules, which will increase the final beam energy to 10 MeV/u for all the isotopes produced at ISOLDE, reaching 14 MeV/u for the lighter ions, for which a mass-to-charge ratio of 2.5 can be obtained. This phase includes the construction of a third beam line in order to increase the flexibility for experiment scheduling. Further in the future a third phase is planned which will include two low-beta cryomodules to replace the REX 7-gap and 9-gap resonators, which should ensure long term reliability and the availability of a continuous energy range starting at 0.3 MeV/u, important for the measurement of cross
sections of astrophysical relevance. A buncher/chopper will be installed, providing broader spacing of the micro-pulses, useful for time-of-flight measurements. A storage ring, which would be injected by an extension of the third beam line, is being envisaged. These initiatives will ensure that ISOLDE and CERN remain at the forefront of radioactive beam science for the foreseeable future.

References

[1] Haas H, Rolfs C, Jonson B, Ravn H L, Allardyce B W and Schempp A 1990 A concept for post-acceleration of radioactive ion beams Proc. 1st Int. Conf. on Radioactive Nuclear Beams (Berkeley) p 59
[2] Habs D 1994 Radioactive Beam Experiments at ISOLDE: Coulomb Excitation and Neutron Transfer Reactions of Exotic Nuclei ISC-94-25. ISC-P-68 CERN, Geneva
[3] Van Duppen P and Riisager K 2011 Physics with REX-ISOLDE: from experiment to facility J. Phys. G: Nucl. Part. Phys. 38 240805
[4] Lindroos M and Nilsson T 2006 HIE-ISOLDE: The Technical Options CERN-2006-013 CERN, Geneva
[5] Riisager K, Butler P and Krücken R 2007 HIE-ISOLDE: The Scientific Opportunities CERN-2007-008 CERN, Geneva
[6] Catherall R et al 2013 An overview of the HIE-ISOLDE design study Nucl. Instrum. Methods Phys. Res. B 317 204–7
[7] Cederkall J et al 2004 REX-ISOLDE—experiences from the first year of operation Nucl. Phys. A 746 17–21
[8] Kester O et al 2003 Accelerated radioactive beams from REX-ISOLDE Nucl. Instrum. Methods Phys. Res. B 204 20–30
[9] Habs D et al 2000 The REX-ISOLDE project Hyperfine Interact. 129 43–66
[10] Ames F et al 2005 Cooling of radioactive ions with the Penning trap REXTRAP Nucl. Instrum. Methods Phys. Res. A 538 17–32
[11] Schmidt P et al 2002 Bunching and cooling of radioactive ions with REXTRAP Nucl. Phys. A 701 550–6
[12] Savard G et al 1991 A new cooling technique for heavy ions in a Penning trap Phys. Lett. A 158 247–52
[13] Gustafsson A, Herlert A and Wenander F 2011 Mass-selective operation with REXTRAP Nucl. Instrum. Methods Phys. Res. A 626–627 8–15
[14] Wenander F, Jonson B, Liljeby L and Nyman G 1999 REXEBIS: The Electron Beam Ion Source for the REX-ISOLDE Project CERN-OPEN-2000-320 CERN, Geneva
[15] Wolf B et al 2004 First radioactive ions charge bred in REXEBIS at the REX-ISOLDE accelerator Nucl. Instrum. Methods Phys. Res. B 204 428–32
[16] Wenander F 2010 Charge breeding of radioactive ions with EBIS and EBIT J. Instrum. 5 C10004–10004
[17] Borge M and Riisager K 2016 HIE-ISOLDE, the project and the physics opportunities Eur. Phys. J. A 52 334
[18] Rao R, Kester O, Sieber T, Habs D and Rudolph K 1999 Beam optics design of the REX-ISOLDE q/m-separator Nucl. Instrum. Methods Phys. Res. A 427 170–6
[19] Wenander F J C and Riisager K 2012 Isotope toolbox turns 10 Cern Cour. 52 33–6
[20] Sieber T, Habs D and Kester O 2004 Test and first experiment with the new REX-ISOLDE 200 MHz IH structure Proc. LINAC 2004 (Lubeck) pp 318–9
[21] von Hahn R et al. 1993 Development of seven-gap resonators for the Heidelberg high current injector Nucl. Instrum. Methods Phys. Res. A 328 270–4
[22] Fraser M A 2012 Beam dynamics studies of the ISOLDE post-accelerator for the high intensity and energy upgrade PhD Thesis University of Manchester
[23] Van de Walle J 2006 Coulomb excitation of neutron rich Zn isotopes PhD Thesis KU Leuven
[24] Fraser M, Jones R M and Pasini M 2011 Beam dynamics design studies of a superconducting radioactive ion beam postaccelerator Phys. Rev. ST Accel. Beams 14 20102
[25] Bracco A et al (ed) 2010 Perspectives of Nuclear Physics in Europe (Strasbourg: European Science Foundation)
[55] Bildstein V et al 2012 T-REX: a new setup for transfer experiments at REX-ISOLDE Eur. Phys. J. A 48 1–10
[56] Raabe R et al 2009 ACTAR: the new generation of active targets AIP Conf. Proc. 1165 339–42
[57] Rodriguez J A et al 2016 Beam commissioning Of The HIE-ISOLDE post-accelerator Proc. IPAC 2016 (Busan) pp 2045–7
[58] Delsolares W V et al 2015 Status of the SRF systems at HIE-ISOLDE Proc. SRF 2015 pp 481–7
[59] Borge M and Riisager K 2016 HIE-ISOLDE, the project and the physics opportunities Eur. Phys. J. A 52 334
[60] Kautzmann G, Gayde J, Klumb F and Kadi Y 2014 HIE-ISOLDE—general presentation of MATHILDE 13th Int. Workshop on Accelerator Alignment (Beijing)
[61] Kautzmann G, Gayde J and Klumb F 2016 HIE-ISOLDE—commissioning and first results of the MATHILDE system monitoring the positions of cavities and solenoids inside cryomodules IWAA2016
[62] Delsolares W V 2016 HIE ISOLDE HW commissioning in 2016 ISOLDE Workshop and Users Meeting
[63] Rodriguez J A 2016 Beam commissioning and operations of the REX/HIE-ISOLDE post-accelerator ISOLDE Workshop and Users Meeting
[64] Borge M and Kadi Y 2016 ISOLDE at CERN Nucl. Phys. News 26 6–13