PROGRESS ON THE HIE-ISOLDE FACILITY

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Abstract

After 20 years of successful ISOLDE operation at the PS-Booster [1], a major upgrade of the facility, the HIE-ISOLDE (High Intensity and Energy ISOLDE) project was launched in 2010. It is divided into three parts; a staged upgrade of the REX post-accelerator to increase the beam energy from 3.3 MeV/u to 10 MeV/u using a superconducting linac [2], an evaluation of the critical issues associated with an increase in proton-beam intensity and a machine design for an improvement in RIB quality. The latter two will be addressed within the HIE-ISOLDE Design Study [3]. This paper aims to provide an overview of the present status of the overall project by giving an insight to the infrastructure modifications, installation and tests of the HEBT lines as well as progress on the commissioning of the SC linac. Plans for the second phase of the project will be highlighted.

INTRODUCTION

The present schedule foresees to deliver beams up to 4.2 MeV/u for the heaviest species this autumn with a single high-beta cryomodule. A second cryomodule will be installed during the winter shutdown 2015/2016 bringing the energy to 5.5 MeV/u for all the radionuclides available at ISOLDE. This will complete phase 1, making Coulomb excitation studies possible up to A/q=4.5. A second phase will consist in adding two more high-beta cryomodules during the winter shutdown 2016/2017, thus doubling the available accelerating voltage. Finally, in phase 3, two low-beta cryomodules would be installed, replacing some normal conducting structures of the present REX-ISOLDE. This will allow varying continuously the energy between 0.45 and 10 MeV/u together with an improved beam quality. A detailed description of the optics and beam dynamics design choices for the linac can be found in [4].

As we write, installation of the HIE-ISOLDE technical infrastructure has been completed with minor disruptions to the parallel running of the Low-Energy physics programs at the ISOLDE facility. The SC linac as well as the HEBT lines have been installed and tested.

This paper offers a snapshot of the main activities as the commissioning of the HIE-ISOLDE linac with beam is in progress.

TECHNICAL INFRASTRUCTURE

The long shutdown of the CERN accelerators in 2013-2014 was used to upgrade the general infrastructure of the existing ISOLDE facility. All the services are by now fully operational.

The overhauled ALEPH compressor units/cold box together with the new cryogenic distribution line (Fig. 1) have been commissioned and supplying LHe at 4.5K since June 2015 [5].

Figure 1: Cryogenic distribution line feeding the SC linac with liquid He at 4.5K.

In the ISOLDE experimental hall, Controls, DC and RF cables with a total length of more than 65 kilometres have been installed and power supplies, beam instrumentation and vacuum equipment racks are in place and operational.

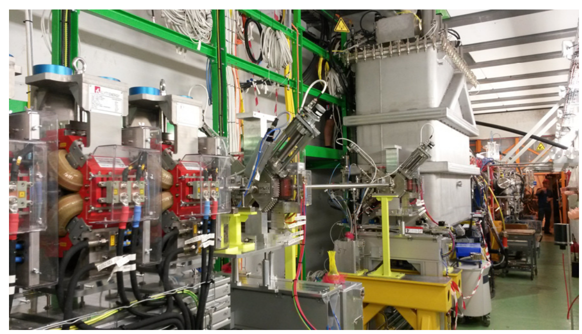

Figure 2: Cryomodule 1 and the first part of the straight section downstream of the superconducting (SC) linac inside the shielding tunnel.

The first high-beta cryomodule (CM1) was transported to the HIE-ISOLDE linac tunnel in May (Fig. 2) and after a dense installation campaign, CM1 was ready for cryogenic cool-down a month later. The installation and commissioning of the second high-beta cryomodule (CM2) is scheduled for the first quarter of 2016.

Subsystems such as cryogenic instrumentation, vacuum controls, RF interlocks, fire and oxygen deficiency alarms have all been tested.

Elements of the SC linac and the first two High-Energy Beam Transfer lines (XT01 and XT02) have all been installed (Fig. 3). The quadrupole, H/V corrector and dipole magnets and associated beam diagnostic boxes have all been tested and commissioned. The first two experiments (Miniball and the Scattering chamber) are being installed in view of the first physics run this coming Fall.

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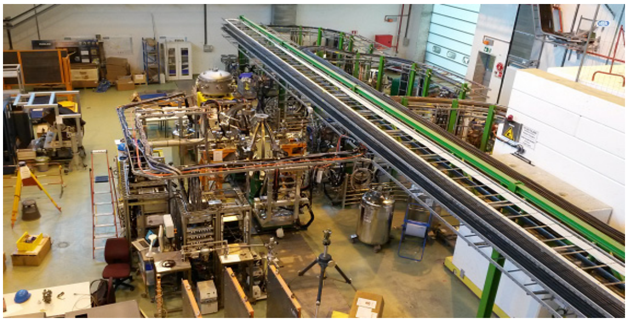

Figure 3: Top view of the SC linac tunnel (bottom right), the three HEBT lines (top right) and the two experiments: Miniball and the Scattering chamber (on the left).

The optics of the third beam line, for which the infrastructure has already been installed, will be added during the course of 2017.

COMMISSIONING THE ELECTRICAL CIRCUITS

49 circuits (HEBT and SC Linac) were commissioned, all complying with the dynamic performance specification. The circuits are grouped as in Table 1.

Table 1: Summary of HIE-ISOLDE commissioned circuits

Circuit Type	Nominal	Nominal Op
SC Solenoid	± 120 A	100 A
Corrector Magnet	± 50 A	± 45 A
Quadrupole Magnet	200 A	132 A
Quadrupole Magnet with Polarity Reversal	± 200 A	± 132 A
Dipole Magnet	± 500 A	± 423 A

Together with the verification that installed converters and all interfacing systems worked appropriately (magnet interlock, all layers of the control infrastructure, etc...), each converter was configured by an equipment specialist with the suitable operational parameters (minimum and maximum current, max allowable current rate). The digital regulation parameters were then set for optimal performance (according to individual circuit electrical resistance and inductance).

For the subsequent performance assessment of the installed converters, Noise Tests were carried out where the measured value of the current is sampled at 1 kS/s for both measurement channels during 8.192 seconds. This test concerns measurement of the noise and power ripple in the frequency range 0Hz-500Hz for both the HEBT and the SC Solenoid circuits and it is graphically illustrated in Fig. 4.

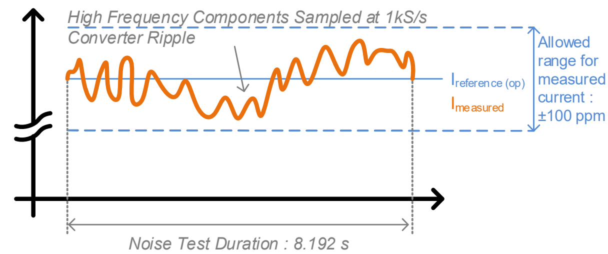

Figure 4: Noise or Ripple Test. The specification of ± 100 ppm (200 ppm pk-pk of the nominal current of the converter) holds strictly for Quadrupole, Dipole and SC Solenoid circuits.

MACHINE COMMISSIONING

The machine commissioning campaign covered the vacuum and cryogenics performance, monitoring and alignment adjustment of the active elements, conditioning and RF measurement of the superconducting cavities, power tests of the superconducting solenoid, and commissioning of the LLRF and of the tuning systems. Cold testing of the first cryomodule started in June 2015.

Vacuum Performance

Before the CM was transported from the assembly area to its final location a helium leak detection was carried out. It also included the pressurization of all the cryogenic circuits with He. To avoid the displacement of dust a slow pump-down procedure was applied [6]. The CM was monitored before and after transport, no abnormal increase of pressure was observed. As soon as the CM was installed the pressure monitoring was re-started while all the vacuum instrumentation (valves, pumps, connections) were installed and commissioned.

During the cool down the He background was continuously followed using one He leak detector. The base pressure of the CM at cold steady state conditions is approx. 5e-11 mbar (measured in the volume between the thermal shield and the vessel). During a period of 1 month the CM was isolated from its turbo-pumping. No pressure variation was observed during that period confirming the excellent tightness of the cryogenic circuits.

Figure 5 shows the pump down curve during cool down.

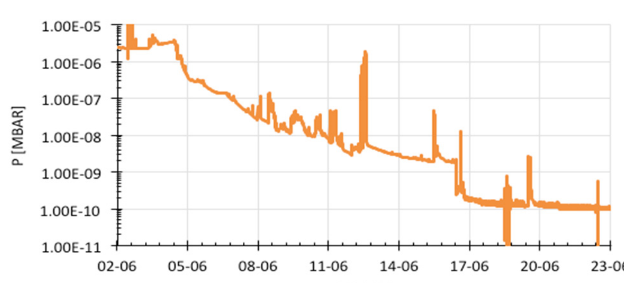

Figure 5: Vacuum monitoring of CM1 during cool-down (Spikes due to parallel RF conditioning of the cavities).

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Cryogenics Performance

In the absence of precise calorimetric measurements on a dedicated test bench, first measurements of the static heat loads of CM1 were done during the commissioning in the HIE-ISOLDE linac. The heat loads to the 4.2 K level were estimated by measuring, via the built-in superconducting level gauges, the reduction in the liquid helium in the reservoir by boil-off at constant pressure.

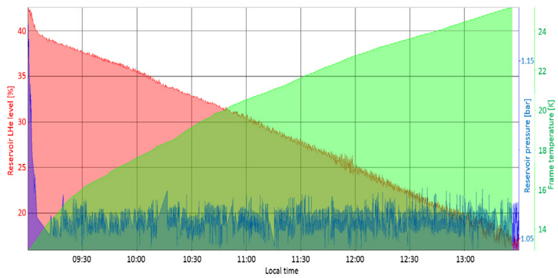

Figure 6: Liquid helium behaviour at constant pressure inside the reservoir during the test.

As illustrated in Fig. 6, at a constant pressure of 1.05 bar, the liquid helium level decreases by 20% during 4 hours of test, which corresponds to an average of 10 litres/h equivalent to a heat load of about 7W. During this time, the un-cooled frame accumulates thermal capacity due to the radiation heat loads from the thermal shield and to solid conduction through the frame supports, as measured by the temperature increases of about 12K. This increase in heat capacity is equivalent to a heat load of about 2.5 W. So, the overall measured static heat load at 4.5 K, in normal operation, amounts to ~9.5W, well below the design value [7].

Monitoring and Alignment System

The Monitoring and Alignment Tracking for Hie-IsoLDE (MATHILDE) system, as fully described in [8], allows reconstructing and monitoring of the positions of the active element beam port centers. Placed on metrological tables, HBCAM cameras are observing, through viewports, the 4 high index (~2) glass ball targets that are attached on each omega plate. The omega plates are supporting and guiding the active element beam ports, one per beam port [9].

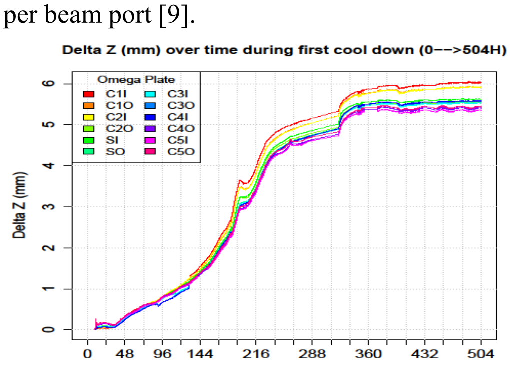

Figure 7: Vertical follow-up during the first cool down of the cavities (C%) and the solenoid (S), entry (I) and exit (O) omega plates.

For each omega plate, Fig. 7 illustrates the follow-up during the cool down of the target vertical movements with respect to measurements done at room temperature. The period plotted is from June 3rd to June 24th 2015, i.e. from room temperature to 4.5 K. The targets went up by 5.2 mm to 6 mm which is consistent with the expected vertical movement. Radially, the follow up with respect to the same original measurement shows that the omega plates moved by 0.3 mm to 0.4 mm to one side.

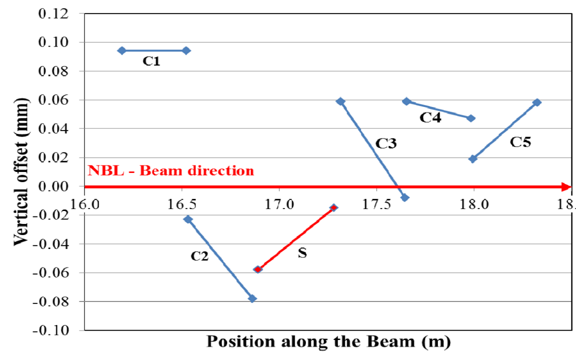

Figure 8: Vertical positions of the beam port centers after cold alignment.

The active element alignment on the nominal beam line is performed at cold. The frame supporting all the active elements inside the cryomodule is remotely moved vertically and horizontally by motors. The resulting alignment (see Fig. 8) was performed in an interval of ±0.1 mm in vertical for all the active elements with a precision level of 0.1 mm at one sigma. The relative precision between the points is about 0.05 mm (one sigma). The entry and exit beam port centers of each cavity and solenoid are plotted.

SC Linac – HIE

All 5 superconducting cavities (in CM1) were successfully RF conditioned at cold. The high field multipacting band around 1.5 MV/m was easily processed in 4/5 hours per cavity.

Extensive RF measurements were pursued, enabling to characterize fully the performance of the installed high-beta cryomodule. An important milestone was reached when all superconducting elements (cavities and solenoid) were successfully powered at nominal field at the same time.

The fully digital HIE ISOLDE low level RF system was deployed for the first time to control the first cryomodule. It was used to tune the SC QWRs very close to the target linac frequency of 101.28 MHz. A detailed status of the SRF systems at HIE-ISOLDE is given in [9].

NC Linac – REX

REX is the ISOLDE normal conducting linac post-accelerator. It is used to accelerate Rare Isotope Beams (RIB) produced at the ISOLDE targets after their charge state is boosted in the EBIS charge breeder. Alternatively, stable beam can be produced in the EBIS when residual gas is ionized [10].

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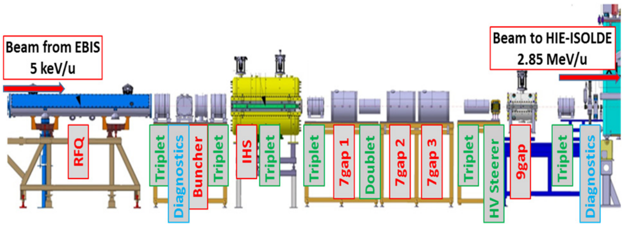

Figure 9: Layout of REX normal conducting post-accelerator.

Seven RF structures (Table 2) are used for longitudinally focussing and to accelerate the beam from 5 keV/u to 2.85 MeV/u. A total of nineteen quadrupoles grouped in triplets and doublets are used for transverse focusing. Two diagnostics boxes and a pair of beam steerers complete the main systems in the accelerator (Fig. 9).

Table 2: Main parameters of the linac post-accelerator normal conducting structures

RF structure	E_f [MeV/u] / β [%]	P [kW] for A/Q=4.0	A/Q acceptance
RFQ	0.3 / 2.5	29	< 5.5
Buncher	0.3 / 2.5	1.3	> 2.5
IHS	1.2 / 5.1	40	< 4.5
7gap1	1.55 / 5.7	60	> 2.5
7gap2	1.88 / 6.3	60	> 2.5
7gap3	2.2 / 6.8	60	> 2.5
9gap	2.85 / 7.8	71	> 2.5

Many components of REX have been replaced or refurbished during the last year. The power converters for the nineteen quadrupoles are new and have been commissioned. New thermal sensors have been retrofitted in several magnets and a high-resistance short in one of them has been repaired. Temperature rises and cooling water flow for many of them have been characterized. Two new fast Penning gauges are used to close a newly installed fast acting valve. Several faulty turbopumps and Penning gauges have been replaced and maintenance in all others has been completed. Maintenance of the RF amplifiers (cooling fans, DC power converters…) has been done. A new RF reference line is now operational. New water cooling circuits for magnets, cavities and amplifiers have been installed as well.

COMMISSIONING WITH BEAM

Beam produced in the EBIS charge breeder using residual gas with A/Q=4.0 (a mixture of $^{20}Ne^{5+}$, $^{16}O^{4+}$, $^{12}C^{3+}$ and $^{4}He^{+}$) and A/Q=3.0 ($^{12}C^{4+}$) has been used during the commissioning with beam.

A first beam accelerated to 0.3 MeV/u (output energy of the RFQ) was transported (all other RF structures were off) to the first HIE-ISOLDE diagnostics box and used to commission the Faraday cup, the silicon detector and the scanning slits.

Determining the Operational Settings of the RFQ

Several components in the LLRF of the amplifier for the RFQ were changed during its refurbishment making it necessary to redefine its operational settings. The beam transmission was measured for different power levels out of the amplifier (Fig. 10) and an amplitude in the 90-95% transmission plateau was chosen.

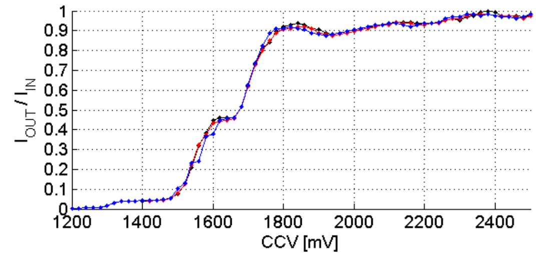

Figure 10: Beam transmission (A/Q=3.0) through the RFQ for different power levels.

First HIE-ISOLDE Diagnostics Box

The first HIE-ISOLDE diagnostics box is located at the end of the normal conducting linac right before the first cryomodule. It is equipped with a Faraday Cup, a scanning slit to measure the horizontal and vertical beam profiles, four circular collimators (20, 10, 5 and 3 mm diameter) and a silicon detector. Both the Faraday cup and the scanning slits have been tested during the commissioning with beam (Fig. 11) and they meet the design specifications [11].

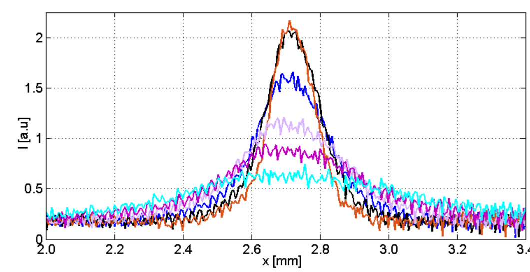

Figure 11: Beam profile for different focusing strengths in the last quadrupole before the cryomodule. Transverse profiles of beam with intensities as low as of a few epA have been measured.

The Si detector is used to measure the ions energy. It is able to detect single particles (Fig. 12) and can be used to measure properties of very low intensity beams.

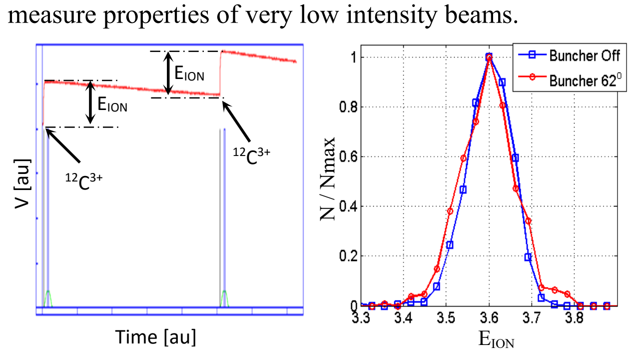

Figure 12: On the left in red: typical signal when ions hit the Si detector. The height of the signal is proportional to

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the energy of the ion (E_{ION}). On the left in blue: train of ions counted by the data acquisition system. On the right: typical energy spectrum of a $^{12}C^{3+}$ beam with 0.3 MeV/u energy with the buncher off and with the buncher at its zero-crossing.

In the near future, the Si detectors will also be used to measure the time of flight (TOF) of the ions. However, this functionality has not been tested with beam yet.

Phasing of Accelerating Structures

One of the main applications of the Si detectors is to measure the changes in the energy of the beam when the RF cavities are operated at different phases. This type of measurements (Fig. 13) allows us to set the operational phase of the amplifier so that the synchronous particle gains the nominal energy when accelerated in the structure.

A large percentage of the time allocated to the commissioning with beam of REX has been spent conducting these measurements. The velocity (and the energy per nucleon since it is a non-relativistic beam) at the exit of each normal conducting cavity is the same for every ion. Therefore, the relative phases for the cavities will not change and it won't be necessary to re-phase the cavities frequently. It will only be necessary if there are changes in the RF reference line and/or the LLRF like the one conducted during the refurbishment REX.

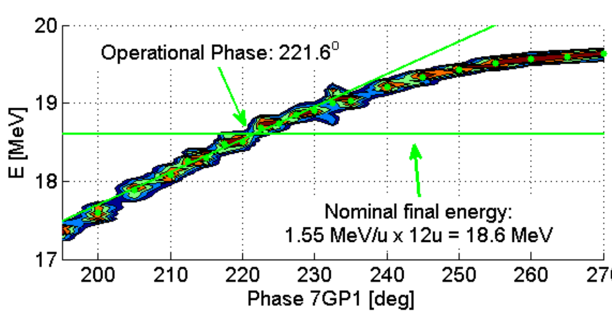

Figure 13: Phasing of the first 7gap RF structure using a silicon detector.

The Si detectors will also be used to phase the superconducting cavities. In this case, the relative phases of the cavities will often change during operations to allow higher final energies per nucleon for beams with lower A/Q.

CONCLUSION

Plenty of challenging physics is waiting for the startup of HIE-ISOLDE in Fall 2015. The physics cases approved expand over the wide range of post-accelerated beams available at ISOLDE with more than six hundred shifts approved for day one physics.

Considerable progress has been achieved:

- The HEBT hardware commissioning was completed;
- The cryomodule was installed, cooled-down and powered. A full test performance campaign was carried out;
- Beam commissioning of the NC Linac – REX is well advanced.

Beam commissioning of SC Linac is scheduled to start in September 2015.

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