BEAM COMMISSIONING OF THE HIE-ISOLDE POST-ACCELERATOR

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Abstract

Phase 1a of the High Intensity and Energy ISOLDE (HIE-ISOLDE) project [1] was completed in 2015. The first cryomodule and two High Energy Beam Transfer lines (HEBT) were installed. In addition, many of the subsystems of the normal conducting part of the post-accelerator (REX) were renovated or refurbished. Following the hardware commissioning of the different systems [2] and, in preparation for the start of the physics program, many tests and measurements were conducted as part of the beam commissioning program. The results of these tests and the plan for the next beam commissioning campaign are discussed in this paper.

INTRODUCTION

ISOLDE is one of the world leading research facilities in the field of nuclear physics. Radioactive Ion Beams (RIBs) are produced when 1.4 GeV protons from the Proton Synchrotron Booster (PSB) are transferred to the facility and impact in a target. The RIB of interest is extracted and transported to different experimental stations either directly or after being accelerated in the REX/HIE-ISOLDE post-accelerator.

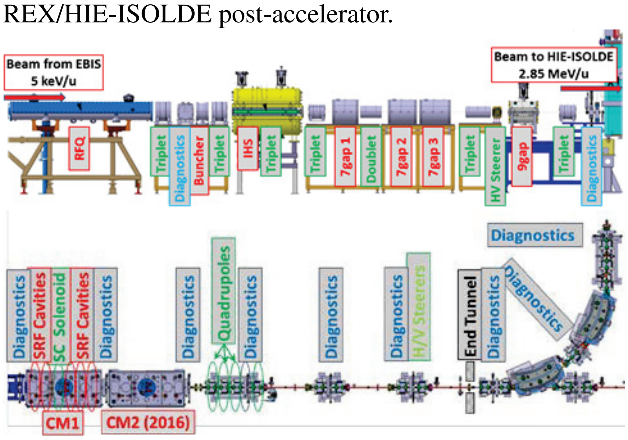

Fig. 1: Layout of the post-accelerator and one of the HEBT lines (REX on the top, HIE-ISOLDE on the bottom). RF structures labelled in red, diagnostic boxes in blue and magnetic elements in green.

REX is the normal-conducting section of the post-accelerator [3]. RIBs are accelerated after they are accumulated and cooled in the REXTRAP [4] and their charge state is boosted in the REXEBIS charge breeder [5]. The linac can also be used to accelerate stable beams produced in the charge breeder when residual gas is ionized or in an off-line ion source located before the REXTRAP.

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Seven RF structures (Table 1) are used to accelerate the beam from 5 keV/u to 2.85 MeV/u. With the exception of the last accelerating structure (9gap) that operates at 202.56 MHz and is limited to 2.5 kW average power, the frequency of the RF systems in the linac is 101.28 MHz and the maximum duty cycle is 10 % (up to 2 ms long pulses and 50 Hz repetition rate). 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 of this segment of the post-accelerator (Fig. 1).

Table 1: Main Parameters of the Normal-conducting Structures of the REX Segment of the Post-accelerator

RF structure	E_f [MeV/u]	β_f [%]	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	> 2.0
IHS	1.2	5.1	40	< 4.5
7gap1	1.55	5.7	60	> 2.0
7gap2	1.88	6.3	60	> 2.0
7gap3	2.2	6.8	60	> 2.0
9gap	2.85	7.8	71	> 2.0

The HIE-ISOLDE project consists of a superconducting extension of the REX normal-conducting linac and three HEBT lines. Phase 1a of the project (Fig. 1) was completed in 2015 and includes one cryomodule (CM1) and two HEBT lines. The cryomodule contains five superconducting Quarter-Wave Resonators (QWR) and one superconducting solenoid. The resonators are based on niobium sputtered on a copper substrate technology. The beamline and cryomodule insulation share a common vacuum which introduces constrains in the materials used inside the cryomodule, but results in a densely packed lattice. The geometrical beta of the resonators is 0.103 and they are expected to reach an accelerating gradient of 6 MV/m with a quality factor higher than $5 \cdot 10^8$. The range in the maximum beam energy reachable with one cryomodule goes from 4.3 MeV/u to 5.6 MeV/u for beams with A/q = 4.5 and 2.5 respectively.

A superconducting solenoid and normal-conducting quadrupoles are used for transverse focusing. Each experimental line consists of two 45 degree dipoles with a quadrupole in between and a triplet at the end for transverse matching into the experimental station. There are steerers before and after the cryomodule and every few meters in the linac and HEBT lines.

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REX HARDWARE COMMISSIONING

Many components of REX were renovated or refurbished during 2015. New water cooling circuits for magnets, cavities and RF amplifiers were installed. The power converters for the nineteen quadrupoles were replaced. Several of the quadrupoles were retrofitted with new thermal sensors and a high-resistance short in one of them was repaired. The rise in temperature and flow of cooling water were measured for many of them and new interlock levels were set. Two fast Penning gauges and a fast acting valve were installed to protect the SRF cavities in case of an accidental venting. Maintenance of the RF amplifiers (cooling fans, DC power converters and LLRF) was completed and the old RF reference line was replaced by the one used for the SRF cavities.

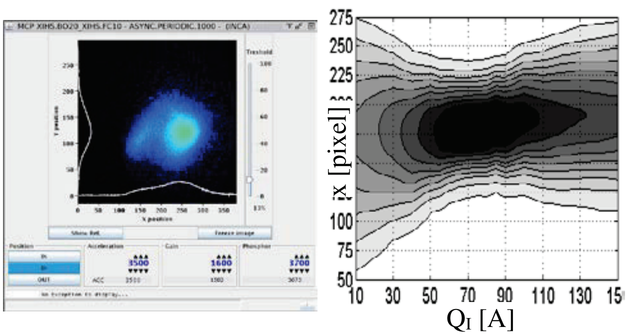

Fig. 2: On the left, typical beam image using the MCP of the REX diagnostics box. On the right, quad scan produced using the beam profiles from the MCP images.

BEAM COMMISSIONING

Beams produced by ionizing residual gas in the REXEBIS charge breeder with A/q = 3.0 ($^{12}C^{4+}$), A/q = 3.5 ($^{14}N^{4+}$) and A/q = 4.0 (a mix of $^{20}Ne^{5+}$, $^{16}O^{4+}$ and $^{12}C^{3+}$) were used during the beam commissioning campaign of the machine.

The campaign was divided into several stages. First, beam accelerated to 0.3 MeV/u was used to re-commission the components of the REX diagnostics box after the operational settings of the RFQ were determined. Second, beam with that same energy (i.e. all other RF structures were off) was drifted along the linac to the first HIE-ISOLDE diagnostics box and used to commission its components. Third, the silicon detector in this diagnostics box was used to find the operational settings of the rest of the accelerating structures (i.e. determine the amplitude and the phase for each RF amplifier). Fourth, beam with the REX nominal energy (2.85 MeV/u) was drifted through the cryomodule while the superconducting cavities were off and used to commission the diagnostic boxes and optical elements of the rest of the linac and the first HEBT line. Fifth, the superconducting cavities were phased using a second silicon detector in a diagnostics box at the end of the linac tunnel. Finally, beam was transported along the second HEBT line and its different devices were tested during the last stage of the beam commissioning.

Beam Diagnostics Boxes

The first diagnostics box in the linac is located between the RFQ and the buncher. It is equipped with a Faraday Cup (FC), a Micro Channel Plate (MCP) viewer, collimators and several beam attenuators. It is an old-style REX diagnostics box and none of its components were modified during the refurbishment of the REX linac. The working condition of all the devices was confirmed during the beam commissioning (Fig. 2).

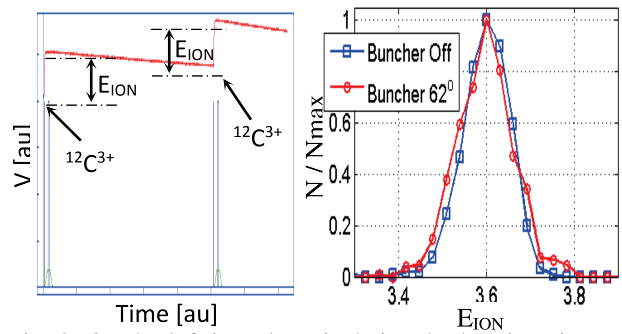

Fig. 3: On the left in red, typical signal when ions impact in the Si detector. Height of the signal proportional to the energy of the ion (E$_{ION}$). On the right, energy spectrum of a $^{12}C^{3+}$ beam with 0.3 MeV/u energy with the buncher off and with the buncher set at its zero-crossing phase. Note that the measured energy spread does not change since it is dominated by the resolution of the detector.

All the beam diagnostic boxes in the linac and HEBT lines are equipped with a FC, a scanning slit and either collimator apertures or collimator slits depending on the location. In addition, there are several silicon detectors that can be used for beam energy and Time-Of-Flight (TOF) measurements, and carbon stripping foils that can be used to clean beam contaminants and increase beam purity of light RIBs. The FCs, the scanning slits and the collimator apertures of the HIE-ISOLDE diagnostic boxes were tested during the beam commissioning and they met the design specifications [6]. Transverse profiles of beams with intensities of only a few epA could be measured.

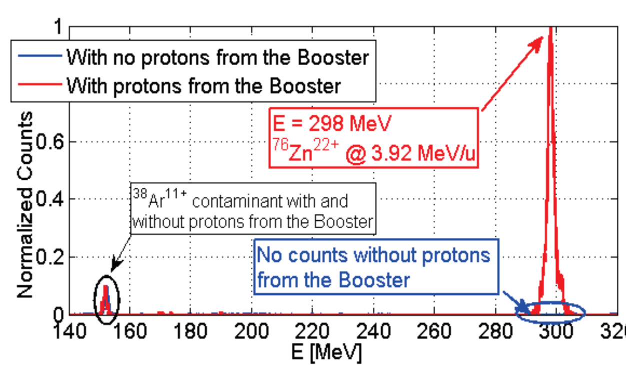

Fig. 4: Energy spectrum of the beam delivered to the Miniball experimental station. RIB of interest ($^{76}Zn^{22+}$) and EBIS contaminant ($^{38}Ar^{11+}$) in red. Only the contaminant is visible when the primary proton beam from the PSB is stopped (in blue).

Two of the silicon detectors and their electronics were tested and performed as expected [7]. Single particles could be identified (Fig. 3) and the detectors were used to measure the energy and the energy spread of very low-intensity beams. As an example, the measured energy resolution (FWHM) for a $^{12}C^{4+}$ beam was ~ 150 keV which allowed rough measurements of the energy spread of the 4 MeV/u beams requested by the users during the 2015 physics campaign. The silicon detectors were also useful to identify beam contaminants with the same energy per nucleon but different total energy (Fig. 4).

Five carbon foils with two different thicknesses (3 x 50 and 2 x 75 µg/cm^2) were tested and the Charge State Distribution (CSD) of the resulting beam was measured ($^{14}N^{4+}$ beam was ionized further into $^{14}N^{5+,6+,7+}$).

Accelerating Structures

In addition to the RF reference line, several other components of the LLRF of the REX linac amplifiers were replaced during their refurbishment. The calibration changed and a redefinition of their operational settings was necessary.

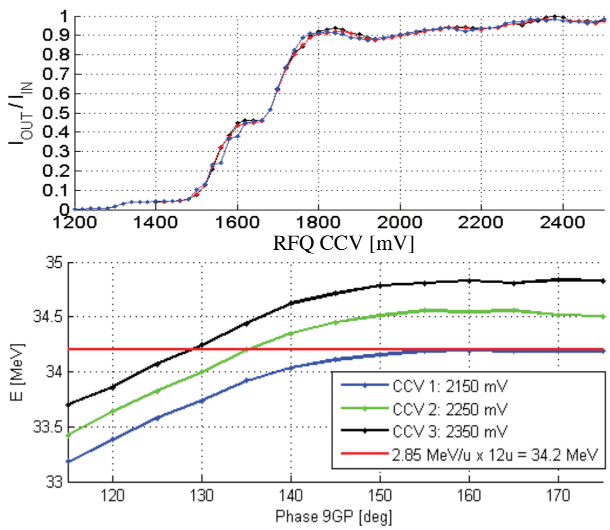

Fig. 5: Beam transmission through the RFQ as a function of the RF amplitude (top). Energy of the beam after the 9gap structure for different RF phases and amplitudes. Nominal beam energy in red (bottom). $^{12}C^{4+}$ beam was used during these measurements. The CCV values are linear on the field amplitude of the RF structures.

The beam transmission was measured for different power levels in the RFQ (Fig. 5 top). The RF amplitude for the ~ 95% transmission plateau was chosen as its operational setting. Silicon detectors were used to determine the operational settings of the rest of the normal and superconducting accelerating structures. The energy of the beam after each structure was measured for different amplitude and phase settings (Fig. 5 bottom). The operational settings were found using this information together with the nominal energy gain and synchronous phase of each structure.

Several problems surfaced and were solved during the beam commissioning of the RF systems. Two of the phase shifters of the REX amplifiers were replaced and changes in the firmware of the LLRF of the SRF cavities were done during this time.

Beam Optics and Alignment

Due to time constrains, the scope of the beam commissioning was limited to tests and measurements that were strictly necessary to get the physics campaign started. Systematic tests of the optical elements were not conducted and the optics model was not completely validated. Despite this, the overall beam transmission (from separator magnet to the end of experimental lines) was typically ~75% after a short optimization. Losses of ~10% were expected due to inefficiencies in the RFQ bunching of a DC beam. The rest of the losses occurred mostly in the first dipole probably because of longitudinal beam mismatches. Strong beam steering was not needed which indicates good alignment of the optical elements.

CONCLUSION AND FUTURE PLANS

The 2015 physics campaign [8] started right after the machine was commissioned and it was reasonably successful. Due to a problem with the cooling of the couplers of the SRF cavities [2], CM1 had to be moved back to the clean room where new couplers were retrofitted. CM1 and the newly assembled CM2 are now being installed in the linac bunker. The hardware and beam commissioning will start in May. During this time, several diagnostic boxes, the superconducting cavities and solenoids in the cryomodules and a new TOF-based energy measurement system will be commissioned.

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