FIRST OPERATIONAL EXPERIENCE OF HIE-ISOLDE

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Abstract

The High Intensity and Energy ISOLDE project (HIE-ISOLDE) [1] is a major upgrade of the ISOLDE facility at CERN. The energy range of the post-accelerator will be extended from 2.85 MeV/u to 9.3 MeV/u for beams with A/q = 4.5 (and to 14.3 MeV/u for A/q = 2.5) once all the cryomodules of the superconducting accelerator are in place. The project has been divided into different phases, the first of which (phase 1a) finished in October 2015 after the hardware and beam commissioning were completed [2, 3]. The physics campaign followed with the delivery of both radioactive and stable beams to two different experimental stations. The characteristics of the beams (energies, intensities, time structure and beam contaminants) and the plans for the next experimental campaign will be discussed in this paper.

INTRODUCTION

ISOLDE is one of the leading research facilities in the field of nuclear physics. Radioactive Ion Beams (RIBs) are produced when 1.4 GeV protons impact in a target. The RIB of interest is extracted and transported to different experimental stations either directly or after being accelerated in the post-accelerator [4].

THE 2015 PHYSICS CAMPAIGN

In preparation for the physics campaign and in order to test the accelerator chain, stable ^{87}Rb was produced in the GPS target, transported to the REXTRAP, charge-bred in the REXEBIS and accelerated to 2.85 MeV/u in the REX linac. In addition, $^{12}C^{4+}$ produced in the charge breeder was used as a pilot beam to phase the superconducting cavities and to set up the High Energy Beam Transfer (HEBT) lines.

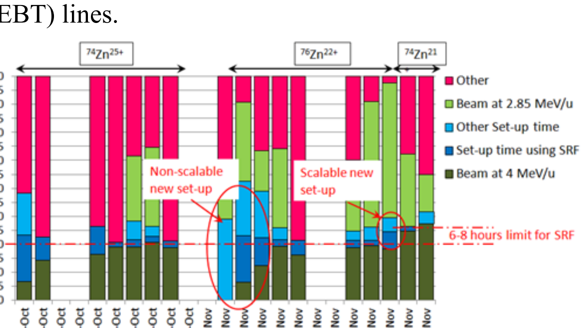

Figure 1: Beam time distribution to the Coulomb excitation experiment at HIE-ISOLDE energies (dark green), at REX energies (light green). Set-up time in blue.

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On Oct. 19th, the physics campaign started with the delivery of stable $^{22}Ne^{7+}$ with an energy of 2.85 MeV/u to the Miniball spectrometer [5]. The first 4 MeV/u RIB was delivered a few days later. Over the following weeks, different charge states of two zinc isotopes ($^{74}Zn^{25+}$, $^{76}Zn^{22+}$ and $^{74}Zn^{21+}$) and energies of 2.85 and 4 MeV/u were sent to the spectrometer (Fig. 1). The 4 MeV/u beam time was limited to 6 - 8 hours per day due to an overheating problem in the couplers of the superconducting cavities. Beam with the REX linac energy was used during the rest of the time. In addition to the radioactive Zn sent to the Miniball spectrometer, several stable beams were delivered for commissioning purposes to the scattering chamber (a few hours of $^{14}N^{4+}$ and $^{12}C^{4+}$ beams) and to the SPEDE spectrometer [6] (4.5 days of $^{133}Cs^{39+}$ beam).

CHARACTERISTICS OF THE BEAM

Beam Intensity

Typical RIBs demanded by the users are often exotic and difficult to produce. They are not very intense (could be as low as tens of ions per second) and traditional beam diagnostic instrumentation like Faraday Cups (FCs) are not generally practical. Rough estimates are possible if the production rates of the targets and the efficiencies of the different elements in the accelerator chain are measured. However, several assumptions need to be made and feedback from the users is usually necessary to properly characterize the intensity of the beam. That said, RIBs delivered to the experiment during the 2015 physics campaign were exceptionally intense (Fig. 2) and could be measured with the FCs (~ $2\cdot10^6$ pps for $^{74}Zn^{21+,25+}$ and ~ 10^6 pps for $^{76}Zn^{22+}$ for a 2 μA proton current). With the exception of the $^{133}Cs^{39+}$ limited to ~ $1.5\cdot10^5$ pps, the rest of the stable beams delivered to the experiments ($^{22}Ne^{7+}$, $^{14}N^{4+}$ and $^{12}C^{4+}$) were attenuated to ~ 10^6 - 10^7 pps.

Beam Energy and Energy Spread

Characterizing the energy of the beam accurately and precisely is critical to many of the users of the facility. Although, only some of them will request RIBs with a very specific energy, almost all them will need to know it accurately and be certain that it does not drift significantly over the duration of the experiment. Three different methods to measure the beam energy were used during the campaign: silicon detectors, the RF calibration of the accelerating structures and the first dipole of the HEBT line. The three methods, explained in more detail below, produce results consistent within ~ 2 - 3 % which was acceptable for the 2015 campaign, but which will not be sufficient for many future experiments.

Silicon detectors [7] were used throughout the physics campaign (Fig. 3) and proved to be the most versatile of all three methods. However, measurements in their current configuration were time consuming. The counting rate of the detector is limited by the repetition rate of the linac (10 Hz in 2015), the energy of the beam and the spread in the distribution of the time between events. A few hundred microseconds in between events are necessary to avoid saturation of the detector. The result is that ~ 15 mins were needed to accumulate enough statistics. In addition, absolute energy calibration of the detectors is difficult. The energies of the α-particles emitted by the radioactive sources used to calibrate these detectors are limited to a few MeV (e.g. 5.486 MeV for the dominant decay channel of ^{241}Am). Linearly extrapolating to ions, often a lot heavier than ^{4}He, with hundreds of MeV of total energy translates into inaccuracies of the measurement method.

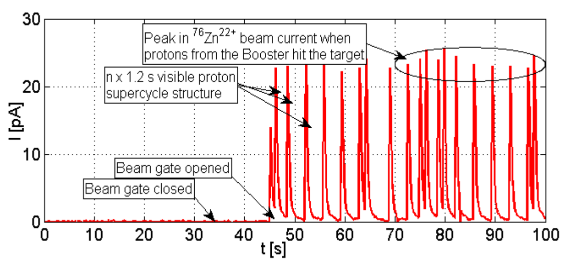

Figure 2: Intensity of the $^{76}Zn^{22+}$ beam delivered to the Miniball spectrometer as measured on the last FC of the first HEBT line. Time structure of the primary proton beam supercycle is visible.

The energy of the beam can also be estimated if the Transit Time Factor (TTF), the accelerating gradient and the operational phase for each cavity are well known. The TTF can be calculated using the EM model of the resonator and all the measurements conducted during the commissioning campaign seem to indicate that the accelerating fields were well known (i.e. good calibrations of the RF pick-ups and the LLRF systems). Discrepancies between the operational phases and the synchronous phases (-20 degrees) were probably the largest source of uncertainty when the energy of the beam was determined using this method. For example, a 5 degree discrepancy between the two, results in ~ 3 % error in the energy gain of the beam in that cavity. Achieving better is challenging and time consuming.

The third method uses the first dipole of the HEBT lines as an energy spectrograph. The beam is collimated horizontally before it is injected into the dipole and the magnetic field is adjusted until the beam leaves the dipole centered on the beam axis. The magnetic rigidity and the energy of the beam can be determined by measuring the magnetic field with a Hall probe and its previously-measured relationship with the field integral. Since the beam needs to be collimated before and after the dipole, this type of measurement was only feasible for relatively intense stable beams. At the same time, the maximum initial beam current was limited to 20 epA because of radiation safety reasons which translates into sub-epA currents after the collimators that are only marginally above the noise level of the FCs.

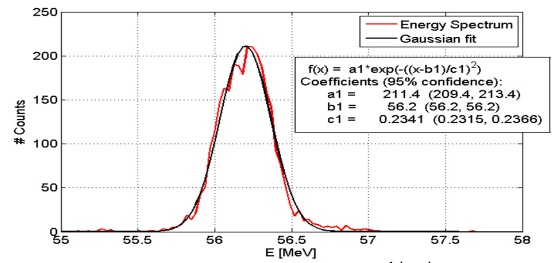

Figure 3: Energy spectrum of a pilot $^{14}N^{4+}$ beam used to set up the accelerator before $^{76}Zn^{22+}$ and $^{74}Zn^{21+}$ were delivered to the users (E = 4.0 MeV/u, $\Delta E_{FWHM} \lesssim 0.7$ %).

Measuring the energy spread of the beam using the dipole magnet was not feasible due to the very low beam currents involved. However, an upper limit for the energy spread could be estimated using the silicon detectors in many cases. The intrinsic resolution of the detectors for light beams is believed to be ~ 150 keV. At low energies, like the 0.3 MeV/u after the RFQ, the measured energy spread is dominated by the resolution of the detector (i.e. it does not change when the amplitude of the buncher is changed). Measurements like the one in Fig. 3 show an energy spread of ~ 400 keV (0.7 %). The actual energy spread of the beam should be smaller after the intrinsic resolution of the detector is de-convoluted from the measurement.

Two additional tools to measure the energy of the beam will be commissioned and available during the 2016 physics campaign. Silicon detectors (a ring-shaped one and disk-shaped one) separated by 7.76 meters of longitudinal drift space will be used to measure the Time-Of-Flight (TOF) of the ions [7]. Although, this method needs to be used in conjunction with others (an initial estimate of the beam energy is necessary to eliminate the ambiguity in the RF bucket populated by the ions), the method should be able to measure the TOF of the beam with uncertainties of ~ 0.5 ns (i.e. ~ 20 degrees of the 101.28 MHz RF period). As an example, for a representative beam with an E = 5 MeV/u (i.e. $\beta \approx \beta_g$ = 0.103, where β = v/c and β_g is the geometrical beta of the Superconducting RF (SRF) cavities), the 0.5 ns uncertainty in the TOF translates into a ~ 0.4 % uncertainty in the absolute energy of the beam. As an added benefit, the detectors could also be used to estimate the bunch length which will help with the validation of the beam dynamics model (i.e. the last SRF cavity can be operated as a buncher and the bunch length measured for different longitudinal focusing strengths at the detector location). In addition, a supplementary silicon detector will be installed after the first dipole of one of the HEBT lines and it will help increasing the dynamic range (in beam intensity) when the energy of the beam can be measured using the dipole as a spectrograph.

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Beam Purity

Residual gas in the REXEBIS will unavoidably be ionized and transported to the REX separator together with the RIB. These contaminants will make it all the way to the linac if their A/q is identical or very close to that of the RIB of interest. Avoiding the most significant contaminants (i.e. stable isotopes of C, N, O, Ne and Ar with high relative abundances) and choosing a clean A/q is required for most experiments. Unfortunately, this is not always possible and some ions (Fig. 4) will make it to the experimental station. In some cases, the silicon detectors can be used to measure the ratio of RIBs of interest to contaminants and use this information to adjust the REX separator and increase the beam purity.

Undesired RIBs produced in the target with the same mass number, close atomic number and long enough half-lives may also make it to the experimental station. Silicon detectors cannot be used to distinguish these contaminants since they have almost identical total energy.

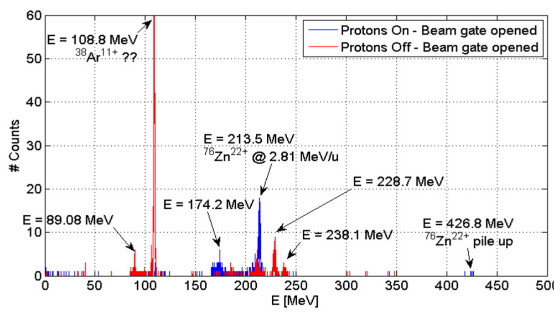

Figure 4: Energy spectrum with and without primary proton beam in the target measured with one of the silicon detectors. $^{76}Zn^{22+}$ and a contaminant (probably $^{38}Ar^{11+}$) are visible. The peaks at 89 and 174 MeV were formed by ions not accelerated by the 9gap structure.

Beam Time Structure

In addition to the 9.87 ns (101.28 MHz) time microstructure produced by the bunching in the first few cells of the RFQ, the beam delivered to the users will also have a macrostructure.

During the 2015 physics campaign and due to a delay in the delivery of the final amplifier, a temporary one with limited capabilities had to be used to power the last cavity of the REX linac (a.k.a. 9gap structure). In addition to a lower peak power, which limited the highest A/q of the beam to 3.6, the maximum repetition rate was 10 Hz and the longest pulse length was ~ 250 µs. The resulting instantaneous rate produced pile-up in detectors of the Miniball setup. The new amplifier arrived at the beginning of 2016, it has been installed and it will be used in the next physics campaign. The post-accelerator should, from now on, be able to deliver beams with A/q as high as 4.5. The maximum repetition rate should be 50 Hz and the longest pulse length should be 2 ms. However, it should be noted that it will not be possible to push these three parameters to the limit at the same time.

Another constrain that defines the macrostructure of the beam is the time needed to charge-breed the RIB of interest to the desired charge state. Optimum breeding times go from tens to hundreds of milliseconds depending on the desired ionization state (i.e. repetition rates between 50 and a few Hz). In addition, the voltage modulation of the electrode that closes the potential well of the charge breeder defines how fast the beam spills out of it. The well empties in tens of µs if it is opened fast, but the beam pulse can be stretch to hundreds of µs if the voltage of the electrode is modulated properly. The pulse was stretched to ~ 200 µs during the last physics campaign. However, the beam intensity was not uniform over it. New software tools are being developed to allow better control of the length and shape of the beam macrostructure in the future.

CONCLUSION AND FUTURE PLANS

The 2015 physics campaign was fairly short but reasonably successful considering the constraints introduced by the delay in the delivery of the final 9gap amplifier and the heating problems in the couplers of the SRF cavities. It started on Oct. 19th and finished on Nov. 24th. A very important project milestone was reached on Oct. 22nd when the first radioactive beam with HIE-ISOLDE energies was delivered to the Miniball spectrometer. Two different RIBs (^{74}Zn and ^{76}Zn) were delivered during the following 3.5 weeks and first nuclear physics results were obtained. The physics campaign will be longer this year. It will start in the second half of August and extend until Nov. 14th. The installation of the second cryomodule should allow energies as high as 6.0 MeV/u for beams with an A/q = 4.5 (8.7 MeV/u for beams with an A/q = 2.5). The new couplers in the SRF cavities should enable continuous operation and will increase the scientific output of the facility.

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