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CHARACTERIZATION OF THE BEAM ENERGY SPREAD AT THE REX/HIE-ISOLDE LINAC

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Abstract

ISOLDE is an on-line radioactive isotope separator located at CERN that works by colliding protons accelerated in the Proton Synchrotron Booster (PSB) onto a fixed target and by separating the resultant ionized isotopes using a magnetic separator. The completion of the HIE-ISOLDE superconducting linac allows the acceleration of these ions to energy levels that were not reachable before, opening the door to new experiments in different fields. These experiments often have special requirements in terms of beam intensity, purity, transverse emittance or energy spread. A possible way to reduce the energy spread of the beam delivered to the experimental stations is to use one or more of the superconducting cavities as bunch rotators. The main results of several tests conducted during the last beam commissioning campaign to prove that this mode of operation is feasible will be presented in this paper.

INTRODUCTION

ISOLDE is a research facility in the field of nuclear physics. Radioactive isotopes are produced when 1.4 GeV protons from the PSB (typically ~ 2 uA average current grouped in pulses of 3E13 protons every few seconds) are transferred to the facility and collide onto a thick target made of diverse materials (UC2C, Ta, Ti, CaO). These isotopes are ionized using diverse techniques (laser ionization, cold surface ionization, plasma ionisation…) and extracted from the target using an electrostatic accelerating field of up to 60 kV. Once the Radioactive Ion Beams (RIBs) are extracted out of the target front-end, they are transported through magnetic separators where the mass of interest can be selected, consequently rejecting all the other masses. The RIB of interest is then transported to the different experimental stations using electrostatic optics elements where the users install the equipment needed for each particular experiment.

One of the ISOLDE beam lines reaches the REX/HIE-ISOLDE post-accelerator [1] where the ions are bunched and transversally cooled in a Penning trap (REX-TRAP). The beam is then transferred into a charge breeder (REX-EBIS) where ions are charge-bred to a mass to charge ratio (A/q) between 2.5 and 4.5 through electron bombardment by an electron beam [2] for later acceleration to the desired final energy in the linac. Once accelerated, the ion beam is transported to one of the three high-energy experimental stations.

With the installation and commissioning in 2017 of all the components included in phase 2A of the HIE-ISOLDE project [3], the post-accelerator linac increased its final energy considerably, reaching 8 MeV/u for a beam with A/q = 3 during one of the experiments of the Physics campaign. The additional superconducting RF cavities and the possibility of changing their amplitudes and phases independently allows the manipulation of the longitudinal beam properties in ways not possible before [4].

ACCELERATOR LAYOUT AND EXPERIMENTAL SETUP

The REX/HIE-ISOLDE linac (Figure 1) is divided into a normal conducting section with seven cavities and a superconducting section with four cryomodules each containing five Quarter Wave Resonators (QWR) (three cryomodules at the time the study described in this paper was conducted). The nominal electrical field of the superconducting cavities is 6 MV/m. A superconducting solenoid in each one of the cryomodules is used to focus the beam transversely.

The energy required by many of the experiments is often lower than the maximum energy achievable by the linac so often, not all the superconducting cavities are needed for beam acceleration. These cavities can then be used to manipulate the longitudinal beam properties and, in this particular case, to reduce the energy spread of the beam delivered to the users. The beam is accelerated to 2.8 MeV/u by the normal conducting section of the linac, and after, its energy is further increased to the requested energy using as many superconducting cavities as needed. For this study, the remaining superconductive cavities were switched off and only the last one (CM3-5) was operated as a buncher. In order to do this, the phase of the last RF cavity was carefully chosen so that the synchronous particle does not see any net voltage when it flies through the cavity but the slightly slower ones are accelerated and the slightly faster ones decelerated bunching the beam longitudinally (i.e. bunching zero-crossing phase). The beam is then sent to the XT01 high energy line where the energy and energy spread of the beam are measured.

For the energy spread measurements, three 1 mm vertical slits were inserted at the XT00.1050, XT00.1300 and XT01.0400 beam diagnostic boxes (Figure 1) and the focusing and steering elements after the first slit were switched off. A silicon detector [5] after the third slit was used as a particle counter and the energy for each particle was calculated based on the magnetic field of the XT01.0100 dipole. For better accuracy in the calculations, a magnetic map of the dipole was done after it was manufactured and its effective length calculated.

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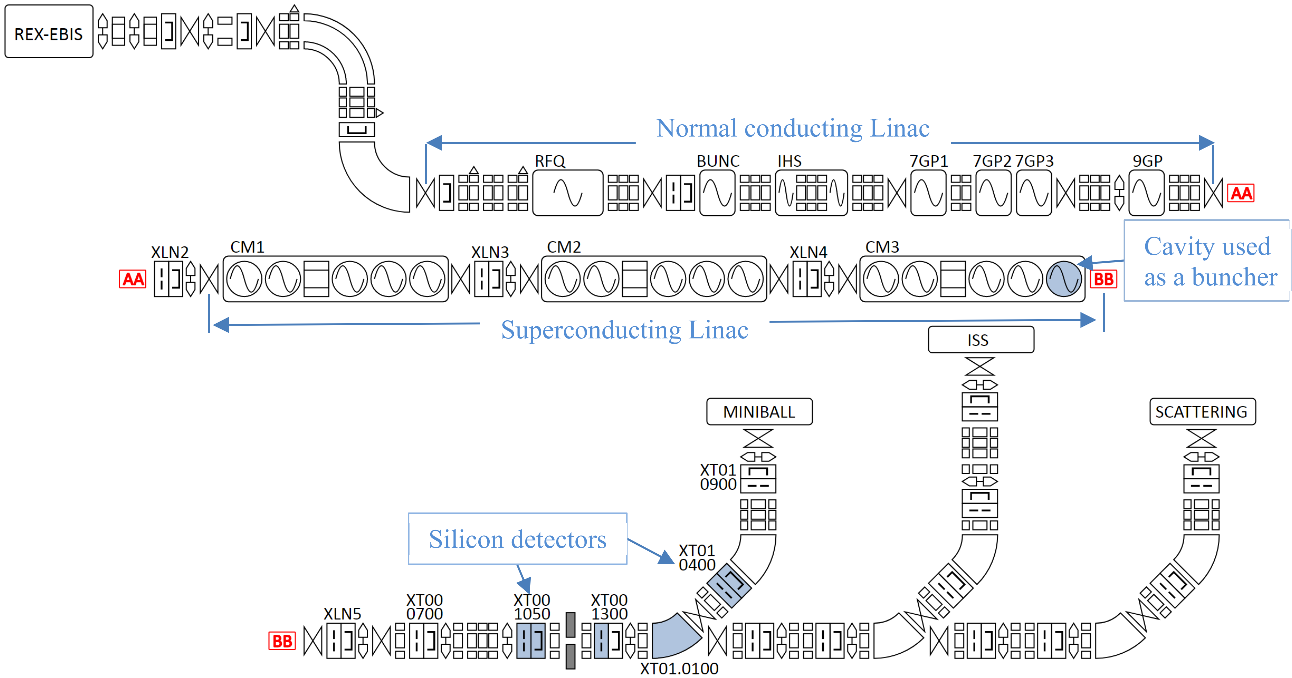

Figure 1: Layout of the REX/HIE-ISOLDE post-accelerator after Phase 2A. The devices used in the study are highlighted in blue (SRF cavity used as a buncher, dipole used as an energy spectrometer and beam diagnostic boxes were the vertical slits, Faraday cups and Silicon detectors are).

The insertion of these three slits guarantees that only particles injected into the dipole on the beam axis reach the silicon detector and are taken into account for the beam energy measurements. This method for calculating the beam energy was cross-calibrated with another method based on the Time-Of-Flight (TOF) between two silicon detectors during the commissioning campaign in 2016 [6].

The bunch length was determined by measuring the time of arrival to a silicon detector located in the XT00.1050 diagnostic box relative to a reference signal from the 101.28 MHz master clock used to synchronize all the RF systems in the linac.

BEAM INTENSITY, TIME STRUCTURE, AND COMPOSITION

The time structure of the beam in the linac is defined by the superposition of the beam pulse extracted from the REX-EBIS and the time structure of the RF pulse of the linac. The extraction time (0.05 to 1 ms) and the repetition rate (1 to 50 Hz) of the REX-EBIS define the time macro-structure of the beam. The RF frequency of the linac, 101.28 MHz, defines the time micro-structure (i.e. bunches separated by 9.87 ns).

The beam intensity reaching the silicon detectors had to be reduced to avoid pile-up effects and damaging the device that is designed for single-particle detection. For this purpose, a 1% transparency attenuator was inserted at the beam diagnostic box after the RFQ cavity and the breeding time of the REX-EBIS was lowered down to a few milliseconds.

A test beam was generated ionizing the residual gas in the charge breeder with an A/q = 3.5 for these measurements. This beam was composed mainly by $^{14}N^{4+}$ with some traces of $^{21}Ne^{6+}$ [7].

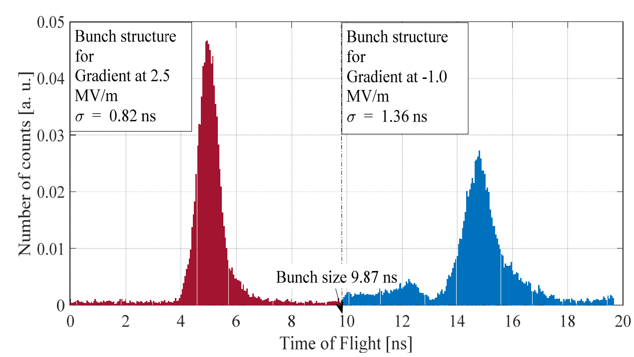

Figure 2: Bunch length measured at XT00.1050 diagnostic box for a 3.83 MeV/u beam when two different gradients were applied to the CM3-5 buncher.

MEASUREMENTS AND RESULTS

The energy spread and bunch length as a function of the gradient in the CM3-5 buncher were measured for two different beam energies (3.42 and 3.83 MeV/u). For the first energy, the first three cavities of the CM1 were used for acceleration. For the second energy, all the cavities of the CM1 were used (Table 1). A summary of the results of these measurements is shown in Figure 3 and Figure 4.

Based on the measurements, the fitted data show that for the lower energy beam, the minimum reachable RMS energy spread is 0.12 % when the buncher is set to 0.37 MV/m. For the higher energy beam, the minimum is 0.07 % for a bunching gradient of 0.13 MV/m.

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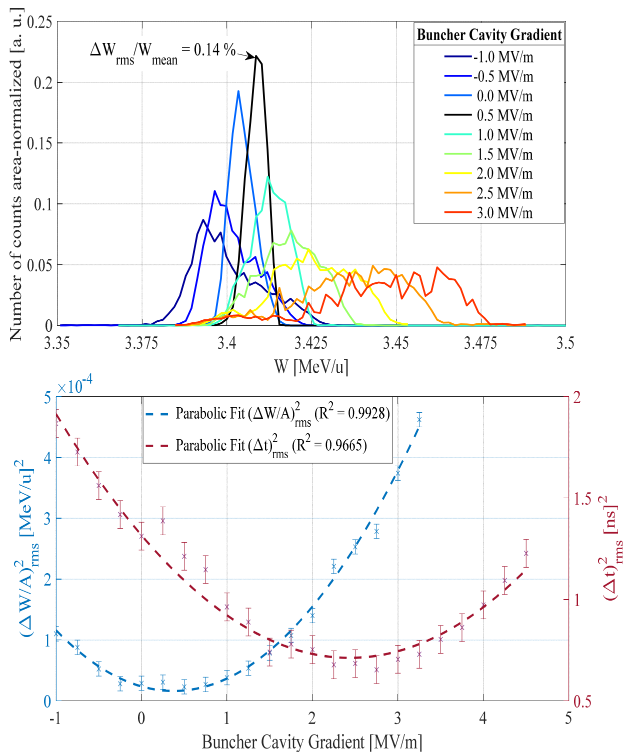

Figure 3: Results of the measurements for a $^{14}N^{4+}$ beam when three SRF cavities were used for acceleration. Energy (3.42 MeV/u) and energy distribution for different gradients in the buncher (top). Bunch length and energy spread as a function of buncher gradient (bottom).

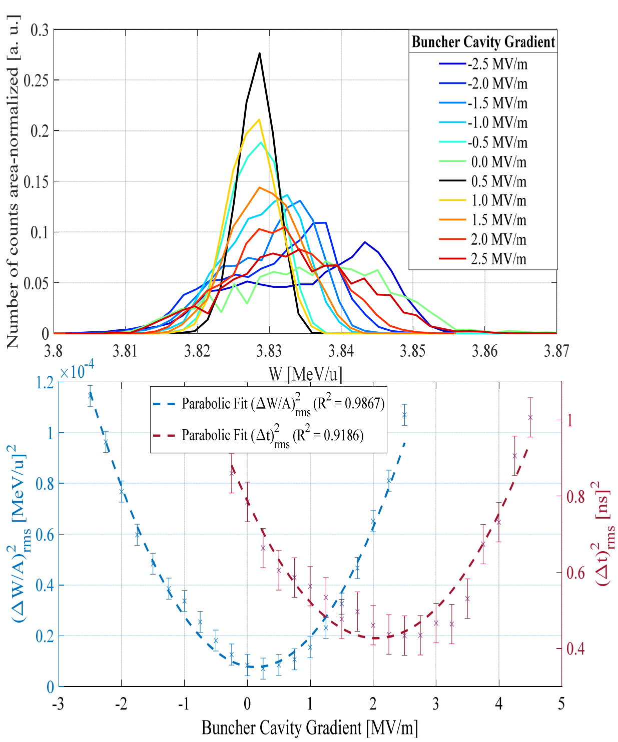

Figure 4: Analog measurements as on Figure 3 for a 3.83 MeV/u beam accelerated using five SRF cavities.

Table 1: Output Energy of the Beam and Gradients and Phases of the SRF Cavities Used in the Study

Cavity	Gradient (MV/m)	Synchronous Phase (deg)	Energy (MeV/u)
CM1-1	3.58	- 40	2.98
CM1-2	3.58	- 20	3.20
CM1-3	3.58	- 20	3.42
CM1-4	3.58	- 20	3.65
CM1-5	2.70	- 20	3.83
CM3-5	0 - 4.50	- 90	-

CONCLUSION

The results presented in the paper prove that the energy spread and the bunch length of the beam can be reduced operating a superconducting cavity as a buncher. This technique allows further optimization of the longitudinal beam properties and opens the door to experiments with more demanding requirements in terms of energy spread.

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