CHARACTERIZATION OF REX/HIE-ISOLDE RFQ LONGITUDINAL ACCEPTANCE AND TRANSMISSION

N. Bidault[*1, 2], E. Matli[1], J. A. Rodriguez[1]

[1] CERN, 1211 Geneva, Switzerland

[2] University of Rome 'La Sapienza' and INFN Sez. Roma1, 00185 Roma, Italy

Abstract

The Isotope mass Separator On-Line DEvice (ISOLDE) based at CERN, is a Radioactive Ion Beam (RIB) facility where rare isotopes are produced from 1.4 GeV-proton collisions onto a target then are manipulated and transported to user experimental stations for studies, notably in the domain of nuclear physics. The RIB of interest is delivered to a dedicated experimental station either at low (up to 60 keV) or high energy (MeV/u range) after acceleration through the recently completed REX/HIE-ISOLDE linac upgrade. The first stage of the linac consists of normal-conducting IH and spiral-resonators and is preceded by a Radio-Frequency Quadrupole (RFQ). A description of the experimental setup and the specifications of the RFQ will serve as an introduction for the presentation of recent results about the transmission efficiency of the RFQ. Furthermore, a newly developed technique will be demonstrated, that allow for the capture of ion beam intensities below the femto-Ampere range. In fine, a measurement of the longitudinal acceptance of the RFQ will be included.

INTRODUCTION

The study of rare radioactive isotopes often implies to face low yields and consequently foster instrumental technique improvements, in particular for accelerating structures characterization at very low beam intensity (< pA). A methodology to measure important RFQ parameters such as its transmission efficiency at beam currents in the fA range will be described after a brief introduction to the REX/HIE-ISOLDE low-energy section. In the last section, a recent result about the longitudinal acceptance of the accelerating structure is discussed and correlated with a potential deduction of the input beam transverse emittance.

The transport of a RIB of interest through the low energy part of REX/HIE-ISOLDE is punctuated by several necessary steps prior to post-acceleration. After production and on-line mass-separation, the continuous ion beam is accumulated and transversely cooled in the REX-TRAP (Penning trap). Singly-charged ions extracted from the trap are transferred towards the REXEBIS charge-breeder and will undergo successive electron-impact ionization in order to increase their charge-state, or equivalently to reduce their mass-to-charge ratio (A/q). The resulting charge-state distribution is thereafter filtered through an A/q-Separator which is of a Nier-type spectrometer. Selecting an A/q suitable for post-acceleration is often a compromise between maximiz-

ing the trapping and charge-breeding efficiency, minimizing the residual gas contamination and respecting the linac A/q-acceptance (between $A/q = 2.5$ and $A/q = 4.5$).

EXPERIMENTAL SETUP

All measurements presented made use of stable $^{39}K^{10+}$ beam, originating from the local ion source installed upstream the REX-TRAP. Verification tests for the calibration of the RFQ electrode voltage pick-up were conducted with ionized residual gas beams extracted at various A/q directly from the REXEBIS.

The room-temperature RFQ is the first module of the REX/HIE-ISOLDE linac, it is a four-rod-$\lambda/2$ design with a total length of 3 m. The construction and testing took place at the Ludwig Maximilian University, in Munich [1]. The resonance frequency and basic parameters are summarized in the Table 1.

Table 1: Basic Parameters of the REX/HIE-ISOLDE RFQ

Parameter	Value
Frequency	101.28 MHz
Number of cells	232
Input energy	5 keV/u
Final energy	300 keV/u
Maximum duty cycle	10 %
A/q-acceptance	< 5.5
Radial acceptance ϵ^{norm}	0.66 π mm mrad
Electrode voltage ($A/q = 4.5$)	42 kV
RF Power ($A/q = 4.5$)	36.3 kW
Quality factor Q_0	3801 [2]

The recent accomplishment of the HIE-ISOLDE project has been accompanied with instrumentation upgrades, notably the installation of 300 μm-thick partially-depleted Passivated Implanted Planar Silicon (PIPS) detectors [3]. The possibility brought by silicon detectors to resolve single incident event is beneficial for beam characterization at very low intensity. Two important aspects need to be asserted for proper use of the ensemble comprising a silicon detector and its preamplifier: the energy deposited on the detector per pulse must remain below 500 MeV (preamplifier and digitizer specifications) and the time-structure of the beam is preferred stretched (> 10^2 μs) to avoid pile-up effect. One large-aperture (15 mm-diameter) silicon detector is installed in XT00.1300 beam-line position (Figure 1).

* niels.b@cern.ch

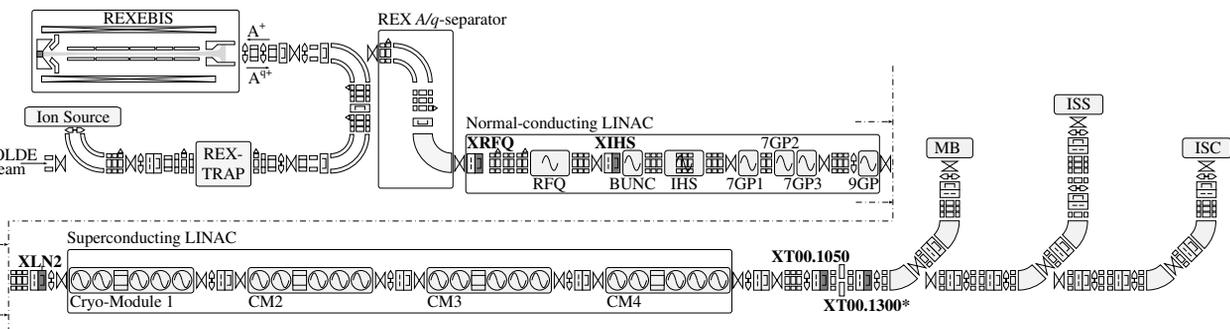**MC4: Hadron Accelerators**

A20 Radioactive Ions

Figure 1: Schematic of REX/HIE-ISOLDE post-accelerator. For all locations indicated in bold (XIHS, XRFQ...), the grayed pictogram indicates a Faraday cup used in the measurements. A large-aperture silicon detector is installed in XT00.1300*.

TRANSMISSION MEASUREMENTS

The RFQ gradient is an essential tune parameter, directly impacting the transmission efficiency throughout the whole linac. An electrode voltage pick-up serves for acquisition and control of the gradient. The correlation between the pick-up and the gradient is linear. At the design electrode voltage for $A/q = 3.9$, i.e. 36.4 kV, the corresponding pick-up value is 2300 mV.

For the purpose of solely characterizing the RFQ, all downstream accelerating structures are turned off. The electrostatic and magnetic optical elements of the beam-line (quadrupoles, steerers and solenoids) are kept at constant values deemed optimal for transport efficiency at the nominal RFQ gradient. During the measurements, the repetition rate (pulse per second) was 20 Hz, with a charge-breeding time of 30 ms.

We first present different transmission efficiency curves obtained using Faraday cups at the previously mentioned locations (Figure 2). During each measurement, the accelerating gradient of the structure is varied while acquiring the output beam current. The resulting transmission curves are normalized with the input beam current measured prior to injection into the RFQ (I_{FC} = 50 pA, at location XRFQ). Particles accelerated at a voltage below the design value of the RFQ are lost in the region between XIHS and XLN2. When the RFQ is operated at an electrode voltage above its design value, the energy spread of the beam becomes non-optimum and parts of the beam may be lost.

Measuring the transmission efficiency in the location XT00.1300 allows for a comparison at a complete different beam intensity scale with the large-aperture silicon detector. Operated as a particle-counter, the silicon detector monitors the transmission through the RFQ, probed similarly as a function of its accelerating gradient. This time the input intensity of the $^{39}K^{10+}$ beam is limited to 800 ions/s, which corresponds to 1.2 fA, approximately 6.10^4 less than I_{FC}, the beam intensity when using Faraday cups. In order to reduce the intensity while preserving the the other beam properties, the heating of the local ion source is reduced. By proceeding this way, the conditions of charge-breeding, notably the degree of compensation of the electron beam, are minimally impacted and one may expect comparable
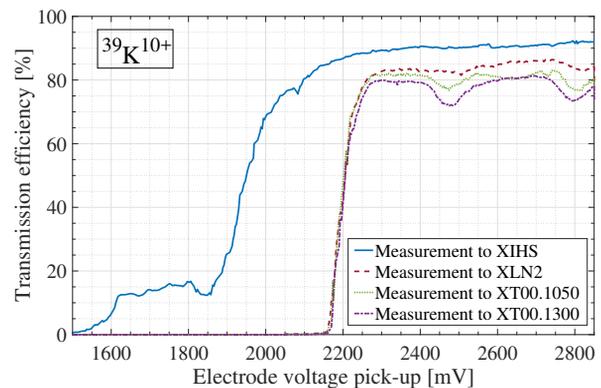

Figure 2: Transmission through the RFQ for $^{39}K^{10+}$ beam, measured in different locations with Faraday cups.

results. Several series of measurements, similar to the one displayed in Figure 3, have corroborated the effectiveness of the method which consists in using the large-aperture silicon detector in XT00.1300. Comparisons in between the two methods were reproduced for different transport tunes and beam-A/q. In the cases where the beam-A/q was changed to different charge-states of $^{39}K^{q+}$ ($A/q = 3.55$ for q = 11 and $A/q = 4.33$ for q = 9) and the transport was purposefully deteriorated to XT00.1300, the results of the two different methods of measurements proved to be consistent.

Scaling linearly the RFQ electrode voltage pick-up from one beam-A/q to another, often yields a few percent shift from the design gradient. When scaling the RFQ to a very low-intensity beam-A/q, one generally uses a more intense pilot beam close in A/q. Traditionally, the RFQ optimal accelerating gradient was tuned for the pilot beam and "blindly" scaled to the very low-intensity beam-A/q. One is now able to tune the RFQ accelerating gradient directly in the sub-fA range of beam intensity. In the purpose of making operational use of this method, a large-aperture silicon detector is planned to be installed in the normal-conducting linac section. The new silicon detector, its preamplifier and digitizer will be specifically calibrated for low-energy beams.

LONGITUDINAL ACCEPTANCE

During the charge-breeding of ions inside the REXEBIS, various heating phenomena contribute to the increase of
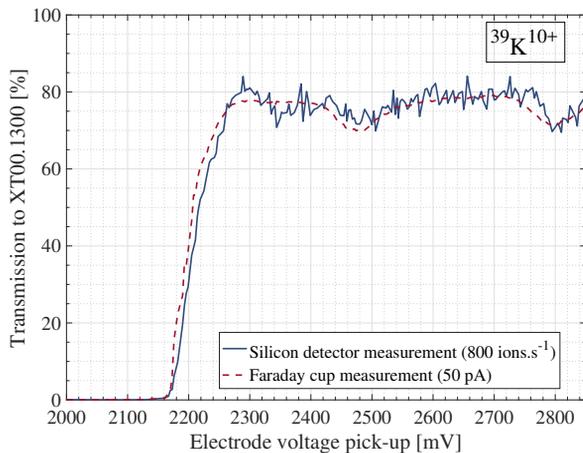
MC4: Hadron Accelerators

A20 Radioactive Ions

Figure 3: Transmission efficiency to XT00.1300 measurements for $^{39}K^{10+}$, using a Faraday cup and a silicon detector.

Figure 4: Measurement of the RFQ longitudinal acceptance and simulations for different transverse emittances [5].

spread in ion energy density distribution. Highly-charged ions are more subject to heating and will show a larger energy spread than low-charged ions. Similarly the transverse emittance of the beam extracted from REXEBIS will grow as the temperature of the ions increases. For highly-charged ions, characterizing the RFQ in terms of longitudinal acceptance becomes necessary to anticipate on potential losses due to large energy spread or transverse emittance.

The REXEBIS resides on a high-voltage platform that defines the input beam-energy into the RFQ. The optimal platform voltage for injection of $^{39}K^{10+}$ beam into the RFQ is $W_0 = 19300$ V. For the measurement of the longitudinal acceptance, the breeding-time is reduced to 20 ms to minimize the energy spread of the beam while maintaining a detectable current using a Faraday cup. The relative input beam energy is then varied via the platform voltage. For each different input energy, the A/q-Separator was scaled to the new energy in order to maximize the transmission efficiency to the XIHS location. The main components from the A/q-Separator that were tuned are an electrostatic 90° cylinder deflector of 0.6 m radius and a 90° magnetic bender of 0.5 m radius. The current measured prior to the RFQ injection, at the location XRFQ, remained constant during the whole scan. An estimate of the uncertainty relative to the measurement of the longitudinal acceptance is given within 5% accuracy (Figure 4). The contributions to the error-bars were not evident to disentangle and essentially are: beam instabilities, instrumentation uncertainties and the A/q-Separator tune.

Finally, the longitudinal acceptance result may be compared to beam dynamics simulations in order to estimate the input transverse emittance of the beam. Beam dynamics studies of the RFQ, using PARMTEQM, have shown the effect of the input transverse emittance on the resulting longitudinal acceptance [4] [5]. In the Figure 4, two of the beam dynamics simulation results are exploited. Both right and left lobe are present in the simulations and the measurement. The central region between the lobes is very similar for the measurement and the simulation with an input normalized rms transverse emittance of 0.08 mm.mrad. A more adapted
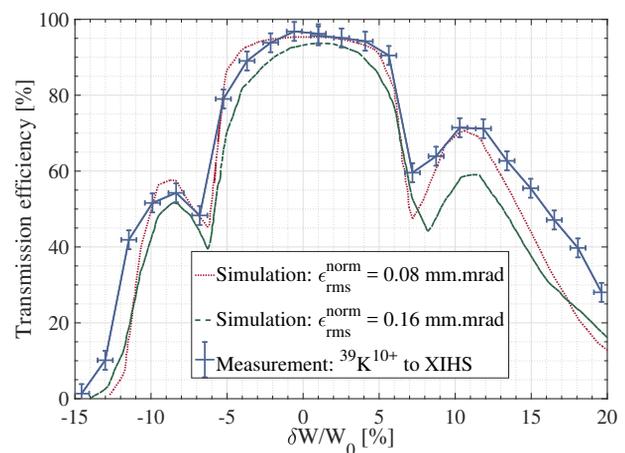
use of the PARMTEQM simulations will be described in a future contribution. The comparison between the displayed simulations and the experimental result here only serves as a demonstration of feasibility rather than a precise statement about the input transverse emittance.

CONCLUSION AND PERSPECTIVES

Transmission efficiency measurements at different locations of the REX/HIE-ISOLDE beam-line are shown, as a function of the RFQ accelerating gradient. A new method reproduces transmission efficiency measurements for beam intensity in the sub-fA range. The use of a silicon detector proves to be particularly interesting for precise tune of the RFQ gradient with beams undetectable by a Faraday cup. The RFQ longitudinal acceptances was measured and shows a relative agreement with simulations that are promising for future input transverse emittance deductions. With the addition of a silicon detector in the XIHS location, the RFQ will be further characterized.

REFERENCES

[1] H. Bongers *et al.*, "Test of the REX-RFQ and Status of the Front Part of the REX-Isolde Linac", in *Proc. 18th Particle Accelerator Conf. (PAC'99)*, New York, NY, USA, Mar. 1999, paper FRA58.

[2] T. Sieber *et al.*, "Design and Status of the RFQ for REX-ISOLDE", in *Proc. 19th Int. Linac Conf. (LINAC'98)*, Chicago, IL, USA, Aug. 1998, paper TH4006.

[3] F. Zocca *et al.*, "Development of a silicon detector monitor for the HIE-ISOLDE superconducting upgrade of the REX-ISOLDE heavy-ion linac", *Nucl. Instr. Meth. Phys. Res. A*, Vol. 672, pp. 21-28, Apr. 2012.

[4] M. A. Fraser, "Beam Dynamics Studies of the ISOLDE Post-accelerator for the High Intensity and Energy Upgrade", *CERN-THESIS-2012-006*, http://cds.cern.ch/record/1423610, University of Manchester, Presented 26 Jan. 2012.

[5] M.A. Fraser and F. Wenander, "Study of Effect of Ion Source Energy Spread on RFQ Beam Dynamics at REX-ISOLDE", *CERN-HIE-PROJECT-Note-0018*, Dec. 2012.