COMMISSIONING RESULTS OF THE REA RFQ AT MSU*

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Abstract

The Facility for Rare Isotope Beams (FRIB) is currently in the preliminary design phase at Michigan State University (MSU). FRIB consists of a driver LINAC for the acceleration of heavy ion beams, followed by a fragmentation target station and a ReAccelerator facility (ReA3). ReA3 comprises gas stopper systems, an Electron Beam Ion Trap (EBIT) charge state booster, a room temperature radio frequency quadrupole (RFQ), a LINAC using superconducting quarter wave resonators and an achromatic beam transport and distribution line to the new experimental area. Beams from ReA3 will range from 3 MeV/u for heavy ions to about 6 MeV/u for light ions.

The ReA3 RFQ, which is of the 4 rod type, is designed to accelerate ions with an Q/A of 0.2 to 0.5 from 12 keV/u to 600 keV/u. The RFQ operates at a frequency of 80.5 MHz and power levels up to 120 kW at 10% duty factor. In this paper we will report on commissioning results from the ReA3 RFQ using H_2^+ and He^+ beam from an auxiliary ion source.

INTRODUCTION

Nuclear science research requires reaccelerated beams in a range of kinetic energies from thermal to near 20 MeV/u. The combination of a gas stopper with a re-accelerator to is of particular importance, since it provides high quality beams of rare isotopes for nuclear research. At the Coupled Cyclotron Facility (CCF) at MSU the first stage of such a ReAccelerator facility (RεA) is currently under construction [1,2]. It will be connected to the NSCL gas stopping area at the end of 2012 to provide reaccelerated rare isotope beams produced by the CCF. Once the Facility for Rare Isotope Beams (FRIB) is completed RεA will serve as its rare isotope post accelerator.

The first stage of the accelerator (ReA3) will be capable of accelerating ions with a charge-to-mass ratio Q/A=0.25 from 300 keV/u to 3 MeV/u and for Q/A=0.5 from 300keV/u to 6 MeV/u. The accelerator consists of an EBIT charge breeder, an off-line stable ion beam injector, a multi harmonic buncher, a room temperature RFQ and fifteen superconducting cavities. Figure 1 shows an overview of the facility. The last of the three cryomodules with a beta equal to 0.085 is still under development. The cryomodule is expected to be installed in July of 2012, after which the installation will be completed.

This paper focuses on the room temperature RFQ that was developed in collaboration with the Goethe-University in Frankfurt, Germany and manufactured at Kress GmbH, Germany. The RFQ was delivered in May of 2010 and testing started in the summer of 2010.

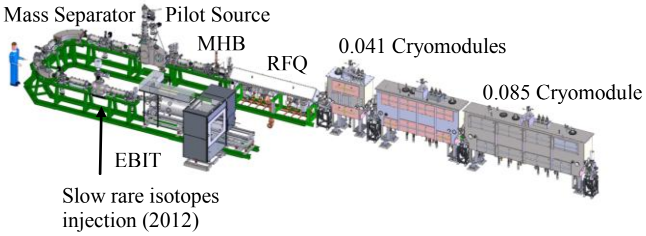

Figure 1: Overview of the ReA3 facility currently under commissioning at MSU.

LEBT

A compact vertical injector using a small external filament ion source was used to provide beam intensities between 300 and 2000 picoA of He^+ and H_2^+ ion beams. The beam gets mass analyzed in a compact velocity filter at 3 keV total beam energy and is then accelerated through a second DC accelerating gap to the nominal RFQ injection energy of 12keV/u. Several diagnostics stations in the Low Energy Beam Transport (LEBT) section are available to measure the ion beam properties of the beam before the RFQ.

The nuclear physics experiments require a beam on target with an energy spread of ~1 keV/u and a bunch length of ~1 ns. Therefore, a longitudinal beam emittance of less than 0.3π ns keV/u is needed from ReA3. This requirement makes the use of an external multi harmonic buncher (MHB) necessary. The MHB uses three harmonics of the base frequency of 80.5 MHz and consists of two coaxial resonators with a single gridded gap and 50 mm drift tube diameter. The transmission through the two grids is about 95% [3].

The bunches are observed about 60 cmdownstream of the buncher using a timing wire detector based on a similar device developed at the ISAC facility in TRIUMF[4]. It

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consists of a wire biased to -2kV and a Multi Channel Plate (MCP) detector. The secondary electrons produced by the beam on the timing wire are accelerated to the MCP and measured in coincidence with the fundamental RF frequency of 80.5 MHz. The time resolution of the detector is better than 0.2 nsec and it can measure currents down to a few pA. Figure 2 shows an example of the bunch structure at the entrance of the RFQ (left figure) and the exit of the RFQ (right figure).

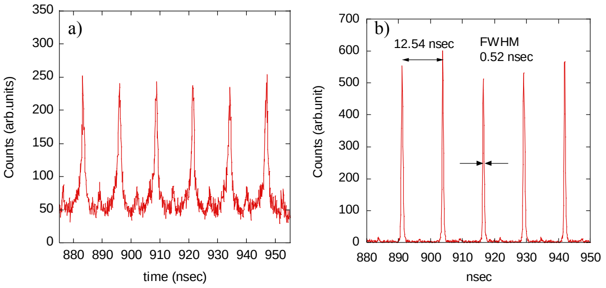

Figure 2: 80.5 MHz bunch structure at the entrance of the RFQ (a) and the exit of the RFQ (b)

RFQ DESIGN

The 3.3 m long 4-rod RFQ accelerates the beam from 12keV/u to 600keV/u. Since the beam enters the RFQ already bunched, the cell design can be optimized for high acceleration efficiency, while maintaining the small longitudinal emittance of the core beam. The detail design [5] and initial tuning parameters of the RεA RFQ [6] can be found in Table 1 which summarizes the main parameters.

Table 1: Characteristics of the ReA3-RFQ

Parameter	**Value**
resonance frequency	80.5 MHz
Rp value, shunt impedance	200 kΩm
input → output energy	12 keV/u → 600 keV/u
operating range Q/A	0.2 to 0.5
nominal intervane voltage	86.5 kV (Q/A=0.2)
fixed tuning plates	17
moveable tuners	2
Tuning range	300 kHz
peak electric field	16.7 MV/m
maximum power	160 kW
transverse acceptance	1 π·mm mrad (1 rms, norm.)
base pressure	$3\cdot10^{-8}$ Torr
longitudinal acceptance	1 π·keV/u ns
modulation factor	1.15 → 2.6
number of cells	94
mid-cell aperture	7.3 mm
synchronous phase	-20 degree
vane tip transverse radius	6 mm

Figure 3 shows a picture of the RεA RFQ. A synchronous phase of -20 degrees and a modulation factor of 1.15, which increases to 2.6 along the length of the RFQ rods, were chosen in the design to maximize the acceleration efficiency while maintaining a good longitudinal emittance. A nominal intervane voltage of 86.2 kV is required to accelerate ions with *Q/A*=0.2, which generate an electric peak field of 1.6 times the Kilpatrick limit. Together with the external MHB in the LEBT, the ReA3 RFQ should achieve an 82% beam transmission. The beam losses occur longitudinally and are caused by the tails of the bunch distribution outside the longitudinal acceptance. Transverse 100% transmission is observed in the parmteq simulation [5].

Figure 3: RεA RFQ during the final installation

RFQ COMMISSIONING EXPERIENCE

Field Flatness

After the RFQ was installed at MSU, the field flatness was readjusted to better than ±1.5% using the fixed tuning plates. The shunt impedance of 200 kΩm and the inter electrode voltage in dependence of RF power was independently verified using x-ray end point measurements. Figure 4 shows the results of the x-ray measurements.

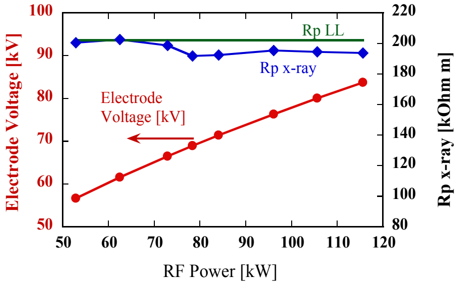

Figure 4: X-ray endpoint calibration of the inter electrode voltages and verification of the nominal shunt impedance.

CW Tests

During the acceptance tests the RFQ was conditioned in pulsed as well as CW mode. While the RFQ was able to reliably reach the required electrode voltage after a few weeks in pulsed mode at 10% duty cycle (average power of 30 to 40 kW) heating was observed on the outside aluminium tank and several feedthroughs. A ΔT of about 16 degree C was observed for 36 kW CW equivalent power level. To operate the RFQ at the required 160 kW CW power level, additional cooling on the outside housing will likely be required. Inspection of the structure also showed signs of heating on the plunge-able tuner and the power coupler. In addition, we observed the failure of some of the silver contacts on the fixed tuner plates, which caused failure of a stem o-ring due to excessive rf heating. Finally, several screws used to mount grounding clamps between the stems and the electrode cooling lines melted and needed to be replaced. Based on the experience gained in the high power tests, upgrades are being designed to enhance cooling and electrical contacts to improve the reliability of the components. These upgrades are in progress and high power tests are planned for later this summer. Until these upgrades are completed beam commissioning will proceed with 10-15% duty factor for heavier beams and CW for lighter beams.

FIRST BEAM TESTS

Helium and H_2 Beam Commissioning

The ion beam delivered from the off-line filament ion source has an emittance of 0.1 to 0.2 π mm mrad rms normalized, which is 3 to 5 times smaller than the transverse acceptance of the RFQ. Therefore, almost 100% beam transmission can be achieved to the Faraday cup after the RFQ. In addition, the Parmteq modelling shows that all the losses in the RFQ are longitudinal. The non-accelerated, low energy particles can be transported through the RFQ. Since there is no dipole magnet between the RFQ and the first SRF cavity module, it can be challenging to optimize the accelerated beam portion at this location. Therefore, the beam was drifted through the first rebuncher cryomodule and the magnetic dipole-correctors in the first cryomodule were used to deflect the non accelerated (low energy) beam component of the beam. A foil-silicon detector [4] was used to analyze the energy of the beam. The beam is scattered at a thin gold foil towards a silicon detector. The amount of charge produced by the ion beam in the detector is linearly proportional to the energy of the incoming particle. To calibrate the detector a ^{241}Am 5.5 MeV alpha source is placed off-axis into the diagnostic vacuum chamber.

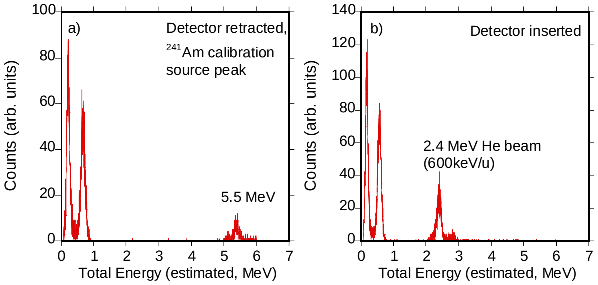

Figure 5: Measurement of the ion beam energy using a foil-silicon detector. Figure 5a) shows the spectrum of the 5.5 MeV calibration source and figure 5b) shows the signal if the detector is placed into the ion beam.

Figure 5 shows the energy spectrum when the detector is retracted from the beam axis and when it intercepts the accelerated beam. Using an α calibration source energy, a preliminary beam energy calibration as indicated in figure 5 has been performed. This energy calibration needs to be confirmed with a time of flight measurement. Once the experimental beam line is completed (end of 2011) a dipole magnet will be available for independent confirmation. The ion-beam current measured in the Faraday cup behind the first cryomodule as a function of the RFQ power is shown in Figure 7 for a H_2^+ beam.

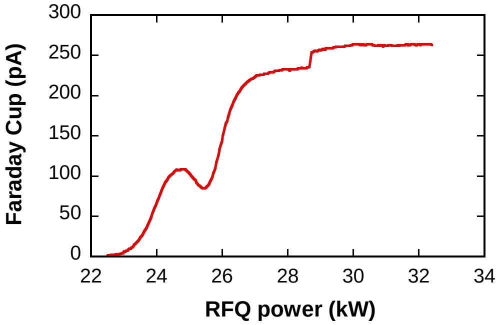

Figure 7: Measured ion beam intensity in dependence of the RFQ power.

As expected, a sharp rise in ion beam transmission is observed once the RFQ reaches the required acceleration gradient (which for H_2^+ is reached at approx. 30 kW power)In these initial tests close to 82% of the beam was captured by the RFQ, which matched the theoretical expected transmission of the RFQ. The beam profile was measured using the combination of two 45 degree slits and a Faraday cup. As expected, the beam diameter was a few millimeters and no steering effects of the RFQ in dependence of the electrode voltages was found once the RFQ accelerating gradient was reached. However, the required power of 30 kW for optimum transmission was 30% higher than expected, a fact that needs to be further investigated. The beam commissioning will continue in the next months to measure the beam properties and optimize the longitudinal emittance of the ion beam.

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