STATUS OF THE REACCELERATOR FACILITY REA FOR RARE ISOTOPES BEAM RESEARCH*

Daniela Leitner, Chris Compton, Alberto Facco[*], Matt Hodek, Alain Lapierre, Sam Nash, Dan Morris, Georgios Perdikakis, John Popielarski, Nathan Usher, Walter Wittmer, Q. Zhao, X. Wu, Facility for Rare Isotope Beams (FRIB) and NSCL, Michigan State University, East Lansing, MI 48824 USA
[*]On sabbatical leave from INFN-Laboratori Nazionali di Legnaro, I-35020 Legnaro, Padova, Italy

Abstract

The Facility for Rare Isotope Beams (FRIB) at Michigan State University (MSU) is currently in the preliminary design phase. FRIB consists of a heavy ion driver LINAC, followed by a fragmentation target station, a fragment separator, a fast beam experimental area, a gas stopping area, a stopped beam experimental area and a ReAccelerator facility (RεA). In its final configuration, RεA will provide heavy ion beams from 0.3 MeV/u to 12 MeV/u for heaviest ions and up to 20 MeV/u for light ions. While FRIB plans to start conventional construction in 2012, the first stage of RεA is already under commissioning and will be connected to the Coupled Cyclotron Facility at MSU end of 2012. The front end of the accelerator consists of a gas stopper, an Electron Beam Ion Trap (EBIT) charge state booster, a room temperature RFQ, followed by a short SRF LINAC, which contains seven β=0.041, eight β=0.085 QWR cavities, and eight 9T focusing solenoids. RεA serves as prototyping test bed for the FRIB cryomodule development since FRIB utilizes similar cavities as installed on RεA. An overview and status of the RεA facility will be presented. The paper will focus on the testing, beam commissioning, and operational experience of the first β=0.041 cryomodules.

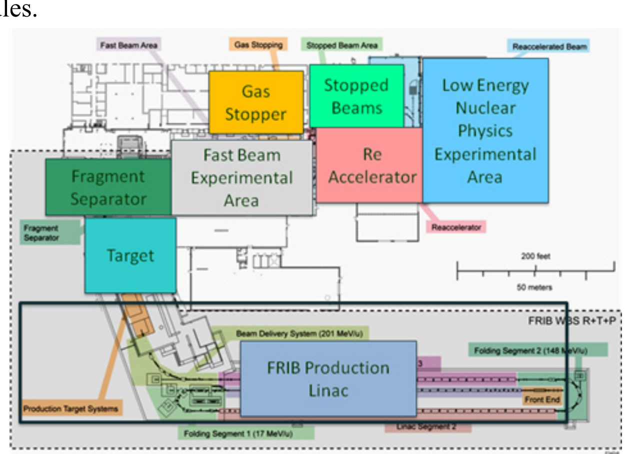

Figure 1: Concept of the facility for Rare Isotope Research (FRIB) at MSU.

INTRODUCTION

Nuclear science research requires reaccelerated radioactive isotope ion beams in a range of kinetic energies from thermal to near 20 MeV/u. The combination of a gas stopper with a re-accelerator is of particular importance, since it provides high quality beams of rare isotopes for nuclear research.

The proposed Facility for Rare Isotope Beams (FRIB) at Michigan State University (MSU) is designed to provide these nuclear physics research tools (see figure 1). FRIB consists of a heavy ion driver LINAC, followed by a fragmentation target station, a fragment separator, a fast beam experimental area, a gas stopping area, a stopped beam experimental area and a ReAccelerator facility (RεA).

While FRIB plans to start conventional construction in 2012, the first stage of RεA (ReA3) is already under commissioning. Therefore, one important role of ReA is to serve as a prototype for the FRIB linac to develop hardware, controls, and gaining commissioning and technical experience in operating a superconducting linac facility. However, the main mission for ReA3 [5,6] in the next few years is to connect to the Coupled Cyclotron Facility (CCF) at MSU to provide reaccelerated rare isotope beams produced by the CCF. Figure 2 shows an overview of the ReA3 facility. 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 300 keV/u to 6 MeV/u. The accelerator consists of an Electron Beam Ion Trap (EBIT) charge breeder, an off-line stable ion beam injector, a multi harmonic buncher, a room temperature RFQ and a buncher cryomodule (CM) and two low beta cryomodules with a total of fifteen superconducting cavities. The last of the three cryomodules with a beta equal to 0.085 is still under development and is expected to be installed in July of 2012, after which the installation will be completed.

In its final configuration RεA will consist of three buncher cryomodules, one β_o=0.041cryomodule and four β_o=0.085 cryomodules with a total of 41 superconducting quarter wave cavities (funding proposal submitted). In this configuration, RεA will provide heavy ion beams from 0.3 MeV/u to 12 MeV/u for heaviest ions and from 0.3 MeV/u up to 20 MeV/u for light ions.

This paper focuses on the commissioning and first beam experiments with the superconducting LINAC.

REA INJECTOR AND FRONT END

The front end system consists of two injectors. A compact vertical off line pilot beam injector (currently a small external filament ion source) provides singly charged He^+ and H_2^+ ions for commissioning and pre-tuning of the LINAC.

*leitnerd@nscl.msu.edu
Project funded by Michigan State University

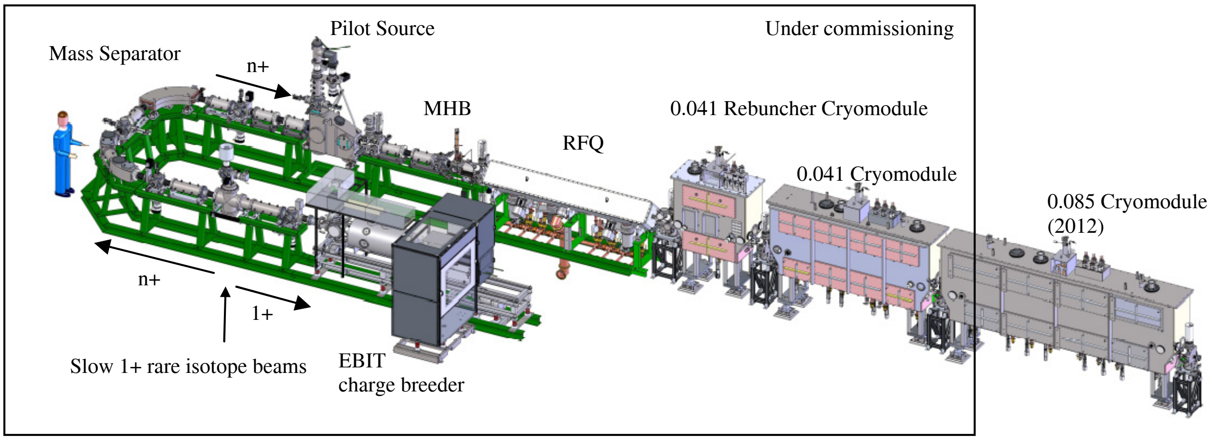

Figure 2: Overview of the ReA3 facility. The devices inside the rectangular are currently under commissioning at MSU[5].

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. An electrostatic bender guides the beam into the LEBT section. For the rare isotope injector an Electron Beam Ion Trap (EBIT) charge breeder is used. The rare isotopes are delivered from the gas stopper to the EBIT charge breeder [9] where the ions are crossed with an intense, focused electron beam, trapped, and further ionized by electron impact ionization.

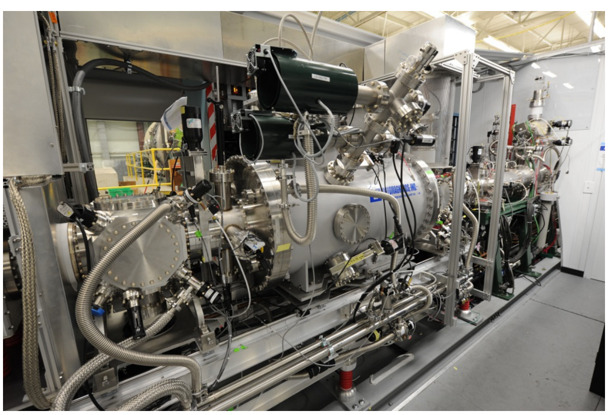

Figure 3: The RεA EBIT charge breeder after its final installation in December of 2010

Once the ions have reached an optimum charge state (typically after a few ms) the trap voltage is lowered and the ions are extracted.

After the charge breeder the extracted highly charged ions are mass separated in an achromatic bend section consisting of an electrostatic bender and a dipole magnet [5]. The section is followed by a short Low Energy Beam Transport (LEBT) line. Several diagnostics stations in these two sections are available to measure the ion beam properties of the beam before injecting into 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 RεA. 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 (80.5 Mhz, 161 MHz, and 241.5 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%[8].

The bunches are observed about 60 cm downstream of the buncher just before the entrance into the RFQ using a timing wire detector based on a similar device developed at the ISAC facility in TRIUMF[10]. The timing wire 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 4 shows an example of the bunch structure at the entrance of the RFQ (left figure) and the exit of the RFQ (right figure).

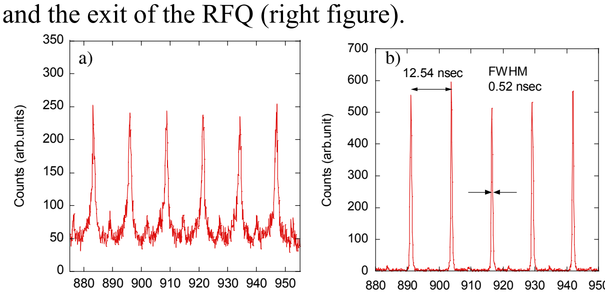

Figure 4: 80.5 MHz bunch structure (a) at the entrance of the RFQ and (b) at the exit of the RFQ

The 3.3 m long 4-rod RFQ accelerates (Figure 5) the beam from 12keV/u to 600keV/u [8,2,1]. Since the beam enters the RFQ already bunched, the cell design was optimized for high acceleration efficiency, while maintaining the small longitudinal emittance of the core beam. The detail design [7] and initial tuning parameters of the RεA RFQ [2] as well as commissioning results can be found in [1]. In these initial tests close to 82% of the beam was captured and accelerated by the RFQ, which matches the theoretical expected transmission of the RFQ [7]. The LEBT and RFQ area is installed in a class 1000 clean room to protect the adjacent SRF cryomodules.

Figure 5: RεA RFQ during the final installation.

SRF LINAC

The first cryomodule (rebuncher) [12,11] contains a single cavity (beta equals 0.041) and two 9T superconducting solenoid magnets with integrated steering dipoles. The magnetic shielding consists of reverse wound coils at the ends of the solenoid, a Meissner shield (Nb can) around the solenoid, and μ metal shields around the Meissner shield and the cavity. The second β_o=0.041 cryomodule consists of six quarter wave cavities and three superconducting 9T solenoids with integrated steering dipoles. The magnetic shielding consists of reverse wound coils in combination with a steel yoke. Cryogenic Ti rail systems are used for support and alignment.

Cryomodule two was installed during the summer of 2010 and commissioned without beam in early 2011 [3]. Since the installation the cavity alignment was checked several times before and after thermal cycles and excellent repeatability of the cavity position after thermo cycling was confirmed. Since the cavities are not heat treated, care is taken during the cool down cycles to go through the critical temperature between 150K to 30 K in less 30 minutes for each cavity [10]. The measured static heat load is about 8W ± 1 W for the rebuncher module and about 14 W ± 1 W for cryomodule 2. The dynamic load was measured to be approximately 1 W per cavity at nominal ReA accelerating gradients. Figure 6 shows the model of the 0.041 cryomodule and the coldmass during assembly. The cavities and the cryomodule design are described in detail in [11] and referenced papers within.

Cryomodule 3 contains eight cavities with a beta equals 0.085 and three 9T solenoids identical to the ones of cryomodule 1. The cold mass assembly has been delayed as more R&D was required to optimize the performance of the 0.085 QWR and ensure reliable performance according to specification. The testing program and development of the final ReA 0.085 cavity design are described in detail in [4]. In the recent cavity tests the 0.085 prototype cavities exceeded the requirements of ReA and FRIB in terms of Q_0 and the electrical peak field by a comfortable margin [4]. After fabrication of the cavities is finished, the assembly of the coldmass is planned for early 2012 and the final installation at ReA is planned for July of 2012. Table 1 contains a summary of the cavity specification for all three cryomodules.

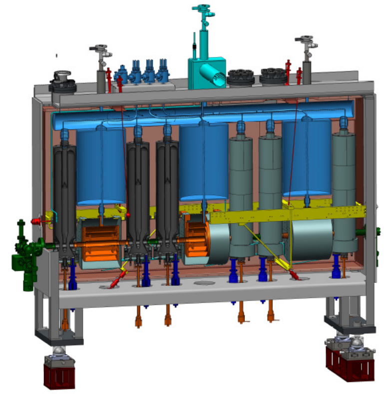

Figure 6: The 0.041 coldmass assembly in the MSU cleanroom.

Every cavity is individually phased and powered to ensure maximum flexibility in terms of final beam energy. For the β_o=0.041cavities 1 kW amplifiers are used, for the β_o=0.085 cavities 2 kW amplifiers will be used.

Table1: Quarter wave resonators parameters for ReA.

Type	λ/4	λ/4
β_{opt}	0.041	0.085
f (MHz)	80.5	80.5
V_a (MV)	0.445	1.03
E_p (MV/m)	16.5	20
B_p (mT)	29	45
R/Q (Ω)	433	408
G (Ω)	15	18
Bandwidth (Hz)	77-88*	90
Design Q_0	5×10^8	5×10^8
Aperture (mm)	30	30
T (K)	4.5	4.5
Rf Amplifier power [kW]	1	2

*measured

OPERATING EXPERIENCE

During the commissioning tests with and without beams the cavities were extensively tested at electric peak field gradients from 16 to 20 MV/m (ReA3 specifications are 16.5MV/m) during 24/7 operation periods. Some cavities were also tested above FRIB field specifications for shorter periods of time. The β_o=0.041 cavities are driven by 1 kW amplifier, which can support operation up to FRIB fields, but for higher field tests a tuneable matching circuit is required. To fully characterize the cavity performance in terms of Q and maximum field gradient inside the cryomodule, rf measurements were performed using a detuning circuit to match the input of the cavity to the RF system. All cavities exceeded FRIB gradients specification with 3 cavities exceeding 50MV/m peak fields[3]. Four cavities exceeded the Q_0 requirement. In the remaining two non linear losses (most likely associated with the power coupler) were observed in the measurements that and only a upper limit for the Q_0 could be determined. This will be further investigated in the near future [3].

One of the early concerns with the ReA3 linac was the location of the cryomodules on a concrete platform. Vibration measurements confirmed that the vibrations on the platform are about 10 times higher than on ground level (400 nM versus 40 nm). However, the bandwidth and the low level control have been shown to be adequate to keep the cavities locked within specifications (see figure 7). As an example, Figure 7 shows the phase and amplitude stability of the six resonators at the nominal ReA peak electric field gradients of 16MV/m. For easy comparison, the phase data were normalized to the control set-value (except for the resonator number 4 that was normalized to the mean value, which was 1 degree higher than the set-value for the phase for this resonator). The measured stability data lie well within the FRIB/ReA requirements of amplitude stabilities of 0.25% RMS, peak to peak amplitude stability of ±1%, and the phase stability of 0.25 degree RMS, and ±1degree peak to peak.

Higher field data were taken with various electrical peak field cavity settings from 18 – 32 MV/m (two cavities operated at FRIB fields). The short term measurements at 32MV/m indicated adequate stability even at these high fields, but more experience and statistics will be necessary to allow for long term 24/7 operation at these field levels. At higher fields some cavities exhibit a slow rise in the vacuum level measured at the power couplers. The reasons for the pressure rise needs to be further investigated but is most likely related to heating and outgassing issues in the power coupler.

Issues which were encountered during long term operations included drop outs due to external interlocks (eg vacuum transients). These are being understood and are being taken care of by the control system. In addition several power supply failures were experienced during the initial operation period.

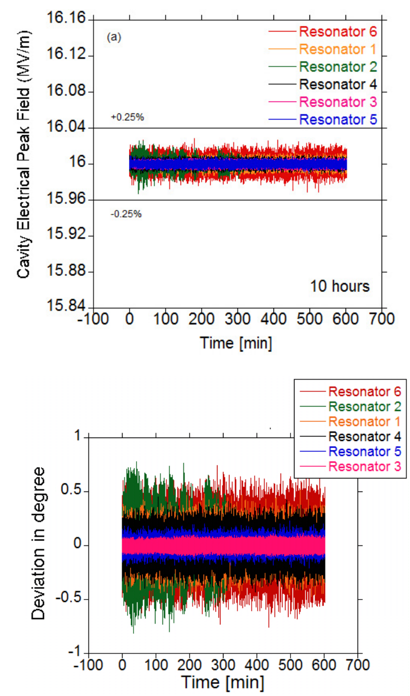

Figure 7: 10 hour data set at an electrical peak field of 16MV/m (nominal ReA settings). The vertical scales are sized to the peak to peak stability requirements for FRIB and ReA. As a reference the ±.25% lines have been added to the amplitude stability data.

FIRST BEAM TESTS

Helium and H_2 Beam Commissioning

A foil-silicon detector [10] is used to analyze the energy of the beam. The beam is scattered at a thin gold foil (0.06 microns) towards a silicon detector, mounted at 30 degrees. A schematic of the detector is shown in figure 8.

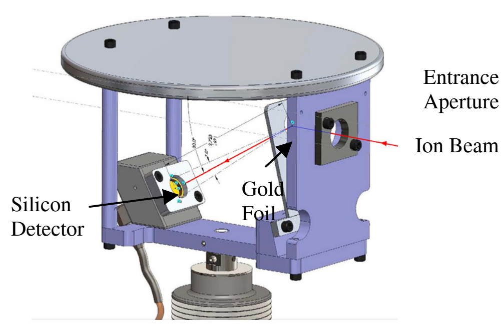

Figure 8: Schematic of the foil-silicon detector.

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, 5.486 MeV alpha source is placed off-axis into the diagnostic vacuum chamber. By using the spectrum observed when the beam is accelerated with the RFQ only (output energy of 600keV/u) together with the spectra observed from the

^{241}Am calibration source, an absolute energy calibration can be performed.

First ion beam acceleration with the RFQ was achieved in February of 2011 using helium (Q/A of .25) and hydrogen molecular ions (Q/A of .5). As an example figure 9 shows the beam intensity after the beam was drifted through cryomodule one (rebuncher) for H_2^+. 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 approximately 30 kW RFQ input 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.

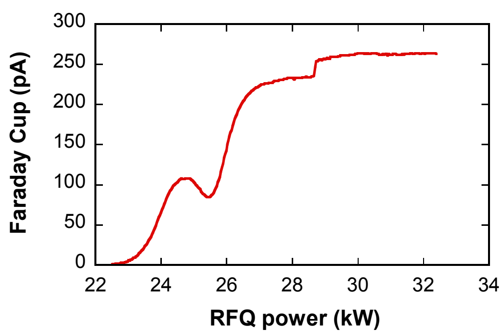

Figure 9: Measured ion beam intensity in dependence of the RFQ power.

Once acceleration of the beam with the RFQ was confirmed the beam was further transported through the first LINAC section. As a first step a phase scan of the rebuncher was performed and the rebuncher was set to maximum bunching at zero crossing at 90 degrees. The zero crossing was confirmed by verifying that the beam energy is unchanged when the amplitude of the cavity is increased. Next a phase scan for all SRF cavities was performed. As an example a phase scan of the cavity number 6 is shown in figure 10.

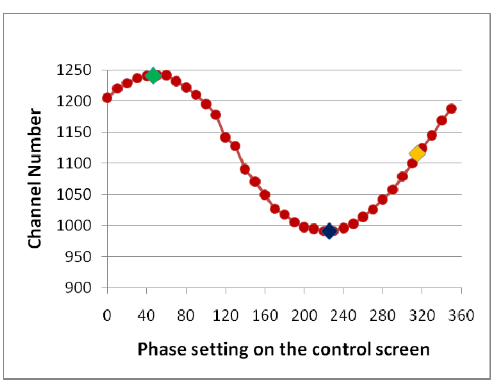

Fig. 10: Phase measurement of SRF cavity L091 (number 6) in cryomodule 2. The three points indicate zero crossing on the phase focusing phase part (maximum rebunching, yellow symbol) and maximum acceleration (green symbol) and maximum deceleration (blue symbol).

With the buncher at zero crossing and all six cavity phased close to the peak acceleration field, a He^+ beam was accelerated through the first cryomodule and the energy gain measured for each additional cavity. Figure 11 shows the energy spectrum of the accelerated beam using only the RFQ together with the spectrum obtained when one cavity after the other is turned on and phased for acceleration at nominal ReA3 gradients (Va=.432MV). Each cavity shifts the energy by about .53MeV (which is higher than expected from the rf calibration). The acceleration voltage of the cavities was chosen such that the final beam energy coincides with the energy of calibration source making the determination of the beam energy explicit.

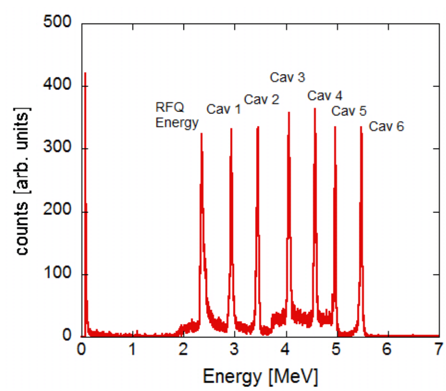

Figure 11: Energy spectra measured with the silicon detector. By turning on one cavity at a time a final energy of 5.486 MeV (1.38MeV/u) was reached.

In addition, the beam energy was measured as a function of acceleration gradient for all cavities. As an example figure 12 shows the energy spectra of the He^+ ion beam measured with the foil silicon detector for cavity L088 in cryomodule 2 with increasing electric field peak gradients. The accelerating gradient was increased in even steps by increasing the electric peak field (control variable set in the control panel) from 2MV/m to 16 MV/m. For cavity L091 a beam energy calibration from 2MV/m to 35 MV/m was performed.

Preliminary analysis of the energy gain shows a linear behavior in dependence of the gradient as expected. For the different resonators energy gains deviated between -5% and +17% from the expected values of the rf calibration. The calibration will be refined in the next operational period.

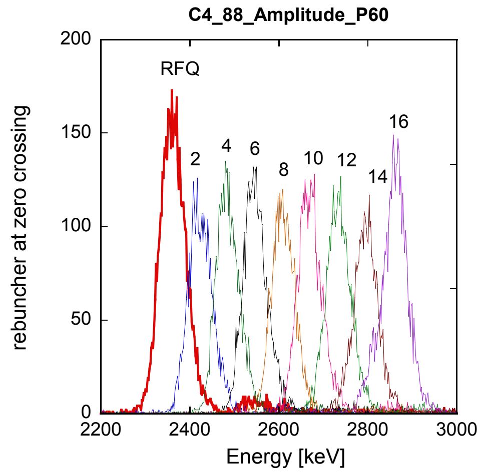

Figure 12 Energy spectra of the He^{+} ion beam measured with the foil silicon detector for cavity L088 in cryomodule with increasing electric field peak gradients.

EBIT Beam Commissioning

At the end of the last operational period a high charge state neon ion beam was produced with the EBIT ion source. For this purpose, neon gas was injected using the gas jet available at the EBIT source. 14.4keV electron energy was used in these tests, and the trapping time was about 250ms. Once the EBIT was optimized, a Ne^{8+} was further transported through the ReA LEBT and accelerated through the ReA linac. This milestone marks the first time that the ReA accelerator system and the EBIT charge breeder have worked as a coupled unit.

OUTLOOK

Commissioning efforts will resume in the next months after a scheduled shutdown to upgrade the power capability of the RFQ. Procurement plans are made for the cryomodule 4 to further increase the energy to 6 MeV for the heaviest ions. In parallel the design of the experimental area beam lines and layout of the experimental halls are in progress. The next milestone will be the delivery of beam at the entrance to the ReA3 experimental system (November 2011) and the installation of cryomodule 3 in July of 2012.

ACKNOWLEDGMENT

The authors would like to acknowledge the colleagues at NSCL for the tremendous effort required to design, build, process, and test the ReA3 QWR's and cryomodules as the design team continues to incorporate changes that will not only increase the reliability of the ReA3 project, but will also serve to reinforce technology being developed for FRIB

The authors and the FRIB project thanks members of technical review teams that have provided feedback on this development effort and especially appreciate the invaluable contributions from collaborators in a weekly SRF teleconference: Curtis Crawford, Walter Hartung, Peter Kneisel, and Bob Laxdal.

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