RESULTS FROM THE LINAC COMMISSIONING OF THE RARE ISOTOPE REACCELERATOR - ReA*

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Abstract

ReA [1] is a radioactive ion beams post accelerator currently being completed at the National Superconducting Cyclotron Laboratory at Michigan State University. ReA is designed to reaccelerate rare isotopes to energies of a few MeV/u following production by projectile fragmentation and thermalization in a gas cell. The facility consists of five main components: an electron beam ion trap (EBIT) charge breeder, an achromatic charge over mass separator, a radiofrequency quadrupole (RFQ) accelerator, a superconducting radio frequency linear accelerator (SRF LINAC) and a transport line into the experimental hall. The first sections up to the SRF LINAC of ReA have been commissioned in the last two years using an offline stable ion beam source and heavy ion beams from the EBIT charge breeder. The final section, transporting beam from the LINAC into the experimental hall, was completed and commissioned this summer. This paper presents the results of the SRF cryo module characterization and the progress of the machine optics model.

INTRODUCTION

The Facility for Rare Isotope Beams (FRIB)[2], a 400kW superconducting heavy-ion driver LINAC, will produce beams of exotic nuclear species with increased intensity of up to three orders of magnitude more than the CCF after fast fragmentation. ReA will reaccelerate these beams with improved characteristics for experiments. Initially the energy of the Rare Isotope Beams (RIBs) will be 3 MeV/u with future upgrades reaching 12 MeV/u. Currently ReA is coupled to the Coupled Cyclotron Facility (CCF) at the National Superconducting Cyclotron Lab (NSCL) at Michigan State University and provides beam of up to 2.4 MeV/u.

Stable beams are accelerated to energies of approx. 100 MeV/u by the CCF and fragmented on a solid target. The secondary beam, comprised of a melange of fragments, is separated achromatically in the A1900 fragment separator. The selected isotope is then thermalized in a He gas cell and extracted at energies up to 60 keV. Following mass selection at a dipole magnet the beam is injected into the Electron Beam Ion Trap (EBIT) where it is charge bred. The beam is then extracted at 12keV/u (RFQ injection energy) and transported through a Q/A achromatic charge-over-mass separator for charge selection and accelerated in the LINAC. The initial acceleration occurs in a four rod RFQ to an energy of 600 keV/u. The beam is then rebunched in a rebunching module with a single quarter wave cavity ($\beta = 0.041$) followed by an accelerating module containing six cavities of the same type. Next, the beam is delivered into the experimental hall. The final accelerating cryo module, comprised of 8 quarter wave cavities ($\beta = 0.085$), is currently in construction and will complete the initial ReA3 installation next year.

The commissioning of the current installation of the reaccelerator has been successfully completed following a commissioning experiment where a ^{37}K ($T_{\frac{1}{2}} = 1.23$s) beam was delivered to the ANASEN [3] detector.

SRF LINAC

The first rebunching module comprises a single quarter wave cavity ($\beta = 0.041$) and two superconducting 9 Tesla solenoids with integrated steering magnets. The second accelerating module houses 6 cavities and 3 solenoids of the same type. Both modules are shown in Figure 1.

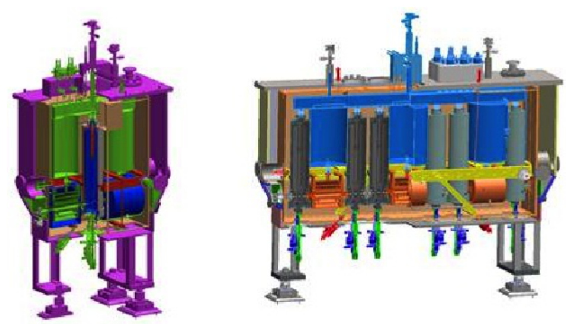

Figure 1: On the left the rebunching cryo module is shown with its cavity at the center between the solenoids. The right shows the first accelerating module with one cavity at each end and groups of two separated by the three solenoids.

Dipole Calibration and Energy Spread Measurement with CAESAR Detector

An experimental setup consisting of an Aluminum target inside the high-efficiency CsI(Na) scintillator array (CAESAR) [4] was used to obtain an energy calibration of a bend magnet, located after the second accelerating module, to measure the beam energy spread and to test the performance of the LINAC.

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Preliminary analysis of the measurement data show good agreement of the derived energy spread and the predicted from the machine model as well as for the beam energy. A detailed analysis is ongoing an will soon be published.

Beam Based Cavity Amplitude Calibration

The initial calibration of the cavity amplitude was based on measurements performed in the SRF test dewar. It was soon noticed that the error of this calibration exceeded 10% and the calibration was repeated with beam based measurements. Two sets of measurements were performed. The first utilized a foil silicon detector where the beam is scattered through a gold foil to reduce the beam intensity and then the energy is measured with a silicon detector. The energy loss due to scattering has to be taken into account. The cavity phase is varied over 360 degrees and the beam energy is measured as shown in Figure 2. After calibrating

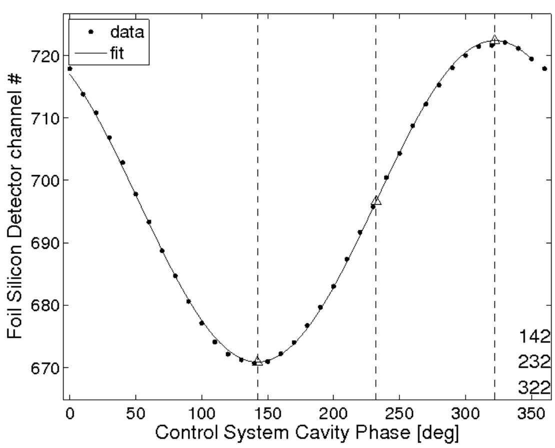

Figure 2: SRF cavity phase scan measured with a foil silicon detector. The dots represent the measured data, the line the fitted curve and the triangles with dashed lines, the location of maximum deceleration, zero crossing for the bunching slope and maximum acceleration.

the detector with an ^{241}Am source the energy difference between maximum deceleration and acceleration can be calculated. This allows calculating the accelerating field.

The second method uses two Beam Position Monitors (BPMs) [5] installed after the second cryo module and allows measuring the beam energy by means of time of flight measurements. A detailed description can be found in [6].

The established calibration factors have been verified with the bend magnet field, calibrated with the CESAR detector described above, and scattering measurements with the ANASEN detector. In both cases the differences were smaller than 2% which can be attributed to the uncertainty of the LINAC cavity phasing.

MACHINE MODEL

The DYNAC [7] code has been chosen for machine modeling based on its capability to simulate all devices in the ReA3 beam line except the EBIT. This includes the multi harmonic buncher, RFQ, superconducting quarter wave cavities, electrostatic and magnetic elements. This allows using a single code when performing beam optics calculations compared to 4 different sequencial codes.

SRF Quarter Wave Cavity Kick Measurements

An analytical model predicting the kick of a SRF quarter wave cavity (QWC) has recently been published [8]. A series of measurements were conducted with the goal to verify the model. If successful, it will allow to measure the cavity offset in the transverse position and minimize the overall kick the beam receives. Adding this effect to the machine model will improve its capability in the control room.

The asymmetric geometry of the QWC results in a vertical kick of the beam depending on the vertical displacement within the accelerating gap, the speed or energy of the particle upon entrance, as well as the cavity amplitude and phase. The location of the third cryo module is currently a drift space with a diagnostic station at each end capable of measuring the beam position. This allows measuring both position and angle of the beam exiting the second existing cryo module.

A first set of measurements was conducted using a molecular hydrogen beam H_2^+ at an RFQ energy of 600 keV/u. A parallel offset was induced to the beam trajectory through the last QWC of the LINAC, which was phased to the bunching zero crossing. The cavity amplitude was varied at each trajectory until the beam was lost in the drift space. A result of this measurement is shown in Figure 3.

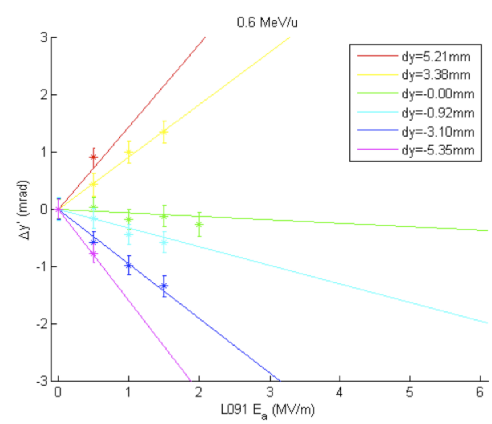

Figure 3: Vertical deflection angle vs. cavity voltage. Each line is the model prediction for different vertical displacement within the cavity from the beam's position. The diamonds including error bars represents the measured data.

All results agree with theoretical predictions. Based on this success a second series of measurements is planned for this fall, repeating this measurement at different beam energies and at different cavities.

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Results of the Application of the Model During Beam Line Commissioning

The model was completed beginning of 2013 and has been benchmarked in the accelerator over the past couple of months. The first practical application of the machine model occurred during the commissioning of the final beam line, connecting the ReA LINAC to the experimental end station. The beam line elements were set to their design values and the beam was transported to the end of this approx. 30-meter long line within three hours. During the following commissioning, the design optics in this area was preserved and the injected beam properties adjusted. Figure 4 shows the simulated (left) and measured (right) transverse beam profile on a scintillating viewer crystal in the diagnostic station. This particular location is at a high dispersion point, which explains the large horizontal beam.

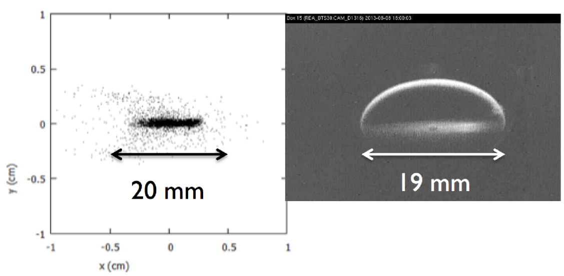

Figure 4: Transverse beam image in the location of a beam diagnostic station in the newly commissioned beam line. The left shows the simulated beam profile, the right the measured beam image.

To analyze the machine model a comparison of all settings was performed. Figure 5 shows as example the quadrupole magnet analysis. The first six magnets are located after the long drift and are part of the achromat that brings the beam line from the ReA deck onto the floor. The settings are optimized to cancel the dispersion. The following six quads are used to match the beam into the second achromat and final focus into the experimental end station. The settings of these element matches precisely the model. Only the final focus doublet needed to be adjusted. Overall the differences are small. The SRF cavity and RFQ settings are the same for model and machine. The solenoids in the SRF LINAC are deviating to a degree that is not fully understood. A possible source is a difference transverse emittance after the RFQ, as used in the simulation and in the machine. Work is ongoing to measure the emittance at this location. With the initial conditions of the beam entering the SRF LINAC section determined and the technique described in this paper, the benchmarking of the machine model will be completed.

The longitudinal emittance is fully understood. The model for the RFQ and SRF QWC is used to setup the beam. The transverse beam optics is well understood and a complete machine model will be available once the source for SC solenoid differences have been identified and incorporated in the model.

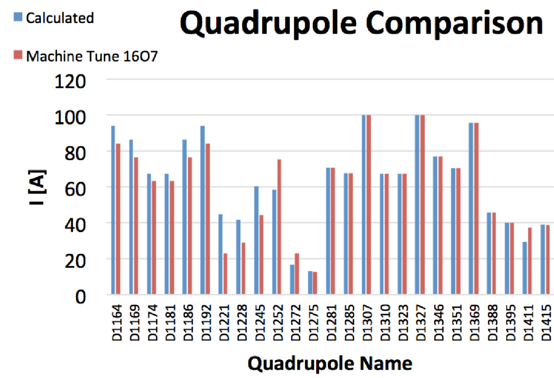

Figure 5: Comparison of quadrupole settings from machine model (blue) and as applied in machine (red).

CONCLUSIONS

The commissioning of the existing LINAC has been successfully completed and has shown a high level of reliability during the first beam delivery. The third cryo module is expected to be installed and commissioned by the end of summer next year. The experience and methods established during the initial commissioning will allow the integration of the final cryo module within a short period.

The machine model, implemented in a single code, has been established starting from the exit of the EBIT to the experiment's target point. The simulated longitudinal beam representation has been within 2% difference when compared to the measured beam. This has been verified by the measurements of the CAESAR and ANASEN detectors. The transverse description shows good agreement except in the cryo module area. Work is ongoing to determine the source of this difference.

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