THE DESIGN AND COMMISSIONING OF THE ACCELERATOR SYSTEM OF THE RARE ISOTOPE REACCELERATOR – ReA3 AT MICHIGAN STATE UNIVERSITY*

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Abstract

The National Superconducting Cyclotron Laboratory (NSCL) at Michigan State University (MSU) is currently constructing the new rare isotope reaccelerator facility, ReA3. The new facility will provide unique low-energy rare isotope beams by stopping fast rare isotopes in gas stopping systems, boosting the charge state in an Electron Beam Ion Trap (EBIT) and reaccelerating them in a compact superconducting linac [1,2,3]. The rare isotope beams will be produced initially by the existing Coupled Cyclotron Facility (CCF) at NSCL and later by Facility for Rare Isotope Beams (FRIB), currently being designed at MSU [4]. The ReA3 accelerator system consists of a Low Energy Beam Transport (LEBT), a room temperature RFQ and a superconducting linac utilizing superconducting quarter wave resonators. An achromatic High Energy Beam Transport and distribution beam lines towards the new ReA3 experimental area will deliver the reaccelerated rare isotope beams to the multiple target station. Beams from ReA3 will range from 3 MeV/u for heavy nuclei such as uranium to about 6 MeV/u for ions with A<50. The commissioning of the EBIT, RFQ and two cryomodules of the linac is currently underway. The accelerator system design and status of commissioning of ReA3 and future plan will be presented.

INTRODUCTION

In-flight Particle Fragmentation (PF) method producing fast Rare Isotope Beams (RIBs) has been used at the NSCL (floor plan shown in Figure 1) for nuclear structure and nuclear reaction research with great success since 1989. Heavy ions produced by two ECR ion sources are accelerated by two coupled superconducting cyclotrons (K500 and K1200) to energies up to ~150 MeV/u with beam power of a few kilowatts, and focused onto the production target. The produced RIBs are separated in-flight by the A1900 Fragment Separator, and delivered to multiple fast beam experimental halls for fast RIBs experiments. To meet the strong demands for high quality low energy RIBs from nuclear astrophysics and nuclear physics program [5], significant R&D has taken

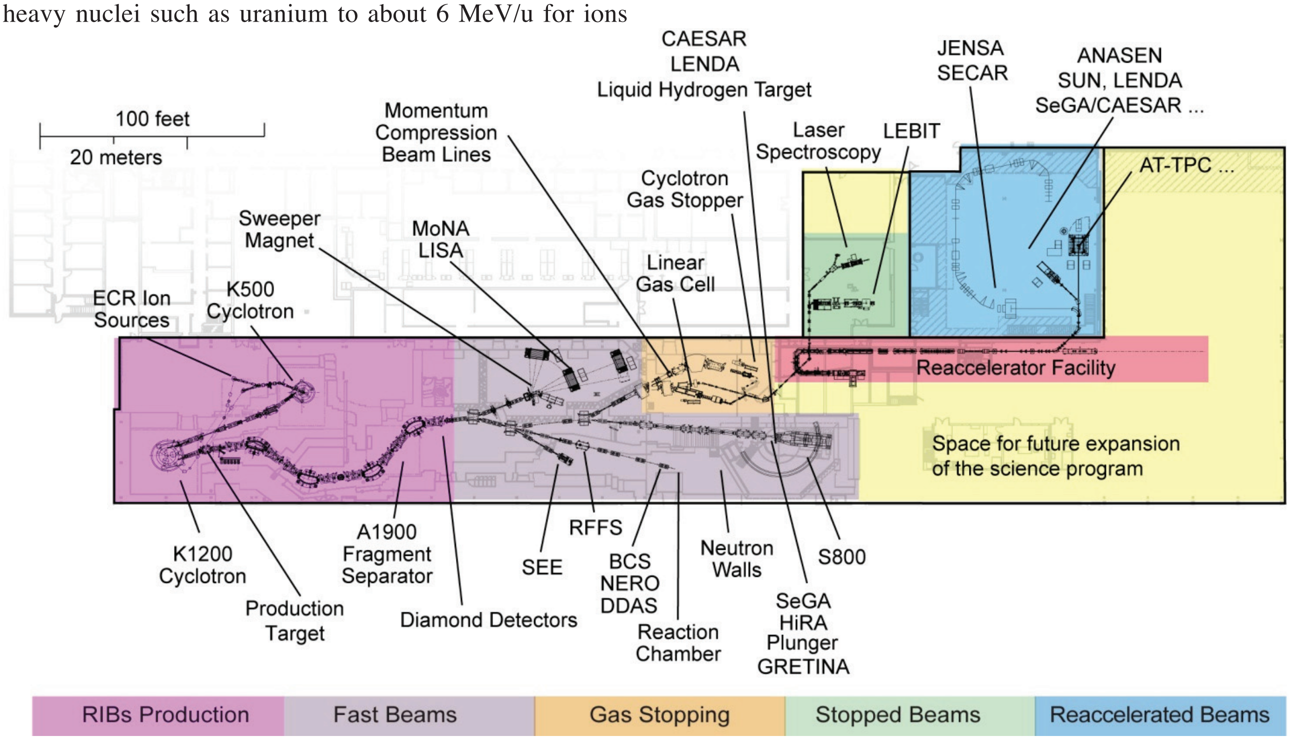

Figure 1: The facility layout of the NSCL.

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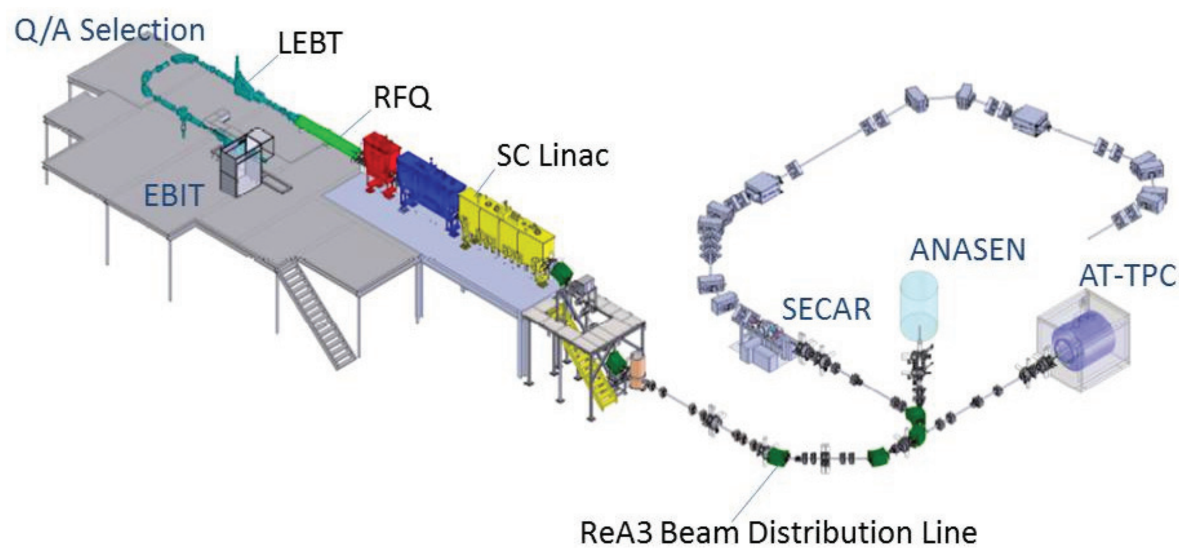

Figure 2: Overview of the ReA3 accelerator system and three planned target stations in ReA3 experimental hall.

place at the NSCL since 2006 to develop a low energy RIBs facility by stopping and re-accelerating RIBs produced and separated in-flight.

RIBs with typical energies of > ~50 MeV/u will be first injected into a gas stopping system with either a linear gas cell developed and delivered recently by ANL or a cyclotron gas stopper under construction at the NSCL. The singly charge RIBs from the gas stopper are then transported towards the ReA3 platform using electrostatic elements, which can either be directly delivered to stopped beam experimental area for Trap experiments and laser spectroscopy, or injected into the electron beam ion trap (EBIT) on the ReA3 platform to boost the charge state of the RIBs in order to achieve more compact and cost-effective reacceleration of the stopped RIBs in the ReA3 accelerator system.

ReA3 ACCELERATOR SYSTEM DESIGN AND THE STATUS OF COMMISIONING

The ReA3 accelerator system consists of a low Energy Beam Transport (LEBT) system, a room-temperature 4-rod RFQ, a superconducting linac, and a beam distribution system, as shown in Figure 2.

The LEBT transports and matches the stable and RIB beams into the RFQ from the EBIT, as well as from a vertical stable ion pilot source delivering He^+ and H_2^+ for commissioning and tuning of the RFQ and the linac. To achieve required beam longitudinal emittance, an external Multi-Harmonic Buncher (MHB) is used. Three diagnostics stations are used in the LEBT to measure the ion beam properties and achieve proper matching into the RFQ. The transverse focusing is provided by electrostatic quadrupole doublets and a solenoid.

The 4-rod 80.5 MHz room temperature RFQ accelerates all ion beams from ~12 keV/u to 600 keV/u. Together with the external MHB in the LEBT, the RFQ was designed to achieve high accelerating efficiency and small longitudinal emittance. The RFQ was built at the University of Frankfurt and delivered to NSCL in 2010.

The measured beam transmission through the RFQ during commissioning is ~ 82%, which matches reasonably well with the design value [6, 7]. The beam transverse and longitudinal parameters from the RFQ were also measured recently and used for ReA3 Linac beam modeling and tuning.

The ReA3 SC Linac uses two types of 80.5 MHz QWR cavities in three cryomodules, as shown in Figures 3 and 4, to accelerate beams from RFQ to the required final energy, while maintaining beam quality and minimizing beam emittance growth. The first cryomodule provides required beam matching from the RFQ with two solenoids and one beta=0.041 cavity. A second cryomodule, with three solenoids and six beta=0.041 cavities, provides beam with acceleration to ~ 1 MeV/u and deceleration to ~ 300 keV/u.

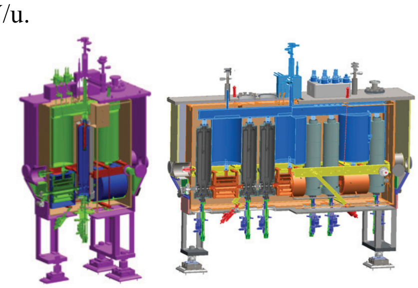

Figure 3: Two ReA3 cryomodules with beta=0.041 QWRs.

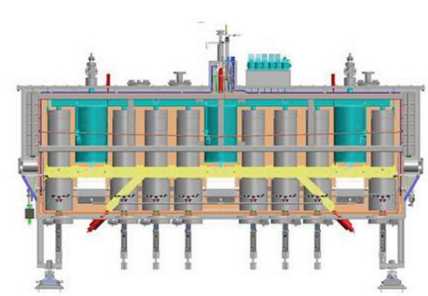

Figure 4: ReA3 cryomodules with refurbished 3rd generation beta=0.085 QWRs.

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The 3rd cryomodule consisting of three solenoids and eight beta=0.085 cavities, accelerates ion beam to the final desired energy. Each solenoid has two dipole coils to provide the beam central orbit corrections due to alignment errors of the cavities and solenoids inside cryomodules.

The 1st two cryomodules with beta=0.041 QWR cavities were installed in ReA3 and commissioned with stable ion beams from both EBIT and the pilot source. The specified design accelerating gradients for both ReA3 and FRIB have been achieved for all seven beta=0.041 QWR cavities, and routine operations of the cryomodules have been established. The 3rd cryomodule with beta=0.085 QWR cavities is currently under development. An R&D program to resolve inconsistent performance of the 2nd generation beta=0.085 QWR cavities resulted in design changes and development of 3rd generation of beta=0.085 QWR cavities, which can meet required accelerating gradients for both ReA3 and FRIB [8]. All eleven 2nd generation beta=0.085 QWR cavities have been refurbished and final RF testing is underway. Once certified, eight of the cavities will be installed in the coldmass of the modified ReA3 3rd cryomodule as shown in Figure 4, which is expected to be completed and installed on ReA3 platform in early 2013.

The ReA3 beam distribution line has been redesigned recently to accommodate proposed new beam diagnostics and future ReA3 energy upgrade plan. It now consists of a vertical achromatic S-bend section to bring beam from the ReA3 platform to the ground, a beam matching section with space for both ReA3 and ReA6 rebunching cryomodules, a high resolution horizontal 90º bending achromat with slit system to limit the beam energy spread, an achromatic beam switchyard with two 45º dipoles with straight beam ports, and the final focusing systems to deliver beams to three target stations in the ReA3 experimental hall. The ReA3 rebunching cryomodule will use a single beta=0.041 QWR cavity to rotate beam longitudinal phase space, minimizing the beam energy spread in order to achieve the required beam energy spread and bunch length on ReA3 target. The 1st part of beam distribution line, the vertical achromatic S-bend section, was completed in July of 2012, and beam commissioning is underway. The rest of the beam distribution line to the ReA3 experimental hall is expected to be completed by 2013.

Beam dynamics simulation studies for ReA3 have been performed using IMPACT [9] and DIMAD [10]. Figure 5 shows the beam energy and envelope along the ReA3 starting at the exit of the RFQ for ions with Q/A of 0.25 and an initial transverse normalized emittance of ~ 1 π mm-mrad, which is obtained from RFQ beam dynamics simulations. Figure 6 shows the final beam phase spaces on one of the ReA3 experimental targets. No noticeable beam transverse or longitudinal emittance growths were observed in the simulation. The rms beam size, bunch length and energy spread on target are estimated to be 0.81 mm, 0.21 ns and 0.41 keV/u, respectively.

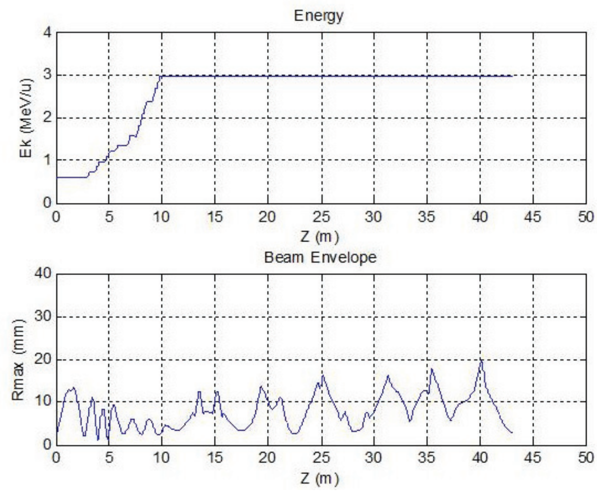

Figure 5: Beam energy (top) and envelope (100%) along the ReA3 from RFQ exit to the ReA3 experimental target.

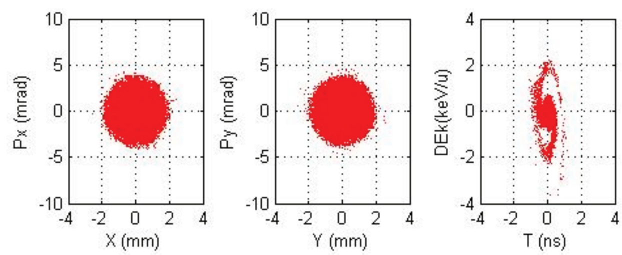

Figure 6: Horizontal (left), vertical (middle), and longitudinal (right) phase spaces on the ReA3 target.

The ReA3 accelerator system currently under commissioning includes LEBT, RFQ, two cryomodules with beta=0.041 QWR cavities, and the vertical achromatic S-bend section. A temporary beam pipe is installed in place of the ReA3 3rd cryomodule for beam transport. The CAESAR γ-ray detector has been installed after the S-bend, and will be used for beam energy measurement calibrations in the near future. Figure 7 shows an energy spectra of accelerated He^+ beam by RFQ and six accelerating beta=0.041 QWR cavities, measured with a silicon detector.

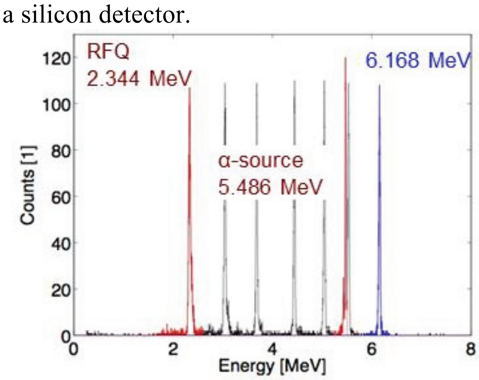

Figure 7: Energy spectra measurement with a silicon detector after the ReA3 2nd cryomodule. The measured total energy of He^+ beam out of RFQ, the reference α-source, and linac are shown.

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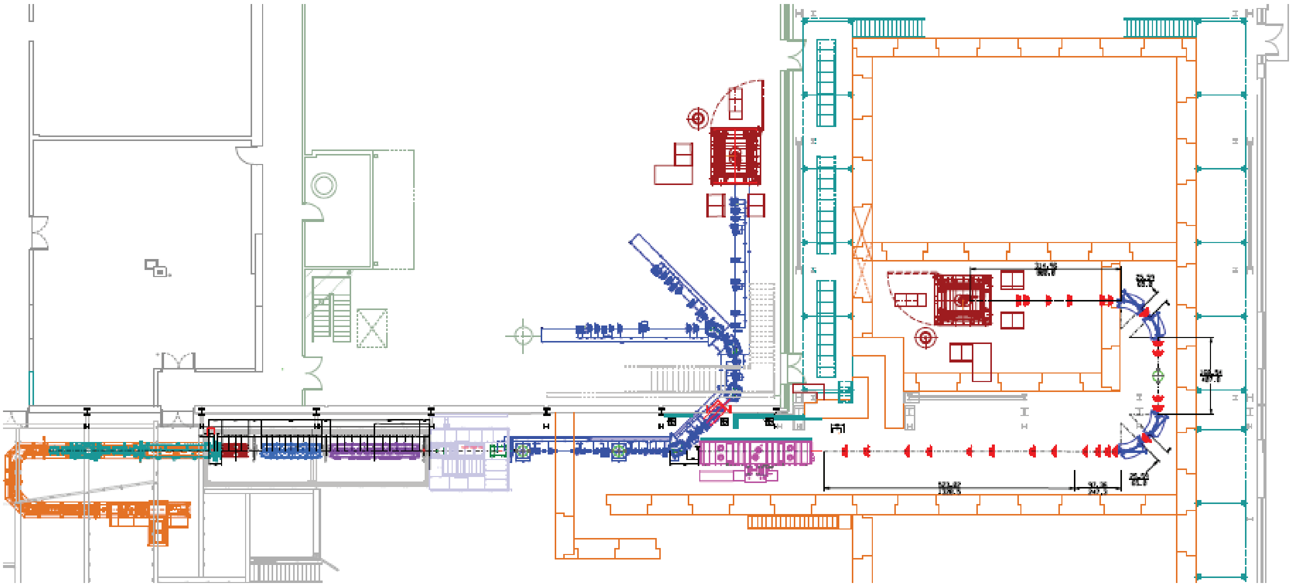

Figure 8: The proposed layout of the ReA6 extended from the ReA3 area.

ENERGY UPGRADE: ReA6 AND ReA12

The possible energy upgrade beyond ReA3 is also planned at the NSCL to increase the RIBs energy to ~6 MeV/u for ions with Q/A of 0.25, and up to ~11 MeV/u for light ions with Q/A of 0.5, as shown in Figure 8. ReA6 will have three Superconducting cryomodules, one for acceleration and the other two for beam longitudinal matching and re-bunching. As the test bed for FRIB driver linac, the ReA6 accelerating cryomodule, shown in Figure 9, will be the same one used in Linac Segment I for the FRIB driver linac, to gain first-hand experiences in design, fabrication, installation and operations of the FRIB cryomodules. The ReA6/FRIB accelerating cryomodule has eight beta=0.085, 80.5 MHz QWRs and three superconducting solenoid magnets with effective length of 0.5 m [11]. A wire position monitor is used for verification of alignment of the elements. A cold beam position monitor attached to each solenoid magnet will be used for beam centroid corrections. The cryogenic system provides separate 2K and 4.5 K liquid helium lines to QWRs and solenoids. The maximum voltage for each QWR is ~ 1.78 MV with E_p of 30 MV/m.

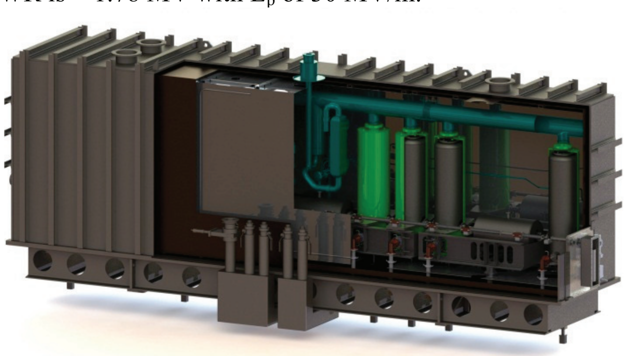

Figure 9: The accelerating cryomodule of ReA6.

The re-accelerated beams after the ReA3 re-bunching cryomodule has a long bunch length and small energy spread, not suitable for further acceleration in ReA6. A ReA6 rebunching cryomodule with a single beta=0.085, 80.5 MHz QWR in the ReA3 beam distribution line before the 1st horizontal bending dipole will be used to minimize the beam bunch length and longitudinally match the ReA3 beams into the ReA6.

The ReA6 beam distribution line after the accelerating cryomodule consists of a section of quadrupole FODO focusing channel, a short matching section, a symmetric 180° achromatic bending section with four 45° dipole magnets, and a final quadrupole focusing system to transport the beam to one of the ReA6 experimental targets. The ReA6 beam distribution line will be capable of transporting beams with a maximum rigidity of 2.5 T-m in order to accommodate future energy upgrade with minimum modification. The 3rd ReA6 cryomodule, also with a single beta=0.085, 80.5 MHz QWR, located in the middle of the 180° achromatic bending section is used control the beam longitudinal phase space in order to meet the requirements of beam bunch length and energy spread on target.

Beam dynamics simulation studies for ReA6 have also been performed using IMPACT and DIMAD. The results show that the ReA6 linac and beam distribution line design has adequate transverse and longitudinal acceptance to meet the required beam conditions on target. Similar to ReA3, no noticeable beam emittance growth was observed in the simulation. Figure 10 shows the beam energy and envelope along the ReA6 with beam from ReA3 for ions with Q/A of 0.25. Figure 11 shows the final beam phase spaces on the experimental target. The rms beam size, bunch length and energy spread on ReA6 target are estimated to be 0.67 mm, 0.22 ns and 0.43 keV/u, respectively.

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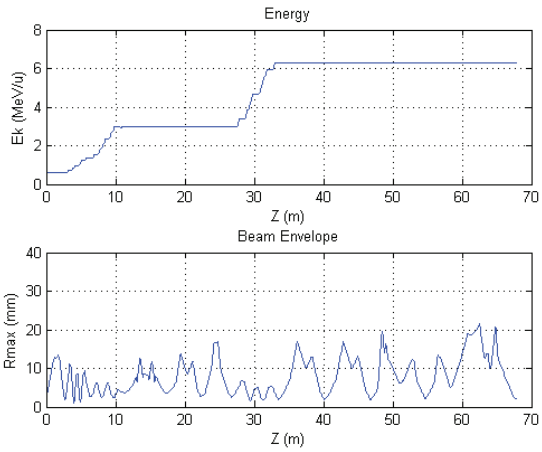

Figure 10: Beam energy (top) and envelope (100%) along the ReA6 to the experimental target.

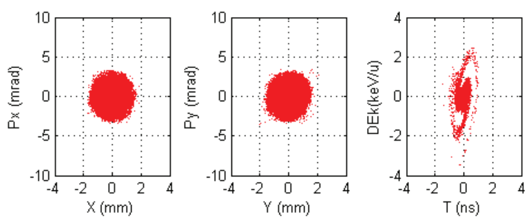

Figure 11: Horizontal (left), vertical (middle), and longitudinal (right) phase spaces on the ReA6 target.

Further energy upgrade from ReA6 to ReA12 to increase the RIBs energy to ~12 MeV/u for ions with Q/A of 0.25, and up to ~20 MeV/u for light ions with Q/A of 0.5, could also be accommodated by adding two more accelerating cryomodules in the ReA6 beam distribution line, replacing the FODO quadrupole focusing channel as shown in Figure 12. A 65 cm long warm region between cryomodules will be used for planned beam diagnostics stations. There is no other modification required for the rest of the beam distribution line, since the ReA6 beam distribution line is already designed for beams with a maximum rigidity of 2.5 T-m, suitable for ReA12 beams as well. Additional beamlines to deliver ReA6/ReA12 beams to multiple target stations in the NSCL experimental area are also possible to meet the needs of future nuclear physics research program.

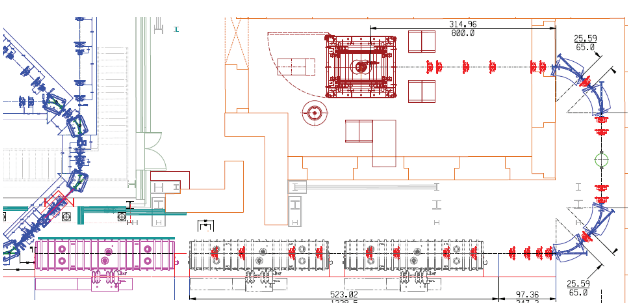

Figure 12: Extending ReA6 to ReA12 with two additional accelerating cryomodules.

SUMMARY

The ReA3 reaccelerator, together with gas stoppers and EBIT charge breeder, will be a unique low energy RIBs facility to provide new opportunities in nuclear astrophysics and nuclear physics. Construction and commissioning are currently underway at the NSCL, and the 1st experiment with RIBs in the ReA3 experimental hall is expected in 2013. The path for energy upgrade to ReA6 has been explored, and the design and procurement of the FRIB-type accelerating cryomodule for ReA6 and ReA12 are in progress.

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