

Project Plan for ReA3

High Energy Beam Transport (HEBT)

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1 Project purpose

The ReAccelerator for 3 MeV/u beams, ReA3, is currently under construction at National Superconducting Cyclotron Laboratory, NSCL. This upgrade of the NSCL user facilities was funded by Michigan State University and is expected to be commissioned in 2009. The upgrade includes a new linear accelerator and accompanying new 9,100 sq. ft. experimental area. ReA3 will provide the world's first capability to reaccelerate rare isotopes produced by in-flight fragmentation and fission. It will make available rare isotope beams of many elements that are currently unavailable due to the chemistry involved in usual rare isotope accelerated beam facilities. Among the exciting science opportunities this facility will open for users is the possibility to measure a set of nuclear reaction rates necessary to accurately model nova nucleosynthesis and study how exotic nuclei with large neutron halos interact at large intranuclear distances.

The ReA3 accelerator uses Superconducting Radio-Frequency, SRF, linear accelerator technology to achieve a final energy ranging from 0.3 to 3 MeV/u for ions with a charge-to-mass ratio of 0.25, and 0.3 to 6 MeV/u for ions with a ratio of charge to atomic mass number of 0.5. The design operating peak surface electric field, E_{peak} , for the two types of SRF cavities used in ReA3 are 16.5 and 20.0 MV/m, respectively. Preliminary tests of the accelerating cavities for ReA3 SC linac indicate that the technology may be capable of delivering higher operating peak surface electric field of 30.0 MV/m for both types of SRF cavities, increasing final beam energies by up to 50%. Table 1 shows possible final beam energies from the ReA3 SC linac with different operating scenarios.

Table 1: Final beam energies from ReA3 SC linac.

Q/A	Final Energy (MeV/u)		
	Deceleration	Acceleration	Acceleration
	($E_{\text{peak}}=16.5/20$ MV/m)	($E_{\text{peak}}=16.5/20$ MV/m)	($E_{\text{peak}}=30/30$ MV/m)
0.20	0.3	2.4	3.8
0.25	0.3	3.0	4.6
0.50	0.3	6.0	9.4

The ReA3 HEBT, which is the cope of this project, will deliver the radioactive beams from the SC linac to the new experimental area. A proposed layout is shown in Figure 1. The beam lines will be capable of transmitting the highest beam energies expected up to a maximum magnetic rigidity of 1.4 T-m. Two user stations will be provided within this project. The project plan that initially includes two user stations, is compatible with future plans to add an additional three stations including a large, high-efficiency recoil separator for astrophysical studies. This layout

has been presented to the user community in a Webinar on January 21, 2009 attended by users from across the nation. Initial comments were all positive.

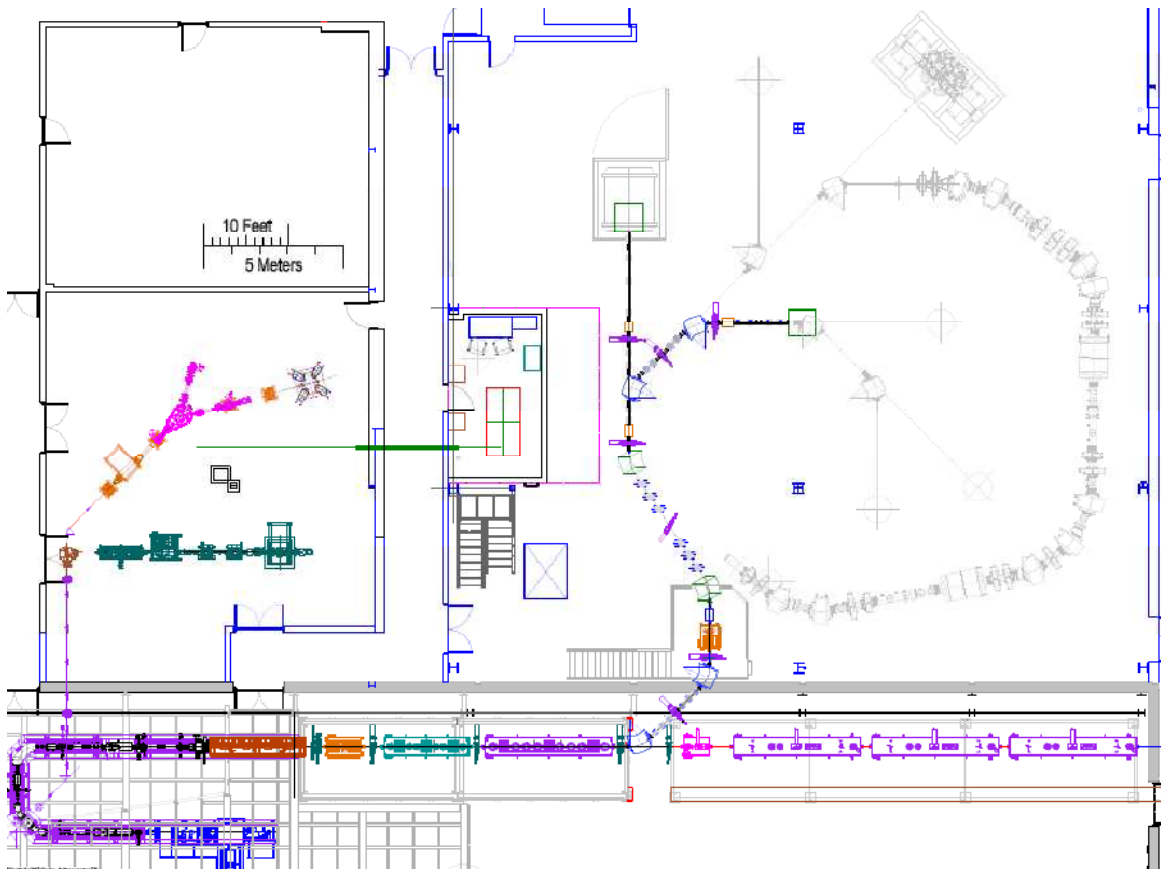


Figure 1: *Proposed layout of the ReA3 HEBT.*

The ReA3 HEBT design provides space along one beam line for the NSF MRI (2008) funded ANASEN detector, which is built as a collaboration of Louisiana State University and Florida State University. The other beam line would provide space for an Active Target Time Projection Chamber, which has been proposed to the NSF MRI 2009 program. Either device would be movable to allow other users to mount their experiments.

The experimental requirements for ReA3 HEBT are

1. Deliver beam from the SC linac to the two planned target stations with final energy of 0.3 to 9.4 MeV/u and charge-to-mass ratio of 0.2 to 0.5.
2. Transport beams with transverse emittance of $\leq 0.6 \pi$ mm-mard, and transmission of $\geq 90\%$.
3. The required beam spot sizes on target for the low energy beams (~ 0.3 MeV/u) are ~ 4 mm, and ~ 2 mm for the high energy beams (2.4 \sim 9.4 MeV/u).

4. The required beam bunch length on target for the low energy beams (~ 0.3 MeV/u) are ~ 4 ns, and ~ 1 ns for the high energy beams (2.4 \sim 9.4 MeV/u).
5. The required beam energy spread on target is ~ 1 keV/u.
6. The required distance between the last beamline element and target is ~ 1.2 m.

2 Project Scope

The ReA3 HEBT will deliver radioactive beams from SC linac to two target stations as shown in Figure 2. It consists

1. Two beamlines (LE and LF):
 - a. The LE beamline consists of two Achromatic Bending (AB) segments and three Straight Sections (SS). The 1st AB segment provides beam with a 90° turn from the SC linac on the linac balcony, and the 2nd AB segment with two reverse bending dipoles configured as a chicane, bring beam down to the ground level in the new low-energy experimental area. The 1st straight section connects the two AB segments, and the other two provide the final transverse transport and focusing to achieve the desired beam conditions on target.
 - b. The LF beamline consists of one AB segment and one Straight Section. The AB segment is used to provide a 90° turn for beam from the LE beamline, and the straight provides the final transverse focusing to achieve the desired beam conditions on the 2nd target station.
2. Total of 6 dipoles, 28 quadrupole, and 6 X-Y steering magnets are required for beam transport, transverse focusing, and centroid orbit corrections in the ReA3 HEBT.
3. A SC cryomodule consisting of a SC solenoid and a SC QWR with β of 0.041 will be used to rotate the longitudinal phase space of the beam in order to achieve an energy spread of ~ 1 keV/u at all energies. This will be required for the determination of astrophysical reaction rates.
4. Total of 7 beam diagnostics boxes are required for beam tuning in order to deliver beam on target required by experiments.

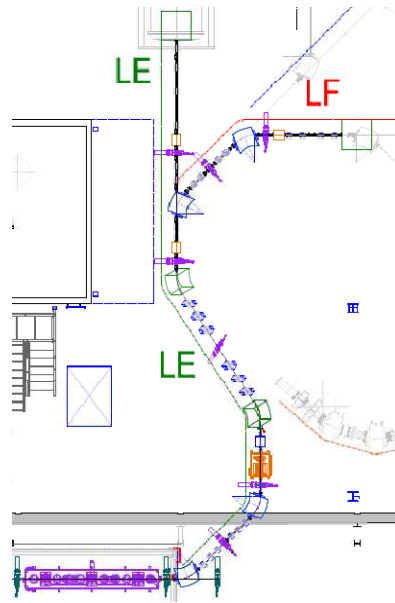


Figure 2: LE and LF beamlines in the ReA3 HEBT.

2.1 Magnet

Total of 6 room temperature dipoles are required to guide the beam from the RaA3 SC linac to the two target stations in the new low-energy experimental area. They are used in pairs in the achromatic bending segments to minimize the beam longitudinal emittance growth during the beam transport. Preliminary magnet design for dipole magnet in the ReA3 HEBT has been completed. Figure 3 shows the cross-section view, and table 2 lists the main parameters of the dipole magnet. Two of the dipole magnets will have a special 0 degree beam port to allow beam passage without bending.

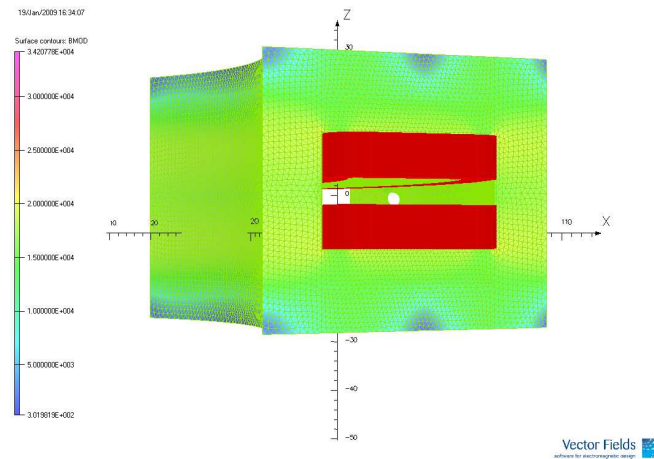


Figure 3: ReA3 HEBT Dipole.

Table 2: Main parameters of ReA3 HEBT Dipole

Number required	6
Bending Angle (°)	45
Edge Angle (°)	22.5

Aperture (m)	0.04
Length (m)	0.75
Vacuum pipe O. D. (in.)	1.5
Maximum Field (Tesla)	1.5
Current (A)	302
Voltage (V)	66.5
Power (kW)	20.1
Resistance (Ω)	0.22
Water Flow (Gal/min)	4.1
Temperature rise ($^{\circ}\text{C}$)	19
Conductor size (cm^2)	0.67 \times 0.67

Total of 28 room temperature quadrupole magnets are required to provide adequate transverse focusing in the ReA3 HEBT. Fourteen quadrupole magnets will come from existing Danby quads available at the NSCL with modified pole tip, and the rest quadrupoles will be designed and manufactured either at the NSCL or outside vendors.

Preliminary magnet design for quadrupoles of ReA3 HEBT has been completed. Figure 4 shows the cross-section view, and table 3 lists the main parameters of the modified Danby quadrupole magnets. The existing Danby quadrupole has an aperture of 8 cm and could not reach the required field gradient of $\sim 25 \text{ T/m}$. The pole tip insert was designed to reduce the aperture to 6.5 cm and increase the field gradient.

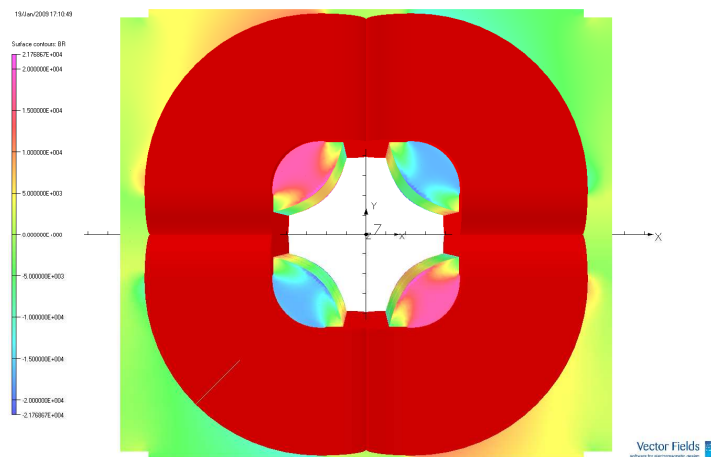


Figure 4: Modified Danby quadrupole for ReA3 HEBT.

Table 3: Main parameters of the Modified Danby quadrupole for ReA3 HEBT.

Number required	14
Effective length (m)	0.15
Aperture (m)	0.065
Vacuum pipe O. D. (in.)	2.5
Maximum Gradient (T/m)	25.0
Current (A)	322
Voltage (V)	28.7
Power (kW)	9.3
Resistance (Ω)	0.09
Water Flow (Gal/min)	1.266
Temperature rise ($^{\circ}\text{C}$)	30
Conductor size (cm^2)	0.476 \times 0.476

Figure 5 shows the cross-section view, and table 4 lists the main parameters of the new ReA3 HEBT quadrupole.

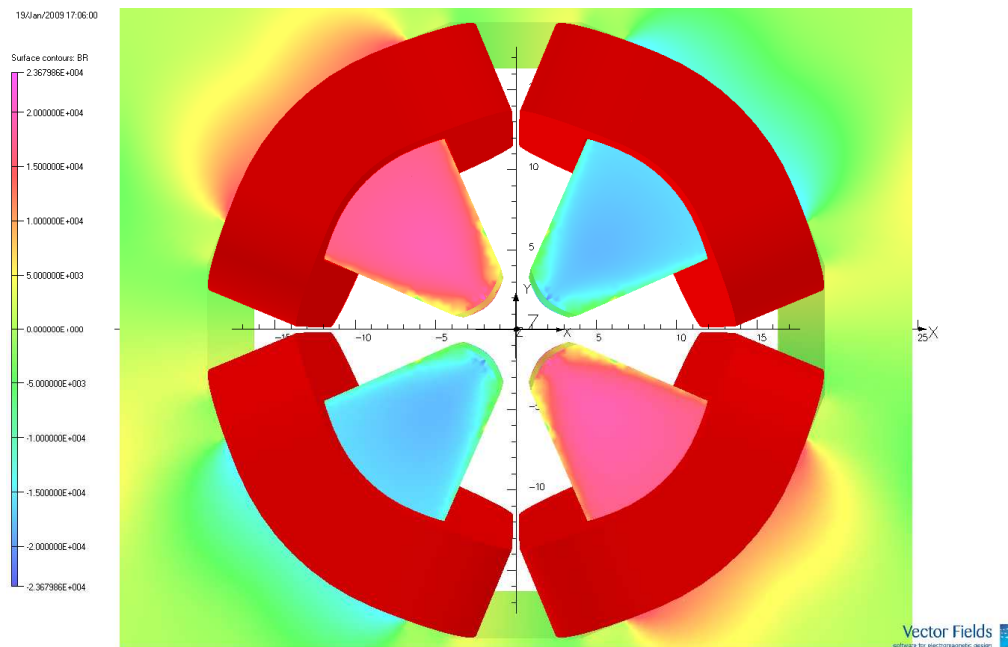


Figure 5: The new ReA3 HEBT quadrupole.

Table 4: Main parameters of the new ReA3 HEBT quadrupole.

Number required	14
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Effective length (m)	0.15
Aperture (m)	0.065
Vacuum pipe O. D. (in.)	2.5
Maximum Gradient (T/m)	25.0
Current (A)	387
Voltage (V)	15.2
Power (kW)	5.9
Resistance (Ω)	0.04
Water Flow (Gal/min)	0.644
Temperature rise ($^{\circ}\text{C}$)	30
Conductor size (cm^2)	0.67×0.67

Total of 6 X-Y corrector magnets are required to provide minimum required central orbit corrections in the ReA3 HEBT. Space in the beamline is reserved for additional X-Y corrector magnets if required in the future. Figure 6 shows the 3D view, and table 5 lists the main parameters of the ReA3 HEBT X-Y corrector magnet.

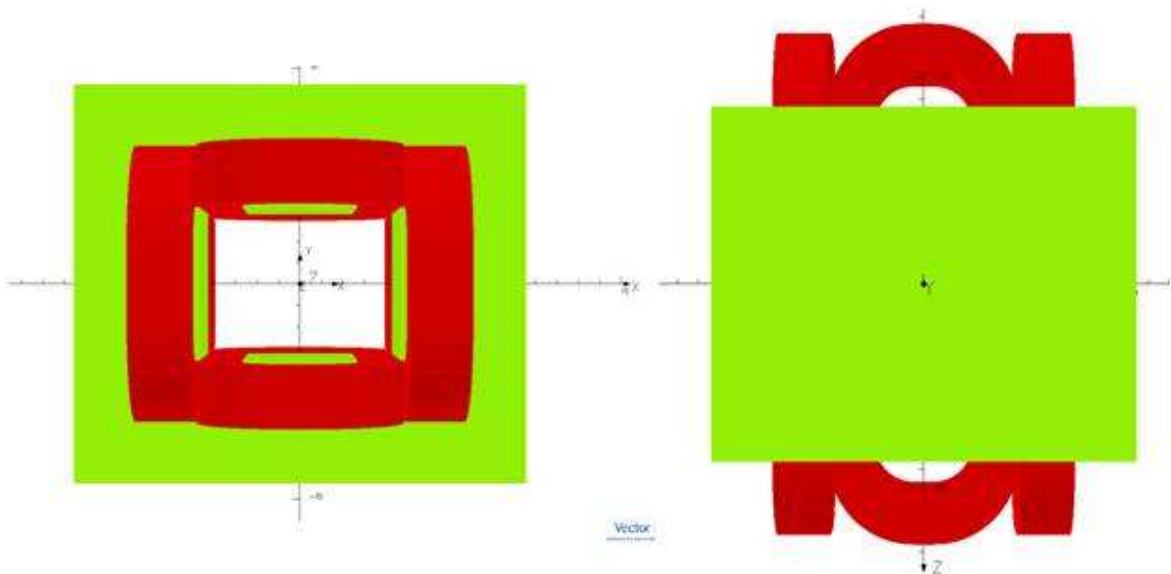


Figure 6: 3D-view of the X-Y corrector magnet.

Table 5: Main parameters of the X-Y corrector magnet of the ReA3 HEBT.

Number required	6
Effective length (m)	0.10
Aperture (m)	0.065/0.086
Vacuum pipe O. D. (in.)	2.5
Maximum Magnetic Field (T)	0.07
Current (A)	200/168
Voltage (V)	1.2/0.8
Power (kW)	0.25/0.125
Resistance (Ω)	0.006/0.005
Water Flow (Gal/min)	1.65/1.9
Temperature rise ($^{\circ}\text{C}$)	0.56/0.25
Conductor size (cm^2)	0.67 \times 0.67

2.2 SC Cryomodule

A SC cryomodule with one solenoid (9T) and one SRF QWR ($\beta=0.041$) will be used in the ReA3 HEFT. The SRF QWR is used to rotate the beam longitudinal phase space in order to achieve the beam bunch length and energy spread on target required by experiments, and SC solenoid provides the transverse focusing. The cryomodule is located in the 1st straight section in the LE beamline, where dispersion is zero and symmetric beam condition is achieved after the 1st achromatic bending segment. Figure 7 shows the ReA3 SC linac matching cryomodule with two solenoids and a QWR. The ReA3 HEFT cryomodule will have a single solenoid instead. All specifications for solenoid and QWR remain same as for ReA3 SC linac.

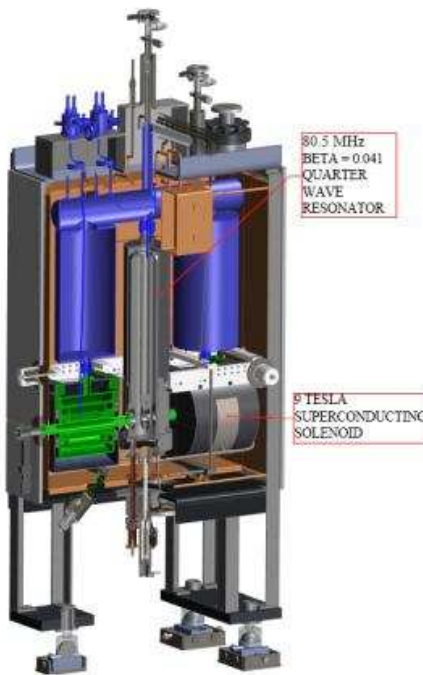


Figure 7: Matching cryomodule in ReA3 SC linac.

2.3 Beam Diagnostics Box

To deliver beam from the SC linac to the two planned target stations with required beam conditions, the ReA3 HEFT uses three achromatic bending and four straight sections. Each section of the beamline will have one beam diagnostics box in order to set up the magnets and SRF cavity to obtain proper beam focusing and matching. Together with required X-Y steering magnets, it will also provide the central orbit correction for RIBs from the SC linac. Two different types of diagnostics pots will be used; one with only transverse diagnostics devices, and the other with both transverse and longitudinal devices. Table 6 lists the required diagnostics device in each diagnostics box.

Table 6: ReA3 HEFT beam diagnostics pot parameters.

Name	Number required	Diagnostics device	Location
DP1	1	VP, FC, Collimation Aperture	AB1
DP2	1	FC, SL, WC, FS	SS1
DP3	1	VP, FC	AB2

DP4	1	VP, FC, WC	SS2
DP5	1	VP, FC	SS3
DP6	1	VP, FC, Collimation Aperture	AB3
DP7	1	VP, FC	SS4
VP: Viewer/Camera WC: Wire and cylinder SL: Movable slit FS: Foil + SI detector FC: Faraday Cup			

In summary, total of 7 beam diagnostics boxes are required for beam tuning in order to achieve the required beam conditions on target. The beam diagnostics pots in the ReA3 SC linac has been designed and specified already. Figure 8 shows the ReA3 SC linac beam diagnostics box #7. The same beam diagnostics box design can be used for DP2 and DP4 in the straight sections of the LE beamline. The rest of the beam diagnostics boxes (DP1, DP3, DP5-DP7) have only viewer plate/Camera and Faraday Cup, except two with additional collimation apertures.

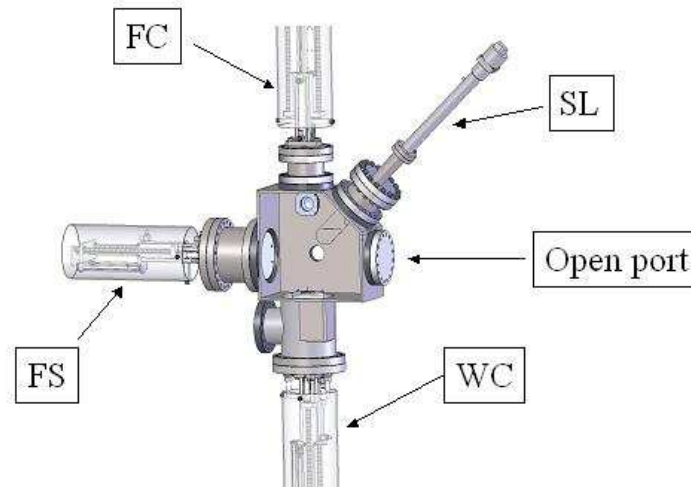


Figure 8: ReA3 SC linac beam diagnostics box #7, which can be used in the ReA3 HEBT.

2.4 Beamline Layout

The beamline components layout in each segment of the LE and LF beamlines are shown in Figures 9-13, and in Figures 14-15, respectively.

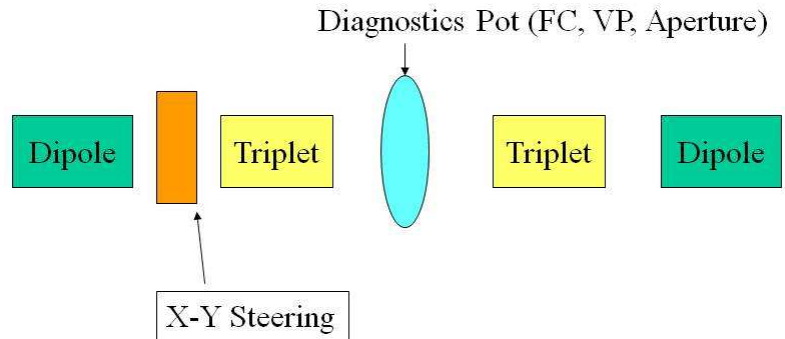


Figure 9: Required beam diagnostics box and other beamline components in the 1st achromatic bending section of the LE beamline.

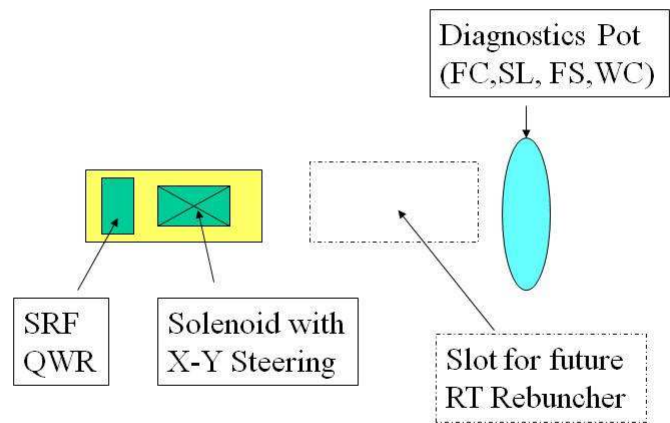


Figure 10: Required beam diagnostics box and other beamline components in the 1st straight section of the LE beamline.

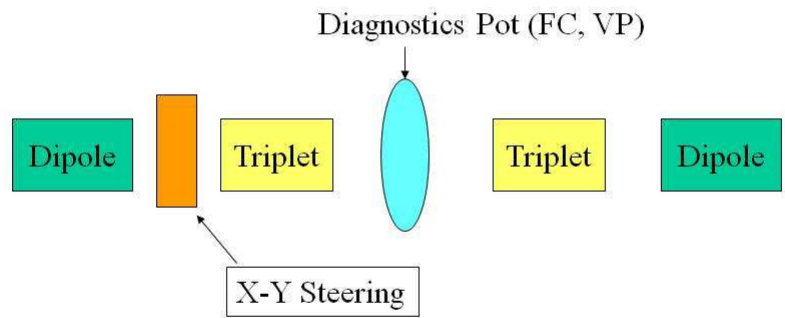


Figure 11: Required beam diagnostics box and other beamline components in the 2nd achromatic bending section of the LE beamline.

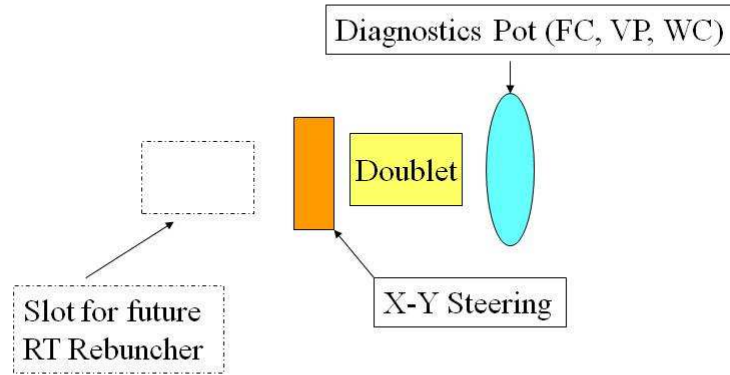


Figure 12: Required beam diagnostics box and other beamline components in the 2nd straight section of the LE beamline.

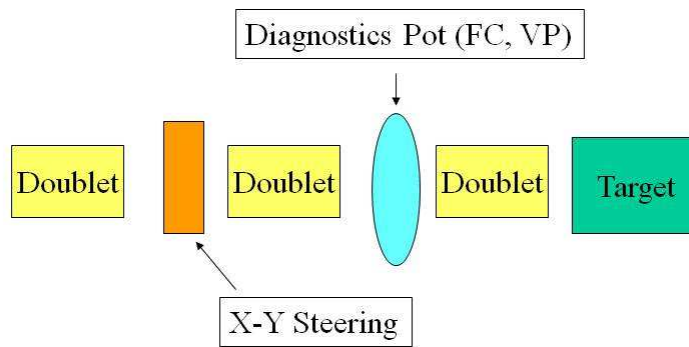


Figure 13: Required beam diagnostics box and other beamline components in the 3rd straight section of the LE beamline.

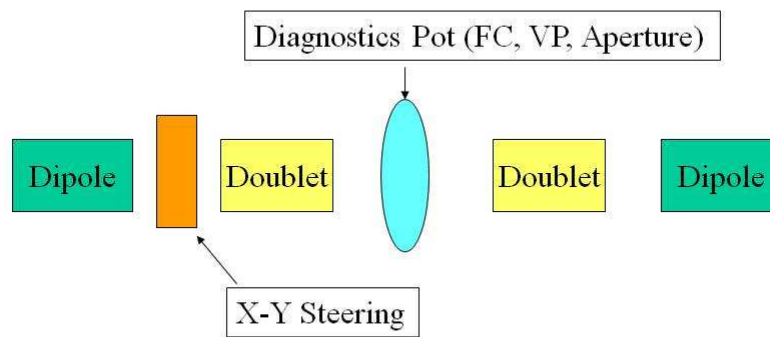


Figure 14: Required beam diagnostics box and other beamline components in the achromatic bending section of the LF beamline.

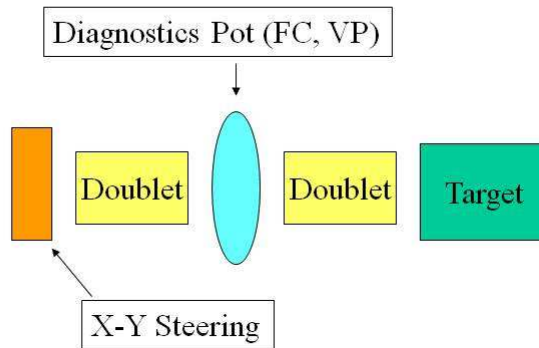


Figure 15: Required beam diagnostics box and other beamline components in the straight section of the LF beamline.

2.5 ReA3 HEBT Performance

Beam simulations were performed from the exit of RFQ through SC linac and HEBT to the target stations to evaluate the ReA3 SC linac and HEBT performance, and exam whether the resultant beam conditions on target meet the experimental requirement. Beam simulations for Q/A from 0.2 to 0.5 were performed through ReA3 HEBT to both target stations. However, only Beam simulation results using beam with reference charge-to-mass ratio of 0.25 are presented here. Figure 16 shows the initial beam phases at the exit of the ReA3 RFQ with Q/A of 0.25 and beam energy of 0.6 MeV/u, and Figure 17 shows the corresponding phase spaces at the exit of the ReA3 SC linac after the acceleration with different beam energies.

Figures 18-19 show the beam envelopes through ReA3 SC linac and the LE and LF beamlines in the HEBT with different final beam energies. Figure 20 shows the corresponding phase spaces on the target.

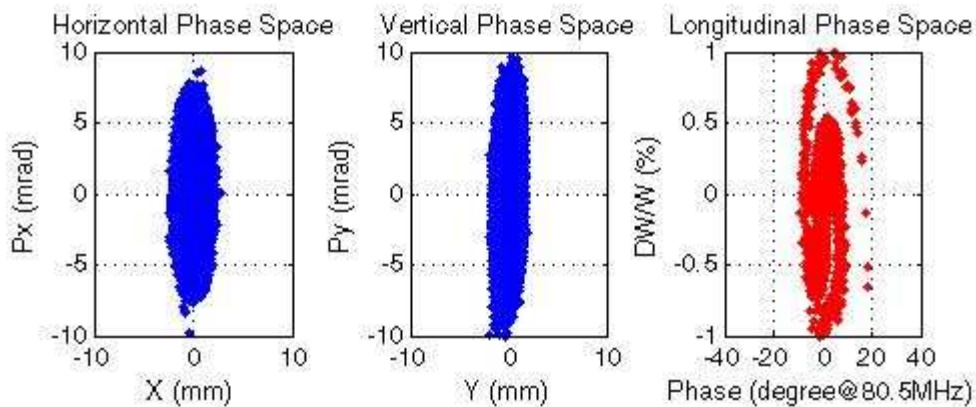


Figure 16: beam phase spaces at the exit of the ReA3 RFQ with Q/A of 0.25 and beam energy of 0.6 MeV/u.

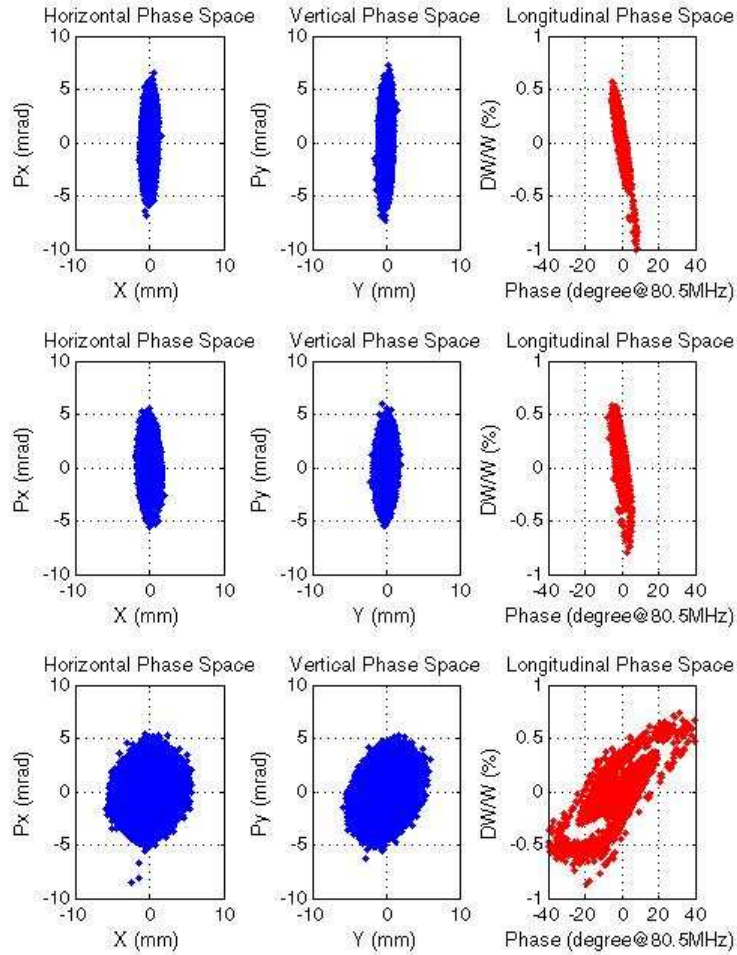


Figure 17: Beam phase spaces at the exit of the ReA3 SC linac for final energies of 4.6 MeV/u (top row), 3.0 MeV/u (middle row), and 0.3 MeV/u (bottom row).

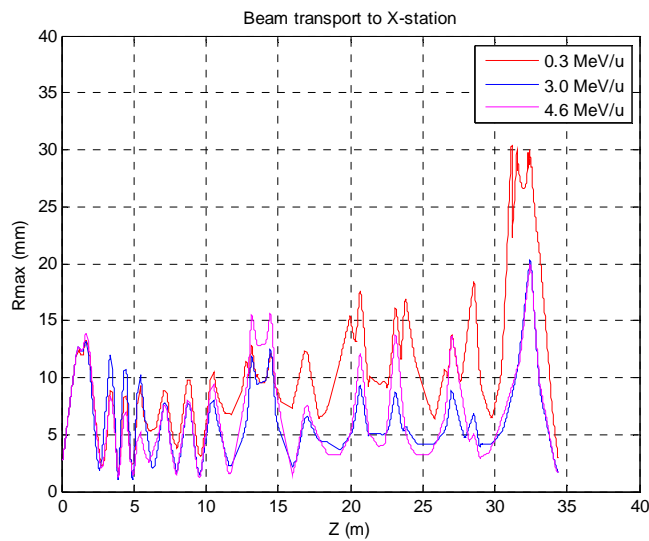


Figure 18: Beam envelopes in ReA3 SC linac and LE beamline of the ReA3 HEBT.

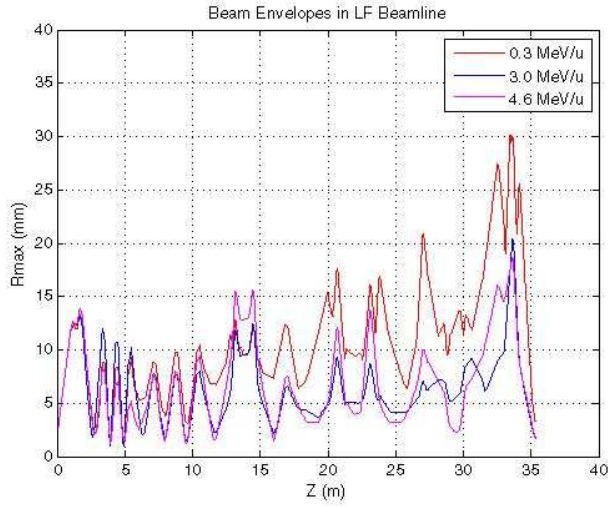


Figure 19: Beam envelopes in ReA3 SC linac and LF beamline of the ReA3 HEBT.

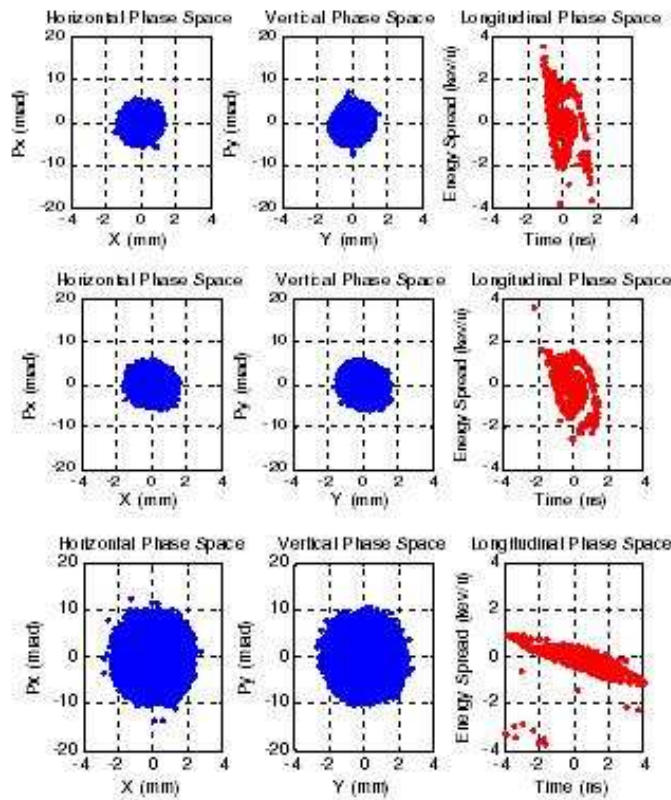


Figure 20: Beam phase spaces on target for final energies of 4.6 MeV/u (top row), 3.0 MeV/u (middle row), and 0.3 MeV/u (bottom row).

Table 7 lists achieved beam parameters on target for different final energies from the beam simulations in comparison with the experimental requirements. For beam with lowest final energy, due to its large geometric emittance and momentum spread, the beam spot achieved on target will be larger. In addition, the SC cryomodule in the HEBT is too far away from the

target to be effective to control the beam bunch length, the beam bunch length on target will be longer as the result. Also, due to multi-pacting limit, the SRF QWR may not be able to operating at the level required to properly rotate the beam longitudinal phase space at 0.3 MeV/u. Additional room temperature cavities will be required in order to achieve the shorter bunch length for low energy beams than what obtained with present design. Slots for such cavities have been reserved in the present HEFT layout.

Table 7: Beam parameters on target for Q/A=0.25.

Final Beam Energy (MeV/u)	0.3	3.0	4.6
Beam Size (mm)			
Simulation (4rms)	4.0	2.4	2.0
Experiment requirement	4.0	2.0	2.0
Bunch Length (ns) (rms)			
Simulation (4rms)	3.5	1.1	1.0
Experiment requirement	4.0	1.0	1.0
Energy Spread (keV/u)			
Simulation (4rms)	1.0	1.2	1.6
Experiment requirement	1.0	1.0	1.0