STUDY ON THE BEAM DYNAMICS IN THE RISP DRIVER LINAC

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Abstract

Rare Isotope Science Project (RISP) has been proposed as a multi-purpose accelerator facility for providing beams of exotic rare isotopes of various energies. The RISP driver linac which is used to accelerate the beam, for an example, Uranium ions from 0.3 MeV/u to 200 MeV/u consists of superconducting RF cavities and warm quadrupole magnets for focusing heavy ion beams. Requirement of the linac design is especially high for acceleration of multiple charge beams. In this paper, we present the RISP linac design and the requirements of dynamic errors to minimize the beam centroid oscillation and preserve beam losses under control.

INTRODUCTION

The RISP (Rare Isotope Science Project) accelerator has been planned to study heavy ion of nuclear, material and medical science at the Institute for Basic Science (IBS). It can deliver ions from proton to Uranium with a final beam energy, for an example, 200 MeV/u for Uranium and 600 MeV for proton, and with a beam current range from 8.3 pμA (Uranium) to 660 pμA (proton) [1, 2]. The facility consists of three superconducting linacs of which superconducting cavities are independently phased and operating at three different frequencies, namely 81.25, 162.5 and 325 MHz.

The layout of the RISP accelerator is shown in Fig. 1. The Uranium ions produced in an electron cyclotron resonance ion source are preaccelerated to an energy of 300 keV/u by a radio frequency quadrupole and transported to the superconducting cavities by a medium energy beam transport. The driver linac is divided into three different sections: low energy superconducting linac (SCL1), charge stripper section and high energy superconducting linac (SCL2). Figure 2 shows a conceptual structure of SCL1 and SCL2. The SCL1 uses the two different families of superconducting resonators, i.e., quarter wave resonator (QWR) and half wave resonator (HWR). The SCL11 consists of 24 QWR's whose geometrical β is 0.047 and 24 doublets. The resonance frequency of QWR is 81.25 MHz. The cryomodule of the SCL11 hosts one superconducting cavity. The SCL12 consists of 138 HWR's whose geometrical β is 0.12 and 36 doublets. The resonance frequency of HWR is 162.5 MHz. This segment has the two families of cryomodules: one type of cryomodule hosts three superconducting cavities and the other hosts six superconducting cavities.

The SCL2 consists of the SCL21 and the SCL22, each consisting of geometric β 0.30, resonance frequency 325 MHz Single Spoke Resonators (SSR) and geometric β

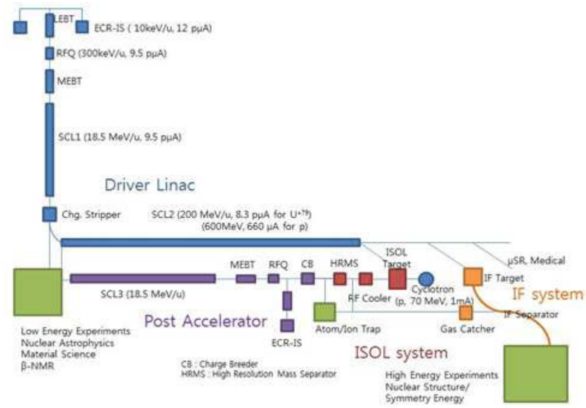


Figure 1: Layout of the RISP accelerator.

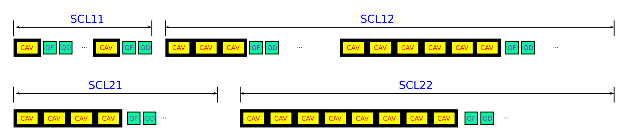


Figure 2: Layout of the SCL: SCL1 (top) and SCL2 (bottom).

0.53, resonance frequency 325 MHz SSR. Single Spoke Resonator type is chosen mainly because it can have a larger bore radius compared with the Half Wave Resonator type, which is very essential to reduce the uncontrolled beam loss in the high energy linac section. The number of cavities in the SCL21 and SCL22 is 88 and 138 respectively. The cryomodule of the SCL21 and SCL22 hosts 4 and 8 cavities respectively. Table 1 summarizes the parameter of four different superconducting cavities. The charge stripper section is located between SCL1 and SCL2. The charge stripper strips electrons from heavy ion

Table 1: Superconducting cavity parameters.

Parameter	unit	QWR	HWR	SSR 1	SSR 2
β_g		0.047	0.12	0.30	0.53
Frequency	MHz	81.25	162.5	325	325
Aperture	mm	40	40	50	50
V_{acc}	MV	1.02	1.07	2.04	3.53
E_{peak}/E_{acc}		5.08	6.2	4.06	4.15
B_{peak}/E_{acc}	mT/(MV/m)	9.16	8.4	7.07	8.6
QR_s	Ohm	37	47	86	108
R/Q	Ohm	480	319	242	304
Temperature	K	2	2	2	2
Q_0	10^9	3.6	4.6	8.1	10

ISBN 978-3-95450-122-9

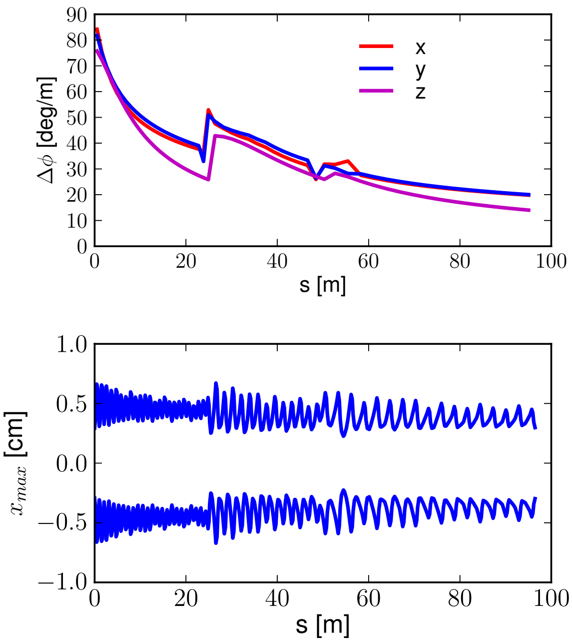


Figure 3: Phase advance per unit length (bottom) and maximum horizontal beam size envelope along the length of SCL1 (top) without machine imperfections.

Table 2: Machine imperfection of RISP lattice using quadrupole as a focusing element. Displacement and rotation errors are uniformly generated. Phase and amplitude errors are 3 σ Gaussian.

Parameters	SC Cavity	Quadrupole
Displacement (mm)	±1	±0.15
Phase (deg)	±1	-
Amplitude (%)	±1	-
Rotation (mrad)	-	±5

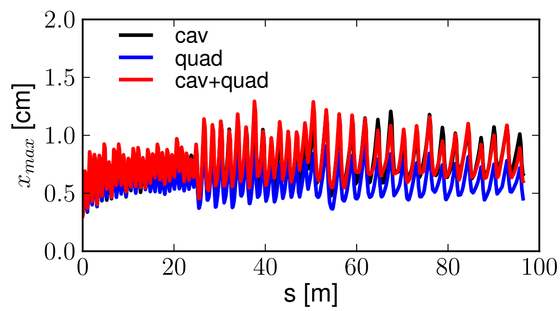


Figure 4: Plot of maximum horizontal envelope for SCL1 due to machine imperfections.

beams to enhance the acceleration efficiency in the high energy linac section. The charge stripping section consists of four normal conducting quadrupole triplets and two room-temperature 45 degree bending magnets. The quadrupole magnets provide adequate transverse focusing and beam matching to the SCL2 and bending magnet provides the momentum dispersion for the charge selection.

The post accelerator (SCL3) is designed to accelerate the rare isotopes produced in the ISOL (Isotope Separation On-Line) system up to 18.5 MeV/u. The SCL3 is, in principle, a duplicate of the driver linac up to low energy linear accelerator. The accelerated rare isotope beams are reaccelerated in the SCL2. Hence, the RISP accelerator provides a large number of rare isotopes with high intensity and with various beam energies.

BEAM DYNAMICS SIMULATIONS

The RISP linac is a flexible structure to deliver heavy ions from proton to Uranium. The linac lattice is optimized by minimizing emittance growth and potential for beam loss by keeping a beam envelope smooth and regular. A transverse phase advance per period is kept under 90 degrees to prevent envelope instabilites. The ratio of transverse to longitudinal phase advance is kept in the range of 1.2 to 1.6 to avoid a resonance due to parametric coupling between longitudinal and transverse planes. Figure 3 shows phase advance per unit length along the length of SCL1. The maximum beam envelopes shown in Fig. 3 are kept less than 7 mm along the linac.

For the actual SCL, machine imperfections cannot be avoided. The error comes from the misalignment of the linac elements and the limitation of manufacturing accuracy and various control errors. For instance, steering magnets are used to correct beam orbit displacements. In the baseline design of the RISP linac, steering magnets are placed where normal conducting quadrupoles are. The misalignment analysis includes all superconducting cavities and focusing elements assuming a uniform distribution. Table 2 summarizes tolerances for the lattice consisting of superconducting cavity and normal conducting quadrupole. It has been well known that the normal conducting quadrupole can be aligned in an accuracy of ±150 μm [4]. The rotation angle about the z-axis is set to 5 mrad. The rotation angle is important due to the skew quadrupole term while it is independent of the solenoid due to symmetry of solenoid field. In the misalignment and RF error analysis, charge states of 33+ and 34+ of Uranium beams are used. Effect of machine imperfection on beam envelope is shown in Fig. 4. The maximum envelope is kept well below the transverse aperture 20 mm of SCL1.

In order to examine the quality of the present quadrupole-based driver linac lattice, effects of machine imperfections on the beam parameters are investigated, compared with the previous linac design based on superconducting solenoids. To summarize the layout of the previous SCL design of briefly, the SCL11 consists of three cryomodules where each cryomodule hosts eight superconducting cavities and eight superconducting solenoids. The solenoid is used to focus the beam. The SCL12 consists of twelve cryomodules where each cryomodule hosts eight cavities and three solenoids. Diagnostic devices and steer-

ISBN 978-3-95450-122-9

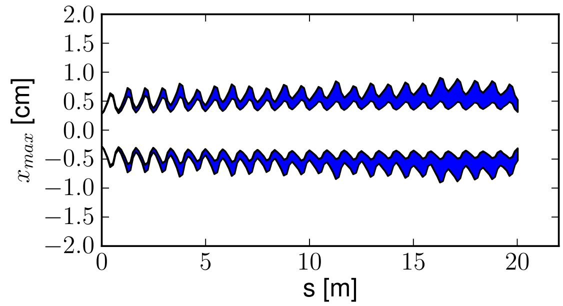
Table 3: Machine imperfection of superconducting solenoid-based lattice. Displacement and rotation errors are uniformly generated. Phase and amplitude errors are 3 σ Gaussian.

Parameters	Quadrupole	Solenoid
Displacement (mm)	±0.15	±0.5
Phase (deg)	-	-
Amplitude (%)	-	-
Rotation (mrad)	±5	±5

Table 4: Variation of beam parameters due to machine imperfections.

Parameters	Initial	Doublet	Solenoid
x_{max} (cm)	0.3	0.7	1.7
y_{max} (cm)	0.6	1.0	1.5
ϕ_{max} (deg)	26.8	10.2	75.6
ϵ_x (cm-mrad)	0.013	0.016	0.026
ϵ_y (cm-mrad)	0.013	0.016	0.024
ϵ_z (keV/u-ns)	1.3	2.74	1.33
$x_{centroid}$ (cm)	0.0	0.32	1.20
$y_{centroid}$ (cm)	0.0	0.50	0.97
$\phi_{centroid}$ (deg)	0.3	3.25	5.60

ing magnets can be placed in the drift spaces between cavity and quadrupole or between quadrupoles in the doublet lattice while they should be placed between cryomodules in the solenoid lattice. The length of quadrupole-based linac is commensurate with solenoid-based linac. The particle tracking with machine errors is performed with the TRACK code which has been developed in ANL [3]. Table 3 summarizes tolerances for the lattice consisting of superconducting solenoids. The maximum transverse displacement of solenoid is set to 0.5 mm. This displacement is half of the offset of superconducting cavities, but the effect of solenoid displacement is expected to be detrimental to beam dynamics in the linac. Only the SCL11 is used for comparison of beam performance. For multi-charge state beam acceleration, a strong focusing is required. The misalignment of superconducting solenoids is, from the error simulations, found to affect the beam properties more than that of normal conducting quadrupole. As shown in Fig. 5, the misalignment of superconducting solenoid increases the maximum beam envelope by 3.5 times while the normal conducting quadrupole error increases the envelope only by 0.8 times. The aperture radius of quadrupole and solenoid is 20 mm. The envelope due to solenoid misplacement goes high up to 1.7 cm just after the SCL11The maximum increase of rms emittance is 10% for doublet lattice, while it is 140% for solenoid lattice. The effects of cavity misalignment and RF error on longitudinal emittance are less sensitive than focusing elements. The dynamics simulation results are summarized in Table 4.



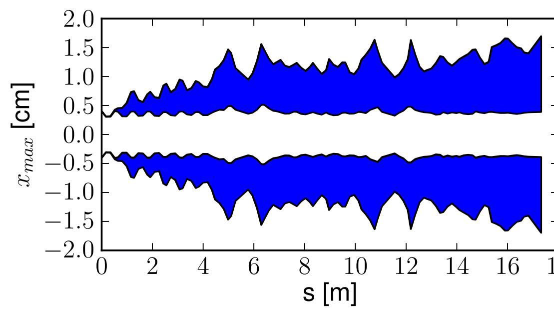


Figure 5: Plot of maximum horizontal beam envelope: doublet lattice (top) and solenoid lattice (bottom). The shade region represents the bounds of envelope variation.

SUMMARY

Beam dynamics design of the RISP low and high energy linac has been presented. In the design, the focusing in the superconducting linacs is provided by normal conducting quadrupole doublets. Four different cavities, such as QWR, HWR, SSR 1 and SSR 2, are used to accelerate the beam in the linac. The number of cavities per cryomodule at each section is optimized to minimize the total number of cavities required for the efficient acceleration. We emphasize the stability of operation, flexibility of maintenance, and the minimization of beam loss. The linac design with normal conducting quadrupole gives a good beam quality.

ACKNOWLEDGMENTS

We thank B. Mustapha for help with the TRACK code. This work was supported by the Rare Isotope Science Project which is funded by the Ministry of Education, Science and Technology (MEST) and National Research Foundation (NRF) of KOREA.

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