END-TO-END BEAM DYNAMICS SIMULATIONS OF THE ISF DRIVER LINAC *

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Abstract

The proposed Isotope Science Facility (ISF) is a major upgrade of the coupled cyclotron facility at the National Superconducting Cyclotron Laboratory (NSCL) that will provide the nuclear science community with world-class beams of rare isotopes. The ISF driver linac will consist of a front-end and three acceleration segments of superconducting cavities separated by two charge-stripping sections, and will be capable of delivering primary beams ranging from protons to uranium with variable energies of ≥200 MeV/nucleon. The end-to-end beam simulation studies including beam element misalignments, dynamic rf amplitude and phase errors, and variations in the stripping foil thickness, have been performed to evaluate the driver linac performance. The beam simulation effort was focused on the most challenging uranium beam with multiple charge states using the newly-developed RIAPMTQ/IMPACT codes. This paper describes the ISF, discusses the beam dynamics issues, and presents the end-to-end beam simulation results.

INTRODUCTION

Lower cost and reduced scope alternatives to the Rare Isotope Accelerator (RIA) project have been explored at Michigan State University (MSU). The proposed Isotope Science Facility (ISF) [1] will be built on the MSU campus providing substantially enhanced capabilities and continue the mission of educating the next generation of nuclear scientists. ISF construction will take full advantage of NSCL expertise in rare isotope research. Major cost savings will be achieved by reuse of NSCL equipment. The initial layout of the facility is given in Figure 1. Stable isotope beams will be accelerated by a superconducting linac to energies ≥200 MeV/u with a beam power ≥100 kW (up to 400 kW if ion source performance permits) for the production of rare isotope beams.

To meet the beam power requirement, the driver linac is designed to allow the acceleration of two-charge state beams from the ion source for ions heavier than xenon. In addition, two charge stripping sections will increase the charge state for the heaviest ions. Only one charge stripping station will be used for light ions. The locations of these stripping stations have been chosen to minimize the required accelerating voltage. Minimal beam loss, high reliability, and low cost are the main driving considerations in the driver linac design. End-to-end beam

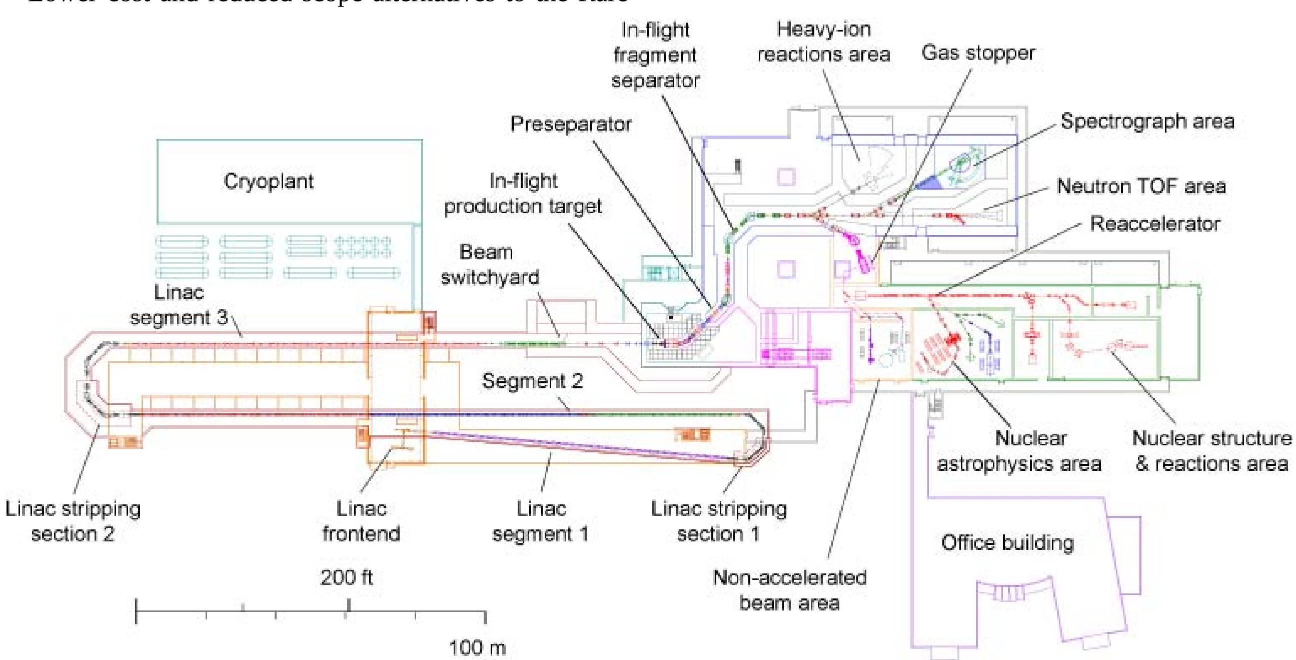

Figure 1: Layout of the accelerator complex and experimental areas. The driver linac consists of a room temperature front end and three superconducting linac segments, separated by two beam-stripping sections. The driver linac is designed to deliver up to 400 kW uranium beam power on a production target. Also shown is the reaccelerator linac, designed to deliver radioactive ions with energies in the range of 0.5 to 12 MeV/u.

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simulations were performed to evaluate the performance of the driver linac with alignment and rf errors and stripping foil thickness variations included. The newly-developed RIAPMTQ/IMPACT [2] parallel codes running on the high performance computers at MSU were used for particle tracking with high statistics [3].

ISF DRIVER LINAC

The proposed driver linac is based on an earlier linac design for the RIA [4], and the superconducting linac is similar to another proposal [5]. The dc ion beam from an electron cyclotron resonance ion source will first be analyzed by an achromatic charge-to-mass selection system. The selected ion beam will be pre-bunched in the low energy beam transport line by a multi-harmonic buncher and matched into the Radio Frequency Quadrupole (RFQ). The 80.5 MHz RFQ will accelerate the beam from 12 keV/u to 300 keV/u. A medium energy beam transport system will then match the beam into the superconducting linac for further acceleration.

The superconducting driver linac will be separated into three accelerating segments. Segment 1 will use 80.5 MHz λ/4 cavities to accelerate uranium beam from 0.3 MeV/u to 12 MeV/u. Segment 2 will consist of 161 MHz λ/4 cavities and 322 MHz λ/2 cavities and accelerate uranium beam from 12 MeV/u to 110 MeV/u. Segment 3 will use 322 MHz λ/2 cavities to accelerate uranium beam to 200 MeV/u. All of the segments will use superconducting solenoids for transverse focusing. No parametric resonance between transverse and longitudinal directions was expected, nor observed in beam simulations. Between Segment 1 and Segment 2 and between Segment 2 and Segment 3, there will be two charge-stripping sections to increase the average charge state of the primary beams. Beams lighter than xenon will only be stripped once in the first stripping section.

All three linac segments will be able to accelerate multiple charge states of the primary beam to achieve the required primary beam power on the production target. Therefore, a larger longitudinal acceptance for each segment is required to avoid beam loss. Uranium will present the most challenge, as the beam will consist of two charge states (28+ & 29+) in Segment 1, five charge states (71+ to 75+) in Segment 2, and three charge states (88+ to 90+) in Segment 3.

END-TO-END SIMULATIONS

Misalignment and RF Errors

The rf phase and amplitude errors have a significant impact on the beam dynamics, especially that dynamic rf errors which can not be effectively corrected, can lead to significant longitudinal emittance growth. Therefore, dynamic rf errors must be controlled within tolerance. Based on the experimental results available, the rf tolerances for the superconducting cavities were set to ±0.5° in phase and ±0.5% in amplitude. In the beam simulations, these errors were assumed to be uncorrelated and have a flat distribution.

The impact of misalignment of the focusing solenoids and superconducting cavities as well as a correction scheme for the central orbit was investigated for all three accelerating segments of the driver linac. The steering effects from the misalignment of the superconducting solenoids are much larger than those of superconducting cavities. But the misalignment of the cavities is also detrimental, since these elements have the smallest apertures. Each superconducting solenoid will have a pair of dipole windings to provide horizontal and vertical beam steering correction. Random alignment errors were assumed for each beam element with a Gaussian distribution truncated at $\pm 2\sigma$ (σ is the standard deviation). For a given seed of alignment errors, DIMAD code was used to simulate beam centroid correction based on beam position monitors at the exit of each cryomodule. The required values for misalignment tolerances were investigated for each segment and were found to be $\sigma = 1$ mm for both the solenoids and cavities.

Particle Tracking without Errors

The most challenging beam for the driver linac is the uranium beam with its multiple-charge-state acceleration. Therefore, end-to-end beam dynamics results will be presented for this beam. Due to the acceleration of multiple charge states and the impact of the stripping foils, both the transverse emittance and the longitudinal emittance increase as the beam propagates through the driver linac even when no errors are included in the simulations. A two-charge-state uranium beam with a total of 1 million particles was tracked from the exit of ion source through the front-end until to the end of the driver linac using RIAPMTQ/IMPACT parallel code. Without alignment and rf errors, the simulated normalized 99.5% transverse and longitudinal emittances are about 0.8 π·mm·mrad and 1.1 π·ns·keV/u at the entrance of the superconducting linac, and approximately 1.5 π·mm·mrad and 17.1 π·ns·keV/u at the exit of the driver linac. The corresponding rms emittances are about ten times smaller. The phase space distributions of sampled multi-charge-state uranium beam at the entrance and exit of the superconducting linac are shown in Figure 2.

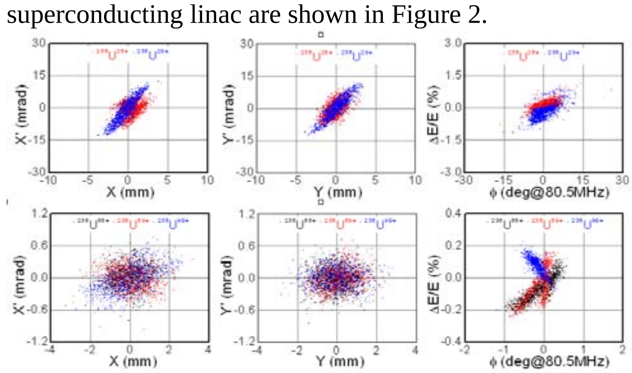

Figure 2: Phase space plots of sampled multi-charge-state uranium beam at the entrance (top) and the exit (bottom) of the superconducting linac.

Particle Tracking with Errors

To estimate performance of the linac under more realistic conditions, simulations were performed with physical misalignments, rf amplitude and phase errors, and thickness variations of the stripping foils. The transverse displacements were assumed to be a Gaussian distribution with $\sigma = 1$ mm and truncated at ±2 mm for both solenoidal magnets and superconducting cavities. The correction of the beam centroid after misalignment was performed using beam position monitors between cryomodules and dipole windings in the solenoidal magnets as discussed above. IMPACT read both the misalignments and the corresponding correctors from DIMAD for particle tracking. The rf phase and amplitude errors for the accelerating cavities were set to $\pm 0.5^o$ and ±0.5% in a uniform distribution throughout the linac. Foil thickness variations at the level of ±5% were also included. The alignment and rf error tolerances are reasonable and have been shown to be achievable in the past.

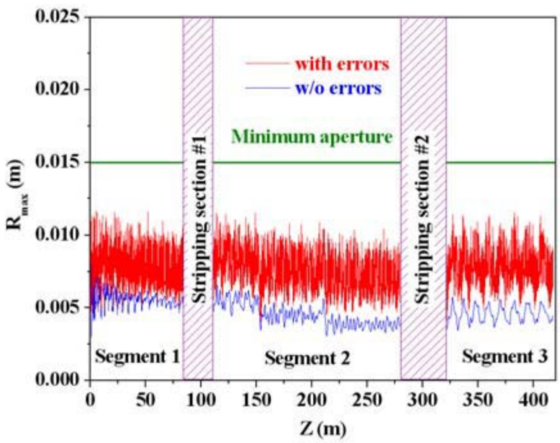

Figure 3: Beam envelopes of a multi-charge-state uranium beam without (blue) and with (red) errors along the driver linac. The minimum linac aperture is also indicated.

To obtain a statistical sampling of possible error distributions, simulations were performed for multiple random seeds. End-to-end beam dynamics through the superconducting linac used the ~1 million particles simulated from the front-end. Figure 3 shows the beam envelopes along the superconducting linac for fifty random seeds. The blue curve corresponds to the beam simulation without errors, and the red curve is for the case of errors included. The green line shows the minimum linac aperture. The red curve is the largest transverse position of any of the tracked particles from the any of the seeds recorded along the linac. The margin between the beam envelope with errors and the linac aperture indicates that the error tolerances are appropriate and that the driver linac will have an adequate transverse acceptance.

Figure 4 shows the evolution of the transverse and longitudinal emittances for the multi-charge-state uranium beam. For the simulations with errors, the emittances along the linac were the worst case among the fifty seeds. At the linac exit, the 99.5% transverse emittance is less than 2 π·mm·mrad, while the 99.5% longitudinal emittance is 37 π·ns·keV/u. The transverse emittance growth is mainly due to the alignment errors, and the longitudinal one is primarily caused from the rf errors. The longitudinal acceptance of Segment 1 of the driver linac is 8 π·ns·keV/u, whereas the beam emittance from the front-end is 1.1 π·ns·keV/u with errors, giving an acceptance-to-emittance ratio of ~ 7.3. The longitudinal acceptance-to-emittance ratios are even larger for the downstream segments as illustrated in Figure 4. No uncontrolled particle loss was observed in the simulations.

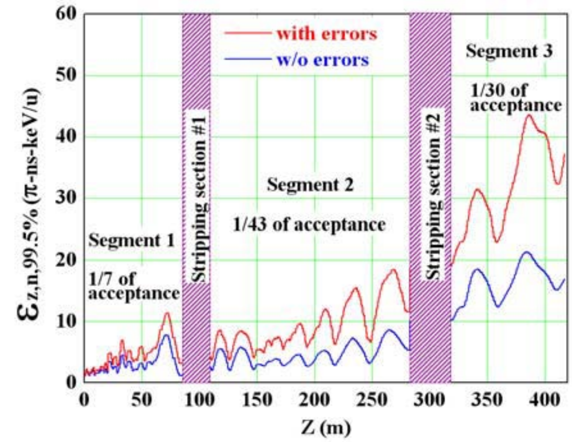

Figure 4: The longitudinal emittance evolution along the superconducting linac for uranium beam with (red) and without (blue) errors.

SUMMARY

The end-to-end beam simulations indicate that the driver linac has adequate transverse and longitudinal acceptances, and will provide good overall performance even for acceleration of the multiple charge states of the uranium beam. The error tolerances are reasonable and known to be achievable from past experience. The emittance growth when all the errors are included was found to be tolerable and remains well within the linac acceptance. The beam envelopes fit adequately within the transverse aperture and no uncontrolled beam loss was observed.

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