BEAM SIMULATIONS FOR THE MSU-RIA DRIVER LINAC USING IMPACT CODE*

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Abstract

Previous beam dynamics simulation studies using LANA code at Michigan State University (MSU) including alignment and rf errors and the effect of the charge strippers have indicated that the Rare Isotope Accelerator (RIA) driver linac proposed by MSU has adequate transverse and longitudinal acceptances to accelerate light and heavy ions to final energies of ≥400 MeV/u with beam powers of 100 to 400 kW [1]. Recently, the beam dynamics simulation studies for the driver linac were performed with the IMPACT parallel code on the high performance computers at MSU. IMPACT [2] code was first benchmarked with LANA [3] code, and the results from the two codes are in good agreement. IMPACT has then been used for beam simulations, especially for high statistics evaluations. In this paper, we present the results of the beam dynamics studies using IMPACT code.

INTRODUCTION

The goal of the RIA driver linac is to produce high energy, high intensity stable heavy ions for the production of rare radioactive isotopes. The driver linac will accelerate any stable isotope (protons to uranium) to energies ≥400 MeV/u, and deliver at least a 100 kW beam and if ion source performance permits, up to 400 kW of stable isotope beam power to radioactive beam production targets. To meet the beam power requirement, the RIA driver linac is designed to allow the acceleration of a two-charge state beam from the ion source for isotopes of mass ≥ xenon. In addition, two charge stripping sections were used to increase the charge state for the heaviest ions. The design of the RIA driver linac is largely determined by the requirement of a 400 MeV/u, 100 kW uranium beam, and the need to accelerate a wide range of ions while limiting the uncontrolled beam loss below 1 W/m to facilitate hands-on maintenance. The minimization of beam losses, enhanced reliability, and low cost are the main driving considerations in the design.

The baseline linac design utilizes a room temperature front end and a superconducting (SC) linac operating in cw mode. Figure 1 illustrates the layout of the MSU RIA driver linac. The front end consists of three systems: 1) the ECR ion source(s) with concomitant high-voltage platforms and charge-state selection systems, and a Low Energy Beam Transport (LEBT) system that bunches the beam and provides the six-dimensional phase space matching; 2) A Radio Frequency Quadrupole (RFQ) to accelerate beam from ~12 keV/u to ~300 keV/u providing beam velocities appropriate for injection into the first segment of the SC linac; 3) A Medium Energy Beam Transport (MEBT) to match the beam from RFQ into the SC driver linac.

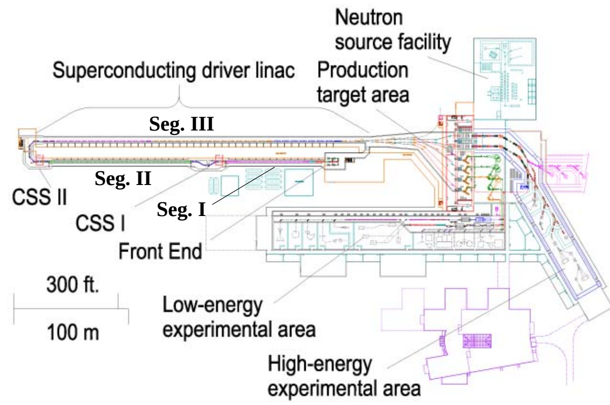

Figure 1: Layout of the MSU RIA facility.

The SC linac consists of three segments connected by two charge stripping and selection sections, as shown in Figure 1. Segment I uses quarter wave resonators and accelerates uranium beam with two charge states (U^{28+}, U^{29+}) from ~0.3 MeV/u to ~12 MeV/u. For uranium, five charge states (U^{71+} to U^{75+}) are selected after the first stripper (CSSI) and accelerated to 89 MeV/u through Segment II half wave resonators. The charge states are further increased through the second stripper (CSSII) where three charge states (U^{87+} to U^{89+}) are selected. Segment III uses elliptical cavities and accelerates uranium beam to the final energy of 400 MeV/u (1GeV for protons).

BEAM SIMULATION CODES

Various computer codes have been used for beam dynamics studies [1]. The simulations for the front end were primarily done using PARMELA and PARMTEQM to include space-charge effects. LANA [3] was used for the 6D phase space particle tracking with rf and alignment errors in the SC linac segments. Recently a special version of IMPACT [2,4] code developed for RIA design was installed at the MSU high performance computer center and used for beam dynamics simulations. In addition, we started to use the newly developed RIAPMTQ code [4] for front end simulation. Both IMPACT and RIAPMTQ are capable of running on parallel supercomputers and therefore are adequate for end-to-end RIA driver linac beam loss studies with high statistics. Multi-processor running is very helpful to

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reduce the execution time in high statistic beam dynamics simulations. Figure 2 shows the running time versus number of processors for tracking 1.6 million particles throughout the linac on the high performance computers at MSU. The running time was 49 hours with a single processor, comparable to LANA, and decreased to 2.4 hours with 40 processors. Ten processors are typically used to track one million particles.

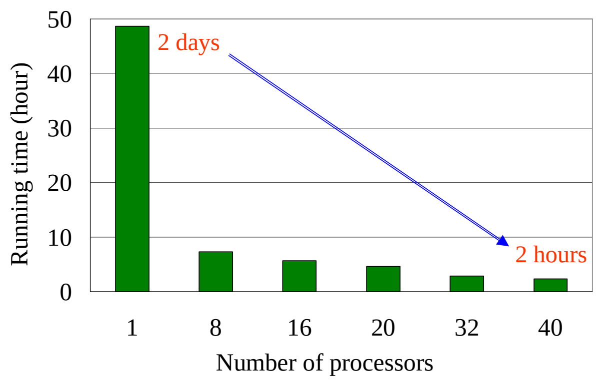

Figure 2: Running time versus number of processors for 1.6-million-particle tracking throughout the SC linac on the high performance computers at MSU.

IMPACT VERSUS LANA

Comparisons of IMPACT and LANA simulation results for MSU-RIA superconducting linac including the charge stripping and selection sections have been performed. As an example, Figure 3 and Figure 4 show the energy gain and rms emittances of multi-charged uranium beam along the MSU-RIA driver linac from both codes. Neither misalignment nor rf errors were included in this simulation. Other parameters, such as 99.5% emittances and transverse beam envelope were also in good agreement.

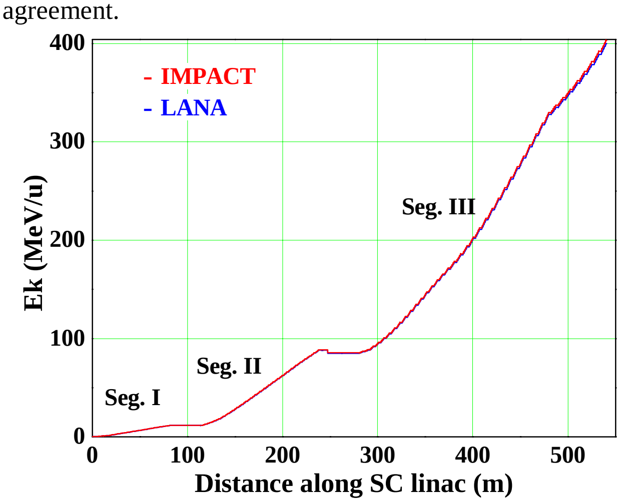

Figure 3: Energy gain along the superconducting linac with IMPACT and LANA code.

BEAM SIMULATIONS WITH ERRORS

A critical design issue for the driver linac is to limit the uncontrollable beam loss along the linac to minimize

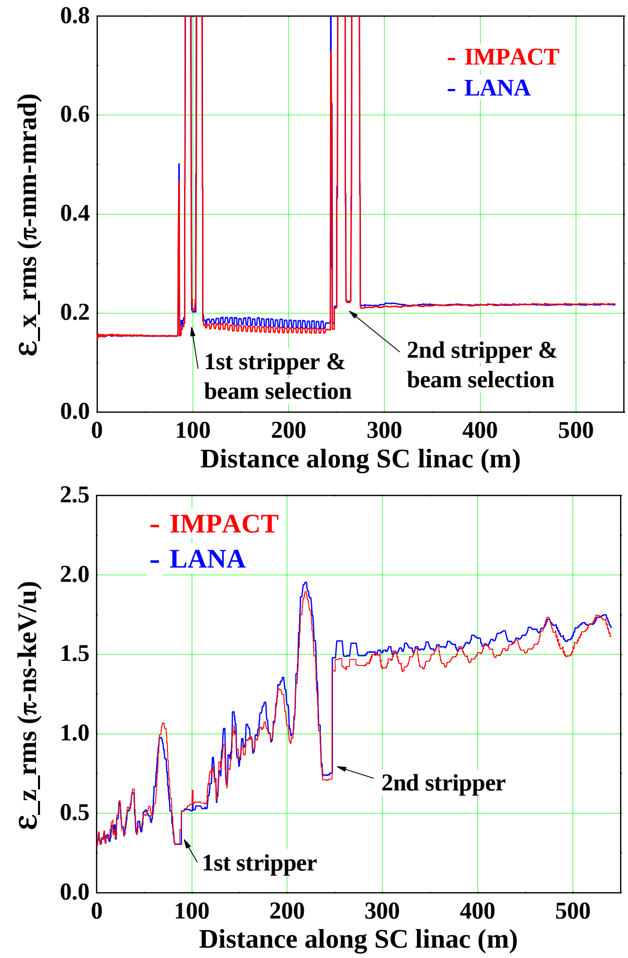

Figure 4: Horizontal (top) and longitudinal (bottom) rms emittances along the superconducting linac with IMPACT and LANA codes. Vertical emittance is not shown but similar to horizontal one.

induced radioactivity and minimize any additional cryogenic load. Therefore, beam simulations with high statistics are crucial to accurately evaluate beam losses under various operating conditions.

Errors including the phase and amplitude of rf field for superconducting cavities, and the misalignment of the focusing elements (solenoid in Segments I and II, quadrupole in Segment III) and rf cavities were simulated for the whole linac. The nominal specifications for rf jitter and misalignment are listed in Table 1. Uniform distribution and ±2σ truncated Gaussian distribution were assumed for rf jitter and misalignment, respectively. An alignment correction procedure using orbit correctors and beam position monitors in the lattice was used to limit the central orbit distortion due to misalignment. In additon, ±5 % variation of stripper thickness was included in beam simulations.

Table 1: Specifications of RF Field and Alignment Errors

Phase jitter	Amplitude jitter	Misalignment
±0.5 %	±0.5 degrees	±1.0 mm

Beam simulations for the SC linac with a total of 100 random seeds of specified errors have been performed using the IMPACT code. Half a million particles tracked from the exit of ion source through LEBT, RFQ and MEBT to the entrance of superconducting linac have been used in the beam simulations studies with errors. The beam envelope of multi-charged uranium beam along the SC linac without errors is shown in Figure 5 together with the maximum transverse beam envelope at each longitudinal position among the 100-seed runs. The minimum transverse apertures along the linac are also shown in the figure, which are 15mm in Segment I and II for SC cavity aperture, and 25 mm for transverse focusing quadrupole aperture in Segment III. The beam envelope growth was found to be mainly due to the lattice element alignment errors. No beam losses were observed for the 100-seed runs with the nominal error specifications. This result is in agreement with that of previous beam dynamics studies using LANA code [1]. For larger rf errors, however, beam losses at the level of 10^{-6} did occur with rf errors ±1 degree of phase and ±1% of amplitude. When rf errors were increased up to ±2deg/±2% and ±5deg/±5%, beam losses were at the level of 10^{-5} and 10^{-3}, respectively. The beam losses were initiated by the longitudinal emittance growth due to the larger amplitude of oscillations in longitudinal phase space for larger rf errors. The longitudinal motion was then coupled into transverse plans and led to the eventual transverse beam loss.

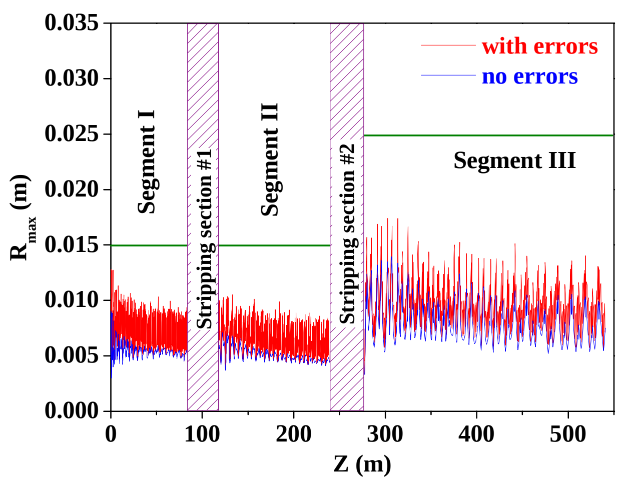

Figure 5: Maximum beam envelope along the superconducting linac with and without errors. Minimum beam apertures in each segment are shown as well.

Figure 6 shows the longitudinal 99.5% beam emittance along the linac with and without errors. With errors the emittance at each position is the maximum value of 100 seeds. The rf errors and strippers were the main contributions to the longitudinal emittance growth along the SC linac. Though the rf errors do not bring about significant emittance increase for individual bunches, their impact on the effective longitudinal emittance of consecutive bunches is significant. However, no beam losses were observed even with the emittance growth.

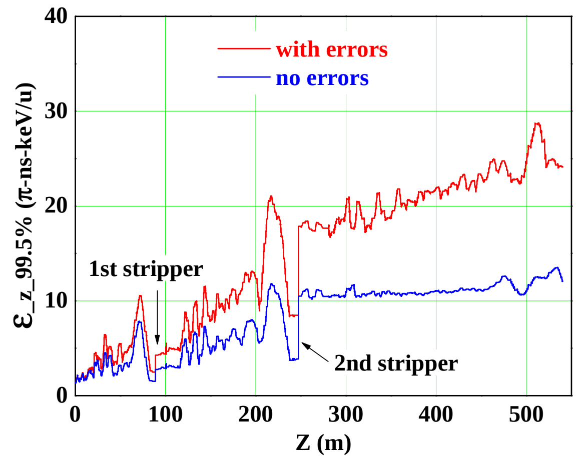

Figure 6: Longitudinal emittance with and without errors along the superconducting linac.

SUMMARY

Extensive end-to-end beam dynamics simulations with high statistics using the recently developed IMPACT code including alignment and rf errors and charge-stripping foils were performed at MSU. The results of these studies show that the MSU RIA driver linac design meets the requirements for the RIA driver linac even for the case of the most challenging acceleration of multi-charge-state uranium beam.

The beam dynamics studies show that the specified rf jitter and misalignment tolerances are acceptable in terms of final beam quality and beam losses. Beam simulation results using IMPACT code are in good agreement to those of LANA code. IMPACT, however, runs much faster with multiple processors making it especially suitable for high statistic beam dynamics studies. A newly developed parallel-processor version of PARMTEQM, named RIAPMTQ [4] is now available for the MSU-RIA front end beam dynamics simulations. In addition, RIAPMTQ/IMPACT codes will also be used to perform end-to-end simulations for other projects, such as the upgrade of existing NSCL facility at MSU [5].

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