ADVANCED BEAM-DYNAMICS SIMULATION TOOLS FOR RIA*

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Abstract

Understanding beam losses is important for the high-intensity RIA driver linac. Small fractional beam losses can produce radioactivation of the beamline components that can prevent or hinder hands-on maintenance, reducing facility availability. Operational and alignment errors in the RIA driver linac can lead to beam losses caused by irreversible beam-emittance growth and halo formation. We are developing multiparticle beam-dynamics simulation codes for RIA driver-linac simulations extending from the low-energy beam transport (LEBT) line to the end of the linac. These codes run on the NERSC parallel supercomputing platforms at LBNL, which allow us to run simulations with large numbers of macroparticles for the beam-loss calculations. The codes have the physics capabilities needed for RIA, including transport and acceleration of multiple-charge-state beams, and beam-line elements such as high-voltage platforms within the linac, interdigital accelerating structures, charge-stripper foils, and capabilities for handling the effects of machine errors and other off-normal conditions. In this paper we present the status of the work, including examples showing some initial beam-dynamics simulations..*

INTRODUCTION

The present concept for the Rare Isotope Accelerator (RIA) project [1] includes a 1.4-GV CW superconducting driver linac. The driver linac is designed for multicharge-state acceleration [2] of all stable species, including protons to 900 MeV and uranium to 400 MeV/u. In conventional heavy-ion linacs, a single charge-state beam of suitably high intensity is extracted from an electron-cyclotron resonance (ECR) ion source and injected into the linac. The linac typically contains one or more strippers at higher energies to further increase the beam charge state and improve acceleration efficiency. However, the limitation to a single charge state from the ion source and from each stripper significantly reduces the beam intensity. This disadvantage is addressed in the RIA driver-linac design concept by the innovative approach of simultaneous acceleration of multiple charge states of a given ion species, which results in high-power beams of several hundred kilowatts for all beams ranging from protons to uranium. Initial beam-dynamics studies [2], supported by experimental confirmation at the Argonne ATLAS facility [3], have demonstrated the feasibility of this new approach.

However, the high-power beam associated with the multiple charge-state acceleration introduces a new design constraint to control beam losses that cause radioactivation of the driver linac [4]. Radioactivation of the linac-beamline components will hinder routine maintenance and result in reduced availability of the facility. Therefore, it will be important for the RIA project to produce a robust beam-dynamics design of the driver linac that minimizes the threat of beam losses. As an important consequence of this design requirement, it will be necessary to develop a computer-simulation code with the capability of accurately modeling the beam dynamics throughout the linac and computing the beam losses, especially at high energies where beam loss translates into greater activation.

The driver linac is made up of three sections. The first is the pre-stripper accelerator section consisting of an ECR ion source, and a low-energy beam transport (LEBT) line, which includes a mass and charge-state-selection system, and a buncher/radiofrequency quadrupole (RFQ) injection system. This is followed by the initial linac stage consisting of a room-temperature RFQ linac, a medium-energy beam transport (MEBT) line, and the low-velocity (low-β) superconducting accelerating structures. The pre-stripper section, accelerates the beam, consisting of two charge states for uranium, to an energy of about 10 MeV/u, where the beam passes through the first stripper and new charge states are produced.

The second section of the linac uses medium-β superconducting structures to accelerate the multicharge-state beam from the first to the second stripper at an energy of about 85 MeV/u. This medium-β section accelerates about five charge states for uranium. This is followed by the third and final section of the linac, which uses high-β superconducting structures to accelerate typically four charge-states for uranium to a final energy of 400 MeV/u.

The overall performance of the driver linac is crucially dependent on the performance of the LEBT and RFQ. The LEBT is designed to focus, bunch, and inject two charge states for uranium into alternate longitudinal buckets of the RFQ. The LEBT RF buncher system consists of two main components. The first RF buncher cavity system (multiharmonic buncher) uses four harmonics and is designed to capture 80% of each charge state within the longitudinal acceptance of the RFQ. A

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second RF buncher cavity matches the velocity of each charge state to the design velocity of the RFQ.

To avoid problems from beam-induced radioactivation, beam losses must be limited to less than about 1 watt per meter [5],[6], particularly in the high-energy part of the accelerator. This low beam-loss requirement imposes a challenge for controlling the emittance growth throughout the driver-linac, especially because of the complication of multiple charge-state beams. In addition to increasing the intensity, acceleration of multiple charge-state beams produces a larger total longitudinal emittance, increasing the threat of beam losses. For any proposed design it is imperative to compute the high-energy beam losses with sufficient accuracy to ensure that the beam-loss requirements are satisfied. Such a computation normally requires the use of simulation codes that accurately track the beam particles through the whole accelerator using a physics model that includes all effects that can lead to emittance growth and possible beam losses.

A significant amount of accelerator design work has already been done at two institutions, Argonne National Laboratory (ANL) [5] and Michigan State University (MSU) [7]. The LANA code [7,8] is presently used at MSU for superconducting linac simulations. The code TRACK [9] is used at ANL. The LANA code was used extensively during the design and commissioning of the radioactive beam linac ISAC-1 at TRIUMF [10]. It was benchmarked as a result of the commissioning measurements, and is also being used for the design of ISAC-II, a superconducting linac for production of ion beams with energies above the Coulomb barrier.

Although much code development has already taken place for RIA, more work to develop faster end-to-end simulation tools will be important for accurate computation of beam losses. The development of such a simulation tool is the primary objective of our work. Additionally, the importance of demonstrating an understanding of the beam-losses justifies the development of more than one such code to provide necessary cross checks of the simulations.

CODE DEVELOPMENT APPROACH

Our starting point for the development of these codes for RIA has been to modify the well-established, and benchmarked, multiparticle-beam-dynamics codes PARMTEQM [11] and IMPACT [12]. The IMPACT code was originally developed to run on parallel-processor machines and models the high-energy superconducting accelerator of the driver linac. However, to provide the necessary speed and statistical accuracy for the low-energy sections, a new parallel-processor version of PARMTEQM, now called RIAPMTQ, has been developed to model the LEBT, RFQ, and MEBT of the RIA driver linac.

RIAPMTQ

The Fortran 90 version of PARMTEQ distributed through the Los Alamos Accelerator Code Group was the basis for RIAPMTQ. For convenience in debugging the code, a PC version of RIAPMTQ was developed simulatneoulsy with the parallel version. This allowed direct comparison of results between the two codes when the NERSC version was run in the single-processor mode. Comparison with results from the PC version was crucial in identifying some programming errors related to the MPI implementation at NERSC.

The code was "parallelized" by incorporating the necessary Message Passing Interface (MPI) commands to allow the code to run in the parallel-multi-processor environment at NERSC. Optimization of the code using "domain decomposition" was not thought to be necessary, therefore, the simpler, more straightforward approach of "particle decomposition" was used. All calls to Windows-based graphics were removed, as were all machine-environment dependent I/O statements. To preserve similarity with the PC-based code, which was our starting point, identical input file formats were retained. The most significant code modifications were required in the parallelization of the space-charge calculations which consume the majority of the computing time in multi-particle simulations. The following RIA-specific modifications were made to RIAPMTQ: transport and acceleration of multiple-charge-state beams (2 at present), beam-line elements including high-voltage platforms within the linac, interdigital accelerating structures, charge-stripper foils, and capabilities for simulations of the effects of machine errors including misalignments, and other off-normal operating conditions.

IMPACT

The IMPACT code is a parallel particle-in-cell (PIC) beam dynamics code. It has a large collection of beamline elements, calculates the acceleration numerically using RF cavity fields obtained from electromagnetic field-solver codes, and calculates 3D space charge with several boundary conditions. Because of already being "parallelized," the IMPACT code has required only minimal modifications for RIA. These include adding the multiple-charge-state capability, modelling of bending magnets, and the stripping models. The multiple-charge-state capability has already been tested. Some benchmarking against the ANL TRACK code, including comparison of energy gain and rms beam properties has been completed. Initial studies of beam loss have also been completed.

SIMULATION RESULTS

Several RIAPMTQ simulations were run as part of the debugging and benchmarking process. A sample input file containing a representative RIA LEBT and RFQ was used. Simulations were run at NERSC using two charge states (28 and 29) of uranium 238. Simulation results at the exit of the RFQ were compared for a single processor on a single node up to 256 processors (16 processors on 16 nodes). Variations in output transverse and longitudinal emittances of up to 11% and 22%, respectively, were observed as the number of processors used or the number of macro-particles was varied. However, average variations in beam transmission were less than 1%. Some numerical noise is expected and a saturation effect should be observed as the number of macro-particles is increased, whereby significant variations in the rms beam properties as a function of the number of particles should diminish.

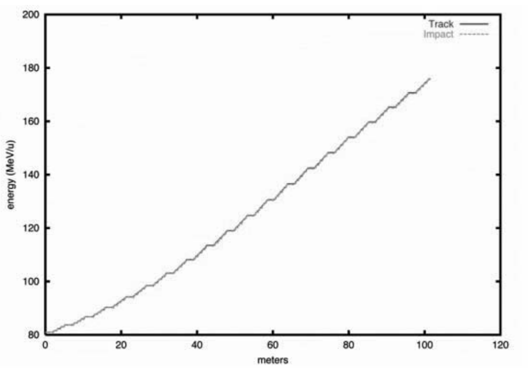

Figure 1: Comparison of IMPACT and TRACK simulations through a portion of the high-beta linac (81 to 177 MeV), showing plots of rms kinetic energy versus distance along the beam line in the superconducting linac.

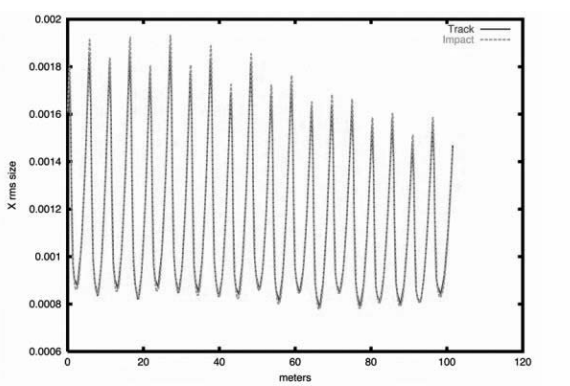

Figure 2: Comparison of IMPACT and TRACK simulations showing plots of horizontal rms beam size versus distance along the beam line in the superconducting linac.

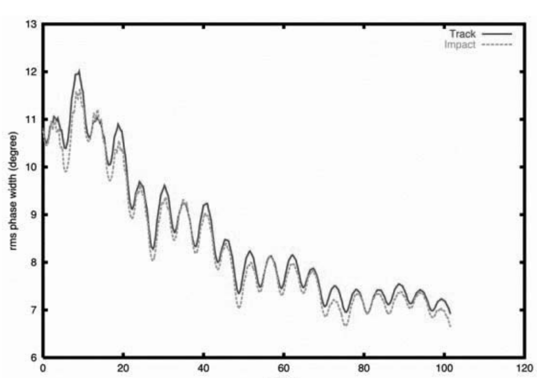

Figure 3: Comparison of IMPACT and TRACK simulations showing plots of longitudinal rms beam size versus distance along the beam line in the superconducting linac.

Figures 1-3 show comparisons of IMPACT simulation results with TRACK through a portion of the RIA high-β linac (81 to 177 MeV). Figure 1 shows a plot of the rms beam energy versus distance in the superconducting linac. Figures 2 and 3 show the horizontal and longitudinal rms beam sizes, respectively, versus distance. Excellent agreement is observed between the two codes (IMPACT and TRACK results overlap). Our next major effort will be to run an end-to-end simulation of a representative RIA driver linac and to do some additional benchmarking against the TRACK and LANA codes.

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