ADVANCED BEAM-DYNAMICS SIMULATION TOOLS FOR RIA*

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Abstract

We are developing multi-particle 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. The codes have the physics capabilities needed for RIA, including transport and acceleration of multiple-charge-state beams, 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. This year will mark the end of our project. In this paper we present the status of the work, describe some recent additions to the codes, and show some preliminary simulation results.*

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 from an electron-cyclotron resonance (ECR) ion source is injected into the linac. The linac typically contains one or more strippers at higher energies to further increase the beam charge states 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.

The high-power beam associated with multiple charge-state acceleration introduces a new design constraint to control beam losses that can cause radio-activation of the driver linac [4]. Radio-activation of the linac beam line 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, we have been developing a computer-simulation code with the capability of accurately modeling the beam dynamics throughout the linac and computing the beam losses.

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 an external multi-harmonic buncher system. The pre-stripper section continues with 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 (multi-harmonic buncher) uses up to four harmonics and is designed to capture 80% of each charge state within the longitudinal acceptance of the RFQ. A second RF buncher cavity matches the velocity of each charge state to the design velocity of the RFQ.

To avoid problems from beam-induced radio-activation, beam losses must be limited to less than about 1 watt per meter [5],[6],[7] particularly in the high-energy part of the accelerator. This low beam-loss requirement imposes a challenge for controlling 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 loss. 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

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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, halo formation, 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) [8]. The LANA code [8,9] is presently used at MSU for superconducting linac simulations. The code TRACK [10] is used at ANL. The LANA code was used extensively during the design and commissioning of the radioactive beam linac ISAC-I at TRIUMF [11]. 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.

Much progress has been made in the last year to develop faster end-to-end simulation tools for RIA to more accurately compute beam losses. The development of such a simulation tool has been the primary objective of our work. This year is the final year of our project. At the end of this year we expect to make our codes, RIAPMTQ and modified IMPACT, available to the RIA accelerator design community. We will also make a users manual available. Eventually, distribution of the RIAPMTQ code may also be available to the general accelerator design community through the Los Alamos Accelerator Code Group (LAACG)

CODE DEVELOPMENT AND STATUS

Our starting point for the development of these codes for RIA has been to modify the well-established and benchmarked, multi-particle beam-dynamics codes PARMTEQM [12] and IMPACT [13]. 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 PARMTEQM distributed through the LAACG was the basis for RIAPMTQ. 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. To preserve similarity with the PC-based code, 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, capabilities for simulations of the effects of machine errors including misalignments, and other off-normal operating conditions, and beam steering. We presently have a PC version of the code, including the modifications, running. The parallel version is still being debugged. Soon we expect to run simulations to benchmark and compare the two codes. An additional stripper model will also be implemented soon. Our RFQ design codes, which are distributed through the Los Alamos Accelerator Ccode Group, including PARI, have also been modified to be compatible with RIAPMTQ.

IMPACT

The IMPACT code is a parallel particle-in-cell (PIC) beam dynamics code. It has a large collection of beam line 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 modifications for RIA. These include adding the multiple-charge-state capability, improved modelling of bending magnets, various stripping models, a beam scraper, and a multipole magnet model including a sextupole, octupole, and decapole.

SIMULATION RESULTS

We recently reported some preliminary simulation and benchmarking results [14]. Additionally, the parallel IMPACT code has been implemented at ANL and is being used to study their driver-linac design [15]. We expect to continue additional benchmarking activities against the TRACK and LANA codes throughout the remainder of this final project year.

For this paper and as an example, we include PC RIAPMTQ simulation results for the Michigan State University (MSU) RFQ design. A sample input file containing a representative RIA RFQ and medium-energy beam transport (MEBT) section was used. Simulations were run using two charge states (28 and 29) of uranium 238. In this example the low-energy beam transport section is not included for simplicity. Two matched initial random input beam distributions were generated at the entrance of the RFQ. The two beams were then simultaneously tracked through the RFQ and MEBT. Table 1 gives some of the RFQ and MEBT parameters, and initial beam parameters used for the simulations. Figure 1 shows the beam envelope as a function of distance along the RFQ and MEBT. The final beam transverse and longitudinal phase-space distributions are also shown. The RFQ transmission is found to be high using our initial input beam parameters. No attempt was made to tune the MEBT parameters to match the downstream driver linac or to give identical output beam parameters for both beams in this example simulation.

After completing the debugging of the parallel version of RIAPMTQ, we hope to soon be able to complete end-to-end simulations using RIAPMTQ and IMPACT for both the ANL and MSU designs.

Table 1. RFQ and MEBT parameters.

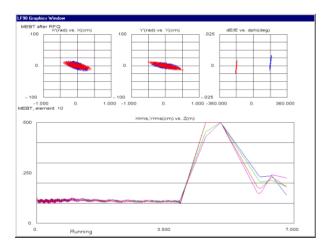| RFQ Frequency	80.5 MHz
RFQ Length	4.09 m
Number of RFQ Cells	175
RFQ Injection Energy	0.01198 MeV/nucleon
RFQ Output Energy	0.29286 MeV/nucleon

MEBT Elements
  Drift
  Solenoid
  Drift
  Buncher
  Drift
  Buncher
  Drift
  Solenoid
  Drift
	
	70.0 cm
	29.1 kG, 40 cm
	102.36 cm
	-90°, VoT=0.039 MV
	4.68 cm
	-90°, VoT=0.039 MV
	32.34 cm
	40.7 kG, 40 cm
	60 cm

Fig.1 RIAPMTQ simulation results for two charge states (28 in black and 29 in red) of uranium 238. Two matched initial random input beam distributions were generated at the entrance of the RFQ. Bottom plots show rms x and y values for the two beams. The two beams were tracked simultaneously through the RFQ and MEBT. The MEBT begins at 4 meters.

SUMMARY AND CONCLUSIONS

By the end of 2005 we expect to have a suite of parallel multi-particle beam-dynamics simulation codes for RIA that will allow simulations extending from the low-energy beam transport (LEBT) line to the high-energy end of the linac. These codes will be used to do realistic high-statistics simulations including operational and alignment errors in order to estimate beam losses and to optimize future design iterations. For any proposed design it is imperative to estimate the high-energy beam losses with sufficient accuracy to ensure that the beam-loss requirements of less than about 1 watt per meter. that will allow hands-on maintenance of the linac, are satisfied.

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