SIMULATIONS OF ION BEAM LOSS IN RF LINACS WITH EMPHASIS ON TAILS OF PARTICLE DISTRIBUTIONS

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Abstract

We present a new approach for beam loss calculations that places emphasis on the tails of the particle distributions. This scheme is used for simulating the SARAF proton/deuteron accelerator, a 176 MHz RF linac complex consisting of a 4-rod RFQ and 44 SC half wave resonator (HWR) cavities designed to operate in CW mode at 4 mA beam current. We discuss our scheme for highlighting the tails of the particle bunches generated by the RFQ. Simulation of the RFQ and RF linac with the tail emphasis technique allows us to increase beam loss statistics by more than an order of magnitude. Error analysis studies now become more feasible and provide a realistic assessment of anticipated beam loss. The technique is also useful for linac tune and optimization with a beam containing the full tail profile but with less CPU time required.

INTRODUCTION

To obtain more statistics in our linac simulations, especially when performing linac tune or error analysis studies, we have developed the tail emphasis technique. The idea behind tail emphasis is straightforward. If a certain region in the initial distribution phase space contains macro-particles that eventually develop into the tail of the distribution, then the number of macro-particles in this region can be multiplied by an enhancement factor. To keep the simulation of space charge correct, the charge contained in each macro-particle in this region is decreased by the same factor.

THE SARAF ACCELERATOR

The SARAF accelerator [1] (figure 1) starts with a ECR ion source. A LEBT transports and matches the beam to a normal-conducting 4-rod RFQ. The RFQ bunches the dc beam into a 176 MHz CW beam and accelerates the ions to 1.5 MeV/u. The MEBT transports and matches the beam into the superconducting (SC) linac. The 40 MeV SC accelerator contains 44 SC HWR cavities at 176 MHz packed in six cryostats as described in details in Ref. [2] The basic linac period is composed of one solenoid and two HWRs. The first 12 HWRs are optimized for geometric β_0=0.09. The remaining 32 HWRs are higher velocity cavities optimized for β_0=0.15.

RFQ SIMULATION

Simulations were performed with the General Particle Tracer (GPT) code [3]. We created an RFQ element within GPT by writing a C-based routine containing parameterization for the RFQ modulations as provided by the RFQ designer [4]. The RFQ potential is approximated by a Bessel-Fourier series, where the eight-term coefficients are calculated using the scheme discussed in Ref. [5]. The solution for the radial matching section is taken from Biscari [6]. Space charge force is calculated by solving for the Poisson equation on a mesh with Dirichlet boundary conditions in the transverse direction, with U_{SC}=0 at r_0. To simulate accurately the influence of the adjacent bunches, we start with a dc beam of length $3\beta\lambda$, where Neumann boundary conditions are applied at the beginning and end with $\partial U/\partial z$=0. The $3\beta\lambda$ beam develops into 3 bunches, where we track the middle one, while the two additional "ghost" bunches are included on either side to provide the correct space charge forces.

The simulations of the RFQ provide a clear picture of the bunching process. Figure 2 shows snapshots in time of the longitudinal phase space of particles in the RFQ. Figure 2a shows the initial dc beam. The green dots represent particles that eventually end up in the middle bunch, while the red dots are particles that end up in the left and right "ghost" bunches. The gray dots are particles that do not succeed in latching on to either the main or ghost bunches, but nonetheless transmitted through the RFQ. Not shown are particles that will be lost inside the RFQ as a result of transverse deflections. Figure 2b shows the longitudinal phase space at an early stage of

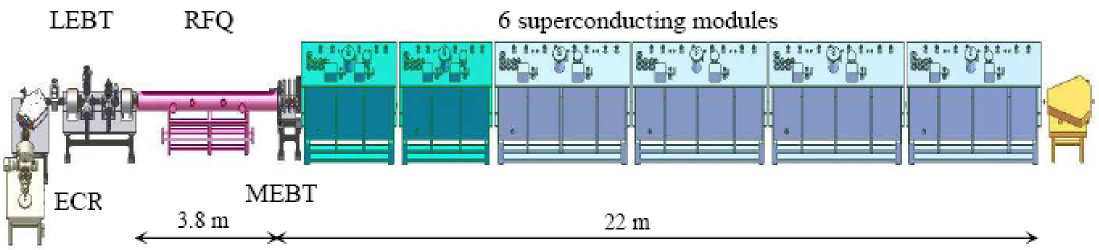

Figure 1: SARAF 40 MeV proton / deuteron superconducting linac.

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** Today at the Department of Physics, Cornell University the bunching process at t=230 ns. Most of the particles quickly find their way towards the nearest bunch, while the particles at the edges of the longitudinal phase are those that form the tails of the longitudinal distribution. Figure 2c at t=567 ns shows the resulting 3 bunches at the end of the RFQ.

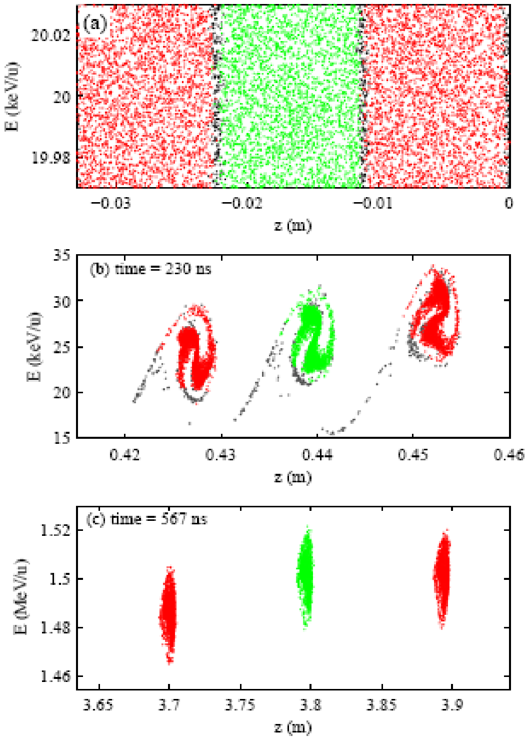

Figure 2: Longitudinal snapshots of mA deuterons along RFQ.
(a): time=0: dc beam of length 3βλ showing main bunch (green), and ghost bunches (red), and long. tail (grey).
(b): time = 230 ns: Bunching at early stage of development.
(c): time = 567 ns: Three bunches at the RFQ exit.

TAIL EMPHASIS AND HIGH STATISTICS RFQ SIMULATION

We have identified the tails in the initial dc beam as the bands between consecutive bunches. For the tail emphasis calculations, we will enhance the number of macro-particles on this tail region by a factor of 100, with a corresponding decrease in the charge of the macro-particles. The two bands are of width of 24^0 each and are about 4.6 % of the initial 3βλ longitudinal distribution. High statistics for the ghost bunches is not necessary, and we therefore reduce ghost bunches by a factor of ten, with a corresponding increase in the charge.

Figure 3 shows longitudinal phase space snap-shots in time for a sample of events using the tail emphasis technique, with tail region enhanced a factor of 100 relative to the main bunch, and ghost bunches are reduced by a factor of 10. The development of the three bunches is similar to that shown in fig. 2, but with a greatly enhanced tail region shown by the blue dots.

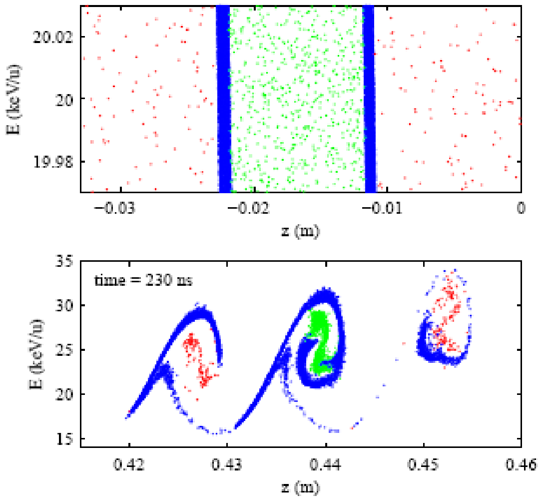

Figure 3: Longitudinal snapshot of 4 mA deuterons along RFQ.Simulations with tail emphasis.
(a): time=0: 3βλ with main (green), and ghost bunches (red).
(b): time = 230 ns: Bunching at early stage of development. Most of the blue macro-particles will end up in the tail, while some will be lost.

SIMULATION OF THE SARAF LINAC WITH TAIL EMPHASIS

Most of the particles in the tail remain within the bunch and are accelerated. The tail particles that remain with the bunch are referred to as 'accelerated particles'. They pose the danger of eventually deviating from the bunch and then hitting the beam pipe, but after obtaining enough energy to cause significant activation of the accelerator components.

Some fraction of the tail particles become sufficiently separated from the bunch that they do not enter the HWR cavities at an accelerating phase and are quickly lost. They do not pose significant danger of activation since they are lost at sufficiently low energies. They are referred to as the 'slow particle' and correspond to about 1.8% of the beam. Details pertaining to the 'slow particles' are discussed in ref. [7].

We perform simulations of SARAF linac with and without tail emphasis for simulations containing 2.1 million macro-particles. For the non-weighted simulation, each macro-particle represents 200 deuterons. With tail emphasis as above, each tail macro-particle corresponds to 10 deuterons.

The linac simulation with the non-weighted distribution did not result in any lost particle, corresponding to an upper limit of 6 nA beam loss over the entire linac. The simulation with tail emphasis also did not result in any lost particle, corresponding to an overall beam loss along the full linac of 0.3 nA. A more realistic assessment of beam loss can be made with an appropriate error analysis study of the RFQ and linac. This subject will be treated in the next section.

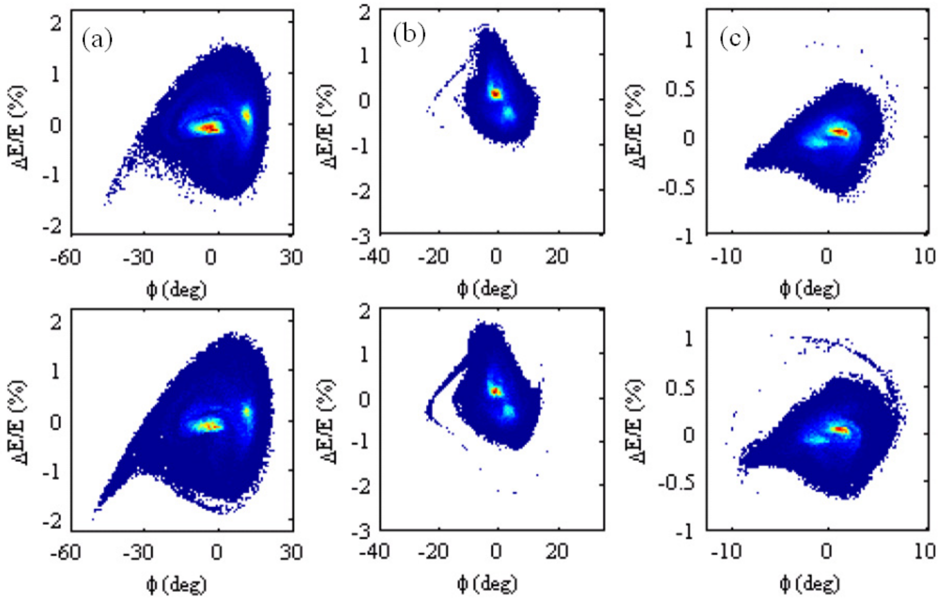

Figure 4: Longitudinal phase space of accelerated particles of main bunch at several locations along linac. Top plots show non-weighted simulation - each macro-particle corresponds to 200 deuterons. Bottom plots show tail-emphasis simulation - each macro-particle in tail corresponds to 10 deuterons. (a) beam at RFQ exit. (b) beam at the exit of the second β_0 = 0:09 cryostat, (c) beam at linac exit.

Figure 4 shows the longitudinal phase space plots of the main bunch at three locations along the linac. The filamentation process is responsible for particles loosing the bunch longitudinally and ultimately for beam loss along the linac. Nonetheless, our simulations show that beam loss along the SARAF linac is low.

END TO END ERROR ANALYSIS

We have made error-analysis simulations at the 1 nA accuracy level. This required a tail emphasis simulation with 600,000 macro-particles, equivalent to a 4 mA deuteron beam. This simulation consisted of 200 randomly generated configurations of the RFQ and the linac. The errors introduced in the RFQ include the voltage and the phase of each cell. The error for the linac include alignment for each of the three MEBT quadrupoles, 22 solenoids and 44 HWRs, and electric fields and phases of the HWRs. The results of these runs are tallied in Fig.5. The average beam loss for all the error configurations is 7.8 nA over the whole linac. Most of the lost particles are at low energy and do not create any hazard. This is within the acceptable upper limits established for the SARAF linac.

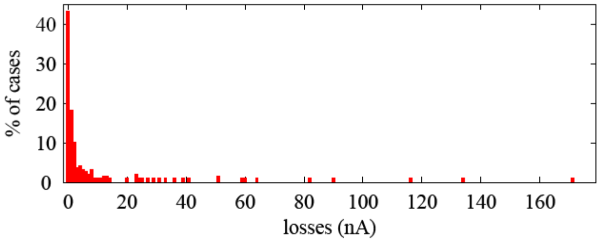

Figure 5: Linac losses for accelerated particles. 200 RFQ and linac error simulations for 4 mA deuterons. Average beam loss 7.8 nA along the whole 22 m linac.

CONCLUSIONS

We have described a method for significantly increasing the accuracy of beam loss simulations by placing emphasis on the tails of the particle distributions. We implemented this method for simulating the SARAF accelerator, starting with RFQ simulations with tail emphasis, and ending with increased sensitivity for beam loss in SARAF linac. We have shown that the tail emphasis method is reliable and can increase statistics in the tail by at more than an order of magnitude. This approach should be suitable for beam loss prediction, error analysis, linac tuning, and simulations where single-particle precision is needed.

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