PROTON BEAM DYNAMICS OF THE SARAF LINAC

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Abstract

We have performed proton beam dynamics simulations for the SARAF (Soreq Applied Research Accelerator Facility), 40 MeV and 4 mA, linac. The simulations are performed using the GPT code and includes effects of space charge. They demonstrate that for an initial 6D ellipsoid Waterbag distribution beam, a tune can be obtained with a longitudinal rms emittance growth of 5% and a transverse normalized rms emittance growth of 20%. Beam loss is estimated by fitting a radial Gaussian to the particle distribution along the linac. A 1 nA beam envelope is obtained by extrapolating the tail of the radial-Gaussian function. The 1nA beam envelope for an initial Waterbag distribution is well within the beam bore radius. However, benchmark simulations with an initial 6D ellipsoid Gaussian distribution, with the same rms quantities, exhibit a more extended tail that may result in higher beam loss.

INTRODUCTION

Beam dynamics simulations for the SARAF [1] linac (fig. 1) are presently being performed at Soreq. We present results of the simulations performed with the General Particle Tracer (GPT) simulation code [2] and the LANA [3] code. Both codes enable precise calculations of particle tracking, taking into account realistic 3D fields of accelerating and focusing elements and also effects of space charge. GPT contains provisions for generating random particles, and for incorporating user supplied codes.

The SARAF accelerator consists of an ECR ion source (20 keV/u), a low energy beam transport (LEBT), a 176 MHz 4-rod RFQ for bunching and pre-accelerating to 1.5 MeV/u, a medium energy beam transport (MEBT), and a linac. The linac is based on independently phased superconducting (SC) 176 MHz half-wave resonator cavities (HWR) and SC solenoids. The accelerator is based on the ACCEL design [4], consists of two types of HWRs, one optimized for η_0=0.09 and a second for η_0=0.15 [5]. The linac consists of six self-contained SC modules. The first module, referred to as the PSM (Prototype SC Module), consists of three solenoids, each followed by two η_0=0.09 HWRs. The remaining five modules consist of 4 solenoids, each followed by two η_0=0.15 HWRs. Figure 1 shows a schematic of the SARAF linac.

Typically, particles simulations generate the initial particle distribution according to a 6D ellipsoid, with either a Waterbag (WB) or Gaussian (Gauss) distribution. The 6D ellipsoid establishes the particle distribution and correlations in x-x', y-y', and z-z', or π-÷E spaces. The WB option establishes a uniform distribution within the 6D ellipsoid, while the Gauss option establishes a density profile with a Gaussian falloff. ACCEL has performed extensive beam dynamics simulations of the linac assuming an initial 6D ellipsoid with a WB distribution. We use the ACCEL linac lattice and tune and repeat their simulation with the codes GPT and LANA.

INITIAL DISTRIBUTION GENERATOR

GPT version 2.52 has no provisions for a 6D ellipsoid, but it does contain option for linking a user routine to the GPT code. We embarked on developing algorithms for creating a 6D ellipsoid, with a WB or Gauss distribution, and incorporating a reliable code into the GPT particle generator. This code was tested and checked for consistency and reliability.

In the algorithm for generating events within a 6D ellipse we first generate random numbers for x, x', y, y', z and z' uniformly distributed within the given boundaries, according to:

$$4\sqrt{\kappa_x\eta_x}\ \Omega x\ \Omega\sqrt{\kappa_x\eta_x}\ \text{and}\ 4\sqrt{\kappa_x\nu_x}\ \Omega x'\ \Omega\sqrt{\kappa_x\nu_x} \qquad (1)$$

and similarly in the y and z plans, where κ is the emittance and η and ν are the Twiss parameters.

If the event is inside the ellipse, i.e. if the inequality in eq.(2) is satisfied then we accept, otherwise, reject the event. This procedure populates a 6D ellipsoid with a uniform particle distribution (except for statistical fluctuations) - a Waterbag distribution.

We base our algorithm for a 6-D Gauss distribution on the acceptance-rejection method of von Neumann [6]. First, we generate an event according to the prescription described above for the 6D WB. The left side of eq.(2),

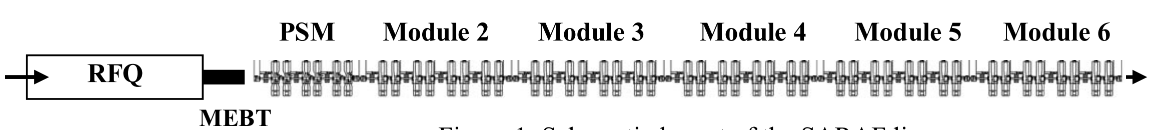

Figure 1: Schematic layout of the SARAF linac.

defined as $\wedge$, represents the fraction of the total for the ellipsoid encompassing the chosen point. $\sqrt{\wedge}$ represents the fraction of maximum extent within the ellipse at the selected orientation. We then generate a random number $0<U<1$. If the inequality, $\exp(4/\sqrt{\wedge}N_\omega)^2/2) \{ U$, where N_ω is the number of standard deviations desired, is satisfied, then we accept the event. This populates a 6D Gauss up to N_ω standard deviations.

$$\left(\begin{array}{l} \frac{1}{\kappa_x}/\nu_x x^2\ 2\ 2\zeta_x xx'\ 2\ \eta_x x'^2)2 \\ \frac{1}{\kappa_y}/\nu_y y^2\ 2\ 2\zeta_y yy'\ 2\ \eta_y y'^2)2 \\ \frac{1}{\kappa_z}/\nu_z z^2\ 2\ 2\zeta_z zz'\ 2\ \eta_z z'^2) \end{array}\right] \Omega 1 \qquad (2)$$

LINAC TUNE

We performed proton beam dynamics simulations of the MEBT+linac using the GPT code and benchmarked the PSM simulation using LANA. The simulations contained the real 3D field maps for the HWRs as calculated by ACCEL using MWS, and included the Scheff prescription for space charge. We generate 5000 macro-particles at 4 mA. The initial particle distribution in GPT was taken as a 6D ellipsoid with a WB or Gauss distribution. The longitudinal rms emittance was 74 ϕ keV deg with Twiss parameters ζ_z=0 and η_z=0.771 deg/keV. The transverse rms normalized emittance was 0.2 ϕ mm mrad, with ζ_x=-1.38 and η_x=0.46 mm/mrad and ζ_y=0.96 and η_y=0.61 mm/mrad. At this stage, misalignment, fabrication and operation errors are not included in the GPT simulation.

A good tune was obtained with small longitudinal and transverse emittance growth, and with a small rms transverse envelope (fig.2) by using exactly the same HWR's amplitude and phase and solenoids field as in ACCEL's PARMELA beam dynamics simulation [7].

We have performed a benchmark simulation of protons in the PSM using LANA. We find a good agreement in the longitudinal phase space in term of bunch width, ion energy and rms emittance. In the transversal phase space there is a good agreement in the rms emittance and a difference in the r_{rms} envelope (fig.3). This difference is caused by the solenoid field approximation. While LANA uses the hard-edge approximation GPT is using a field parameterization that predicts a much closer approximation to the field of the solenoid simulated by ACCEL using OPERA.

We have also performed beam dynamics calculations for 5000 protons with an initial 6D ellipsoid Gaussian distribution. Using the same tune as for the WB distribution we obtained a 33% normalized transversal rms emittance growth along the linac. The r_{rms}

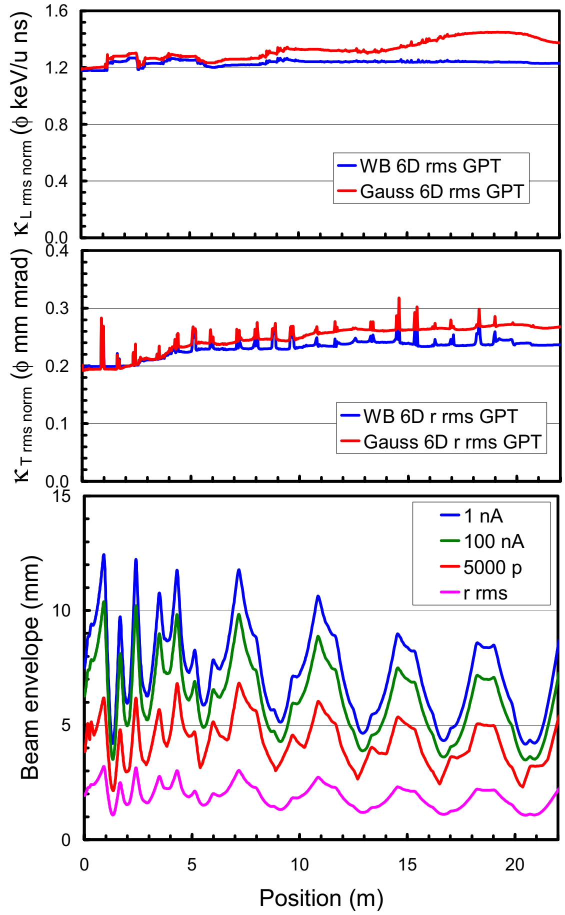

Figure 2: Longitudinal (top) and Transversal (middle) normalized rms emittance along the 22 m of the linac for initial WB and Gauss proton distributions. Bottom: the rms and 5000proton 6D WB simulated envelopes and the prediction of the 1 and 100 nA envelopes along the linac based on eq.(4). The jumps in κ_T are due to the tangent velocity at the solenoids entrance and exit.

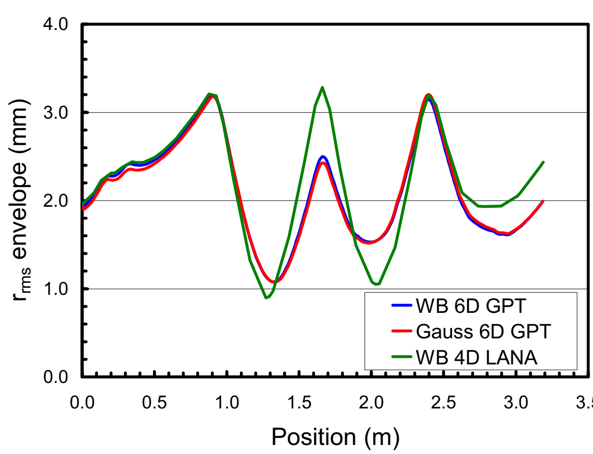

Figure 3: Benchmark simulations of the PSM for different initial proton distributions using GPT and LANA.

($r = \sqrt{x^2 + y^2}$) envelope along the linac for an initial 6D Gauss is very similar to that of the 6D WB (fig.2).

BEAM LOSS PREDICTION

Beam dynamics calculations that contain real 3D fields for the RF cavities and include space charge effects for intense beams are very time consuming. To determine the Hands-On maintenance criterion of 1 nA beam loss out of a 4 mA beam would require a simulation containing at least 4×10^6 macro-particles. Instead, extrapolations relying on simulations with a modest number of macro-particles will provide a rough estimate on the expected beam loss.

At various locations along the linac, histograms are made of the transverse deflections of the simulated particles. Each histogram is fit with a radial Gaussian function. Using this function, an extrapolation is made to the beam bore radius to determine the fraction of events that hit the beam pipe. Alternately, an extrapolation for a 1 nA beam profile can be made.

For our calculations, we assume that the transverse beam has a cylindrical symmetry. This is justified since the MEBT delivers a beam symmetric in x and y to the linac. Although the HWRs introduce a relatively small quadropole effect, the solenoid magnets rotate the beam transversely and help maintain a beam symmetric in x and y. We parameterize the transverse spread as a "modified radial Gaussian" function in r, as follows:

$$dI = k \frac{r}{\sigma^2} e^{\left(-(r-r_1)^2 / 2\sigma^2\right)} \cdot dr \qquad (3)$$

where r_1 is a free parameter, I is the beam current and K is a normalization factor.

Figure 4 shows probability function histograms of the transverse distribution of the 5000 macro-particles at the location of the 3rd and 8th solenoids, where the largest transverse size occurs. Also superimposed on the histogram is a best fit of the "modified radial-Gaussian" probability function of eq.(3). The events in the tail of the histogram lies below the curve of this modified radial-Gaussian fit for the initial 6D WB distribution, however, the initial 6D Gaussian simulation show events that deviate significantly from the "modified radial-Gaussian" fit.

For a beam pipe bore radius $R >> r_1$ (and approximating $r_1=0$) the beam loss is given by:

$$\frac{I_{loss}}{I_0} = \exp\left(-\frac{R^2}{2\sigma^2}\right) \quad \text{and} \quad \sigma = \frac{r_{rms}}{\sqrt{2}} \qquad (4)$$

$$\frac{1\,\mathrm{nA}}{4\,\mathrm{mA}} = 2.5 \times 10^{-7} \quad \Rightarrow \quad R = 5.5\sigma$$

The method for determining the 1 nA transverse beam profile is straightforward. We take the profile for r_{rms} and multiply by a factor of $5.5/\sqrt{2}$, as shown in eq.(4). The result is the 1 nA profile as shown in fig.2. This 1 nA envelope is well within a beam bore radius of 15 mm.

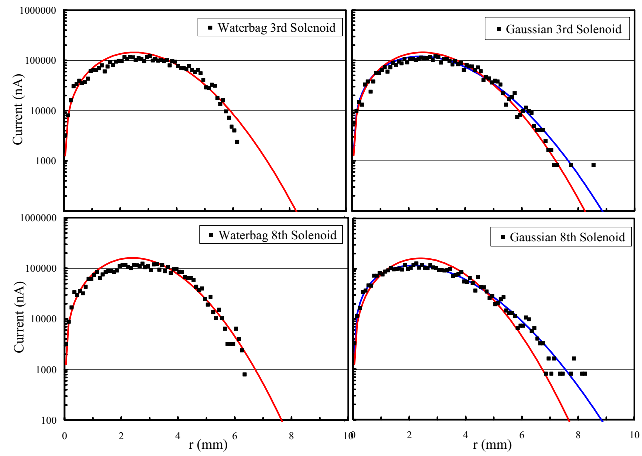

Figure 4: Proton transverse distribution probability function at the location of the 3rd solenoid (top) and the 8th solenoid (bottom) for initial WB and Gauss 6D distributions and best fits to the data using eq.(3). The fitting curve of the WB distribution (in red) is presented on top of the Gauss histograms (right) in order to guide the eye.

CONCLUSIONS

The SARAF proton beam dynamics simulation demonstrate that for an initial 6D WB distribution a tune with rms emittance growth less than 5% longitudinally and 20% transversally and envelope well within the beam pipe is obtained. The 1 nA radial-Gaussian extrapolation appears to be justified for an initial 6D WB distribution. However the 6D Gauss distribution exhibits a more extended tail than the prediction of the "modified radial-Gaussian" curve.

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