DESIGN STUDIES OF THE DARHT PHASE II INJECTOR WITH THE GYMNOS PIC CODE*

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Abstract

We have used the GYMNOS 2D (r-z) electro-/magnetostatic PIC simulation code to help design a high current, high brightness, 3.2-MV injector for the DARHT Phase II accelerator. GYMNOS is particularly noteworthy for its use of piece-wise linear approximations to curved boundaries within a regular orthogonal mesh, which aids in modeling complex surfaces. We present a number of comparisons between GYMNOS and EGUN results, both in terms of "coarse" parameters such as emitted current and beam envelope dynamics, and "fine" details such as the transverse phase space distribution.

1 INTRODUCTION

The DARHT Phase II accelerator is a 20-MV, 4-kA, induction linac to be built at LANL with a nominal pulse length of $2-\mu$s. This pulse will subsequently get chopped into four short duration ($\Delta\tau \sim 60$ ns) pulses which will then be focused onto a metallic converter for radiographic imaging purposes; a more detailed summary is available in Ref. [1]. Among the various challenging physics aspects of the injector and accelerator design is the need to produce a very low transverse emittance over the full temporal pulse width. At present, our goals for ε_n (edge) are $\leq 500\pi$ mm-mrad for the injector and $\leq 1200\pi$ mm-mrad at the x-ray converter approximately 20-m downstream of the accelerator. Success in this area for the injector requires, among other things, a very "quiet" and highly uniform emission surface, very careful design of the electrode geometry to minimize nonlinear electrostatic fields and to prevent unwanted electrical breakdown, and appropriate longitudinal shaping of the solenoidal magnetic field in the A-K gap and beyond to prevent radial oscillations of the beam from converting space charge energy into transverse emittance.

This paper presents the current status of LBNL/LLNL PIC simulations of the DARHT II injector with the time-dependent, azimuthally symmetric GYMNOS code[2] and compares its results with those obtained with the EGUN ray-tracing code[3]. GYMNOS is a fully relativistic, 2-1/2 D, electro- and magnetostatic code which uses an iterative ADI approach to solve the necessary elliptic field equations. Both electric and magnetic collective fields are determined, including the diamagnetic A_θ induced by beam rotation in external solenoidal focusing fields. GYMNOS employs the "Embedded Curved Boundary" (ECB) method[4] for representing curved boundaries via a piece-wise linear approximation on a uniformly-spaced Cartesian mesh. The ECB method is far more detailed than simple staircase approximations to curved surfaces while remaining more computationally efficient than most adaptive mesh techniques.

We first discuss the overall injector geometry and compare the the steady-state GYMNOS and EGUN beam envelope results. We then examine details of the emission near the cathode/Pierce shroud boundary where apparent limitations of the simulation grid resolution and/or present ECB formulation results in difficulties when modeling extremely low emittance beams.

2 INJECTOR GEOMETRY AND FULL VOLTAGE CURRENT FLOW

In order to minimize the possibility of electrical breakdown in the 30-cm A-K gap, the present injector design uses a relatively large (10-cm radius), heated dispenser cathode surrounded by a Pierce shroud extending radially outwards to 40 cm. "Velvet" cathodes, while more robust in terms of insensitivity to vacuum contamination, are believed to produce too transversely warm and possibly insufficiently uniform emission to satisfy the high brightness requirements. The anode surface facing the cathode has a radius of curvature of 8 cm and 16 cm for r less than and greater than 20 cm, respectively. At a 3.2 MV potential drop, the peak electric field is approximately 162 kV/cm on the shroud and 189 kV/cm on the anode. The anode entrance opening radius asymptotes to 12.5 cm. Within the anode is a solenoid magnet, typically run at a current sufficient to produce a peak field of about 500 G to keep the beam well-confined radially as it drifts from the anode into the first accelerator cell magnets. Equidistant behind the cathode is an identical bucking solenoid to zero out any B_z field at the emission surface.

Given this configuration, the EGUN code predicts a steady-state beam current of 4.1 kA for a nominal injector voltage of 3.2 MV. The beam envelope radius smoothly shrinks down to approximately 7 cm as it passes into the anode opening and remains at that radius until it enters the first accelerator cell another 40 cm downstream. In these runs the beam rays were emitted at the 5 kV potential con-

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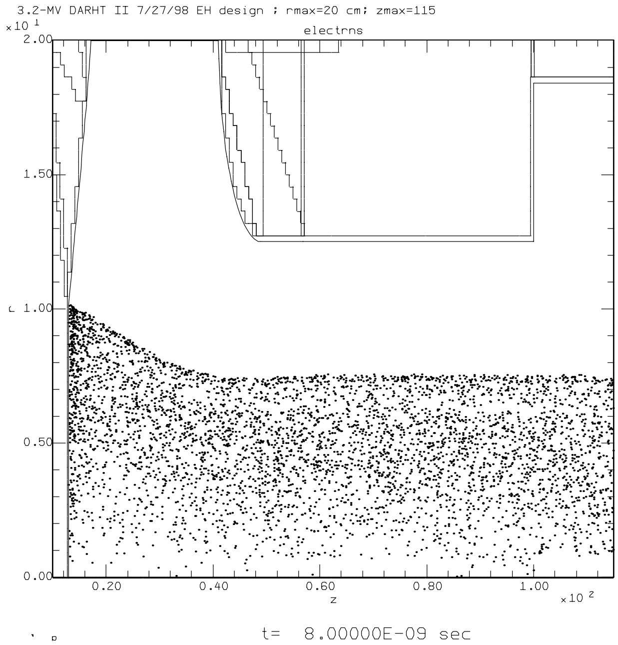

Figure 1: $r - z$ particle scatter plot from a GYMNOS simulation of the DARHT II injector

tour, approximately 4 mm downstream of the cathode surface, and very fine ($\Delta r = \Delta z = 1$ mm) gridding was used. More information on the design and EGUN results are available in Ref. [5].

GYMNOS runs with the same injector parameters show similar but not identical results. Since GYMNOS is a "normal" time-dependent PIC code, it is necessary to gradually ramp up the electrode voltages to minimize "shock" excitation of beam and electric field oscillations. We found that a 2-ns voltage risetime gave a smooth increase of emitted beam current and minimal radial bounces and/or particle reflection from virtual cathodes. The beam envelope evolution with z is quite similar to that predicted by EGUN. Figure 1 displays an r-z scatter plot of a GYMNOS simulation at $t = 8$ ns. Of the actual 100,000+ macroparticles in the simulation volume at this time, only ~10% are shown. For the simulation volume of 120 cm in z and 20 m in r, we used 126 and 45 grid points in z and r, respectively, leading to $\Delta r = 0.45$ cm and $\Delta z = 0.7$ cm.

Despite the good agreement in the beam envelope dynamics, there is a surprising disagreement in the magnitude of the emitted current with GYMNOS results being consistently $\sim 10 - 15\%$ higher. Some numerical tests have shown that while this discrepancy is insensitive to the grid cell size, there is an apparent sensitivity of I_{emit} to details of the macroparticle "birth" algorithm for space-charge limited flow. In each timestep GYMNOS places newly born particles within a "sheath" approximately one longitudinal grid cell wide downsteam of the emitting surface. As the sheath width is decreased by up to a factor of four, the total emitted current can change by some tens of percent. Since other tests at non-relativistic energies and previous GYMNOS modeling of ion injectors[2] showed

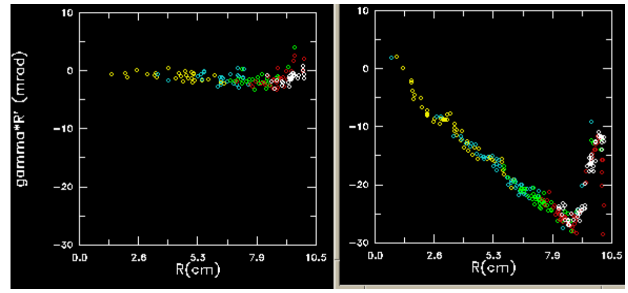

Figure 2: $r - \gamma r'$ snapshots at $z = 13.05$ and $z = 13.65$ cm for the same simulation shown in Fig. 1; the cathode surface is at $z = 13.0$ cm. Each plot includes particles within 0.05 cm of the nominal z position. The ordinate ranges from -30 to 10 mrad, the abscissa from 0 to 10.5 cm.

good agreement between Child's Law and the emitted current, we suspect that the emission algorithm need improvements for accurate resolution of the current sheath density and velocity profile for the relativistic injector energies relevant to DARHT.

3 PHASE SPACE EVOLUTION AND MODELING DIFFICULTIES NEAR THE CATHODE/SHROUD BOUNDARY

Given the high brightness wanted from the DARHT II injector, a great deal of effort has been spent on optimizing the gap geometry and solenoidal focusing profile downstream. At present, EGUN predicts that the normalized emittance jumps to approximately 1000 pi mm-mrad some 50 cm downstream of the cathode, stays this high for about one additional meter, and then (according further single-slice transport by the SLICE code[6]) oscillates and damps down to an exit emittance of ~500 pi mm-mrad at the exit of the first 8-cell block 5-m downstream of the cathode. These numerical values correspond to the "edge" emittance, defined as $4 \times \varepsilon_{RMS}$.

GYMNOS runs, which have been limited by CPU constraints to ~1 m of transport beyond the cathode, have shown consistently higher transverse emittance values, generally by a factor of 2-3X. After some development of post-processing tools to permit detailed investigations of particle dump "snapshots" (we cannot stress too highly how useful tools like these are in examining the fine details available in multi-dimensional PIC codes), we discovered that transverse phase space anomalies began appearing immediately downstream of the cathode surface. Specifically, a "hook" in $r - \gamma r'$ develops for $r \geq 9.0$ cm such that the smoothly increasing radial convergence for lesser values of r suddenly drops by a factor of two. An example of this behavior is shown in the $r - \gamma r'$ phase plots of Fig. 2, 0.5 and 6.5 mm downstream of the cathode. The equivalent normalized transverse emittance increase is close to 1000 pi mm-mrad within 1 cm downstream of the cathode, many times greater than found in the EGUN simulations.

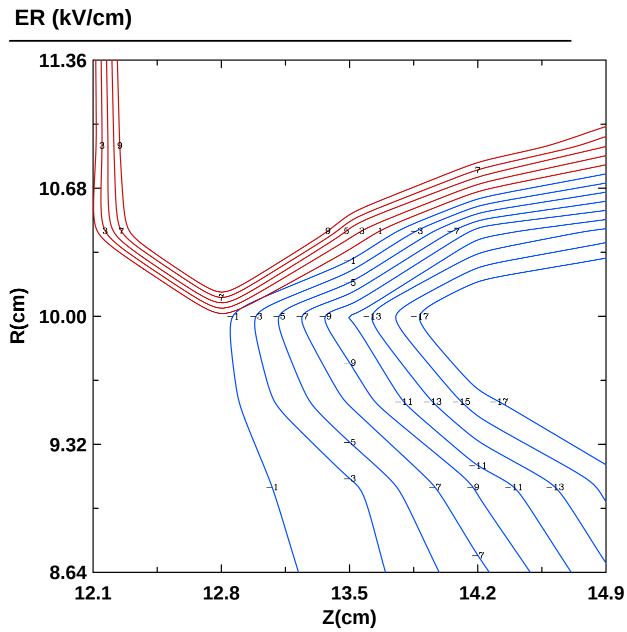

Figure 3: Contours of E_r near the outer radial boundary of the cathode. Between $r = 8.6$ and $r = 10.0$ cm the magnitude of this defocusing field nearly triples, leading to strongly nonlinear behavior in the electron beam's transverse phase space. Most of the nonlinearity occurs within $1 - 2\ \Delta r$ of the beam edge.

The origin of the hook drives from a strong increase in the defocusing E_r at radii just inside the cathode-Pierce shroud boundary. Inspection of the $r - z$ contours of the electrostatic potential show an enhanced "bowing" inward (toward smaller z) for $r \geq 9.5$ cm, one radial grid cell below the cathode/shroud boundary at 10.0 cm. At present, we believe the underlying cause for the bowing in Φ and nonlinear E_r dependence is a numerical artifact arising from a unwanted interaction of the 5-7 mm grid resolution, the sharp edge of the emitted beam, and the "kink" in the zero potential surface at the cathode-shroud boundary as modeled by the ECB formulation. We hope to find an appropriate solution that will not require decreasing the grid resolution to the 1-mm size of the equivalent EGUN calculations. Otherwise, the required number of grid points and macroparticles might jump by greater than an order of magnitude.

4 CONCLUSIONS

The underlying rationale for our use of GYMNOS in simulating the DARHT II injector behavior was to provide an independent check of both the EGUN results and overall physics design. Despite the problems discussed in the previous paragraphs, we note that GYMNOS does confirm that the injector design will produce ≈ 4 kA of emitted current together with a well-behaved envelope as the beam passes through the anode. While the GYMNOS results cannot confirm the high brightness EGUN runs, even with the present numerical limitations they indicate that the design is no worse than a factor of ~ 2 from the desired result.

5 REFERENCES

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