A BEAM-SLICE ALGORITHM FOR TRANSPORT OF THE DARHT-2 ACCELERATOR*

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Abstract

A beam-slice algorithm has been implemented into the LSP particle-in-cell (PIC) code to allow for efficient simulation of beam electron transport through a long accelerator. The slice algorithm pushes beam particles along a virtual axial dimension and performs a field solve on a transverse grid which moves with the particle slice. External electric and magnetic fields are also applied to the slice at each time step. For an axisymmetric beam the slice algorithm is very fast compared to full 2-D $r - z$ PIC simulations. The algorithm calculates beam emittance growth due to mismatch oscillations, in contrast to standard envelope codes which assume constant emittance. Using the slice algorithm we are able to simulate beam transport in the DARHT-2 accelerator at LANL from the region just downstream of the diode to the end of the accelerator, a distance of about 55 meters. Results from the slice simulation are compared to both 2-D PIC simulations in LSP and the beam envelope code LAMDA. The sensitivity of the final emittance to imperfect tuning of the transport solenoids is calculated.

INTRODUCTION

The DARHT-2 accelerator [1] at LANL is designed to produce a 2 kA 18.4 MeV electron beam of duration 1.6 μs. 74 accelerating gaps are distributed relatively uniformly along the 55 m accelerator, with solenoidal magnets used to focus the beam. In the region downstream of the accelerator a dynamic stripline kicker selects several shorter pulses from the flattop of the initial pulse, which are then focused onto a high-Z target for flash radiography applications. In addition to the voltage and current, the useful X-ray dose also depends on the beam emittance at the target. For this reason it is important to minimize emittance growth in the accelerator. Envelope codes, such as LAMDA [2], can be used to quickly simulate beam transport though the entire DARHT-2 accelerator, but emittance growth, due to non-linear forces or stochastic effects, is not modeled with such methods. By contrast, full $r - z$ PIC simulations can capture emittance growth due to both beam and applied field nonlinearities, but large-scale simulations are quite time-consuming and susceptible to numerical instabilities. For this reason $r - z$ PIC simulations are generally limited to simulating short segments of the accelerator. We describe here a beam-slice algorithm, implemented into the LSP code [3], in which an initial transverse slice of beam particles are initialized on a transverse grid. Both the particles and grid fields are propagated in time, and can be thought of as moving in a virtual z direction, with any external fields added at the instantaneous z position. The results of the slice model are compared with both full PIC simulations and an envelope model for the DARHT-2 accelerator.

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DESCRIPTION OF BEAM-SLICE MODEL

The beam-slice algorithm is a simplified PIC model for steady-state beam transport in which the paraxial approximation is assumed. A slice of beam particles located at an incident plane of constant z are initialized on a transverse grid. Initial electro- and magnetostatic solutions are performed prior to the first particle push to establish the self-fields of the beam, including the diamagnetic field B_z if the beam is rotating. After this initialization step, Maxwell's equations are solved on the transverse grid with $\partial/\partial z = 0$. In contrast to a static transverse field solve this allows the axial and azimuthal components of the electric field to be retained. The particles are pushed by the full Lorentz equations. Although a small spread in the z positions of the particles may develop after many time steps due to space-charge depression and other small non-paraxial effects, this is neglected, and at each time-step the grid is assumed to be located at the axial center-of-mass of the slice particles $\langle z(t) \rangle$. External fields, which are input as functions of z, are applied at the instantaneous axial center-of-mass location. The slice approximation requires that the external fields be slowly varying and that the axial spread of the particles remains small. The algorithm is numerically stable if the particles do not cross a transverse cell in a single timestep. For a highly paraxial beam this allows for a timestep $c\Delta t$ which can be considerably larger than the transverse cell size Δr. An implicit field solver is used to avoid the courant instability.

The initial particles comprising the slice are extracted from a full $r - z$ PIC simulation and are then input into a slice simulation. In the following axisymmetric simulations the on-axis external fields are given as input. The off-axis fields are calculated up to sixth order in r using a series representation [4]. In this way the nonlinearities of the accelerator optics are included in the slice simulations. Although we restrict ourselves here to consideration of axisymmetric beams by using a 1D radial grid in the slice model, the algorithm can also be used for 2D slice simulations in either polar or cartesian transverse coordinate systems.

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2D R-Z PIC DIODE SIMULATIONS

To initialize the slice simulations of the DARHT-2 accelerator, an initial 2D $r-z$ simulation of the injector is carried out. Figure 1 shows the injector geometry. The cathode surface is at $z = 20.62$ cm. A 2.5 MV steady-state voltage across the 7.6-cm AK gap produces a 2-kA space-charge-limited current. The first 6 of the 74 2.5-cm accelerating gaps can also been seen in plot (a) at the accelerator wall just downstream of the diode, between 2 and 5 m. A steady-state voltage of 185 kV is applied to each of these gaps. The remainder of the accelerating gaps are set at 216 kV. The constriction in the beam pipe between 6 and 8 m is the beam cleanup zone (BCUZ) [5], which may be fitted with apertures (absent in the present simulations) to prevent charge from the mismatched beam head and tail from reaching downstream accelerator components.

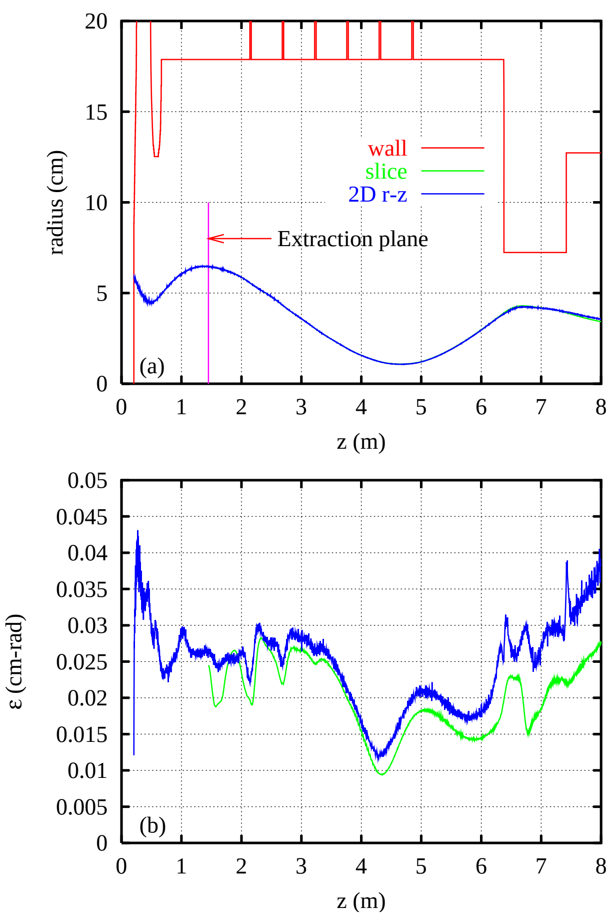

Figure 1: Comparison of slice algorithm and full 2-D $r-z$ LSP simulation of the DARHT-2 injector. The diode voltage is 2.5 MV and the beam current is 2 kA. (a) Edge radius and (b) normalized edge emittance as a function of z are shown.

The phase-space information for the particles to be used in the slice simulation are collected in a specified time window at an extraction plane at $z = 1.45$ m, as shown in the Fig. 1a. Best agreement between the 2D $r-z$ and the slice model results when particles are extracted at a local extremum of the beam radius. Using the extracted particles as input, the slice algorithm is started at the extraction plane and continues downstream from that point. Figure 1 shows good agreement between both simulations for the equivalent edge radius ($\sqrt{2}\times$ rms radius) and normalized edge emittance as a function of z. In the 2D r-z simulation each accelerating gap was driven by an input voltage wave and allowed to come to steady-state. For the slice model, a thin-gap expression for the on-axis E_z, in conjunction with a series representation for the off-axis fields, was used to model the fields of the accelerating gaps. The variations in wall radius were considered in the thin-gap model for the gaps, but a constant wall radius was assumed in the field solve on the transverse grid.

To illustrate the computational savings of using the slice model, we note that the 8-m long 2D diode simulation, run to steady-state and containing more than 700,000 particles, required on the order of 12 hours to complete for a single processor on a desktop computer. By contrast the slice model, when initialized with 4000 particles and a similar radial cell size as the 2D run, is able to transport the particle slice down the entire 55 meters of the accelerator in a few minutes when run on the same machine.

SLICE MODEL AND ENVELOPE CODE

LAMDA [2] is an envelope code which retains terms that are dropped in the usual paraxial approximation [6], including effects due to space-charge depression of the beam energy, beam rotation, and the axial variation of the beam envelope. Applied fields are however assumed to be perfectly linear in r, and emittance is assumed to be a constant. Both the accelerating and focusing effects of the gaps are included, but are treated using a thin-lens approximation. Figure 2 shows the edge radius as a function of z for the slice algorithm and the envelope code, which assumes a fixed emittance of 0.015 cm-rad. The on-axis magnetic field component B_z is also shown as a function of z. The good agreement between the two envelopes resulted only after some adjustments ($\sim 10-15\%$) to the current settings of two solenoids in the BCUZ and the region just downstream, centered at $z = 729$ and 821 cm. As will be noted in the next section, downstream beam mismatch is very sensitive to the magnet settings in this region. All other magnets settings are identical in the simulations.

EMITTANCE PRESERVATION THROUGH THE ACCELERATOR

As mentioned in the previous section, small changes in the downstream magnet settings can result in significant beam mismatch. This can be seen in Fig. 3, which shows the edge radius and emittance for slice simulations of matched and mismatched beams. The matched beam results from the tune shown in Fig. 2, while the mismatched beam comes from increasing the current on the solenoid at

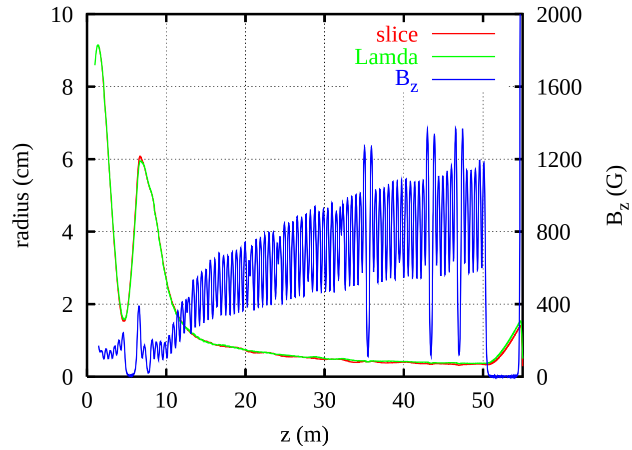

Figure 2: Comparison of the LSP slice algorithm and envelope code LAMDA. The beam edge radius is shown as a function of z for the entire length of the DARHT-2 accelerator. The on-axis magnetic field for the slice simulations is also shown.

$z = 821$ cm by 15%. For the matched beam the downstream emittance is relatively constant at ~ 0.015 cm-rad, which was the value used in the envelope code results discussed in the last section. For the mismatched beam, emittance growth results from the envelope oscillations, which drive the formation of halo particles [4]. Emittance is increased by phase-mixing of these particles in the nonlinear self and applied fields. For the mismatched case the oscillations are seen to damp somewhat in the last 20 m of the accelerator, as the free energy of the oscillations is gradually converted to beam temperature.

The mismatch sensitivity of the main beam body is due to the beam envelope tune in the region between the injector and the BCUZ, which is optimized so that the beam head is blocked by apertures. In general there is a tradeoff between head cleanup effectiveness and mismatch sensitivity.

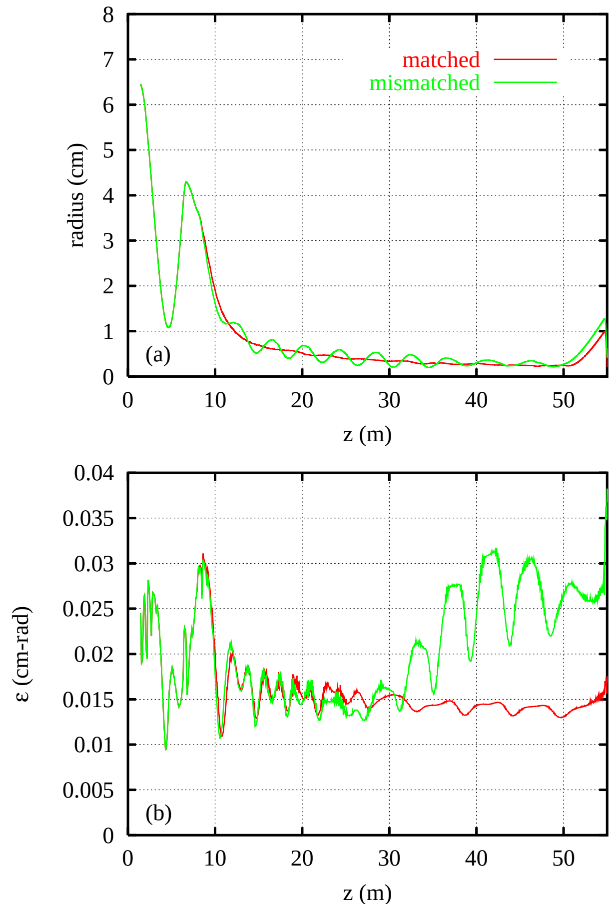

Figure 3: Comparison of edge radius and emittance for matched and mismatched transport. In the mismatched case the current applied to the solenoid centered at $z = 8.2$ m is increased by 15 %.

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