THE EFFECT OF ASYMMETRIC PLASMA PLUMES ON THE TRANSPORT OF HIGH-CURRENT ELECTRON BEAMS

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Abstract

Advanced accelerator-based radiographic diagnostics require multiple high-current electron beam pulses for temporal resolution. The use of “kicked” beams or the failure of a transport element on a prior pulse can result in the production of a plasma plume from locations where the beam sweeps across the beam pipe, due to high thermal deposition by the beam. It is possible for this plasma to evolve to significant sizes (a substantial fraction of the pipe radius) over the course of several pulses. This asymmetric plume can then have deleterious effects on the transport of subsequent beam pulses due to dynamic image charge and current effects, as well as ion emission into the beam, even if the beam does not pass directly through the plume. Some of these effects on beam deflection and emittance will be examined as a demonstration of three-dimensional numerical studies using highly customized desktop-based tools.

1 INTRODUCTION

The latest advancement in radiographic techniques based on high-current electron induction linacs is to obtain temporal resolution through the use of multiple beam pulses. An example of this is the DARHT facility under construction at Los Alamos National Laboratory [1]. The separate pulses will be produced by cleaving out short pulses, of order tens of nanoseconds, from a single much longer pulse, of order microseconds. This is done with a dynamic transport element called a *fast kicker* [2], which steers short pulses down a second transport line which splits from the main, long-pulse line.

One concern with beam transport in such a scheme is that, during the switching process, the beam must sweep across the wall dividing the two beampipes. At a nominal 2kA and 20MeV, the beam is capable of delivering a high thermal load to the wall. If the beam size is too small or the sweeping trajectory not sufficiently distributed, gas desorption and subsequent ionization can occur near the walls. This plasma plume breaks the symmetry of the fields near the beam.

Two types of interaction are possible between the beam and an offset plasma (i.e., the beam does not transport directly through the plasma.) In the first, the space charge field of the beam will extract ions from the plasma. With sufficient time, the ions will flow into the beam and produce partial charge neutralization, causing mismatched transport down the line. This problem has been studied with respect to the plasma generated when the beam strikes a bremsstrahlung converter target at the end of the beamline [3]. The second type of interaction is that of the beam with the image charge and current generated in the plume due to the dynamics of the beam pulse and the plume itself. In general these forces are nonlinear, not well-balanced between the electric and magnetic components, and therefore capable of deflecting the beam from its desired trajectory and increasing its emittance.

While ion emission is ultimately the more virulent effect, let us focus on the latter, MHD-type interaction between the beam and plasma. For a given beam, the behavior will be a function of the conductivity of the plume, its size, its proximity to the beam, and the time scale of the beam pulse. To investigate this system via numerical simulation, we require tools which can perform efficient parametrics on an inherently three-dimensional system which self-consistently couples beam transport and plasma evolution.

2 COMPUTATIONAL TOOLS

The ability to simulate fully three-dimensional, time-dependent systems is now available in very moderately priced desktop computers. The following simulations were all performed with a 500MHz Motorola G4 CPU, running the Macintosh operating system and equipped with 1 gigabyte of RAM, of which several hundred megabytes were used (with eight-byte floating point numerics). The SIMD vector capabilities of the processor were not used in these runs; however, preliminary testing shows that the most time-consuming portions of the simulation, involving the linear algebra for field solutions, can achieve close to the theoretical maximum 400% performance improvement using vectorized algorithms.

The software consists of independently coded C++ objects encompassing such parts of the problem as field solutions, PIC beam transport, and Lagrangian MHD fluids. The object-oriented approach allows much flexibility in customizing codes to particular problems, and allows a standardized approach to putting together the different physics packages – e.g. beam transport and plasma physics in this case – without losing development time to bookkeeping issues. The backbone of the library is a general PDE solver that uses fast iterative techniques to solve the resulting linear systems [4].

3 MODEL

A very simple geometry will be considered in these investigations. Consider a 20 MeV, 2kA electron beam, 2cm in radius and with a normalized Lapostolle emittance of 400 π-mm-mrad. The beam has a round cross section and is transported through a 20cm length of cylindrical pipe with radius 6cm; the pipe wall will be considered a perfect conductor. The beam enters at a waist and, left unperturbed, undergoes negligible expansion over this distance. A plasma source is located on the wall midway down the pipe. Consider a simple ideal MHD model of the plasma

$$D\mathbf{v}/Dt = (\mathbf{J} \times \mathbf{B} - \nabla P)/mn \qquad (1)$$

$$Dn/Dt = -n\nabla\cdot\mathbf{v} \qquad (2)$$

$$DT/Dt = (1-\gamma)\, T\, \nabla\cdot\mathbf{v} \qquad (3)$$

$$P = nqT \qquad (4)$$

where **v** is the velocity, P the kinetic pressure, n the number density, m the mass of the ions, and T the temperature. **J** is a current density and **B** the magnetic field. T is in units of eV, hence the appearance of q, the electron charge in Coulombs, in the ideal equation of state. γ is the ratio of ideal specific heats, 5/3. The D/Dt operator is the convective derivative. The plasma differs from purely ideal in that it has a finite conductivity, relating the current density to field quantities through a simple Ohm's Law:

$$\mathbf{J} = \sigma(\mathbf{E} + \mathbf{v} \times \mathbf{B}) \qquad (5)$$

The conductivity model is somewhat unrealistic: instead of using a pure, density-independent Spitzer model, we shall use the Spitzer value scaled by the ratio of local-to-peak density in order to take into account the transition of the plasma from over- to under-dense with respect to the beam density. This will not be justified but will suffice for a numerical demonstration.

The electron beam is assumed to be quasi-steady; that is, the transit time for any single electron through the domain (~0.7ns) is much shorter than any other time variation, such as the ramping of the beam current (~10ns) or the plasma evolution (L_p/v_{th} ~ 1μs). This allows the beam to be propagated numerically in locally transverse slices using PIC techniques. Sampling the electron phase space with spatial coordinate **x** and normalized momentum $\mathbf{p} = \gamma\mathbf{v}/c$, the electrons in a slice are advanced in an arc length coordinate s in the local normal direction $\mathbf{e}_n$ according to

$$d\mathbf{x}/ds = \mathbf{p}/(\mathbf{e}_n\cdot\mathbf{p}) \qquad (6)$$

$$d\mathbf{p}/ds = \mathbf{F}/(m_e c\mathbf{e}_n\cdot\mathbf{p}) \qquad (7)$$

where **F** is the usual Lorentz force. The process is iterated until the resulting plane is truly transverse to the centroid direction of motion, within a specified criterion.

Finally, the beam and plasma sources are coupled to the quasi-static form of Maxwell's equations with a spatially varying conductivity, for the self-consistent electric and magnetic fields.

4 SHORT PULSE SCENARIO

Consider a short pulse of duration 50ns interacting with a previously generated plume. A plasma of size L_p ~ 1cm and thermal velocity ~1cm/μs (corresponding to 1eV hydrogen) does not evolve significantly on this time scale and therefore acts like a blob of motionless conductor extending from the wall. The rise and fall of the beam current will produce image charge and current whose influence on the beam is, in this case, purely a function of the plume size at the time of the pulse; even a cold plasma is a good conductor for these times and the behavior does not vary strongly with conductivity. Figure 1 shows a cutaway view of the geometry. Figures 2 and 3 show curves of the beam emittance and centroid motion in the x-z plane as a function of centroid z, at various times during a pulse past a large plume. Negative deflections are towards the plume. The plume has a roughly Gaussian density profile with scale length ~1.5cm. The over-dense/under-dense "hard edge" of the plume is 3cm into the pipe.

The centroid deflections are not visibly large over 20cm but Table 1 shows the "strike distance," the location where the beam will steer into the wall due to the deflection, as a function of time.

Table 1: Strike distance vs. time, size: Short pulse

Time (ns)	Edge Scrape	Centroid Strike
0	∞	∞
5	47m	70m
10	23m	34m
25	22m	33m
40	22m	33m
45	40m	60m

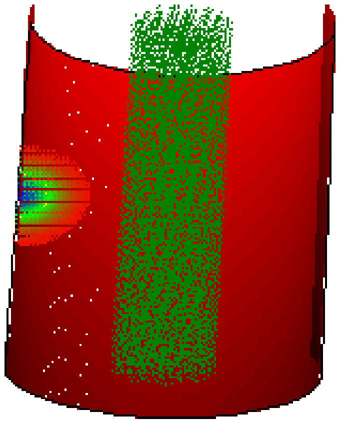

Figure 1. Cutaway view of plume and beam

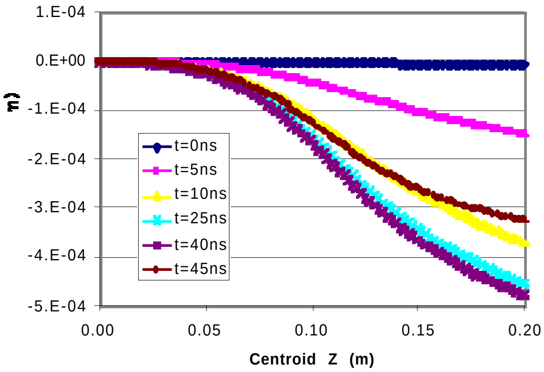

Figure 2. Beam centroid path at various times

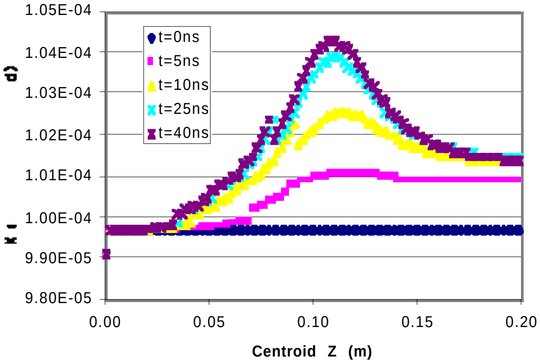

Figure 3. X-plane emittance at various times

5 IMPLICATIONS FOR A LONG PULSE SCENARIO

In the long-pulse line, the plasma is presumed to form during the pulse itself. The flattop beam current does not produce time-varying fields. However, on this time scale, ~2µs, the plume can grow significantly and the **v** × **B** conduction current enables magnetic interaction between the beam and plasma. While the motion of the plasma would be affected, for cold plasma the current is not strong enough to influence the beam; therefore, the beam will experience mostly the attractive image charge force from the plume as it grows towards the beam, without any counterbalance from magnetic forces as occurs in the short-pulse case. Evidence for this supposition can be seen in the short-pulse results. Consider the time asymmetry present in Figure 1: the beam behavior during ramp-up (t=5ns) is quite different than that during ramp-down (t=45ns) even though the beam carries the same current at these times. Examination of the field and current profiles shows that the difference is due to current penetration. At early times, the plasma shunts out the beam magnetic field and the plasma current is counter to that of the beam. By the time ramp-down occurs, the flattop beam field has penetrated to the plasma core; but the electric field is completely shunted at both times. Without the countering flow of plasma current, the beam is more strongly attracted to its image charge at t=45ns. The effect is enhanced by the fact that the decreasing beam current starts to drive a co-directional plasma current in the outer regions of the plume.

6 CONCLUSIONS

Fully self-consistent, three-dimensional simulations of reasonably smooth physical systems are now well within the capabilities of desktop computing. Object-oriented programming techniques greatly simplify the implementation of systems that couple different governing equations. As an example, a beam undergoing macroscopic interactions with an offset plasma plume has been simulated in a short-pulse regime relevant to advanced radiographic accelerators. Even for a large plume (scale length ~1.5cm, 3.0cm edge) the steering effect is not dangerous unless the field-free transport distance beyond the plume is very long (many tens of meters). Emittance growth is only a few percent. However, it is possible that the effect will be more serious in the long-pulse regime, where magnetic and electric forces will be less balanced due to the lack of strong image current. Evidence of this is seen in the time asymmetry of the short-pulse results.

7 ACKNOWLEDGEMENTS

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