NUMERICAL STUDIES OF ION-FOCUSED TRANSPORT IN A RECIRCULATING ACCELERATOR

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Abstract

In Ion-Focused Transport (IFT), an intense electron beam is injected onto a preformed, low-density plasma channel, and expels the plasma electrons. The resulting ion column focuses the beam. A numerical study of the application of IFT to recirculating accelerators is presented. A 3-D simulation of beam injection into a curved channel shows beam erosion at close to the predicted rate. During induction-gap acceleration, both the beam and channel are found to shrink in radius, thereby increasing the focusing force on the beam, and reducing the loss of particles due to centrifugal force. Finally, simulations of the the ion-resonance instability show the theoretically predicted growth rate. In the absence of stabilizing measures, the instability leads to strong disruption of the beam and channel.

Introduction

For about the past six years, several laboratories have been attempting to accelerate multi-kiloampere electron beams to high energy in recirculating geometries [1-3]. These efforts have primarily relied on magnetic fields to confine and steer the beam, as in conventional, low-current accelerators. To date, however, no recirculating design has demonstrated high current (> 1 kA) acceleration using purely magnetic focusing. Two experiments that have achieved high current acceleration [2, 4] had a neutralizing background to cancel the space-charge of the beam.

Ion-focused transport (IFT) offers an attractive alternative to magnetic transport for high-current beams. It is presently being used in the 10 kA, 50 MeV linear induction Advanced Test Accelerator (ATA) [5], where it both eliminates the need for magnetic focusing, and stabilizes the beam break-up instability. A laser is used to create the ionized channel prior to firing the beam. Experiments are currently under way at Sandia National Laboratories to apply IFT to a recirculating accelerator, using a magnetically guided low-current, low-energy beam to make the channel [6]. Here, we look at some of the basic physics issues concerning the dynamics of the beam and channel in an IFT recirculating accelerator.

Injection of a High Current Beam into a Curved, Ionized Channel

When an intense electron beam is injected into a low-density plasma channel, the space-charge of the beam expels plasma electrons from the channel, leaving a positively charged column which confines the beam [5]. In order to avoid a violent electron-electron two-stream instability, all the channel electrons must be expelled. This means that the line density of plasma electrons must be less that the line density of electrons, i.e., $f < 1$, where f is the ratio of the line densities in the body of the beam.

To study in detail what goes on at the head of the propagating beam, we performed a 3-D particle-in-cell simulation using the code IVORY. A 15 kA, 2.5 MeV beam is injected into a curved, $f = 0.5$ ionized channel with the same radius as the beam (1 cm). The beam current rises from zero to peak value in a linear 5 ns ramp. The drift-tube is a 90 degree bend with a 1 m radius of curvature. In the simulation, we observe that the low-current head of the beam is inefficient at expelling plasma electrons, and moves along a straight line to the wall. As the current rises, channel electrons are expelled and the beam starts to track the curved, positively charged channel. The process of clearing the channel drains energy from the beam head, and two low-energy bunches of beam particles soon form (Fig. 1). Space-charge blows these electrons radially outward, so that the beam erodes. Over the 90 degree bend, the beam loses about 4.3 ns off the head, thereby considerably sharpening the current rise. This erosion rate of 0.45 cm/cm is roughly equal to that predicted by an analytic estimate [7], although the observed behavior is more complicated than that assumed in the derivation of the analytic result. By the end of the run, all the channel electrons have been expelled, and the beam propagates stably, as one would expect. At the low energy simulated, the displacement of the body of the beam due to centrifugal force is slight.

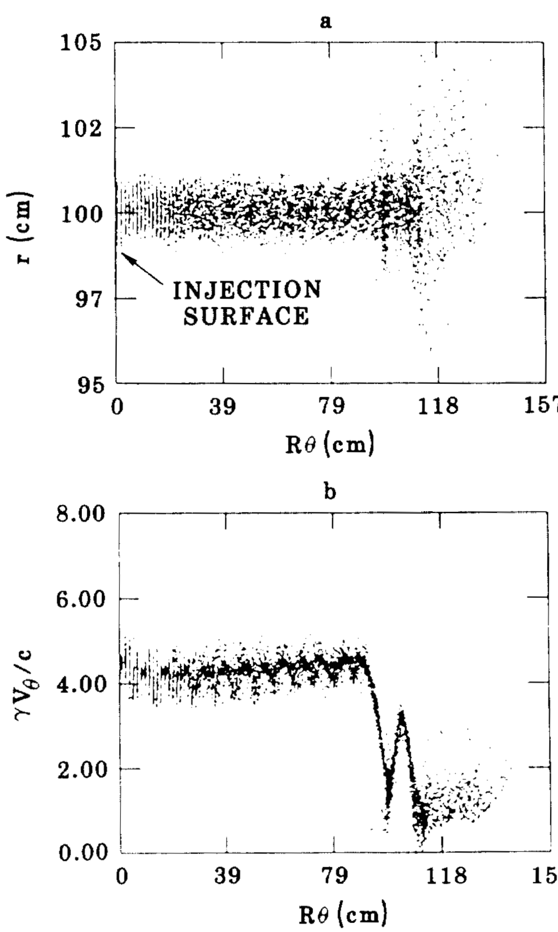

Figure 1. Particle plot from 15 kA, 2.5 MeV injection simulation at time ct = 200 cm. Only the beam electrons are shown. Particle positions are shown in (a) and axial momenta are shown in (b). θ is toroidal angle.

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Particle Loss During Acceleration

As the beam is accelerated in a curved orbit, the centrifugal force increases. Thus, the beam tends to pull away from the ion channel. Two effects result. First, if the centrifugal force exceeds a certain value, then current will be lost. Second, even if all the current is confined, the centrifugal force on the beam results in a drag on the channel. This can cause the beam and channel to drift to the wall before high energies can be reached. Concerning the first effect, one can show from force balance that the maximum beam energy that can be confined by a fixed channel in the absence of external magnetic fields is

$$\gamma_{max} = \frac{2\nu fR}{a\beta^2} \tag{1}$$

where $\nu = I_{beam}/17$ kA, R is the radius of curvature of of the channel, a is the beam minor radius, and β is the beam velocity normalized to c. For a 15 kA, 1 cm radius beam with f = 1/2 and R = 1 m, this gives γ_{max} = 88. However, when we performed a numerical simulation simulation for these parameters, we observed particles being lost for $\gamma > 24$. We proceeded to obtain a more accurate threshold for particle loss by calculating the turning points of a particle in the presence of centrifugal force [8]. The worst case is for a particle which starts at the inner edge of the beam. We find that this particle is confined only for

$$\gamma \leq \gamma_{max}/3.59 \tag{2}$$

where γ_{max} is given by Eq. (1). This gives $\gamma \leq 24.4$ for the simulation parameters, which agrees well with the observed loss threshold.

Note that the threshold increases as the beam radius decreases. In a study of the effect of acceleration on the beam, we found that the beam radius shrinks as the energy increases, thereby automatically pushing up the loss threshold. Shrinkage of the beam radius is a well-known result in the case of adiabatic acceleration, but in a gap accelerator the energy does not change adiabatically. Figure 2 shows results of a simulation in a 1 m major radius torus with 1 MeV accelerating gaps at 0 and 180 degrees around the torus. Starting at an energy of 2 MeV, we accelerate a 15 kA, 1 cm radius beam to 17 MeV (γ = 35) in an f = 1/2 channel of Xenon ions. If the beam and channel radii had not decreased, particles would have been lost for $\gamma > 24$, as discussed above. However, no particles are lost by the end of the run, and the final beam and channel radii are both about 0.5 cm, as shown in Fig. 2. Centrifugal force causes the beam and channel to drift to the wall in 100 ns, or about 5 revolutions of the beam around the device. This period agrees well with the prediction from simple equations of motion. The scaling of the drift-time can be seen from the result for a fixed energy:

$$\tau_D = 2(RAb/\gamma)^{1/2} \quad \text{nanoseconds} \tag{3}$$

where A is the atomic mass of the ions and b is the wall radius. In trying to increase τ_D, there is not a lot of leeway in varying the major and minor radii R, b without giving up the compactness of the device. In addition, it is difficult to increase the atomic mass A. Noble gas elements are preferred for forming the channel because of their low recombination rates [7]. Xenon (A = 131), which was used in the simulation shown in Fig. 2, is the heaviest noble gas, apart form the radioactive radon. Thus, to go to higher energies, it

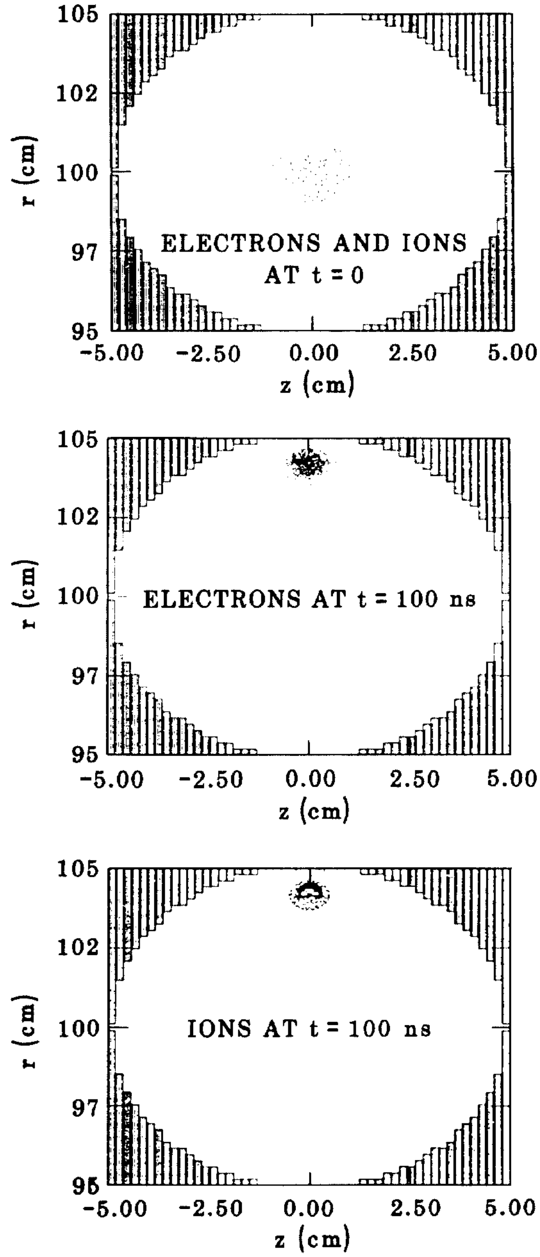

Figure 2. Decrease in beam and channel radii due to acceleration. Centrifugal force causes drift to wall.

is necessary to counter the centrifugal force by applying a dipole magnetic field, as in a conventional betatron. Exact matching is obtained when the Larmor radius of the beam in the magnetic field is equal to the radius of curvature of the channel. In that case, the channel drift is eliminated. If the matching is not exact, then the γ in Eq. (3) is replaced by the energy mismatch $\Delta\gamma$. To avoid current loss, $\Delta\gamma$ can be no larger than the right-hand side of Eq. (2).

Ion-Resonance Instability

The ion-resonance instability is a potentially serious problem for the use of ion-focused transport. The instability occurs when the Doppler-shifted transverse oscillation frequency of the electron beam resonates with the ion bounce frequency. Linear theory [9] predicts a large growth rate, on the order of the ion bounce frequency. In Fig. 3, we show growth rates for hydrogen and helium ions and typical beam parameters.

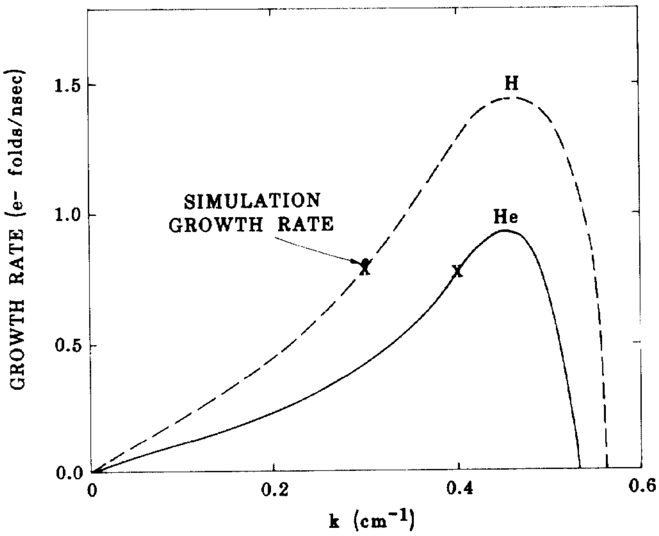

Figure 3. Growth rate versus axial wavenumber for ion-resonance instability for 15 kA, γ = 4.6, f = 1/2, a = 1 cm. "X's" mark modes simulated with IVORY.

In order to test the linear theory, and observe the nonlinear development of the instability, we performed 3-D simulations using IVORY for the parameters in Fig. 3. To save computer time, we took the beam and ion channel to be uniform rings, and simulated just one toroidal Fourier mode with a large expected growth rate. Two modes simulated are marked in Fig. 3. For the case of helium ions, the result was a numerical growth rate about an order of magnitude less that the theoretical prediction. At present, we do not fully understand the discrepancy. The cutoff at high k seen in Fig. 3 depends on the beam radius, and may also be sensitive to the beam profile. We speculate that the "equilibrium" used in the simulation evolved during the run in such a way as to push cutoff below the mode simulated.

For the case of hydrogen ions, the growth seen was close to the predicted result, as shown in Fig. 4. The agreement with theory is probably due to the fact that the mode chosen is well away from the cutoff. The nonlinear effect of the instability on the beam was severe: about two thirds of the beam particles and one half of the ions were lost to the wall, and the radii of the remaining beam and channel went from 1 cm to about 4 cm (the wall radius is 5 cm). We have thus far made no attempt to introduce stabilizing features. For example, a spread in ion bounce frequencies has been shown to be stabilizing [10], at least in cases where the ion population is small.

Summary

IFT can completely replace magnetic transport for recirculating accelerators only in the high-current, low-to-moderate energy region. This, however, is the regime most difficult to handle with conventional methods. To reach high energies, the centrifugal force must be balanced with a dipole magnetic field. Methods of stabilizing the ion-resonance instability require further study.

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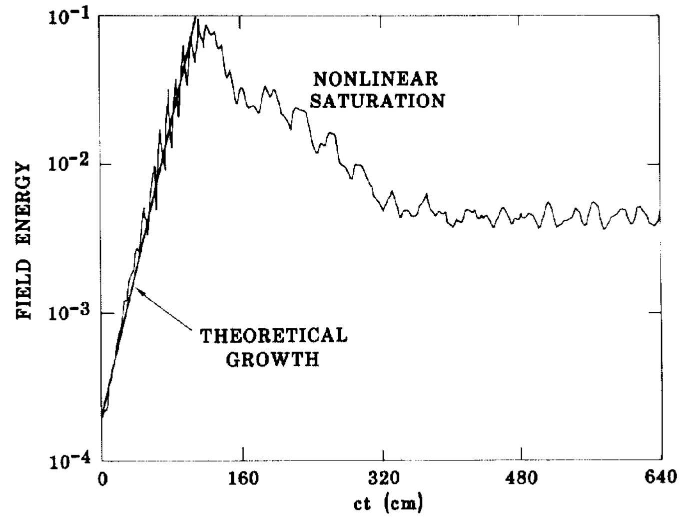

Figure 4. Energy in k = 0.3/cm mode relative to energy in equilibrium fields as a function of time for hydrogen ion channel.

References

[1] J. Golden, F. Mako, L. Floyd, T. Smith, K. F. McDonald, and C. A. Kapetanakos, Bull. Am. Phys. Soc. 31, 1462 (1986).

[2] H. Ishizuka, J. Saul, Y. Song, R. Prohaska, A. Fisher, and N. Rostoker, Bull. Am. Phys. Soc. 31, 1463 (1986).

[3] S. Humphries, Jr., private communication; T. P. Hughes and B. B. Godfrey, IEEE Trans. Nuc. Sci. NS-32, 2498 (1985).

[4] D. Taggart, M. Parker, H. Hopman, R. Jayakumar and H. Fleischmann, Phys. Rev. Lett. 52, 1601 (1984).

[5] W. E. Martin, G. J. Caporaso, W. M. Fawley, D. Prosnitz, and A. G. Cole, Phys. Rev. Lett., 54, 685 (1985).

[6] S. Shope, W. Tucker, D. Hasti, and G. Kamin, this conference.

[7] B. B. Godfrey, B. S. Newberger, L. A. Wright, and M. M. Campbell, AMRC-R-741, MRC, 1985.

[8] T. P. Hughes and B. S. Newberger, AMRC-R-896, MRC 987.

[9] H. S. Uhm and R. C. Davidson, Phys. Fluids 23, 813 (1980).

[10] W. M. Manheimer, Part. Accel. 13, 29 (1983).