Evolution and Control of Ion-Beam Divergence in Applied-*B* Diodes

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The time evolution of beam divergence induced by electromagnetic instabilities in applied-*B* ion diodes is examined using the 3D particle-in-cell code QUICKSILVER. The evolution is generally characterized by a high-frequency, low-divergence phase, associated with the diocotron mode, followed by a low-frequency, high-divergence phase, associated with the two-stream-like ion mode. Limiting the extent of the electron density profile evolution allows the diocotron phase to be sustained with a resulting divergence of ~ 10 mrad.

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Inertial confinement fusion (ICF) with light ion beams [1] has been the subject of an extensive theoretical and experimental effort for nearly twenty years [2–5]. In this approach to inertial fusion, the directed kinetic energy of an intense ion beam is focused onto a small fusion pellet. Optimum ranges for energy deposition favorable to pellet compression translate into beam energies on the order of $\sim 10^6$ electronvolts per nucleon of the accelerated ion. Existing fusion target designs require $\gtrsim 100$ TW of focused power for tens of nanoseconds. For Li^{+1} as the accelerated ion, this corresponds to approximately 30 MV of diode voltage and 4 MA of ion current. One approach to achieving these energies and currents is through the use of an applied-*B* ion diode driven by a pulsed power accelerator. The applied-*B* ion diode consists of an anode-cathode acceleration gap, usually in a cylindrical symmetry, with an external magnetic field $\mathbf{B}_0$, applied transverse to the gap and symmetry directions. The magnetic field serves to magnetically insulate the freely emitted electrons from the anode [2,6]; the electrons drift primarily in the $\mathbf{E}\times\mathbf{B}_0$ symmetry direction. Example parameters for operation at 30 MV would be a gap of 3 cm and a field of 6 T.

A long-standing question concerning the utility of light ion beams for inertial confinement fusion has been whether or not the ion beam can be sufficiently focused to deposit energy efficiently onto a small pellet. Two measures of the focusability of the ion beam are the microdivergence angles $\delta\theta_\parallel$ and $\delta\theta_\perp$ representing the half width at half maximum (HWHM) angles of the distribution of the normalized transverse beam velocities parallel and perpendicular to the applied magnetic-field direction. Current schemes for ICF require divergences $\lesssim 10$ mrad to efficiently couple the beam to the fusion pellet.

One mechanism that is of considerable concern as a cause of divergence is symmetry-breaking electromagnetic fluctuations that result from instabilities. These fluctuations produce primarily $\delta\theta_\perp$ but may also contribute to $\delta\theta_\parallel$ if there is significant parallel mode structure. The diode configuration is conducive to numerous instabilities that have been the subject of considerable study in recent years. Many of these instabilities, such as the magnetron [7] and the diocotron [8], carry over directly from the much earlier literature concerning microwave devices [9]. Other instabilities, such as the ion-beam modes [10,11], are of more recent vintage. A linear stability analysis of an ion diode that includes the virtual cathode [12] appears to be in good agreement with much of the behavior described here. An important issue, given that ion diodes are subject to instabilities, is whether or not an acceptable divergence ($\lesssim 10$ mrad) can be obtained. Central to this question is the nonlinear evolution of the various modes of the system. This includes mode coupling, saturation amplitudes, and temporal history of the mode spectrum.

Since linear theory can provide at best only suggestions as to what the full nonlinear behavior might be, an in-depth understanding of divergence in ion diodes has been slow in coming. The complicated geometry and finite nature of the equilibrium charge distribution make analytical nonlinear treatments very difficult. A powerful new tool for the study of the diode divergence problem is the three-dimensional, fully electromagnetic, relativistic, particle-in-cell code QUICKSILVER [13]. The main code allows detailed modeling of multispecies plasmas within complicated three-dimensional conductor configurations, and includes transmission line power input ports and applied magnetic fields. This is supplemented with an interactive preprocessor to set up the simulations, and several postprocessors to analyze diagnostic output.

A schematic of an ion diode is shown in Fig. 1. Power is fed in from the upper right transmission line port in the form of a TEM transmission line mode. The left boundary is a midplane symmetry boundary with the other half of the device. Although the actual device is cylindrically symmetric, the large aspect ratio R/d allows the use of Cartesian coordinates. The applied magnetic field $B_0\hat{\mathbf{z}}$ is uniform in space and time. As the power from the generator reaches the anode-cathode gap, electrons are emitted from the cathode tip and cathode surfaces and begin to circuit the device in the $E_x\hat{\mathbf{x}}\times B_0\hat{\mathbf{z}}$ symmetry direction. The magnetic field prevents most of the current from being carried by the much less massive electrons. These electrons quickly form a virtual cathode that is connected to the cathode tip and that defines the acceleration gap for the ions. A recent theory has been successful in modeling the virtual cathode self-consistently and describing the nonlinear impedance characteristics of the ion current

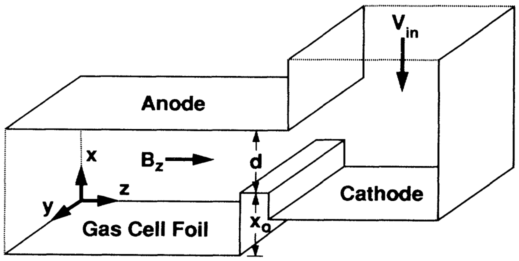

FIG. 1. Geometry and coordinate system.

[14]. This rotating electron cloud provides a significant source of free energy for instabilities—the configuration bears a strong resemblance to early magnetron devices, the smooth-bore magnetron in particular. The replacement of the solid cathode by the virtual cathode of the electron cloud makes conditions particularly favorable for the diocotron mode. Once the ion beam begins to interact with the electron cloud, another source of instability appears in the ion-beam modes, the lowest-order mode of which bears a close resemblance to the two-stream mode.

We have performed many simulations of the applied-B diode configuration. The basic simulation uses a representation of 5 cm of the diode circumference (experimentally about 1 m) and one side of the midplane symmetry and requires about 50 to 60 h of Cray Y-MP CPU time. The generic time history of the electromagnetic fluctuation spectrum consists of an early phase, sometimes only a few nanoseconds in duration, characterized by the high-frequency diocotron mode, followed immediately by a low-frequency ion mode. The diocotron mode is a ubiquitous mode of crossed field electron flows, and its most virulent form arises when there are two free surfaces to the streaming electron layer. The driving mechanism behind the instability is the shear in the electron drift velocity across the layer. In this respect it bears a close resemblance to the Kelvin-Helmholtz instability of sheared fluid flow [15].

In describing the mode frequency ν, the qualifiers "high" and "low" are in reference to the quantity $\nu\tau_i$, where τ_i is the ion transit time from the anode to the gas cell boundary. For typical experimental parameters for Sandia National Laboratories' Particle Beam Fusion Accelerator (PBFA) II, the ion transit time is on the order of 1 to 2 nsec. The dominant diocotron frequency in the simulations is about 2 to 4 GHz. The ion mode appears consistently with $\nu \lesssim 1/\tau_i$. Since the transverse momentum variations (divergence) generated by these fluctuations on the ion beam fall off as $1/\nu$ for $\nu\tau_i \gg 1$, the ion-beam mode contributes much more to the divergence of the ion beam than the higher-frequency ($\nu\tau_i \gtrsim 4$) diocotron mode for comparable transverse electric-field amplitudes. Typical wavelengths for both modes are 2.5 to 5 cm.

To be suitable for ICF applications, it is necessary for the ion-beam divergence to be sustained at ≈ 10 mrad for periods on the order of 20 nsec. The simulations we have performed of the basic diode configuration have fallen well short of this goal. In most simulations, and in particular those simulations characteristic of typical PBFA II operating parameters, the transition to the high-divergence ion mode phase takes place within 10 nsec. The resulting divergence then settles down at about 30 to 40 mrad, consistent with experimental measurements. An exception to this fairly rapid transition to the ion mode was found in simulations with a very large magnetic field for the given operating voltage. For these cases the magnetic field was nearly 3 times the value necessary to insure magnetic insulation of the electrons for the diode voltage. Shown in Fig. 2 are the time histories of the divergence for several simulations with different diode gap and magnetic-field combinations chosen to produce an 8.5-MV operating point based on the saturated limit of the diode theory [14]. Also shown in Fig. 2 are representative points in the time history of the dominant wave frequency for case b obtained by Fourier analyzing a 2.4-nsec window centered on each point in the history. The highest magnetic-field case shows a prolonged evolution to the high-divergence ion mode phase. Examination of the evolution of the equilibrium reveals that the strong magnetic field slows the relaxation of the electron charge towards the asymptotic state.

The suggestion from the high-magnetic-field simulations that the transition is related to the equilibrium relaxation points to the possibility of an underlying unity to the varied time histories. One measure of the equilibrium relaxation is the time-dependent total electron or ion charge in the diode. A useful normalization of the charge in the diode is the ion charge corresponding to the saturated constant density equilibrium profile at the calculated operating point for the same accelerator load line. This quantity is denoted by Q_{sat}. Shown in Fig. 3 are the same divergences as shown in Fig. 2 now plotted against the ratio Q/Q_{sat}. The varied time histories in Fig. 2 show

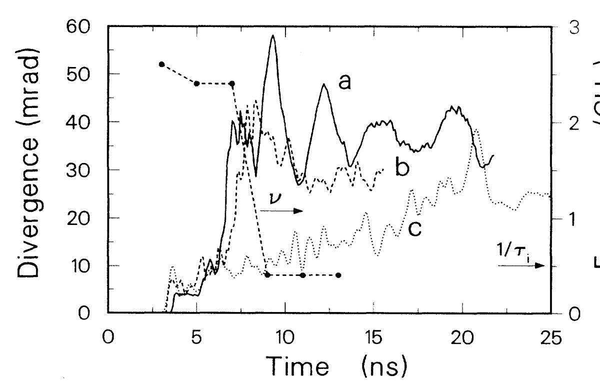

FIG. 2. Time histories of the divergence for, curve a, $B_0=3.5$ T, $d=1.5$ cm, $x_0=1.0$ cm; curve b, $B_0=5.2$ T, $d=1.16$ cm, $x_0=1.0$ cm; curve c, $B_0=7.5$ T, $d=1.0$ cm, $x_0=0.5$ cm. Also shown is the dominant frequency history for curve b.

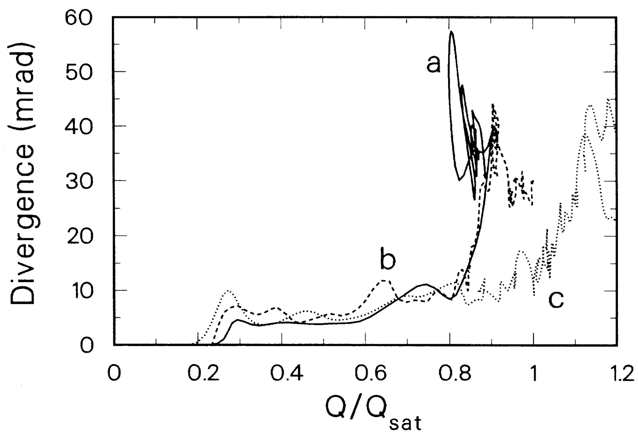

FIG. 3. The divergence vs Q/Q_{sat} for the parameters of Fig. 2.

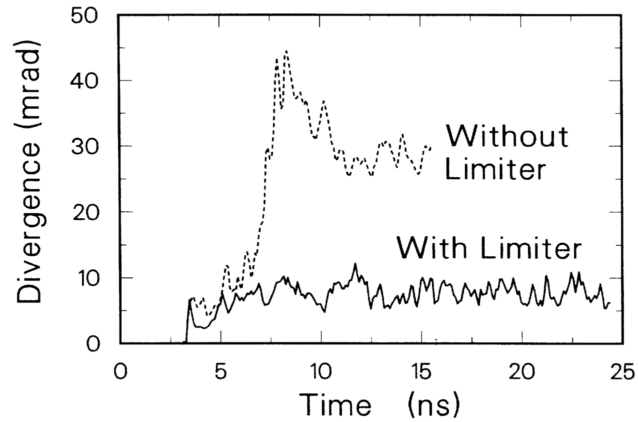

FIG. 4. Comparison of the divergence between simulations with and without an electron limiter.

a great deal of similarity when plotted as a function of the equilibrium charge. The high-magnetic-field case follows the same evolution as the lower-field cases, but prolonged in time because of the reduced relaxation rate. The plot indicates that when Q/Q_{sat} exceeds about 0.8, a transition is made to the higher-divergence (ion mode) phase. More simulations are needed to examine the generality of this relationship.

The divergences are below the 10-mrad level for values of Q/Q_{sat} below about 0.6. This suggests that if a method can be found for limiting the evolution of the equilibrium charge ratio Q/Q_{sat} to a sufficiently low value, the divergence might be sustained at the lower level corresponding to purely diocotron oscillations.

One way of testing this principle is through the use of a device known as a "limiter" [16]. The limiter is a short, nonemitting axisymmetric protrusion from the anode that is fully penetrated by the diode's applied magnetic field. In theory, electrons that migrate onto those flux surfaces that intersect the limiter will be collected by the limiter [14]. The asymptotic operating state is then one in which those flux surfaces that intersect the limiter are essentially devoid of electrons. These equilibria will then have lower values of Q/Q_{sat}.

Simulations with a limiter demonstrate the utility of this concept in reducing the divergence. Shown in Fig. 4 is the divergence for curve *b* of Fig. 2 with and without the limiter. In the simulation without the limiter the diocotron phase lasts only about 5 nsec and generates a divergence of about 11 mrad. This is followed by the characteristically abrupt transition to the ion mode and a resulting divergence of about 25 to 40 mrad. The simulation with the limiter shows an average of 7.7 mrad. The ion charge normalized to Q_{sat} reaches 0.4 and stays there. The limiter reduces the average diode efficiency, the fraction of total diode current in ions, from 79% to 45%. This represents a loss of energy into electron flow that is more than made up for in the reduced divergence. There is a significant increase in the diode impedance with the limiter; the diode operated at 12 MV as opposed to 9 MV without the limiter. This implies that lower insulating magnetic fields can be used in the limiter case to achieve a desired voltage, a distinct benefit. At twice the CPU time, we have repeated these two simulations with the periodic length doubled to 10 cm to increase the spectral resolution and introduce a longer wavelength. The above results were corroborated but with a 40% increase in the average diocotron-phase divergence resulting from the addition of a smaller-amplitude and lower-frequency diocotron oscillation at the longer wavelength. However, a 20-cm limiter simulation showed no further increase over the 10-cm limiter simulation.

There are significant problems with the simple midplane limiter employed in the simulations. First of all, it is questionable as to whether the limiter can remain a nonemitter for sufficiently long to maintain a good diode impedance and uniformity. A second problem is that the location of a limiter within the ion emission region can cause a stationary deformation of the equipotentials and adversely affect the beam focus in the direction parallel to $\mathbf{B}_0$. Research is continuing on limiter configurations that minimize these problems.

If the diocotron phase can be sustained for sufficiently long periods, it is useful to know the divergence induced on the ion beam by the diocotron fluctuations. Analysis of the saturation of the diocotron mode in the simulations suggests that the wave is saturating through electron trapping, resulting in large $\mathbf{E}\times\mathbf{B}$ rotating electron vortices superposed on the mean equilibrium drift. We estimate the saturation level by equating the configuration space $\delta\mathbf{E}\times\mathbf{B}_0$ rotation frequency $E_y k_x/B_0$ to the linear growth rate of the diocotron mode ω_i. This is a spatial analog to the saturation of a single strong wave in the two-stream system in which accurate estimates of the saturation amplitude are obtained by equating the bounce frequency of the wave to the linear growth rate [17]. The configuration space analog has been used to estimate the saturation of drift instabilities [18]. The $\hat{\mathbf{y}}$ component of the saturated electric field determined in this manner is given by $E_{y_{\rm sat}} = \omega_i B_0/k_x$, where k_x is the effective wave number of the eigenfunction of the saturated diocotron mode. Analysis of the simulations reveals that this is well represented by $k_x = \pi/(d+x_0)$ corresponding to a half sinusoid between the anode and the gas cell. Treating the electric field as independent of x, but using the mean value $2E_{y_{\rm sat}}/\pi$, results in the calculated divergence scaling $\delta\theta_\perp = \alpha(d+x_0)B_0\sqrt{q/MV}$, where the constant of proportionality α represents $\sqrt{2}\omega_i/\pi^3 v$ and order unity contributions from the orbit integral. A best fit to the divergences for the 5-cm nonlimiter simulations results in $\alpha = 0.092$, in very good agreement with the numerical values of $v = 2.4$ GHz and $\omega_i \approx 5\times 10^9$ sec^{-1}. Linear stability analysis suggests that the ratio ω_i/v is approximately constant and we treat it as such here. For the 5-cm limiter simulations the scaling is best fit with $\alpha = 0.064$, a reduction of about 30% resulting in part from a decrease of the perturbation field near the anode. In each of these two sets of data the scaling is in very good agreement with the divergence during the diocotron phase. The 10- and 20-cm simulations suggest that these coefficients could be 40% higher when longer wavelengths are allowed. Provided that other causes of divergence such as source temperature are sufficiently low, this scaling for $\delta\theta_\perp$, including the possible effect of longer wavelengths, suggests that a divergence $\lesssim 10$ mrad is possible with lithium ions at 30 MV using a limiter. A divergence below 10 mrad is thought to be adequate for igniting a pellet with light ion beams.

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