Magnetic Fusion with High Energy Self-Colliding Ion Beams

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Self-consistent equilibria are obtained for high beta plasma where almost all of the ions are energetic with a gyroradius of the order of the plasma scale length. Magnetohydrodynamics would not apply to such a plasma. Recent experiments with tokamaks suggest that it would be insensitive to microinstabilities. Several methods are described for creating the plasma with intense neutralized ion beams.

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The observed confinement times in tokamaks are usually 10–100 times shorter than classical predictions. The energy confinement time scales with the square of the minor radius so that long confinement times require large systems such as TFTR and JET. If the confinement were classical (determined by Rutherford scattering which is inversely proportional to the square of the energy) it would be possible to obtain long confinement times with a small device and energetic ions.

There is a growing body of experimental evidence that superthermal ions in tokamaks [1] slow down and diffuse classically in the presence of superthermal fluctuations that cause anomalous transport of thermal ions. These experiments involve low densities of beam ions and should be considered as test-particle experiments. For much higher densities, beams are observed to drive Alfvén and other MHD modes. We consider the possibility of obtaining very long confinement times consistent with classical theory for plasmas that consist almost entirely of large orbit nonadiabatic ions: (i) MHD modes would not be applicable, but long-wavelength instabilities for nonadiabatic plasma must be absent. (ii) Nonadiabatic ions are insensitive to microinstabilities as previously observed [1] and explained in this paper. (iii) Electrons must be well confined; in the configurations described in this paper, the plasma is positively charged, which enhances electron containment. (iv) The plasma density near the container walls must be negligible, or the energy containment time will be dominated by thermal conduction, electron transport, etc.

It is well known from accelerators that nonadiabatic ions can be magnetically confined. Indeed the confinement is much better than it is for adiabatic ions in a plasma. The evidence from accelerators is limited to very low density. However, there have been experiments where large orbit particles (electrons [2] or ions [3]) of high density are confined for long times in field-reversed configurations.

Aneutronic reactions such as D-^{3}He require a relative ion energy an order of magnitude larger than D-T reactions. For D-^{3}He, the maximum reactivity $\langle \sigma v \rangle$ is smaller by a factor of 4 compared with D-T so that a higher density or longer confinement time is required. The plasma configurations discussed in this paper that involve high-energy ions produced externally by accelerators are particularly appropriate for a small D-^{3}He reactor where a tokamak [4] would be so large and involve so many technological advances that it has been relegated to the distant future in spite of the obvious advantages of the D-^{3}He reaction.

In Fig. 1 various confinement systems for high-energy ions are illustrated. Simplified physical models will be

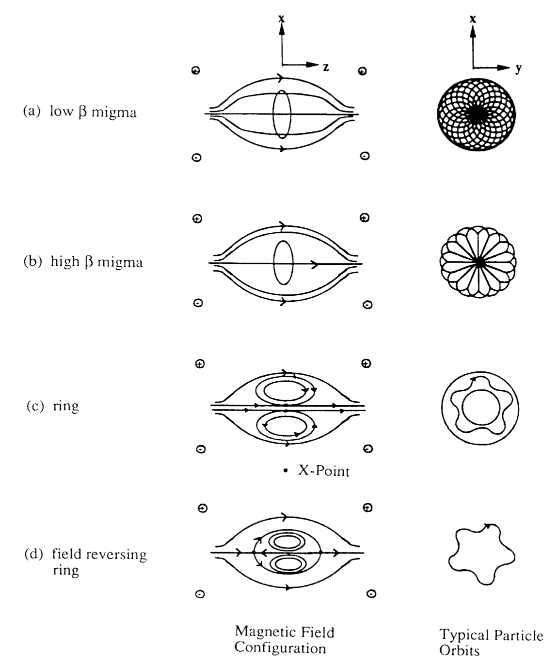

FIG. 1. Self-colliding systems. Left column: magnetic field configuration; flux lines and the current carrying conductors in the x-z plane. Right column: typical ion orbits in x-y plane.

developed from self-consistent solutions of the Vlasov-Maxwell equations. Several methods for creating these configurations with ion beams are considered.

1. General solution of the Vlasov-Maxwell equations.— Consider distribution functions of the form

$$f_j(\mathbf{x},\mathbf{v})=n_j(\mathbf{x})\exp-m_j[\mathbf{v}-\mathbf{u}_j(\mathbf{x})]^2/2T_j(\mathbf{x})\,; \tag{1}$$

different values of j correspond to electrons and various ion species. If $\mathbf{u}_j(\mathbf{x})$ and $T_j(\mathbf{x})$ are the same for all ions, ion-ion collisions will not change the distribution function and ion-electron collisions change it on a very long time scale. In order to satisfy the Vlasov equation, $T_j(\mathbf{x})$ must be constant and $\mathbf{u}_j(\mathbf{x})=(\omega_j y,-\omega_j x,0)$, where ω_j is constant [5]. The density is determined by the following simultaneous equations:

$$n_j=n_{0j}\exp\left[\frac{m_j\omega_j^2r^2}{2T_j}-\frac{e_i\phi}{T_j}-\frac{e_j\omega_j\psi}{cT_j}\right], \tag{2}$$

$$\frac{\partial B_z}{\partial r}=-\frac{4\pi}{c}\sum_j n_je_j\omega_j\,, \tag{3}$$

$$\sum n_je_j=0\,. \tag{4}$$

ϕ,ψ are electric and magnetic potentials. The electric and magnetic fields in cylindrical geometry are $B_z=(1/r)\partial\psi/\partial r$ and $E_r=-\partial\phi/\partial r$. Equation (4), the condition of quasineutrality, implies a relation between ϕ and ψ. For a single ion species Eqs. (2) to (4) combine to the nonlinear partial differential equation

$$\left\{\frac{1}{r}\frac{\partial}{\partial r}\frac{1}{r}\frac{\partial}{\partial r}+\frac{1}{r^2}\frac{\partial^2}{\partial z^2}\right\}\ln n_e=-\frac{4\pi e^2(\omega_i-\omega_e)^2n_e}{c^2[T_e+(T_i/Z)]}\,. \tag{5}$$

Assuming $\omega_e=0$, $Z=1$, $\partial/\partial z=0$, and that the density has a maximum value n_0 at r_0 (the plasma is assumed to be formed by beam injection direction towards $r\cong r_0$), the solution is

$$n=n_0/\cosh^2\left(\frac{x-x_0}{\sqrt{2}}\right), \tag{6}$$

$$B_z=B_0\left[1+\frac{1}{\sqrt{2}}\left(\frac{T_e+T_i}{W}\right)\tanh\left(\frac{x-x_0}{\sqrt{2}}\right)\right], \tag{7}$$

$$\phi=-\frac{B_0R^2}{2c}\frac{\omega_iT_e}{W}\ln\left[\cosh\left(\frac{x-x_0}{\sqrt{2}}\right)\bigg/\cosh\frac{x_0}{\sqrt{2}}\right], \tag{8}$$

where $x=r^2/2\sqrt{2}R^2$, $W=\frac{1}{2}M(R\omega_i)^2$, and

$$\frac{1}{R^2}=\left(\frac{4\pi n_0e^2}{T_e+T_i}\right)^{1/2}\frac{\omega_i}{c}\,,$$

$$B_0=-\frac{cM}{e}\omega_i\,.$$

Typical data for deuterium plasma might be $T_i=100$ keV, $T_e=20$ keV, $r_0=30$ cm, $n_0=10^{14}$ cm^{-3}, and $\omega_i=2.9\times10^7$ sec^{-1}. For these data $\frac{1}{2}M(r_0\omega_i)^2=800$ keV, $B_0=5.9$ kG, $R=5.2$ cm, $B_z(x=0)=-15$ kG, and $B_z(x=\infty)=27$ kG. Equations (6), (7), and (8) represent field-reversed configurations if $x_0>0$ and $T_e+T_i>\sqrt{2}W$. If $x_0=0$ the peak density is on the axis. For this migmalike solution there can be no field reversal. In the limit that $\omega_i\cong0$, $x_0=0$,

$$B_z=[8\pi n_0(T_e+T_i)]^{1/2}\tanh(x/\sqrt{2})\,, \tag{9}$$

$$\phi=-(T_e/e)\ln[\cosh(x/\sqrt{2})]\,. \tag{10}$$

2. Finite boundary conditions.— A reasonable boundary condition is $\phi(r_B)=\phi(0)=0$ in which case $n(0)=n(r_B)=n_B$. The previous solution satisfies these conditions if $r_B=\sqrt{2}r_0$, $r_0\neq0$. The solution is not yet determined. From Eq. (6),

$$n_B=n_0/\cosh^2(x_0/\sqrt{2})\,. \tag{11}$$

If (r_B,n_B) are fixed, this is a transcendental equation for n_0 because x_0 depends on n_0. If $\lambda=(n_0/n_B)^{1/2}$ and

$$x_B=\frac{r_B^2}{2\sqrt{2}}\left(\frac{4\pi n_Be^2}{T_e+T_i}\right)^{1/2}\frac{\omega_i}{c}\,,$$

the equation to be solved for λ is from Eq. (11), $\cosh(\lambda x_B/2\sqrt{2})=\lambda$. If $x_B<1.9$ there are two solutions for λ which can be labeled λ_D and λ_S where $\lambda_D>\lambda_S$. Since $n_0/n_B=\lambda^2$,λ_D the deep solution gives much better density contrast than λ_S, the shallow solution. As x_B approaches 1.9 the two solutions merge and for $x_B>1.9$ there is no solution. These properties of the solution [6] are called bifurcation and $x_B=1.9$ is the point of bifurcation. Two-dimensional [5] (r,z) equilibria have similar properties as illustrated in Figs. 2(a) to 2(c). For fusion applications it is essential to have a low plasma density at the wall which is easily achieved with the deep solution but not with the shallow solution. It is not necessary to have $\phi=0$ at the walls in which case the equilibria are less restrictive. However, this will involve large bias potentials which may create experimental difficulties such as breakdown.

Possible microinstabilities include drift modes, drift cyclotron modes, loss cone modes, Harris instabilities, etc. The list is long and it seems unlikely that they can all be avoided. They produce turbulence in tokamaks and anomalous transport. However, experiments in tokamaks show that high-energy test particles are insensitive to this turbulence. The probable reason is that the test-particle averages the fields so that only wavelengths long compared to the gyroradius contribute to transport. For adiabatic particles this includes much of the spectrum of field fluctuations. For high-energy particles most of the spectrum is excluded. This explanation has been verified in a computer simulation study of transport [7]. It is likely that microinstabilities will not be important except for low-energy particles for which a short containment time is desirable.

Of course a high density of high-energy particles can

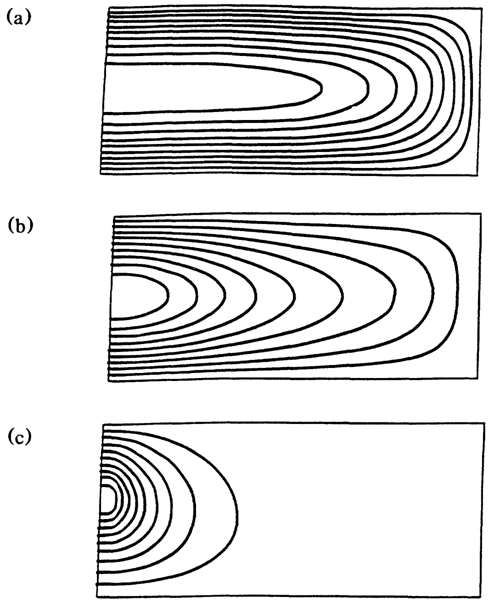

FIG. 2. Contours of constant density and/or equipotentials for conducting walls. (a) Shallow solution near bifurcation, $n_0/n_B = 2.23$. (b) Deep solution near bifurcation, $n_0/n_B = 8.2$. (c) Deep solution not near bifurcation, $n_0/n_B = 330$.

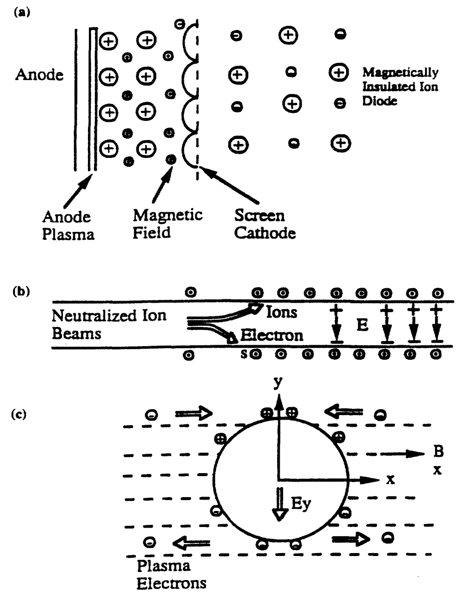

FIG. 3. Intense neutralized beams. Particle disposition and motions for (a) magnetically insulated ion diode; (b) propagation of neutralized ion beam across the magnetic field without deflection; and (c) shielding of beam polarization by plasma electrons.

produce instabilities and it is essential that long-wavelength macroinstabilities be avoided. From the extensive research in FRCs (field-reversed configurations) [3] we know of two such instabilities: the rotational instability that has been eliminated with quadrupole windings and the tilt mode that is stabilized by energetic particles. The rotational instability merits further study; it is conceivable that with the large gyroradii discussed here, the quadrupole windings will be unnecessary. To date there had been only one stability calculation [8] for an idealized model of a field-reversed system which indicates that a long thin annular layer is susceptible to the kink instability. The techniques of this paper are being applied to the ring and the high β migma.

A low density plasma in the migma configuration has been [9] produced by injecting 1.4 MeV D_2^+ ions that are ionized by collisions. A density of 10^{10} cm^{-3} of 0.7 MeV D^+ was achieved with a confinement lifetime of 20–30 sec. This confinement time was measured by observing charge exchange neutrals. An instability was encountered and stabilized by applying a bias potential to the boundary of about 300 V. The density could be increased by increasing the accelerator current which was only 0.5 mA. Many other instabilities are expected before reaching 10^{14} cm^{-3} and it may be possible to control them with a bias.

Another method to reach high density involves pulsed ion diodes and intense neutralized ion beams. Such a beam may cross a magnetic field without deflection in vacuum [10] if the beam density satisfies the inequality

$$\frac{4\pi n M c^2}{B^2} > \left(\frac{M}{m}\right)^{1/2} . \tag{12}$$

The beam is polarized; the resultant field cancels the Lorentz force on the ions and makes the electrons drift with the ions. When the beam reaches a region of significant electron density electrons can freely move along the field lines and neutralize the polarization as illustrated in Fig. 3. Then the beam moves on a single-particle orbit and is trapped. Preliminary successful experiments on trapping neutralized ion beams have been carried out with mirror and tokamak geometry [11]. With this method the density can be increased to 10^{14} cm^{-3} in less than a microsecond so that instabilities characteristic of a low density plasma do not have time to develop. It can be used to produce migma or ring configurations by directing the beam to the axis or off axis.

The current in a ring required for field reversal [12] as in Fig. 1(d) is

$$I = \frac{Mc^3}{2\pi e} \frac{v/c}{1-(1/2\pi)\ln(8R/r)} = 632\ \text{kA} , \tag{13}$$

where R is the major radius, r the minor radius, and v the ion velocity. $R = 20$ cm, $r = 5$ cm, and $v = 0.88 \times 10^9$ cm/sec corresponding to an 800 keV beam of D^+.

The field-reversed configuration could also be produced by injecting a long pulse beam of 10–100 A of D_2^+ or D into a preformed FRC made with standard techniques

[3]. Since the energetic particles have a much longer lifetime they would eventually dominate.

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