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MAGNETIC FUSION WITH HIGH ENERGY SELF-COLLIDING ION BEAMS*

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Abstract

Field-reversed configurations of energetic large orbit ions with neutralizing electrons have been proposed as the basis of a fusion reactor. Vlasov equilibria consisting of a ring or an annulus have been investigated. A stability analysis has been carried out for a long thin layer of energetic ions in a low density background plasma. There is a growing body of experimental evidence from tokamaks that energetic ions slow down and diffuse in accordance with classical theory in the presence of large non-thermal fluctuations and anomalous transport of low energy (10 keV) ions. Provided that major instabilities are under control, it seems likely that the design of a reactor featuring energetic self-colliding ion beams can be based on classical theory. In this case a confinement system that is much better than a tokamak is possible. Several methods are described for creating field reversed configurations with intense neutralized ion beams.

Introduction

Aneutronic reactions such as D-He^3 require a relative ion energy an order of magnitude larger than D-T reactions. For D-He^3 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. Since the Rutherford scattering cross-section is inversely proportional to the square of the ion energy the confinement time should be longer by two orders of magnitude.

The observed confinement times are anomalous; in tokamaks they are 10-100 times shorter than classical predictions. The energy containment time scales with the square of the minor radius in a tokamak so that long confinement times (about 1 sec) can be obtained only with very large systems such as TFTR and JET. If the confinement were classical (determined by Rutherford scattering) it would be possible to obtain long confinement times with a small device; ion containment would be determined primarily by slowing down which is size-independent, rather than by diffusion. There is a growing body of experimental evidence that super-thermal ions in tokamaks[1] slow down and diffuse classically in the presence of the super-thermal fluctuations that cause anomalous transport of thermal ions.

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Confinement systems are considered where the characteristic size is comparable to the ion gyroradius. The ions do not follow adiabatic particle dynamics as in tokamaks; it is well known from accelerators that non-adiabatic ions can be magnetically confined. Indeed the confinement is much better than it is for adiabatic ions in a plasma. It has been assumed that good confinement obtains only for 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.

In Fig. 1 various confinement systems for high energy ions are illustrated. Simplified physical models will be developed from self-consistent solutions of the Vlasov/Maxwell equations. Several methods for creating these configurations with ion beams are considered.

Equilibria for Confinement of High Energy Ions

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.[4] The density is determined by the following simultaneous equations

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

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

$$\sum n_j e_j = 0 \ . \tag{4}$$

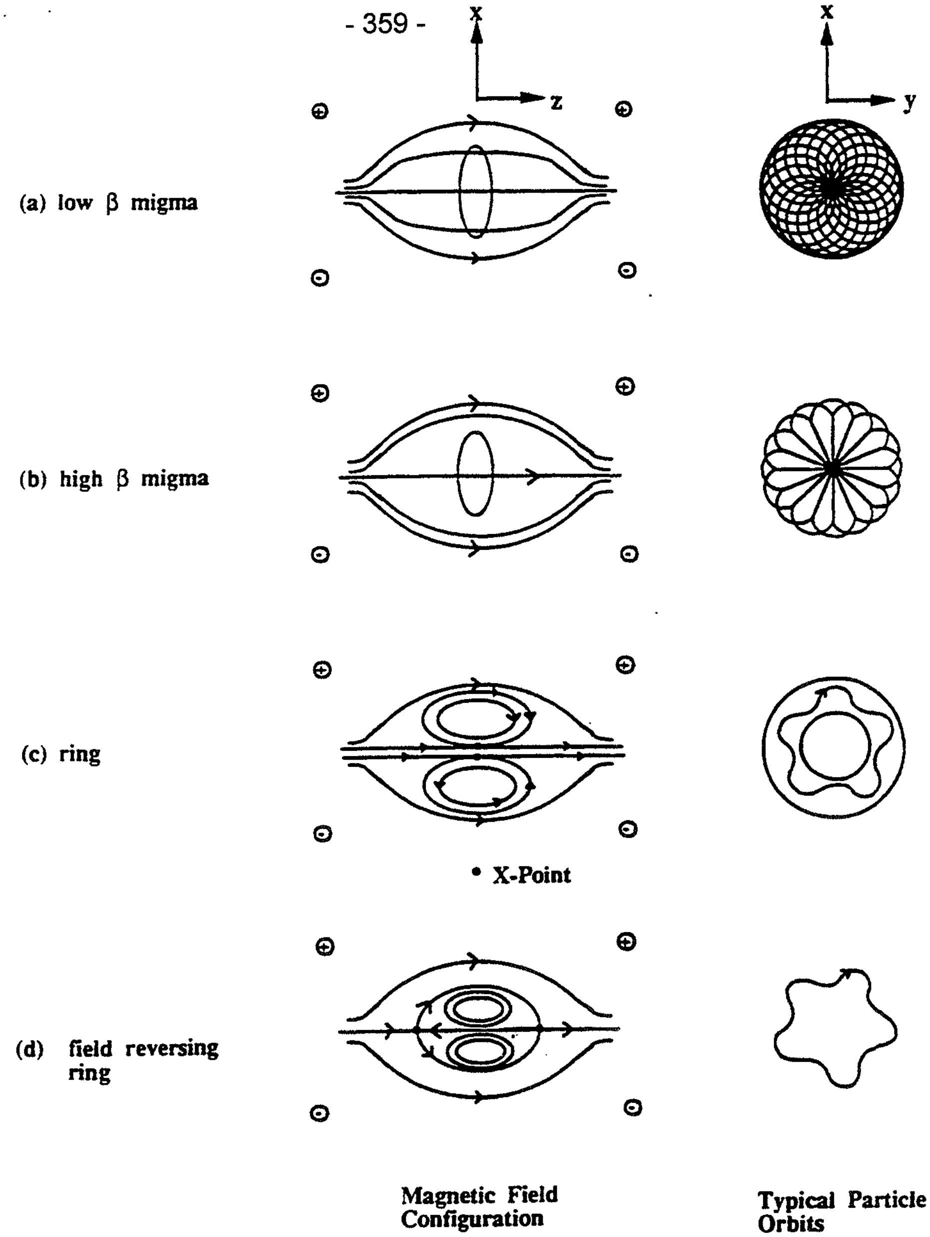

Fig. 1 Equilibria for high energy self-colliding beams

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 quasi-neutrality, implies a relation between ϕ and ψ. For a single ion species Eqs. (2) to (4) combine to the nonlinear partial differential equation

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

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 at $r = r_0$), the solution is

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

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

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

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

$$\frac{1}{R^2} = \left(\frac{4\pi n_0 e^2}{T_e+T_i}\right)^{1/2}\frac{\omega_i}{c}$$

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

Typical data for a deuterium plasma might be $T_i = 100\,\text{keV}$, $T_e = 20\,\text{keV}$, $r_0 = 30\,\text{cm}$, $n_0 = 10^{14}\,\text{cm}^{-3}$ and $\omega_i = 2.9\times10^7\,\text{sec}^{-1}$. For these data $(1/2)M(r_0\omega_i)^2 = 800\,\text{keV}$, $B_0 = 5.9\,\text{kG}$, $R = 5.2\,\text{cm}$, $B_z(x=0) = -15\,\text{kG}$ and $B_z(x=\infty) = 27\,\text{kG}$. 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 migma-like solution there can be no field reversal. In the limit that $\omega_i = 0$, $x_0 = 0$

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

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

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 $r_B = \sqrt{2}\,r_0$, $r_0 \neq 0$. 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 $\lambda = \sqrt{n_0/n_B}$ and

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

the equation to be solved for λ is from Eq. (11), $\cosh \frac{\lambda x_B}{2\sqrt{2}} = \lambda$. 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[5] are called bifurcation and $x_B = 1.9$ is the point of bifurcation. Two dimensional (r, z) equilibria have similar properties as illustrated in Fig. 2a to 2c. 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.

Stability

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.[6] 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 produce instabilities and it is essential that long wavelength macroinstabilities be avoided. From the extensive research in FRCs[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 has been only one stability calculation[7] for an idealized model of a field reversed system which indicates that a long thin annular layer is susceptible to the kink instability. Techniques appropriate to the ring or the high β migma are not yet available.

Experimental Realization

A low density plasma in the migma configuration has been[8] produced by injecting 1.4 MeV D_2^+ ions that are ionized by collisions. A density of $10^{10}\,\text{cm}^{-3}$ of .7 MeV $- D^+$ was achieved with a confinement lifetime of $20 - 30$ sec. An instability was encountered and stabilized by applying a bias potential to the boundary of about 300 volts. The density could be increased by increasing the accelerator current which was only .5 milliamperes. Many other instabilities are expected before reaching $10^{14}\,\text{cm}^{-3}$ 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[9] if the beam density satisfies the inequality

$$\frac{4\pi n M c^2}{B^2} > \sqrt{\frac{M}{m}} \,. \tag{12}$$

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.[10] With this method the density can be increased to $10^{14}\,\text{cm}^{-3}$ 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 as in Fig. 1d is

$$I \cong \frac{1}{\pi} \frac{Mc^3}{e} \left(\frac{v}{c}\right) \cong 560\, kA$$

for an 800keV beam of D^+. This is within the present state of the art for pulsed power devices. A configuration with mainly closed field lines like Fig. 1c requires only about 50 kA.

The field reversed configuration could also be produced by injecting a long pulse beam of 10-100 amperes of D_2^+ or D into a pre-formed FRC made with standard techniques.[3]

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

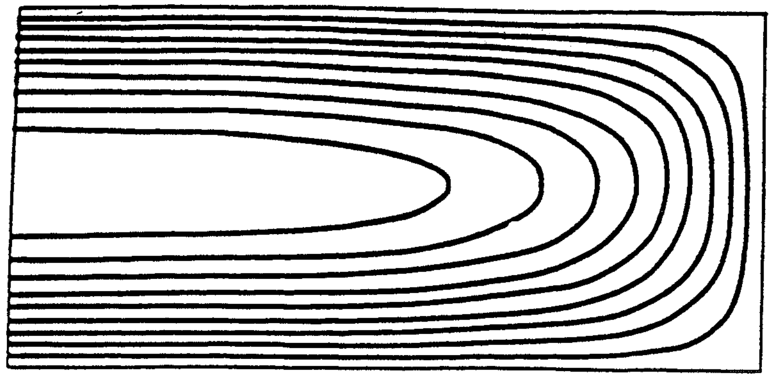

Fig. 2a Shallow solution near bifurcation $n_0/n_B = 2.23$

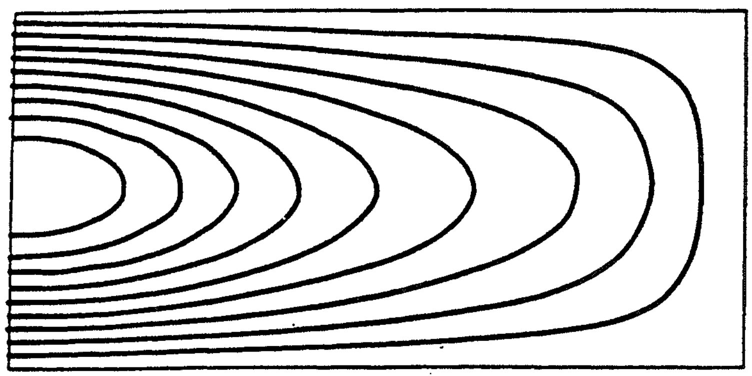

Fig. 2b Deep solution near bifurcation $n_0/n_B = 8.2$

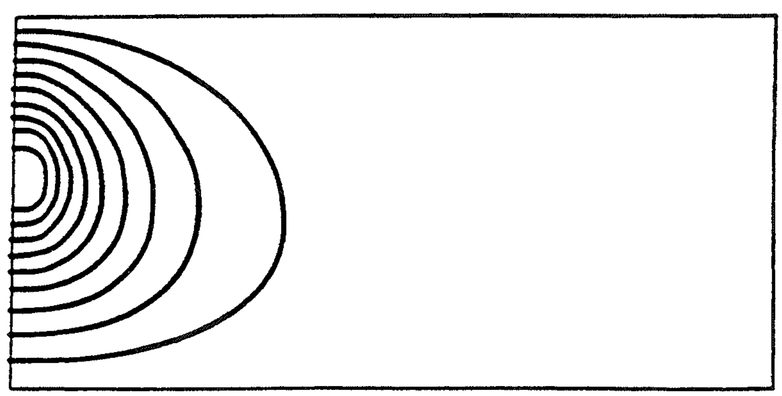

Fig. 2c Deep solution not near bifurcation $n_0/n_B = 330$

Fig. 2 Contours of constant density and/or equipotentials for conducting walls

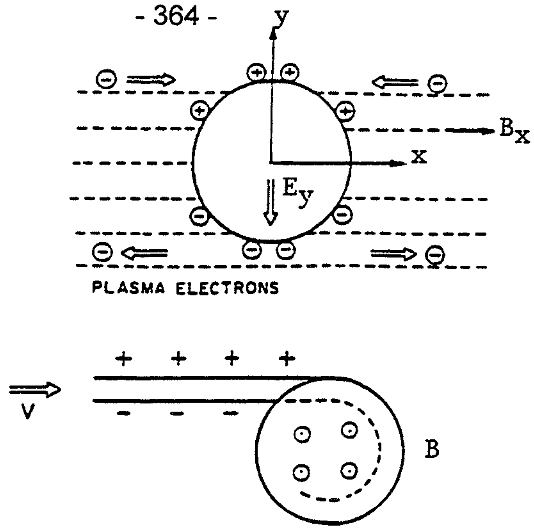

Fig. 3 Trapping of an intense neutralized ion beam

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