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MODIFIED BETATRON FOR ION BEAM FUSION

Norman Rostoker and Amnon Fisher
Department of Physics
University of California
Irvine, California 92717 USA

An intense neutralized ion beam can be injected and trapped in magnetic mirror or tokamak geometry. The details of the process involve beam polarization so that the beam crosses the fringing fields without deflection and draining the polarization when the beam reaches the plasma. Equilibrium requires that a large betatron field be added in tokamak geometry. In mirror geometry a toroidal field must be added by means of a current along the mirror axis. In either case, the geometry becomes that of the modified betatron which has been studied experimentally and theoretically in recent years. We consider beams of d and t ions with a mean energy of 500 kev and a temperature of about 50 kev. The plasma may be a proton plasma with cold ions. It is only necessary for beam trapping or to carry currents. The ion energy for slowing down is initially 500 kev and thermonuclear reactions depend only on the beam temperature of 50 kev which changes very slowly. This new configuration for magnetic confinement fusion leads to an energy gain of 10-20 for d-t reactions whereas previous studies of beam target interaction predicted a maximum energy gain of 3-4. The high beam energy available with pulsed ion diode technology is also essential for advanced fuels.

Introduction

Magnetically confined plasmas are usually treated with adiabatic dynamics; the particles are assumed to have an orbit radius that is small compared with characteristic dimensions - they follow the magnetic field lines except for a slow guiding center drift. Confinement of plasma in a torus requires a poloidal and a toroidal magnetic field. The magnetic field lines have a rotational transform

$$\frac{\iota}{2\pi} = \frac{R B_p}{r B_T} \qquad (1)$$

r is the minor radius of the plasma, R is the major radius; B_T is the toroidal magnetic field and B_p is the poloidal magnetic field. The Kruskal-Shafranov condition is that $\iota < 2\pi$. When $\iota = 2\pi$ there is no rotational transform to compensate the toroidal drift of a particle. Alternately instabilities are associated with $k \cdot B = (n/R)B_T \pm (m/r)B_p = 0$ where n and m are integers. This condition means that particles following the field lines remain in resonance with the perturbation characterized by the integers m and n. The quantity $q = 2\pi/\iota$ is called the safety factor and an essential restriction for toroidal confinement is $q > 1$. This means that

$$B_T = B_p \frac{R}{r} q \qquad (2)$$

must be very large. For example $q = 4$, $B_p^2/8\pi = nT$ with $n = 2 \times 10^{14}$ cm^{-3}, $T = 50$ kev so that $B_p = 20$ kG. To keep B_T below 100 kG, R/r must be near unity. The inescapable result is an enormous energy investment in the toroidal field energy which serves no useful purpose except that it is necessary for stability. The requirement that $q > 1$ is the main reason for the poor economics of a tokamak fusion reactor.

Accelerators on the other hand are usually treated with the paraxial approximation. The particles have a large orbit radius; they do not follow the field lines or drift. Conventional accelerators are non-neutral, limited to low densities and have $B_T = 0$. We have studied high current accelerators [1] where these three conditions are all violated. In many of these experiments the particles are non-adiabatic, do not follow field lines and therefore do not require $q > 1$ for confinement. Experimentally confined energetic electron rings with $q < 1$ have previously been observed by H. Fleischmann [2] and collaborators and by A. Mohri [3].

Large orbit particles are more difficult to treat theoretically. The great body of plasma stability literature avoids them with some recent notable exceptions [4]. Experimentally the problem is how to create a high density plasma where most of the particles have a high energy. The DCX experiments [5] and more recent work of Maglich [6] show that building up the density slowly by injecting beams from a conventional low current accelerator does not succeed in reaching a density of more than about 10^{10} cm^{-3}. It is necessary to pass through various instabilities with a density threshold. This is the generally accepted explanation of the DCX results. Maglich attributes his density limitation of 10^9 cm^{-3} to charge exchange and low injection rate. Recent experiments with high current accelerators [1] indicate that there are also instabilities with an energy threshold so that it is difficult to build up the energy slowly. In this paper we propose methods to build up the energy and density very rapidly in order to avoid instabilities. That this can succeed is demonstrated by the work of H. Fleischmann [2] and collaborators who have created a stable field-reversing electron layer. The electron layer involves large orbit axis encircling particles and should be a good simulation of a plasma with energetic ions.

A ring of energetic ions that produces field reversal has been proposed as the basis for a fusion reactor [7]. The ring is essentially a coil to produce a desirable magnetic configuration for confinement of small gyro-radius plasma. (It may also heat the plasma.) This is the point of departure of the present work. We propose to use a ring of energetic ions - specifically d and t with about 500 kev translational energy for each ion. The beam would have a temperature of about 50 kev. d and t collisions with a relative energy of 50 kev would result in fusion reactions. The beams would be essentially drifted Maxwell distributions so that collisions would not change the distributions. A necessary background of neutralizing electrons would have a much lower particle energy. In previous proposals that involve the fusion of energetic ion beams [8] there is usually a dense background plasma with hot electrons and cold ions. Because of the cold plasma ions the beam ions slow down rapidly and the maximum value of fusion energy/beam ion energy is 3-4. With high density energetic beams and a very low density background plasma the slowing down is greatly reduced and the energy multiplication factor can be 10-20. This makes it feasible to consider a fusion reactor without ignition which will be of modest size and have reasonable economics. For advanced fuel reactions the proposed scheme has particular advantages because the particle energy required for fusion reactions is much larger than for d-t reactions.

Intense Neutralized Ion Beams

Pulsed ion beams can be produced with ion diodes and Marx generators. The technology exists to produce high energy ion beams efficiently [9]. A neutralized ion beam has an equal number of co-moving electrons. The resultant beam is electrically neutral and has no net current or charge. It is feasible to accelerate about 10^{18} ions to .5 Mev in a single pulse of about 100 nsec with existing generators. The beam particle density could be as high as 10^{14} cm^{-3}.

The basic processes and conditions for transport of a neutralized ion beam across a magnetic field are now understood [10] and documented by experiments [11]. As illustrated in Fig. 1, when a neutralized ion beam is incident on a transverse magnetic field, there are several possibilities:

- The ions may separate from the electrons in the longitudinal direction and form a space charge layer of thickness $a_h \simeq u_o(\Omega_i\Omega_e)^{-1/2}$; u_o is the beam velocity, Ω_i and Ω_e are gyrofrequencies for ions and electrons. The beam is thereby reflected by the magnetic field.
- The ions may separate from the electrons in the transverse direction. There is then a transverse electric field such that $\underset{\sim}{u}_o = c(\underset{\sim}{E} \times \underset{\sim}{B})/B^2$ and the beam transports across the magnetic field.

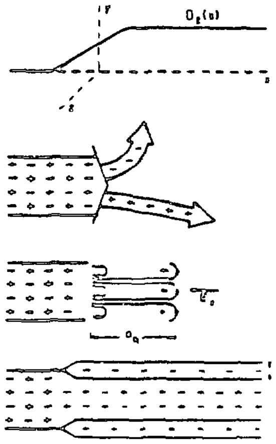

Fig. 1. Polarization of a neutralized ion beam

The latter process requires that $1/2\, nMu_o^2) \gg E_y^2/8\pi$ which with $u_o = cE_y/B_z$ gives the condition

$$\epsilon_\perp \simeq 4\pi nMc^2/B^2 \gg 1 \qquad (1)$$

Further investigation shows that the characteristic width of the space charge layer is

$u_o/\Omega_i\,\epsilon_\perp$. A more demanding condition for the formation of the space charge layer that facilitates transport is that $u_o(\Omega_i\epsilon_\perp)^{-1} \ll u_o(\Omega_i\Omega_e)^{-1/2}$ or

$$\epsilon_\perp \gg (M/m)^{1/2} \qquad (2)$$

A neutralized ion beam may be injected across a magnetic field into a confinement device by means of the polarization effect. It may also be trapped in the device if it contains plasma. The plasma may drain the polarization and then the motion of the beam particles is determined by the confining magnetic fields.

Injection and trapping in tokamak geometry and mirror geometry are illustrated in Fig. 2.

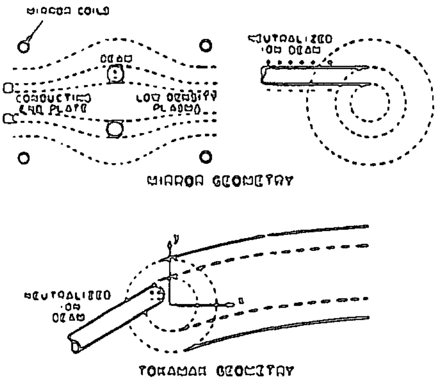

Fig. 2. Injection and trapping in mirror and tokamak geometry

Preliminary experiments have confirmed injection and trapping for both cases [12], [13]. The background plasma density was 10^{12} - 10^{13} cm^{-3} for these experiments. Referring to Fig. 2, the beam crosses the magnetic field by the polarization effect. In the case of mirror geometry the polarization is drained along the field lines that connect with a conducting annular end plate. In tokamak geometry the polarization is drained along the field lines that form a magnetic surface. There is a physical similarity to the stabilization of flutes in both cases. The depolarization by the plasma is not quantitatively understood but does have some experimental documentation.

Fusion Without Ignition

In order to contain the 3.5 Mev α-particles the minor radius of a tokamak must be at least 10 times the gyro-radius of the α-particle which is 10.7 cm in a magnetic field of 50 kG. For this [15] and other reasons a tokamak reactor with ignition must be very large.

Without achieving ignition it is possible to produce net energy by using a tokamak plasma as a target for a high energy ion beam. The plasma electrons must have a sufficiently high temperature. The plasma ions may be cold. The high energy ion beam must be injected, trapped and confined in the tokamak so that scattering which is always more frequent than fusion will not quickly lead to loss of the high energy ion or the investment. This idea has been called a wet wood burner, or a two-component plasma. It was first discussed by W. Linlor [14]

An energetic ion beam trapped in a tokamak plasma will slow down according to the formula[8]

$$\frac{dW}{dt} = -\frac{4\pi e^4 \ln\Lambda}{V}\left[\frac{n_i}{M_i} + \frac{4}{3\sqrt{\pi}}\frac{n_e}{M_B}(m/M_B)^{1/2}\left(\frac{W}{T_e}\right)^{3/2}\right] \qquad (3)$$

W is the energy of beam ions of mass M_B and velocity V; n_i is the density of plasma ions of mass M_i; n_e is the density of electrons of mass m and temperature T_e. The quantity ln Λ is about 20. The first term of Eq. (3) is due to scattering of beam ions by plasma ions. It is based on the assumption that $V > v_i$ the ion thermal velocity defined by $M_i v_i^2 = T_i$ the ion temperature. Since this term is independent of T_i it obtains even for $T_i = 0$. The second term is due to scattering of beam ions by plasma electrons. It has been assumed that $V < v_e$ where $mv_e^2 = T_e$.

Fusion takes place according to the formula

$$(dn_d/dt) = -n_t n_d \langle v\,\sigma_{dt}(v)\rangle \qquad (4)$$

We shall assume that the beam is deuterium and the plasma ions are tritium i.e. $n_i = n_t$ and $n_B = n_d$. v is the relative velocity of deuterium and tritium ions; the brackets indicate an average over the ion distributions. The energy gain is defined as

$$F = f\,W_F/W_o \qquad (5)$$

where W_F = 22.4 Mev [8] is the fusion energy per reaction, W_o is the initial beam ion energy and f is the fusion probability which can be determined from Eqs. (3) and (4).

The previous study of energy multiplication [8] indicated that to obtain $F > 1$ required $T_e \gtrsim 4$ kev. For $T_e < 4$ kev the beam ions slow down in the plasma so fast that little time is spent at energies where σ_{dt} is significant. F increases when T_e is increased because the slowing down due to electrons decreases like $T_e^{-3/2}$. Even if $T_e = \infty$ the slowing down due to cold ions is sufficient to limit F to $F \leq 4$. Thus, although it is possible to produce fusion energy without ignition, and a small reactor is then feasible since the α-particles need not be contained, the energy gain is insufficient to make the reactor economically attractive.

To reduce the effect of ion drag we propose a configuration where there are beams of d and t-ions with energies of 400 kev and 600 kev respectively. The distributions are described by drifted Maxwell distributions

$$f_j(v) = n_j\left(\frac{m_j}{2\pi T}\right)^{3/2} \exp - \frac{m_j}{2T}(\underset{\sim}{v} - \underset{\sim}{V})^2 \ldots \qquad (4)$$

where $j = d,t$, $V = .625 \times 10^9$ cm/sec and $T = 50$ kev, for example. To create these distributions intense neutralized ion beams would be injected and trapped as previously described. This requires a background plasma to drain the polarization. However, only the conduction properties matter and the density need not be large; experiments indicate a density of about 10^{12} cm^{-3} is sufficient. The slowing down by the cold plasma ions can be neglected because of their low density and because they would soon escape confinement. The electrons that accompany the beams would be stopped by the magnetic field when the transverse polarization is drained. There would be an induced electric field according to Lenz's law to oppose the change in current; the induced current might be in the background plasma or the conducting boundary. Thus the electron distribution cannot be anticipated without detailed knowledge of the configuration. The ion beams would have a temperature of 50 kev which is a reasonable expectation if they are produced in a diode. The electrons might have a similar temperature. If less, they would be heated by the beam after trapping. For slowing down the ions have an energy of about 500 kev; for fusion which depends only on the relative velocity of d and t-ions the temperature would be 50 kev. The slowing down time would be much greater than in the usual dense target configuration thus increasing the gain. If it can be made larger than the fusion time $T_F = [n\langle\sigma v\rangle]^{-1} = 11.8$ sec. the maximum possible gain would be 22.4.

Reactor Configuration

The configuration of Fig. 3 will be considered. The ion layer would be built up and maintained by injecting repetitive pulses from a series of ion diodes. With each nuclear reaction a pair of ions disappears since neither neutrons nor α-particles would be contained. We consider steady operation with d.c. applied magnetic fields and ion sources that emit repetitive pulses.

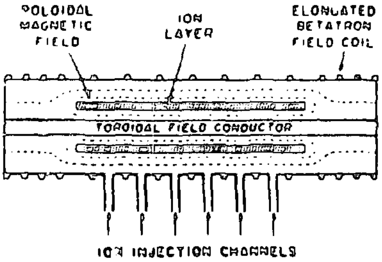

Fig. 3. Schematic diagram for reverse field reactor configuration

To be specific consider ion energies of 400 kev for d and 600 kev for t-ions so that both species have a velocity of $.625 \times 10^9$ cm/sec. The ion layer is assumed to be 1 m long with internal radius 22 cm and external radius 27 cm; the volume is $.77 \times 10^5$ cm^3 and the ion density is 2×10^{14} cm^{-3} so that the total number of ions is 1.5×10^{19}. With six injectors each emitting 10^{17} ions every .5 sec the ion layer can be replaced in 12 sec. which is the fusion time. The average ion beam power is .1 Mw and the fusion power is $P = \langle\sigma v\rangle n_d n_t \times [22.4$ Mev/reaction$] = 2.24$ Mw. The ion beam trapping would be like the trapping in tokamak geometry. In that case, as well as in a field reversed configuration, the positive and negative charges of the beam polarization are connected by a magnetic field line which is a long path along which charge can move freely to drain the polarization.

The mean applied betatron field would be 5 kG so that the gyro-radius in this field is 25.2 cm for d-ions and 37.8 cm for t-ions. The magnetic field is substantially altered by the toroidal current of the beam. It produces closed poloidal field lines that are necessary to confine the beam pressure. Assume $n = 2 \times 10^{14}$ cm^{-3} and $T = 50$ kev. From the relation $nT = B_p{}^2/8\pi$, the poloidal magnetic field must be 20 kG. Now this means a field reversal factor of 4 is required. Factors of 2 are conventionally observed [2] in the electron ring experiments and a factor of 4 has been observed for short times [16]. We assume the latter figure in order to realize $B_p = 20$ kG. Assuming a uniform current density between $r = 22$ cm and $r = 27$ cm, a circular orbit for d-ions would be found at 25.2 cm and a circular orbit for t-ions at 25.5 cm. The magnetic field changes rapidly so that the momentum difference between t and d-ions does not lead to a large difference in location. Most of the particle orbits oscillate about the circular orbit radius since the beams are assumed to have a temperature of 50 keV. The poloidal magnetic field is $B_p \sim (2\pi/c)\ nev\ \Delta r$ if only ions carry current. In that case $B_p = 62.8$ kGauss. As previously discussed the current due to electrons cancels the ion current before trapping. After trapping it is not simple to evaluate and it is not obvious that it would be just the right value to give a net current such that $B_p = 20$ kG. However, various diamagnetic effects can adjust either the toroidal or poloidal fields to obtain an equilibrium. The current will also change as reactions take place, or due to electron ion interactions. The continuous injection of ions can maintain the current at an acceptable value, but the determination of the current and the details of equilibrium require further study.

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