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Importance of Field-Reversing Ion Ring Formation in Hot Electron Plasma

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Further communication about this report is to be sent to the Research Information Center, Institute of Plasma Physics, Nagoya University, Nagoya, JAPAN.

Abstract

Formation of the field-reversing ion ring in the mirror-confined hot electron plasma may offer a device to confine the fusion plasma even under the restriction of the present technology.

One of the topics in the field of the plasma containment is the formation of the field reversing ion ring (i.e. I-layer)[1] by magnetic compression to provide ideal MHD stability for a thermonuclear plasma.[2] This gives us a hope of designing a fusion reactor with use of the I-layer even under the restriction of the present technology.

It is the purpose of this paper to discuss a new scheme of the field reversing ion ring formation by magnetic compression in a low density hot electron plasma in an axially symmetric mirror field. In the present scheme the ion beam energy of order 10 MeV and its current of order 10 kA is azimuthally injected into a standard magnetic mirror field in which the hot electron plasma of its density of order 10^{12} cm^{-3} is contained. It should be noted that the magnetic neutralization of the ion ring current by the background electron may be neglected since the electron current decays quickly because of the decay of the electric field. In the initial plasma the characteristic slowing down time τ_s of protons by Coulomb scattering is of order 2 sec. Therefore, the magnetic compression must be completed rapidly compared with the slowing down time in order to accelerate significantly the ion beams. The advantage of the present compression scheme may be that the compression time scale is able to be in the order of 0.1 sec because of the long slowing down time of the beam. Therefore, the compression coil might be designed by using a superconductive material.[3]

One of the important problem in the initial phase, may be the stabilization of the precessional instability[4] of the injected ion beam just after the beam is launched in the equilibrium orbit. Woodall, Fleischman and Berk has recently shown that the instability can be suppressed by adding a sufficiently strong quadrupole Ioffe field5) to the normal mirror field. However, in the Ioffe field, the field strength on a local coil surface may become so intense that there is a possibility to destroy the super-conductivity of a compression coil. This difficulty of the Ioffe field may be avoided by using the hot electron cloud in the normal mirror field as a electron coil. The positive field gradient can be formed by the hot electron current6) which may be expected to stabilize the precessional mode. An example of the magnetic vector potential A_θ produced by the hot electron cloud may be approximately described by

$$A_\theta = -\frac{B_c}{2} r \left[1 + \frac{z^2}{b^2} + \frac{(r-R)^2}{4a^2} - \frac{R}{4a^2}\left(\frac{2}{3} r - R\right)\right] , \quad (1)$$

where B_c represents the magnetic strength at the center of the mirror machine, and a and b are the characteristic distances along the z and the r axis, and R is the major radius of the ion beam ring. Since the mirror confined hot electron current is composed of the off-axially gyrating particles, the current changes its sign at a certain point r_c. In the present model

$$r_c = \frac{Rb^2}{2(a^2 + b^2)} . \quad (2)$$

The field strength is given by

$$B^2 = B_c^{\,2}[1 + (\frac{r-R}{a})^2 + (\frac{2}{b^2} + \frac{R^2}{b^2})\; z^2\;] \;. \qquad (3)$$

We see that the magnetic isobars form a family of closed surfaces near r = R and z = 0, where the field strength is minimum.

After the ion beam is launched in the stable orbit in the low density plasma, the magnetic field is rapidly increased in its strength by a factor of 10^2. In order to accomplish this compression under the restriction of present technology, the initial magnetic field strength must be of order 10^3 gauss. This strength of the field and the initial ion beam energy uniquely determines the dimensions of the machine size which is shown in Fig.1. In the compression phase we note that the hot electrons do not contribute to the field reversal because of their off-axial motion even if they are non-relativistic. After the compression the slowing down time τ_s of protons becomes of order 20 sec and the density of the hot electron plasma does of order 10^{14} cm^{-3} because of the longer life time of the hot electron plasma than the compression time.

Although the process of the compression of the ion beam ring was discussed in detail by using a set of the complicated equations[2), it is kinematically discussed here again under the assumption that the aspect ratio A of the ion ring is constant in the compression phase, where the aspect ratio is defined by the ratio of the major radius R to its minor radius a, i.e. A = R/a. The radius of the ion ring is approximately the ion Larmor radius R_L.

$$R \simeq R_L = \frac{Mv}{eB} \quad , \tag{4}$$

where M and e are the mass and the charge of the ion respectively, and v is the velocity of the ion beam. And the self-field B_d at the surface of the ion beam ring can be written by

$$B_d = - \frac{\mu_0 eA}{4\pi^2} \frac{Nv}{R^2} \quad , \tag{5}$$

where N is the whole number of the ions which compose the ring. In the compression phase of the ring the adiabatic moment of the single ion should be conserved.

$$\mu = \frac{Mv^2}{2B} = \text{constant.} \tag{6}$$

With the helps of Eq.(4), Eq.(6) means that the magnetic flux linked by the ring remains constant in the compression phase.

$$BR^2 = B_0 R_0{}^2 \quad , \tag{7}$$

where B_0 and R_0 are the magnetic field and the Larmor radius of the ion at the begining of the compression. Eliminating v and R in the expression (5) by using Eqs.(4) and (6) we have

$$B_d = - \frac{Ne^2 \mu_0}{4\pi \ M} \left(\frac{B}{B_0}\right)^{3/2} B_0 R_0 A. \tag{8}$$

In order to attain the field reversal the field reversal factor defined by

$$\alpha \equiv \left|\frac{B_d}{B}\right| \tag{9}$$

must be larger than unity. This condition can be rewritten by the requirement of the necessary particle number as follows.

$$N > N_c \doteqdot \frac{4\pi^2 M}{Ae^2 \mu_0 R_0} \left(\frac{B_0}{B_f}\right)^{1/2} , \tag{10}$$

where B_f is field strength at the end of the compression. For the parameters

$B_0 = 10^3$ gauss

$B_f = 10^5$ gauss

$R_0 \simeq 200$ cm

and $A \simeq 10$,

the necessary particle number N_c of the protons becomes

$$N_c \simeq 10^{17}.$$

This means that the necessary proton current I with energy of order 10 MeV must be larger than

$$I > 2 \times 10^4 \text{ Amp.}$$

This value is within the reach of the modern electric pulse technology considered by many authors.[7] And, moreover, the stability condition of the field reversing ion ring is compatible with the condition (10).[8]

In order to obtain a positive energy from the present scheme the fusion out put energy must be larger than the total plasma particle energy plus the energy required for the production and the acceleration of the ion beam, and the synchrotron loss energy from the hot electrons.

The total fusion power, P_f, for a nuclear reaction can be written by

$$P_f = n_A n_B \langle \sigma v \rangle_{AB} F_{AB} \quad , \tag{11}$$

where n_A and n_B are the particle densities of A and B species, $\langle \sigma v \rangle_{AB}$ is the probability of A-B fusion reaction and F_{AB} is the energy released by the reaction.

The energy E_p required to heat the plasma at temperature T is

$$E_p = 3(n_A + n_B)kTV \ , \tag{12}$$

where V and k are the volume of plasma and the Boltzman constant. The total energy E_b to accelerate the ion beam is

$$E_b = NW \quad , \tag{13}$$

where W is the final ion beam energy.

The synchrotron radiation loss P_s per unit volume from the hot electrons of a Maxwellian distribution is

$$P_s = \frac{4}{3}\frac{e^4 B^2}{m^3 c^3} n_e k T_e , \qquad (14)$$

where m, n_e and T_e are the mass, the density and the temperature of hot electrons.

Thus, the condition of the positive energy out put becomes

$$(P_f - P_s)V\tau > E_p + E_b , \qquad (15)$$

where τ is the confinement time of plasma. A problem for further discussions of the positive energy out put is the lack of knowledge of the plasma confinement time in the astron type configuration. We must leave the precise knowledges of the plasma confinement time in the astron configuration for a future study. And we consider here a rather pesimistic case, i.e. the confinement time of plasma is the same order of the slowing down time of the beam.

$$\tau \simeq \tau_s . \qquad (16)$$

Then, the condition (15) is reduced to

$$n > 4 \times 10^{17} \text{ cm}^{-3} \qquad (17)$$

for the D-T reactions, where the plasma volume is chosen to be $V \simeq 1.25 \times 10^4 \text{ cm}^3$, $n = n_A = n_B$. The other parameters, i.e., W, n_e and T_e, are chosen to be $n_e = 10^{14} \text{ cm}^{-3}$, $T_e \simeq 10^{10}$ °K and $W \simeq 10^9$ eV, and the plasma temperature T is $T = 10^8$ °K. Thus, the positive energy out put can be obtained for a rather high plasma density even if the plasma containment time is comparable to the slowing down time of the ion beam.

In summary, we have noted in this consideration that there is a possible parameter range of designing a device of the plasma containment by the magnetic compression of an ion ring in a hot electron plasma even under the restriction of the present technology. The dense plasma may be produced if the D-T ice pellet is impacted by the ion beam ring.

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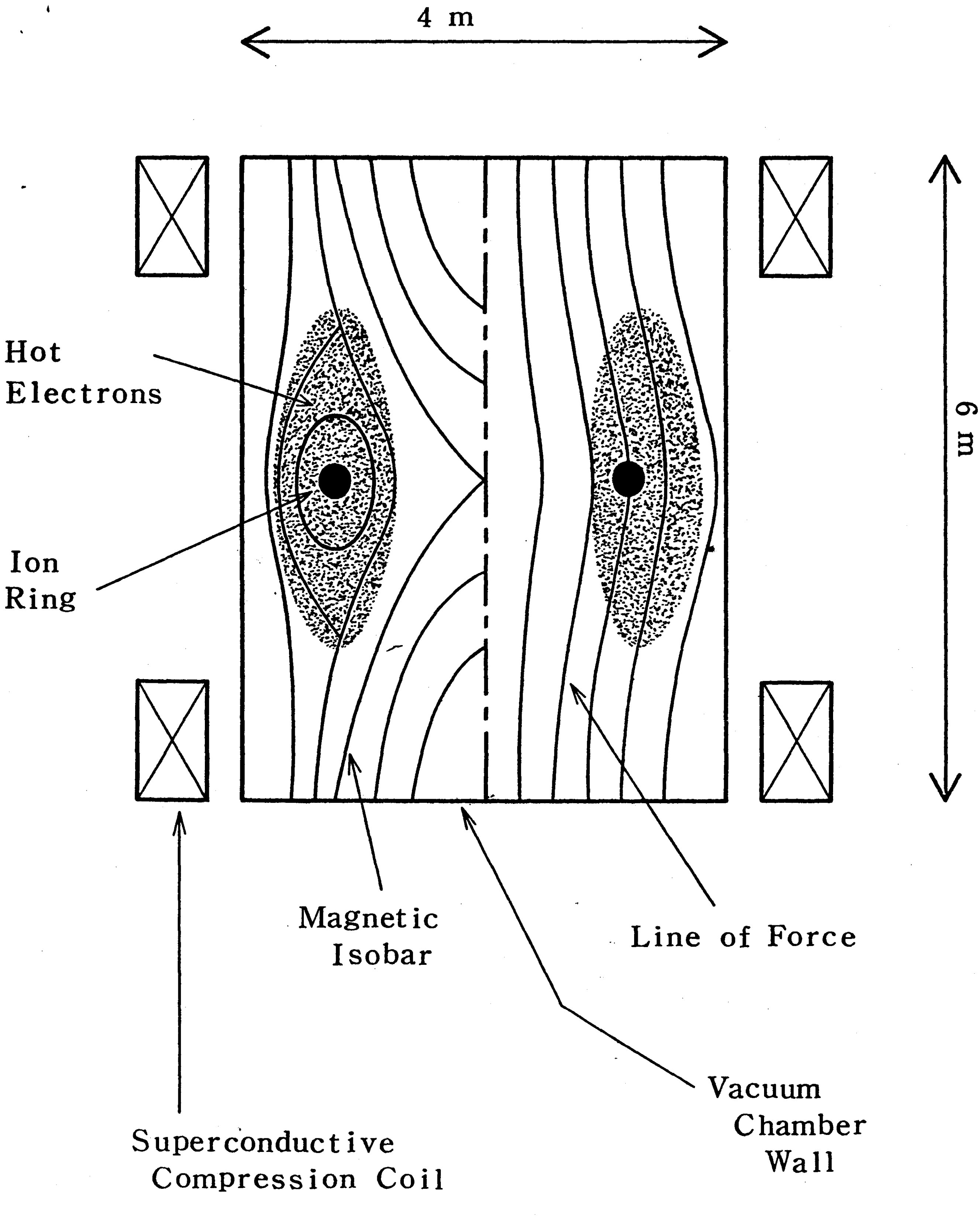
Figure Caption

Schematic view of the confinement system. Strong current ion beam ring is launched in the absolute minimum B region produced by the hot electron plasma.


4 m
6 m
Hot Electrons
Ion Ring
Magnetic Isobar
Line of Force
Vacuum Chamber Wall
Superconductive Compression Coil