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Formation of Reverse Pinch Configuration in Static Toroidal Field

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Abstract

Possibility of producing a reverse pinch mode in a static toroidal field by using two kinds of energetic beam is considered. Strong current ion beam of its energy 20 MeV is required for the fusion reactor.

The reverse pinch configuration[1)] is one of the stable equilibrium states in toroidal geometry, where the poloidal magnetic field is comparable in strength to the toroidal magnetic field, having a number of desirable properties for fusion reactor. A decisive disadvantage of the reverse pinch configuration, however, was the difficulty of start-up of the mode in an externally given static toroidal field. In order to create the configuration the toroidal field must change its sign when the toroidal current reaches its maximum. This fact makes the reverse pinch configuration questionable as a confinement scheme in large device. However, once a method of producing the configuration in a static toroidal field is discovered this equilibrium is superior to others in that the fusion reactor can be constructed without use of superconductors. Recently, it is suggested that a strong plasma current itself creates the reverse pinch mode[2)]. In this case, unfortunately, plasma in the start-up period is so turbulent that there occurs a close contact between plasma and the wall of the chamber and that only a low temperature plasma can be produced.

In the present paper another possibility of creating the reverse pinch mode is suggested, aiming at the fusion reactor with a static toroidal field, by making use of the energetic beams produced by means of the high voltage pulse technology recently developed[3)]. An important thing to be noticed is how to create the field reversal inside a beam. This is possible if the toroidal current of the beam is below the Alfvén limit I_A[4)]. Once the internal toroidal field of the beam has reversed against the external vacuum field, another beam which exceeds the Alfvén limit by a large factor should be injected to sustain the field profile. Energetic ion beam of order 10 MeV is desirable for the aim of the toroidal field-reversal, and after the slowing down time of injected ions the plasma temperature can be raised to attain the fusion ignition condition. The sustaining of the field profile is completed by means of the relativistic electron beam injection of order 10 MA.

For simplisity, we discuss the process of creating the field reversal in the uniform magnetic field B_1 in the z direction. Just after injection the mono-energetic ion beam should form a thin, hollow cylinder of radius a. This can be regarded as a solenoidal coil carrying the ion current. The radius a should be very close to the Larmor radius.

$$a \simeq \frac{Mv_\theta}{eB_1} , \qquad (1)$$

where M and e are the mass and the charge of ion and v_θ is the azimuthal component of the beam velocity. In case the beam is intense enough, the beam current produces the magnetic field. If $\vec{B} = (0, B_\theta, B_z)$ is the resultant field, we can write

$$\begin{aligned} B_z &= B_1 & r > a \\ &= B_1 - \frac{\mu_0 Nev_\theta}{2\pi R}, & r \leqq a , \end{aligned}$$

and

$$\begin{aligned} B_\theta &= \frac{\mu_0 Nev_z}{2\pi r} , & r > a \\ &= 0 , & r \leqq a , \end{aligned}$$

where v_z is the velocity of ion in z direction, and R is the simulated major radius of torus, and N is the total ion number. The field reversal can be attained if

$$B_1 < \frac{\mu_0 N e v_\theta}{2\pi R} \qquad (3)$$

Just after the field reversal is attained by the help of ion beam, the relativistic electron beam is injected, whose current exceeds the Alfvén limit by a large factor. In this case the inertia of electron can be neglected. Then the configuration is composed of both the ion beam and the electron currents. And the field structure is subjected to

$$\mu_0 (\vec{J}_i + \vec{J}_e) = \nabla \times \vec{B} \quad , \qquad (4)$$

$$\vec{J}_e \times \vec{B} = 0 \quad , \qquad (5)$$

where $\vec{J}_i$ and $\vec{J}_e$ are the current densities of ion and electron, respectively. A set of Eqs. (4) and (5) can be treated without difficulty, provided that the ion current density is known. Since the ion beam $\vec{J}_i$ tends to vanish in the slowing down time scale, we will ignor this term here after. And we have the well-known force free configuration. In the cylindrical system the configuration is subjected to

$$B_z \frac{dB_z}{dr} + \frac{B_\theta}{r} \frac{d}{dr} (rB_\theta) = 0 \quad . \qquad (6)$$

Assuming the B_z-component to be

$$
\begin{aligned}
B_z &= B_1 + (1 - r^{\ell}/a^{\ell})B_2 \ , \quad r \leqq a \ , \\
&= B_1 \qquad\qquad\qquad\qquad\quad , \quad r > a \ ,
\end{aligned}
\tag{7}
$$

where B_2 is an arbitrary constant and $\ell \geqq 2$, we can solve B_θ and deduce the total electron beam current I to be

$$I^2 = \frac{4\pi^2}{\mu_0{}^2} \frac{\ell^2}{(\ell+1)(\ell+2)} B_2{}^2 a^2 [1 + \frac{2(\ell+1)}{\ell} \frac{B_1}{B_2}] \ . \tag{8}$$

From the point of view of M.H.D. theory in the reverse pinch mode[1], the ratio $|B_1/B_2|$ should be close to 0.15. Substituting this value and taking the limit $v_z \to 0$, we obtain the necessary ion energy from Eqs.(1) and (8) for a given value of the total electron current, I.

$$W = 0.1125 \times (\frac{\mu_0 I}{4\pi})^2 \frac{\ell(7\ell-3)}{(\ell+1)(\ell+2)} \frac{e}{M} \ (\mathrm{eV.}) . \tag{9}$$

The current I required by a toroidal fusion reactor is estimated as of order 10 MA[5], which implies that for the case of $\ell=2$ proton coil the ion energy should be

$$W = 0.1976 \times 10^2 \ \mathrm{MeV.} \tag{10}$$

The necessary current of the proton coil can be directly obtained by Eq.(3).

Here, we have not considered the case of the diffuse current profile of proton coil. The effect of diffuse current profile can easily be taken into account by following Yoshikawa[6]. And the result obtained is very close to Eq.(9). In the mixed state with the ion current term described by Eqs.(4) and (5) the toroidal effect should be considered to optimize the fusion reactor$^{7)}$.

In conclusion it is demonstrated that there is a possibility of constructing the reverse pinch mode in the static toroidal field with a heating mechanism of ions. The key technique to accomplish this method is to produce the strong current of 20 MeV ion beam.

References

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