INSTITUTE OF PLASMA PHYSICS

NAGOYA UNIVERSITY

Two Component Plasma Vortex Approach to Fusion

Kazunari Ikuta

IPPJ- 355 September 1978

RESEARCH REPORT

NAGOYA, JAPAN

Two Component Plasma Vortex
Approach to Fusion

Kazunari Ikuta

IPPJ- 355 September 1978

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

ABSTRACT

Two component operation of the field reversed theta pinch plasma by injection of the energetic ion beam with energy of the order of 1 MeV is considered. A possible trapping scheme of the ion beam in the plasma is discussed in detail.

Many people have been considered to form field-reversed configurations in order to confine plasmas for thermonuclear purposes. Astron [1] is one of the field-reversed configurations formed by energetic charged particles. In the astron devices injected charged particles gyrate in an axially symmetric magnetic field, thereby creating a current layer. The electric current from the layer, together with current in external windings, produce the magnetic field which confines the charged particles. Under certain conditions, closed magnetic surfaces are generated. On the other hand, the reversed field equilibrium is naturally obtainable in the reversed field theta pinch devices [2]. We hereafter call the plasma in the field-reversed theta pinch as "plasma vortex". During the formation of the plasma vortex a resistive instability is believed to play an essential role. Development of the field reversal in the theta-pinch plasma is roughly as follows. The plasma forms at the walls and implodes to form an annulus separating the external lines of force and the anti-parallel field lines in the core. Outside the coil region, where the electron temperature is low, magnetic lines break and reconnect to form a family of closed field lines encircling the plasma. Once the plasma vortex is created, there appears a set of cusp points in the vicinity of plasma ends. The long-lived reversed field structure is recently demonstrated [3] with life time of the configuration being of the order of 50μ sec.

In this situtation it is timely to consider a possible break through to fusion by an application of the well-known two-component-torus (TCT) concept [4] to the plasma vortex.

The motivation to think better of the TCT is that a difficulty is anticipated for the production of intense neutral beams with energy 150 $\sim$ 300 keV. By the development of modern high-power electrical pulse technology, the production of several kiloamperes of ion pulse (with voltage $\sim$ 300 keV) by slight modification of existing relativistic electron beam technology has been reported [5]. Near future, pulse ion beam with energy of the order of 1 MeV can be hopefully expected. Instead of neutral beam we use the ion beam with energy of the order of 1 MeV, and a complicated process for neutralizing the beam ions can be completely eliminated in this case since the ions with low axial velocity are easily trapped in a time-varying magnetic field configuration such as the plasma vortex.

The trapped beam in the plasma delivers energy to the plasma electrons and, since the beam ion velocity is much greater than the electron thermal speed, the heating time is given by the characteristic slowing down time of ions [6], i.e. $\tau_s \simeq 10^{11} (W)^{3/2} /n$ sec, where W is the ion beam energy in MeV, n the density of plasma ions in cm^{-3}. The plasma electrons heat up until the electron thermal speed becomes comparable to the speed of ion beam. After a slowing down time of the beam, the electron temperature is able to be heated up to several kiloelectron volts provided that the current of the ion beam is sufficiently high. At this time, the beam energy enters into the state of maximum fusion cross section, i.e. $W \simeq 0.15 \sim 0.2$ MeV. We are, thus, lead to a version of TCT reactor concept, i.e. two component plasma vortex (TCV) reactor, where the fusion cross section is

maximized by the slowing down of the injected beam by the electron drag in the cold bulk plasma.
The application of the slow, magnetic compression to the plasma vortex, at this instance, is able to clamp the maximum state of the fusion reactions [7].

One scheme of the injection and the trapping of the ion beam in the plasma vortex is shown in Fig.1. By superposition of a magnetic field on the initial plasma and starting the main theta pinch discharge with reversed direction, the antiparallel field situation is achieved for an annular plasma, and the pulse ion beam is being ejected along converging lines of force from a certain type of ion beam source (Fig.1a). Outside the coil region, where the electron temperature is low, magnetic lines break and reconnect to form a family of closed lines encircling the plasma. The closed lines act as a cage for the injected beam. The beam is propagating along field lines which forms the closed magnetic surfaces. The two exterior parts of the plasma are expelled out of the coil region (Fig.1b). The beam particles are arriving at one end of plasma where a cusp point exists, and a part of the beam particle crosses over the cusp point towards a burial chamber. The remaining ions turn around the toroidal plasma along lines of force (Fig.1c) and stay in the plasma vortex as a magnetic trap (Fig.1d).

In order to trap efficiently the energetic ion beam in a time-varying "plasma vortex" configuration, the rotating ion beams of low axial velocity should be used [8], and the particles should not encircle the axis of symmetry of the device since a particle injected off axis remains attached to a magnetic flux surface [9]. And a necessary condition of the beam trapping can be roughly described by the following inequality:

$$\frac{\ell}{v_z} \lesssim t_f \lesssim \frac{L}{v_z} \quad , \tag{1}$$

where L is the length of the device, t_f the rise time of the configuration, and v_z and ℓ are the axial velocity and the axial length of the ion beam. Another important condition for beam trapping, together with (1), is the strength of the magnetic field. The Larmor radius, r_b, of the energetic ion beam should be sufficiently smaller than the plasma radius, a.

Now, we are at the position to assess the feasibility of the beam trapping scheme presented here. In order to design an attractive reactor configuration we see from (1) that the length of the device, L, should be as short as possible. This means that the pitch angle of the rotating ion beam has to be close to $\pi/2$, since the relation between the speed of the ion beam, v_b and the axial velocity v_z is

$$v_z = v_b \cos\gamma \quad , \tag{2}$$

where γ represents the pitch angle of the beam against the axis of symmetry of the device. The axial length of the ion beam, in this case, is described by

$$\ell = v_b \, \Delta t \cos\gamma \quad , \tag{3}$$

where Δt is the pulse duration of the high voltage generator for ion beam production. Both the shortening of the length, ℓ, and the slowing down of the axial velocity, v_z, could be expected if the beam is injected in the build-up phase of the plasma vortex (See Fig.1a) because of the increase of the pitch angle in the annular plasma. These facts make the trapping of the beam more easily. As the beam speed and a typical field rise time, t_f, are of the order of 10^9 cm/sec for $W \simeq 1$ MeV and $t_f \simeq 10^{-6}$ sec respectively, the length of the device can be $L \gtrsim 5 \times 10^2$ cm for $\gamma \simeq 60^\circ$.

We now estimate the necessary current of the ion beam which can attain break-even conditions given by Dawson, Furth and Tenny [4], i.e. $n\tau_E$ (the product of bulk ion density and plasma-energy confinement time) $\simeq 10^{13}$ sec/cm^3. Since almost energy injected as a deuterium beam goes to electrons, we have a relation

$$WI \ \Delta t \simeq \pi a^2 L \, n \, kT_e \tag{4-a}$$

or

$$I \simeq \frac{\pi a^2 kT_e}{w\Delta t} nL \quad , \tag{4-b}$$

where k is the Boltzmann constant and I is the current of the ion beam. We see easily from (4-b) that the current, I, becomes quite large ($I \simeq 40$ MA) for a theta pinch plasma, i.e., $n=10^{16}$ cm^{-3}, $L \simeq 10^3$ cm, $a \simeq 10$ cm, $T_e = 5$KeV and $\Delta t = 10^{-6}$ sec.

In order to attain the break-even condition by the smaller value of the ion beam the possible break through could be the utilization of the well-known phenomenon of the axial contraction in the theta pinch [10], i.e. the plasma can contract rapidly in the axial direction in the plasma vortex.

Even if the axial contraction is successfully utilized to minimize the current, I, the stability of the contracted plasma vortex will give rise to a problem which is left to a future study. One technique, however, available for stabilization of the plasma is to adopt the shaped coil in which the effect of the metalic wall stabilization is useful. A schematic drawing is shown in Fig.2. The plasma is created in a mirror configuration with a couple of long neck (Fig.2a). Outside the coil region magnetic lines break and rejoin to form a long plasma vortex in a similar way as shown in Fig.1b (Fig.2b and Fig.2c). At this time, the ion beam has to be trapped already in the plasma. By the rapid and violent axial contraction the plasma vortex as well as the trapped ion beam is gathered up at the center of the device (Fig.2d). An important contribution to stabilization can come from the good conductivity of the shaped metalic wall. In this case for $L^* = a = 10$ cm together with $n=10^{16}$ cm^{-3}, then, $I \simeq 0.4$ MA necessary to attain the break-even condition, where L^* is the length of plasma vortex after axial contraction. This means that the production of low density plasma in the initial phase is an important problem.

We have described a possible break through to fusion with the use of slowing down beam together with the plasma vortex. In the TCV we claim that the electron temperature of the target plasma need not to be high. Furthermore, no neutral beam is necessary. High energy intense ion beam and the plasma vortex does everything necessary to attain breakeven condition, provided that the energy confinement time is sufficiently long. Because the field-free plasma can be produced in the theta pinch devices, the approach to fusion discussed here may lead us to a high-β fusion reactor although the stability questions remain unsolved yet.

References

[1] CHRISTOFILOS, N.C., in Proc. Second Conf. Peaceful Uses of Atomic Energy, 1958 (U.N., Geneva, 1958), p.279.

[2] BODIN, H.A.B., Nucl. Fusion 3 (1963) 215.

[3] ES'KOV, A.G., ZOLOTOVSKY, C.A., KALYGIN, A.G., KURTMULLAEV.R.Kh., LAUKHIN, Ya. N., MALYUTIN, A.I., MARKIN, A.I., PROSHLETSOV, A.P., and SEMENOV, V.N., in Proc. Seventh European Conf. Controlled Fusion and Plasma Physics, Lausanne, 1975 (CRPP) p.55.

[4] DAWSON, J.M., FURTH, H.P., TENNEY, F.H., Phys. Rev. Lett. 26, (1971) 1156.

[5] PRONO, D.S., SHEARER, J. W., BRIGGS, R.J., Phys. Rev. Lett. 37 (1976) 21.

[6] SPITZER,L., in Physics of Fully Ionized Gases (Interscience, New York, 1956).

[7] FURTH, H.P., JASSBY, D.L., Phys. Rev. Lett. 32 (1974) 1176.

[8] KAPETANAKOS, C.A., PARKER, P.K., CHU, K.R., Appl. Phys. Lett. 26 (1975) 284.

[9] SCHMIDT, G., Phys. Fluids 5 (1962) 994.

[10] GREEN, T.S., Nucl. Fusion 3 (1963) 57.

Figure Captions

Fig.1 Development of field reversal in an annular plasma cylinder produced in a theta pinch with reversed trapped magnetic field. During the development of the field reversal ion beam is trapped in the closed line configuration. Arrows indicate the direction of the magnetic field and the velocity of the injected beam respectively.

Fig.2 Development of field reversal and axial contraction in an annular plasma cylinder produced in a theta pinch with both reversed trapped magnetic field and a shaped coil. Arrows indicate the direction of the magnetic field.

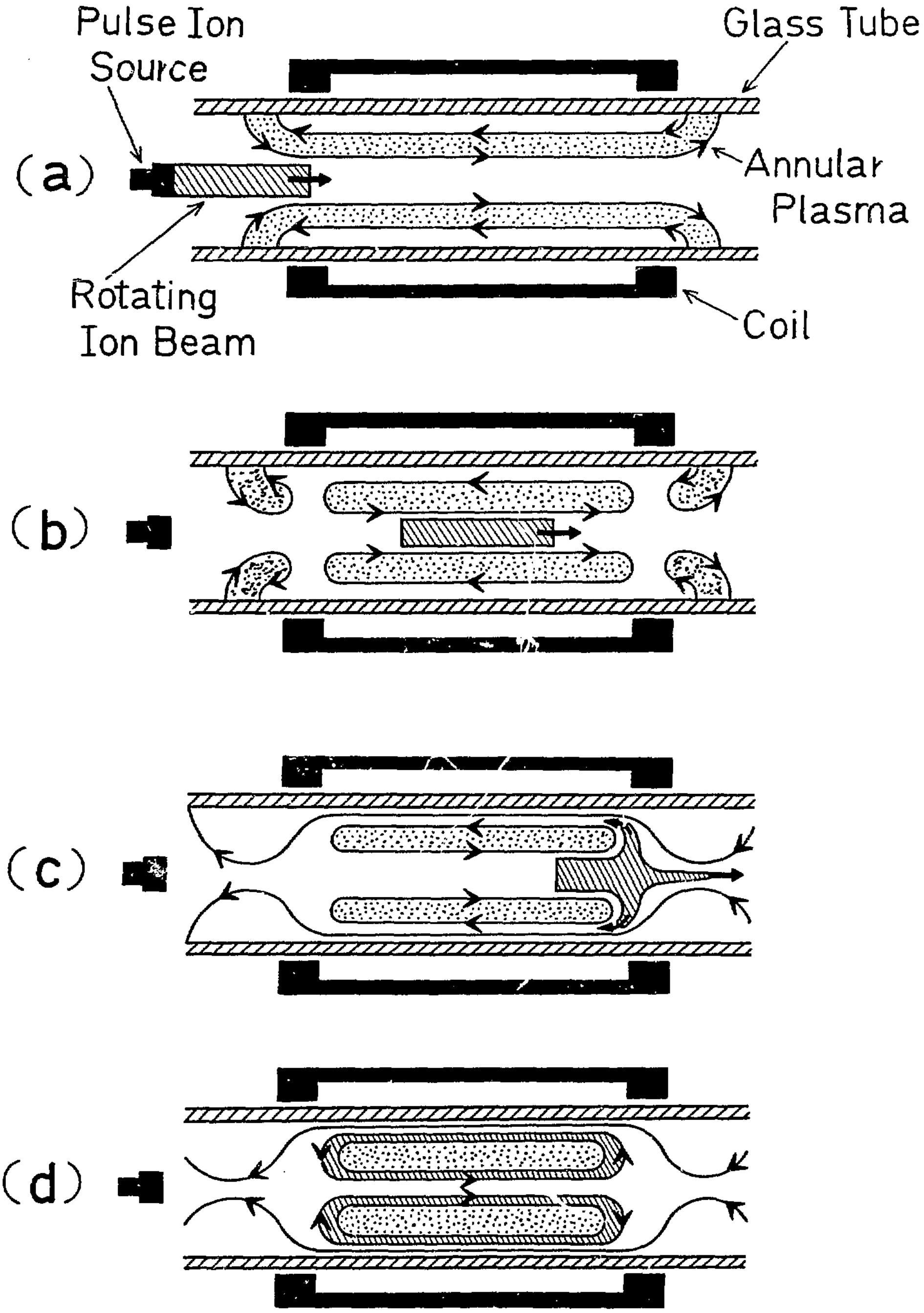
Pulse Ion Source
Glass Tube
(a)
Annular Plasma
Rotating Ion Beam
Coil
(b)
(c)
(d)

Fig.1

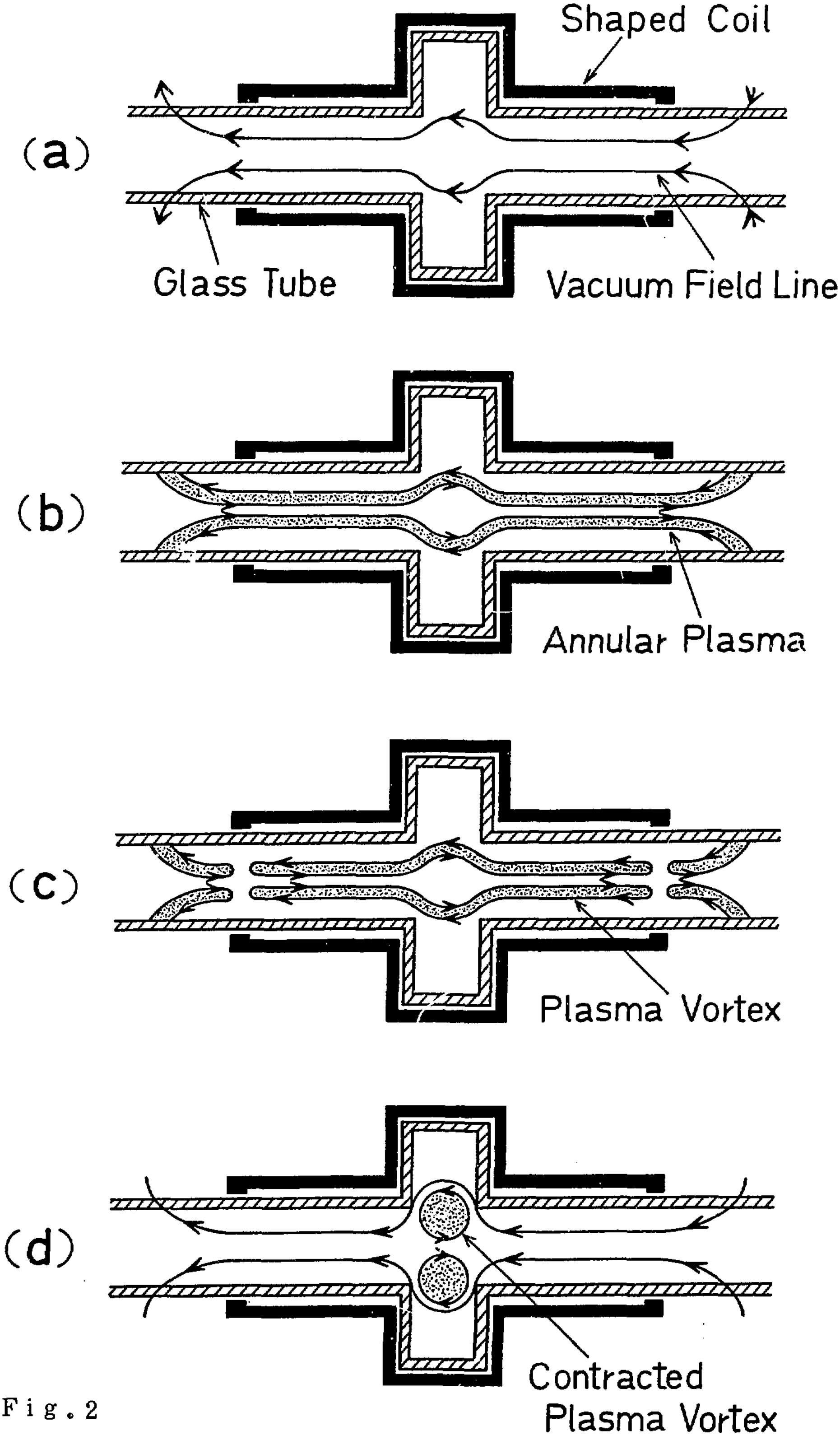
Shaped Coil
(a)
Glass Tube
Vacuum Field Line
(b)
Annular Plasma
(c)
Plasma Vortex
(d)
Contracted Plasma Vortex

Fig. 2