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Compression of Toroidal Plasma by Imploding Plasma-Liner

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ABSTRACT

A new concept of compressing a plasma in a closed magnetic configuration by a version of liner implosion flux compression technique is considered. The liner consists of a dense plasma cylinder, i.e. the plasma-liner. Maximum compression ratio of toroidal plasma is determined just by the initial density ratio of the toroidal plasma to the liner plasma because of the Rayleigh-Taylor instability. A start-up senario of plasma-liner is also proposed with a possible application of this concept to the creation of a burning plasma in reversed field configurations, i.e. burning plasma vortex.

§1. Introduction

The imploding liner flux compression using nondestructive technique together with closed plasma configuration is one of the most promising ways of obtaining fusion plasma.[1] One important problem to apply the compression by the imploding liner technique to a closed configuration is a choice of the liner material, since the liner motion has to respond promptly to the situation of the closed configuration created in the liner. Because of the slow response of a liquid metal as a liner material, the liquid liner is not always applicable to a compression of pulsively formed rather short-lived torus plasma.

In this note we discuss a current carrying dense plasma cylinder as an imploding liner. Section 2 describes the basic concept of the imploding plasma-liner applied to the compression of toroidal plasma. In section 3 we discuss one of the start-up senarios of the plasma-liner by injection of relativistic electron beam (REB) ring[2] into a coaxial plasma focus device.[3]

§2. Basic Concept of Imploding Plasma Liner

Consider a rectangularly cross-sectioned toroidal plasma surrounded by dense plasma cylinder between the conductive discs as shown in Fig.1. The plasma cylinder is assumed to work as a liner. A pulsed start-up mechanism (this will be discussed in the next section) of the toroidal plasma can permit embedding a toroidal magnetic field in this plasma ring.

After the capacitor bank in the figure is fully charged up the cylindrical plasma liner is supposed to be created instantaneously containing the closed magnetic surfaces. Then the plasma liner starts to implode compressing the plasma in the closed magnetic surfaces as long as the liner works as a piston.

The maximum attainable compression of plasma in the closed container would be limited by an on-set of the so-called Rayleigh-Taylor instability[4)] in the interface between the plasma-liner and the toroidal plasma even if the skin depth of liner-plasma is sufficiently less than the thickness of the plasma. Let the uniform plasma densities in the plasma-liner and in the toroidal magnetic surfaces be n_ℓ and n_t respectively. For stability we roughly have a condition:

$$n_\ell > n_t \quad . \tag{1}$$

If the particle number is conserved both in the plasma-liner and in the torus plasma, we have

$$n_\ell = n_{\ell 0} \frac{R_0 h_0 d_0}{Rhd} \quad , \tag{2}$$

$$n_t = n_{t0} \frac{{R_0}^2 h_0}{R^2 h} \quad , \tag{3}$$

where R is the radius of the liner-torus interface, h the distance between the discs and d the thickness of the plasma-liner. The suffix 0 corresponds to the initial condition. For h and d to be constants we have a relation for the marginal stability from (1), (2) and (3).

$$n_{\ell 0} = n_{t0} \frac{R_0}{R_m} \quad , \qquad (4\text{-a})$$

or

$$R_m = \frac{n_{t0}}{n_{\ell 0}} R_0 \quad , \qquad (4\text{-b})$$

where R_m is the radius for marginal stability. By (4-b) together with(3) the compression ratio C of the toroidal plasma becomes

$$C \equiv \frac{n_t}{n_{t0}}$$

$$= \left(\frac{n_{\ell 0}}{n_{t0}}\right)^2 \quad . \qquad (5)$$

From (5) a critical technical problem in order to attain high compression ratio is to find out a method of generating a dense plasma-liner initially.

In order to have a rough idea of the implosion dynamics of the plasma-liner, we shall treat the idealized case, where the current, I, in the circuit remains constant (i.e. capacity of the capacitor banck is sufficiently large). Then, the equation of motion of the plasma-shell is described by[5)]

$$R \frac{d^2R}{dt^2} \simeq - \frac{\mu_0}{4\pi} \frac{I^2}{m} \quad , \qquad (6)$$

where the repulsive force derived from the toroidal magnetic field and plasma in the liner is neglected, m is the mass of the plasma-liner per unit length, μ_0 the magnetic permeability of vacuum and t represents the time. Fortunately the equation of motion, (6), is easily integrated and the implosion velocity of the liner at the on-set of Rayleigh-Taylor instability becomes, together with (4-b),

$$\left(\frac{dR}{dt}\right)^2 = \frac{\mu_0 I^2}{8\pi m} \ \ln\left(\frac{n_{\ell 0}}{n_{t0}}\right) \qquad . \qquad (7\text{-a})$$

As long as our approximation works the equation (7-a) suggests that the implosion velocity does not depend strongly on the compression ratio since the expression (7-a) can be rewritten by

$$\left(\frac{dR}{dt}\right)^2 = \frac{\mu_0 I^2}{16\pi m} \ \ln C \qquad . \qquad (7\text{-b})$$

We now discuss about the scaling for magnetic compression of toroidal plasma by the plasma-liner assuming that the compression process is adiabatic and that the toroidal plasma is a perfect conductor on the time scale of the compression. For collisional compression we have the constraint on the plasma parameters:

$$T \ n_t^{-2/3} = \text{const} \qquad , \qquad (8)$$

where T represents the plasma temperature and the specific heat ratio is chosen to be 5/3. In terms of the initial density ratio, $n_{\ell 0}/n_{t0}$, the temperature of toroidal plasma is scaled by, from (8),

$$T \rightarrow (n_{\ell 0}/n_{t0})^{4/3} \qquad . \qquad (9)$$

If the temperature of initial plasma is about equal to 100 eV, we see from (9) that the initial density ratio, $n_{\ell 0}/n_{t0}$, must be

$$n_{\ell 0}/n_{t0} \simeq 10^{3/2} \simeq 32 \qquad (10)$$

in order to attain the fusion ignition temperature of fuel plasma after the compression.

§3. A Start-up Senario of Plasma-Liner

The SPAC program in Nagoya[2] has a purpose to confirm a technique of forming a REB ring in a torus chamber and the technique is already completed with confidence. This technique together with a big coaxial plasma focus device[3] might offer one of the interesting scheme to set up the plasma-liner and a field reversed configuration, the spheromak,[6] in an isolated volume of plasma simultaneously.

Consider a plasma focus device with the third electrode in a uniform magnetic field, where the third electrode is the ejector of relativistic electron beam installed in the wall of the (outer) electrode of the device as shown in Fig.2. By the closure of the circuit of the capacitor bank, the annular plasma sheet is formed along the insulation surface and removes from the surface by the electro-magnetic force to the end of the inner electrode. In the volume surrounded by the electrodes, the insulation and the annular plasma sheet, we note that the toroidal magnetic field is generated by current along the sheet. The volume should act as a cage of the REB ring. The instant the plasma sheet arrives at the end of the inner electrode the energetic electron beam is injected from the third electrode into the volume. The electron beam is quickly formed into a ring with embedded toroidal magnetic field and the volume is filled with a family of closed magnetic surfaces. And a part of the outermost closed surface settle at the surface of the insulation. The lines of force along the insulator surface become short pathes of electrons between the electrodes. Thus a new arc discharge will follow automatically after the annular sheet plasma by REB injection, provided that the capacity of the capacitor bank is sufficiently large. The new annular arc plasma becomes a plasma-liner which propels the toroidal plasma together with the annular plasma sheet to the end of the inner electrode by electro-magnetic force. The end surface of the inner electrode and the outer casing is arranged in order to work as a plasma focus device developed by Filippov. Driven toroidal plasma is caged in this section of the divice also shown in the figure. In such situation the contracting plasma-liner can compress the toroidal plasma until the Rayleigh-Taylor instability develops in the plasma-liner. This compression phase is discussed in the preceding section. In the compressed toroidal plasma, fusion ignition condition could be realized providing the initial density ratio between the plasma-liner and the toroidal plasma is properly chosen. However, the impurities from the electrodes will follow after the imploded liner. To avoid mixing of the impurities into the burning plasma it is better to take the burning plasma vortex out of the chamber. In this case we needs a hole at the center of the casing. If a hole with radius equal to R_m is bored through the central part of the outer electrode shown in Fig.2 the compressed toroidal plasma will be ejected from the compressor through the hole without the Rayleigh-Taylor instability. This ejection mechanism is understood if we refer to a textbook about a pinch engine.[7] The ejected toroidal plasma into a guide field forms a reversed field configuration[6] with embedded toroidal field.

§4. Conclusions

A liner implosion magnetic flux compression scheme is applied to compress a toroidal plasma under an essential assumption that a cylindrical plasma could work as a liner, i.e., the plasma-liner. The maximum compression is shown to be limited by on-set of the Rayleigh-Taylor instability in the liner, although further detailed investigations about the instability during the compression are necessary. And a start-up senario of the plasma-liner is also considered. By a proper choice of the initial liner density it is concluded that a formation of "burning field-reversed plasma" (which we call "burning plasma vortex") could be possible using a compression device considered here.

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Figure Captions

Fig.1 Basic concept of plasma-liner compression scheme of toroidal plasma. Liner plasma has to be denser than the toroidal plasma for compression.

Fig.2 Focus device with third electrode. Succesive positions of the toroidal plasma and the plasma-liner are shown schematically. In order to eject the compressed toroidal plasma from the compression chamber a hole with a certain radius is bored at the center of the wall shown.

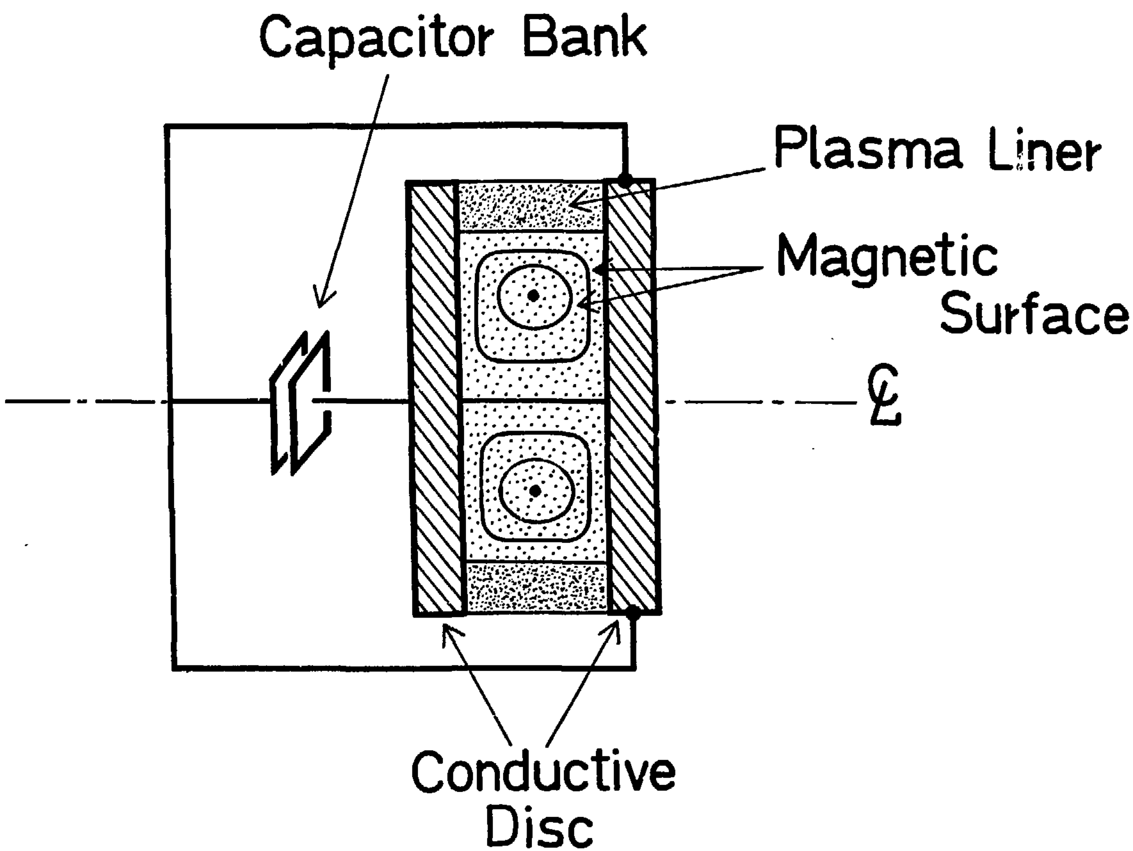
Capacitor Bank
Plasma Liner
Magnetic Surface
℄
Conductive Disc

Fig. 1

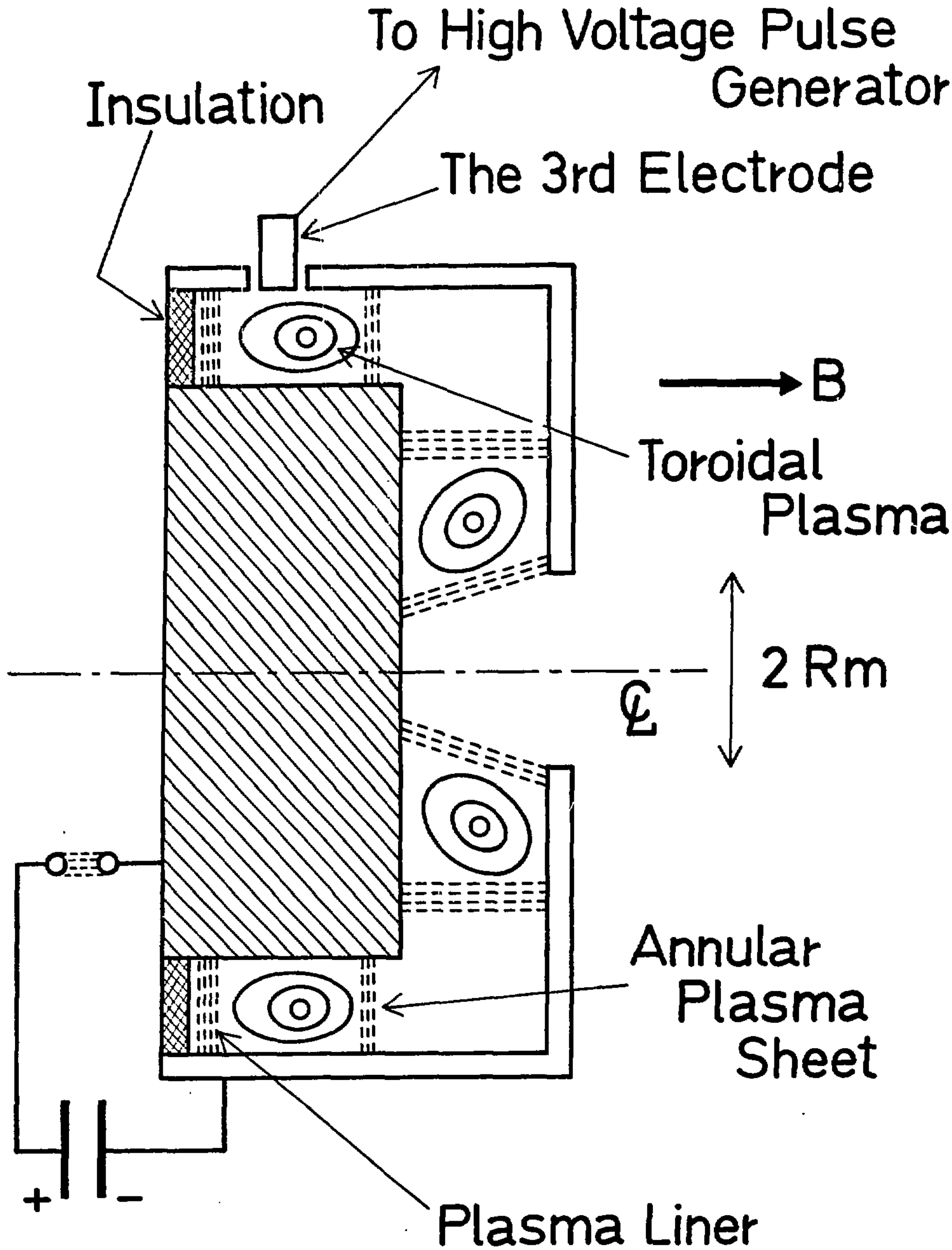
To High Voltage Pulse Generator
Insulation
The 3rd Electrode
B
Toroidal Plasma
2 Rm
℄
Annular Plasma Sheet
+
-
Plasma Liner

Fig. 2