INSTITUTE OF PLASMA PHYSICS

NAGOYA UNIVERSITY

Plasma Focus Breeder

Kazunari IKUTA

(Received - Sept. 7, 1981)

IPPJ- 541 Sept. 1981

RESEARCH REPORT

NAGOYA, JAPAN

Plasma Focus Breeder

Kazunari IKUTA

(Received - Sept. 7, 1981)

IPPJ- 541 Sept. 1981

Further communication about this report is to be sent to the Research Information Center, Institute of Plasma Physics, Nagoya University, Nagoya 464 Japan.

Abstract

Instead of using linear accelerators, it is possible to breed fissile fuels with the help of high current plasma focus device. A mechanism of accelerating proton beam in plasma focus device to high energy would be a change of inductance in plasma column because of rapid growth of plasma instability. A possible scheme of plasma focus breeder is also proposed.

§1. Introduction

One of the most important evidences observed in plasma focus devices[1] is the creation of energetic ions whose energy is about 200 times the charging voltage of capacitor-bank. This means that the plasma focus device acts as the voltage amplifier possibly by a certain mechanism of current collapse.

On the other hand, the rising costs of U235 and other fissile fuels and the schedule for implementing the breeder reactor have renewed interest in the utilization of accelerators for breeding U233 or Pu239. The necessary energy and the proton current for accelerators are about 1GeV and 0.3 amperes respectively in order to obtain economically the fissile fuels by the processes in accelerator breeding.[2]

Let us imagine a plasma focus device (See Fig. 1) whose working voltage and the energy amplification factor are 5 MeV and 200 respectively, we are able to expect proton beam with energy about equal to 1 GeV. Since the structure of plasma focus devices is quite simpler than linear accelerators (in other word, plasma focus device is much cheaper than linear accelerator), this possibility of generating 1 GeV proton beam would be worth while to be considered in order to convert fertile material into fissile fuels utilizing spallation neutrons produced by energetic ($\sim$1 GeV) protons thus generated.

In §2 we pictorially discuss a possible mechanism of generating high voltage in pinched plasma in plasma focus device using rather phenomenological approach, although Bernstein[3] have considered duetron acceleration in an electric field generated by rapidly constricting current discharge from computing deutron trajectories. Section 3 describes the concept of plasma-focus breeder in detail with an illustration.

§2. High Voltage Generation in Plasma Focus Device

The voltage, V, generated in high current plasma column may be described by

$$V = RI + \frac{d}{dt}(LI) , \tag{1-a}$$

where I is the total current along the plasma column, R and L are the plasma resistivity and the inductance of the plasma column and t represents the time.

A remarkable feature in current-carrying plasma is a rapid growth of macroscopic plasma instability which can change drastically the inductance of current circuit, even if the total current is approximately constant. In this case the expression for the voltage V is written by

$$V = RI + I\frac{dL}{dt} . \tag{1-b}$$

The change of the inductance by instability in plasma column would occur within a time scale of Alfvén transit time, i.e.

$$\frac{dL}{dt} \simeq \frac{\Delta L}{\Delta t} \simeq \frac{LV_A}{a} , \tag{2-a}$$

where a corresponds to the radius of plasma column and V_A is the Alfvén velocity defined by

$$V_A = \frac{B}{(\mu_0 M n)^{1/2}} . \tag{3}$$

Here n, M and μ_0 are the number density of plasma particle, mass of proton and the magnetic permeability of vacuum, and B is the magnetic field strength given by

$$B = \frac{\mu_0 I}{2\pi a} . \tag{4}$$

Then, with the help of (2-a), (3) and (4), the voltage V can be described by

$$V \simeq RI + \frac{LIV_A}{a} . \tag{1-c}$$

An important conclusion from the expression (1-c) is that the voltage induced inductively in the plasma column is able to be quite larger than the applied voltage which is about equal to RI. In other word, since the product IV_A is in proportion to I^2, this means that $(LIV_A/a) \gg RI$ for sufficiently large plasma current, I.

Once the high voltage is induced in plasma column, the magnetic field generated by current, I, could works as an insulator for electrons like that in magnetically insulated diode, because the induced electric field is right across the magnetic field lines.

By a straight forward but tedious arithmetics like that peformed in our previous work on ion beam source[4], we obtain the expression for the current of accelerated proton beam, I_b, as follows.

$$I_b \simeq \frac{8\pi\sqrt{2}}{9} \varepsilon_0 \left(\frac{e}{M}\right)^{1/2} \frac{a}{d} \left(\frac{LIV_A}{a}\right)^{3/2}, \quad (5)$$

where the applied voltage is approximated to be

$$V \simeq \frac{LIV_A}{a}, \quad (1\text{-d})$$

and d is the skin depth of dense plasma, i.e.

$$d \simeq \left(\frac{M}{ne^2\mu_0}\right)^{1/2}.$$

In this calculation, diamagnetic effect from the plasma electrons to the magnetic field is neglected. This formula, (5), is simply the Child-Langmuir's one[5] in the case of strong, inductive electric field in a plasma sheath. Important points to notice in this formula is that the proton current, I_b, is in proportion to I^3.

§3. Plasma Focus Breeder

The basic processes in accelerator breeding is described in the literature.[2] One accelerates a proton (or deutron) by any means to a high energy (e.g. 1000 MeV) and directs it onto an appropriate target. Interactions with target nuclei produce many secondary particles in a cascade with ultimate production of anywhere from 40 to 60 neutrons. The available data on spallation neutron production[2] indicates that the proton energy should be 1 GeV or greater to achieve efficient neutron production. In our case the accelerator is the plasma focus device. When we consider a target of Th232 or U238, most of neutrons are captured producing U233 or Pu239. The presence of this fissile material and fast fission of U238 lead to an additional neutron multiplication.

The most important relation between neutron yield, Y, and accelerated beam energy, E, for 250 MeV < E < 1 Gev is approximately

$$Y = 20\ E^{1.66}, \tag{6}$$

where the energy E is measured in GeV. This means that the accelerator energy, E, must be larger than 250 MeV in order to multiply the number of neutron. If the proton energy is less than 250 MeV neutron yield is less than the protons directed onto the target.

Since the energy of accelerated proton in plasma focus device can be approximated by (1-d) in our case, the number, N, of proton directed onto target by one pulse having time duration Δt is

$$N = \frac{I_b}{e}\,\Delta t \tag{7-a}$$

$$\simeq \frac{I_b}{e}\,\frac{a}{V_A} \tag{7-b}$$

$$\doteq \frac{8\pi^{1/2}\,L^{3/2}\,e^{1/2}n^{1/4}\,I^2}{9c^2M^{5/4}\,\mu_0^{1/4}}, \tag{7-c}$$

Where c is the speed of light

That is, N is in proportion to I^2 and does not depend on the radius of plasma column.

The number, N_n, of spallation neutron can now be calculated as long as the inductance of the plasma column is known. If the inductive voltage is higher than about 250 MeV we have, from (6) and (7-b),

$$N_n = 20 \times \frac{I_b}{e} \frac{a}{V_A} [\frac{LIV_A}{a} \times 10^{-9}]^{1.66}. \qquad (8)$$

Modern high voltage pulse technology enables us to generate plasma current, I, of order 10 MA without difficulty, and plasma density in plasma focus device for energetic beam production is about equal to $10^{17}cm^{-3}$. Then, the induced voltage may be estimated to be, for $a \simeq 0.1$ cm with column length about equal to 10 cm,

$$V = \frac{LIV_A}{a} \simeq 10^9 \text{ volts}, \qquad (9)$$

where the inductance of plasma is taken to be $L = 10^{-7}$ Henry. We see from (8) and (9) that the number of spallation neutron could be about an order of magnitude larger than the number of protons directed onto the target. From (7-c) together with (9), the number of proton becomes

$$N \simeq 10^{17}. \qquad (10)$$

This means, with the help of (8), that

$$N_n \simeq 10^{18}.$$

Since the necessary proton number with energy 1 GeV in order to produce 1000 kg/year of U233 or Pu239 fuel is $10^{18}\,sec^{-1}$[2], the result (10) tells us that the plasma focus breeder must be fired 10 shots per every second.

We are now able to imagine the plasma focus breeder which is illustrated in Fig. 2. Instead of the linear accelerator used in the case of well-known accelerator-breeder concept, high current plasma focus device, in this case, produces protons with energy 1000 MeV because of the high voltage generated by plasma instability. The protons thus produced are directed onto a target of Th232 or U238 producing U233 or Pu239.

§4. Discussions and Conclusion

An experimental evidence[1] that the energetic ion beam production is possible in rather low density plasma is reasonably described in our model equation (1-c), since the Alfvén velocity is in proportion to $n^{-1/2}$. This means that the induced voltage tends to be weaker for the case of denser plasma column. In very low density plasma, however, the number of protons accelerated would become so little as described by (7-c). The optimum plasma density should be present for the production of intense, energetic proton beam.

One of the most important facts for estimating the induced voltage generated in the plasma focus is the choice of the inductance of the plasma. Fortunately, the pinched plasma in plasma focus devices is thought of as a coaxial conductor from the structural reasons, the inductance of the plasma column is able to be as large as 10^{-7} Henry[6] which results such a high voltage as 10^{9} volts in a thin, short plasma column.

We may conclude from the above considerations that a high current plasma focus device would be a possible candidate for the generation of energetic, intense proton beam which could be utilized for breeding fissile fuels.

References

1) H. L. Sahlin : 2nd Int. Conf. on Energy Storage, Compression and Switching, 1978 Venice.

2) P. Grand, K. Batchelor, J. R. Powell and M. Steinberg : IEEE Trans. Nucl. Sci., NS-24 (1977) 1043. See also, H. Takahashi : Nihon-Genshiryoku-Gakkai shi, 23 (1981) 500 (in Japanese).

3) M. J. Bernstein : Phys. Rev. Letters, 24 (1980) 724.

4) K. Ikuta, A. Mohri and M. Masuzaki : Jpn. J. Appl. Phys. 14 (1975) 1569.

5) C. D. Child : Phys. Rev. 32 (1911) 492.
Also, I. Langmuir : Phys. Rev. 2 (1913) 450.

6) See, for example, H. Knoepfel : Pulsed High Magnetic Field (North-Holland Publishing Company, Amsterdam·London, 1970) p. 314.

Figure Captions

Fig. 1 Schematic structure of focused plasma in plasma focus device. Plasma current flows mainly in thin skin on the surface of dense plasma.

Fig. 2 A possible set-up of plasma focus breeder. Energetic proton and spallation neutron fly in direction of fat arrows shown.

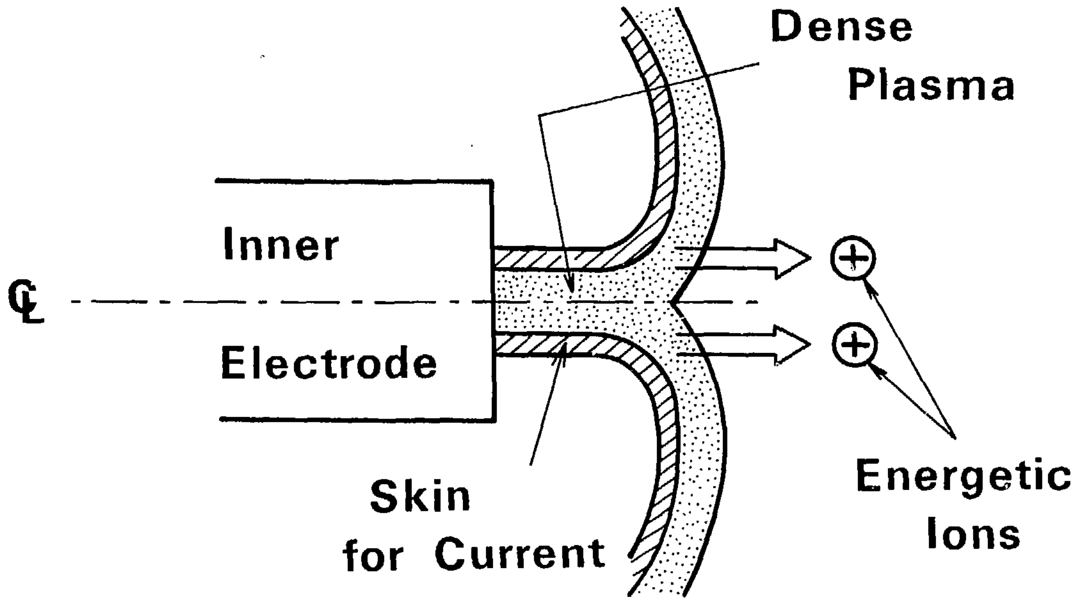
Dense
Plasma
Inner
℄
Electrode
Skin
for Current
Energetic
Ions

Fig. 1

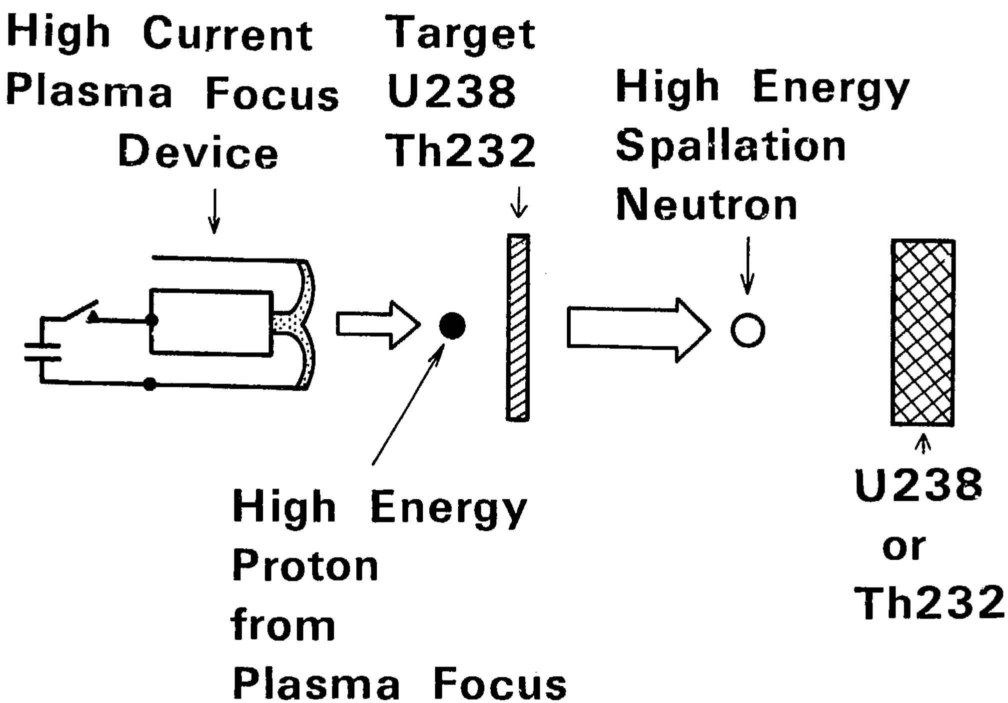
High Current
Plasma Focus
Device
Target
U238
Th232
High Energy
Spallation
Neutron
High Energy
Proton
from
Plasma Focus
U238
or
Th232

Fig. 2