

## **Fusion-Fission-Fusion Fast Ignition Plasma Focus**

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### **Abstract**

A crucial advancement in the problem for the controlled release of energy by nuclear fusion appears possible by an autocatalytic fusion-fission-fusion microexplosion, where the deuterium-tritium (DT) fusion reaction of a dense magnetized DT plasma placed inside a thin liner made up of U238, Th232 (perhaps B10) releases a sufficient number of 14 MeV fusion neutrons which by fission reactions in the liner implode the liner on the DT plasma. The liner implosion increases the DT plasma density and with it the neutron output accelerating the fast fission reactions. Following the fast fission assisted ignition, a thermonuclear detonation wave can propagate into unburnt DT to reach a high gain. The simplest way for the realization of this concept appears to be the dense plasma focus configuration, amended with a nested high voltage magnetically insulated transmission line for the heating of the DT. The large magnetic field needed for the  $\alpha$ -particle entrapment of the DT fusion reaction is here generated by the thermomagnetic Nernst effect, amplifying the magnetic field of the plasma focus current sheet.

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## **1. Introduction**

The release of energy by nuclear fusion on a macroscopic scale has so far been successful only with the assistance of a fission chain reaction, depending on a comparatively large critical mass of the fission trigger. But it has been shown that a very large reduction in the critical mass is possible by compressing the fissile material with intense laser- or particle beams [1, 2]. In principle one could then use a micro-fission chain reaction in highly compressed fissile material to ignite a small thermonuclear reaction in the same way as it is done for the ignition of large thermonuclear explosive devices. As for laser- or particle beam fusion this would require a large effort, bringing us not much closer to an inexpensive solution of the thermonuclear ignition problem. Instead we will follow here a different approach to couple the nuclear fusion and fission reactions, not requiring a large compression, but the heating of a magnetized dense DT plasma to the DT ignition temperature, by surrounding the DT plasma with a thin liner of U238, Th232 (or perhaps B10) [3]. Even for modest densities the DT reaction produces a sufficiently large number of 14 MeV neutrons capable to implode the liner onto the DT by fast fission reactions in the liner, increasing the density of the DT plasma thereby releasing even more neutrons, in turn increasing the fission reaction rate. It is a fortunate coincidence that this “autocatalytic” fusion-fission-fusion process can be realized with a simple modification of the well known plasma focus device, one of the cheapest but most efficient fusion devices which on its own just could not make it.

## **2. Fusion-Fission-Fusion Fast Ignition Plasma Focus**

Fig. 1 shows the usual Mather-type plasma focus configuration with two substantial modifications:

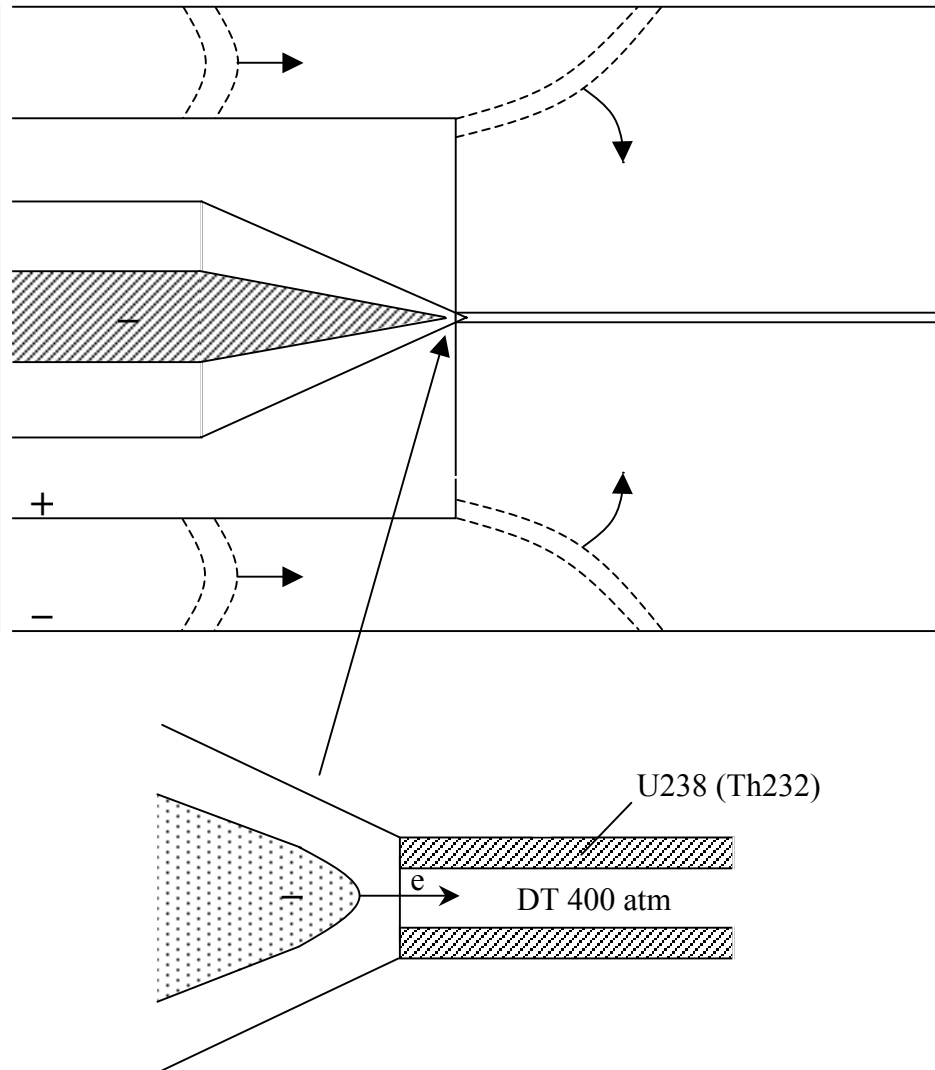


Fig. 1 Fusion-Fission-Fusion Fast Ignition Plasma Focus.

1. Along its axis is placed a thin liner made up of U238 (or Th232), containing liquid or gaseous DT under high pressure.
2. Centered and nested inside the inner conductor is a magnetically insulated high voltage transmission line with an electron field emission cathode at its right end facing the left end of the liner.

Because of the energy cumulation in the plasma sheet, the plasma focus has an effective impedance as small as  $\sim 10^{-2} \Omega$  [4], which permits to use inexpensive capacitor banks eliminating the need for the more expensive high voltage Marx generator banks. An externally applied axial bias field and the axial shear flow of the plasma focus should ensure sufficient stability of the liner.

Concurrent with the collapse of the plasma sheet setting up a large azimuthal magnetic field around the liner, a high voltage pulse passing through the centered magnetically insulated transmission line releases into the DT a field emitted intense relativistic electron beam from the cathode at the end of the transmission line, heating the DT to thermonuclear temperatures with the DT becoming the source of 14 MeV DT fusion reaction neutrons. Because of the large temperature gradient between the hot DT plasma and the cold inner liner wall, a large azimuthal magnetic field is generated in the DT plasma by the thermomagnetic Nernst effect, entrapping the fusion reaction  $\alpha$ -particles within the DT plasma and magnetically heat-insulating the DT plasma against the wall.

### 3. The Coupling of the Fusion and Fission Reactions

As shown in Fig. 1 we are considering a hot DT plasma cylinder inside a metallic liner of U238 (or Th232). The fusion reaction rate in the DT plasma per unit volume is

$$\frac{\partial n}{\partial t} = -\frac{n^2}{4} \langle \sigma v \rangle \quad (1)$$

with  $n$  the DT atomic number density and  $\langle\sigma v\rangle$  the fusion reaction cross section velocity product averaged over a Maxwellian. From (1) one obtains for the flux of the 14 MeV DT fusion neutrons at the surface of the DT cylinder of radius  $r$  :

$$\phi = (1/2\pi r) \int_0^r (n^2/4) \langle\sigma v\rangle 2\pi r' dr' = (r/8) \langle\sigma v\rangle n^2 \quad (2)$$

With the macroscopic fission reaction cross section in the liner  $\Sigma_f = n_f \sigma_f$ , where  $n_f \approx 4 \times 10^{22} \text{ cm}^{-3}$  is the atomic number density and  $\sigma_f \approx 2 \times 10^{-24} \text{ cm}^2$  the fast neutron fission cross section of U238, one obtains for the reaction length  $\Sigma_f^{-1} \approx 10 \text{ cm}$ . Therefore, if  $\delta \ll \Sigma_f^{-1}$ , where  $\delta$  is the liner thickness, the neutron flux in the liner is nearly constant, with the fission energy released per unit volume and in the time  $\tau$

$$\varepsilon = \Sigma_f \phi (\varepsilon_f + \varepsilon_0) \tau \quad (3)$$

where  $\varepsilon_f \approx 180 \text{ MeV}$  is the energy per fission and  $\varepsilon_0 \approx 14 \text{ MeV}$  the kinetic energy of the DT fusion neutrons. The time  $\tau$  is the inertial confinement time of the liner, which by order of magnitude is

$$\tau \approx \delta/a \quad (4)$$

where  $a \approx \sqrt{p/\rho}$  is the velocity of sound in the hot liner of density  $\rho$ . With (4) and the reaction length  $L = \Sigma_f^{-1}$  one can write for (3)

$$\varepsilon = \phi (\varepsilon_f + \varepsilon_0) \left(\frac{\delta}{L}\right) \frac{1}{a} \quad (5)$$

Without the division by the velocity of sound  $a$ , (5) is the energy flux density in the liner. Since by order of magnitude  $p \approx \varepsilon$ , one has

$$\tau \approx \delta \sqrt{\rho/\varepsilon} \quad (6)$$

whereby (3) becomes

$$\varepsilon = \left[ \Sigma_f \phi (\varepsilon_f + \varepsilon_0) \delta \right]^{2/3} \rho^{1/3} \quad (7)$$

and by inserting from (2) the expression for neutron flux  $\phi$

$$\varepsilon = (1/4) \left[ \Sigma_f (\varepsilon_f + \varepsilon_0) \langle \sigma v \rangle n^2 r \delta \right]^{2/3} \rho^{1/3} \quad (8)$$

If  $\varepsilon > 2nkT$ , where  $2nkT$  is the DT plasma pressure, the liner implodes onto the DT plasma increasing the DT fusion reaction rate and in turn the fission reaction rate. With (8) the condition  $\varepsilon > 2nkT$  can be written as

$$n(r\delta)^2 > \frac{(kT)^3}{\langle \sigma v \rangle^2} \frac{5/2}{\left[ \Sigma_f (\varepsilon_f + \varepsilon_0) \right]^2} \rho \quad (9)$$

which gives a lower bound for the DT plasma density at the minimum of  $(kT)^3 / \langle \sigma v \rangle^2$  located at  $T \approx 15$  keV, where  $(kT)^3 / \langle \sigma v \rangle^2 \approx 2 \times 10^8$  erg<sup>3</sup>s<sup>2</sup>/cm<sup>6</sup>. We thus have

$$n(r\delta)^2 \Big|_{\min} \approx 10^{11} \left[ \Sigma_f (\varepsilon_f + \varepsilon_0) \right]^{-2} \rho^{-1} \quad (10)$$

With  $\rho = 18$  g/cm<sup>3</sup> for U238 (or Th232) one finds that  $n(r\delta)^2 \Big|_{\min} \approx 10^{19}$  cm. For  $n = 10^{22}$  cm<sup>-3</sup>,

valid for DT gas at 400 atm one has  $(r\delta)^2 = 10^{-3}$  cm<sup>4</sup>. Choosing  $\delta \approx 2r$ , equal thickness of DT cylinder and U238 liner, one has  $r = 0.13$  cm. For  $n = 10^{22}$  cm<sup>-3</sup> and  $T = 15$  keV the plasma pressure is  $p = 2nkT \approx 5 \times 10^{14}$  dyn/cm<sup>2</sup>.

#### 4. Relativistic Electron Beam Heating by the Electrostatic Two-Stream Instability

With  $\varepsilon \sim p = 5 \times 10^4$  dyn/cm<sup>2</sup>,  $\rho = 18$  g/cm<sup>3</sup>, and  $\delta \approx 0.1$  cm, the inertial confinement time of the liner is  $\tau = \delta \sqrt{\rho/\varepsilon} \approx 2 \times 10^{-8}$  s, shorter than the DT bremsstrahlung loss time. This means that an energy larger than  $\varepsilon \approx 3nkT \times \pi r^2 \times 2r \approx 3 \times 10^{15} r^3$  erg must in less than  $2 \times 10^{-8}$  s

be deposited within the length  $l \leq 2r$  of the DT cylinder. For  $r \approx 0.1$  cm this energy is  $E \approx 300$  kJ. The range of the electron beam by the electrostatic two stream instability, is [5, 6]

$$\lambda_c = \frac{1.4c\gamma}{\omega_p \varepsilon^{1/3}}, \quad \varepsilon = \frac{n_b}{n}, \quad \gamma = (1 - v^2/c^2)^{-1/2} \quad (11)$$

where  $\omega_p = \sqrt{4\pi n e^2 / m} \approx 10^{16} \text{ s}^{-1}$ , and  $n_b \approx 10^{15} \text{ cm}^{-3}$  the number density in an electron beam of several  $10^5$  A focused down to a radius of 0.1 cm. For these numbers one obtains  $\lambda_c \approx 10^{-2}$  cm, sufficiently short to stop the beam over a distance less than  $l = 2r \approx 0.2$  cm.

The energy  $E$  delivered by a relativistic electron beam of voltage  $V$  and current  $I$  lasting  $\tau = 2 \times 10^{-8}$  s is  $E = IV\tau = 2 \times 10^{-8} IV$  [J]. Choosing  $V = 2 \times 10^7$  [V], and  $I = 6 \times 10^5$  [A] below the Alfvén limit, one obtains  $E \approx 240$  kJ, of the right order of magnitude.

## 5. Nernst Effect Dynamo Inside the Liner

Thermonuclear burn requires the entrapment of the fusion reaction  $\alpha$ -particles inside the DT plasma, a condition satisfied if  $r_L \gg r$ , where  $r_L = 2.7 \times 10^5 / H$  [cm], is the  $\alpha$ -particle Larmor radius and  $H$  the magnetic field in Gauss by the plasma current. With  $H = 0.2I/r$ , this condition means  $I > 5 \times (2.7 \times 10^5) = 1.3 \times 10^6$  [A], well satisfied for  $I \geq 10^7$  [A]. In the described configuration the thermomagnetic Nernst effect acts as a dynamo amplifying the magnetic field of the plasma focus current serving as a seed field. The field rises until the magnetic pressure balances the pressure created by the fission reactions in the liner.

In the presence of a temperature gradient  $\nabla T$  perpendicular to a magnetic field  $\mathbf{H}$ , the Nernst current density is (in Gaussian units) [7]

$$\mathbf{j}_N = \frac{3knc}{2H^2} \mathbf{H} \times \nabla T \quad (12)$$

or with the temperature gradient perpendicular to the liner wall

$$\mathbf{j}_N = \frac{3}{2} \frac{kn c}{H} \times \nabla_{\perp} T \quad (13)$$

With Maxwell's equation  $(4\pi/c)\mathbf{j}_N = \text{curl}_{\perp} \mathbf{H} = -\nabla_{\perp} \mathbf{H}$  this becomes

$$6\pi k n d T = H d H \quad (14)$$

The force density  $\mathbf{f}$  exerted by the Nernst current on the DT plasma is

$$\mathbf{f} = \frac{1}{c} \mathbf{j} \times \mathbf{H} = \frac{3}{2} \frac{nk}{H^2} (\mathbf{H} \times \nabla T) \times \mathbf{H} = \frac{3}{2} nk \nabla T \quad (15)$$

Inserted into the magnetohydrostatic equation

$$\mathbf{f} = \nabla p = \frac{3}{2} nk \nabla T \quad (16)$$

with  $p = 2nkT$  one finds

$$2nk \nabla T + 2kT \nabla n = (3/2) nk \nabla T \quad (17)$$

or

$$\frac{\nabla n}{n} = -\frac{1}{4} \frac{\nabla T}{T}; \quad n = n_0 \frac{T_0^{1/4}}{T^{1/4}} \quad (18)$$

where  $T = T_0$  inside the plasma and  $T = 0$  at the wall. Inserting (18) into (14) and integrating

from the wall into the plasma one finds that

$$\frac{H_0^2}{8\pi} = 2n_0 k T_0 \quad (19)$$

For the example  $2n_0 k T_0 = 5 \times 10^{14} \text{ dyn/cm}^2$  one finds that  $H_0 \approx 10^8 \text{ G}$ . Within the DT plasma of radius  $r = 0.1 \text{ cm}$ , the current flowing through the DT plasma inside the liner would there be  $I \sim 5 \times 10^7 \text{ A}$ , sufficiently large to entrap the fusion  $\alpha$ -particles. Therefore, if the current of the plasma focus is  $\sim 10^7 \text{ [A]}$ , it would be 5-fold amplified by the Nernst effect. To let the seed-

field generated by the initial  $10^7$  A diffuse through the liner into the DT, the liner can be segmented or its electrical conductivity be made small by making it as a ceramic liner. Fig. 2 shows two ways where the Nernst current forms closed loops, in Fig. 2a for a segmented liner, and in Fig. 2b inside a heated segment of the liner.

## 6. Conclusion

Facilitating the ignition of thermonuclear burn in the described way would require only a small amount of U238 (Th232) placed at one end of the liner. Following ignition, a burn wave can then propagate through the remaining part of the DT filled liner, with the liner made from some other substance.

With an electron beam radius of about 0.1 cm, one can also use for ignition a current neutralized megajoule relativistic electron beams well above the Alfvén current. Because the beam is there hot, stopping is less efficient with a larger segment of the liner heated up. Finally, with a plasma focus currents up to  $10^8$  [A], attainable with a convoluted transmission line feed [8, 9], the U238 (Th232) liner could be replaced with a liner made from B10, where the neutron induced fission reaction splits B10 into  $\text{He}^4$  and  $\text{Li}^7$  with the release of 3 MeV.

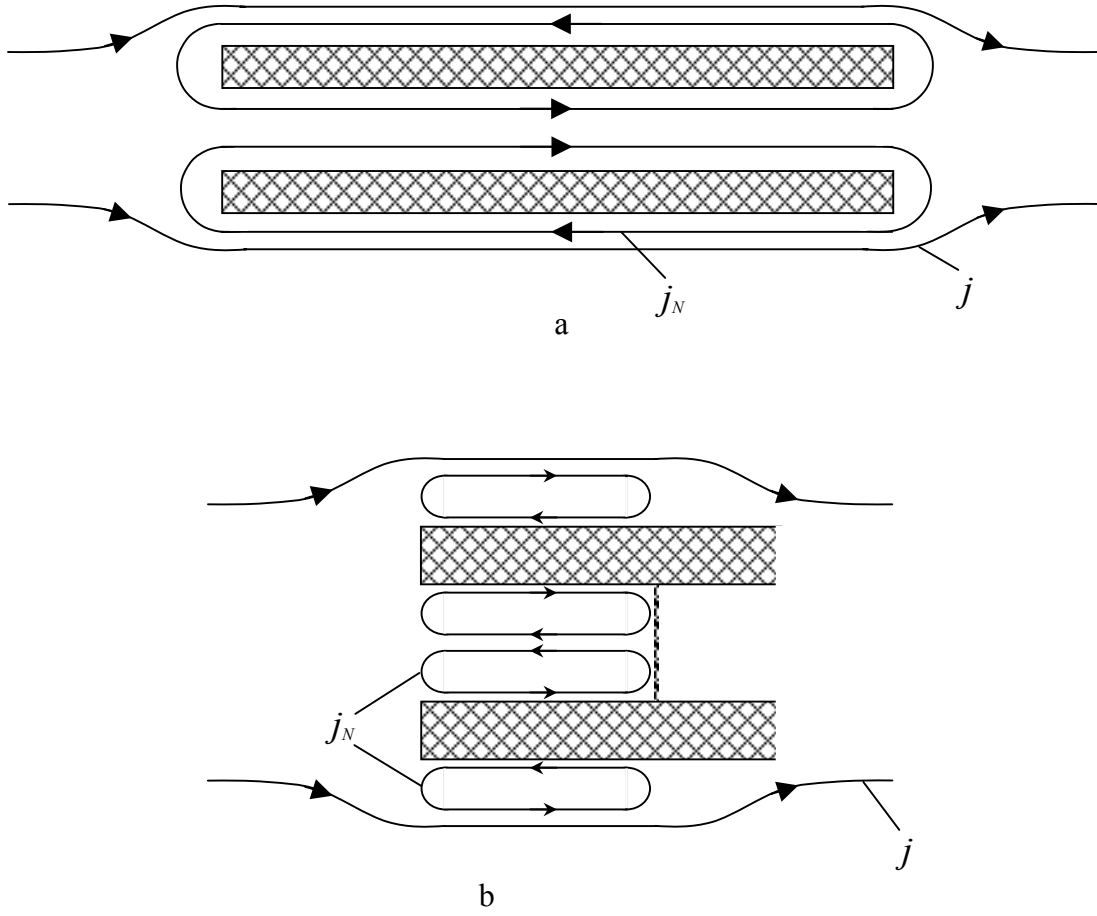


Fig. 2. Current  $j$  in plasma surrounding liner, with Nernst current  $j_N$ .

## References

1. F. Winterberg, *Nature* **241**, 449 (1973).
2. G.A. Askar'yan, V.A. Namiot, M.S. Rabinovich, *JETP Lett.* **17**, 424 (1973).
3. F. Winterberg, *Z. f. Naturforsch.* **58a**, 612 (2003).
4. T.J. Dolan, *Fusion Research Vol. II*, Pergamon Press, New York, 1982, p. 312 ff.
5. O. Buneman, *Phys. Rev.* **115**, 503 (1959).
6. F. Winterberg, *Phys. Rev.* **174**, 212 (1968).
7. L. Spitzer, *Physics of Fully Ionized Gases*, Interscience Publishers, New York, 1962, p. 145.
8. I. Smith, in *Proceedings of The International Topical Conference on Electron Beam Research and Technology*, 3-6 November 1975, Albuquerque, New Mexico, edited by G. Yonas (Sandia National Laboratories, Albuquerque, NM, 1976), SAND76-5122, Vol. I, pp. 472ff.
9. F. Winterberg, *Nucl. Instrum. Methods* **136**, 437 (1976).