Propagating Thermonuclear Burn by Laser Ignition of a Dense Z-Pinch

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Z. Naturforsch. **53a**, 933–936 (1998); received September 4, 1998

A linear pinch discharge above the Pease-Braginskii current and stabilized by axial shear flow can radiatively collapse to high densities. A thermonuclear detonation wave can then be launched from one end of the discharge channel by ignition with a powerful laser pulse. Axial shear flow stabilization may be realized by injecting a fast moving jet along the pinch discharge channel, possibly in combination with a frozen DT fiber positioned on the pinch axis.

1. Introduction

In the fast ignitor concept of inertial confinement fusion [1], a petawatt laser pulse ignites at one point a laser compressed high density target (for example highly compressed liquid DT), launching a thermonuclear detonation wave from the point of ignition. Here we propose to implement a similar idea to a highly compressed dense *z*-pinch [2].

In a *z*-pinch plasma high densities can in principle be reached for currents above the Pease-Braginskii current provided a means can be found to keep the discharge stable. A thermonuclear detonation wave propagating along the pinch channel can then there be ignited by a pulsed laser beam. To stabilize the pinch one may superimpose on it an axial shear flow, as it was proposed by the author many years ago [3], and recently reconsidered by Arber and Howell [4]. For stabilization by axial shear flow to work, the stagnation pressure $(1/2)\,\rho\, v^2$ of the flow must be by about one order of magnitude larger than the magnetic pressure of the pinch discharge, with a change in the radial direction over the pinch by about the same order of magnitude. In the original proposal by [3], the stagnation pressure was created by shooting a thin solid projectile through the core of the pinch discharge channel. Even though the axial flow removes thermal energy from the discharge channel, these energy losses are unimportant as long as the axial flow velocity does not exceed the detonation wave velocity. The removal of heat by an axial flow should even be helpful, because it increases the cooling of the discharge channel needed to reach a high density.

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2. Laser Ignition of a Shear Flow Stabilized Z-Pinch

The implementation of the proposed idea is illustrated in Figure 1.

1. In the first stage, a large current drawn from a fast Marx capacitor bank C_1, implodes a wire array resulting in a ~100 TW-megajoule soft X-ray pulse [5].
2. The X ray pulse ablatively propels dense DT placed (in liquid or solid form) inside a thin tube, with a supersonic jet emitted from the tube into the second stage pinch discharge chamber.
3. After the jet has reached the other end of the chamber, a second Marx bank C_2 is discharged over the jet. Then, as long as the axial stagnation pressure $p_s = (1/2)\,\rho\, v^2$ of the jet (ρ, v density and velocity of the jet) is larger than the magnetic pressure $p_H = H^2/8\pi$ of the pinch (H magnetic field strength of the pinch discharge), the pinch can be dynamically stabilized.
4. After the pinch has radiatively collapsed down to a small diameter reaching a high density, a powerful laser pulse ignites a thermonuclear detonation wave propagating supersonically through the pinch channel.

3. Shear Flow Stabilization

The jet propagating along the pinch axis has a pressure tensor for which $p_\parallel \gg p_\perp$, where $p_\parallel = (1/2)\,\rho\, v^2$. Near the surface of the jet the magnetic forces predominate and one there has $p_\perp \approx H^2/8\pi$. Provided $p_\parallel \gg p_\perp$ or $v > H/\sqrt{4\pi\,\rho} = v_A$, where v_A is the Alfvén speed, the pinch can be inertially stabilized by the jet [3]. In the original concept by the author it was proposed to shoot at a high speed a thin solid projectile through the core of the dis-

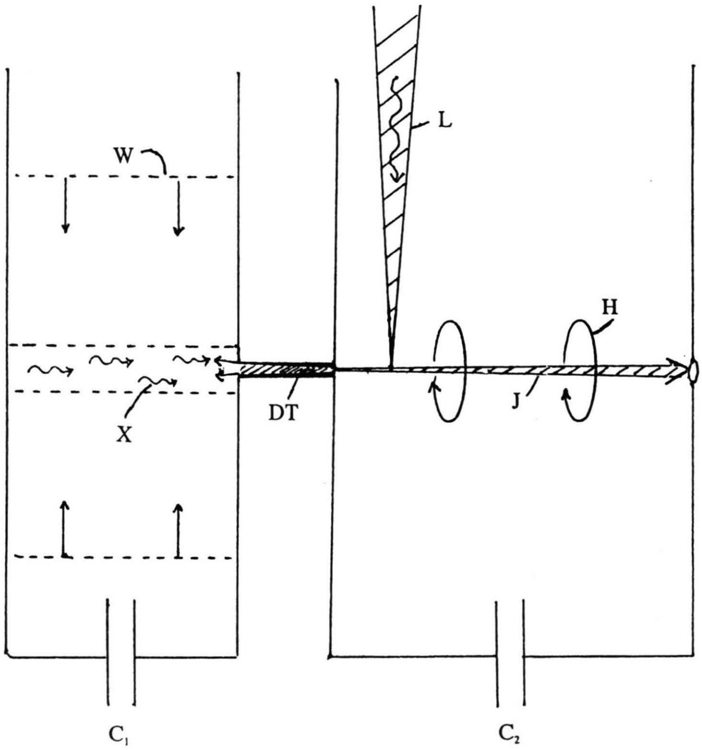

Fig. 1. Laser ignited shear flow stabilized dense z-pinch. C_1, C_2 Marx capacitor banks; W wire array imploded by discharge of C_1; soft x-rays X heat solid or liquid DT contained in thin tube, resulting in an ablatively driven jet J over which C_2 is discharged forming a dense z-pinch with azimuthal magnetic field H. L is a pulsed laser beam igniting the dense pinch channel.

charge channel. Because the density of such a projectile is large if compared with the plasma density in the discharge channel, smaller projectile velocities are there needed in comparison to jet velocities for jet densities comparable to the plasma density.

Computer simulations show that for a jet with a Mach number $\mathrm{Ma} = v/v_A > 3$ and a radial variation of the Mach number by the same order of magnitude, magnetohydrodynamic disturbances do not grow [4]. Since these computer models assumed the same density in the jet and pinch discharge plasma, the condition Ma > 3 implies that $(1/2)\,\rho\, v^2 > 9\ (H^2/8\pi)$, or $p_{\|} > 9\ (H^2/8\pi)$. Accordingly, the kinetic energy of the jet should be larger by one order of magnitude than the magnetic energy of the pinch. To increase the overall shear by a radial variation of the Mach number, one may put across the pinch discharge chamber a solid DT fibre, following the well established technique used in micropinches. There, the jet would flow along the fibre, with a small Mach number on the pinch axis, similar to a high velocity projectile shot through the core of the pinch. The shear will be sustained if the mass of the fibre and jet are of equal magnitude.

The jet is injected through a hole into the discharge chamber. To prevent it from hitting the other electrode, by which it may destabilize the pinch, a hole is put into the other electrode to let it pass through.

4. Radiative Collapse

For pinch currents in excess of the Pease-Braginskii current $I_{PB} \sim 1.7\times10^6$ A, the pinch column shrinks down to a small diameter until it becomes optically opaque at a radius about equal one photon path length. For a fully ionized hydrogen plasma the photon path length is [6]

$$\lambda_p \sim 4\times10^{22}\, n^{-2}\, T^{3.5}\, Z^{-3}\,. \tag{1}$$

Assuming that $T \sim 10^7$ K, $n \sim 5\times10^{24}$ cm^3, corresponding to a ~100 fold compression above of the solid density, and $Z = 1$, one finds $\lambda_p \sim 5\times10^{-2}$ cm.

The radiative collpse time is

$$\tau_R \sim 3\times10^{11}\, T^{1/2}/Z^3\, n\,. \tag{2}$$

For the example $T = 10^7$ K, $Z = 1$ and $n = 5\times10^{22}$ cm^{-3} (valid for a solid density DT fibre) one has $\tau_R \sim 10^{-8}$ s.

The plasma pressure is there $p = 2n\,k\,T = \sim 10^{14}$ dyn/cm^2, requiring that $H \sim 5\times10^7$ G, and for $r \sim 10^{-2}$ cm, that $I \sim 5$ Hr $\sim 2\times10^6$ A, above the Pease-Braginskii current. At solid densities the radiative collapse time is of the same order of magnitude as the discharge time to drive the pinch, becoming shorter in proportion to $1/n$ with the pinch shrinking down to a smaller diameter. For a 100 fold compression above solid density, it would be $\sim 10^{-10}$ s.

5. Pinch Current Assisted Thermonuclear Detonation

If the azimuthal magnetic field H_ϕ set up by the pinch current I is strong enough to confine the charged fusion products inside the pinch discharge channel, a thermonuclear detonation wave can propagate along the channel [2]. The magnetic field of the pinch

$$H_\phi = 2I/r\,c \tag{3}$$

with a Larmor radius for the charged fusion products of charge $Z\,e$, mass M_f and velocity v one has

$$r_\mathrm{L} = M_\mathrm{f}\,v\,c/Z\,e\,H_\phi = r\,M_\mathrm{f}\,c^2/2Z\,e\,I. \tag{4}$$

To confine the fusion products inside the pinch channel requires that $r \geq r_\mathrm{L}$, from which it follow that

$$I > I_0 = M_\mathrm{f}\,c^2\,v/2Z\,e\,. \tag{5}$$

With the kinetic energy of the fusion products $\varepsilon_0 = (1/2)M_\mathrm{f}\,v^2$ one has

$$I_0 = \frac{c^2}{Ze}\sqrt{\frac{M_\mathrm{f}\,\varepsilon_0}{2}}\,. \tag{6}$$

For the α-particles of the DT reaction one has $M_\mathrm{f} = 4$M (M proton mass), $Z = 2$ and $\varepsilon_0 = 3.5$ MeV $= 5.4\times10^{-6}$ erg, hence $I_0 \sim 4\times10^{15}$ esu $\sim 1.3\times10^6$ A, only somewhat smaller than the Pease-Braginskii current.

The detonation wave can be viewed as a shock wave driven by thermonuclear reactions. For a fully ionized hydrogen plasma the wave propagates supersonically with the velocity [2] ($M = 2.5\,\mathrm{M_H}$ for DT)

$$v_0 = \sqrt{32\,kT/3M}\,. \tag{7}$$

For the specific heat ratio $\gamma = 5/3$ the Mach number of the wave is Ma $= \sqrt{32/10} = 1.8$. To sustain the detonation, the energy supplied by the charged fusion products must exceed the energy lost by the wave propagating into the still unburnt fuel.

The energy supplied to the wave is

$$\varepsilon_\mathrm{in} = (1/4)\,n^2\,\langle\sigma\,v\rangle\,\varepsilon_0(1/2)\,\lambda_0\,, \tag{8}$$

where $\langle\sigma\,v\rangle$ is the nuclear reaction cross section velocity product averaged over a Maxwellian, and

$$\lambda_0 = a\,(kT)^{3/2}/n \tag{9}$$

($a \sim 2\times10^{34}$ cm^{-2} erg$^{-3/2}$) the range of the α particles from the DT reaction, with the fraction 1/2 of them emitted in the forward direction of the detonation.

The energy removed from the detonation wave is

$$\varepsilon_\mathrm{out} = 3n\,kT\,v_0 = 4\sqrt{6}\,n\,(kT)^{3/2}/\sqrt{M}\,. \tag{10}$$

The detonation to be sustained requires that $\varepsilon_\mathrm{in} = \varepsilon_\mathrm{out}$, hence

$$\langle\sigma\,v\rangle \geq 32\sqrt{6}/\varepsilon_0\,a\,M^{1/2}\,. \tag{11}$$

Inserting numerical values one finds $\langle\sigma\,v\rangle \approx 3\times10^{-16}$ cm^3/s, well below the maximum value $\langle\sigma\,v\rangle \approx 10^{-15}$ cm^3/s for the DT reaction.

With the detonation going at supersonic speed, axial losses to the electrodes can be neglected as long as the length of the pinch channel is larger than the range of the α particles. This condition is satisfied if the density is larger than $n \sim 10^{22}$ cm^{-3}.

6. Ignition

Launching a thermonuclear detonation wave requires that the pinch channel is larger than the α-particle range at $\sim 10^9$ K (where $\langle\sigma\,v\rangle$ is largest), and that the ignition energy is supplied in a time less than the disassembly time at this temperature. At $T \sim 10^9$ K one has (with a particle number density $n = 5\times10^{24}$ cm^3, corresponding to a 100 fold compression above solid density), $\lambda_0 \sim 0.2$ cm, and a sound velocity $a_0 \sim 2\times10^8$ cm/s, with the axial expansion time $\tau \sim \lambda_0/a_0 \sim 10^{-9}$ s within an order of magnitude as the radiative collapse time. For ignition, a cylinder of radius $r \sim 5\times10^{-4}$ cm and length λ_0, must be heated to $T \sim 10^9$ K. This requires the energy

$$E_\mathrm{ign} = 3kT\,\pi\,r^2\lambda_0\,n\,, \tag{12}$$

or because of (9)

$$E_\mathrm{ign} = 3a\,\pi\,r^2\,(kT)^{5/2} \sim 3\times10^{11}\ \mathrm{erg} \sim 30\ \mathrm{kJ} \tag{13}$$

to be delivered in $\sim 10^{-9}$ s. The laser power therefore must be $P = E_\mathrm{ign}/\tau \sim 3\times10^{13}$ Watt. The energy balance looks as follows:

1. The energy to generate the jet with a 100 TW soft x-ray pulse lasting 10^{-8} sec, is of the order 10^6 J, generating a jet propagating with a velocity of $\sim 10^8$ cm/s, having a length of ~ 10 cm, a diameter of ~ 0.1 cm and a density n of $\sim 10^{20}$ cm^{-3}.
2. To generate the pinch discharge too requires an energy of the order 10^6 J.
3. The thermonuclear energy released is ~ 100 times larger than the kinetic jet and the pinch energy, that is of the order $\sim 10^{15}$ erg $\sim 10^8$ J.

7. Fusion Chain Reactions

A further increase in the reaction rate is possible through a fusion chain reaction [7]. It requires that the nuclear reaction cross section σ is larger than the stopping power cross section, the latter defined by

$$\sigma_s = |\mathrm{d}E/\mathrm{d}x|/n\, E_0\,, \tag{14}$$

where E_0 is the initial energy of a charged particle and $\mathrm{d}E/\mathrm{d}x$ the stopping power. For a cold electron gas one has [8]

$$\sigma_s^{(0)} = \frac{2\pi M Z^2 e^4}{m E_0^2} \log \Lambda\,. \tag{15}$$

A typical value is $\sigma_s^{(0)} \approx 10^{-21}$ cm^2, about 10^3 times larger than a nuclear reaction cross section. For a hot electron gas the stopping power is reduced and there one has [9]

$$\sigma_s = \frac{4}{3\sqrt{\pi}} \left(\frac{m E_0}{M kT}\right)^{3/2} \sigma_s^{(0)}\,. \tag{16}$$

To make $\sigma \geq \sigma_s$, one finds that $kT > 100$ keV. The fusion chain reaction does not have to be critical to increase the reaction rate. This is even possible for a subcritical multiplication factor $k<1$. Multiplication factors of the order ~ 0.5 have been calculated for the DT reaction at densities and temperatures projected for laser fusion by Afek et al. [10]. Assuming that a multiplication factor of the order $k \sim 0.5$ can be reached, it would double the reaction rate by the factor $1 + k + k^2 + \ldots = 1/(1-k) \approx 2$.

8. Staging

The energy released in the thermonuclear reaction can be used to ignite a second stage implosion type target, further increasing the total energy output. Staging concepts of this kind were previously proposed for magnetized fusion targets [11].

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