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HIGH DENSITY, HIGH MAGNETIC FIELD CONCEPTS FOR COMPACT FUSION REACTORS*

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Abstract

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One rather discouraging feature of our conventional approaches to fusion energy is that they do not appear to lend themselves to a small reactor for developmental purposes. This is in contrast with the normal evolution of a new technology which typically proceeds to a full scale commercial plant via a set of graduated steps. Accordingly, several concepts concerned with dense plasma fusion systems are being studied theoretically and experimentally. A common aspect is that they employ: (a) high to very high plasma densities ($\sim 10^{16}cm^{-3}$ to $\sim 10^{26}cm^{-3}$) and (b) magnetic fields. If they could be shown to be viable at high fusion Q, they could conceivably lead to compact and inexpensive commercial reactors. At least, their compactness suggests that both proof of principle experiments and development costs will be relatively inexpensive compared with the present conventional approaches. In this paper, the following concepts are considered:

(1) The staged Z-pinch
(2) Liner implosion of closed-field-line configurations
(3) Magnetic "fast" ignition of inertial fusion targets
(4) The continuous flow Z-pinch.

1. STAGED Z-PINCH

A staged Z-pinch [1-3] is projected to achieve breakeven fusion in a compact laboratory device. Initially a pulsed, electrical generator drives current through an annular plasma shell of several centimetres radius (Fig. 1). A cryogenic fibre is located on-axis [4,5]. Between the shell and the fibre there is a magnetic field. As the shell implodes, eddy currents are induced on the fibre surface via flux compression. The result is a fibre current risetime that is decreased by orders of magnitude and a fibre current that is amplified several fold relative to the shell current. The large value of compressed field confines alpha particles and provides transient shear to improve stability against MHD instabilities [6] as the target heats adiabatically.

The experiment at the University of California, Irvine (UCI) utilizes a low-voltage-capacitor-bank driver. At full charge the characteristics are: $W_{stored} = 62.5$ kJ, $V_{charge} = 50$ kV, $I_{max} \sim 2$ MA, $\tau_{1/4} \sim 1.8$ µs. Diagnostics include: current and voltage monitors, multi-channel XRD array, PIN diode spectrometer, X ray pinhole camera, X ray spectrometer, laser imaging, visible-light framing and streak imaging. Two capacitor banks (each 25 µF, 60 kV) and switched by railgaps, symmetrically feed a plate-transmission line, 6.4 mm thick, 2 m wide, and 2.5 m long. The anode-cathode gap is 1.5 cm and the gas puff is 5 cm diameter; the total system inductance is 32 nH. The puff valve and annular-gas nozzle are mounted on the cathode electrode and provide access for the fibre target. The pinch gas is Ne, Ar or Kr. Cryogenic fibres of H_2, D_2, and Ne have been extruded on a separate test stand [7]. An external guiding system positions the fibre with mm accuracy.

Our analysis has considered a range of UCI parameters that will achieve break-even yield using single-step staging. In zero-D with a D-T target, our code [1] predicts: 5 MA fibre current, $\tau \sim 0.1$ ns confinement time, 6.10^{25} cm^{-3} density, 10 keV ion temperature, $n\tau \sim 3.10^{14}$ cm^{-3}-s, and a 10-fold energy gain ($E_{neutrons}/E_{bank}$). One-dimensional calculations, using the LLNL TRAC-2 MHD code, including ideal equation of state, magnetic diffusion, radiation losses and thermal transport give similar results. Figure 2 displays the 1-D results for a krypton Z pinch and DT target. These outputs were compared with another LLNL radiation MHD code (run in 1-D "non-optimized" configuration). The outputs were comparable, confirming current transfer, amplification, and fibre heating.

2. ADIABATIC COMPRESSION OF CLOSED FIELD LINE CONFIGURATIONS BY CENTIMETRE SIZE LINERS

Imploding liners have been considered for generating fusion-grade plasma since the '70s. However, in these early assessments, systems with large dimensions and, accordingly, large energy inputs (~10s–100s MJ) were considered. In the last decade, remarkable progress has been made in two relevant areas of plasma physics and technology: (i) Achievement of high convergence ratios in implosions of centimetre size liners [8]; (ii) Much better understanding of the properties of dense wall-confined plasmas (see, e.g., [9]). Accordingly, we have reconsidered the fusion prospects of the liner concept.

We consider small initial dimensions and relatively short implosion times ~ 1-2 μs. Initial liner length, radius and weight are assumed to be in the range 5-10 cm, 1-2 cm, and 5-10 g, respectively. We consider an option provided by a self-similar implosion of the liner in both r- and z-directions and show that this has advantages over purely radial implosion. We consider only closed field line configurations which would provide good plasma thermal insulation from the liner and the end walls; we seek conditions under which the fusion alpha particles would also be confined. We focus on the situation in which the initial plasma has a pressure comparable with or exceeding the initial magnetic pressure of the B-field inside the liner, so that essentially all the energy of the implosion goes to plasma heating and not on the increase of the energy of the B-field. We find that it is possible to achieve a plasma density $\sim 10^{21} cm^{-3}$ and fusion break-even (Q=1) at a plasma energy level ~0.1 MJ while values of Q as high as 5-6 are probably within the reach of the experiments with a plasma energy content ~1 MJ. We have considered the following magnetic configurations: FRC; spheromak; and Z-pinch (in the latter case, there is no confinement of alpha-particles).

A candidate system geometry is shown in Fig. 3, where the magnetic configuration is of the FRC type, with the field reversal maintained by plasma currents (not by an electron or ion beam). Initially, a magnetically confined FRC has $\beta_0 \sim 1$ as a "natural" state (see, e.g., [10]). Here, with the confinement volume restricted on all sides by conducting material walls, an FRC configuration with $\beta > 1$ is also possible. After the initial configuration is prepared, an external voltage is applied between the electrodes (Fig.3) with a pulse-length short compared to the liner skin-time. The liner is assumed to be made of some heavy material and its velocity during all phases of the implosion is assumed to be much smaller than the plasma sound velocity. Therefore, plasma compression occurs in the adiabatic manner.

We consider a self-similar compression which maintains a constant length/radius ratio of the FRC. This is achieved by properly tailor the mass density of the liner along the axis. If the central part is heavier than the ends, its compression lags behind, maintaining an approximate constancy of the length/radius ratio of the plasma object nesting inside the liner.

Due to heat flow from the plasma and Joule dissipation in the skin-layer at the inner side of the liner, this inner surface will be evaporated and ionized. As both the ion gyroradius and mean free path of these relatively cold ions will be 2-3 orders of magnitude smaller than the plasma radius, they will not directly penetrate the plasma. In addition, in a high beta plasma, the impurities get repelled from the hot region, under the action of the thermal force and plasma convection towards the walls.

Analysis presented in Ref. 11 has shown that even with quite pessimistic assumptions regarding thermal conductivity to the liner walls, thermal losses do not limit the quality of pellet performance. Bremsstrahlung also constitutes an insignificant energy sink (unless one deliberately seeds the plasma with heavy impurities, in order to use the system as a pulsed source of X-rays).

The plasma gain Q, is limited by a relatively short liner dwell time near the turning point [11]. The Q value determined by this process can be presented as:

$$Q = 0.5(\beta_0^{1/3}\rho L/E^{2/3}T_0)^{1/2}(W_{max}B_0)^{1/3}$$

Here liner density is measured in g/cm^3, initial temperature T_0 in eV, plasma energy E in the final state in kJ and initial magnetic field in T.

We have considered a hypothetical breakeven experiment with a 5 MA pinch current and 2 μs implosion time. The initial characteristics of the FRC are: diameter 2 cm, length 5 cm, plasma density 10^{24} m^{-3}, plasma temperature 100 eV, magnetic field 10 T. Linear convergence of the liner was 10 (volume convergence was 1000).

3. MAGNETIC FAST IGNITION

This is a scheme to ignite fuel compressed to ICF densities (~ few x 10^2 g/cc), where the compression is achieved by laser or x-ray driven implosion but the ignition hot spot is generated from the JxB collapse of a magnetic "bubble" within the imploded capsule. The ignition is "fast" ignition in the sense of the fast ignitor concept [12] and offers advantages of improved gain and a reduction in the required convergence ratio. The magnetic bubble must be established within an electrically conducting region in the capsule before the implosion.

In conventional, isobaric, ICF, burn initiates from a low density, central hot spot in near pressure equilibrium with high density cold fuel. An interesting alternative is "isochoric" ignition where the density is nearly uniform. The hot spot is then at much higher pressure than the surrounding fuel. Because of the rapid disassembly, high power "fast" ignition is required employing, for example, a short pulse laser [12]. Here we discuss the use of magnetic forces to achieve fast ignition.

Consider a compressed, nearly Fermi-degenerate cold fuel mass, with a magnetic-field-containing toroidal void (Fig. 4). The void, or magnetic bubble, will not close if it contains an azimuthal field with magnetic pressure about equal to the surrounding fuel pressure and the conductivity prevents diffusion of field. Because of the 1/r dependence of the field, the bubble cannot be in exact equilibrium and it will distort radially inward. The initial motion of the bubble is of order the cold fuel sound velocity. This is also of order the final assembly velocity in the capsule implosion as required to reach this state in a realistic implosion. As the distortion extends to smaller radius, the flows accelerate because the magnetic pressure increases as $1/r^2$. A narrow, rapidly collapsing neck forms as in "sausage" instabilities in a Z-pinch. The plasma pressure and temperature climb in the neck until the ignition temperature is reached. Ignition occurs if there is sufficient $\rho . r$ (density x radius). This ignition method has also been suggested for a high current Z-pinch [13].

2D radiation MHD simulations of the ignition process starting from the compressed state show isochoric (or density enhanced) ignition can occur. We have modeled an initially stationary sphere of DT with a radius of 105 μm, density of 320 g/cc, temperature of 220 eV and total energy of 54 kJ. The initial state has a small toroidal void centered at 52.5 μm with mean magnetic field of 1.5x 10^9 Gauss and 5 kJ of magnetic energy. The "neck off" occurs after 60 ps, igniting a burn wave that encompasses the fuel mass by 110 ps. The yield is 122MJ, corresponding to a gain of 68 for a 1.8MJ driver and driver-to-capsule energy conversion efficiency of 0.03.

Achieving the desired compressed state is a challenging 2D design problem. An azimuthal magnetic field ~ 1 MG must be established within the capsule before implosion, possibly employing laser generated fields. Fields of order 25 MG have been produced in CO2 laser experiments [14]. Initial 1 and 2D calculations show that field diffusion into the conducting (beryllium) structure may be important in the early portion of the implosion. In the calculations, diffusion can be limited with thicker conductors, aided by plasma conductivity. This leads to good conservation of magnetic flux and compression of the magnetic field to the required conditions. Future calculations will include the 2D implosion of conductors and DT fuel.

4. CONTINUOUS FLOW PINCH

We are also revisiting the prospects for high power density fusion devices based on the continuous flow Z-pinch [15,16]. In particular, existing experiments and new theory suggest that the instability modes of the conventional Z-pinch may be fully stabilized by the addition of plasma flow. This, at least, suggests the potential for low cost, intense fusion neutron sources for various practical applications [16].

The continuous-flow pinch (CFP), one of the simplest magnetic confinement fusion systems, is a Z-pinch with axial plasma flow formed by injection of magnetized plasma from a coaxial plasma gun. The CFP was extensively studied in the former Soviet Union and successfully developed as a high purity source of accelerated plasma. In 1967, a Marshall plasma gun [17] operating regime was discovered which resulted in the formation of a continuous-flow Z-pinch (CFP). The pinch column was ~50cm long, <1cm dia, with $n \sim 10^{24} m^{-3}$, and T~0.1-0.2keV[4]. It demonstrated a fusion product of $n\tau \sim 5.10^{17} m^{-3}s$, about the same as the "break-through" value achieved by the low density, closed confinement in the T3 tokamak of that time which exhibited an $n\tau$ of $\sim 4\times10^{17} m^{-3}s$ [18]. Most remarkably, this CFP appeared to be stable for many hundreds of Alfven times against the conventional "sausage" and "kink" instabilities that have continued to plague conventional, static Z-pinches.

We now believe we may understand the reason for this stability and predict that it can be exploited to realize a stable, high-gain fusion plasma based on the Z-pinch, providing a radial velocity shear is induced in the axial plasma flow stream [19,20]. In the 1967 experiment, a sheared flow was probably induced by the method of formation as suggested by our recent 2-D modeling studies. In a high power fusion neutron source based on this principle, we would propose actively tailoring the shear profile though electrode control [16]. Note, however, that a recent parallel study has suggested that the required flow velocities may be high [20]. If so, this would require pulsed operation to realize acceptable fusion gain, Q.

We have also performed a conceptual design of a high power D-T neutron source based on the CFP applied to the transmutation of long-lived radioactive waste from fission reactors [16]. The design is configured in a reflex configuration to ensure electrode survivability. The injectors, typical Marshall guns with tailored electrodes, introduce plasma which flows radially inward and divides at a null point into oppositely directed flow pinches. The core of each pinch column enters an end burial chamber where rapid expansion takes place and the exhaust power is dissipated over a large surface. The capital and development costs are projected to be low for such a neutron source based on this principle

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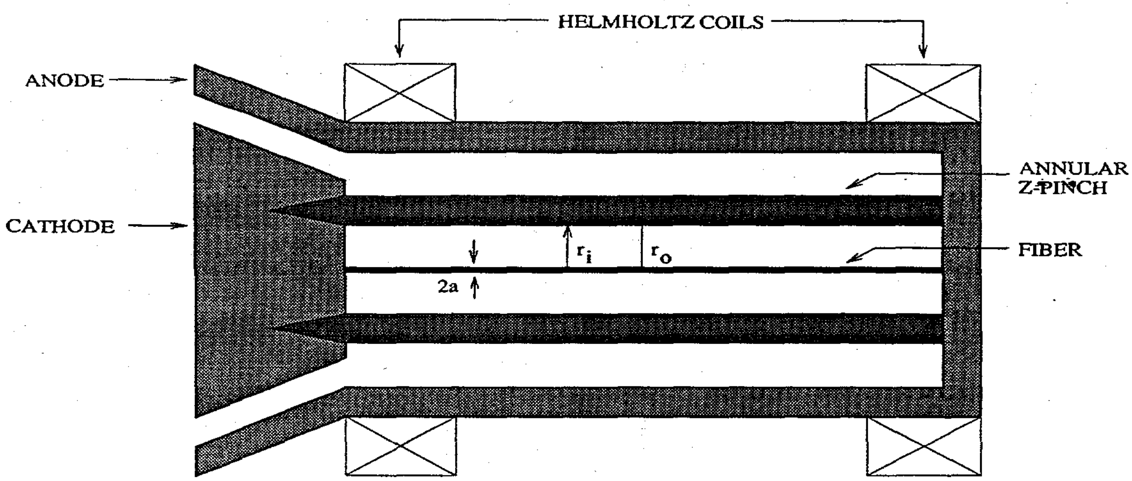

Figure 1. Staged Z-Pinch.

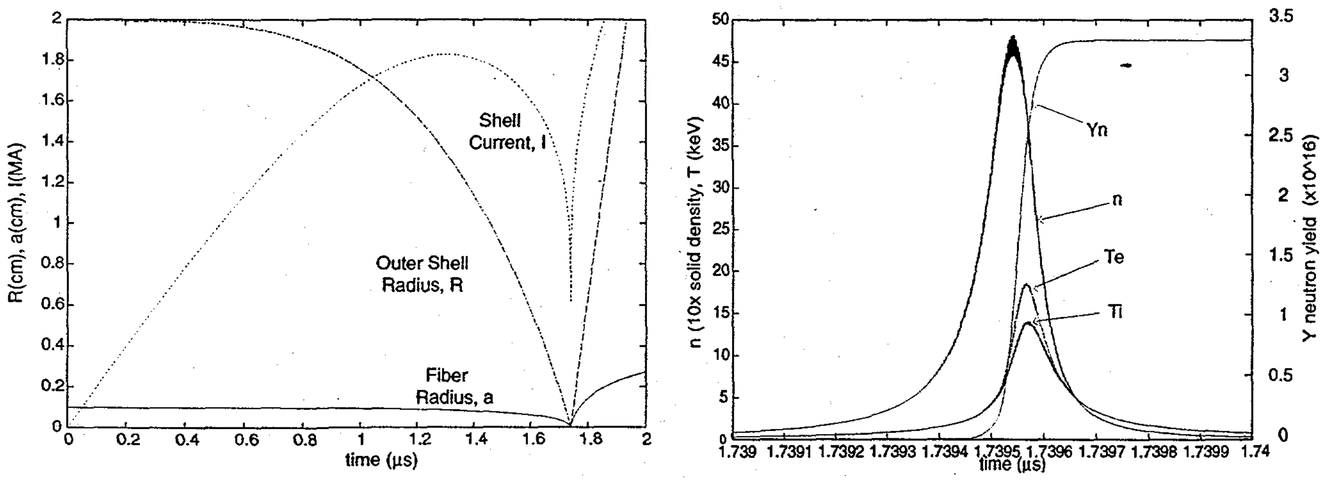

Figure 2. TRAC2 1-D outputs for a krypton liner staged pinch onto a DT fiber; (left) current and radii, (right) density, temperature, and neutron yield.

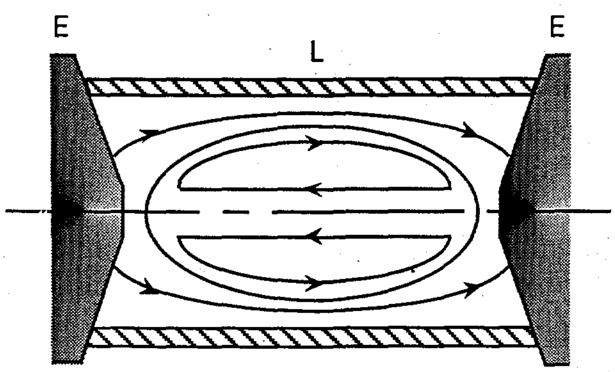

Fig 3. Schematic of the imploding liner system for our reference FRC plasma configuration. Electrodes (E) drive the current in liner (L)

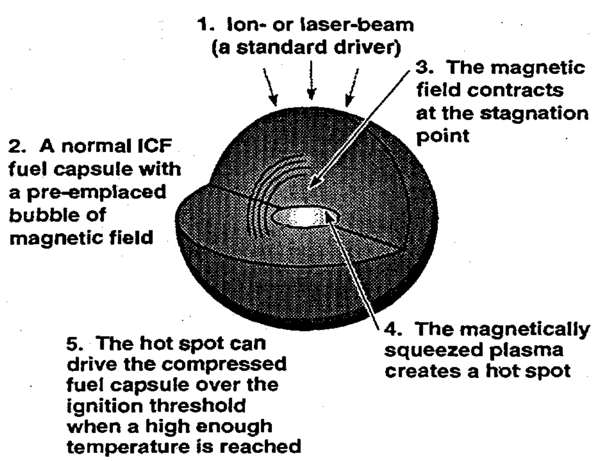

Fig. 4. Schematic of magnetic fast ignition within an ICF capsule