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HIGH DENSITY, HIGH MAGNETIC FIELD CONCEPTS FOR COMPACT FUSION REACTORS

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During the past year, several concepts concerned with dense plasma fusion systems have been theoretically/numerically re-examined at LLNL, with a conclusion that they may become strong candidates for future alternatives research programs. A common feature of theseschemes is that they employ (a) plasmas with densities ranging from $\sim10^{16}$ cm^{-3} up to ICF-like densities ($\sim10^{26}$ cm^{-3}) and (b) magnetic fields. Their salient feature is also that, if successful, they would give rise to a compact and inexpensive reactor. Their compactness means also that the "proof-of-principle" experiment will be relatively inexpensive; the same is true for the developmental cost. Specifically, we consider the following concepts: 1. Liner implosion of the closed-field-line configurations; 2. Flow-through pinch; 3. Magnetic ignition of inertial fusion.

Although the first two concepts have been known in some form for a decade or so, new developments in fusion-related science and technology (e.g., direct experimental demonstration of a high-convergence 3D liner implosion and theoretical identification of a strong favorable effect of the shear flows on the stability of the pinches) certainly make them much more attractive than before. The third concept that emerged during last one or two years, also relies on a great progress in the understanding of the properties of high-density magnetized plasma.

1. Adiabatic Compression of the Closed Field Line Configurations by Centimeter-Size Liners
In this section, adiabatic compression of a pre-formed closed field line configuration by an imploding liner is considered. Three configurations are discussed: the field-reversed configuration, the spheromak and the Z-pinch. It is shown that, by employing a 3D compression, one can reach a break-even condition with an energy input into the plasma as low as 30 kJ. Typical initial dimensions of the liner are: the length 5-6 cm, the radius ~1 cm, wall thickness ~0.01 cm. Liner mass is in the range of a few grams. It is assumed that the initial plasma beta is of the order of unity; in this case, the final beta is much greater than 1 and plasma is in "wall-confined" regime. Typical plasma parameters for the final state (for the linear compression ratio equal to 10) are: density 10^{21} cm^{-3}, temperature 10 keV, magnetic field 10^3 T. To improve the liner stability near the turn-around point, one can use a recently proposed technique of creating an azimuthal shear flow inside the liner near the plasma-liner interface (the liner behaves as a liquid at this point). The technique (similar to the one proposed in paper [1] in conjunction with laser pellet stabilization) is based on using the liners with fine East-West asymmetric structures impregnated into the liner material at the desired depth. The compression wave approaching this layer sets liner material there in a rotational motion.

A brief discussion of various phenomena affecting the wall confinement is presented (magnetic field diffusion, radiative losses, impurity penetration); conclusion is drawn that all these effects are modest and are not a factor that limits plasma enhancement Q. The scaling law for the Q versus the input parameters of the system is derived which shows a relatively weak dependence of Q on the input energy. Reactor potentialities of the system are briefly described, with the understanding that one of the difficult problems of pulsed fusion devices with a high repetition rate is the rapid neutron and thermo-mechanical damage to the pulse-power source. Possible solution of this problem based on the "detached energy source" technique is discussed.

2. Continuous Flow-Through Pinch. We are revisiting the prospects for fusion devices based on the "continuous flow Z-pinch" (CFP). Relative to conventional, low density, magnetically-confinement concepts, the CFP offers the potential advantages of a compact linear geometry, steady-state operation, high power density, and the absence of complex magnet systems. In particular, existing experiments and new theory suggest that the instability modes of the conventional Z-pinch can 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.

In 1967 a Marshall plasma gun [2] operating regime was discovered which resulted in the formation of a continuous-flow Z-pinch (CFP). The pinch column was ~50cm long, <1cm in diameter, with a plasma density of $\sim 10^{24} m^{-3}$, a plasma temperature of ~0.1-0.2keV and a fusion confinement product of $n\tau \sim 5.10^{17} m^{-3}s$. Most remarkably, this CFP was stable for many hundreds of Alfven times against the conventional "sausage" and "kink" instabilities that have continued to plague conventional, static Z-pinches. We believe we now understand the reason for this stability and predict that a high-gain fusion plasma based on the Z-pinch can be stabilized providing a radial velocity shear is induced in the axial plasma flow stream [3]. In the 1967 experiment, we suggest that a sheared flow was induced by intrinsic viscosity effects. In a high power neutron source based on this principle, we propose actively tailoring the shear profile though electrode control. If such a stable flow state can be maintained in steady-state, this becomes the cheapest, simplest method of realizing a high yield neutron source compared with other candidates, namely conventional fusion reactors or accelerator-driven, spallation neutron sources.

3. Magnetic ignition of inertial fusion. This is a scheme to ignite fuel compressed to ICF densities, where the compression is achieved by x-ray or laser driven implosion. In conventional ICF, the fuel is assembled to a state with high density, low temperature material surrounding a low density, high temperature "hot spot". The hot spot plasma is in approximate pressure balance with the cold fuel, and given sufficient temperature and ρR (density x radius) the fuel will ignite, a condition described as "isobaric" ignition [4]. An interesting alternative is "isochoric" ignition where the density is uniform, but with a hot spot at high temperature and pressure compared to the surrounding material. Isochoric ignition requires rapid heating of the hot spot and is virtually impossible to attain in a conventional implosion, however the gain for a given drive energy can be higher by as much as 2 orders of magnitude. This is the motivation for the Fast Ignitor concept employing a short pulse laser for rapid ignition [5].

Magnetic ignition is a possible alternative means of achieving isochoric ignition. In this concept, an azimuthal magnetic field ~ 1 MG is established within the capsule before implosion. The most likely candidate for generating the initial field is a laser with a pulse length ~ 1 ns or less. The field confining volume should contain either vacuum or high-Z gas that will radiatively cool to avoid buildup of plasma pressure in this region. The void containing the magnetic field will compress until the magnetic pressure becomes comparable to the plasma pressure. The initial field is chosen so that this does not occur until capsule stagnation with a final field-containing volume of 10 - 20% of the stagnated volume. For azimuthally directed field, the compressed state should resemble a toroidal "bubble" embedded in a roughly spherical cold fuel mass, with stored magnetic energy (typically $\sim 10^4$ J) sufficient for ignition. Design of a capsule with a field containing region that retains sufficient symmetry to reach high density and the desired final state remains a challenging problem, although isochoric ignition allows relaxed conditions on the quality of the implosion[2].

Once the magnetic pressure becomes comparable to the plasma pressure, the pinch effect can become important. If the field and plasma have not strongly intermixed, a narrow, rapidly collapsing neck forms as in "sausage" instabilities in a z-pinch. The plasma pressure and temperature climb in the neck region, driven by the increasing $B^2 \sim R_{neck}^{-2}$. This method of ignition has been suggested for fuel compressed by a high current z-pinch. 2D radiation magnetohydrodynamic simulations of the ignition process starting from the compressed state with cold fuel and magnetic field in pressure balance show isochoric (or density enhanced) ignition occurs as described. 1D calculations of the implosion show the expected amplification of the magnetic field to the required level, and 2D integrated calculations are in progress.

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