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Adiabatic Compression of a Closed-Field-Line Configuration by a Centimeter-Size Liner[+]

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ABSTRACT

The paper considers adiabatic compression of a pre-formed closed field line configuration by an imploding liner. Three configurations are discussed: the field-reversed configuration, the spheromak and the Z-pinch. It is shown that, by employing a 2D-compression, one can reach a break-even condition with an energy input as low as 100 kJ. It is emphasized that the possibility of performing crucial experiments on small-to-medium-scale experimental devices may considerably shorten the development path for the system under consideration.

I. INTRODUCTION

Imploding liners have been considered as a way for generating fusion-grade plasma since the '70s. However, in these early assessments, systems with large dimensions and, accordingly, large energy inputs (in the range of tens and even hundreds MJ) were considered. During the last decade, remarkable progress has been made in two areas of plasma technology and plasma physics relevant to this fusion concept: i) high convergence ratios have been obtained in implosions of centimeter-size liners [1]; ii) much better understanding of the properties of dense wall-confined plasmas has been reached (see, e.g., survey [2]). Based on these achievements, we reconsidered the fusion prospects of the liner concept.

We have in in mind 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 mode of implosion has advantages over purely radial implosion (in what follows, we call this r-z mode a 2D implosion; we call a purely radial mode a 1D implosion). We consider only closed field line configurations which would provide good plasma thermal insulation from the liner and the end walls; we try to find conditions under which the fusion alpha particles would also be confined. We concentrate on the situation in which the initial plasma (which is to be adiabatically compressed by the imploding liner) has a pressure comparable with or exceeding the initial magnetic pressure of the magnetic field inside the liner, so that essentially all the energy of the implosion is spent on the plasma heating and not on the increase of the energy of the magnetic field immersed into the plasma. What we find is that, with all these ingredients combined together, it is probably possible to achieve a plasma density ~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. The present paper is based on our recent report [3] which contains a more detailed analysis of various physics and engineering issues of liner implosions.

In the same range of input energies, another compact pinch system may work: this is a so-called staged Z-pinch (see recent paper [4] and references therein). A staged Z-pinch is supposed to use considerably lighter (e.g., gaseous) liners and to obtain much higher final densities (~10^{24} cm^{-3}). The physics involved may be considerably different but the required experimental hardware is very similar, so that two sets of liner experiments can be, in principle, carried out on the same device.

II. GENERAL DESCRIPTION OF THE CONCEPT

A possible geometry of the system is illustrated by Fig.1. This figure depicts a situation when the magnetic configuration is of the FRC type, with the field reversal maintained by plasma currents (not by an electron or ion beam). Other possible configurations will be discussed later.

We characterize the initial state of the FRC by its initial beta value,

$$\beta_0=8\pi p_0/B_0^2 \qquad (1)$$

Here and below, the subscript "0" denotes the initial values of the corresponding quantities. As we are going to restrict ourselves only to order-of-magnitude estimates, we don't precisely specify the point in which p_0 and B_0 entering (1) are taken: this is just some "characteristic" point inside the FRC.

As is well known, initially a magnetically confined FRC has β_0~1 as a "natural" state (see, e.g., survey [5]). For the system under consideration, with the confinement volume restricted on all sides by conducting material walls, an FRC configuration with β_0>1 is also possible. Therefore, we consider β_0 as a free parameter that is a subject to constraint

$$\beta_0 \geq 1 \qquad (2)$$

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After the initial configuration is prepared, an external voltage is applied between the electrodes 2 and 3 (Fig.1) with a pulse-length short compared to the liner skin-time. The axial current is then excited only in the liner and does not penetrate into the plasma volume. The current must be large enough that the pressure of the azimuthal (φ) component of the driven magnetic field considerably (at least by a factor of a few) exceeds the initial plasma pressure inside the liner. Then the liner gets accelerated in the inward direction and stores considerable kinetic energy. After the liner radius decreases several times with respect to its initial value, the plasma pressure inside the liner becomes larger than the magnetic pressure outside the liner, and the liner decelerates. At the point of maximum compression, it stops and then expands again under the action of the plasma pressure.

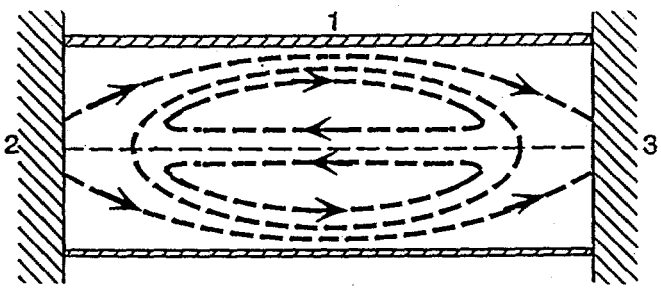

Fig.1. A schematic showing the geometry of the imploding-liner system.The liner (1) will implode to adiabatically compress the plasma and the closed magnetic-field configuration. Our reference case of an FRC is shown by the dashed lines. The structures (2) and (3) are the electrodes which drive the current that implodes the liner.

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.

Of most interest is the dynamics of the system near the point of the maximum compression where the fusion "flash" can occur. For the plasma parameters that are typical for our system, the maximum plasma pressure is such that the compressibility of the liner material becomes important. In order to eliminate the adverse effect of the liner compressibility (which reduces possible compression rates), we consider only thin liners, whose thickness even in the final state is less than the plasma radius in this state. In such a case, a first rough assessment of the liner dynamics can be carried out under the approximation that the liner is just an infinitely thin massive surface; the liner compressibility for a thin liner becomes, obviously, unimportant. This model of a structureless liner will be used throughout this paper. The liner will be characterized by its linear mass density μ (mass per unit length in the z-direction).

We introduce the *elongation* of the FRC as the ratio of its length L to its diameter 2a,

$$E=L/2a \qquad (3)$$

We consider a self-similar 2D compression which maintains a constant value of E. This means that the FRC should be compressed not only radially but also axially. A concrete way of achieving this mode of compression is to properly tailor the mass density of the liner along the axis [5]: if the central part is heavier than the ends, its compression lags behind, maintaining an approximate constancy of E of the plasma object nesting inside the liner. Exact constancy of E is not of principal importance. However, since current experiments with FRC's show the best performance for E=3-4, we believe that it would be reasonable to maintain E relatively close to 3-4. Another reason for choosing E=3-4 is that this value seems convenient from the viewpoint of the implosion physics: (not too large to make the kink instabilities of a great concern and not too small to make the electrode effects dominant).

Other possible candidates for configurations to be placed into the liner are the prolate spheromak and the Z-pinch configuration. In this latter case the azimuthal component of the magnetic field inside the liner does not necessarily serve for the plasma confinement (which can be provided by the material walls), and the Bennett relationship does not necessarily hold. In terms of the problem under consideration, the spheromak configuration does not differ much from the FRC. If the prolate spheromak can be MHD stable at $\beta>1$, it should be considered as a good candidate for the adiabatic compression experiment. An obvious difference of the Z-pinch configuration from the other two is that in the Z-pinch geometry the particle drift trajectories intersect the walls (more specifically, the end walls). Still, for low-Q systems this may not be too a severe problem. As for the drift losses of the alpha particles in the Z-pinch, they occur within such a short time that one can't count on any alpha-particle heating. This is of little concern for the low-Q systems but may become important at Q>5.

The obvious advantage of the Z-pinch for "filling" a liner is that this configuration can be easily created inside the liner, just by using a simple electrode discharge. The preparation of a miniature FRC or a spheromak will probably require some ingenuity. One possible approach could be the preparation of these objects outside the liner and translation of them into the liner through a hole in one of the electrodes. Then, the liner implosion should be organized in such a way that, on the hole side of the discharge, the liner would collapse on the axis relatively early in time, to prevent the ejection of the plasma back into the preparation chamber. The preparation of the FRC and spheromak inside the liner is also conceivable. In this case, the liner would have to have cuts in the axial direction, to allow the Z-component of the magnetic field to penetrate into the liner. In case of a spheromak, one can in principle count on the helicity injection technique.

It's quite clear that, under the action of the 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 into the plasma. In addition, it turns out that, 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.

III. PARAMETERS OF A CONCEIVABLE EXPERIMENT

Analysis presented in Ref.[3] has shown that even with quite pessimistic assumptions regarding plasma thermal conductivity to the liner walls, thermal losses do not constitute a factor that limits 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 under consideration as a pulsed source of X-rays).

Table 1 presents possible set of plasma parameters in the experiment where energy deposited to the plasma was 100 kJ, with total neglect of energy losses from the plasma.

Table 1.
Parameters of a Conceivable Experiment

Parameter	Initial state	Final state
Plasma temperature, keV	0.1	10
Magnetic field, T	10	10^3
Plasma beta	1	10
Plasma density, cm^{-3}	$1.25\cdot10^{18}$	$1.25\cdot10^{21}$
Plasma radius, cm	1	0.1
Plasma elongation, E	3	3
Plasma energy, kJ	1	100
Magnetiz. parameter $\omega_{Bi}\tau_i$	1	100
Parameter $s=a/\rho_i$	40	40
Collisionality a/λ_{ii}	40	0.4

For this set of parameters, the gyroradius of fusion alpha-particles in the final state is equal 0.03 cm and is smaller by a factor of 3 than a plasma radius. Therefore, if the drift trajectories of the alpha particles are closed inside the plasma volume (as in the FRC and Spheromak configurations), a considerable fraction of the alphas is confined and deposits its energy in the plasma. In the Z-pinch geometry, the alphas will drift away along the axis before depositing any substantial amount of their energy into the plasma.

In the Table 2 we present a possible set of the parameters of the liner and the value of the initial external current that are compatible with the plasma parameters listed in Table 1. We show the liner parameters in the equatorial plane. We choose the initial liner thickness in a such a way that the final liner thickness is equal to a half of plasma diameter in the final state.

Table 2
Parameters of the Compressing System

Initial liner radius, cm	1
Final liner radius, cm	0.1
Initial liner thickness, cm	0.01
Final liner thickness, cm	0.1
Current through the liner, MA	5
Initial magnetic field at the outer surface of the liner, T	100
Liner density, g/cm^3	20
Total compression time, μs	2
Liner dwell time (Eq. (39) near the point of maximum compression, μs	0.15

In our considerations we have assumed that the Z-current that drives the liner does not penetrate through the liner into the compressed plasma. This is certainly true if the liner thickness exceeds the skin-depth for the characteristic time of order of τ_{total}. For the typical set of parameters listed in Tables 1 and 2, τ_{total} exceeds the current penetration time by a factor of 2-3, so that some of the driving current would switch to the plasma. However, until very late in the compression phase the plasma conductivity is orders of magnitude smaller than the liner conductivity and the fraction of the driving current switched to the plasma remains small.

If necessary, one can completely eliminate any penetration of the driving current into the plasma by using a two-layer liner. The outer layer can be made of aluminum and have a thickness exceeding the skin-depth; the inner layer should be made of a heavy material. A possible example for the parametric domain covered by Tables 1 and 2 could be: 0.3 mm of Al (ρ=2.7 g/cm^3) and 0.1 mm of Au (ρ=18 g/cm^3). The outer shell is lighter than the inner one and will not considerably affect the implosion dynamics. It will prevent the driving current from penetrating into the heavy inner shell and into the plasma. The presence of this thick outer shell will also eliminate any problems of a premature thermal explosion of the inner part of the liner.

As it turns out (see[3]) the factor that limits plasma gain Q, is a relatively short liner dwell time near the turning point. The Q value determined by this process can be presented as:

$$Q=0.2(\beta_0^{1/3}\rho_L/E^{2/3}T_0)^{1/2}(W_{max}B_0)^{1/3} \qquad (4)$$

Here liner density is measured in g/cm^3, initial temperature T_0 in eV, plasma energy content in the final state in kJ and initial

magnetic field in T. We remind that β_0 is initial plasma beta and E is plasma elongation (3).

IV. REACTOR ISSUES

We can write the net power generated by an electricity-producing plant based on our liner-driven capsule scheme as:

$$P_{e,\,net} = r\,Q\,W\,(1-f_{aux})\,[0.8\,M\,\eta_{th} - 1/(Q\,\eta_i)] \qquad (5)$$

where r is the repetition rate, W is the input drive energy (i.e. Q·W is the fusion energy released per shot), M is the blanket energy multiplication, η_i is the efficiency of conversion from wall plug energy to input energy, η_{th} is the thermal cycle efficiency, and where f_{aux} is the fraction of gross electrical power required to supply the plant auxiliaries other than the energy input to the fusion core itself. Equation (5) assumes that no useful electrical power is generated from either the input power (rW) or the fusion alpha power (rQW/5).

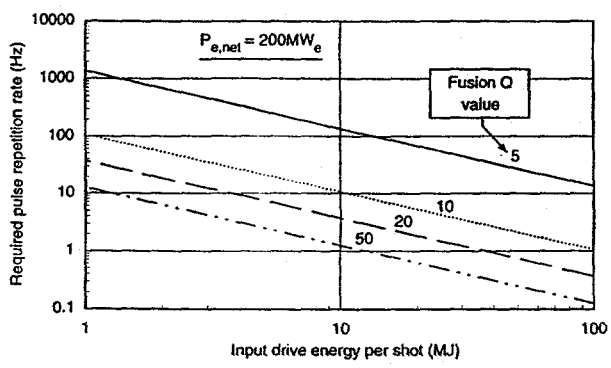

Fig 2 Energy parametrics for a 200MW$_e$ pulsed, liner-driven FRC reactor. The required pulse repetition frequency is plotted as a function of the input drive energy for various values of the fusion gain Q. Assumptions on plant performance are supplied in the text.

Taking typical values of, say, M~1.3, η_{th}~0.35, η_i~0.6 and f_{aux}~0.05, Fig 2 shows the required repetition rate r to sustain a 200MW$_{e,net}$ reactor as a function of the input energy W to the liner-driven capsule for various values of the fusion Q value. Note that no net electric power is possible for such a reactor for Q values less than about 5. Great benefits are seen by increasing the Q to the range of 20 to 30. In particular, for Q=20, an input energy of 12 MJ would require a pulse repetition rate of only ~3Hz, surely feasible for a repetitive mechanical target system such as this. Under such conditions, the energy loading on a liquid first wall would be~300MJ. This is very similar to that of an ICF reactor although there would be a greater momentum transfer from the liner mass relative to the hohlraum mass of an indirect-drive ICF capsule. Certainly, the 3Hz repetition rate is sufficiently low to allow for adequate chamber clearing between shots.Therefore, the further work on the proposed scheme should be concentrated on the ways of a considerable increase of Q.

Relationship (4) shows that the plasma enhancement factor Q depends relatively weakly on the parameters of the system. For example, in order to increase Q from 1.5 to 3, one would have to increase W_{max} to 0.8 MJ . Therefore, in its present form, the concept we are considering, would work as the basis of an energy producing facility only at the level of the input energies exceeding 10 MJ. Potentially, Q can be increased somewhat by lengthening the liner dwell time near the point of a maximum compression. One possible way of achieving this objective, is an ablation of some amount of the liner material near the maximum compression point and using the resulting reactive force to balance the plasma pressure near the turning point. The ablation could be produced by a pulsed laser. Simple estimates show that an increase of Q by a factor of 2 is possible in this way but more detailed assessment would be desirable. Another seemingly obvious way of increasing Q is just increasing the liner thickness but the evaluation of the potentialities of the thicker liners would require a more detailed study.

One discouraging feature of the 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. Therefore, the prospects for the near term realization of fusion, and perhaps the ultimate commercial reactor, would be improved, if it could be introduced through a compact, cheap system such as the wall-confined system of this paper.

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