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Magnetized Target Fusion With Centimeter-Size Liners

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Abstract. The author concentrates on the version of magnetized target fusion (MTF) that involves 3D implosions of a wall-confined plasma with the density in the compressed state ~ 10^{21}-10^{22} cm^{-3}. Possible plasma configurations suitable for this approach are identified. The main physics issues are outlined (equilibrium, stability, transport, plasma-liner interaction, etc). Specific parameters of the experiment reaching the plasma Q~1 are presented (Q is the ratio of the fusion yield to the energy delivered to the plasma). It is emphasized that there exists a synergy between the physics and technology of MTF and dense Z-pinches (DZP). Specific areas include the particle and heat transport in a high-beta plasma, plasma-liner interaction, liner stability, stand-off problem for the power source, reaching a rep-rate regime in the energy-producing reactor, etc. Possible use of existing pulsed-power facilities for addressing these issues is discussed.

INTRODUCTION

Magnetized target fusion (MTF) is a term designating a broad variety of approaches based on a unifying idea of adiabatic compression of a pre-formed magnetized plasma by a conducting liner. MTF systems span a broad range of plasma parameters intermediate between those typical for magnetic confinement and those typical for inertial confinement. A history of MTF research is briefly described, e.g., in Refs. [1]-[3].

The author concentrates on the version of MTF that involves three-dimensional (3D) implosions of a wall-confined plasma with the density in the compressed state ~ 10^{21}-10^{22} cm^{-3}, in the spirit of Ref. [1]. This version offers a relatively inexpensive path to obtaining fusion-grade plasmas and reaching the break-even condition by creating a plasma with the energy content in the final state of only 100 kJ [1]. An interestingdiscussion of the development path for MTF can be found in Ref. [3].

There is a broad variety of plasma configurations which can serve as targets for the liner implosion. Those include field-reversed configurations (FRC), spheromaks, diffuse pinches, and others [4]. The best results can be expected in 3D implosions [1], when the liner compresses the target both in the radial and in the axial direction: in this case the plasma pressure in the target grows faster than the magnetic pressure, and the *pdV* work performed by the liner is spent mostly on the plasma heating, not on the increase of the magnetic energy. These 3D implosion may allow reaching acceptable fusion gains for the modest energy depositions (in the range of 10-20 MJ).

Consider 3D implosion of a target with the initial beta ~ 1 (beta is the ratio of the plasma pressure to the magnetic pressure). The 10-fold linear compression (1000-

fold volumetric compression) would mean that the plasma beta in the imploded state is high, ~ 10 [1, 5]. This, in turn, means that one will have to deal with the so-called wall confinement, where the magnetic field embedded into the plasma will serve mostly to suppress the heat loss, while the mechanical equilibrium would be provided by the liner inertia, with the possibility that a thin layer of a high field is formed at the plasma-liner interface [6-8].

Under typical MTF conditions, the particle collision frequency is much higher than the frequency of the drift waves. In this respect, MTF systems differ dramatically from the conventional magnetic confinement systems, where the opposite relation holds by a huge margin. The consequence is that the anomalous heat transport will be determined by strongly collisional drift waves [9]. In a number of cases, the resulting heat loss will be substantially slower than that determined by the much-feared Bohm transport [9, 10]. In addition, because of a much higher density (and therefore, much shorter confinement time needed to reach a certain Q value), the limitations on the acceptable level of the anomalous transport are much more forgiving than in the canonical low-density magnetic confinement systems. Combined, these two factors make the cross-field transport in MTF systems less of an issue compared to, e.g., tokamaks.

One more difference is related to the possible role of alpha particles. As MTF systems favor relatively low plasma temperatures in the imploded state (compared to devices like ITER), the relative pressure of the slowing-down alpha-particles is much lower in the MTF case, thereby alleviating concern of possible additional drive for various types of instabilities [11]. A summary of recent studies of various features of the high-beta plasma confinement can be found in Ref. [10].

Possible parameters of the break-even experiment (Q=1) and a reactor-relevant system (Q=5) are presented in Table 1. By Q we mean the ratio of the fusion yield to the plasma energy content in the imploded state W_{final}). Initial plasma beta in both cases is assumed to be 1, and the final plasma temperature in both cases is 10 keV. The ratio of the plasma length to the plasma radius remains constant during the implosion.

TABLE 1. Key parameters of the break-even (Q=1) and energy producing (Q=10) experiments

	r_0, cm	r_{final}, cm	B_0, T	n_0 cm^{-3}	T_0 keV	W_{final}, MJ
Q=1	1	0.1	10	1.25×10^{18}	0.1	0.1
Q=5	4	0.4	15	2.7×10^{18}	0.1	10

The issue of the gross MHD stability of the wall-confined plasmas had not been looked at in much detail and needs further experimental studies. It would be very important for the whole MTF approach to get experimental information on the stability of high-beta (β=1-10), collisional plasmas. In this regard, it is hard to overestimate the significance of the FRX-L experiment at Los Alamos [12, 13], where a plasma with the density n~3×10^{16} cm^{-3}, and the total temperature T_e+T_i ~ 400 eV has recently been obtained and found sufficiently stable. [A summary of the results obtained in other experiments with FRC s and spheromaks can be found in Ref. [14].]

The FRX-L plasma may serve as a target for the planned liner-on-plasma experiment on the Shiva-Star facility, where successful experiments of liner implosions (without the plasma target inside) have been carried out a few years ago [15, 16], with the radial convergence >10. Compressing the target plasma generated in the FRX-L experiment would produce a plasma with the density approaching 10^{19} cm^{-3} and the total temperature of a few keV.

An interesting MTF-related experiment has been proposed at University of Nevada (Reno) [17, 18], where a high-beta plasma would be produced in the inverse-pinch geometry.

After this introduction, we consider in some detail two issues related to the development of the MTF reactor: the optimization of the liner performance and the stand-off power-supply.

OPTIMIZING THE LINER PARAMETERS

The plasma pressure in the imploded state is in the range of 30 — 100 Mbar [1] and, therefore, the compressibiltity of the liner material becomes important. However, if the liner is thin, so that its thickness in the final state is less than the plasma radius, then its dynamics can be described just as a dynamics of a zero-thickness shell of a certain mass. The main energy deposition occurs at the very end of the implosion process, where the plasma volume changes from, roughly $3V_{final}$ to V_{final}. For the ideal gas (γ=5/3), the energy increases from $W_{fimal}/3^{2/3}$ to W_{final}, i.e., the energy increases by more than a factor of 2. The fusion reactions begin at the plasma volume roughly equal to $2V_{final}$ (because of a strong dependence of the reaction rate on the temperature). In other words, the energy is produced when the liner radius changes from $2^{1/3}r_{final}=1.26r_{final}$ to $r_{final,}$ and then bounces back to $1.26r_{final}$. The time τ that the plasma spends is the imploded state (the dwell time) is, obviously, determined by the liner inertia. So, for a given W_{final} (i.e., for a given liner energy), one might want to use as heavy liner as possible, to make the dwell time τ_{fus} as long as possible. However, this approach has a natural limitation: if the liner is too slow, the radiative losses at the compression stage would never allow the plasma to reach a fusion temperature of 10 keV. In other words, if the compression time (which is equal to $\tau/2$) becomes longer than the radiative loss time τ_{rad}, the fusion yield becomes very small. Conversely, for too light (and, therefore, fast) liner, the yield becomes short just because of the shortness of the dwell time. This is illustrated by Fig. 1

The cooling time τ_{rad}, for a 10-keV plasma can be evaluated as $\tau_{rad}(s)=2.8\times10^{15}/n(cm^{-3})$. On the other hand, the plasma Q for a 10-keV plasma can be evaluated as $Q=10^{-14}n(cm^{-3})\tau(s)$. For the optimum value of τ/τ_{rad}=0.3, Q is equal to about 9. This is a maximum possible value that can be achieved under any circumstances in the case of a thin liner. This estimate seems to agree with the conclusion made in Ref. [19], where a broad parameter study of the MTF implosions was carried out. The Q value (defined in that paper as the ratio of the fusion yield and the energy initially stored in the condenser bank) did never exceed 2.8. The authors have, however, considered compressed states with very high temperatures approaching 80 keV. This seems to be too high to be an optimum.

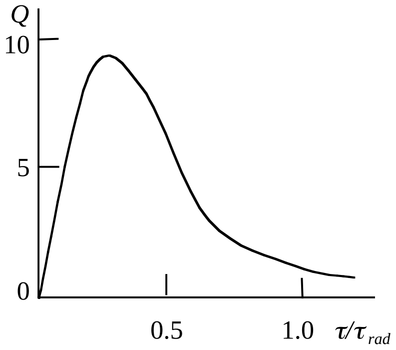


Figure 1 The dependence of Q on the dwell time

In order to improve the Q value, it might be worthwhile to consider more sophisticated scenarios of the liner implosion, where some mass would be added to the liner after it reaches the stagnation point, so that the $r(t)$ dependence would become asymmetric with respect to the turning point, and the liner would spend a longer time near the point r_{final} at the expansion stage. Adding the mass is, hovewer, a non-trivial task.

Another improvement can come from a more thorough analysis of the liner compressibility which may play a positive role in the context of this particular problem.

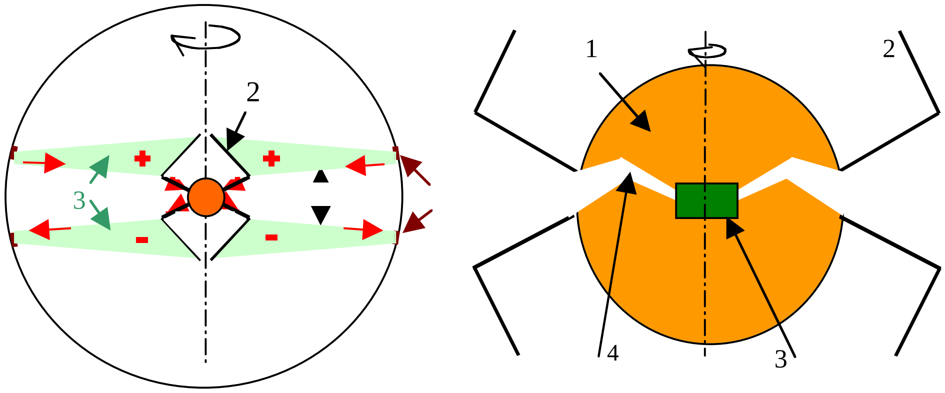
Now we switch to a discussion of the way by which one can accomplish a #D liner implosions. One of the possible techniques [1] would be to use a liner, whose initial shape is cylindrical, but its thickness varies along its axis. In this case, the thinner parts would implode faster than the thicker ones, and one can, therefore, obtain the desired shape of the liner. An alternative would be to use quasi-spherical liners sliding along the conical electrodes, as was done in Ref. [20] for heavy liners and as was discussed in Ref. [21] for fast light liners.

STAND-OFF ENERGY SOURCES

To be of relevance for commercial fusion power production, the fusion energy release per pulse should be in the range of 100 — 300 MJ, or even more. This means that the general scheme of the reactor chamber should be roughly the same as in other pulsed fusion systems. As a prototype, one could mention the Osiris and SOMBRERO designs [22] of reaction chambers for inertial fusion energy. What is different, however, in our case is that we have to supply a high current to the target, to drive the liner. One possibility would be to use long disposable transmission line that would be inserted into the chamber before every shot [23]. As the replacement process takes a few seconds, the need to produce sufficient average power drives the energy per shot to high values of order of a few GJ, this, in turn, leading to large dimensions of the reaction chamber.

A concept of a plasma liner relies on the process of merging of many highly-supersonic jets injected from the walls; the fast liner formed in this way would compress the target [24-26]. Instead of very fast jets, one can use a relatively slow spherical liner driven by thermal plasma with a few eV temperature [27].

Some proposed techniques are are based on the concept of a disposable assembly [1] that would be dropped to the chamber and which, in addition to the liner, would contain the necessary circuitry for creating the plasma target and for conditioning the pulsed power that will be supplied from outside. In particular, the power could be supplied by a relativistic electron beam that would drive the inverse diode installed in the assembly [1]. Another method of power supply could be based on the use of magneto-compressive generator installed in the assembly and driven by a fast projectile. Both approaches are compatible with the idea of a solid spherical blanket made of Li or LiH [28] whose radius will be in the range of 0.5 m. The neutrons released in the center of the sphere will heat and evaporate it. This will be assisted by a strong blast wave driven by the energy of fusion alpha-particles, whose absorption length in the blanket is infinitesimal compared to all other dimensions and which, therefore, would deposit all the energy near the center [29].



(a) (b)

Figure 2. (a) A spherical reaction chamber with the assembly placed in the center. Plasma jets injected by an azimuthally distributed array 1 of plasma guns forms two disc electrodes 3. Terminals for these electrodes are axisymmetric collars 2 made of thin aluminum. (b) A blow-up of the assembly: 1 — a 50-cm radius sphere made of Li or LiH [], 2 — aluminum collars serving as terminals for plasma jets; 3 — The housing for the MTF target; 4 — vacuum transmission line.

Fig. 2 shows how this technique can be combined with the use of disc plasma electrodes created in each shot, after the target surrounded by the blanket is dropped into the chamber. Preliminary analysis [30] shows that the plasma electrodes can allow transferring 20-30 MA to the target, with a characteristic time-scale of a few microseconds. Inductive effects are modest, and resistive losses are small.

DISCUSSION

There is a lot of synergy between the studies of fusion systems based on fast Z-pinches [31] and MTF. Those include the rep-rate primary energy source, capable of supplying tens of MJ of energy per pulse, the need to transport this energy into reaction chamber in such a way that the primary source would not be damaged by the fusion energy release, and the need to create a blanket compatible with pulsed-power source. As we have shown, in recent years possible solutions of some of these problems have been identified, at least at the conceptual level.

Obvious similarities exist also in the area of the physics issues, especially in the area of the liner stability. One can therefore expect that mutually-profitable collaboration between two groups will continue. Of special importance would be the coordinated use of the University-scale facilities.

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