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SOLVING THE STAND-OFF PROBLEM FOR MAGNETIZED TARGET FUSION: PLASMA STREAMS AS DISPOSABLE ELECTRODES, PLUS A LOCAL SPHERICAL BLANKET

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Solving the stand-off problem for Magnetized Target Fusion: plasma streams as disposable electrodes, plus a local spherical blanket

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Abstract

In a fusion reactor based on the Magnetized Target Fusion approach, the permanent power supply has to deliver currents up to a few mega-amperes to the target dropped into the reaction chamber. All the structures situated around the target will be destroyed after every pulse and have to be replaced at a frequency of 1 to 10 Hz. In this paper, an approach based on the use of spherical blanket surrounding the target, and pulsed plasma electrodes connecting the target to the power supply, is discussed. A brief physic analysis of the processes associated with creation of plasma electrodes is discussed.

Key words: Magnetized Target Fusion; plasma liner; spherical blanket; plasma electrodes

1. Introduction

A challenging problem of magnetized target fusion (MTF) [1, 2] (as well as Z-pinch fusion, e.g. [3]) is delivering the energy of the order of tens of megajoules to the target situated at a distance of 3-6 m from the walls of the reaction chamber. In the past, several ways of solving this problem have been considered, including the insertion of disposable transmission lines [4], using fast projectiles to drive the magneto-compressor generator [1], injecting particle beams in combination with the inverse diode [1], etc. In this paper we consider an approach prompted by the concept of a plasma liner, combined with a concept of a spherical local blanket.

The concept of a plasma liner was suggested by Thio et al. [5]; various modifications to this concept were studied in Refs. [6, 7]. The idea of using a local spherical blanket in pulsed fusion systems was suggested by Velikhov [8] and then revisited by several authors. The most detailed and insightful analysis of this concept was carried out by B. Grant Logan [9].

In Refs. [8, 9], it was suggested that the blanket would be fully evaporated and partially ionized, so as to make the blanket material suitable for the use in a high-efficientcy pulsed MHD converters. This gave rise to a requirement of a high energy yield per pulse, in excess of 1 GJ. Such a yield is difficult to achieve in a batch-burn MTF targets [1], where a more probable yield would lie in the range of 300 MJ. So, we consider a somewhat down-graded version of the concept [8,9]: in our case, the blanket would be just evaporated, and its thermal energy would be extracted either by the use of the evaporated material to drive the gas turbines, or by heat exchangers.

For the batch-burn MTF targets, a reasonable choice of the driving pulse parameters are [1]:

$$I\text{=5 MA}, \; U\text{= 1 MV}, \; \tau\text{=10 μs}, \qquad (1)$$

where I, U, and τ are the current, the voltage, and the pulse duration. We will use this set of parameters as a reference point in the further discussion. The energy yield of 300 MJ sets the scale for the size of the reaction chamber. In a detailed design of a dry-wall chamber for inertial confinement fusion ("Sombrero," Ref. [10]) it was concluded that a 3,5 m radius chamber would accommodate the yield of ~ 400 MJ. Therefore, the yield of 300 MJ could be accommodated in a chamber of the radius

$$r_0=3 \text{ m} \tag{2}$$

This number will also be used as a reference point in the further analysis.

The paper is organized as follows: In Sec. 2, we describe a concept of a local spherical blanket for the case where the fusion energy is produced in an MTF plasma. In Sec. 3, we consider possible parameters of pulsed electrodes. Sec. 4 contains a brief discussion of the results obtained.

2. Local spherical blanket

The concept is illustrated by Fig. 1. We consider a sphere made of lithium hydride (LiH), of a radius a=25-30 cm. As described in Ref. [9], the neutronics of LiH is such that this thickness would be sufficient to breed tritium with a breeding ratio somewhat exceeding unity. For the expected energy release of 300 MJ, the sphere would be evaporated or almost completely evaporated, thereby eliminating the shrapnel problem. The mass of the blanket is ~50-100 kG.

The MTF system will be installed inside the LiH sphere and then the whole assembly would be dropped into reaction chamber. The MTF system has to include magnetic coils, the initial plasma source, electrical circuitry, switches, etc. It would be placed in a vacuum-tight volume; only current leads would connect it to the external world. In Fig. 1, the MTF system is shown just as a "black box," with the position of the current terminals indicated by thick lines at the side surfaces of the black box.

The material of the assemblies that will be dropped into the reaction chamber every 0.3-0.5 s, would be continuously reprocessed and sent to the target manufacturing system, very much as this is envisaged for any pulsed fusion system. The cost of every assembly (including the reprocessing cost) should not exceed ~ $1 (for the energy yield of ~ 300 MJ). All this looks somewhat as a science fiction but the problem of a target cost is common among all the pulsed fusion concepts, like laser-driven fusion, Z-pinch fusion, and others. The hope is that the problem of cost will be solved by applying the mass-production methodology.

Each assembly will include a "jabot" made of a thin metal and having the shape shown in Fig. 1 (note that this figure provides a cross-sectional view of an axisymmetric system). The role of this jabot is to provide a more surface area for the contact with plasma streams, as described in the next section. The jabot can be made of lithium; to make lithium more easily machineable, one might think of manufacturing this jabot (as well as a whole assembly) at lower temperatures, minus 30 – 40 C. The thickness of the metal sheets can be quite small, ~ 1 mm, given that this whole system will be subject for a pulsed load for only 10 μs, during which no substantial displacement of the jabot would occur. Resistive losses in lithium in our setting are negligible (the magnetic diffusivity at a room temperature is 680 cm^2/s, yielding the skin-depth for a 10 μs pulse of ~ 1 mm; the Joule heating of the jabot will lead to the temperature increase of a mere 10 – 20 C).

The assemblies, with the jabots attached, will be dropped from a 10-20 m tall tower where a gas pressure will be in the range of a few torr. The tower will be separated from the reaction chamber by a massive (rotating?) shutter that will be closed after the assembly enters the chamber but before it reaches its center. After each shot, the chamber would have to be pumped down to a pressure of ~ 0.1 torr, to create conditions suitable for the use of the plasma jets. If doing that within 0.3 s turns to be difficult, one might consider the use of multiple reaction chambers driven by the same power-supply system and shared target factory.

Plasma Electrodes

We assume that the target embedded into the spherical blanket made as described in the previous section is dropped into reaction chamber. When it reaches a desired point (roughly, a center of the chamber), disc plasma electrodes are created, connecting the current-collecting jabot, with the terminals situated in the walls of the reaction chamber. The plasma electrodes are created in a two-step process: first, supersonic gaseous jets will be injected, creating gaseous links between the terminals and the jabot; second, the breakdown over the inner surfaces of the jets will be triggered, creating a current path needed for our purpose. The inner surfaces are preferential from the viewpoint of lowering the inductance. This second (breakdown) step can be accomplished either with the external sources, including lasers, or just during the first instants of the main pulse, where the current would seek the lowest-inductance path and the breakdown would occur.

The example parameters of the conducting layer could be: density $n\sim 10^{17}$ cm $^{-3}$, temperature $T\sim$ 10 eV, and thickness $\Delta h\sim$ 3 cm:

$$n\sim 10^{17} \text{ cm}^{-3},\ T\sim 10 \text{ eV},\ \Delta h\sim 3 \text{ cm} \qquad (2)$$

This layer would be backed up by a several times thicker and denser layer of the neutral gas. As we will see shortly, the skin-depth during the current pulse does not exceed 3 cm, so that the heating and ionization caused by the current flow would be limited to this relatively narrow layer.

The magnetic diffusivity for a fully ionized plasma can be evaluated as [11] D_M(cm^2/s)=410^6/[T(eV)]$^{3/2}$. For $T\sim$ 10 eV, it is ~ 10^5 cm^2/s. In other words, the skin-layer during the pulse, $(2D_M\tau)^{1/2}$, will be ~ 1.5 cm thick and indeed less than Δh.

The energy required to generate the plasma with the aforementioned parameters is $W_i=\pi(E_i+3T)n\Delta h(r_0^2-r_1^2)$, where E_i is the energy required to create one electron-ion pair r_0 is the chamber radius, and r_1 is the radius of the current-collecting jabot. Assuming that E_i=30 eV, r_0=300 cm, and r_1=100 cm, and taking the other parameters from Eq. (2), we find that W_i=1.4 MJ, a mere 3% of the energy that has to be delivered to the target. Radiative losses are negligible (Cf. Ref. [6]).

The inductance of the plasma electrode system will be L(H)=6.410^{-10} D(cm)ln(r_0/r_1) where D is the distance between the two disc electrodes. For D=20 cm, it is equal to 15 nH and is comparable with the expected initial inductance of a typical MTF load [1]. As the load inductance will significantly increase during the implosion process, this value of the external inductance seems to be acceptable.

Of some concern may be the current leak between the plasma electrodes. However, the magnetic insulation will suppress the electron leak. Indeed, the magnetic field inside the gap is weakest near the chamber walls and grows as 1/r towards the axis. At the nominal current (1), and r_0=300 cm, the magnetic field at the wall is 3 kG. The electron gyro-radius corresponding to the energy of 1 MV in such a field is a mere centimeter, well below the inter-electrode spacing D. The ion leak will be limited by the space-charge and, for D=20 cm and U= 1 MV, will be, according to the Child-Langmuir law, only 0.3 A/cm^2. In addition, the deuteron current will be somewhat suppressed by the magnetic field. Therefore, the ion current leak over the whole surface of the plasma electrodes will not exceed 0.2 MA.

The plasma electrodes will be pushed away from each other by the magnetic pressure. This would create an undesirable effect of the increasing the inter-electrode gap D and, therefore, the inductance of the system. The magnetic pressure is maximum at the smallest radius, $r=r_1\sim 100$ cm. For the nominal current (1), the magnetic field here is $B\sim 10^4$ G. The conducting plasma layers alone would be swept by the magnetic pressure within the time shorter than the duration of the pulse τ=10 μs. This is why it is important that the conducting layers "lean" on a denser gas, which would immediately be involved in the acceleration process because of a very high charge-exchange cross section. Therefore, the expansion velocity should be evaluated for the number density n_0 of the neutral gas. Assuming that the thickness of the neutral gas involved in the motion is comparable to the thickness Δh of the ionized layer, one obtains that the mass m of the accelerated material (per unit surface area) will be $\mu=m_d n_0 \Delta h$. The Newton equation then shows, that, during the duration of the pulse τ, the gap will increase by the distance $\Delta D=\tau^2(B^2/8\pi)/\mu$. Assuming that the density of the underlying gas layers is 310^{18} cm^{-3}, and taking $B=10^4$ G, we obtain that ΔD=15 cm. This seems to be satisfactory, as such a displacement would occur only in the inner-most zone of the disk electrodes and will rapidly decrease at the larger radii.

The relative velocity u of the electrons and ions in a current-carrying plasma is proportional to the current density j, $u=j/en$, and is maximum near the surface of the jabot. At this point, $j=I/2\pi r_1\Delta h\sim 310^3$ A/cm^2, so that $u\sim 610^4$ cm/s. This velocity is substantially less than the ion thermal velocity $v_{Ti}=(2T/m_d)^{1/2}\sim 310^6$ cm/s meaning that there will be no current-driven instabilities. It means also that the sheath resistance at the interface between the jabot and plasma streams will be negligible (see [12]).

To provide a well-shaped gaseous jets that would not expand too strongly in a vertical direction at a distance of 2-3 m, one would have to have their angular divergence of less than $\Delta\theta\sim 1/30$ rad. This, in turn, means that the gaseous jets would have to have quite high Mach number ~ 30. The possibility of generating jets with M as high as 14 has been demonstrated in Ref. [13]; in these experiments, the density profile across the jet had very sharp edges. But this was done with relatively small-scale jets. Getting to $M\sim 30$ is a difficult task. What may help in forming weakly diverging gaseous jets, is the formation of clusters [14], which will then be propagating as individual particles. So, one can prevent the expansion of the jets in the inward direction (to the equatorial plane of the chamber) by putting limiters near the chamber walls, in the zone where the condensation would already occur.

The reactor chamber will serve as a grounded electrode. One set of plasma jets (say, the lower one in Fig. 2), would be at the potential of the wall. The other set would have to be at the positive potential (to alleviate the problem of electron leaks from the plasma to a surrounding metal parts at the stage of the jet formation). The geometry of the jets should be such as to eliminate irradiation of the insulators by the intense light emerging from the reaction chamber. Another issue would be to protect the insulators from the effect of the LiH vapor.

Potentially, one might think of replacing the plasma electrodes by liquid lithium electrodes made of an array of a large number of lithium jets. This would however require a significant increase of the lithium throughput and may adversely interfere with the use of the vaporized assembly to drive gas turbines (the potential problem is associated with the presence of a large number of droplets formed of the jet material).

Discussion

Attractive features of the approach proposed in this paper include a drastic reduction of lithium throughput compared to the liquid-lithium "waterfall" approach, and the potential possibility of using the evaporated material of a spherical blanket to drive gas turbines. The chamber walls will be well protected by the local blanket from fusion neutrons and the blasts of x-ray radiation.

Main difficulties specifically related to the use of plasma electrodes are caused by the need to generate highly-collimated gaseous jets and ionize their inner surface layers (i.e., layers facing the equatorial plane), to create a highly-conducting plasma. Although possible in principle (as demonstrated in this paper), such technique may be not so easy to implement in a real life. On the other hand, this approach seems to be very amenable to the tests at smaller-scale experiments, where individual gaseous jets would be generated and characterized and various ionization techniques would be tried.

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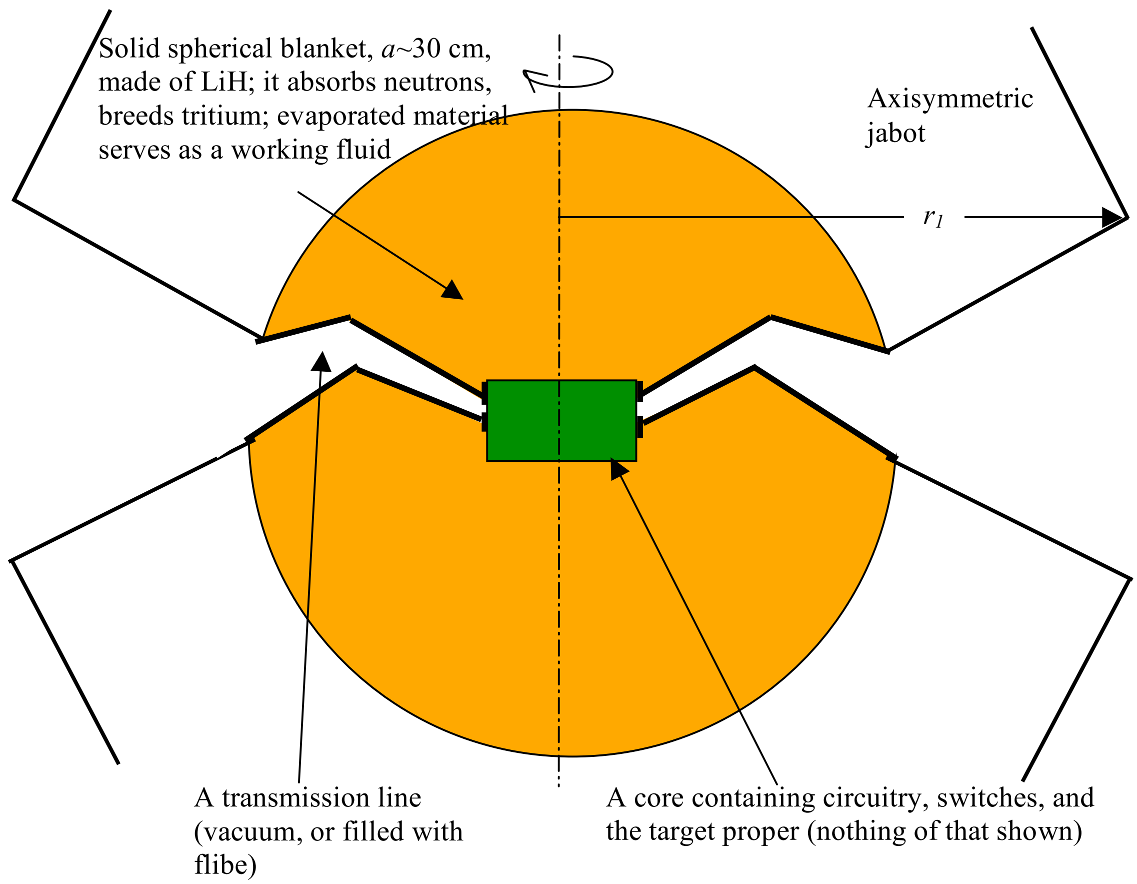
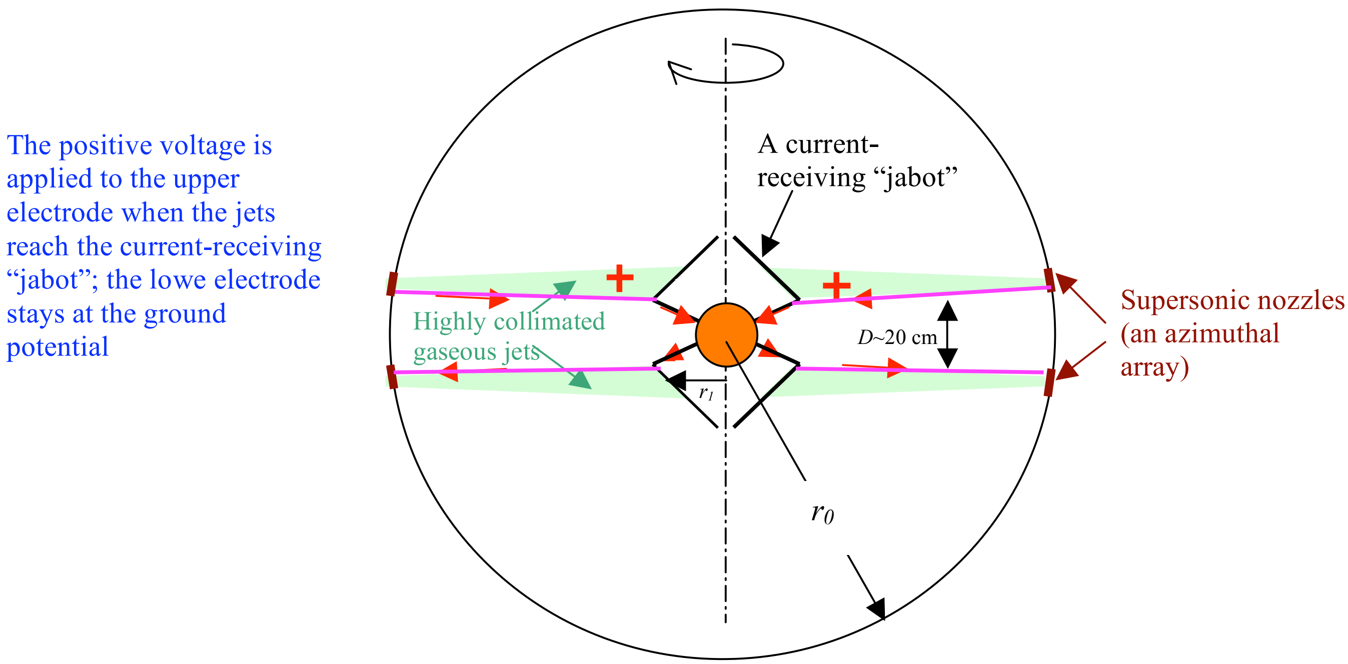


Fig. 1 Cross-section of an MTF target surrounded by a spherical LiH blanket. The structuee of the target is not shown. The inner surface of a transmission line inside the LiH sphere is coated by a conducting material (e.g., metal Li). The shape of the jabot (made of conical surfaces) is explained in Fig. 2.



The target, with the jabot attached, is dropped to a 3-m radius reaction chamber. The jabot is made of thin (~1mm thick) lithium sheets, it collects the current flowing along the disc-shaped plasma electrodes and directs it to the target.

Fig. 2 Schematic of the target dropped into reaction chamber. The scales are distorted for a better visibility. The shape of the jabot is determined by the requirement that the gas and plasma are deflected away from the equatorial plane. The blow-up of the blanket and the target are shown in Fig. 1. Magenta lines show the highly conducting plasma layers formed as a result of a surface breakdown of the gas