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Variations on the theme of a plasma liner*

D.D. Ryutov

Lawrence Livermore National Laboratory, Livermore, CA 94551

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ABSTRACT

One of the challenging problems of Magnetized Target Fusion (e.g., [1]) is development of the ways of transporting energy to the target situated at a large-enough distance from the energy source: the distance should be such as to prevent a damage to the permanent parts of the source. Several schemes have been considered in the past, including the use of particle beams coupled with the inverse diode [1], mechanical projectiles in combination with magneto-compressional generators [1], and the plasma liner [2].

The advantage of the plasma liner over the other concepts is that it directly drives the compression of a magnetized target, with no need to initially convert the liner energy to the energy of the magnetic field. A difficulty is related to the need of concentrating the energy of the plasma flow (that originated at a distance of more than a meter from the target) on the target with a size of a few millimeters (in its final state).

We discuss two possible approaches to solving this problem for the plasma liner concept. The first approach consists in creating a thin, higher density shell made of a dense gas and dust particles and compressing it onto an MTF target by a plasma liner. In this way, the plasma liner energy would be transferred to a thin cold shell which would then converge on the target. We discuss the constraints on the parameters of the gas-dust mixture and evaluate convergence ratio that can be expected in this scheme. The second approach is based on injecting two dense gaseous jets whose outer parts would be ionized and serve as conductors for delivering a large current to the target, to drive the "canonical" scheme of the imploding metal liner. [In this regard, this second scheme can be considered as a "hybrid" of a metal liner concept and a plasma liner concept.] The constraints on the dimensions of the jets and radial density distribution are formulated.

[1] R. P. Drake, J.H. Hammer, C.W. Hartman, L.J. Perkins, D.D. Ryutov. "Submegajoule liner implosion of a closed field line configuration." Fusion Technology, **30**, 310 (1996)

[2] Y.C.F. Thio, C.E. Knapp, R.C. Kirkpatrick, R.E. Siemon, P.J. Turchi. "A Physics Exploratory Experiment on Plasma Liner Formation." J. Fusion Energy, **20**, 1 (2001).

OUTLINE:

- A concept of a heavy gaseous liner

    - General description

    - Characteristic parameters

    - Issues

- A concept of plasma jets as electrodes for MTF

    - General description

    - Characteristic parameters

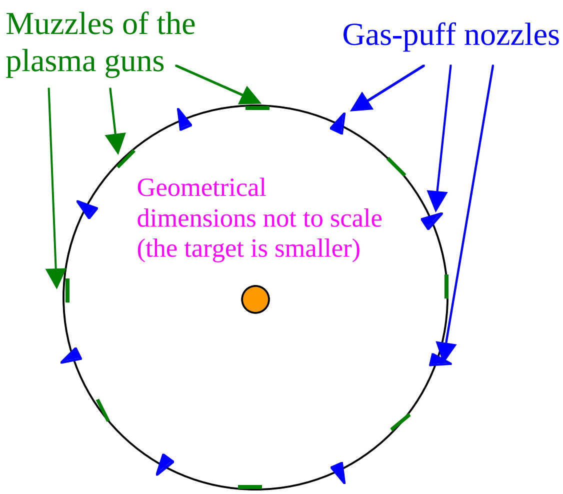
    - Issues

- Summary

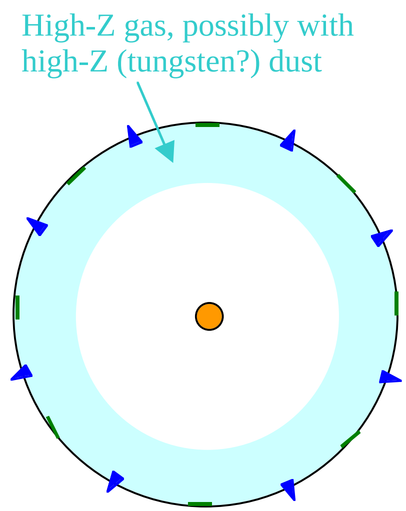
This work is merely a description of a conceptual framework, with only a very cursory (and rough) analysis of the particular issues

Discussions with F. Thio and P. Parks are gratefully acknowledged

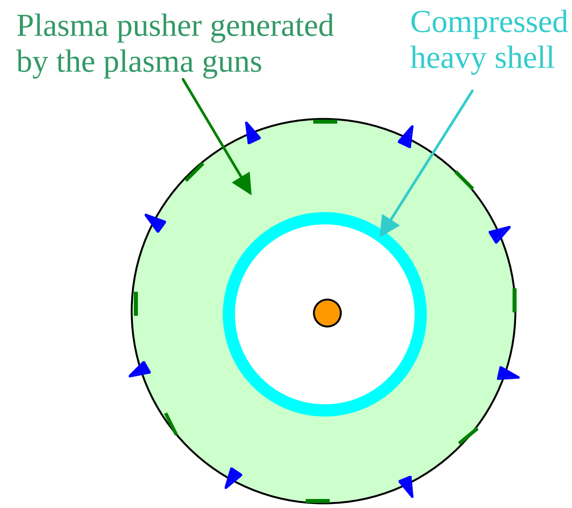
A concept of a heavy intermediate liner driven by the plasma liner



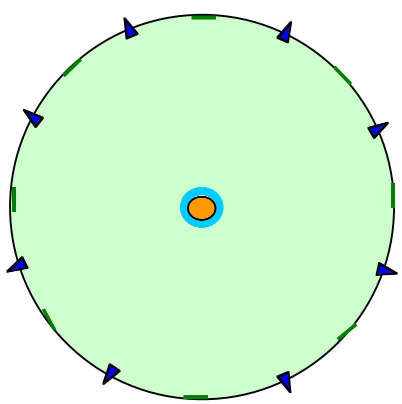
Stage 1: Empty chamber with a target in place



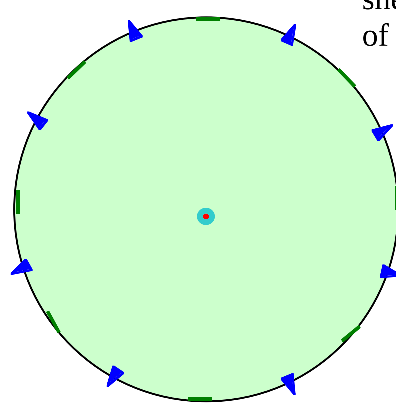
Stage 2: Heavy gas (possibly, dusty) puffed in, to create a shell



Stage 3: Plasma guns turn on and create a plasma pusher; heavy shell thins down under the action of acceleration and radiative losses



Stage 4: Heavy liner reaches the target at v~10 km/s and starts to compress it



Stage 5: Maximum compression is reached at stagnation

Caveats:

We do not consider the structure of the target (which will be of the type described by Drake et al)

Issues of the damage to the guns and gas injector by neutron irradiation and target debris are not considered (hopefully, they will not be too severe because one can imagine a design in which there will be no direct line-of-sight exposure of the “sensitive” parts, like dielectrics)

We do not discuss issues of the compatibility of this approach with a thick-liquid-wall concept

Characteristic parameters of the driver for the system with Q~10 (of the type described in Drake et al, Fusion Technology, **30**, 310 (1996))

Plasma chamber radius R~3 m

Fusion yield ~ 100 MJ

Heavy liner energy W~10 MJ

Heavy liner velocity v_{HL}~15 km/s

Heavy liner mass M_{HL}~100 G

Plasma liner density $n_L \sim 10^{17}$ cm^{-3}

Plasma liner temperature T_L~10 eV

Plasma liner mass M_L~ 15 G

Velocity: subsonic

Radiative losses from the heavy liner: substantial

Initial target radius a_0~4 cm

Issues: 1) Heavy liner thickness; 2) Heavy liner stability

1) Heavy liner thickness

The heavy liner thickness *h* (at least at the time of a maximum target compression) must not exceed the target final radius a_f~4 mm, as otherwise the hydrodynamic efficiency becomes too low.

The thickness *h* is set by the "gravitation equilibrium",

$$T_{HL}\frac{dn_{HL}}{dr} = -\mu g n_{HL} \qquad (1)$$

where T_{HL} is a temperature of the heavy liner, μ is its average molecular weight and g is the acceleration (the sign chosen corresponds to the liner decelerating in the course of the target compression).

1) Heavy liner thickness (cont)

From Eq. (1), the liner thickness can be evaluated as a scale-height:

$$h \sim \frac{T_{HL}}{\mu g} \qquad (2)$$

This expression shows that it is beneficial to use the liner made of high-Z material: it radiates very strongly and holds the temperature at a low level; the other benefit is that μ is large.

Esitmate g: $g \sim v^2_{HL}/2a_f$. For the example above it is ~2.5×10^{12} cm^2/s. Assuming the heavy liner temperature ~ 20 eV, and $\mu \sim 50 m_{proton}$ (gold, ionized to Z=3) one finds: $h \sim$ 1mm.

For the acceleration phase one has: $g \sim v^2_{HL}/2R \sim 3\times10^9$ cm^2/s. Assuming that at this phase $T_{HL} \sim 1$ eV, and $\mu \sim 100 m_{proton}$, one finds $h \sim 3$ cm.

2) Liner stability

- At the stage of heavy liner acceleration, the RT stability will be provided by a feedback approach: Deviation of the heavy liner shape from the spherical shape, would be detected by several optical and/or UV imagers surrounding the chamber; the correcting signals will be sent back to the power supplies of the plasma guns.

Note that the heavy liner moves with a velocity which is much less than the sound velocity of the hydrogen plasma in a plasma liner (the "pusher"). Therefore, a changed inflow from a certain gun will cause change of the pusher pressure in the desired area.

- The presence of the dust (say, gold flakes) at the early stage (before the dust evaporates and mixes up with the gas) would help to stabilize the short-wave perturbations because of the friction between the gas and the dust particles).

- At the later stage of the heavy liner motion, it reaches a coasting regime, where the RT instability is absent.

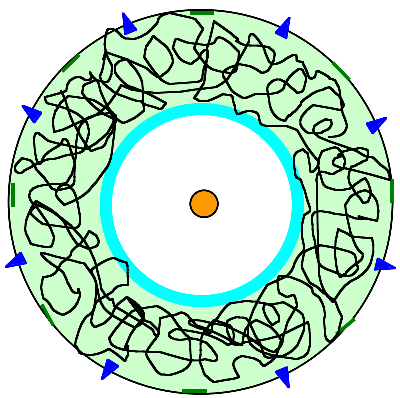
- At the stage where the liner reaches the target and starts to decelerate, the stability issues are the same as for all other schemes; the hope is that the initial perturbations will be small enough; the other possibility is that stability may be favorably affected by the presence of the magnetized target.

Heat losses from the plasma pusher are acceptable.

Radiative loss time τ_{rad} evaluated as

$$\tau_{rad} = \frac{3n_e T}{Q_{rad}} \qquad (3)$$

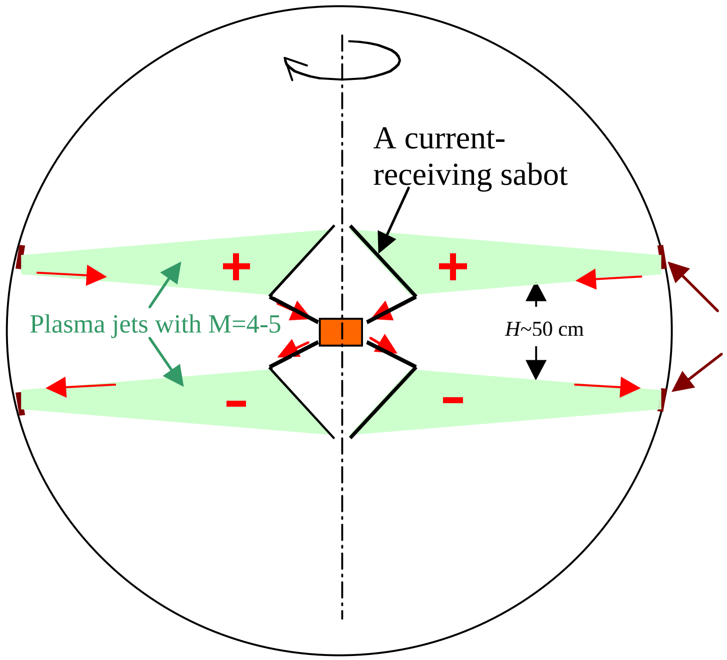
is long enough, ~ 200 μs. In addition, the plasma reabsorbs a significan fraction of the radiative losses. Obtaining hard numbers for τ_{rad} would require some effort.



Electron thermal conduction both to the walls and to the heavy liner is also slow, given that the plasma pusher will be “filled” with tangled magnetic field. Making a modest assumption that the characteristic field-line length is 3R, one finds that the thermal conduction time is ~ 5 ms.

A concept of plasma electrodes for connecting the target assembly and the permanent power supply

The voltage between the upper and the lower jet arrays is applied when the jets reach the current-receiving sabot



Plasma gun muzzles (an azimuthal array)

The target, with the sabot attached, is dropped to a 3-m radius reaction chamber. The sabot is made of thin (~0.5 mm thick) aluminum sheets, it collects the current flowing along the disc-shaped plasma electrodes and directs it to the target.

Characteristic parameters of the system:

Distance between the jets H~50 cm

Jet thickness at the intersection with the sabot ~H~50 cm

Jet electron density ~ 10^{17} cm^{-3}

Jet material: a mixture of hydrogen and carbon

Jet temperature T ~ 10 eV

Jet velocity v~(2-3)×10^6 cm/s

Current transmitted to the target I~5 MA

Duration of the current pulse t~ 5 μs.

The magnetic field at the intersection with the sabot: B~2T

Jet vertical displacement during the current pulse ΔH~10 cm

The magnetic energy stored in the gap: 2.5 MJ

Applied voltage 0.4 MV

Other features of the system

Electric insulation between the jets is provided by the presence of a magnetic field ("magnetic insulation")

Ohmic losses in the jets are insignificant

The current velocity in the jets is low, well below the ion sound velocity

CONCLUSION

- We suggested two modifications of the plasma liner concept:

  - an intermediate heavy liner driven by the sub-sonic plasma “pusher”,

  - gas-plasma jets forming a disposable circuit for connecting a “canonical” (z-pinch driven) MTF target and permanent power supplies.

- Both may lead to an attractive solution of the problem of a stand-off energy source for MTF.

- Key physics issues requiring a more detailed analysis are

  - For the first concept:
    - Feed-back control of stability at the acceleration stage
    - Heat losses from the pusher to the heavy liner and the walls

  - For the second concept:
    - A good electric contact between the jets and the metal receiver
    - Attainability of the jets with specified parameters