Preliminary analysis of a slow plasma liner for MTF*

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ABSTRACT

A plasma liner concept [1] provides a promising path to solving the stand-off problem for magnetized target fusion (MTF) [2]. We consider a version of this concept where an intermediate liner made of a high Z_eff plasma is placed between the target and the surrounding thermal hydrogen plasma. The latter is deeply subsonic and accelerates the heavy liner simply by the PdV work. We present a brief scoping study concentrated on the critical issues: ways of creating the heavy liner; generation of the thermal hydrogen plasma; protection of the plasma sources from damage; radiative losses from the heavy liner as a way of maintaining its compactness; thermal transport in the hydrogen driver; possible ways of stabilizing the liner at both acceleration and deceleration stages; possible advantages of introducing rotation and shear flow in the heavy liner. Work performed for US DoE by UC LLNL under contract # W-7405-Eng-48.

[1] Y.C.F. Thio, C.E. Knapp, R.C. Kirkpatrick, R.E. Siemon, P.J. Turchi.. J. Fusion Energy, **20**, 1 (2001).

[2] 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)

OUTLINE:

- General description of the concept
- Characteristic parameters
- Issues
    - Compactness of a heavy liner
    - Stability of a heavy liner
    - Protection of plasma injectors
- Summary

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

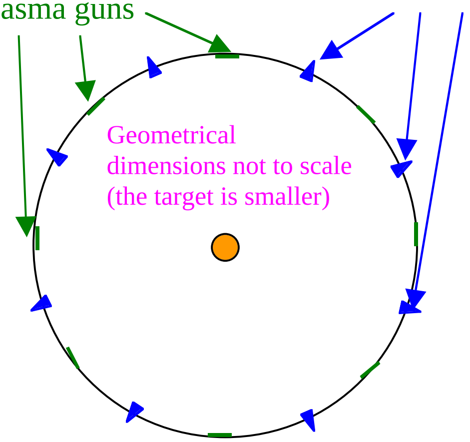
A concept of the plasma liner:

Y.C.F. Thio, C.E. Knapp, R.C. Kirkpatrick, R.E. Siemon, P.J. Turchi.. J. Fusion Energy, **20**, 1 (2001).

Detailed analysis of the liner based on the merging of very-high-Mach-number jets:

P.B. Parks, Y.C.F. Thio. Prepared for submittal to “Physics of Plasmas”

A concept of a heavy intermediate liner driven by a thermal plasma pusher

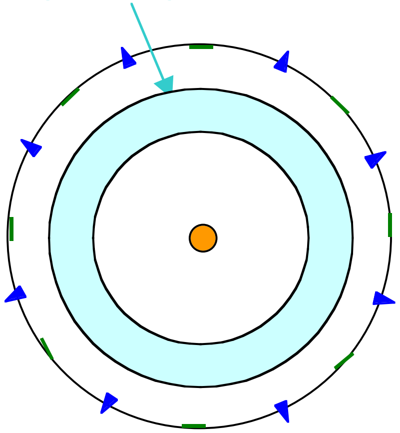


Muzzles of the plasma guns

Gas-puff nozzles

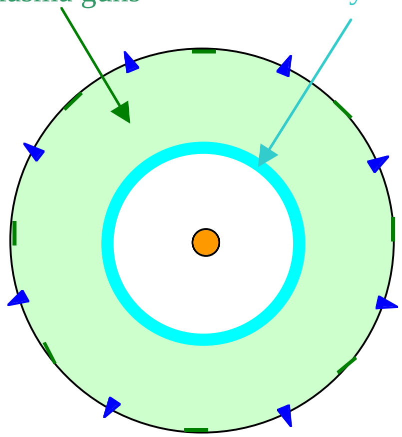
Geometrical dimensions not to scale (the target is smaller)

Stage 1: Empty chamber with a target in place



High-Z gas, possibly with high-Z (tungsten?) dust

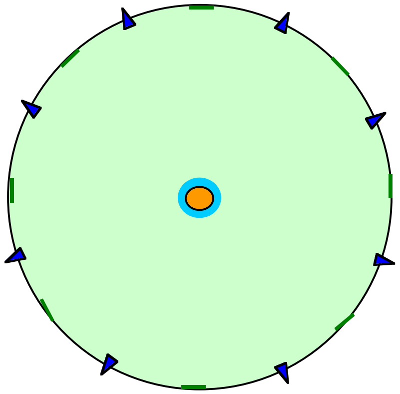
Stage 2: Heavy gas (possibly, dusty) puffed in, to create a shell



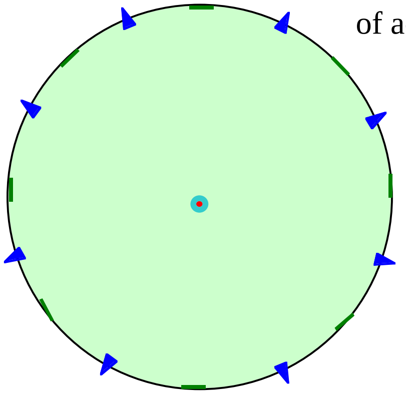
Plasma pusher generated by the plasma guns

Compressed heavy 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 in 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)

Issues of the damage to the guns and gas injector by neutron irradiation and target debris are considered at the “cartoon” level (hopefully, these issues 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~10^{17} cm^{-3}

Plasma liner temperature T_L~10 eV

Plasma liner mass M_L~ 15 G

Velocity: subsonic

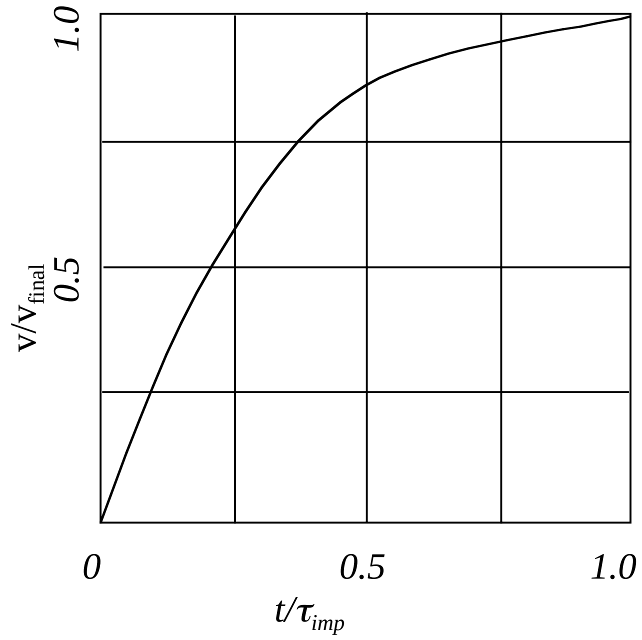
Radiative losses from the heavy liner: substantial

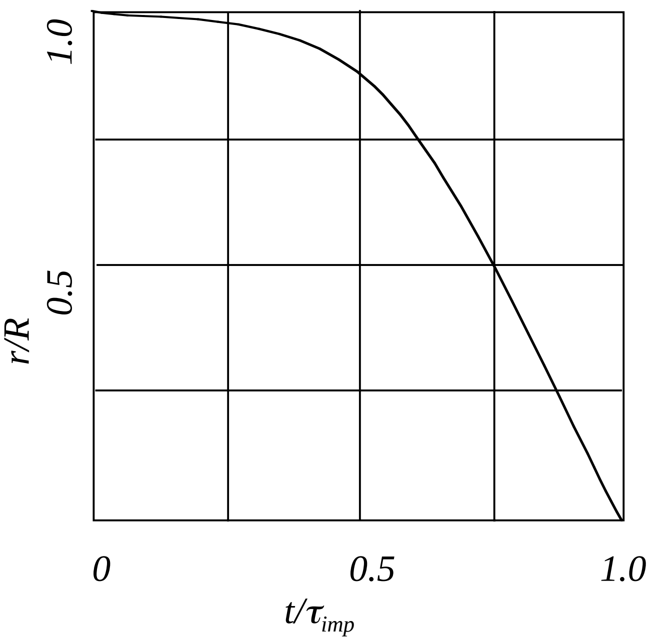
Initial target radius a_0~4 cm

The acceleration time of the heavy liner is of the order of 100 μs

Consider a constant pressure drive, p=const

$$M\frac{d^2r}{dt^2} = -4\pi r^2 p\,, \qquad \frac{M\mathrm{v}^2}{2} = \frac{4\pi p R^3}{3}\left(1-\frac{r^3}{R^3}\right)$$





$$\mathrm{v}_{final} = \left(8\pi p R^3/3M\right)^{1/2}$$

$$\tau_{imp} = 0.5\left(M/pR\right)^{1/2}$$

For $n=10^{17}$ cm^{-3},
T=10 eV. R=300 cm,

$\mathrm{v}_{final}=2.7\cdot10^6$ cm/s,
$\tau_{imp}=160$ μs

Note that even the final liner velocity is much less than the sound velocity in the "pusher" plasma $\mathrm{v}_s \sim 10^7$ cm/s.

Thermal balance of the heavy liner: heat flux from the hydrogen plasma is re-radiated as a black-body radiation:

$$\sigma T_{HL}^{4} = q \approx Q_{rad} R$$

(This equation is valid for the time not very close to the beginning of the implosion). It yields

$$T_{HL} = 0.6 \text{ eV}$$

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).

Heavy liner thickness (cont)

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

$$h \sim \frac{T_{HL}}{\mu g}$$

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 $\sim 2.5\times10^{12}$ 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

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

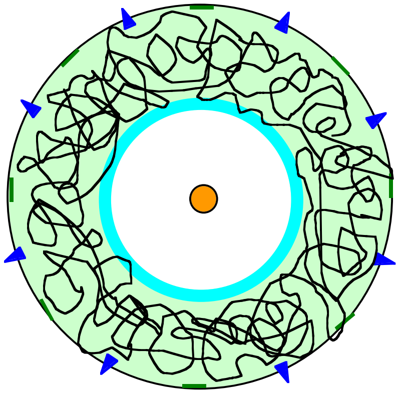
is long enough, ~ 400 μs. Obtaining hard numbers for τ_{rad} would require some effort.

Electron thermal diffusivity,

$$\chi_e(cm^2/s) \approx 10^3 \left[T(eV)\right]^{5/2} / n(cm^{-3})$$

is small, ~ 10^6 cm^2/s, so that the heat conduction time over the length ~ 1 m is quite long, more than 1 ms.

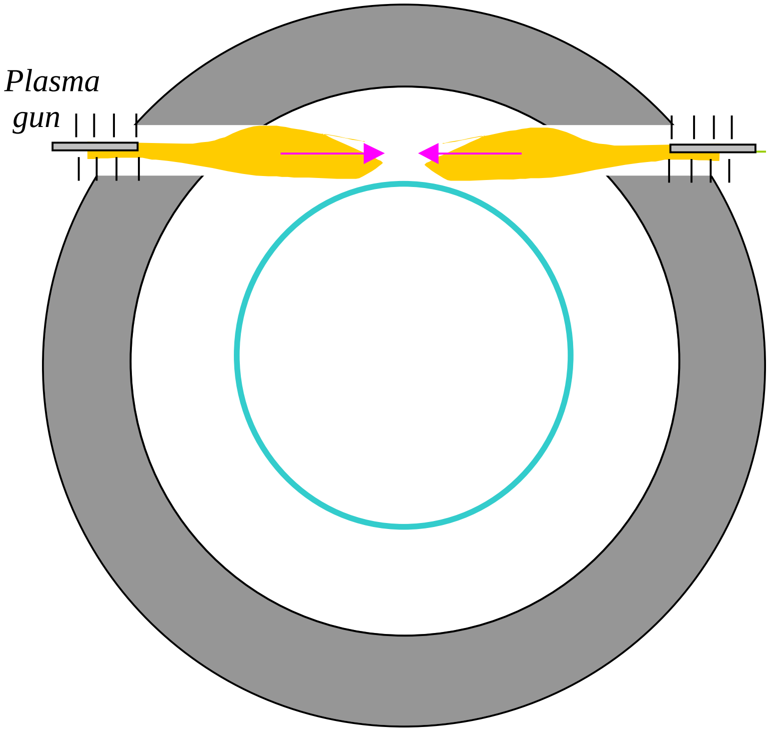
The presence of the tangled magnetic field may also help



Electron thermal conduction both to the walls and to the heavy liner can be further suppressed if the plasma pusher is “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 ~ 10 ms. The magnetic field required to “magnetize” 10-eV electrons is modest, ~ 0.3 T. Such a field does not cause any substantial “dynamic” effect, as its pressure is small.

Plasma injectors can be protected from the direct impact of fusion energy release

The generation of the subsonic pusher does not require a radial injection. The tangential “counter-injection” is preferable in many respects



Shown are two injectors injecting the plasma in the opposite directions; the plasma streams collide and contribute to a quasi-isotropic thermal plasma pusher behind the heavy liner. There will be many (~50) such pairs of injectors distributed over the surface of a thick chamber (shown in grey). They will create an (almost) spherically-symmetric pusher. Injectors will not directly “see” the fusion plasma.

CONCLUSION

- We discussed a modification of the plasma liner concept that includes an intermediate heavy liner driven by the sub-sonic plasma “pusher”
- The compactness of the heavy liner is provided by the black-body radiation from it, which holds the pusher temperature at the level ~ 1 eV during the acceleration phase
- The stability of the heavy liner during the accelerator stage can be provided by a feed-back control, with plasma injectors being the “active elements” of the control
- Plasma injectors can be protected by using the tangential injection of the plasma jets

- A more detailed analysis of the stability problem during the last phase is needed

- Issues of creating the initial magnetized target have not been assessed yet.