Strategy and Issues for Solid Liner MIF Energy

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Dense Plasmas in Ultrahigh Magnetic Fields

Overarching Question: Can fusion-relevant thermonuclear temperatures be obtained when plasma is compressed with megagauss fields?

- Recently we (~30 contributors) wrote a community white paper on Magnetized HEDLP. (April 20, 2007)
- Copies are available at

http://fusionenergy.lanl.gov/mhedlp-wp.pdf

- Merging OFES panel recommendations with Davidson reports
- Basically, adding a new research thrust: dense plasmas in ultrahigh magnetic fields, or MHEDLP

Science issues:

Can multi-keV temperatures be obtained by compression of a magnetically confined plasma to megabar pressures using a solid metal liner?

- *What limits liner compression and dwell time? How do nearby boundaries (walls) driven by intense magnetic and radiation fields turn into plasmas? How are hydrodynamic instabilities at boundaries changed in the presence of a thermonuclear (fusing) plasma? How can we minimize impurity influx?*

- *Do we have the right material conductivity and transport models (for both walls and plasma)? What effects do velocity shear, initial density profile, finite Larmor radius, and other conditions have on particle and energy transport at MHEDLP conditions?*

- *Can we take advantage of ultra high magnetic fields and high density to enable plasma diagnostics that are not possible in more conventional regimes?*

- *What happens when the liner stagnates on the plasma target pressure? What is the realistic energy partition between liner ablation consequent generated plasma, radiation and ion flux? How does the sheath at the liner- plasma boundary behave? To what extent do the liner and plasma mix?*

Looking forward for solid liner MIF/MTF

3-5 years

- Physics scans at 3-9 MJ levels
- Full integrated modeling simulations/verification
- Wall interaction/ plasma impurity studies
- Higher density end-state tests

10 years

- “Performance Extension” …100 MA, 30-50 MJ, Q=n experiments, where n is a small integer. In DD equivalent and actually with DT

20 years

- High efficiency rep-rated stand-off drivers
- Rep-rated liquid target chambers
- Demonstration of low gain, rep-rated MIF energy system

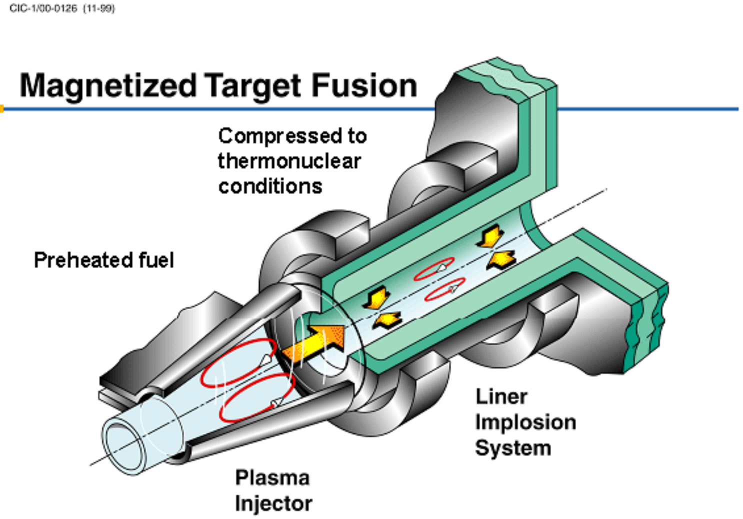
MIF/MTF approach has many common features with IFE

- Pulsed, rep-rated systems, storage and switching of driver energy
- Achieving driver stand-off under rep-rated conditions (but the problem typically takes a different form)
- Designing a chamber to take the intense energy and particle loads
- Chamber clearing. Isotope and chemical separations at the back end for DT and blanket materials

<u>There are also some significant differences:</u>

- Target physics/gain (ρR, liner mass tamping, rB)
- Lower velocity compression, high mass driver
- Target manufacture/formation (no cryo, but plasma target)
- Electrical connections
- Symmetry needs (only low convergence ratio needed)
- Driver power levels (lower peak power)

Magnetized Target Fusion (FRC):



This is a fusion concept where:

- The plasma beta ranges from 0.8 to 1
- The heart of the device fits on a modest table-top
- The plasma density is intermediate ~10^{19} cm^{-3} (MFE~10^{14} cm^{-3}, ICF ~10^{25} cm^{-3})
- The current density can be 1000 MA/m^2
- The magnetic field confining the plasma is 500 Tesla
- The auxiliary heating power level is ~ 1000 Gigawatts
- MHEDP achieved by “slow” adiabatic compression (to ~1 MBar)
- Research can be conducted with existing facilities and technologies
- In a reactor, on each pulse the liquid first wall is fresh➔ no materials problem!
- The repetition rate would be ~0.1 Hertz, so that there is time to clear the chamber from the previous event

Starting from the End Point

- Consider a 4.1 GigaJoule yield (1 metric ton) from a pulsed MTF device, in a ~1 microsecond burn.
- Consider a rep-rate of 0.1 Herz, which also gives more time to clear the chamber.
- Pick a thermal conversion efficiency to electricity of 35%, so one would produce 1.4 GJ electric per pulse (gross, not net), or 140 MW electricity (average).
- Use a thick liquid wall, with liquid pool at the bottom of the chamber. The liquid will absorb neutrons, and breed tritium. Have voids in it to dissipate shock from the explosion, and cushion the final wall of the system.

Energy? Basic points to consider (1)

3.6 MJoules = 1 kW-Hour

10 cents/kWH means 1 GigaJoule of electricity is worth \$27.8

At 35% conversion efficiency, then 4.1 GJ thermal is worth only \$40 of electricity

One metric ton (1000 kg) of high explosive has an energy content of 4.1 GJ

To produce 4.1 GJ from DT fusion, at 17.6 MeV per DT reaction, and 1 eV = 1.6×10^{-19} Joules, one has 2.8×10^{-12} Joules per DT reaction; so you need 1.4×10^{21} reactions per 4.1 GJ released.

Basic points (continued) (2)

A mole of D2 is 2x6.02x10^{23} D atoms, and same for mole of T2. So each 4.1 GJ pulse burns up approximately 1 milliMole of D2, and 1 milliMole of T2. D2 has a molecular weight of 4 grams/Mole, and T2 has a molecular weight of 6 grams/mole

If the (batch burn, no alpha heating) fractional burn-up of DT is 10%, then you need 10 milliMoles of each, in the final compressed MTF plasma. At least 20 milliMoles of each in the beginning target plasma, assuming 50% plasma inventory losses during translation from the formation region.

The initial target fuel load must be “preheated” to 200 eV (Te+Ti). This is an energy investment of $2\text{x}(20 \text{ x } 10^{-3}) \text{ x } 6\text{x}10^{23} \text{ x } 200$ eV = 4.8x10^{24} eV, or 0.75x10^{6} Joules, or 0.75 MJ. Add in a factor of 2x for formation losses, so we are talking 1.5 MJ of energy needed to form the MTF “target” plasma.

Basic points (continued) (3)

Then the gain is 4100 / 1.5 = 2733 relative to the initial plasma energy content. But work also had to be done to compress the initial plasma to get it to the final state (alphas assumed not to contribute). The energy content of the final state is defined to be same number of particles, heated up to 8 keV. The temperature increase (energy content increase) is 8000/200 = 40. Assume the liner drive energy is about 2x the final plasma state energy. Then the system I have just described has a gain (classic Q_{DT})~ 35.

If the electric-to-liner drive efficiency is ~50%, the system gain is reduced to ~17, when considered from wall plug to thermal output. (i.e., you needed to put in 260 MJ into the pulsed energy storage to get 4.1 GJ thermal out from pure fusion). If conversion to electricity is 35% efficient, then electricity output is 1.4 GJ, so the recirculating power is about 18% .
If the rep-rate is 0.1 Hz, the average electric output is 140 MW.

So a 10% fractional burn-up is the minimum performance needed, from a fusion-only, MTF batch-burn system.

Fusion energy gain of Solid Liner MTF

- **The fusion gain** $G = \dfrac{\text{WHAT YOU GET}}{\text{WHAT YOU PAY FOR}} = 293\left(\dfrac{10}{T_0}\right) f_b \eta_h \eta_E$

  T_0 : target temperature at stagnation (keV)

  f_b : fuel burnup fraction, η_h : liner hydro efficiency, η_E : electrical efficiency

- **Parameters at stagnation time *t* = 0**

  R_0, (R_{liner}) : target radius (outer liner radius)

  $\rho_0 = m_{DT} n$: target density, ρ_L : liner density,

  $f_{alpha} = fraction\ \ alpha\ \ energy\ \ deposition$

- **Characteristic expansion time** $t_{\exp} = (R_0 / c_{s0})\sqrt{\rho_L / \rho_0}, \quad c_{s0} = (2T_0 / m_{DT})^{1/2}$

- **Fractional burnup using an ideal spherical target expansion model (Parks)**

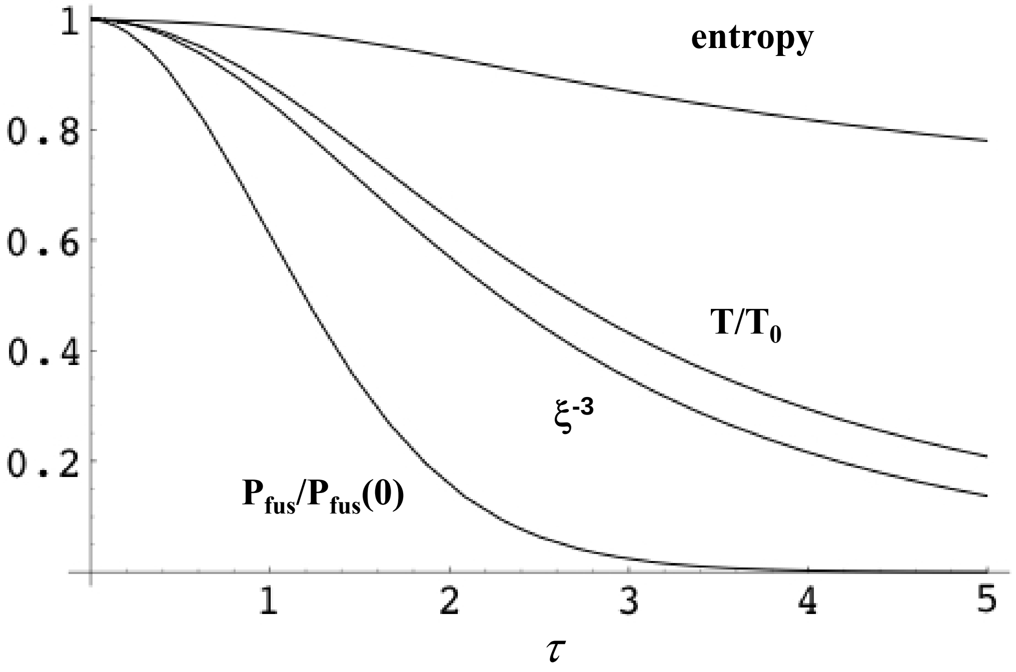
$$\boxed{f_b = f_{b0} \Lambda(C, \alpha)}$$

$$\tau = t / t_{\exp}, \quad \xi = R / R_0$$

where $$f_{b0} = \frac{\langle \sigma v \rangle (T_0) n t_{\exp}}{2}, \quad C = \frac{f_{alpha} f_{b0}}{6} \frac{E_{alpha}}{T_0}, \quad \alpha = \frac{R_L}{R_0}, \quad \Lambda = \int_0^\infty \frac{\langle \sigma v \rangle (T)}{\langle \sigma v \rangle (T_0)} \xi^{-3} d\tau$$

Time Evolution of Target Plasma

$f_{alpha} = 0.1$



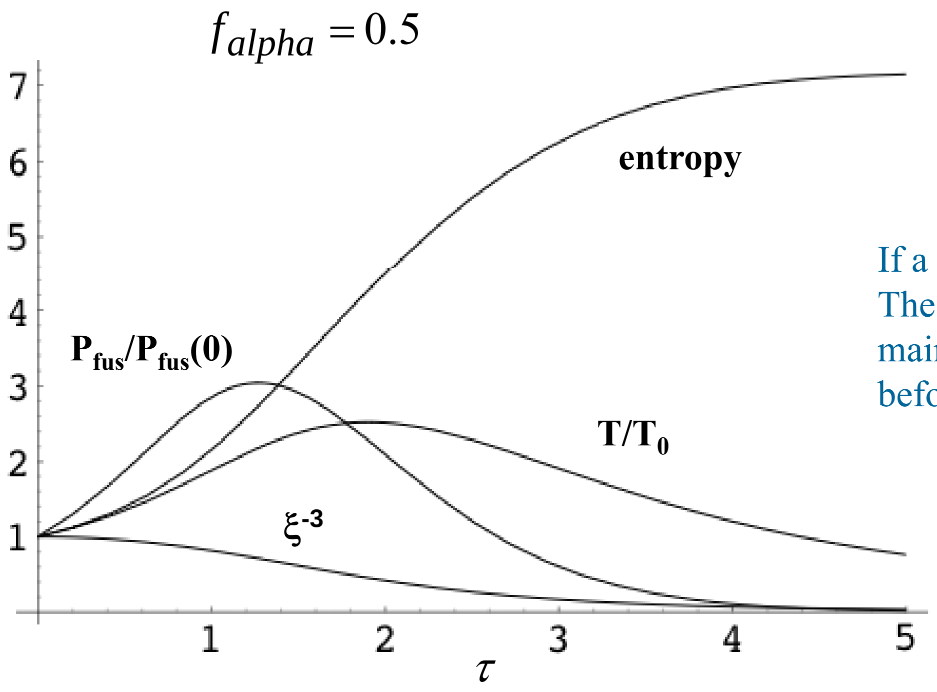
With little alpha trapping, you essentially have batch burn, expansion and cool-down.

- **Nominal parameters**

$$n_0 = 2\times 10^{21}/cc,\ \rho_L = 10g/cc,\ \rho_0 R_0 = 0.00415 gm/cm^2,\ f_{b0} = 0.0224$$

$$T_0 = 10\,\text{keV},\ \alpha = 3,\ \eta_h\eta_E = 0.5$$

Time Evolution of Target Plasma



If a B field is confining the alphas, The temperature climbs in the main fuel, and gain increases, before expansion takes over.

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Gain versus f_{alpha}

f_{alpha}	Λ	Gain
0.1	1.29	4.255
0.4	4.43	14.56
0.5	6.27	20.63
0.6	7.43	24.45
0.7	8.04	26.45

- **Using Nominal Parameters where $f_{b0} = 0.02246$**
- **So, not only do we need a B field to insulate the target, but we need a B-field to confine the alphas**
- **Remember, the fractional burnup is larger for a given ρR than in pure ICF case, due to the effect of the liner mass tamping. f = ρR /(ρR + 7/tamp)**

Can the neutron energy multiplier be bigger than 1.1?

•Why is it 1.1 for “pure” fusion?….because we take an exothermic energy credit for n-Li reactions in a blanket.

•Are there other possibilites? Yes……..**Fusion-Fission Hybrid, because per fusion, fusion is energy rich, and neutron poor. Fission is neutron rich, and energy poor.**

•If the blanket is 0.6 meter thick hot liquid FLIBE with 10% UF4, one can protect standard solid structural elements for a long life (~30 years), while getting a tritium breeding ratio of >1.1, and an energy amplification of 1.9 (due to fission in the blanket!). [Mustafa Ubeyli, Journal of Fusion Energy, Vol. 25, no. 1-2, pg 67-72, (2006)]

•So, as most of us know, if you are willing to be a fissile breeder, then it is straightforward to double the Q.

Differences & similarities between MTF and Z-IFE reactors

- Both envision reactors with multi-GJ yields, and liquid first walls
- Both envision slower rep rates (~0.1 Hz) than IFE, with resultant advantages in clearing the chamber and setting up the target
- Both require target standoff delivery of energy to the imploder (liner/wire array)
- Neither requires target tracking in the reactor chamber
- Z-IFE expects higher Q (due to burning cold-fuel) than batch-burn MTF
- MTF delivers energy on slower timescales, with lower driver voltages, than Z-IFE
- MTF compression ratios and implosion velocities are smaller than needed by Z-IFE
- MTF needs a higher quality vacuum (for its target plasma) than Z-IFE
- It may be possible to combine magnetic insulation with a Z-IFE target

Reactor References

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Summary

- Magnetized plasma pervade the physical universe. Some of these plasmas occur at extreme HEDP conditions, including white dwarf stars and magnetars, or with magnetic reconnection, etc. Magnetized HEDLP conditions can be achieved by a variety of approaches, embodied by MIF/MTF systems.
- Beyond just enabling fusion (a grand challenge in itself), MHEDLP is a scientifically rich set of parameter space.
- At the moment, it pushes our technologies to the limits, in order to create the cm-scale, multi-keV, dense, ultra-high field plasmas.
- Energy production scenarios from pulsed fusion can be considered with fusion gains of order 20-40, (especially if fusion-fission hybrids are allowed) for high efficiency, high energy, solid liner driver (MTF) systems.
- Existing driver systems allow us to study the physics for the next 5 years at megajoule levels. The cost is low. We lead the world.