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Sandia National Laboratories

Cryogenic DT layers for high performance MagLIF

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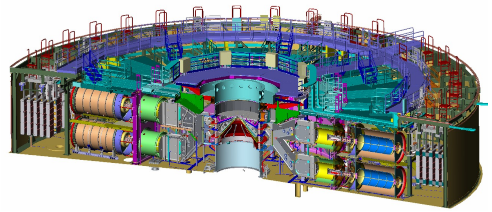
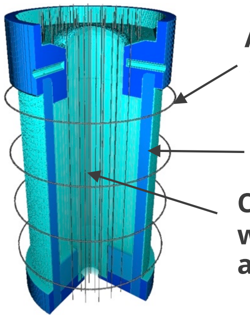
Typical MagLIF shots produce 10^{13} DD fusion neutrons at the Z facility, but higher yields are possible



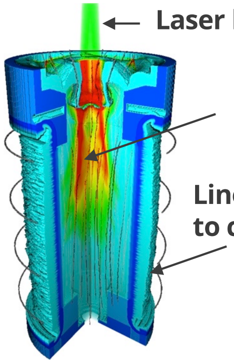
Z generates high magnetic pressures to drive cylindrical implosions, while Z-Beamlet provides fuel preheat



Azimuthal drive field

Liner (Be)

Cold DD/DT gas with imbedded axial B field



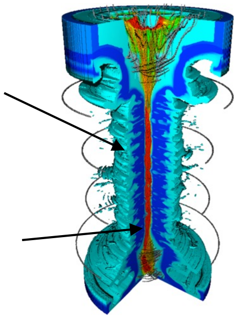
Laser beam

Laser heated fuel

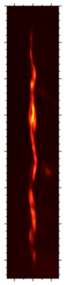
Liner starting to compress

Liner unstable but sufficiently intact

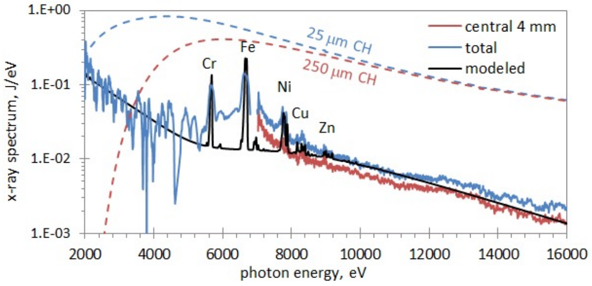
Compressed fuel and magnetic field reaches fusion temperatures



X-ray Image at stagnation

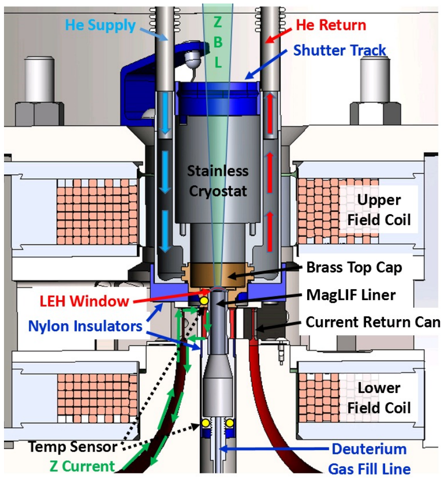


Mix of liner material into the fuel has been observed spectroscopically



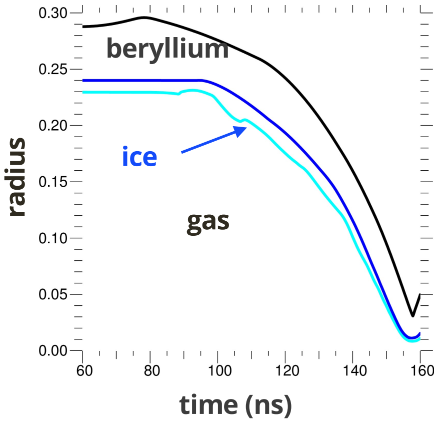
S.A. Slutz *et al.*, Phys. Plasmas (2010) ; Gomez et al. Phys. Rev. Lett. (2020); Hansen et al. Phys. Plasmas (2015)

Cryogenic DT layers could improve MagLIF performance



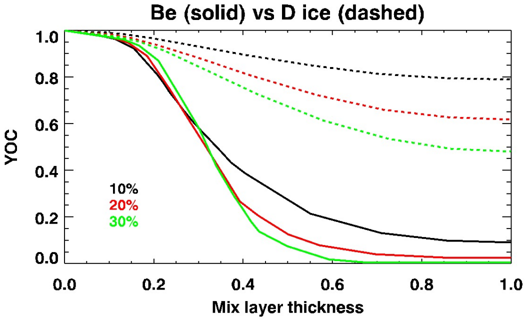
Cryogenic cooling has been developed at the Z facility

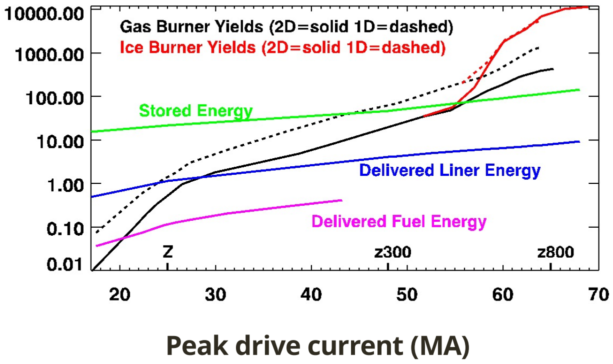
Cryogenic temperatures lower the fuel pressure, which allows thin LEH windows and improved laser coupling



A DT ice layer protects the liner from the laser induced blast wave

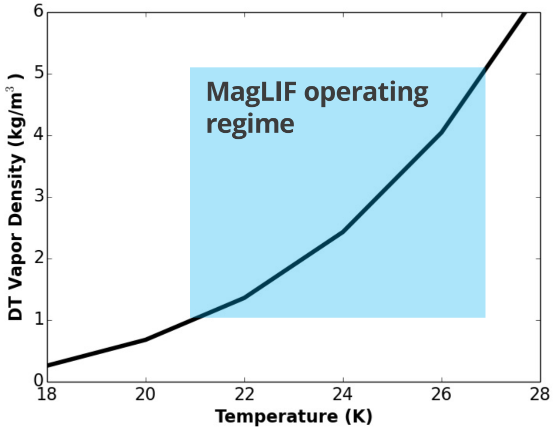
Mixing cold DT into the fuel does not lower the yield as much as mixing higher Z material

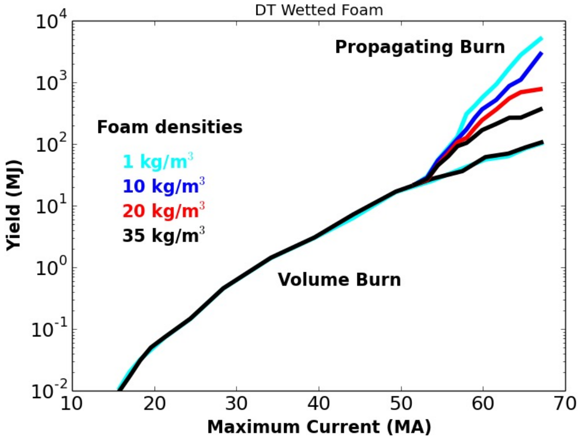




Dense DT layers can contribute to yield and gain

Low density DT wetted foam could provide suitable gas densities, an anti-mix layer, and high gain





The vapor density is too low for MagLIF at the maximum temperature of DT ice (18 K)

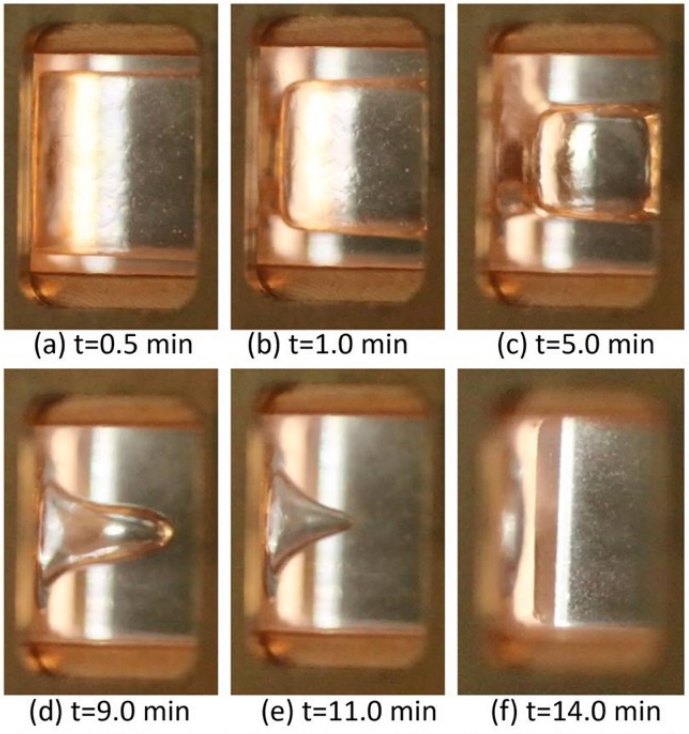
A DT wetted foam layer would have suitable vapor densities for 21 < T < 27

Lasnex simulations with a foam layer with the voids filled by liquid DT. The materials are assumed to be atomically mixed with a total density ~ 220 kg/m^3

Gas burner yields unaffected by foam density, but the layer mitigates mix

Lasnex simulations indicate significant yield increases require foam densities less than 35 kg/m^3, thus fabrication is challenging

Ice layers could be grown in MagLIF liners with desublimation[1]



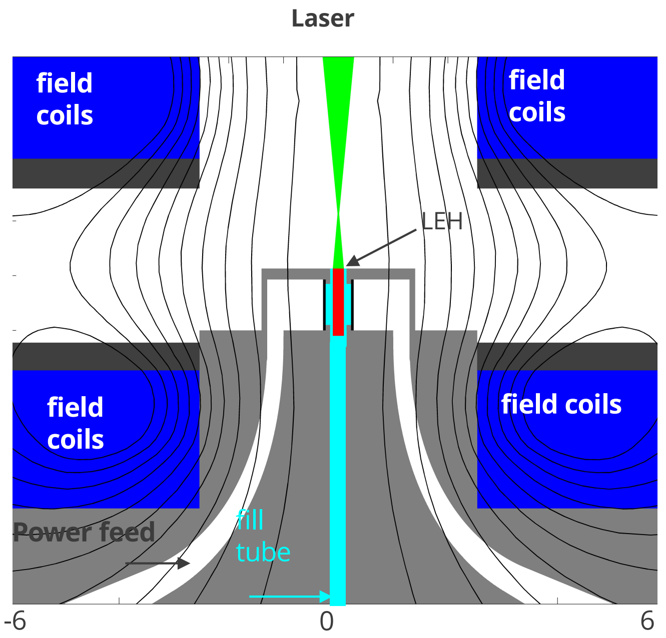
(a) t=0.5 min (b) t=1.0 min (c) t=5.0 min

(d) t=9.0 min (e) t=11.0 min (f) t=14.0 min

- The vessel is held at 15 K
- Deuterium gas enters from the left side
- Ice layers are formed on the top and bottom
- The layers are clear indicating ice rather than snow

1. T.J. Awe et al., RSI 2021

Gas can be puffed in from the end opposite to the laser entrance hole



- After the ice formation at 15 K warmer (40 K) gas can be injected at the desired density.
- The warmer gas will condense on the cold ice and possibly melt or grow the ice layer
- We have developed a model of this process

Gas injection thermal model

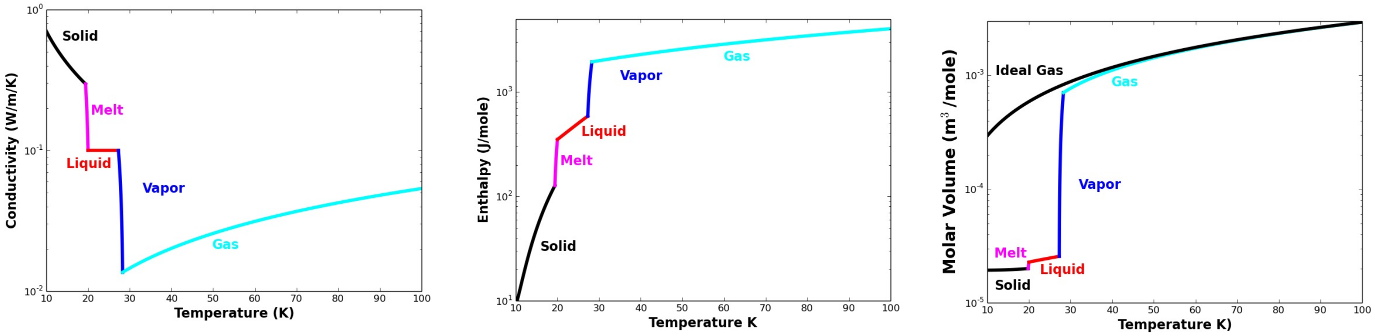
An explicit spatially centered difference scheme is used to solve the conduction equation. The time step is set to 0.4 of the diffusion Courant time. The thermal flux across a grid point and the entropy change within a cell for a time step Δt are

$$q_l = -\frac{4\pi r_l \kappa_{l+1/2}(T_{l+1} - T_l)}{r_{l+1} - r_{l-1}} \quad \text{where} \quad \kappa_{l+1/2} = 2\left(\kappa_l^{-1} + \kappa_{l+1}^{-1}\right)^{-1}$$

$$h_l^{n+1} = h_l^n + \Delta t\,\frac{q_{l-1} - q_l}{M_l} \quad \text{and for stability} \quad \Delta t < min\left(\frac{\Delta r^2}{\kappa}\frac{dh}{dT}\right)$$

The properties of DT depend on temperature and pressure. As an example, DT gas with a density of 4.5 kg/m^3 and temperature 40 K has a pressure of 2.8 atm

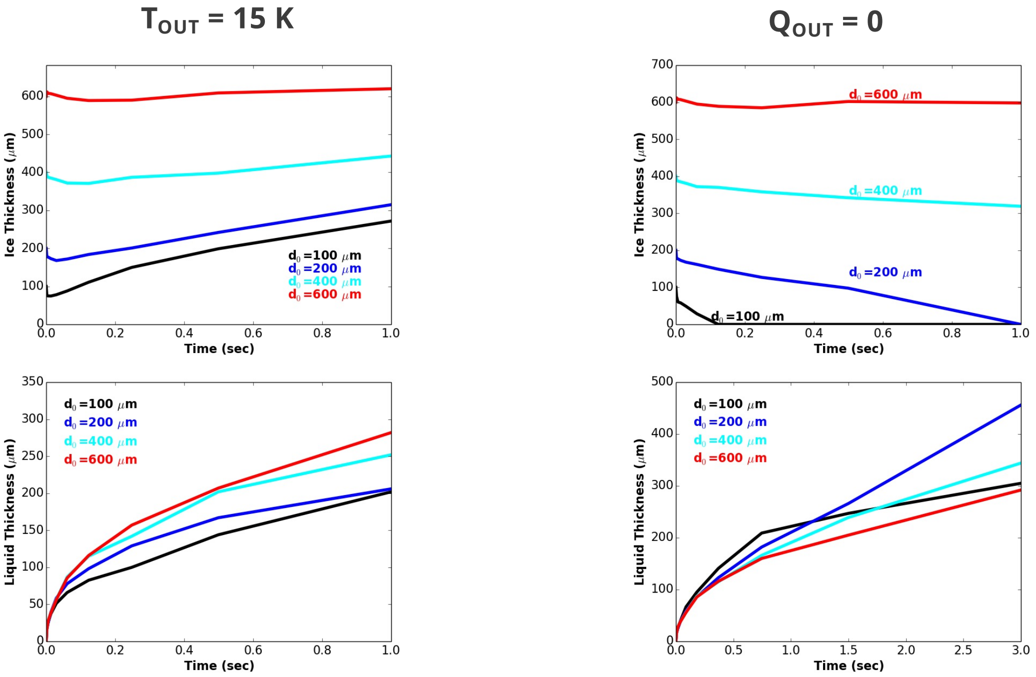
Properties of DT at pressure 2.8 atm[1]



1. P. Clark Souers, “Hydrogen Properties for Fusion Energy” University of California Press 1986

DT layers will persist for long times (seconds) for MagLIF on Next Generation Pulsed Power (NGPP) machines

liner radius = 5 mm, gas density=4.5 kg/m³ injected at 40 K. Ice layers of 400-600 μm are appropriate for high gain propagating fusion burn.



T_{OUT} = 15 K

Q_{OUT} = 0

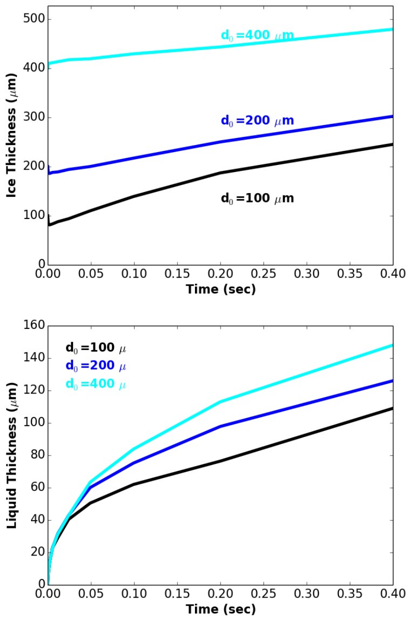
Cooling through a beryllium liner should maintain an outer boundary temperature of 15 K.

Q_{out}=0 is calculated for the possibility of poor conducting liners

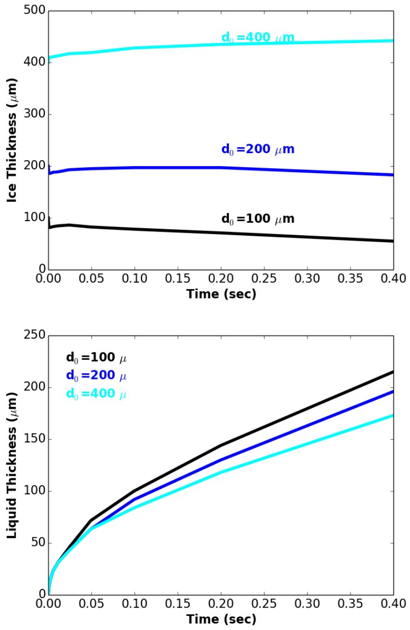
Ice layers will also persist for long times for MagLIF on the Z machine

liner radius = 3 mm, gas density=1.5 kg/m³ injected at 40 K. Ice layers of 100 μm should be sufficient for mix mitigation

T_{OUT} = 15 K

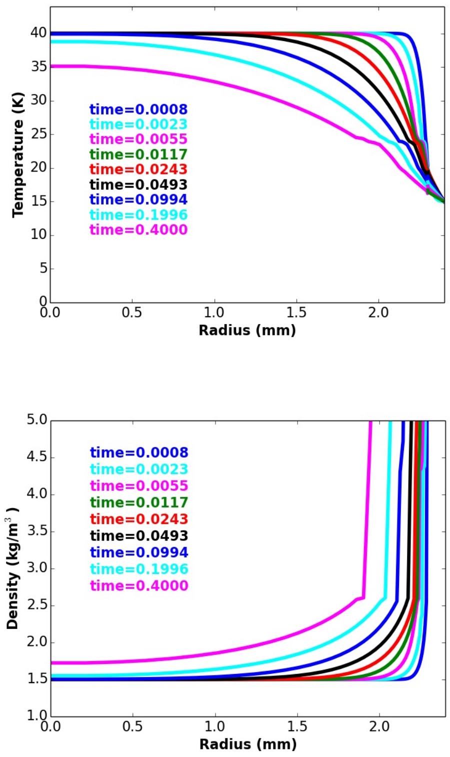


Q_{OUT} = 0

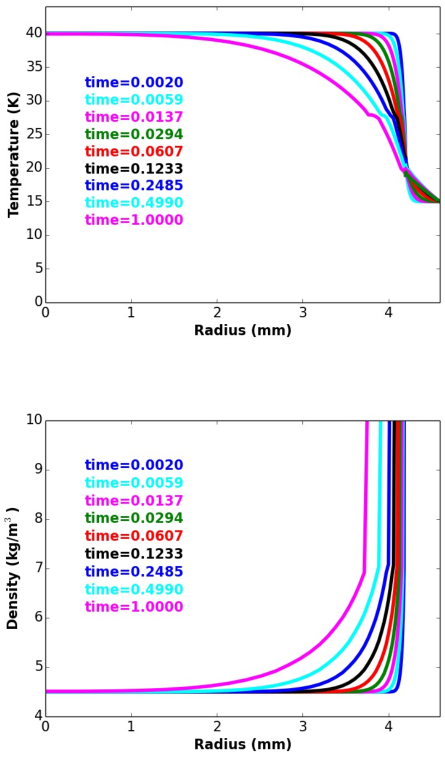


Ice layered MagLIF can be tested on Z

The gas density forms a light pipe for the laser



Z Machine d_0=100 μm



NGPP Machine d_0=400 μm

The melted layer thickness will be limited by gravity

The thermal simulations indicate the liquid layer grows at about $\dot{d}$ = 200 μm/sec. The vertical velocity of the liquid when it condenses is zero. The time since condensation is

$$t = \frac{x}{\dot{d}}$$

where x is the distance from the liquid vapor interface. The vertical velocity is then

$$v = \frac{gx}{\dot{d}}$$

The rate of liquid mass falling to the bottom of the liner is then

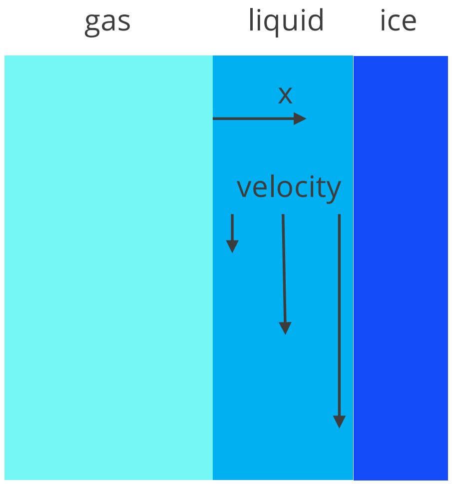
$$\frac{dM_F}{dt} = 2\pi r\rho \int_0^d \frac{gx\,dx}{\dot{d}}$$

where d is the thickness of the liquid layer

The rate of mass condensing is $\frac{dM_C}{dt} = 2\pi r L\rho\dot{d}$

The equilibrium thickness is then $d = \left(\frac{2L}{g}\right)^{1/2}\dot{d}$

which is only about 10 μm



Summary

Dense cryogenic fuel layers can improve MagLIF performance

- Very thin laser entrance foil can be used at cryogenic temperatures thus allowing good coupling to the fuel
- Provide a mix mitigation layer
- Large yields (> 1GJ) and large gains (>1000) due to propagating burn at currents above 60 MA

Vapor density is too small at ice temperatures (T < 20 K)

  - The proper vapor density can be obtained at liquid temperature
  - A layer can be produced by liquid fuel wetting a low density foam
  - The foam increases radiation losses
  - Lasnex simulations indicate propagating burn for densities less than 35 kg/m^3

Gaseous fuel can be introduced after ice layer formation

- Calculations indicate the ice layer survives for seconds
- The resultant gaseous fuel density is minimum on axis thus keeping the preheat laser from hitting the liner