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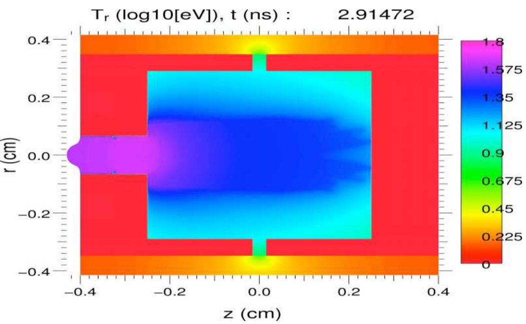

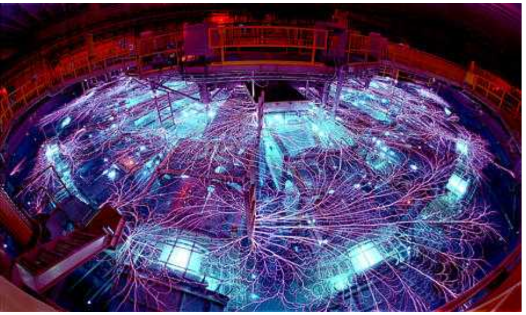

Energy and magnetic flux confinement in high energy density plasmas relevant to the Magnetized Liner Inertial Fusion scheme

A. J. Harvey-Thompson, S. A. Slutz, D. B. Sinars, A. B. Sefkow, and many others

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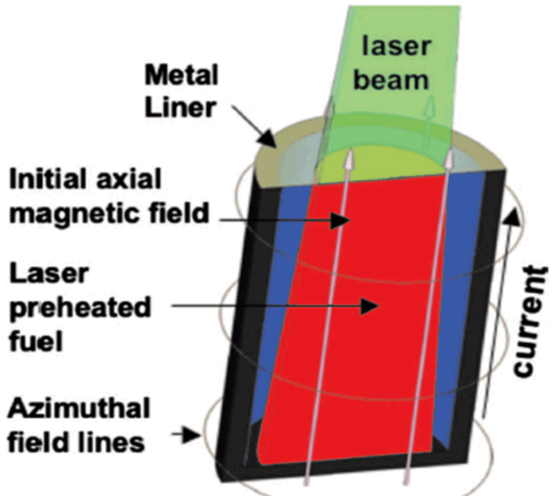
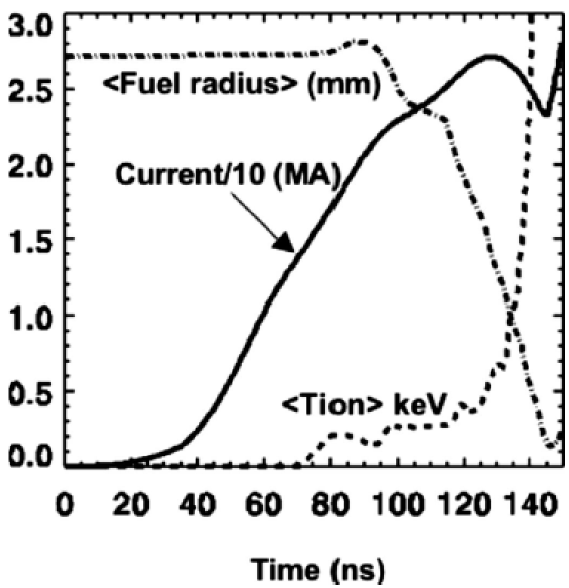
Overview of the MagLIF fusion scheme





S. Slutz et al., PoP (2010)

MagLIF uses the Z generator at Sandia National Labs (24 MA current, 100ns risetime) to implode a metal liner containing fusion fuel (2mg/cc D2) using the pinch effect

Implosion relatively slow – ~100 ns. To achieve fusion temperature/density at stagnation requires additional aspects

- Fuel heating with a ~8 kJ external energy source during the implosion – currently using Z-Beamlet (ZBL) laser (2 kJ in 2 ns) fired into fuel down axis of liner
- An applied ~30 T axial magnetic field – reduce electron thermal conduction during the implosion keeping the preheated fuel hot

Both of these aspects have significant uncertainties – these and other MagLIF issues can be tested on medium scale laser facilities

MagLIF issues that may be addressed at laser facilities

Issues to be addressed		Possible timeline/facility	Notes
Effect of magnetic field on plasma temperatures and cooling rate		OmegaEP: FY14-FY16	
		SNL: FY13 (with no magnetic field) SNL: FY14 onwards (with magnetic field)	Preliminary experiments have been conducted at SNL with no applied B field
Study of factors that affect absorption of laser energy in fuel	Effect of applied magnetic field	OmegaEP: FY14-FY16 SNL: FY14 onwards	
	Effect of laser non-uniformities	SNL: FY14 onwards	Effects of non-uniformities potentially significant on ZBL – needs to be investigated.
	Effect of increased laser energy/duration	SNL: FY14 onwards OmegaEP: FY14-FY16	Increased duration expected to increase fuel length over which energy is coupled
Effect of plasma dynamics on magnetic field topology	Dynamics due to laser heating	OmegaEP: FY14-FY16	Requires targets compatible with proton probing
	Dynamics due to imploding liner	SNL: FY13	Experiments currently being conducted at Z without fuel preheat
Study of losses at LEH/LEH design	LEH closure rate	SNL: FY14 onwards	Can also be investigated at other laser facilities e.g. Omega
	LEH burn-through energy	SNL: FY14 onwards	Can also be investigated at other laser facilities e.g. Omega
	Backscatter from LEH/fuel	TBD	Requires backscatter diagnostics currently unavailable on OmegaEP

Possible Omega experiments

Experiments at Omega and Omega EP can answer the following questions:

- How well will an applied magnetic field suppress thermal conduction in the MagLIF scheme?
    - Validity of classic Braginskii scaling
- Can a laser be used to couple the required energy into the MagLIF fuel?
    - MagLIF target 7.5 mm long with 2 mg/cc D_2 fuel – can 8 kJ of laser energy be absorbed over this length?
    - Can the beam profile be altered to increase absorption by e.g. increasing filamentation?

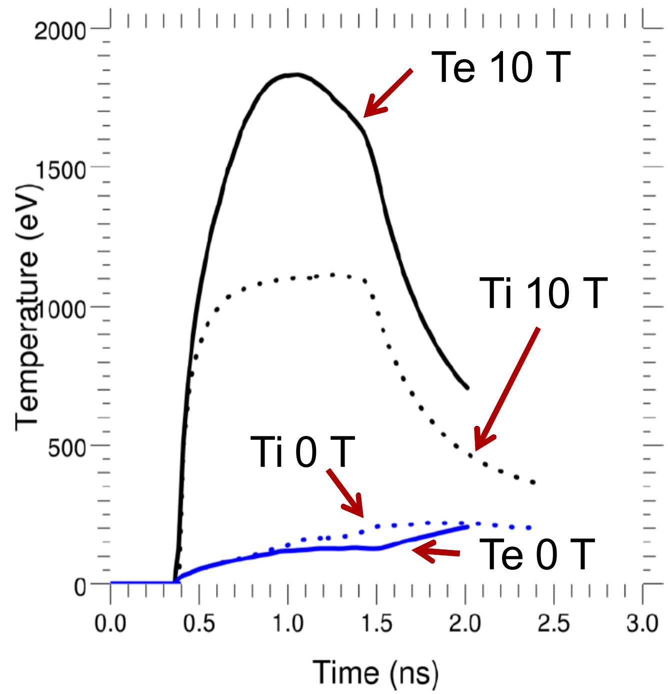
Omega and Omega EP have several advantages over Sandia:

- Increased laser energy – 4 kJ max vs. 2.5 kJ at Sandia
- Better beam profile, ability to reduce/increase smoothing
- Multiple shots per day possible
- More sensitive and more appropriate diagnostics

Electron thermal conduction suppression by B fields

- In presence of B field electrons gyrate around field lines
- In presence of B fields no perpendicular transport in absence of collisions – for large B fields each collision transports electron by order cyclotron radius – perpendicular transport suppressed
- Transport affected by:
  - Instabilities
  - Anomalous transport
  - Magnetic field advection/Nernst term

- Effect of 10 T B field on laser-heated plasma dynamics/temperature of laser heated plasma expected to be large/observable.



Ion and electron temperature profiles with and without a 10 T applied B field for a 2mg/cc D2 gas heated with a 3w laser delivering 2.5 kJ in 1 ns. Hydra sims by A. Sefkow.

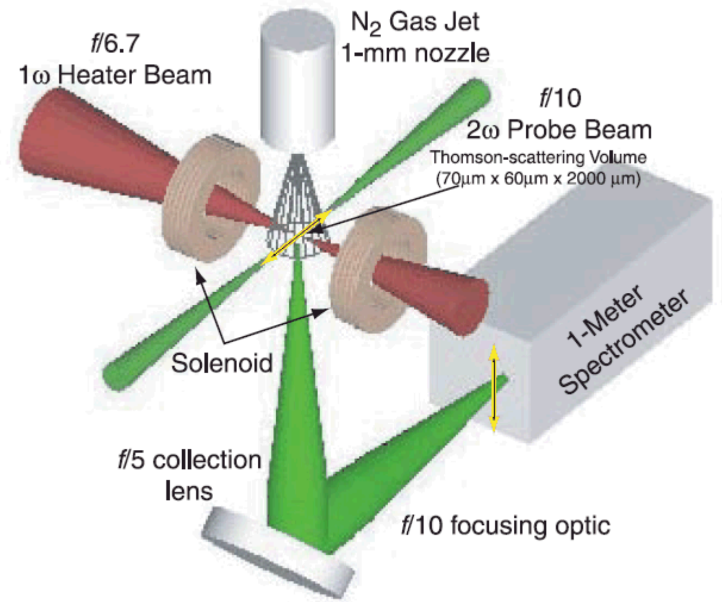
Electron thermal conduction suppression by B fields - Previous experiments

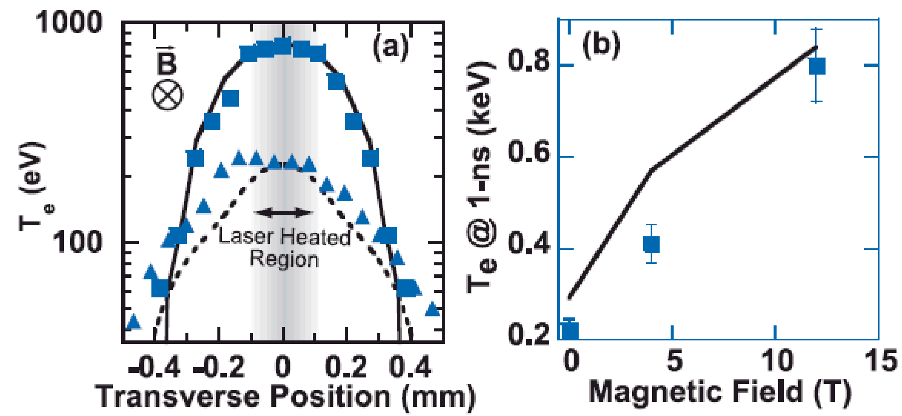
D. Froula et al., fired laser (1w, 100 J, 1 ns) into Nitrogen jet (ne = 1.5e19/cc) with applied B field (max 12 T)

Thomson scattering used to determine temperature profile perpendicular to B field lines

For 12 T B field electron thermal conduction found to be suppressed according to classic Braginskii heat transport

Proposed work extends this to plasma densities a factor of 20x greater, laser energies a factor of 50x greater and peak plasma electron temperatures a factor of ~5x greater





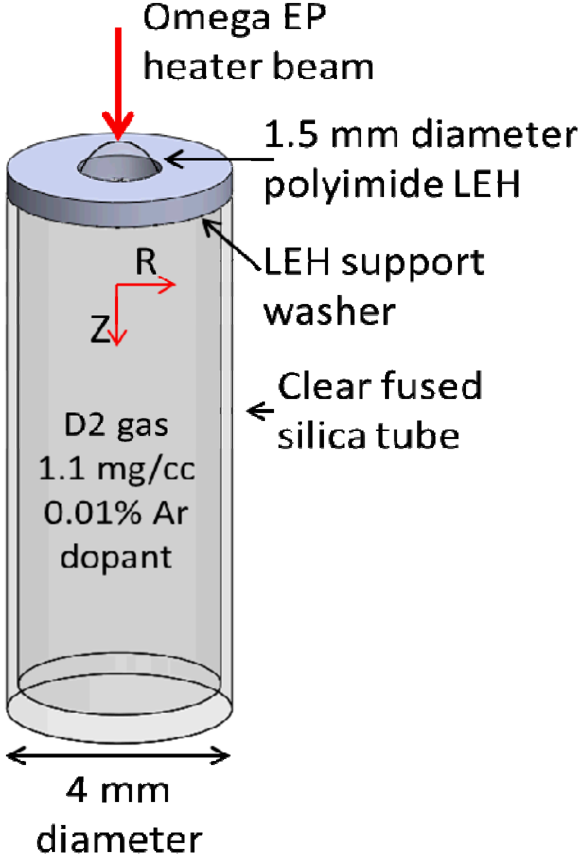
D. Froula et al., PRL (1998)

Electron thermal conduction suppression by B fields - Experimental setup

Simple large rigid tube target proposed

- Dimensions: 4 mm diameter, 10+ mm long
- Fused silica walls – transmission of 4w probe light
- 1.1 mg/cc D2 gas fill
- LEH at one end – Omega EP beam fired down axis of tube
- MIFEDS Helmholts-like coils wrapped around/close to target diameter to give ~10 T magnetic field

Temperature as a function of time and dynamics observed with/without 10 T magnetic field



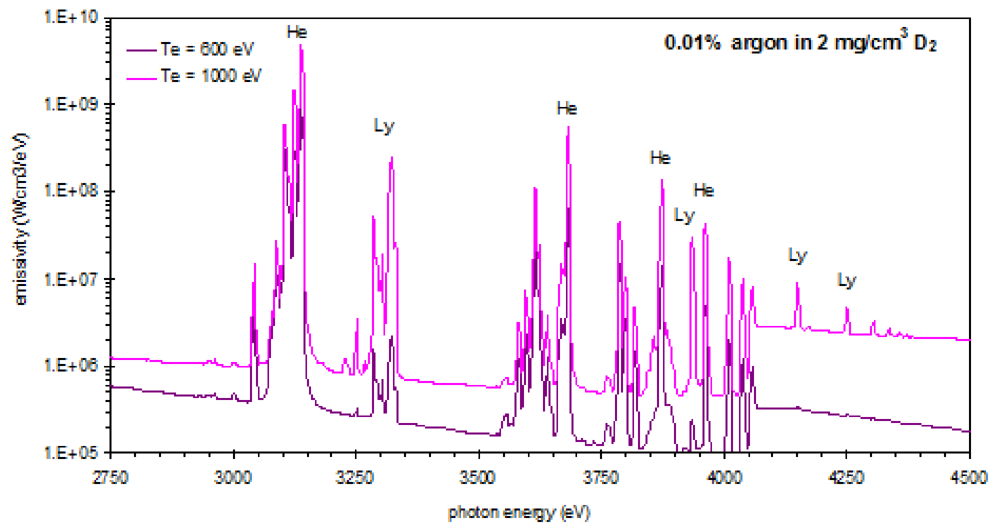
Electron thermal conduction suppression by B fields - Diagnostics

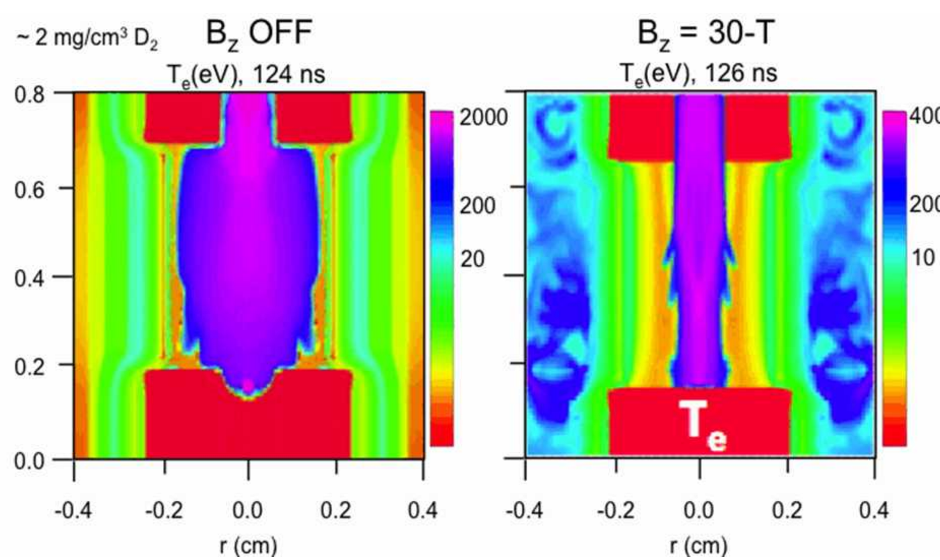
Temperature measured with Streaked x-ray spectrometer (SXS) Coupled to XR streak camera A (SSC-A)

- 0.01% Ar dopant in fuel provides emission lines – varies significantly with temperature
- Thin polyimide window bonded to tube allows x-rays to escape
- 9 ns streak time allows measurement of temperature evolution

Dynamics and laser transmission measured with 4ω schlieren diagnostic (4WSSD) and X-ray framing camera (XRFC)

- Fused silica walls – 4w light transmission
- Polyimide window – X-ray transmission





6.5 kJ in 4 ns 2w laser. Hydra simulations by A. Sefkow.

Electron thermal conduction suppression by B fields - Shot plan

2 shot days requested as part of Laboratory basic sciences proposal in Q2 and Q4

Magnetized and unmagnetized shots requested

Multiple shots to vary diagnostic timing – streaked spectrometer window: 9 ns

4w schlieren gives single point (in time) image

#	Magnetization	Diagnostic timing
Day 1		
1	Unmagnetized	During heating
2	Unmagnetized	During/after heating
3	Unmagnetized	After heating
4	Magnetized	During heating
5	Magnetized	During/after heating
6	Magnetized	During/after heating
7	Magnetized	After heating
Day 2 – flexible magnetization and diagnostic timing		
1	Unmagnetized	During heating
2	Unmagnetized	During/after heating
3	Unmagnetized	After heating
4	Magnetized	During heating
5	Magnetized	During/after heating
6	Magnetized	During/after heating
7	Magnetized	After heating

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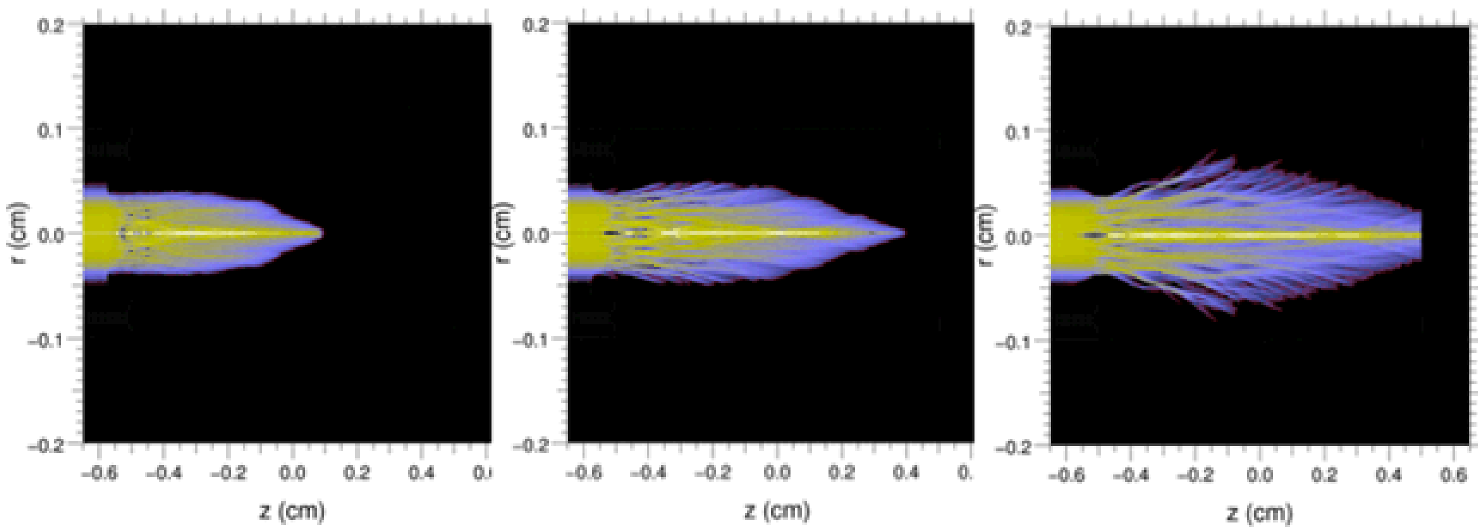
Laser energy coupling into fuel

- Want to absorb 8 kJ of laser energy in ~9 mm long liner filled with ~2 mg/cc D2 without significant energy reaching end of liner
- Lasers propagate in underdense gases in a ‘bleaching wave’ that travels many times faster than the plasma sound speed
- Simulations suggest that even with modest laser energies (2 kJ, 2 ns) not all energy is deposited into the fuel
- Intensity variations in beam lead to filamentation which alters the laser energy deposition profile



Hydra sims of laser intensity contours for 2.5 kJ, 1ns, 3w laser in 2 mg/cc D2 fuel.

Laser energy coupling into fuel – Previous experiments

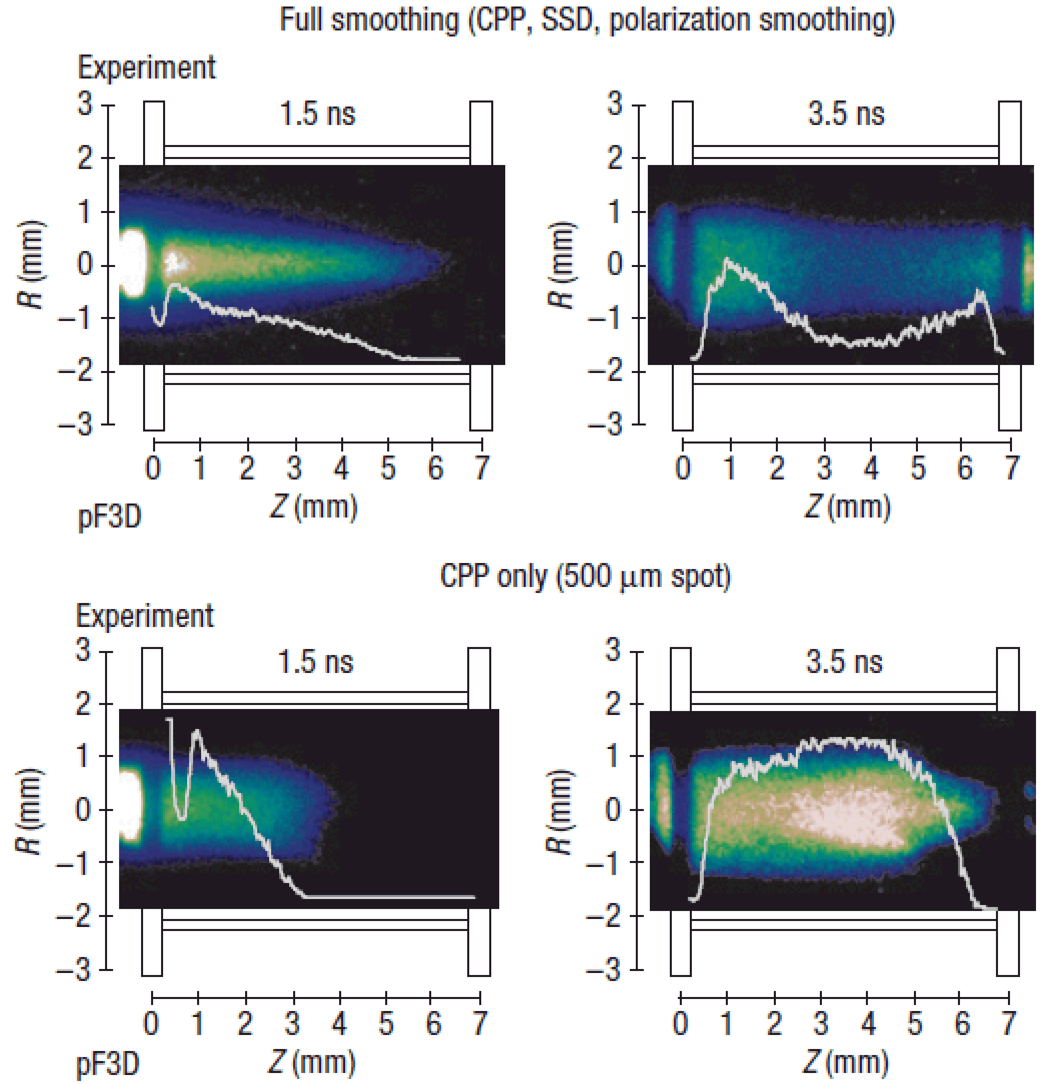
Glenzer et. al., investigated beam propagation through CO2 gas (n_e = 6e20/cc) - relevant to NIF hohlraum

One quadrant of the NIF (16 kJ, 3ω, 3.5 ns, I_0=2e15 W/cm^2) was focused into a 7 mm long gas tube target

Different smoothing resulted in different beam propagation – less smoothing = worse propagation (bad for laser ICF)

We want to absorb as much energy in as shorter distance as possible – want less smoothing?

Also want to have applied B field during experiment



Glenzer et al., Nat. Phys. (2007)

Laser energy coupling into fuel – Experiments at Sandia

First integrated MagLIF experiments will be performed with present ZBL parameters - ~2 kJ in 2 ns

Before the first shot we want to determine amount of laser energy absorbed in fuel – including amount lost to LEH

Experiment required to give measurement of energy per length absorbed in fuel

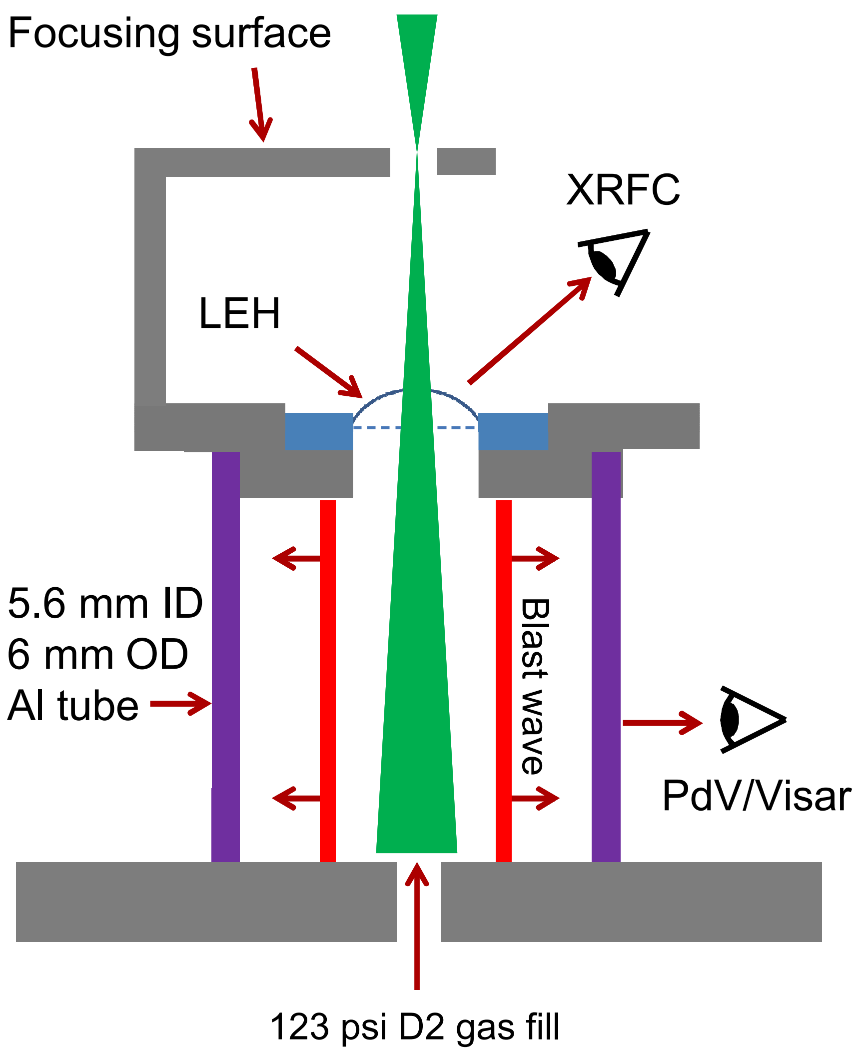
Laser energy deposition in gas drives a blastwave – time taken to reach edge of cylinder gives measurement of energy deposited

Blast wave timings predicted by Lasnex (S. Slutz)

1 D Lasnex simulations were performed for an aluminum liner (Ar=10, outer radius=1.5 mm, length=7.5 mm)

E_{dep} (kJ)	V_{max} (km/s)	T_{delay} (ns)
2.0	3.27	22.81
1.6	2.84	24.14
1.2	2.40	25.53
0.8	1.93	27.72
0.4	1.45	31.61

Laser energy coupling into fuel – Experiments at Sandia



Experimental setup summary:

- ZBL defocused onto 2 mm thick polyimide LEH
- 10 T axial magnetic field applied
- XRFC observes LEH condition during experiment
- Laser enters thin walled tube filled with 123 psi D2 gas
- Blastwave driven radially outwards
- Time for blastwave to reach tube walls measured with point visar and PdV diagnostics

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Laser energy coupling into fuel – Possible Omega experiments

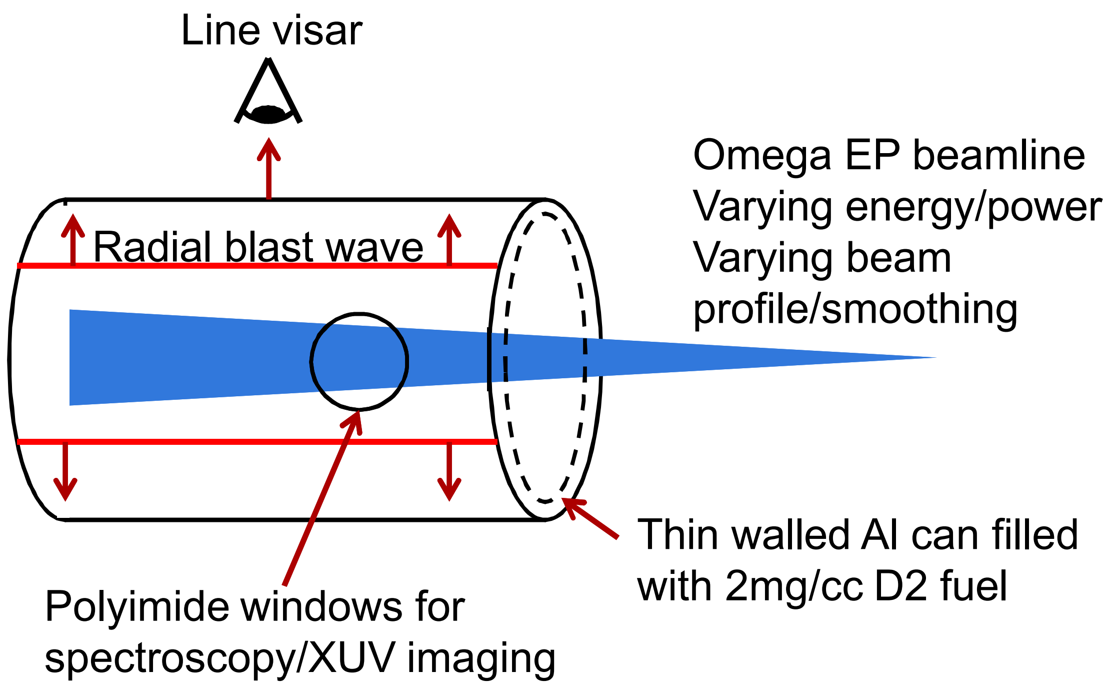
On ZBL we are limited to 2 kJ/ns energy and a non-ideal beam profile that is not typically measured and has no smoothing applied.

Planned upgrades to ZBL will keep power at ~1 TW and increase duration to ~6 ns giving 6 kJ of energy

Omega EP experiments may measure energy deposited using blast wave technique with line visar to measure shock timing

Omega EP parameters can be changed to optimize energy deposition by altering:

- Beam energy
- Beam power
- Beam smoothness



Summary

- There are multiple challenges and unknown associated with the MagLIF concept.
- Investigating fuel preheat and the effects of magnetization can be done at laser facilities such as Omega
- Experiments have been proposed that test the effects of fuel magnetization on electron thermal transport at MagLIF-relevant conditions
  - The results would be relevant to MagLIF and magnetized plasmas in general
- Experiments at Sandia are planned to measure laser energy deposition into a D2 fuel using the generation of a blast wave
- Experiments at Omega may be able to investigate optimizing laser energy deposition by adjusting beam parameters