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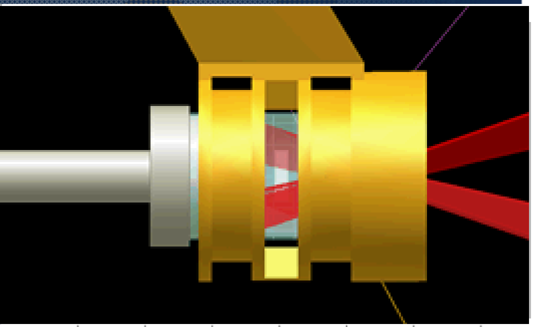

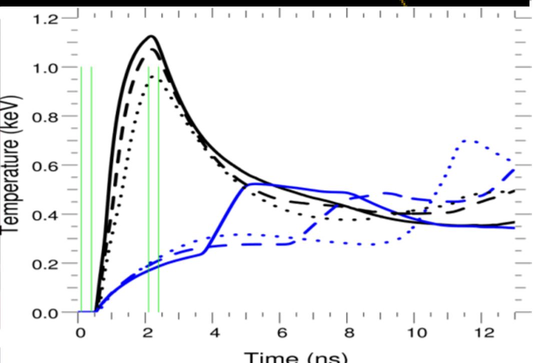

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Laser-only experiments in support of the Magnetized Liner Inertial Fusion scheme

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U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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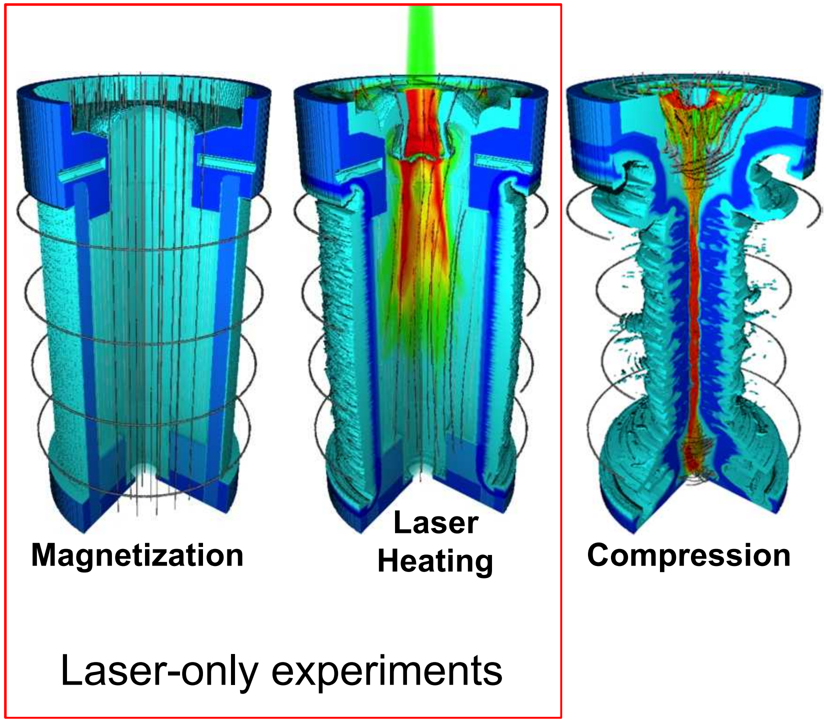
Magnetized Liner Inertial Fusion (MagLIF) concept needs to heat a gaseous fuel with e.g. a laser

- MagLIF [1] is an ICF scheme that uses the Z generator at Sandia National Labs (24 MA current, 100 ns risetime) to implode a cylinder containing the D2 fuel

- The implosion is slow (<100 km/s) – to achieve fusion we magnetize the fuel and preheat it with a laser – this reduces the velocity requirements

Magnetized Liner Inertial Fusion (MagLIF) scheme



Magnetization – suppresses electron thermal conduction preventing the fuel from cooling

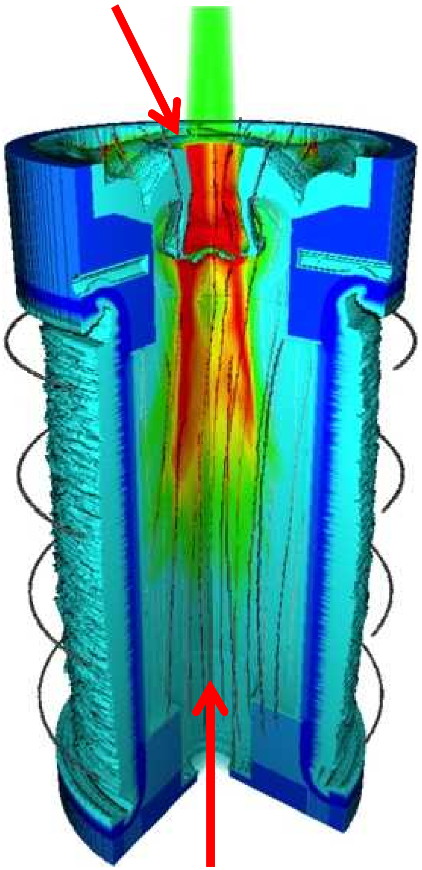
Laser heating – raises the fuel to an initial temperature allowing PdV work to be done

Compression – Heats the fuel through PdV work and compresses the fuel to higher densities

[1]: S.A. Slutz et al., Phys. Plasmas 17, 056303 (2010)

Laser-only experiments can address questions relating to preheat and magnetization

Laser preheat – transmission through LEH and coupling into gas



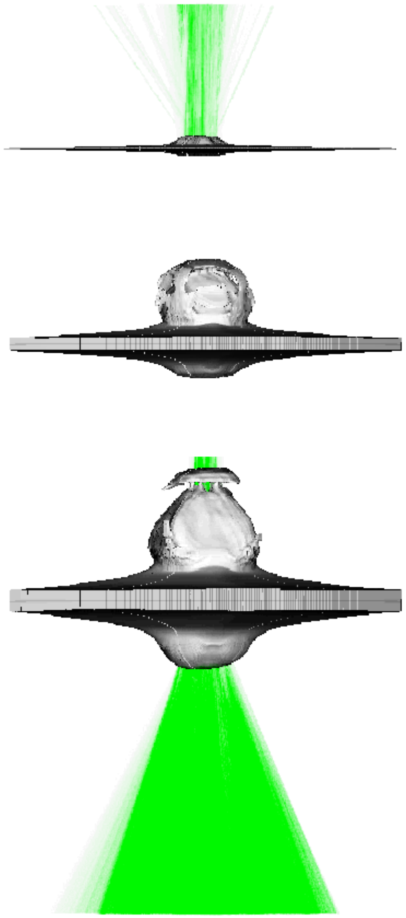
Applied B field - suppresses electron thermal conduction

- How do lasers deposit energy into underdense gasses and what factors affect this?
  - How does beam smoothing and magnetization affect energy coupling?
  - How is laser energy transmitted through laser entrance hole foils?
- How well does an applied magnetic field suppress electron thermal conduction at MagLIF-relevant conditions?
  - Take temperature measurements of laser-heated D2 plasma both during and after heating
  - Measurement accuracy sufficient to constrain simulations

Before entering the fuel ZBL needs to penetrate a laser entrance hole (LEH) foil

- High gas fill pressures require 'very thick' windows (e.g. >3 μm for 180 psig). These thicknesses are not well studied or understood.
- How much energy penetrates dependent on
  - Foil thickness
  - Laser spot size
  - Laser temporal pulse shape
  - Beam conditioning
- Structure of the beam may change after passing through an LEH affecting coupling to gas
- Dependence on beam conditioning necessitates investigation with the ZBL laser used in integrated MagLIF experiments

Simulation by C. Jennings

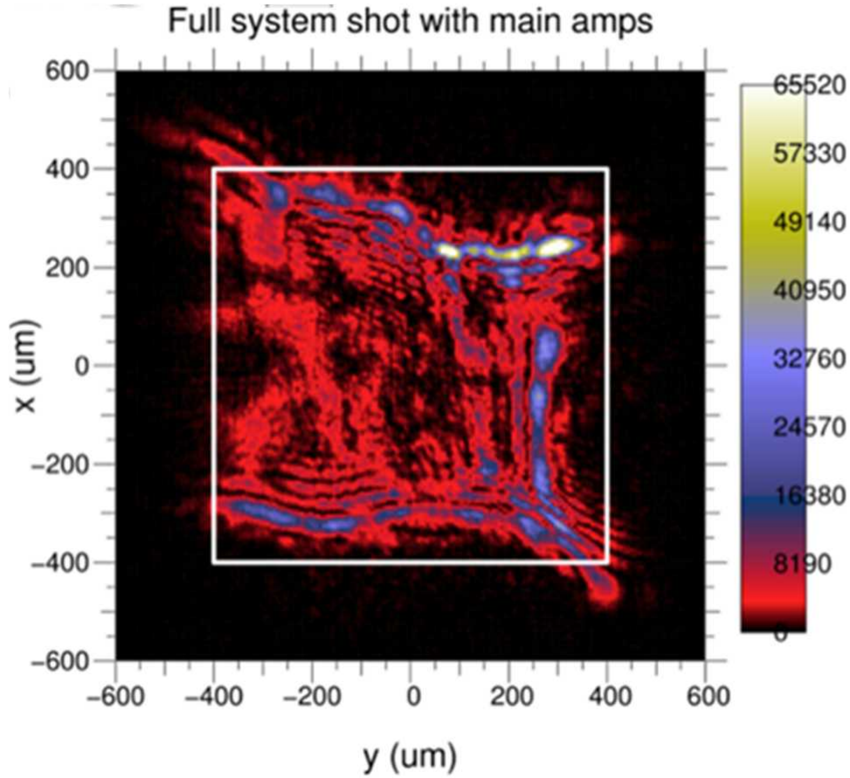


Laser preheat is complicated by ZBL conditioning and LPI

- ZBL currently has no smoothing applied – beam is highly non uniform
- Large F-number (10) and wavelength of laser (527 nm) put us above filamentation threshold for unsmoothed beam

$$\mathrm{FFOM} = \frac{I_p \lambda_0^2}{10^{13}} \left(\frac{n_e}{n_{\mathrm{cr}}}\right)\left(\frac{3}{T_e}\right)\left(\frac{f^\#}{8}\right)^2, \quad [1]$$

- Given these complications it's not certain how laser is behaving in the fuel
- Want to predict beam size required for good energy coupling – we need to address this uncertainty!



[1]. D. Froula et al., PRL 98, 085001 (2007)

April 2014 Omega EP experiments investigating fuel magnetization

MagLIF uses an applied magnetic field to suppress electron thermal conduction, keeping D2 fuel hot after preheat

Codes assume Braginskii transport – we want to test the validity in MagLIF-like conditions

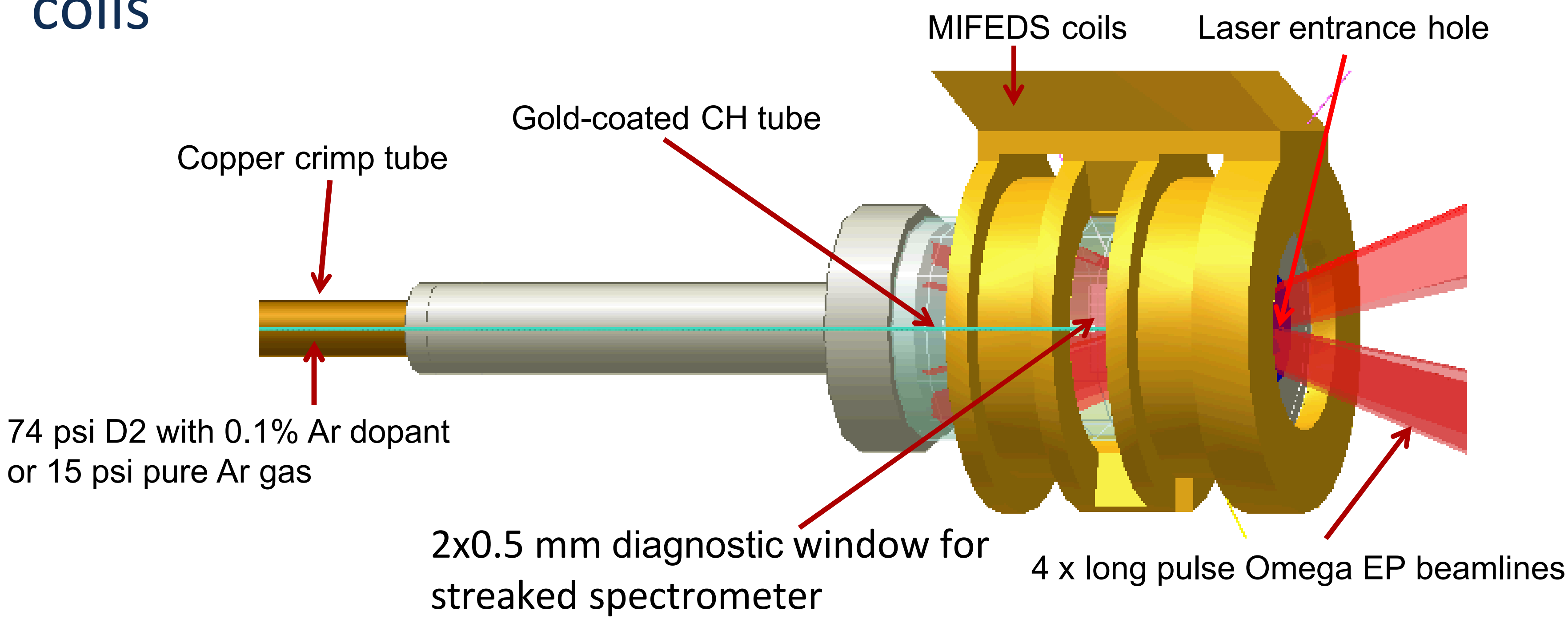
Experimental aims

- To test how magnetizing a D2 plasma affects its heating and cooling – is electron thermal conduction suppressed as we expect?

Physics Objectives

- Create a hot (>500 eV), magnetized (~11 T) D2 plasma using Omega EP long pulse beam lines
- Measure the temperature time history of the plasma using streaked spectroscopy (SSCA on SXS)
- Repeat the measurement with an unmagnetized plasma
  - Magnetized and unmagnetized data will be compared to HYDRA and LASNEX simulations

Targets were gas-filled CH tubes held within magnetic field coils



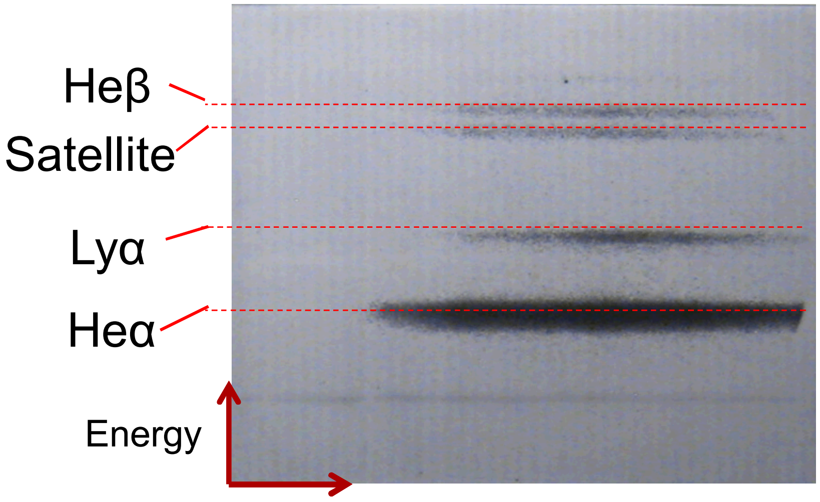
- Targets were 8 mm long, 5 mm diameter 75 um wall thickness CH tubes
- MIFEDS coils provided 10T B field ~uniformly along region of interest
- Temperature measured with streaked Ar K-shell spectroscopy through diagnostic window

Five targets were fired –

- 3 filled with 1 atm. pure Ar (2 unmagnetized, 1 magnetized)
- 2 filled with 5 atm. 0.1% Ar doped D2 (1 magnetized 1 unmagnetized)

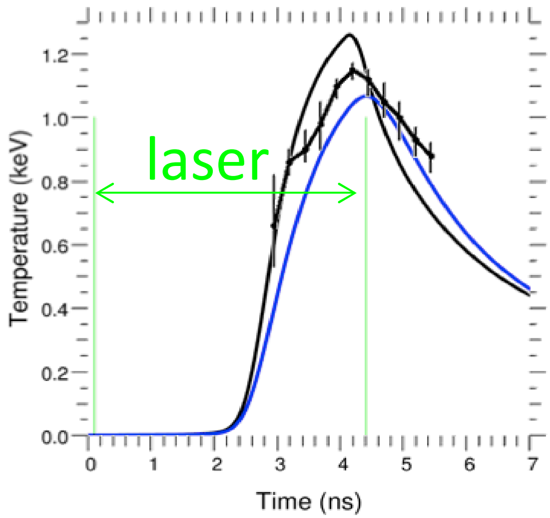
Ar filled targets showed good streaked spectra – Te in agreement with simulations

Raw streaked spectrometer data

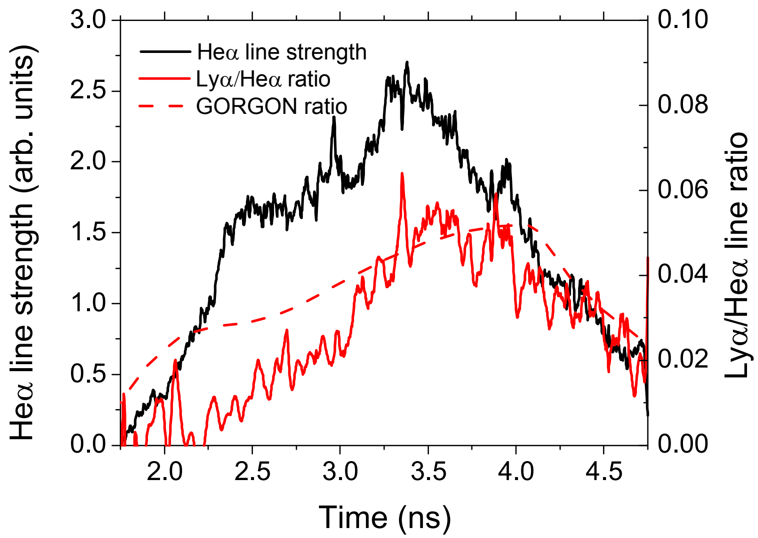


- Streaked spectrometer shows Ar K-shell emission as fn. of time from diagnostic window
- HYDRA and GORGON match heating of the Argon relatively well based on analysis of Lyα/Heα line ratio's

Temperature comparison to HYDRA



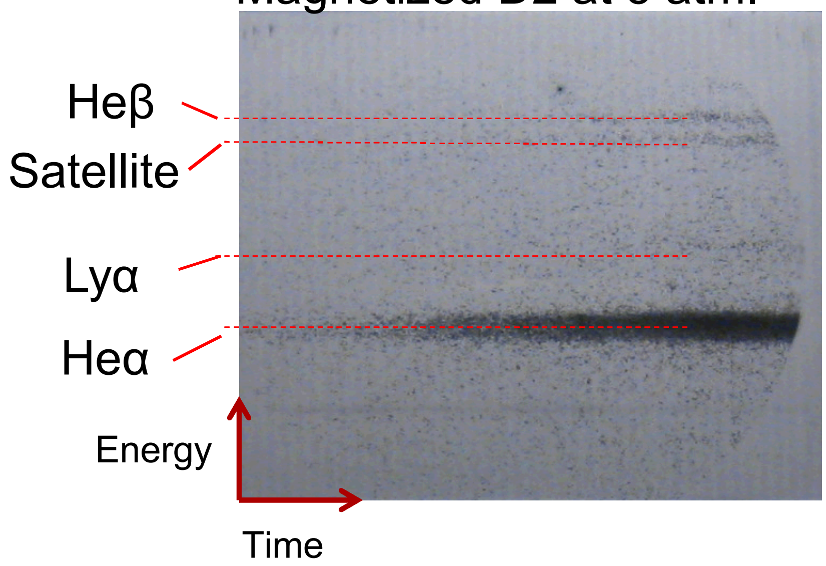
Line ratio comparison to GORGON



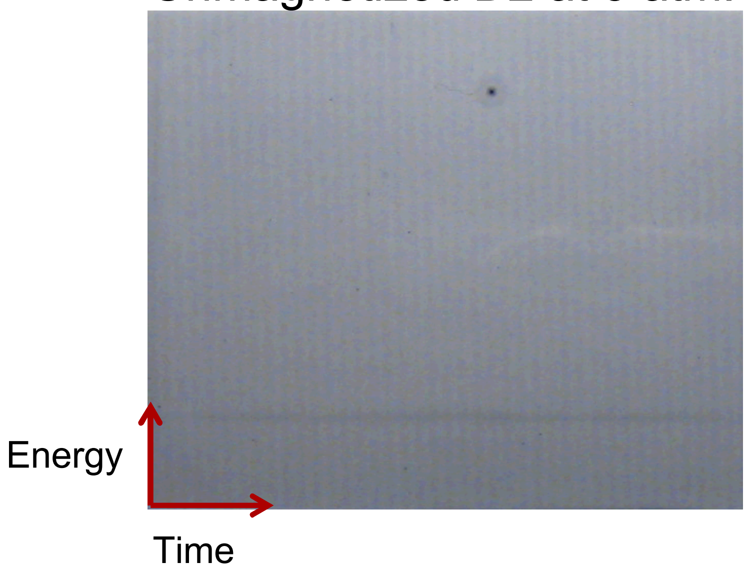
D2 filled targets showed big difference in streaked spectrum for magnetized vs. unmagnetized

- no spectrum for unmagnetized target!

Magnetized D2 at 5 atm.



Unmagnetized D2 at 5 atm.



- Targets filled with 5 atm D2 + 0.1% Ar dopant (by particle no.)
- Magnetized D2 shot returned spectrum unmagnetized D2 did not – possible indication of lower temperatures
  - Peak temperature of magnetized target 750-1000 eV
  - Temperature required for no observable spectra <500 eV (crude estimate)
- D-D neutrons measured in both shots – D2 was present in unmagnetized target!

Conclusions/Future work

- Beam propagation into Argon matches the simulations well – including initial analysis of plasma temperature

- Magnetized D2 experiments showed Ar K-shell emission and unmagnetized targets did not – possible indication of lower temperatures in unmagnetized experiments

- Maximum D2 pressure in targets was 5 atm (ne ~ 0.025 n_{crit}) – insufficient to effectively stop the beam future experiments will aim to increase this pressure to 10 atm.

July 2014 Omega EP experiments investigating laser absorption in underdense gasses

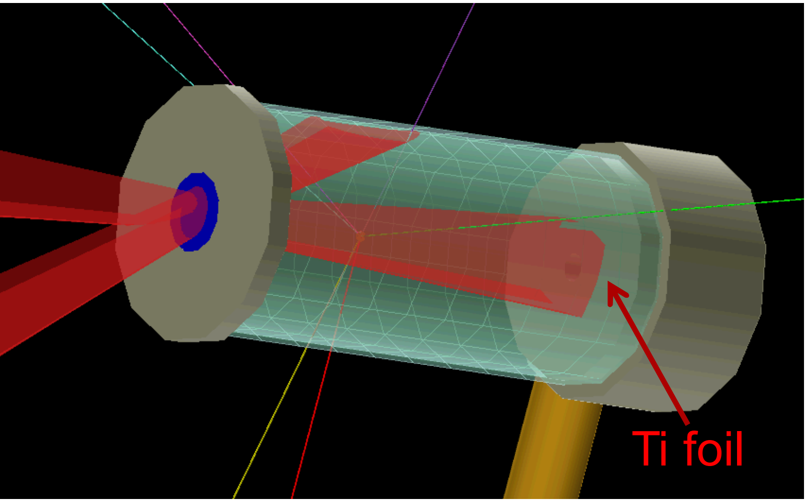
Laser energy is absorbed in an underdense gas by inverse Bremmstrahlung absorption – but high intensities can lead to complications from LPI including ponderomotive filamentation

Experimental aims

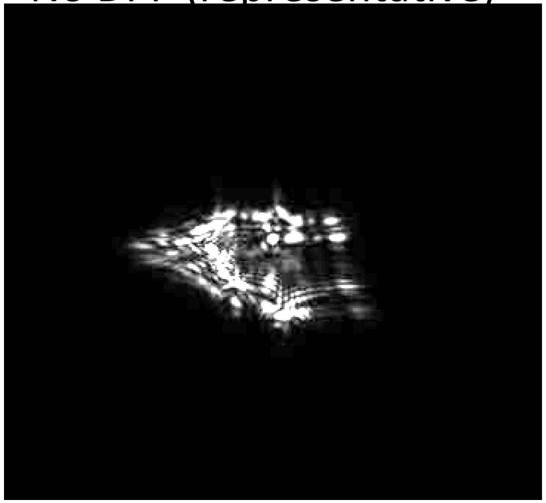
- Obtain data on beam propagation in underdense gases for code comparison
- Observe effect of removing phase plates on propagation of a laser beam
- Observe effect of thicker LEH on propagation of smooth/unsmooth beam

Targets were Ar filled CH tubes, beam energy, duration varied

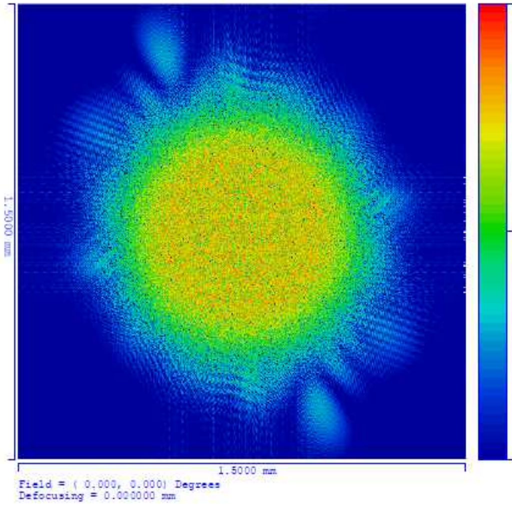
- Targets are 10 mm long CH tubes filled with 1 atm. Argon gas (n_e=0.05n_{crit}), 1 or 2 um LEH



No DPP (representative)

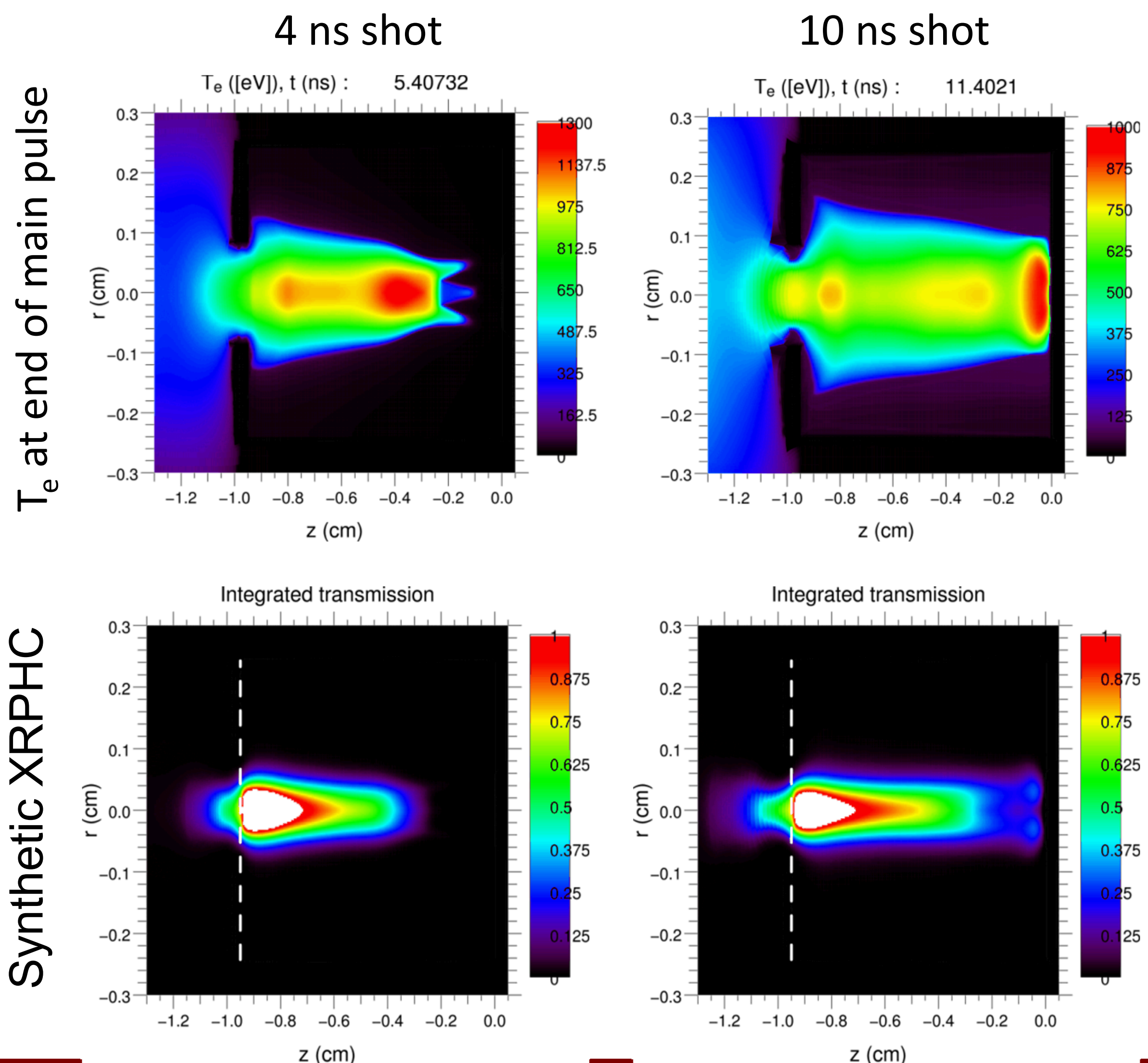


750um DPP



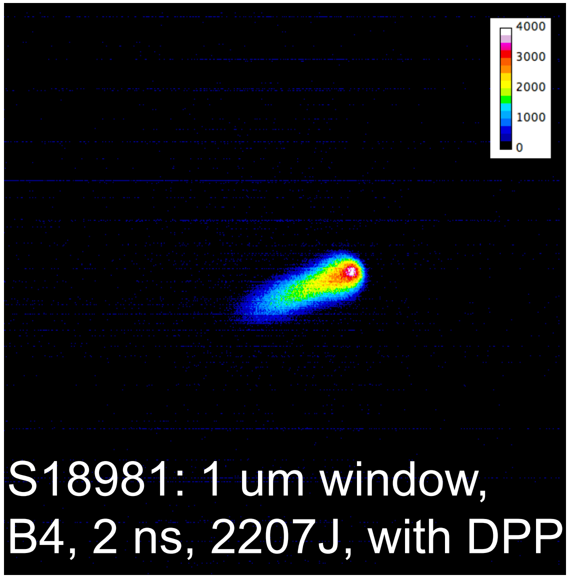
- Laser propagation observed with x-ray pinhole cameras, x-ray framing cameras and time resolved, spatially resolved x-ray spectrometer
- For DPP smoothed beam, FFOM<1, for unsmoothed beam FFOM>1 (estimated)

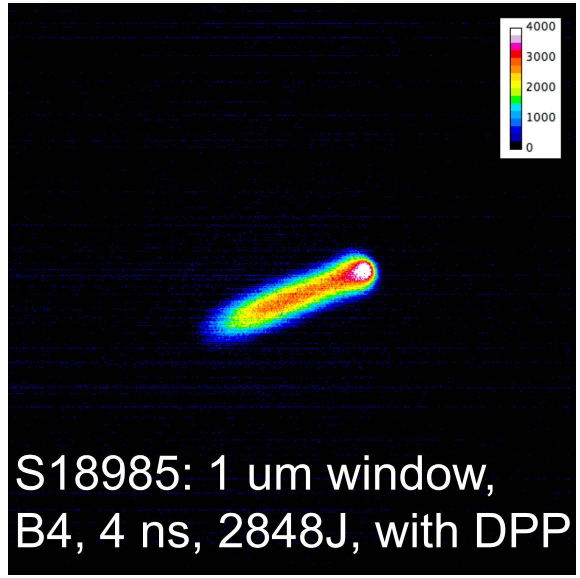
Hydra simulations show depth of propagation for varying beam durations (A. Sefkow)

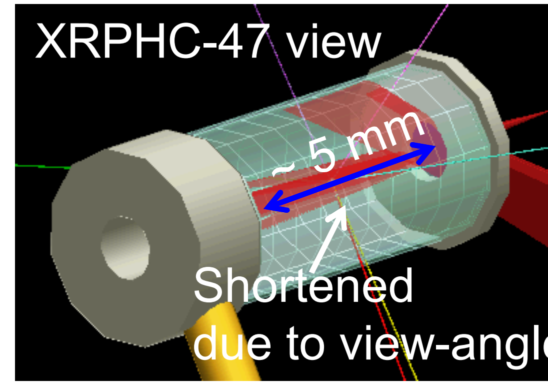


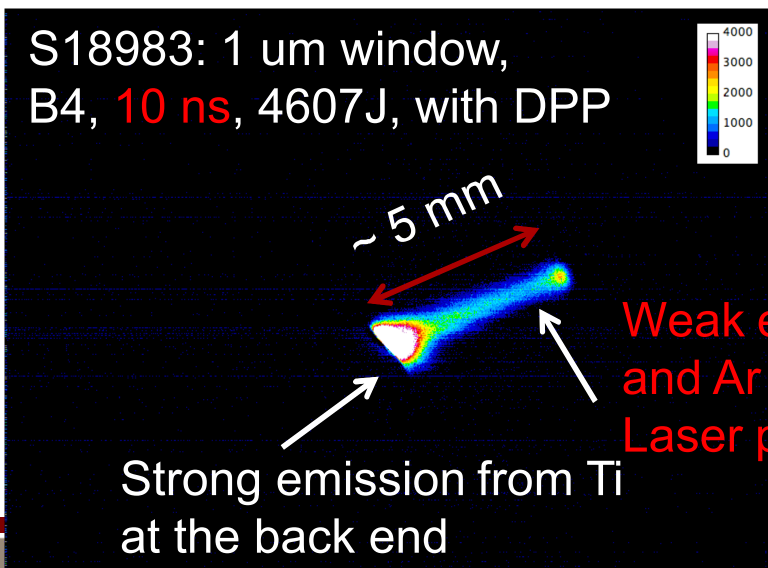
- 4 ns beam deposits energy before reaching back wall
- 10 ns beam reaches back wall – should hit Ti coated end-plug

XRPHC-47 showed laser propagation and heating dependence on laser pulse duration/power









Weak emission from LEH and Ar plasma due to lower heating Laser power and cooling

- **4 ns pulse shows good propagation along the axis with strong heating**
  - **Consistent with XRFC data**
  - **Consistent with HYDRA simulations**

X-ray framing camera images show beam propagation through the gas at different times

Shot 5

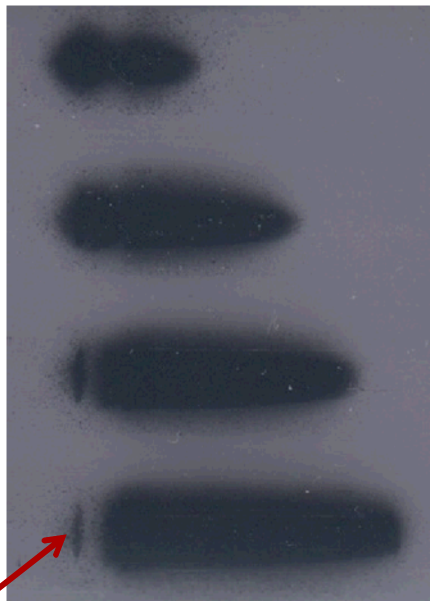
4 ns no prepulse 2 um LEH

1 ns

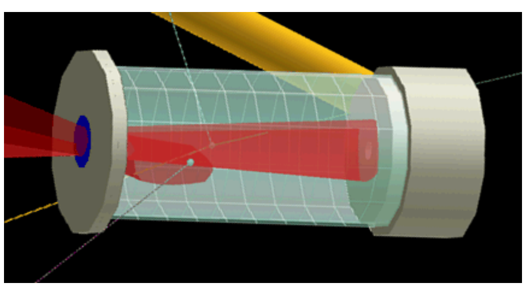
2 ns

3 ns

4 ns



LEH



Shot 4

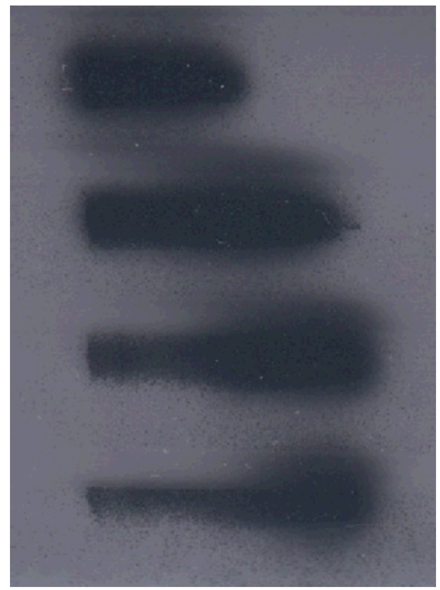
10 ns no prepulse 1 um LEH

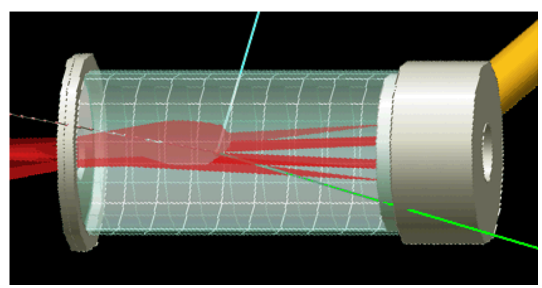
5 ns

6.1 ns

7.2 ns

8.3 ns

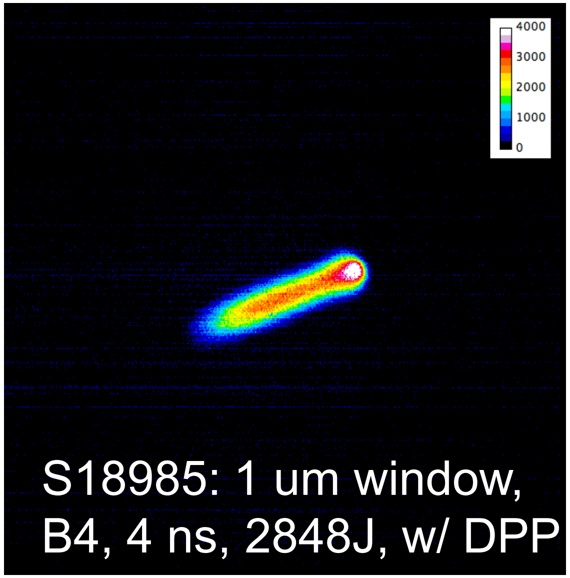


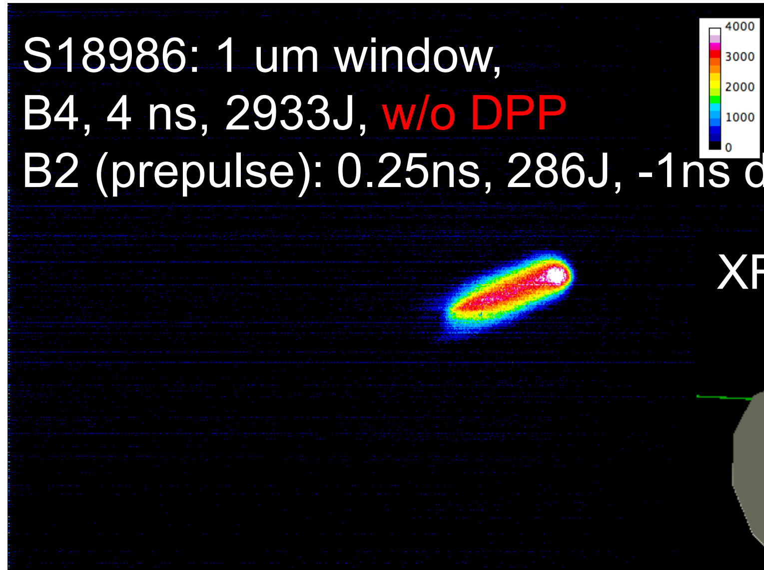


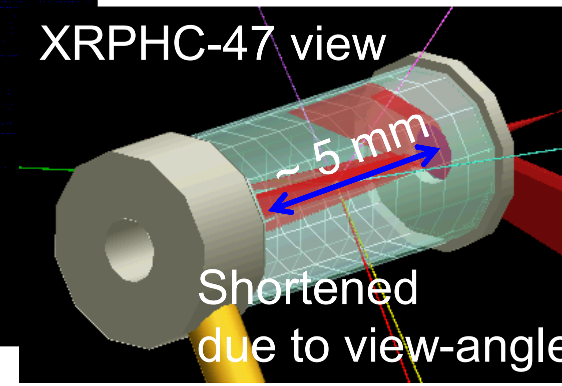
Framing cameras had 500 ps temporal resolution

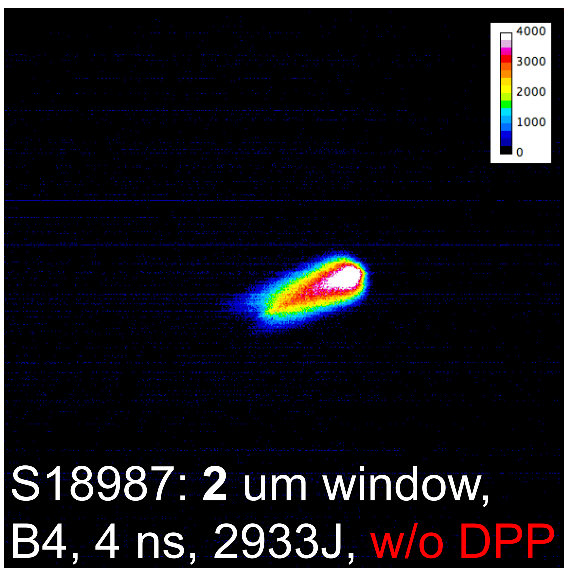
Quick scans shown only – awaiting final film scans

XRPHC-47 showed laser propagation and heating dependence on beam smoothing









- **Un-smoothed beam w/o DPP showed a shorter propagation distance with spreading sideway**
  - **Filamenation result in back and side scattering inhibit propagation**
- **Prepulse created plasma at LEH seemed to facilitate unsmoothed beam propagation**

ZBL experiments investigating laser transmission through foil windows (M. Geissel)

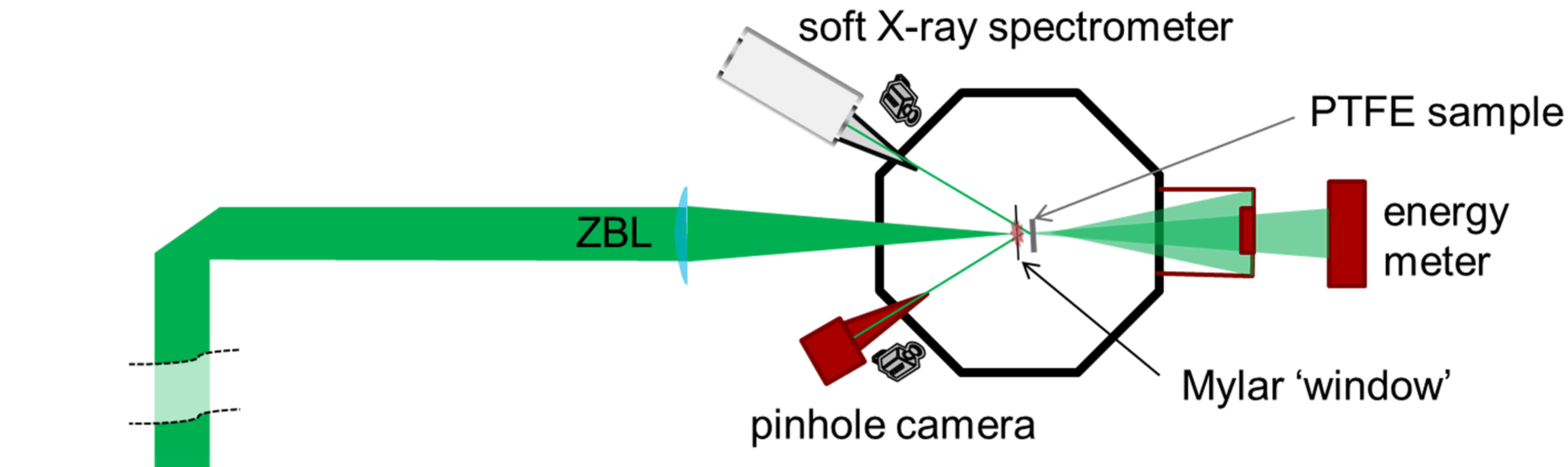
The LEH foils used in integrated MagLIF experiments are significantly thicker than those used in e.g. NIF targets (~3 um vs ~500 nm)

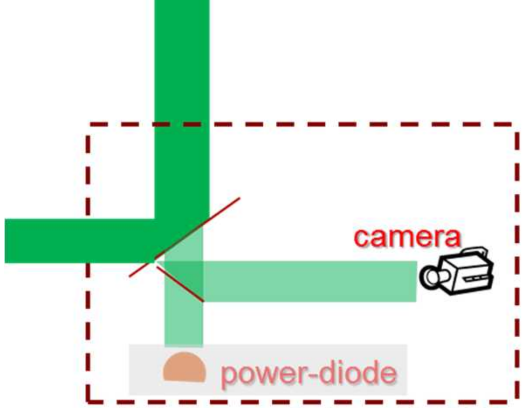
Absorption by the foils will limit the amount of laser energy entering into the MagLIF targets and hence their performace

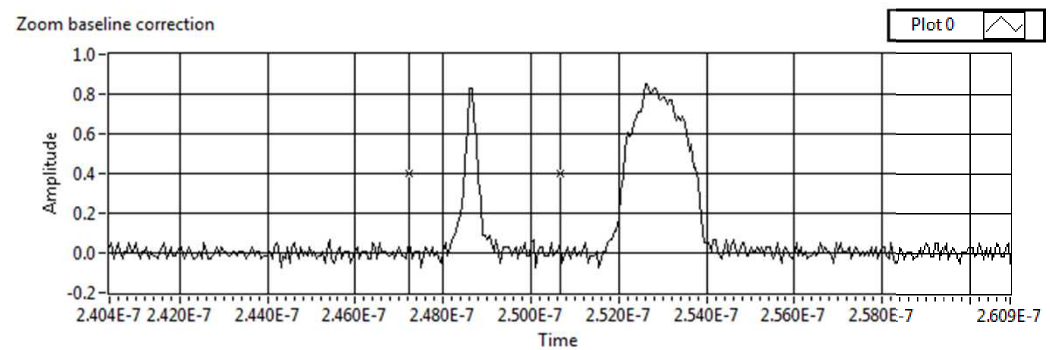
Experimental aims

- Measure the transmission of laser light through foil windows
  - Determine how much laser energy was transmitted into integrated MagLIF experiments
  - Optimize the setup for transmitting laser light (foil thickness, beam pulse shape, beam spot size, beam smoothing)
  - Observe the beam condition after passing through the LEH

The PECOS chamber is being developed for dedicated ZBL experiments

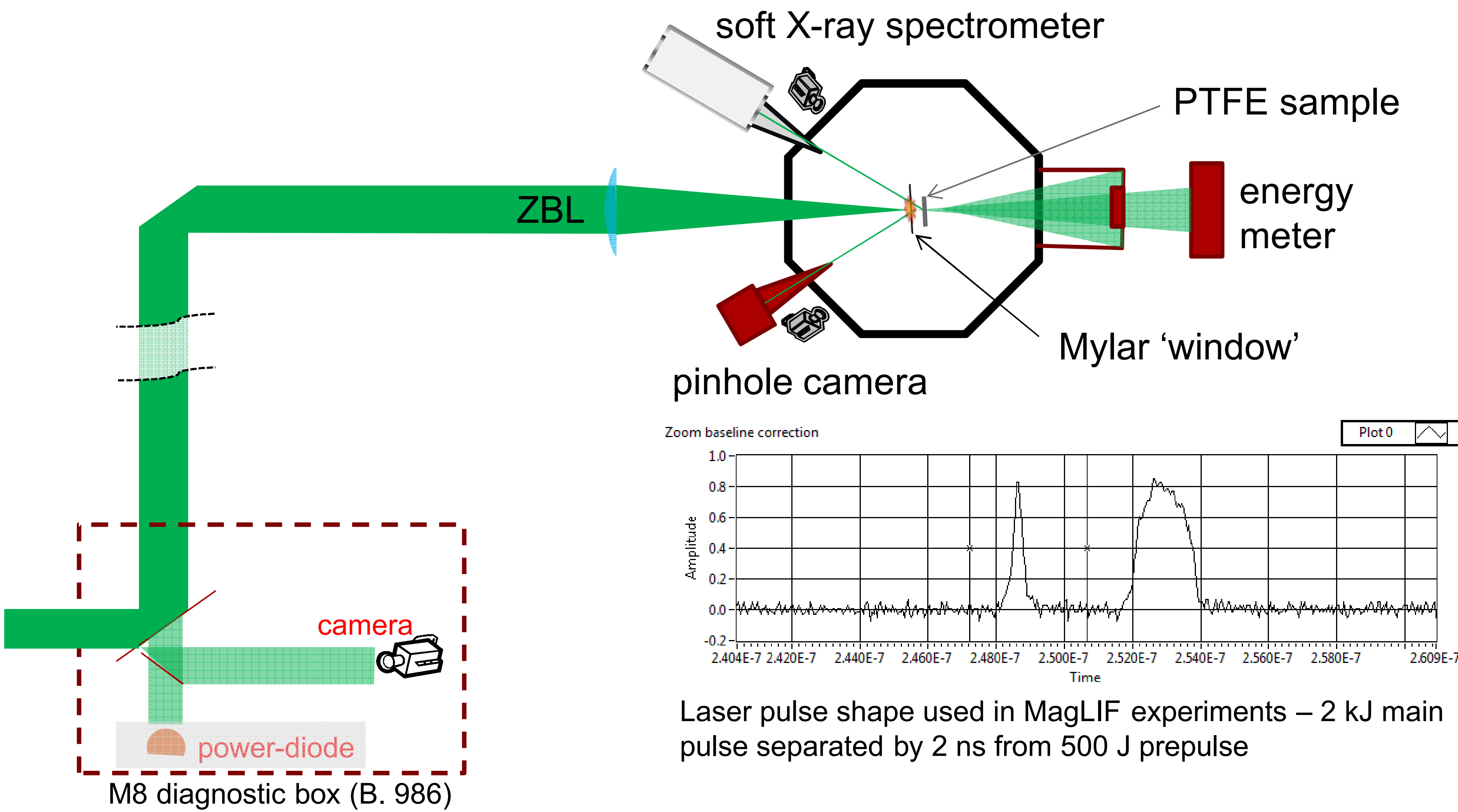






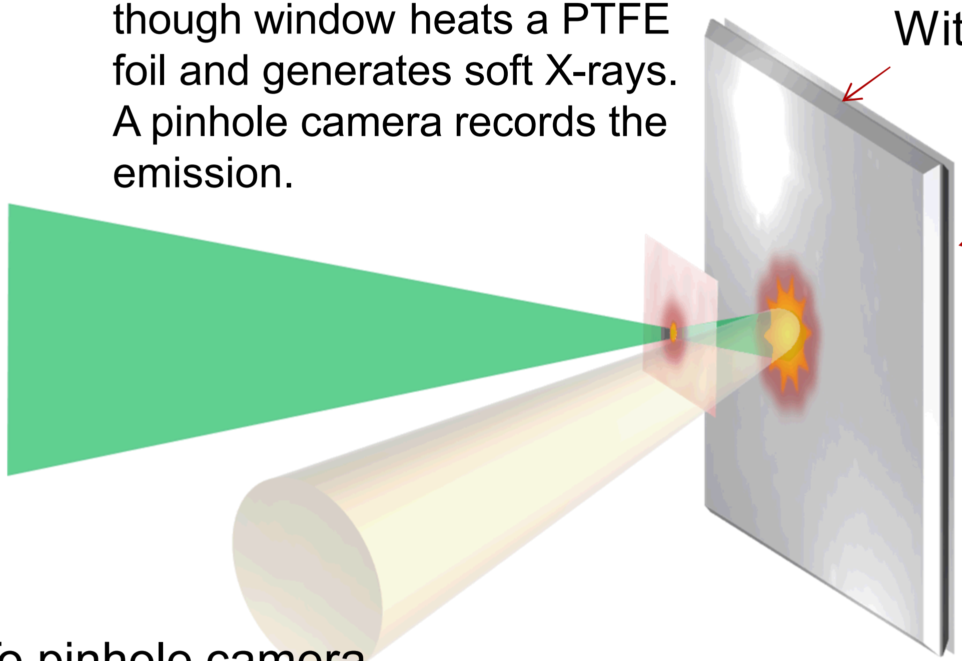
Laser pulse shape used in MagLIF experiments – 2 kJ main pulse separated by 2 ns from 500 J prepulse

The PECOS chamber is being developed for dedicated ZBL experiments

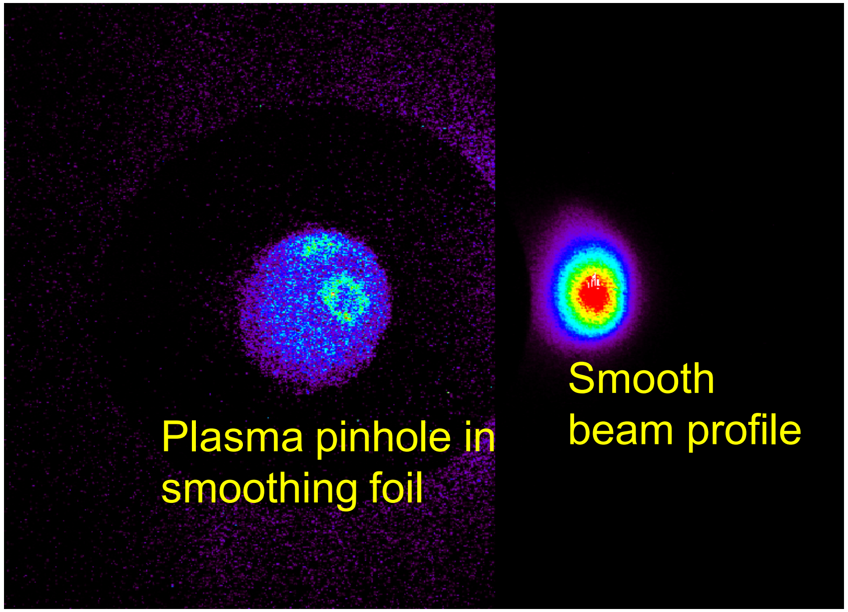


Laser pulse shape used in MagLIF experiments – 2 kJ main pulse separated by 2 ns from 500 J prepulse

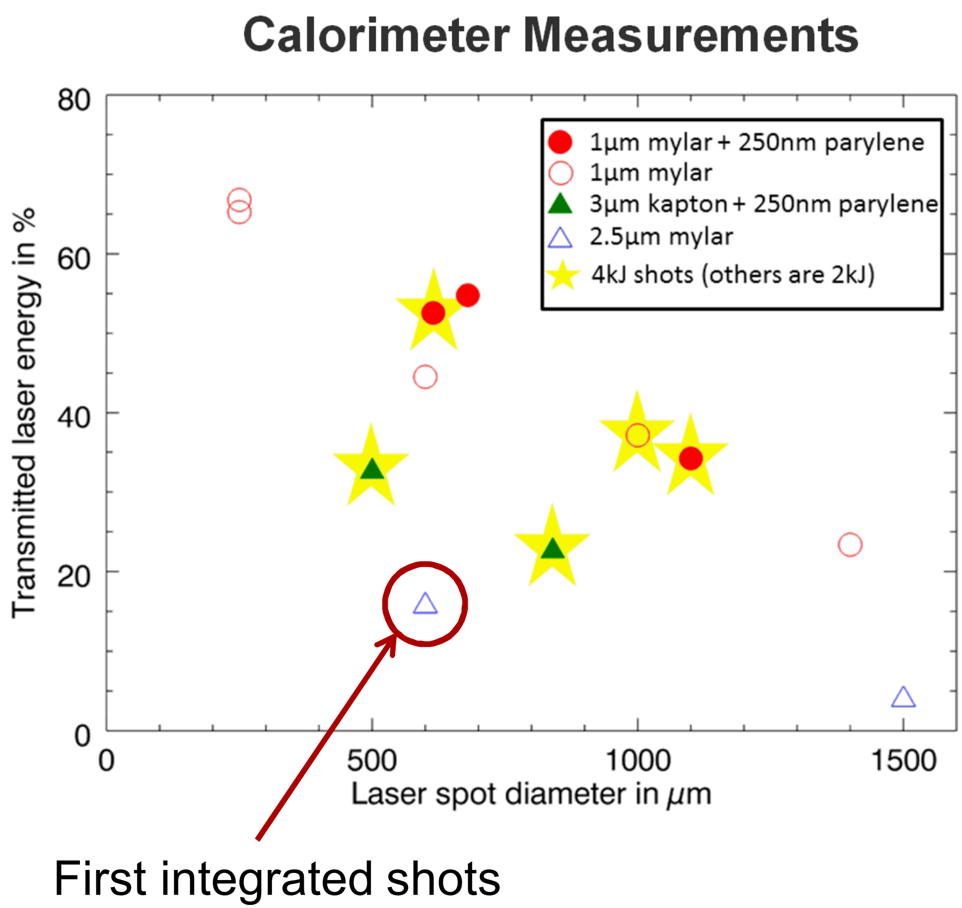
Thin (250 nm) mylar foil windows can smooth the beam profile without loss of energy



Measurement



Calorimeter measurements show that a lot of laser energy can be lost to the LEH windows



- Calorimeter collects light in ~original f/10 beam cone
- Data shows that a lot of energy is not transmitted for thicker foils and 2 kJ laser energy
- Improvements in transmission for 4 kJ laser energy and beams smoothed with foils
- Need to account for missing energy – is it scattered/reflected or refracted out of the beam cone?

Summary

- >50% of laser energy can be lost in LEH
- Pre-pulse is essential to transmission
- Adjustable smoothing can be achieved with sacrificial foil without additional energy loss
- Smooth beam behavior comes close to Hydra simulations

Outlook

- Increase flexibility with pre-pulse (e.g. longer separation)
- Temporal resolution for X-ray diagnostics
- Implement gas-filled target cell with/without magnetic coils ('stand-alone')