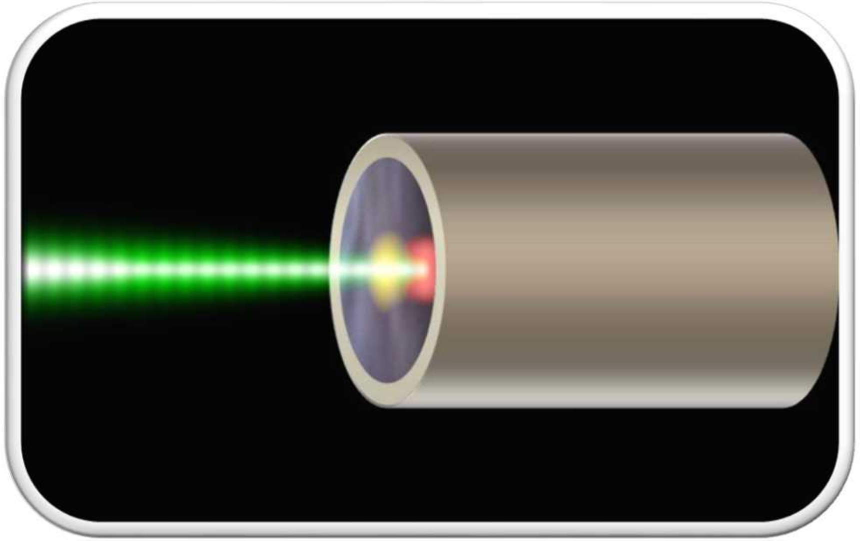
SAND2016-0763C

Delivering Kilojoules of Pre-Heat to Fusion Targets in Sandia's Z-Machine:

Or: Why do we care about nonlinearities in laser-plasma interactions?

Exceptional service in the national interest

Sandia National Laboratories



Matthias Geissel

T.J. Awe, E.M. Campbell[†], M.R. Gomez, E. Harding, A.J. Harvey-Thompson, S.B. Hansen, C. Jennings, M.W. Kimmel, P. Knapp, S.M. Lewis[††], R.D. McBride, K. Peterson, M. Schollmeier, A.B. Sefkow, J.E. Shores, D.B. Sinars, S.A. Slutz, I.C. Smith, C.S. Speas, R.A. Vesey, and J.L. Porter

Sandia National Laboratories

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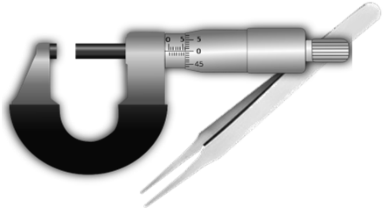
Non-linear Physics with Lasers

Dominant fields (e.g. this conference):
- Frequency combs
- Higher harmonics
- Nonlinear materials
- High intensity effects in solids/fibers

Characteristic parameters:
- **Femto- to picosecond pulses**
- **Micro- to millijoule pulse energies**
- **Kilo- to megahertz rep-rate**
- **Nondestructive interaction**



This presentation:

2-4 kJ, few ns, 1-3 shots/day, targets fully destroyed.

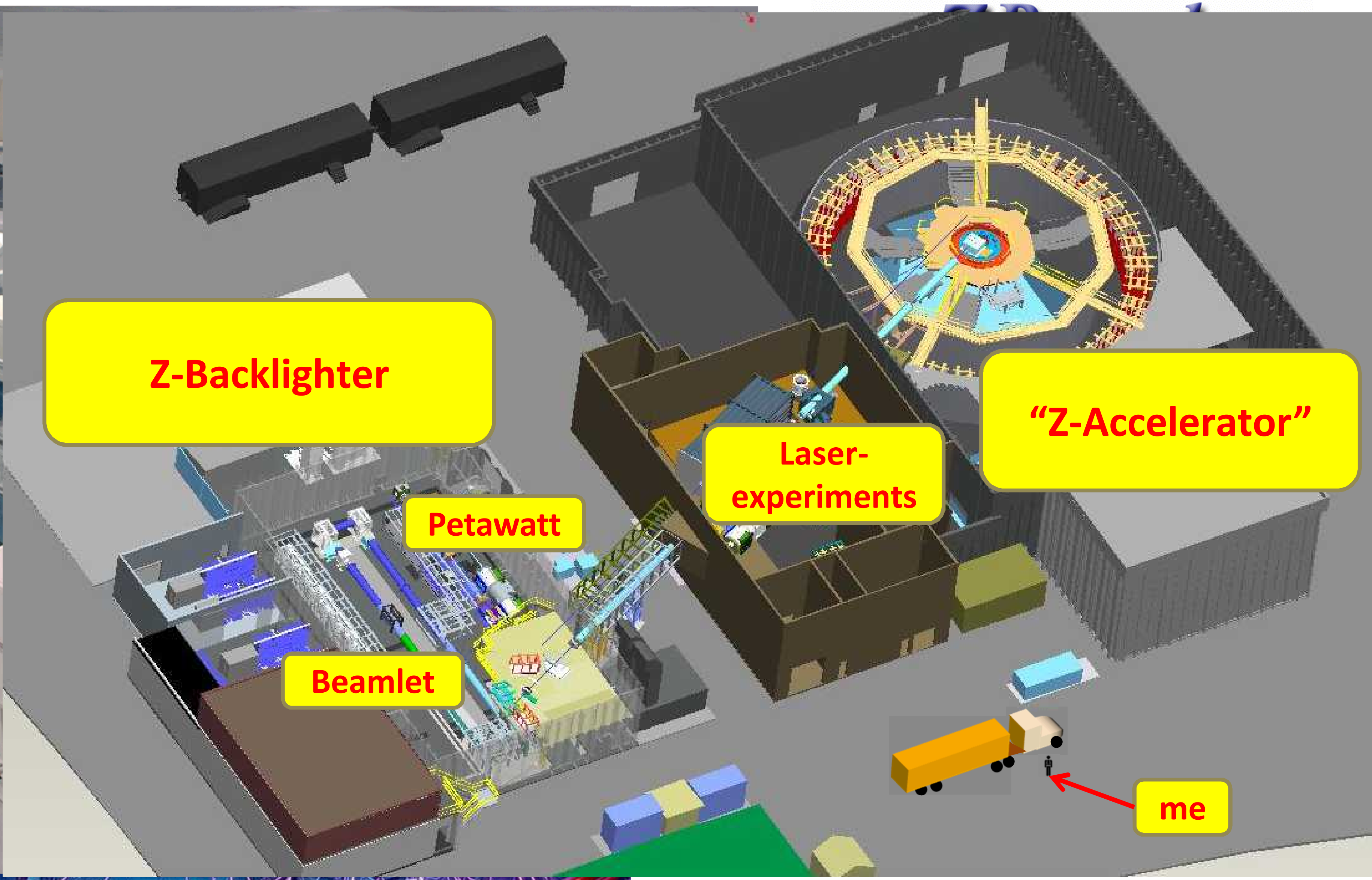
So What?

~~Understanding the workings of a Sledgehammer is straight forward.~~

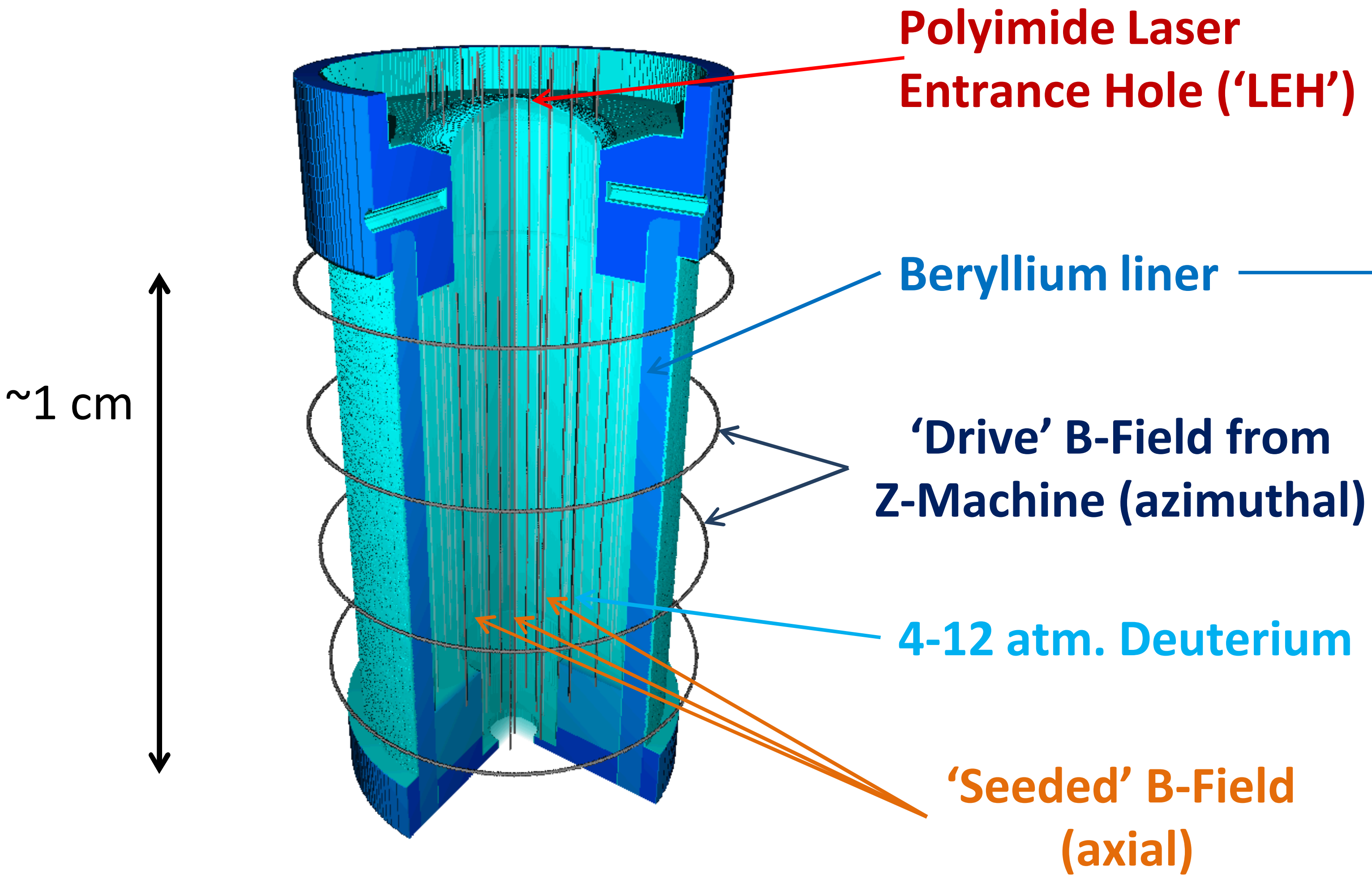
… not in the world of lasers

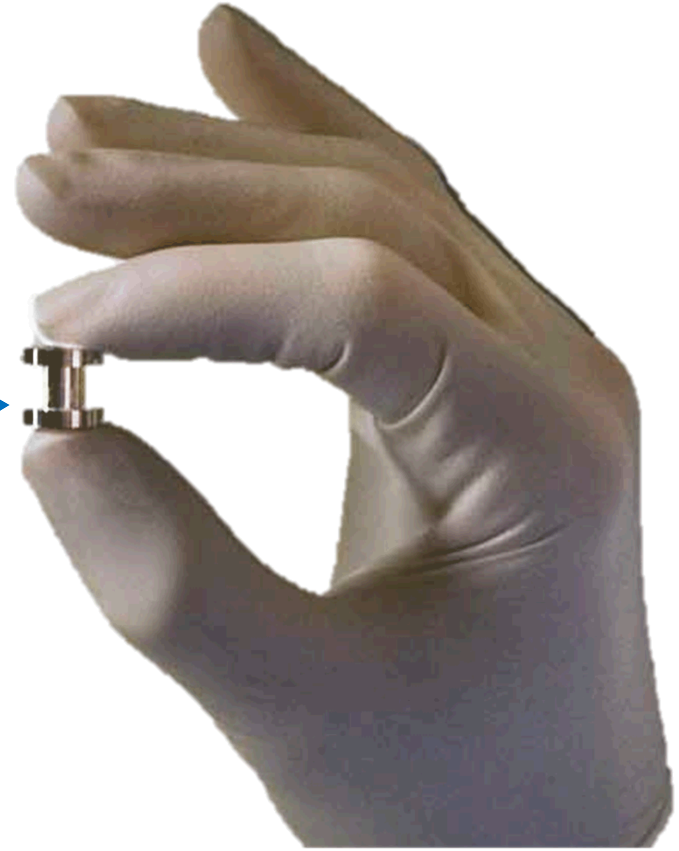
Contents

Sandia National Laboratories' Pulsed Power Center



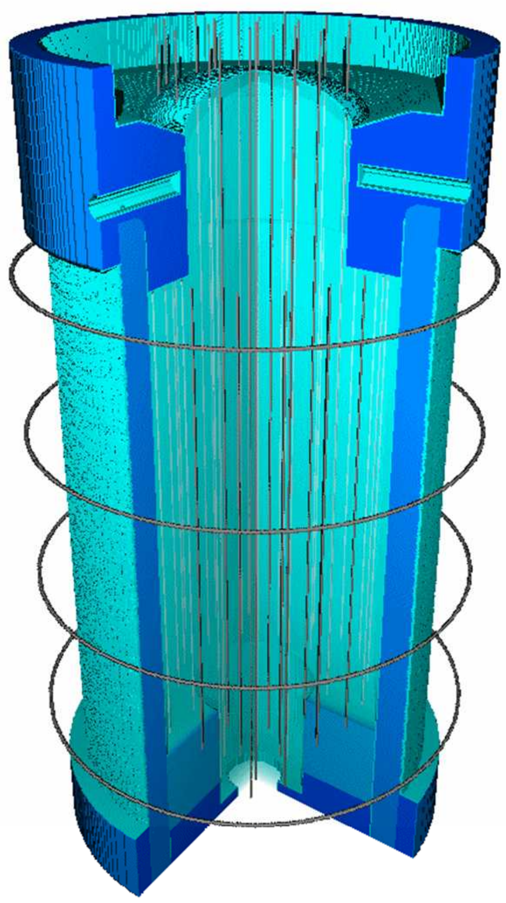
Magnetized Liner Inertial Fusion (MagLIF)





S.A Slutz et al.:
Physics of Plasmas **17**, 056303 (2010)

Magnetized Liner Inertial Fusion (MagLIF)



Phase 1:
B-Field from Z's Drive-Current starts to compress liner (and fuel)

Phase 2:
Z-Beamlet injects several kilojoules of pre-heat into fuel

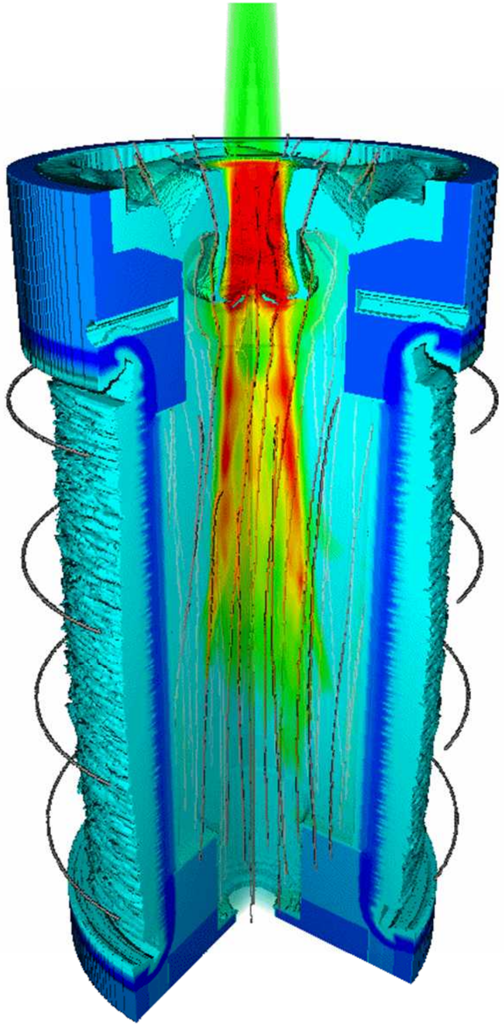
- Magnetization of fuel
- Minimization of heat conduction losses
- B-Field Compression possible
- $T_{compressed}$ is proportional to $T_{preheat}$

Movie: Courtesy of C. Jennings

ZBacklighter

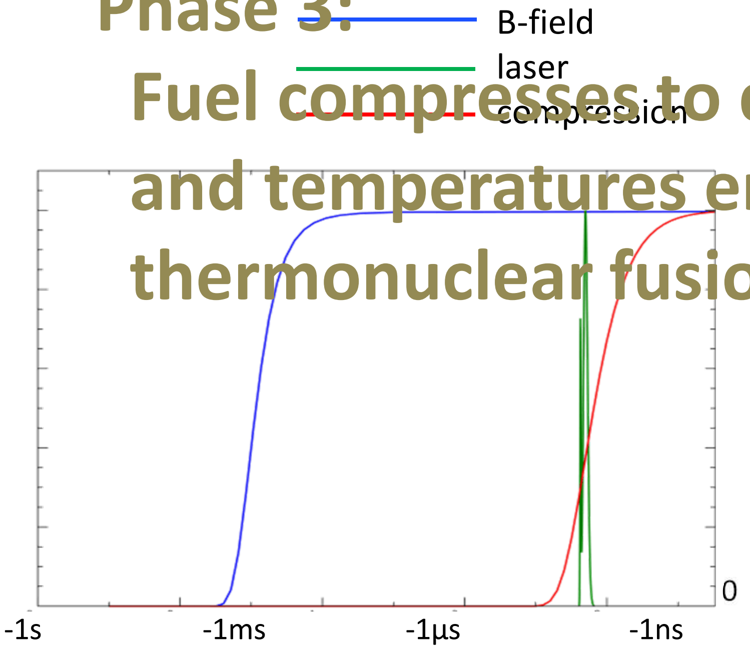
Magnetized Liner Inertial Fusion (MagLIF)

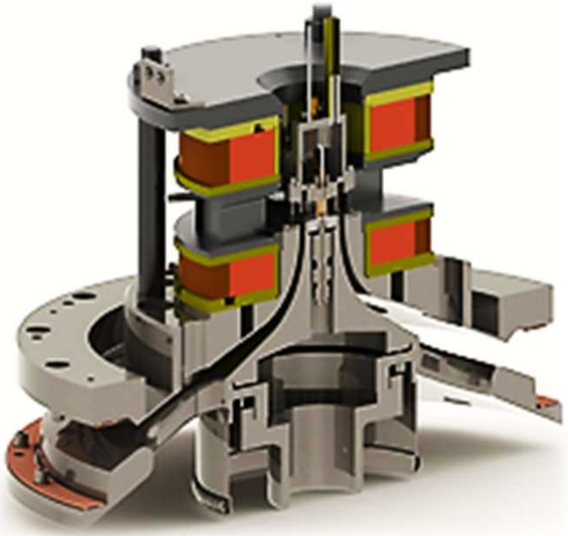
Sandia National Laboratories



Phase 3:

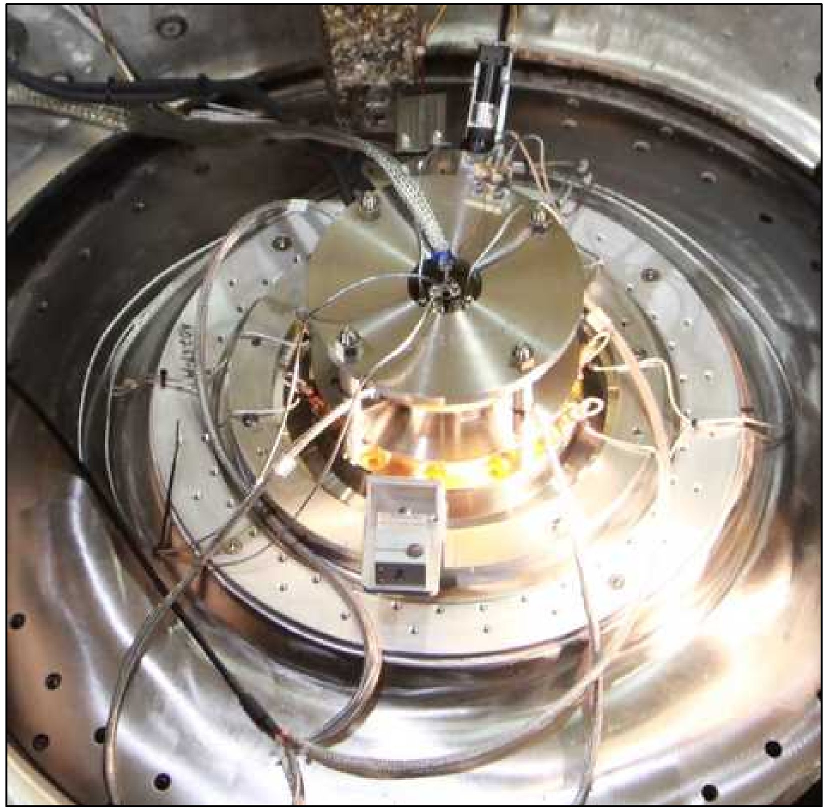
Fuel compresses to densities and temperatures enabling thermonuclear fusion





MagLIF experiments are “a bit destructive”

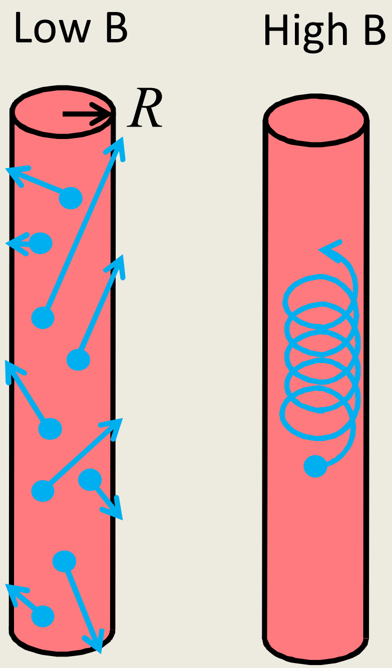
Before



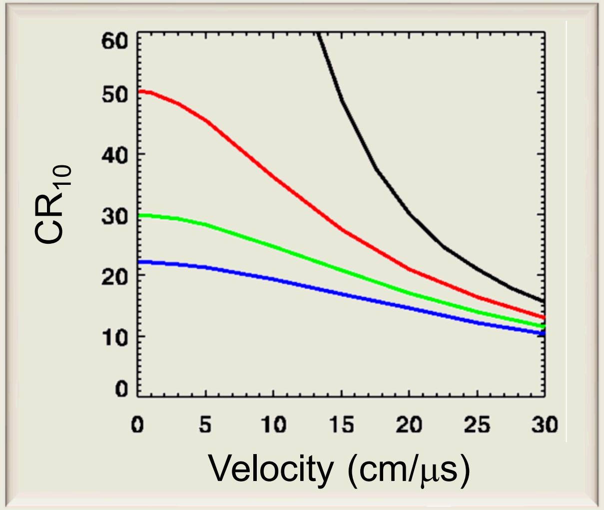
After

Once Again: Why initial B-Field and Pre-Heat?

The axial B-Field inhibits heat conduction



An initial temperature relaxes compression requirements

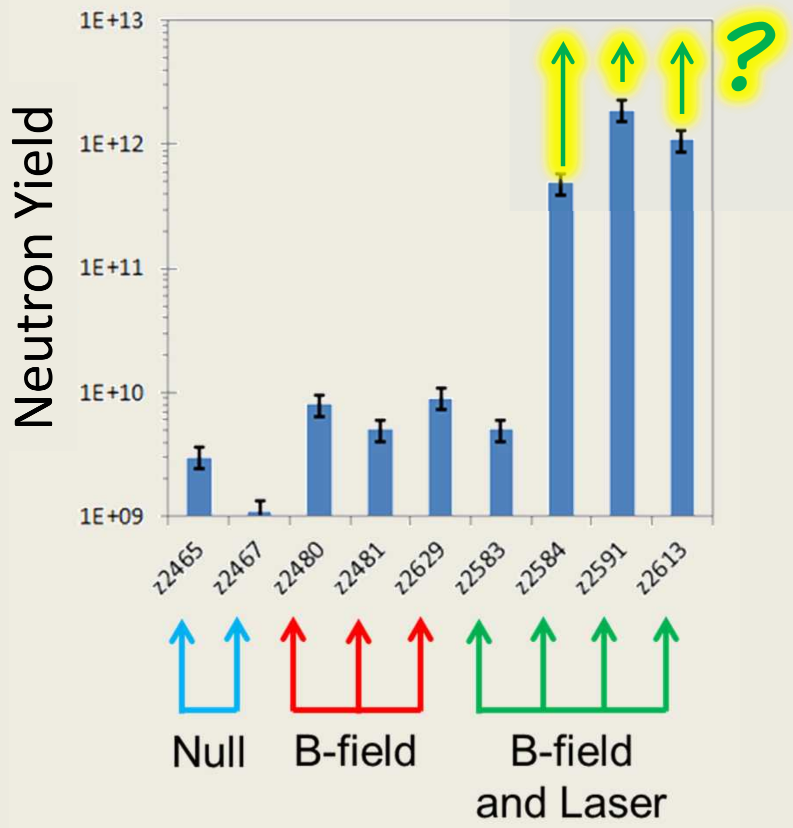


Initial Temperature:

--- Room-temp.
--- 50 eV
--- 100 eV
--- 150 eV

(CR_{10}: R_{start}/R_{end} req. for 10 keV.)

Early MagLIF Experiments in Z



Gomez *et al.*: *PRL* **113**, 155003 (2014).

Pre-Heat Challenges

Ideal World vs. Real World

(nonlinear laser-plasma interaction)

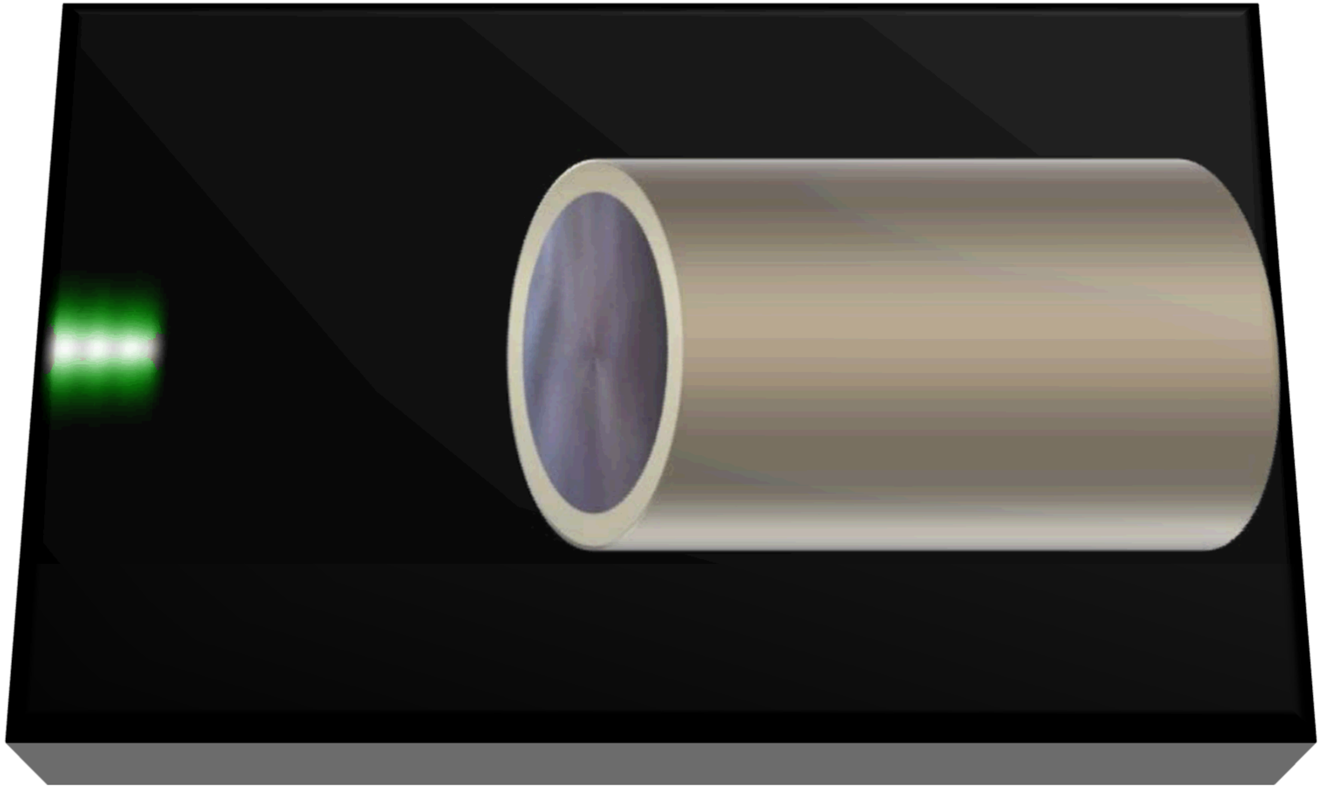
IF Pre-Heat Behaved

Absorption ***K*** via inverse Bremsstrahlung:

$$K = \frac{\frac{\nu_{ec}}{c}\left(\frac{n_e}{n_c}\right)^2}{\sqrt{1-\frac{n_e}{n_c}}} \propto \frac{1}{T^{3/2}} \cdot \frac{\left(\frac{n_e}{n_c}\right)^2}{\sqrt{1-\frac{n_e}{n_c}}}$$

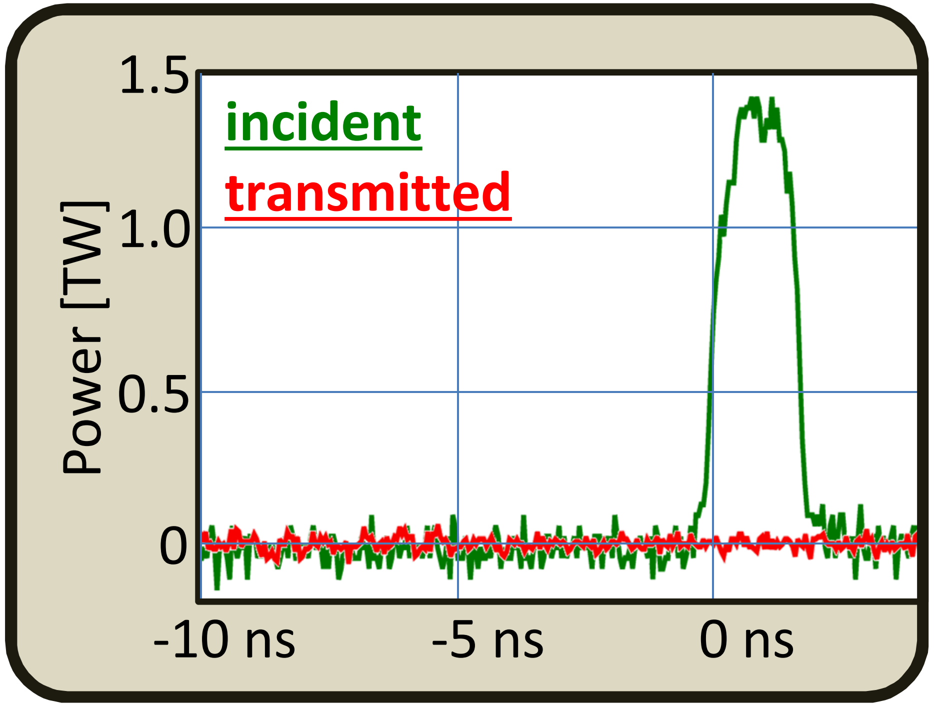
Absorption is lower with higher temperature

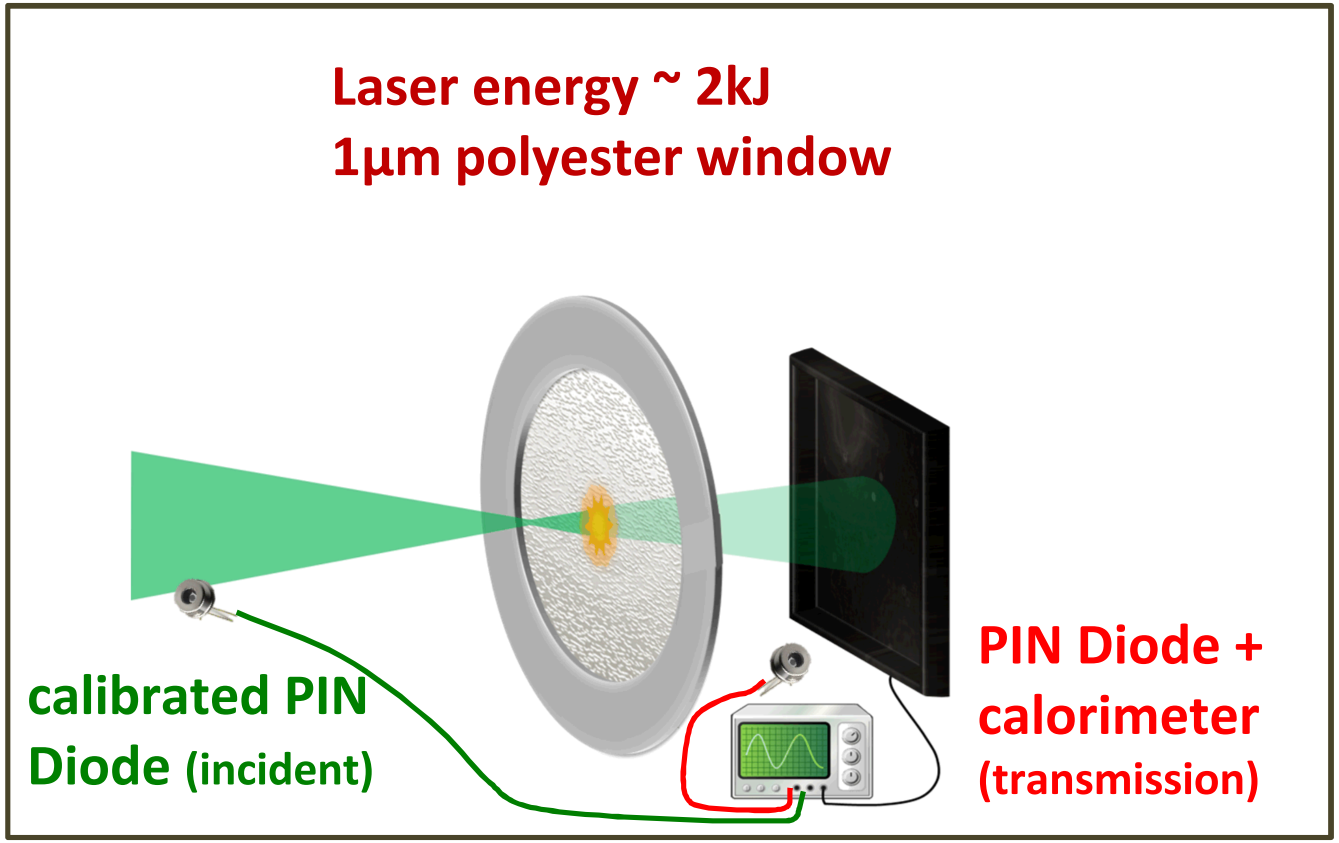
Absorption is higher with higher electron density



How Pre-Heat Actually Behaves

(a first indication: window transmission)





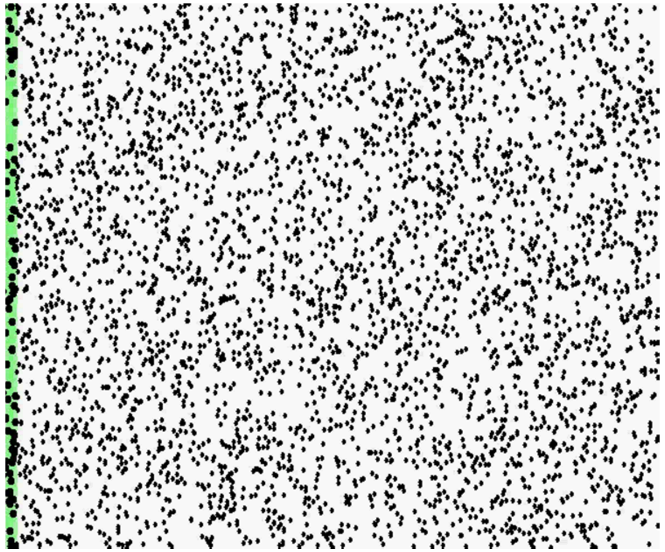
Possible dilemma:

- Too large laser spot doesn't efficiently destruct window
- Too small laser spot may drill through fuel too fast

LPI: Laser-Plasma Instabilities 1

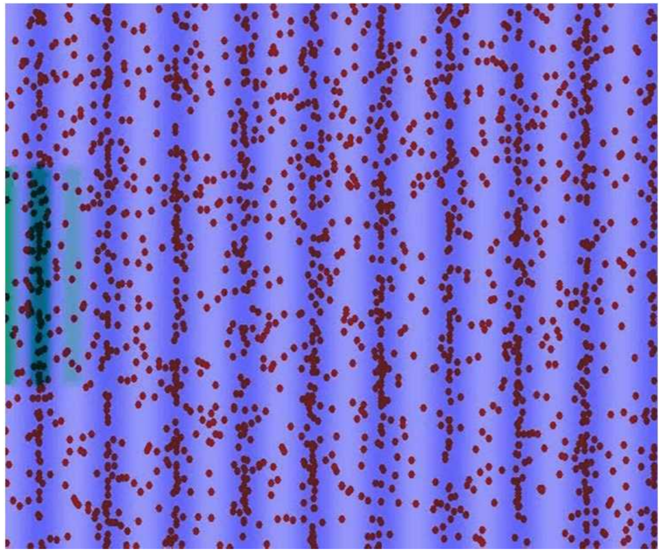
(A Line-up of Common Suspects)

Basics: Laser Driven Electrostatic Waves



- Laser energy is transferred to plasma oscillations.
- Resonant process
- Driver for instabilities

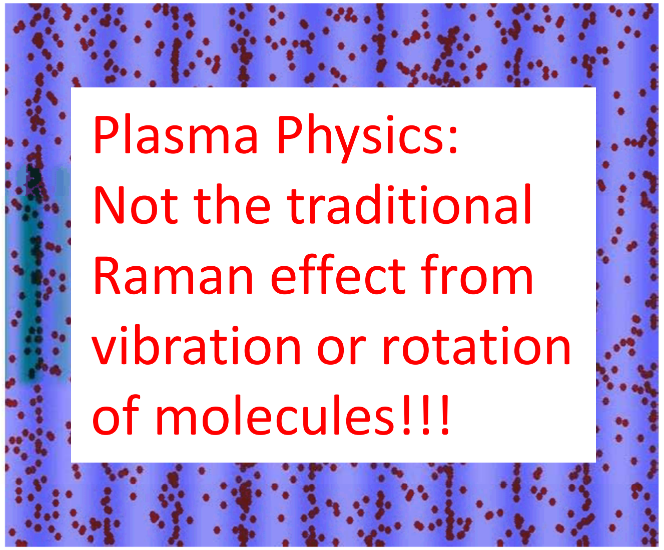
Stimulated Brillouin Scattering (SBS)



e^--gas ions

- Momentum transfer to ions (ion acoustic wave/soundwave)
- Little energy transfer
- Small wavelength shift for scattered wave

Stimulated Raman Scattering (SRS)



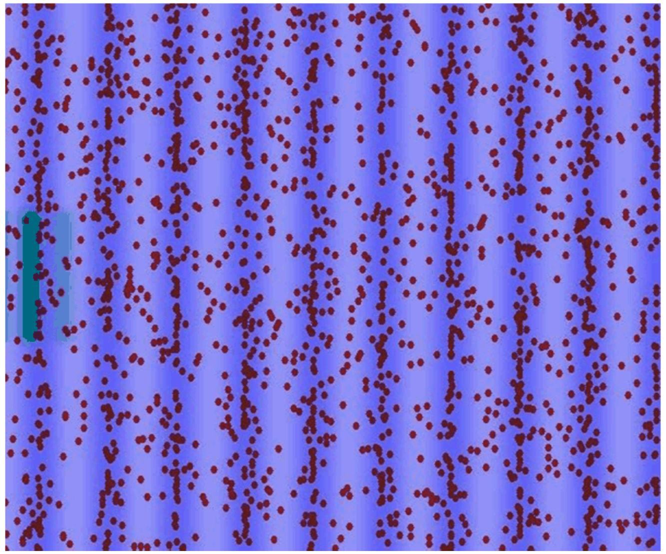
e^--gas ions

- Momentum transfer to electrons (electron plasma wave/ω_p plasmon)
- Stronger energy transfer
- Red-shift of scattered wave
- Generation of hot electrons likely

LPI: Laser-Plasma Instabilities 2

(A Line-up of Common Suspects)

Only at $n_e = ¼\, n_{crit}$: Two-Plasmon-Decay

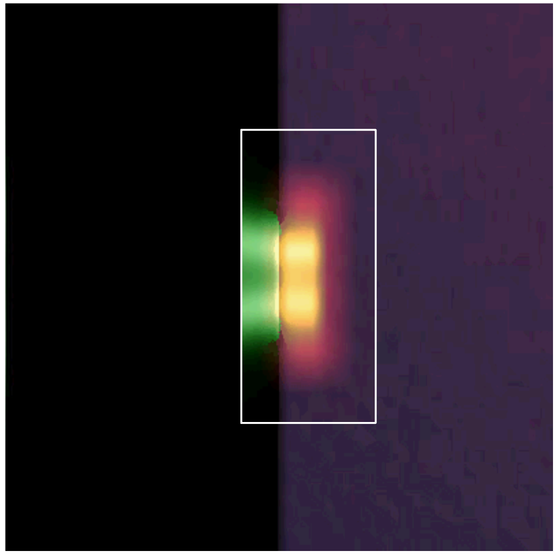


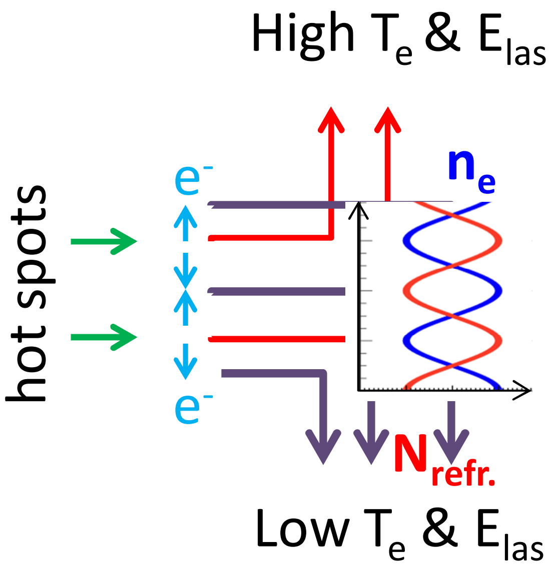
e^--gas ions

- Absorption of photon
- Hot electrons very likely
- Not possible in low plasma densities ($n_{e,max} < ¼\, n_{crit}$)
- Can occur during LEH heating and expansion

$$\omega_p = \sqrt{\frac{n_e}{n_{crit}}} \cdot \omega_{las} = \frac{1}{2}\omega_{las} \Big|_{n_e=\frac{1}{4}n_{crit}}$$

Self-Focusing and Filamentation



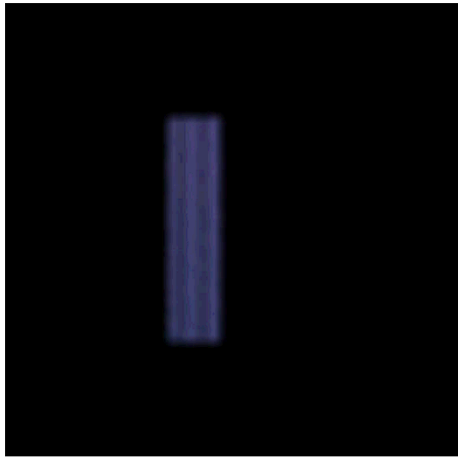


- Heat transport and ponderomotive force **expel electrons from hot spots**
- Refractive index in hotspots increases: $N^2 \propto (1-n_e/n_{crit})$
  - ➢ Focusing effect!

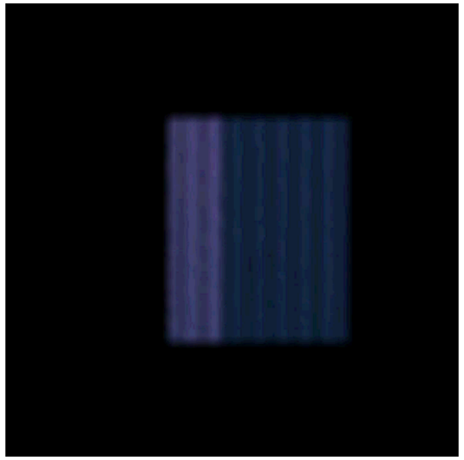
LPI: Laser-Plasma Instabilities 3

Good to know…

Thin and dense plasma



Add thick but less dense plasma



Line Density and Volume Matter!!

LPI grows exponentially with propagation depth ℓ:

$$E_{LPI} \propto \mathrm{EXP}\,(\kappa \cdot \ell)$$

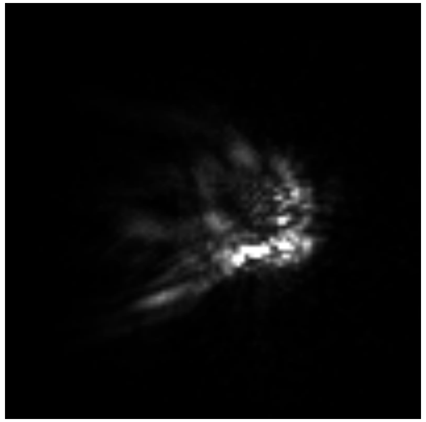
The Gain κ increases

- inversely with $n_{crit} \propto (\omega_{laser})^2$
- linearly with I_{laser}
- linearly with n_e

Reducing LPI: Beam Smoothing

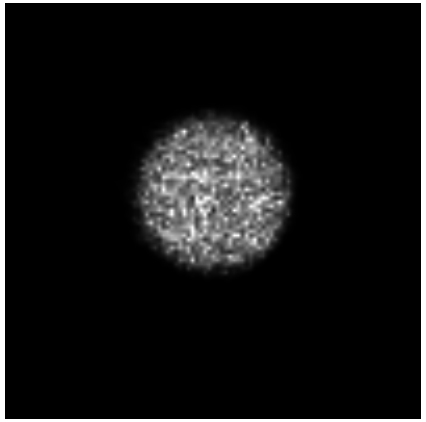
1.: Phase Plates

unconditioned



intermediate field shows very strong intensity modulations

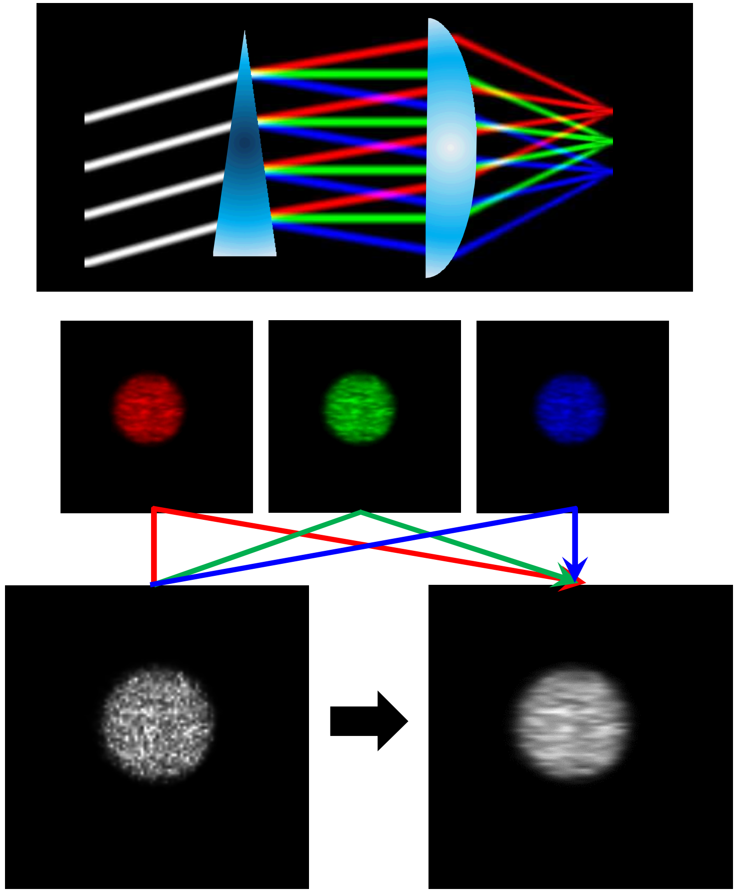
with phase plate



small scale modulations decrease by means of heat conduction

2.: Spectral Dispersion (SSD)

Requires added bandwidth



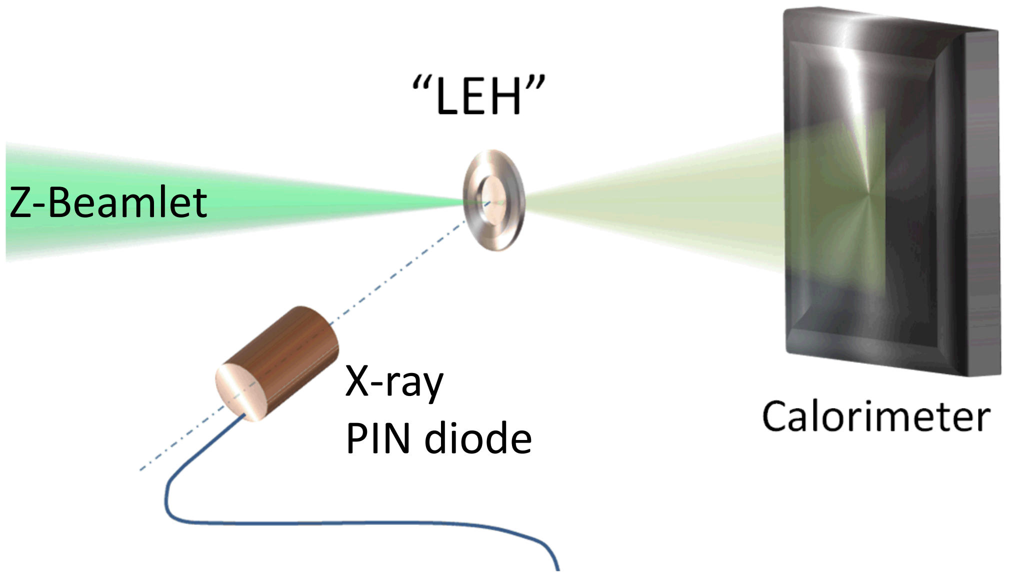
Other methods:

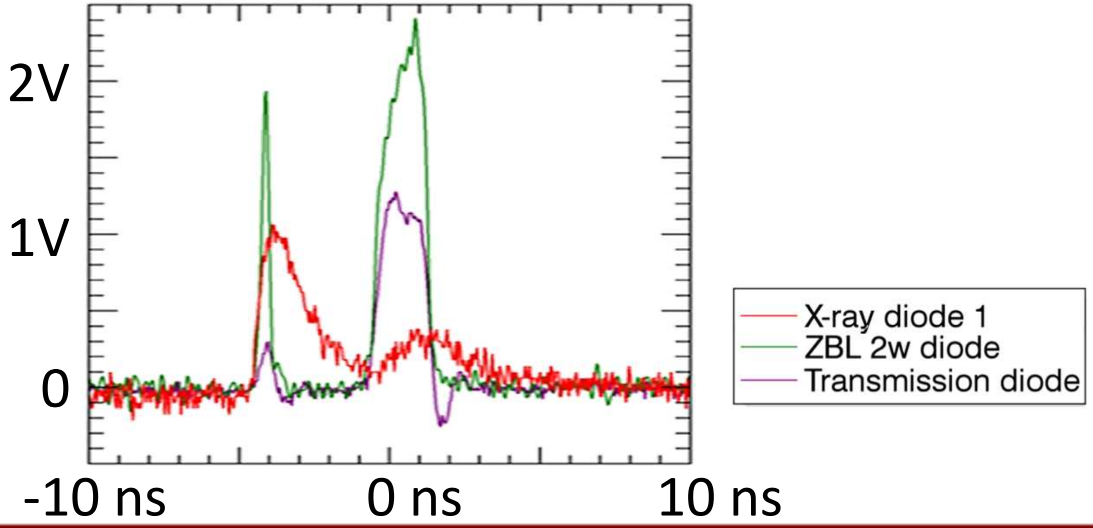
- 2-Dimensional SSD
- Polarization Smoothing (PS) for $\sqrt{2}$ reduction of modulations
- Induced Spatial Incoherence (ISI)

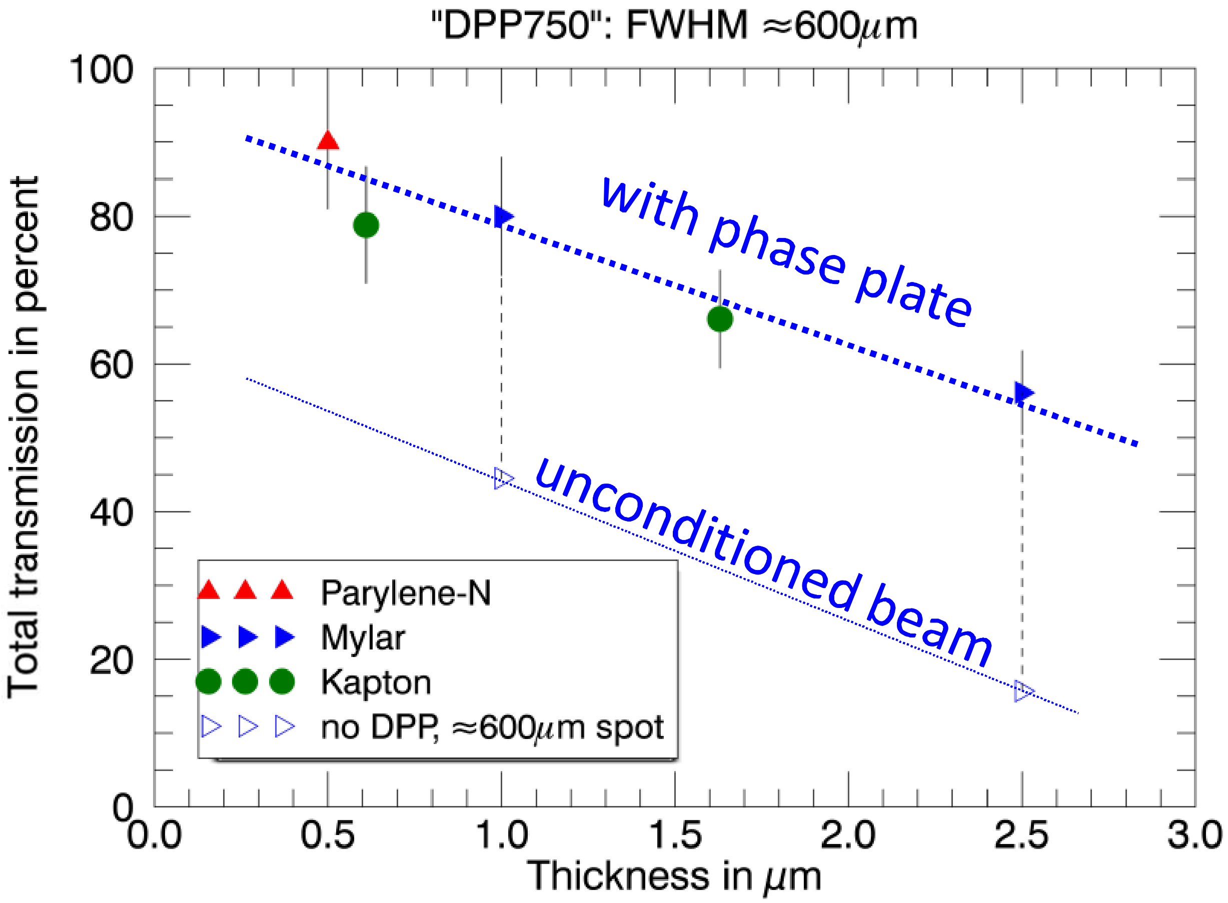
Experimental Results

Measurement Concepts and Data

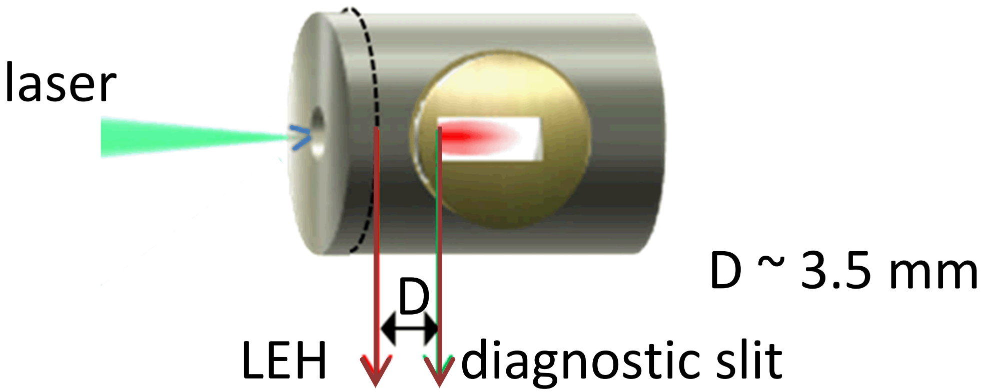
Laser Entrance Hole Transmission

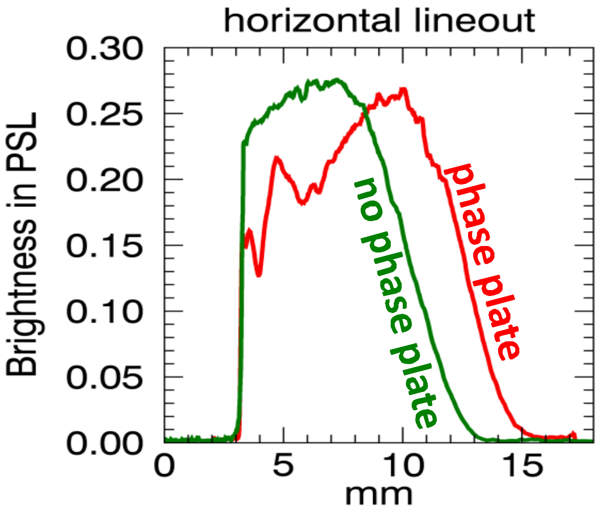




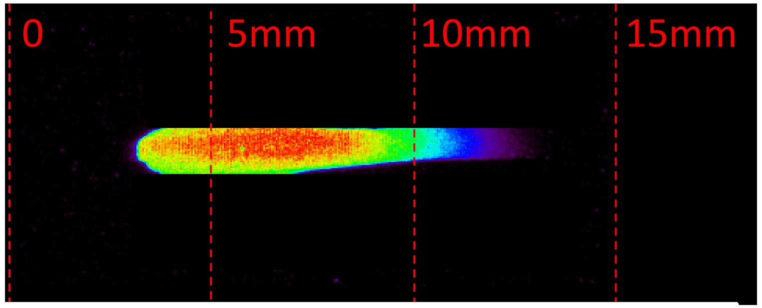


Laser Penetration Into a Gas Cell



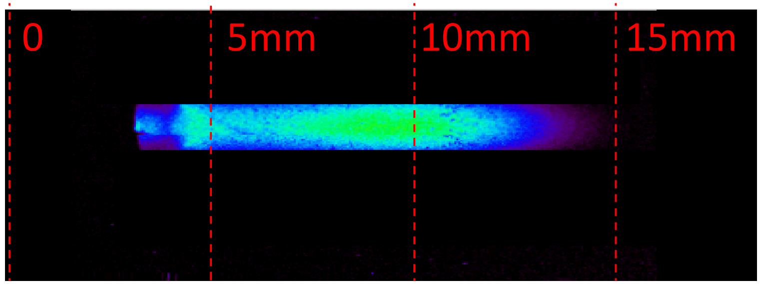


~ 900µm laser spot, uncond.
315 torr Ne (2.1% n_{crit})



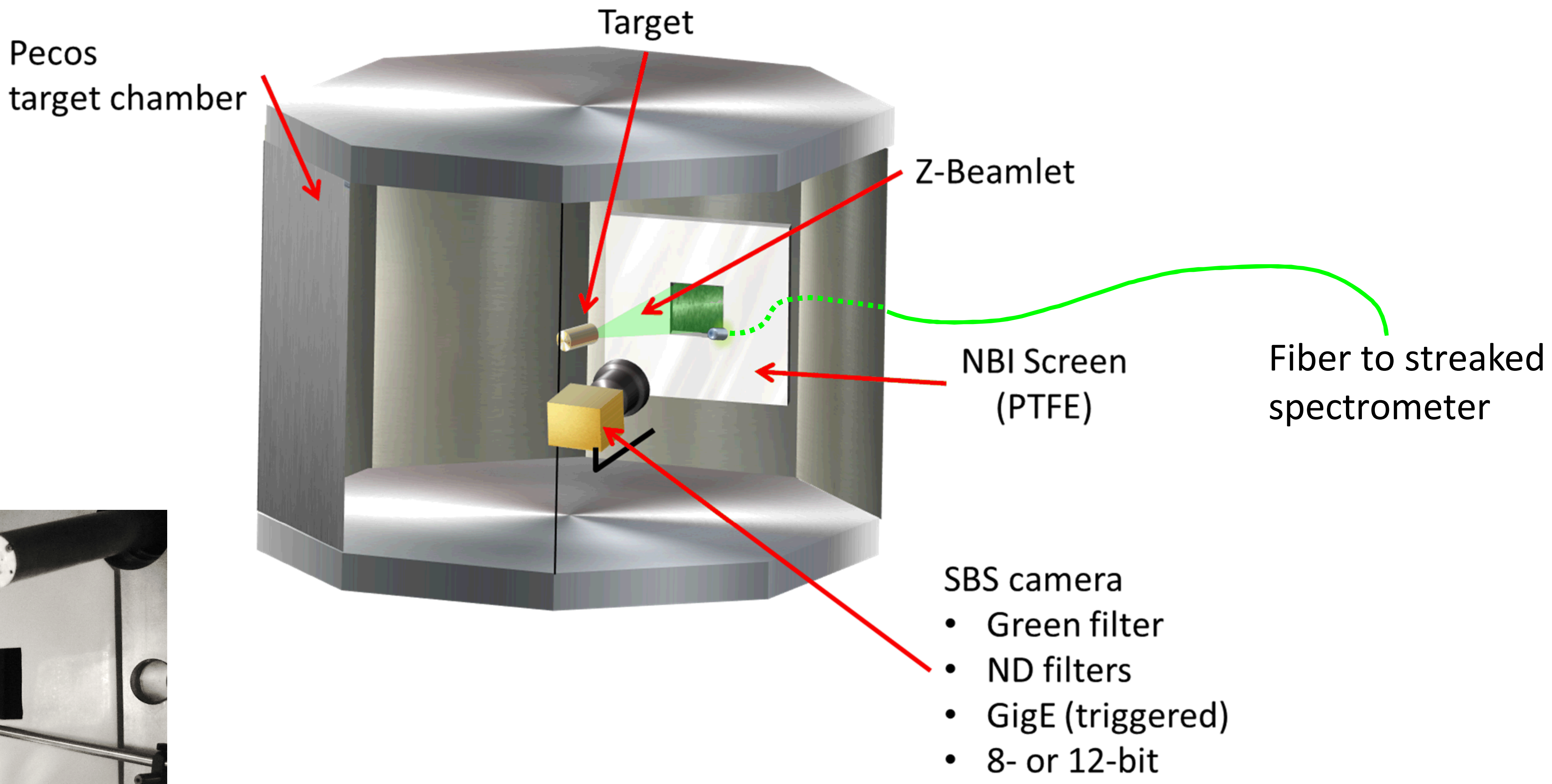
X-ray filter: **1µm** mylar

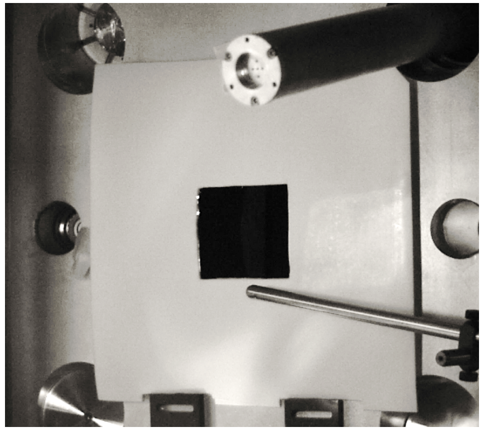
Phase Plate, ~ 900µm @ 95%
376 torr Ne (2.5% n_{crit})



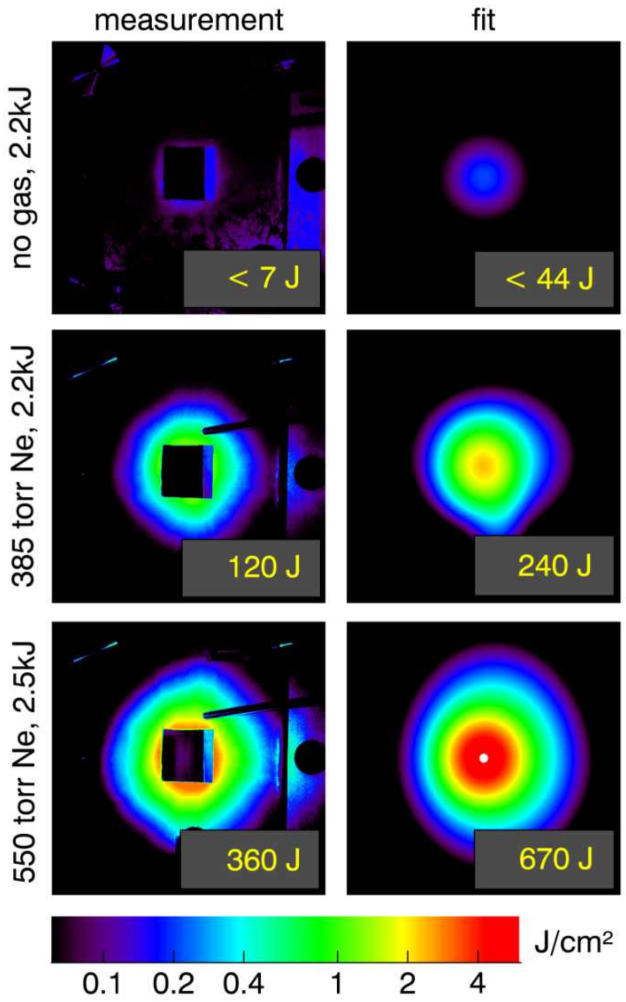
X-ray filter: **2µm** mylar

SBS Backscatter Measurements

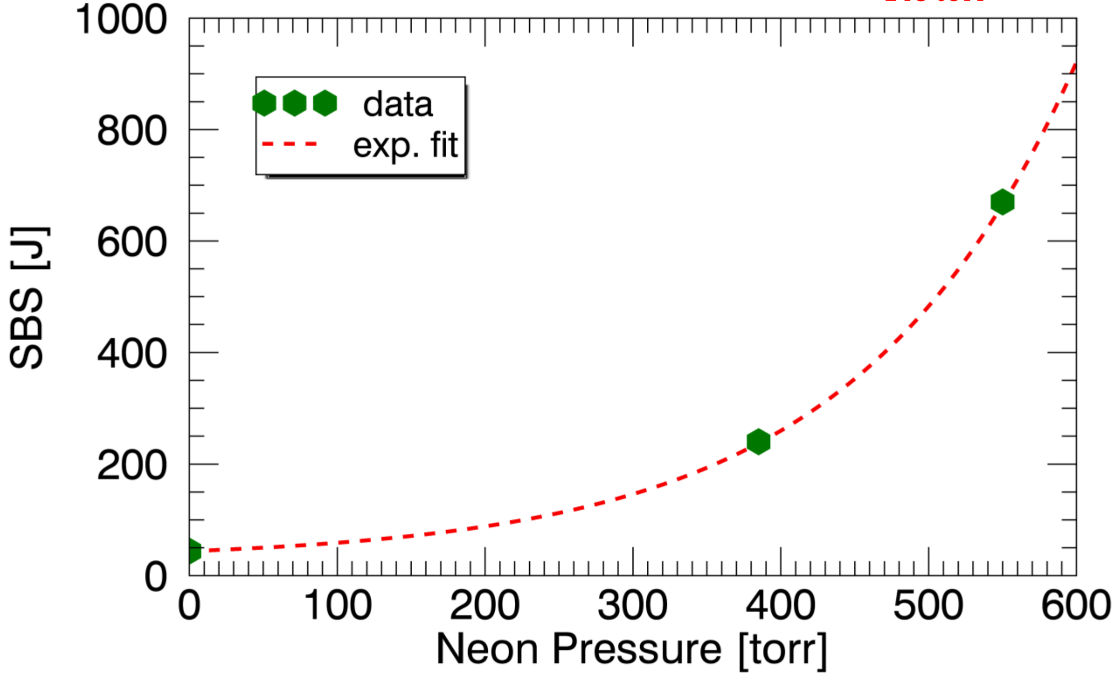




SBS Backscatter Measurements



$SBS \sim 28.5\text{J} + 15.5\text{J} \cdot \text{EXP}\left(\frac{p}{148\ \text{torr}}\right)$

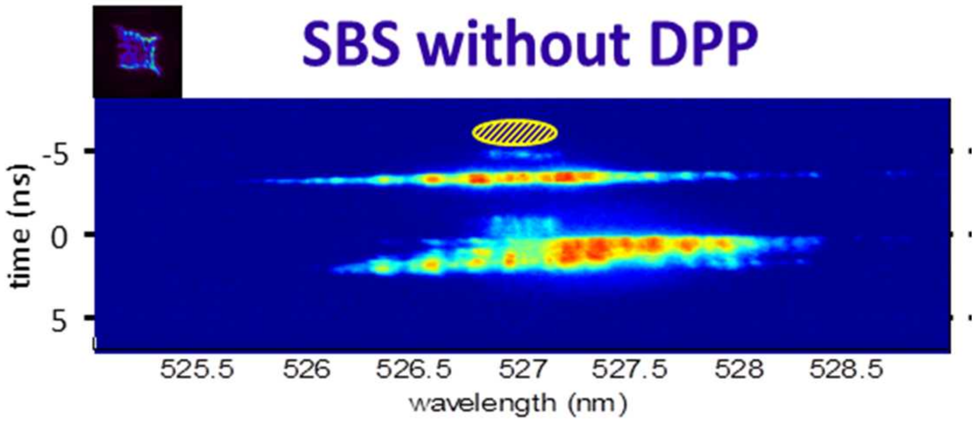


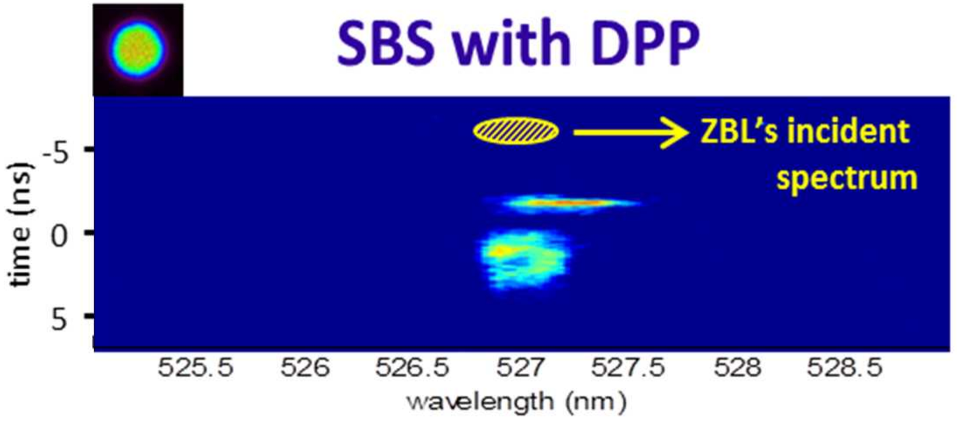
All data without phase plate

(data with phase plate pending)

SBS Backscatter Measurements

Temporally and spectrally resolved





Courtesy of David Bliss

Poor beam quality:

- More SBS
- Bigger $\Delta\lambda$ (filamentation)
- Spectral shift

Notes: Gas is D_2 (less SBS than Ne)
Measurements taken in Z

Summary

Take this home:

- ❑ *Few things in plasma physics follow simple textbook rules.*
- ❑ *If you heat plasma with kJ-class lasers, you will see nonlinear LPI !!!*
- ❑ *The only thing better than a smooth beam is an even smoother beam.*

Pending:

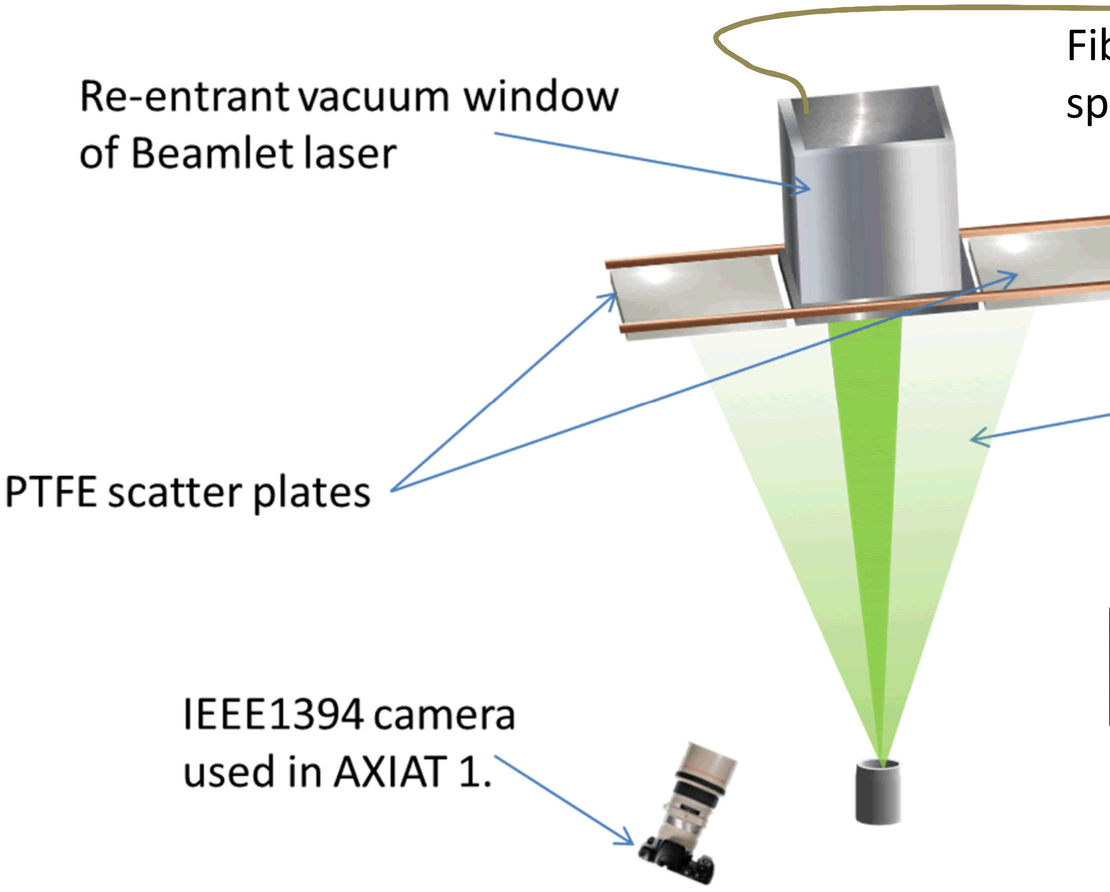
- ❑ *More measurements on SBS and additional capabilities (e.g. SRS!!).*

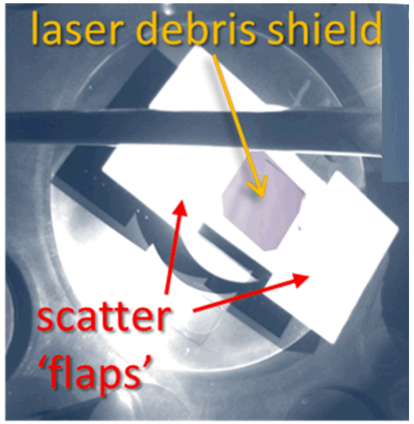
Wish us luck…

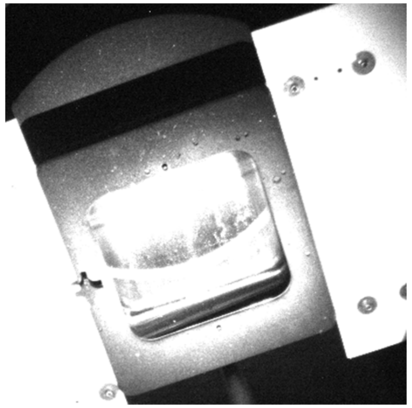
- ❑ *Even if LPI is reduced in favor of high laser deposition, we still worry for MagLIF:*
  - *Contamination/mix of heavier elements (radiation loss!)*
  - *Hydrodynamic instabilities (hopefully O.K.)*
  - *Driver-Target coupling (under investigation)*
  - *And more…*

EXTRAS

SBS Backscatter Measurements in Z



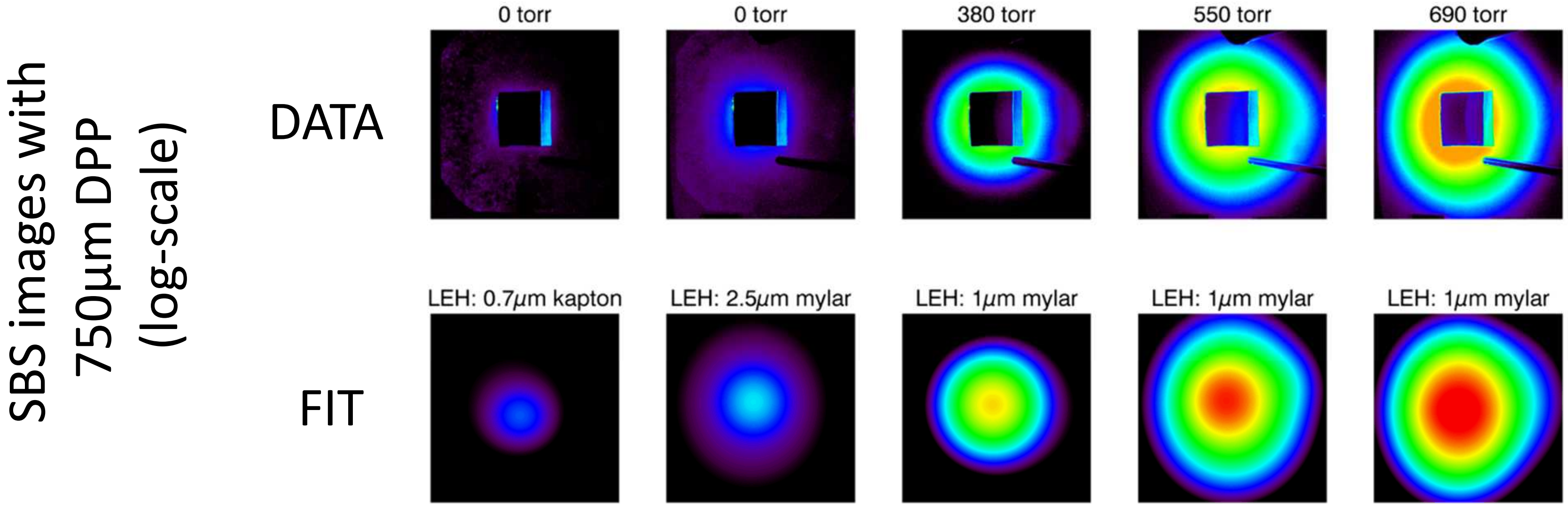


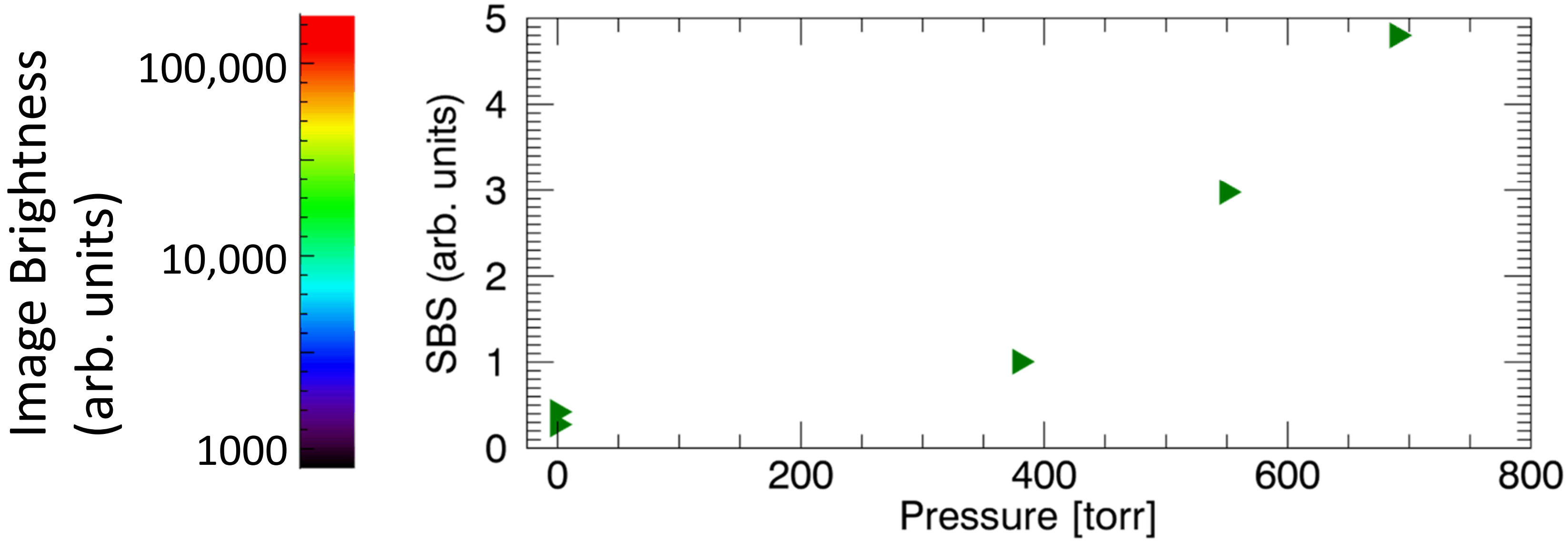

no phase plate


w/ phase plate


w/ phase plate (adjusted brightness)

SBS Backscatter Measurements





Calibration Pending