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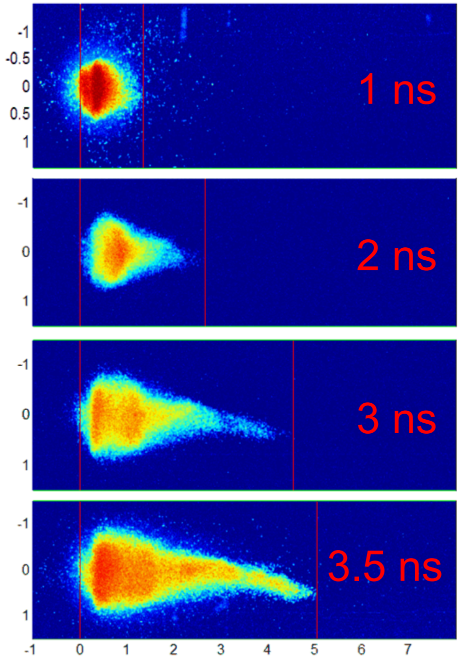

Investigating the laser heating of underdense plasmas at conditions relevant to MagLIF

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Support provided in part by the Laboratory Directed Research and Development Project No. 173190

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Summary: OMEGA-EP experiments are systematically testing laser heating of magnetized underdense plasmas

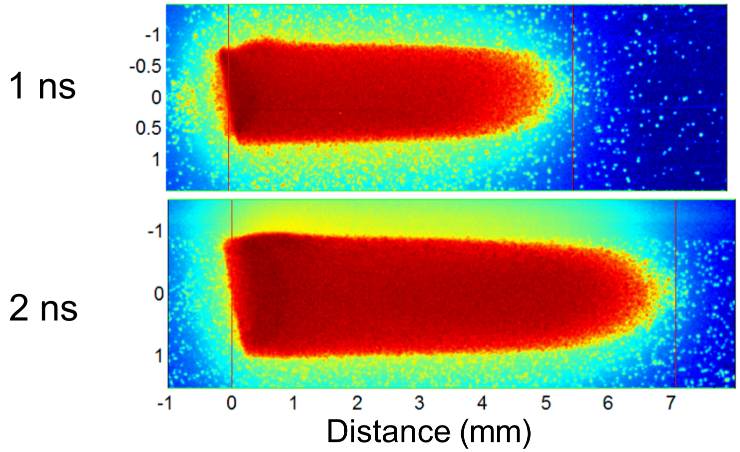
- OMEGA-EP experiments systematically test energy deposition at conditions relevant to MagLIF preheat

- Experiments tested inverse Bremms. absorption in Ar – suggest 8 kJ can be coupled into MagLIF targets

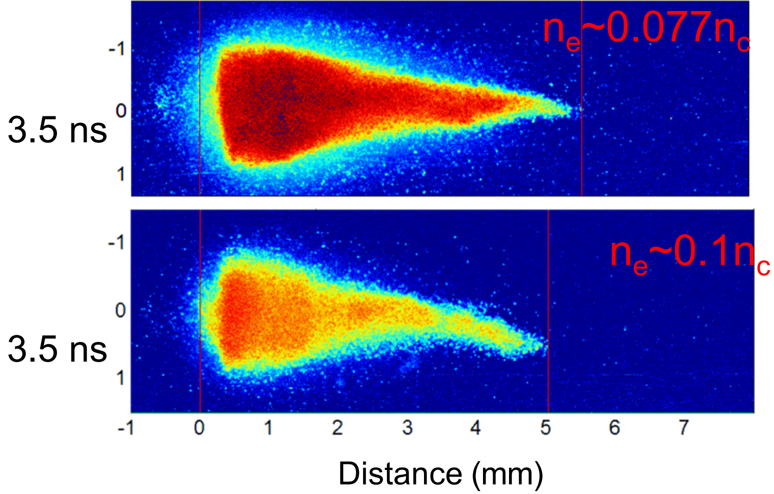
- Experiments in D_2 show high densities (n_e=0.1n_c), thick laser entrance hole foils increases LPI

- Using a prepulse can reduce effect of thick laser entrance hole windows reducing LPI

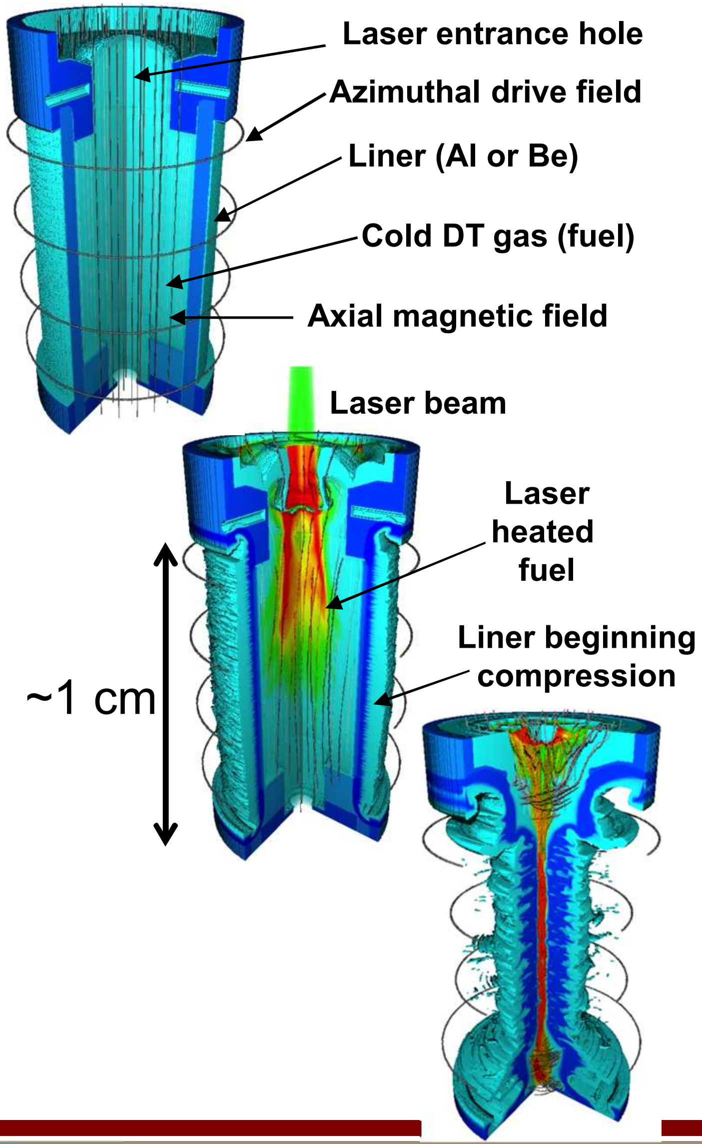
Time gated emission images
Propagation in pure Ar



Propagation in doped D_2



MagLIF* could produce 100 kJ D-T fusion yields with the Z current drive and 6-8 kJ of preheat energy

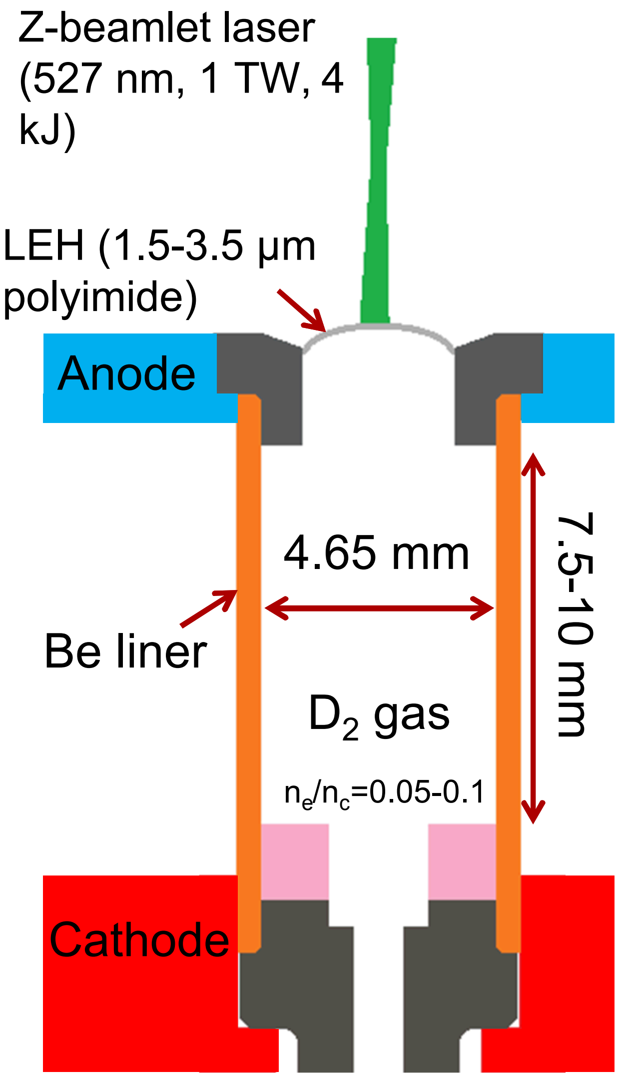


In addition to compressing the fuel with the Z current drive, MagLIF adds two extra elements:

- An initial 30 T axial magnetic field is applied produced by external B-field coils
  - Inhibits thermal conduction losses
  - Confines alpha particles when compressed for greater self-heating
- During the ~100 ns implosion, the fuel is heated using the Z-Beamlet laser (about 6 kJ in designs)
  - Preheating to ~300 eV reduces the compression needed to obtain fusion temperatures to $R_{initial}/R_{stagnation}$ ~ 23 on Z
  - Preheating reduces the implosion velocity needed to ~100 km/s, allowing us to use thick liners that are more robust against instabilities

*S.A. Slutz *et al.*, Phys. Plasmas 17, 056303 (2010). S.A. Slutz and R.A. Vesey, Phys. Rev. Lett. (2012).

MagLIF preheat challenge: Coupling 6-8 kJ of laser energy into an underdense D_2 gas in a MagLIF target without mix



What are the experimental parameters that will allow 6-8 kJ to be coupled effectively?

- Laser intensity and energy required
- Gas fill density
- Other target parameters (length, LEH window thickness)

We need to minimize LPI

Systematic studies are required to validate simulations in the relevant parameter space and to guide experimental design

Physics and target geometry similar to NIF hohlraum studies (e.g. Glenzer et al., Nat. Phys. 2007) – different motivation, longer scale lengths, lower intensities

OMEGA-EP laser has relevant energies and consistent performance to enable systematic studies

OMEGA-EP has characteristics ideal for MagLIF preheat studies

- Long duration (up to 10 ns), high energy beams (up to 5 kJ per beam)
- Good time gated diagnostics
- Up to 10T applied B fields provided by MIFEDS
- Beams are DPP smoothed with energy stability (~3-4%) and timing
- High shot rate – 7 shots per day per beam

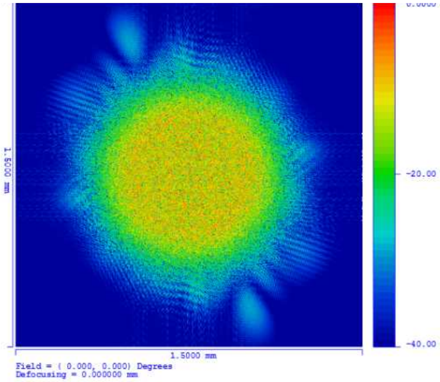
This talk focuses on two main studies

- Experiments in pure Ar testing inverse Bremmstrahlung absorption models
- MagLIF surrogate experiments in D_2 testing density and magnetization

Beam energies available on OMEGA-EP (3ω, f/6.5)

Duration	Beam 1	Beam 2	Beam 3	Beam 4
1 ns	1250 J	1250 J	1250 J	1250 J
2 ns	1950 J	1950 J	2250 J	2200J
4 ns	2800 J	2800 J	3150 J	3100 J
10 ns	4400 J	4400 J	5000 J	4900 J

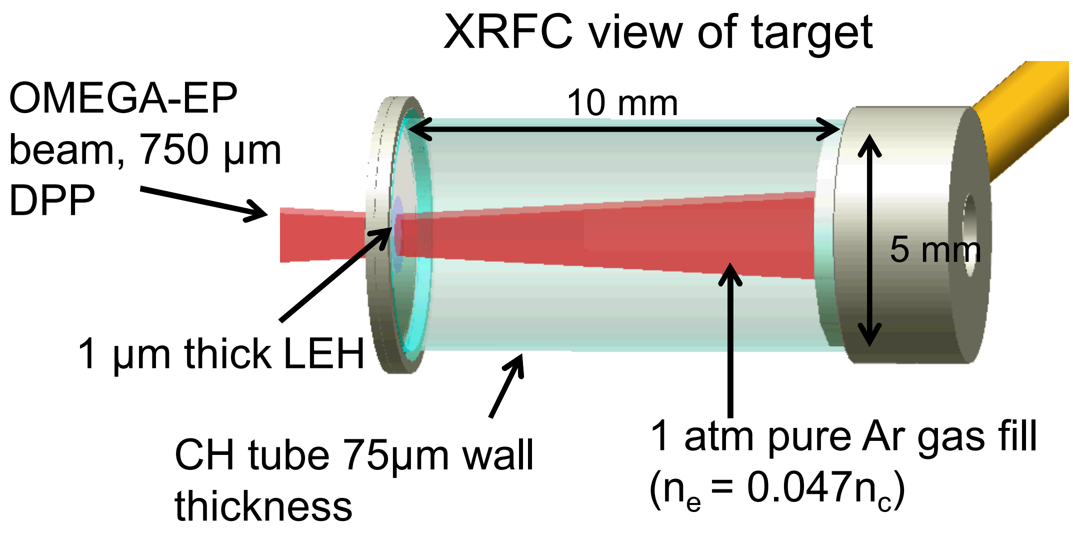
750 um DPP point spread function



OMEGA-EP is not a surrogate for Z-beamlet – experiments are still required on that laser (see M. Geissel, JO6.00002)

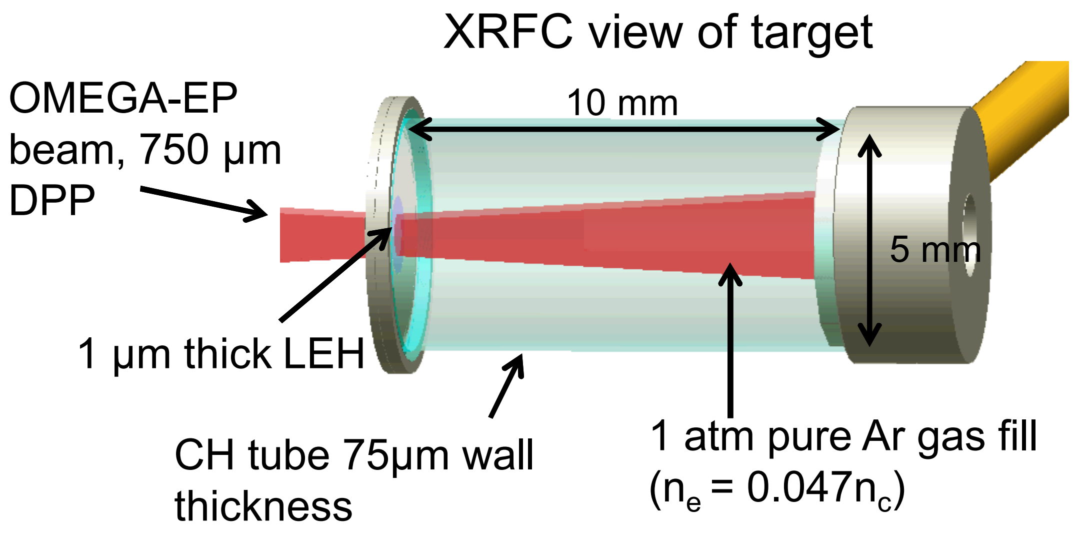
A. Harvey-Thompson et al., Phys. Plasmas, in review

Experiments in pure Ar test inverse Bremms. absorption at relevant scale lengths



- Pure Ar gas allows relevant n_e/n_c at low pressures – simplifies target design, reduces LEH thickness but reduces surrogacy
- Ar density based initial MagLIF target designs – (0.68 mg/cc D_2 - n_e=0.052 n_c)
- Physics is similar for Ar and D_2 – some differences due to higher Z

Experiments in pure Ar test inverse Bremms. absorption at relevant scale lengths



XRFC view of target

OMEGA-EP beam, 750 μm DPP

10 mm

5 mm

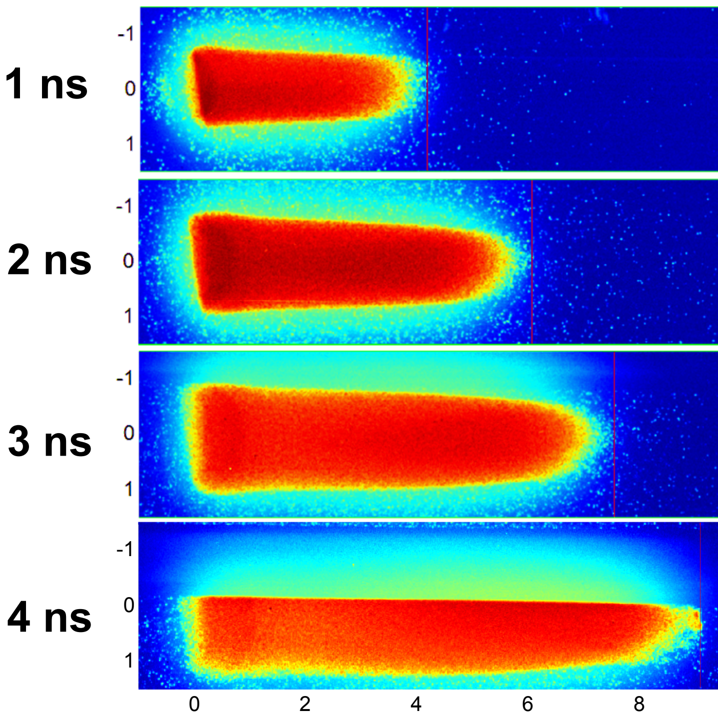
1 μm thick LEH

CH tube 75μm wall thickness

1 atm pure Ar gas fill ($n_e = 0.047n_c$)

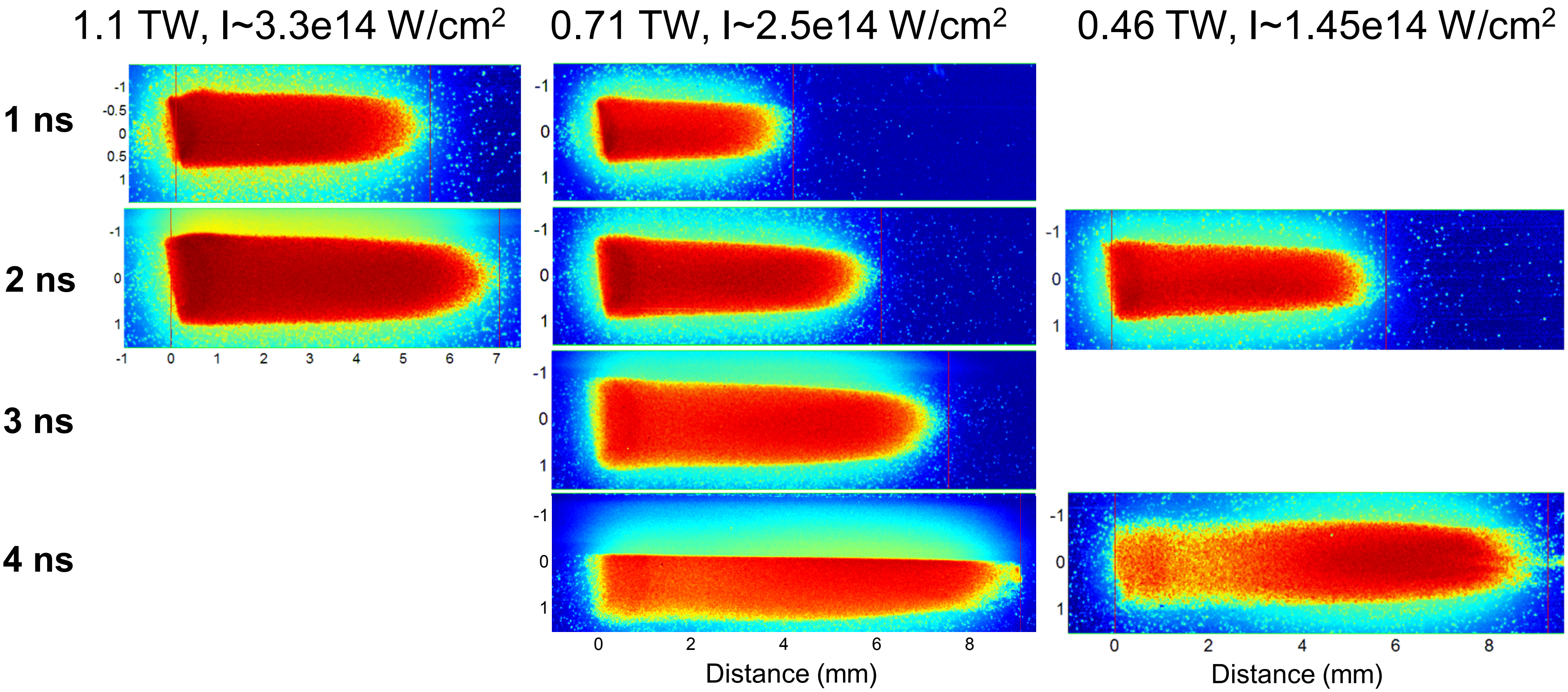
X-ray framing camera images

0.71 TW, I=2.5e14 W/cm^2



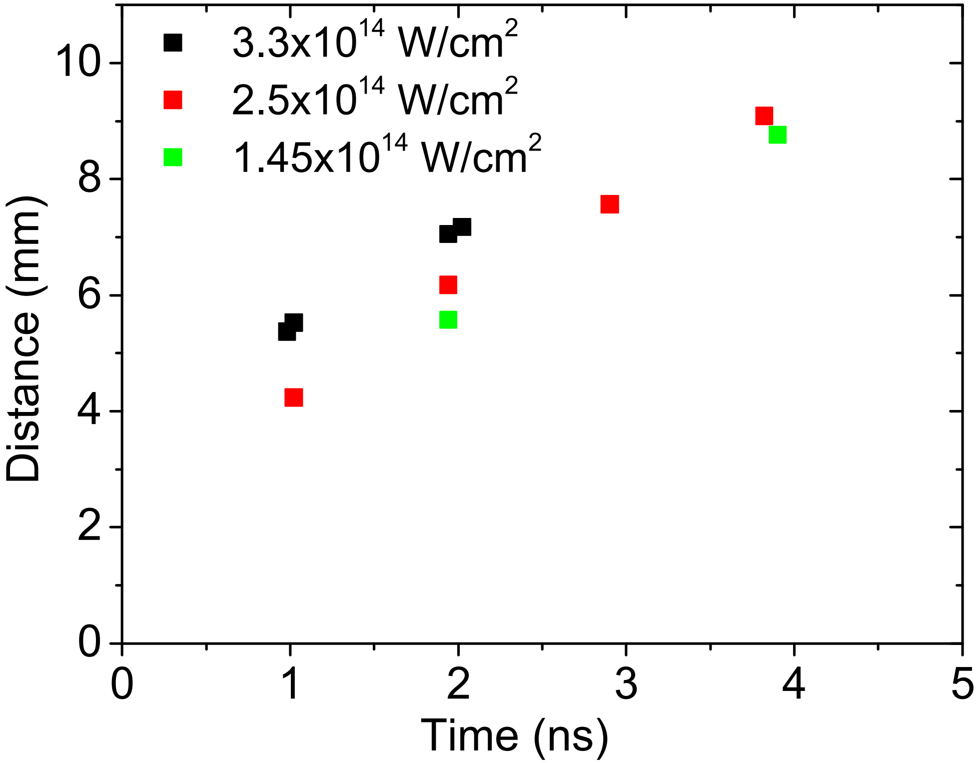
- Propagation proceeds as a supersonic “bleaching” (ionization) wave – observed with XRFC
- Targets kept consistent – 1 μm thick LEH, same gas pressure, same spot size, square pulse shape - only power/intensity varied
- Levels of LPI were low – no hard x-rays detected in experiments (no backscatter diagnostics)

Changing the beam intensity alters the propagation velocity in pure Ar (n_e~0.047 n_c)



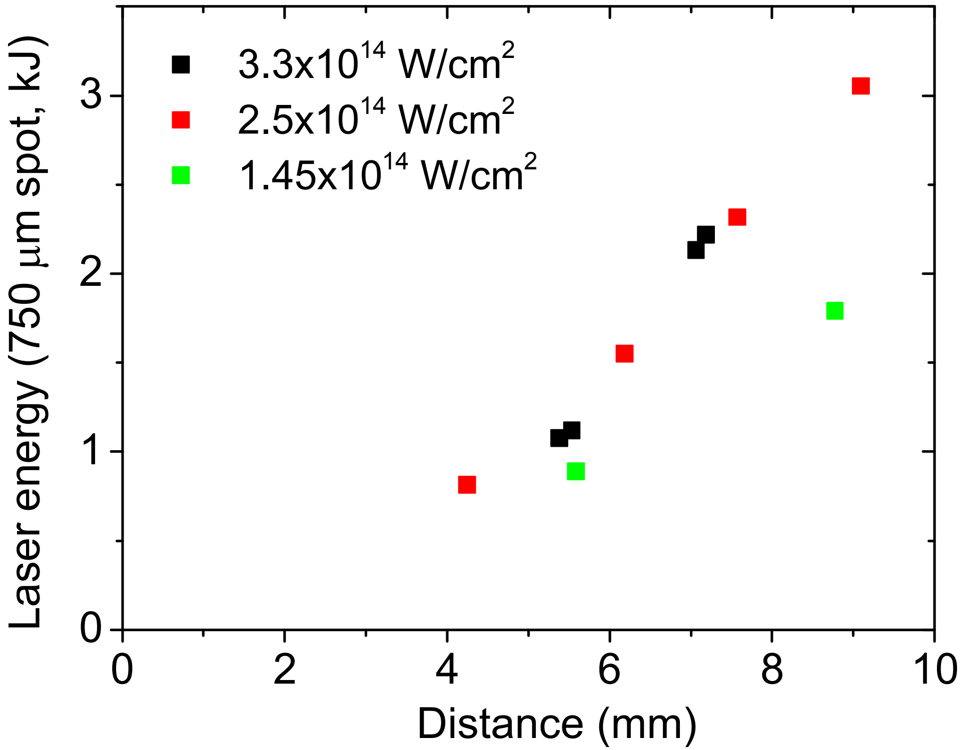
- Red lines indicate LEH position and “end of propagation”

Propagation velocity varies with beam intensity – surprising similarity between 1.45 and 2.5x10^{14} W/cm^2



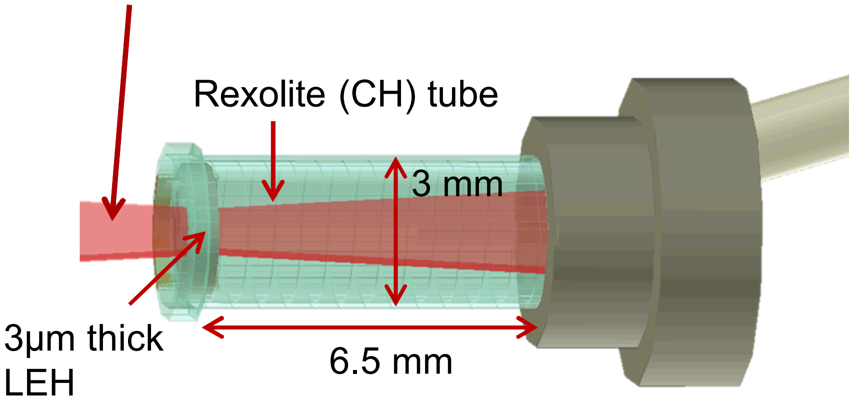
- Little difference in propagation velocity between 1.45 and 2.5x10^{14} W/cm^2

The data show that over 3 kJ of energy was deposited in 10 mm for a 750 µm spot, and I = 2.5x10^{14} W/cm^2



- 3 kJ is deposited into the target length for a modest spot diameter (750 µm), modest intensity (2.5x10^{14} W/cm^2) and low density (n_e/n_{crit}~0.05)
  - Simulations suggest 0.35 kJ deposited into LEH window
- A 1.2 mm spot size would deliver 8 kJ for 10 mm long target, 2.5x10^{14} W/cm^2 (if energy/distance α beam area)

MagLIF-like experiments tested energy deposition for D_2 gasses with n_e = 0.055 – 0.1 n_c and B=0 and 5T



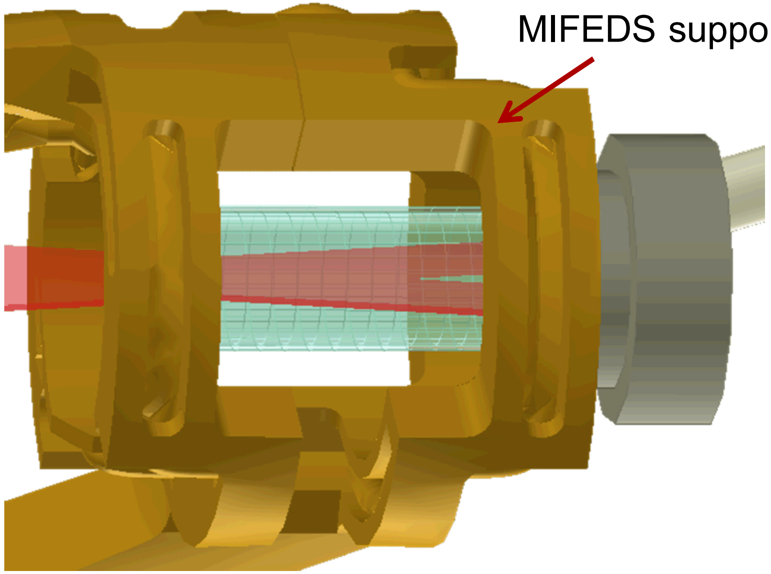
4 ns, 3 kJ, 0.78 TW, 750 μm DPP, ~2.5e14 W/cm^2 square pulse

- Using D_2 requires high pressures (>10 atm.), creates target challenges
  - Thick (3μm) LEH c.f. ~3.5 μm LEH in MagLIF
- Ar dopant (<0.25%) added to D_2

Propagation in 3 gas densities tested – relevant to first MagLIF experiments (n_e= 0.052-0.1 n_c) [1] – laser parameters kept constant

- n_e = 0.055 n_c (10 atm pressure, 1.67 mg/cm^3)
- n_e = 0.077 n_c (14 atm pressure, 2.34 mg/cm^3)
- n_e = 0.10 n_c (18 atm pressure, 3.01 mg/cm^3)

MagLIF-like experiments tested energy deposition for D_2 gasses with n_e = 0.055 – 0.1 n_c and B=0 and 5T



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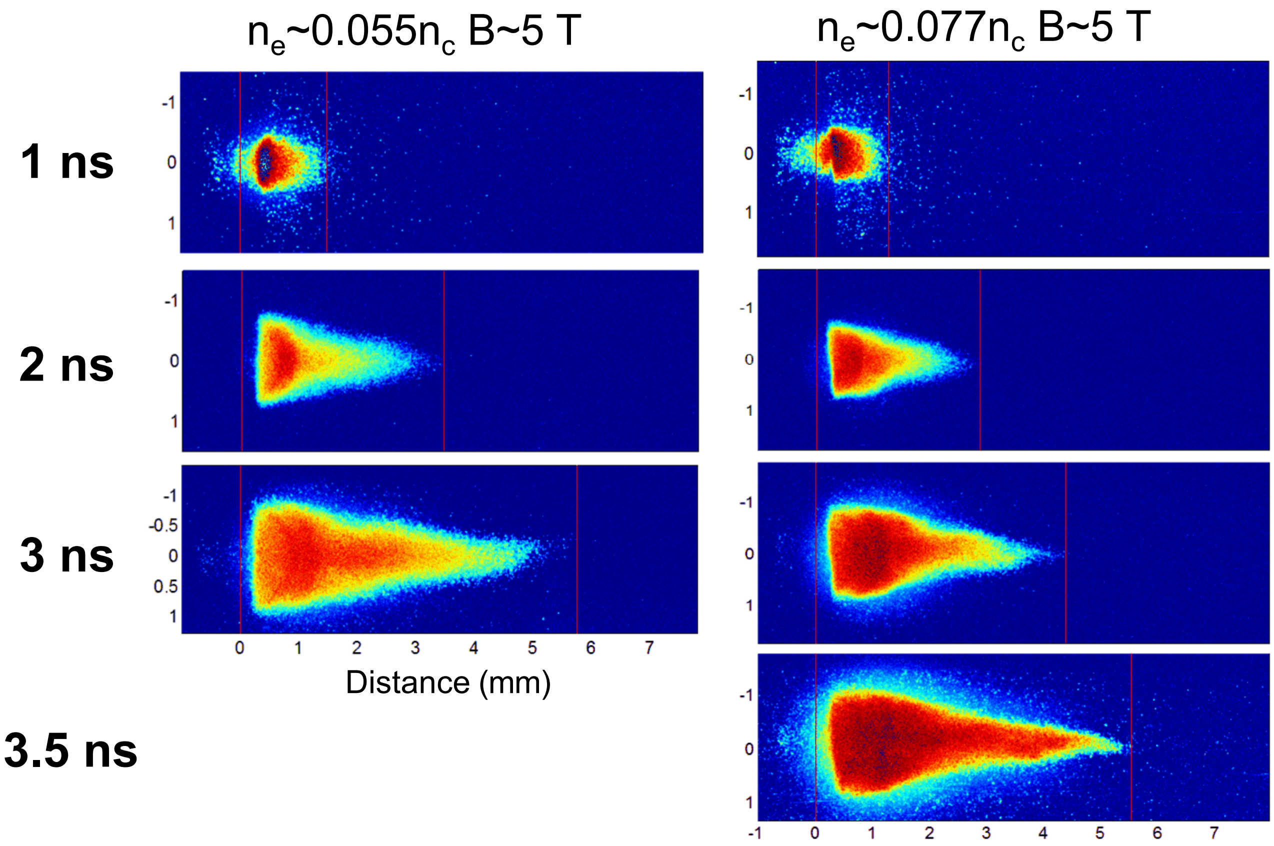
Propagation in 3 gas densities tested – relevant to first MagLIF experiments (n_e= 0.052-0.1 n_c) [1]

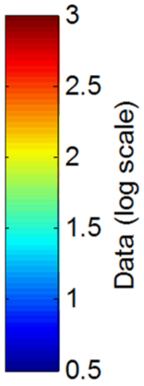
- n_e = 0.055 n_c (10 atm pressure, 1.67 mg/cm^3) **– ωτ ~ 1.1**
- n_e = 0.077 n_c (14 atm pressure, 2.34 mg/cm^3) **– ωτ ~ 0.8**
- n_e = 0.10 n_c (18 atm pressure, 3.01 mg/cm^3) **– ωτ ~ 0.6**

5T B field applied with MIFEDS – propagation tested with and without B field

X-ray framing camera (250 ps frame times) views Ar dopant emission

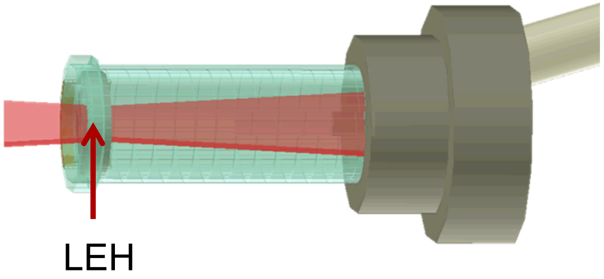
XRFC images show the propagation in D_2 for n_e=0.055 and 0.077 n_c and B=5T





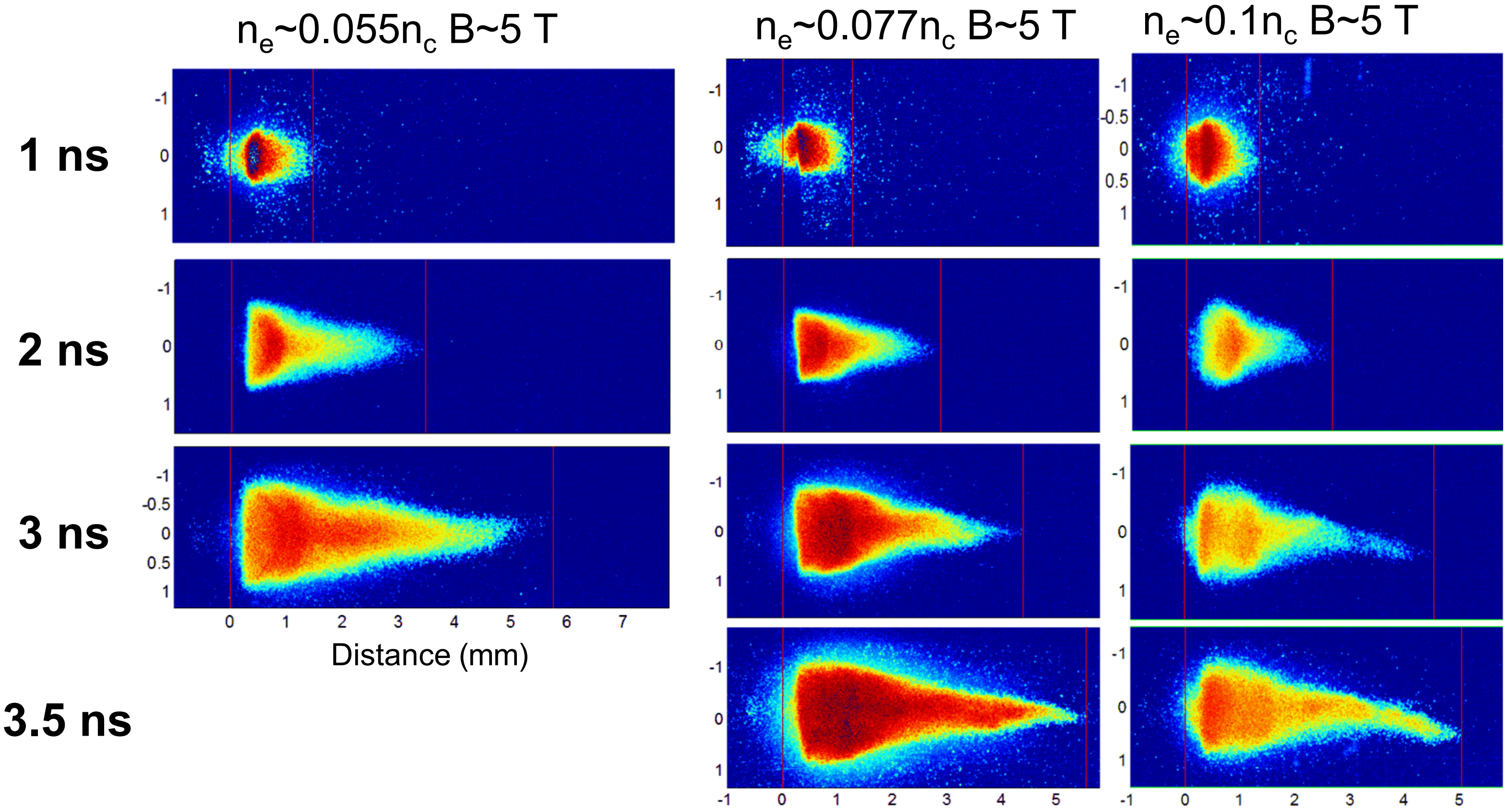
(200 ps frame times)

XRFC view (no MIFEDS)



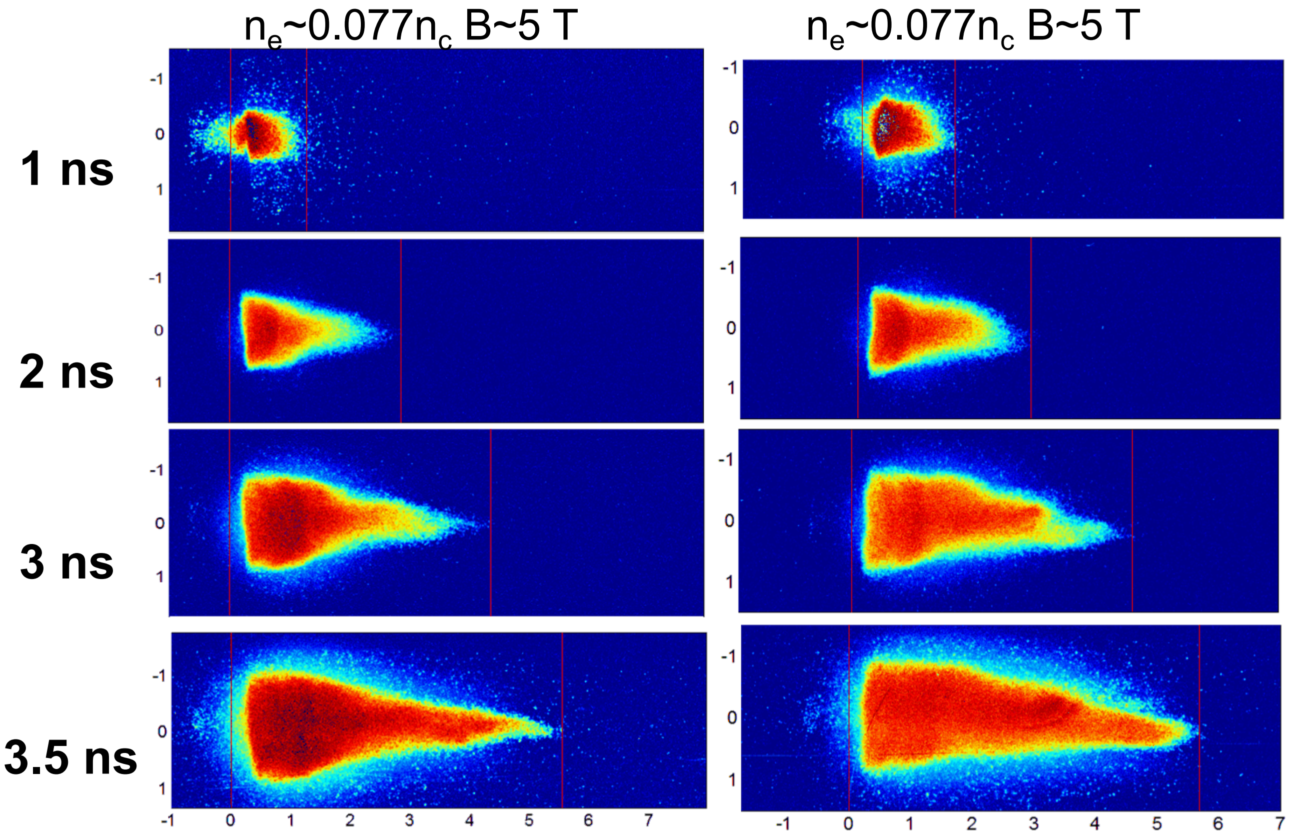
- XRFC's primarily view Ar He-alpha line emission – emission dependent on T_e

For n_e=0.1 and B=5T the propagation starts to bend



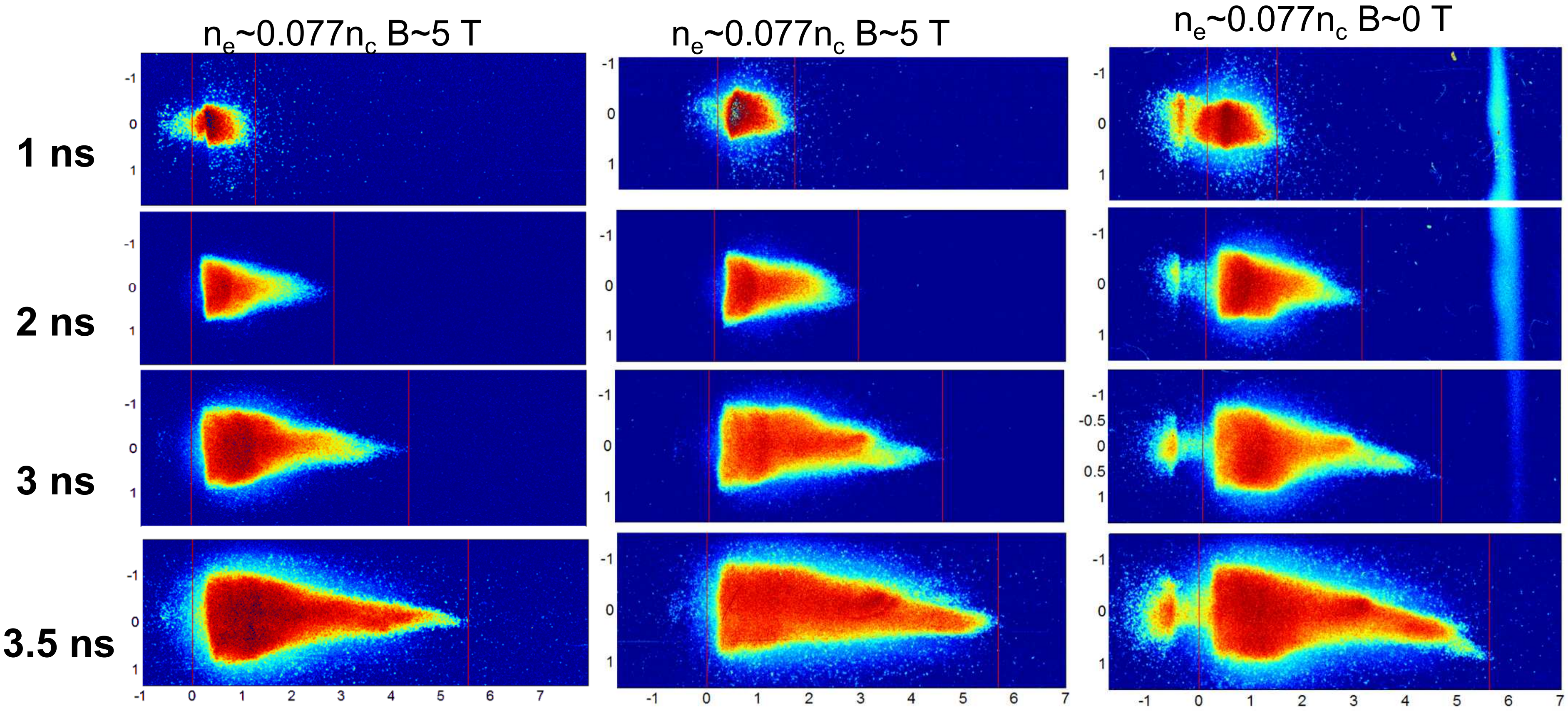
- XRFC's primarily view Ar He-alpha line emission – emission dependent on T_e
- At n_e=0.1n_c propagation starts to bend and there's more apparent structure in the emission

Propagation is consistent between magnetized shots for n_e=0.077n_c



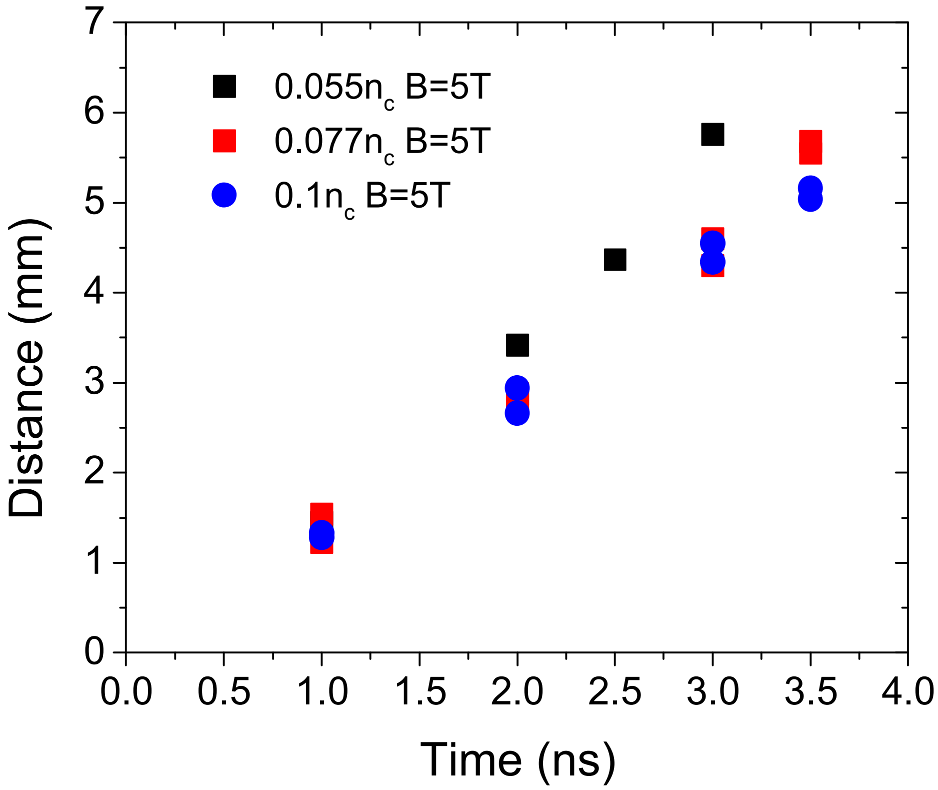
- Repeat shots for n_e=0.078n_c and B=5T show similar propagation distances and generally 2D behavior, though some different structures apparent in the emission

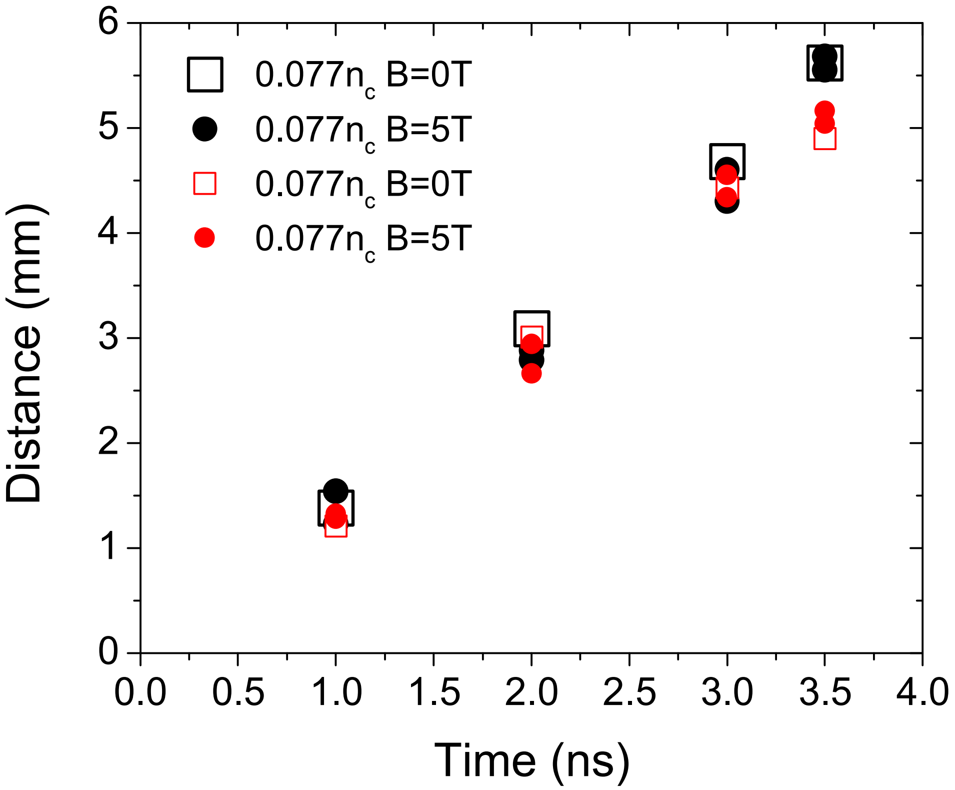
Bending in the propagation is also observed at n_e=0.077n_c when B field is turned off



- Repeat shots for n_e=0.078n_c and B=5T show similar propagation, though some different structures apparent in the emission
- For n_e=0.078n_c and B=0 T emission starts to bend again

Results show little difference in propagation between n_e=0.077n_c and 0.1n_c and with/without a 5T B field

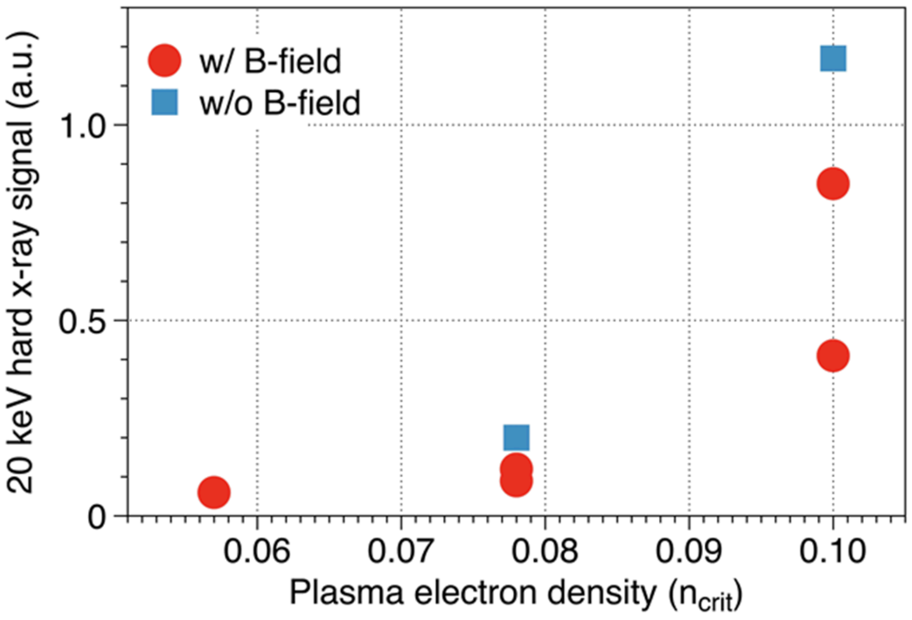




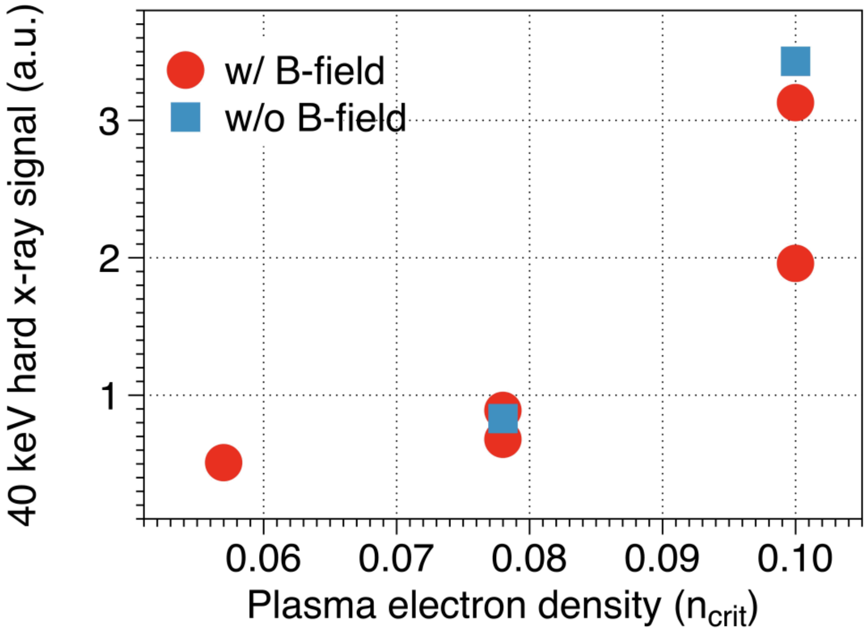
- Propagation distance is defined as being at the edge of observable emission down the tube – comparison to simulations are required to validate this metric

More hard x-rays are generated for 18atm fill

20 keV x-rays



40 keV x-rays



Hard x-rays are indicative of electron generation from LPI

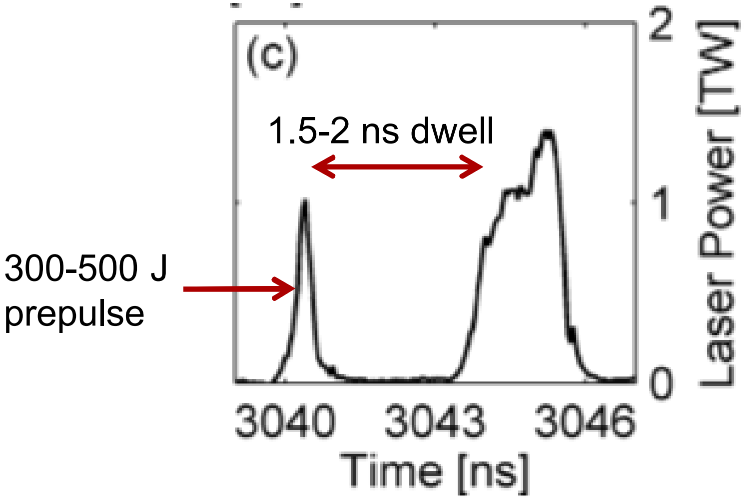
Number of electrons still needs to be calculated – may an issue for MagLIF if energy converted to electrons is significant

Implementing a backscatter measurement on OMEGA-EP will help to understand source of x-rays

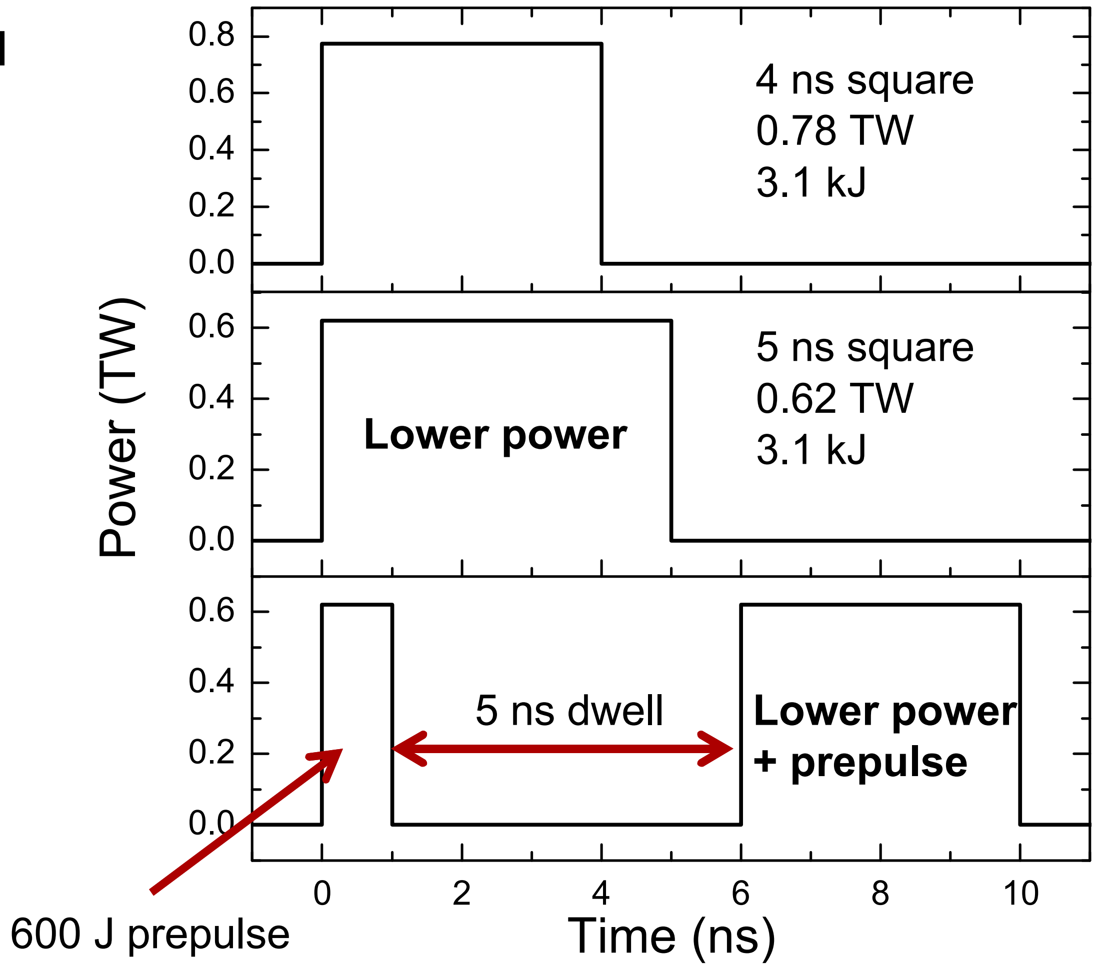
In recent experiments prepulses were tested to help LEH window disassembly in n_e=0.1n_c B=0 targets

Pulse shaping used in MagLIF experiments to disassemble LEH

MagLIF ZBL pulse shape



M. Gomez et al., PoP (2014)



XRFC frames show propagation when same energy has been delivered to the target

Pulse shaping used in MagLIF experiments to disassemble LEH

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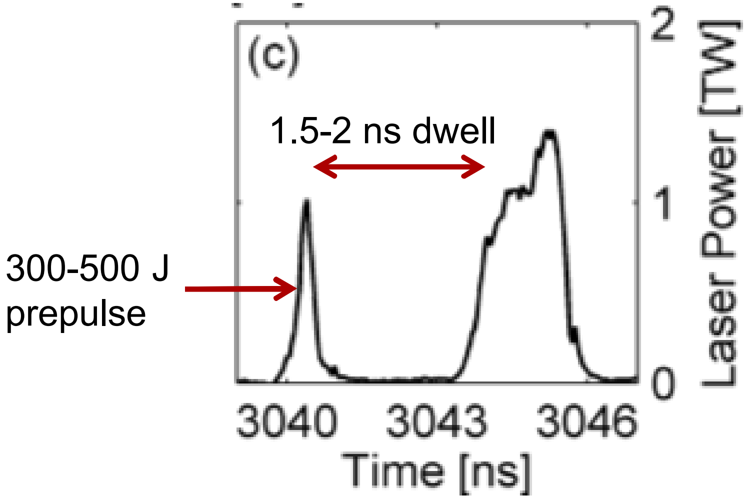

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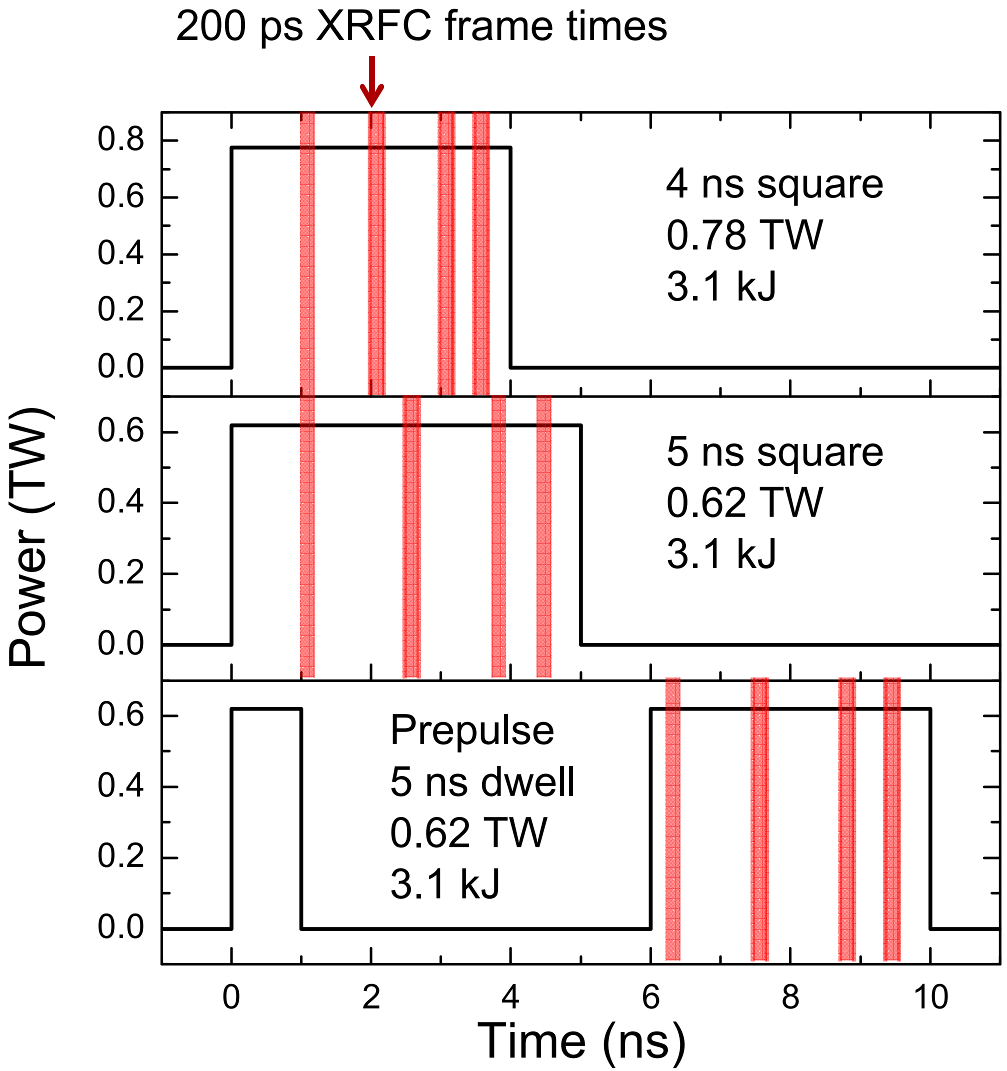
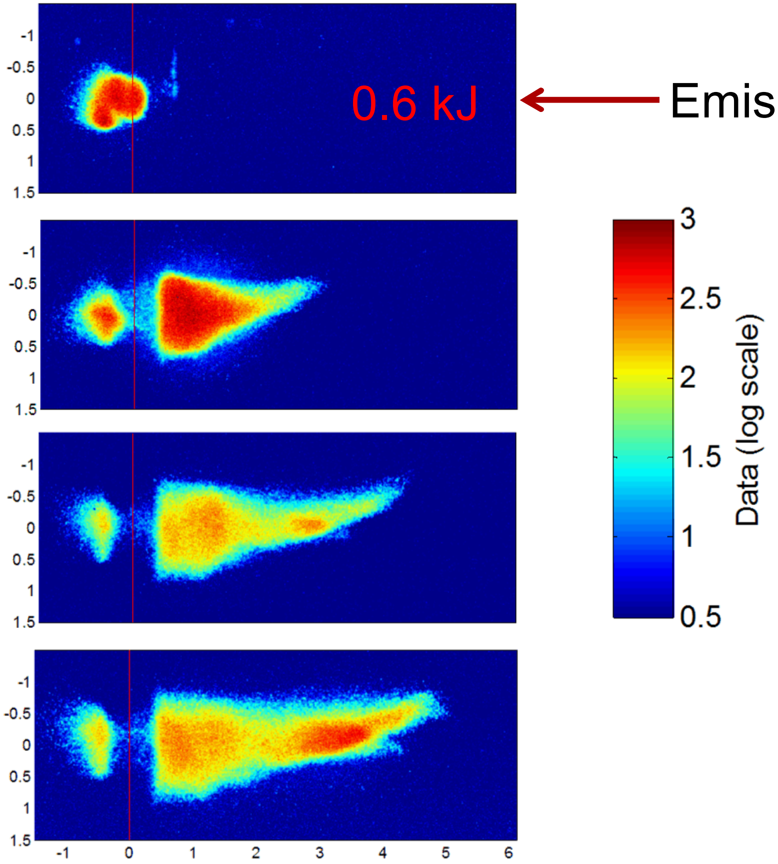
XRFC images taken when same energy is delivered to target

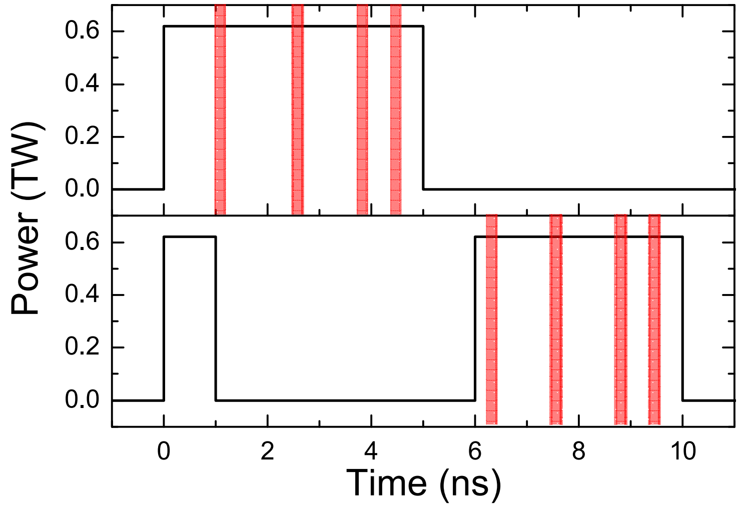


Propagation for looks similar for 0.6 TW square pulse

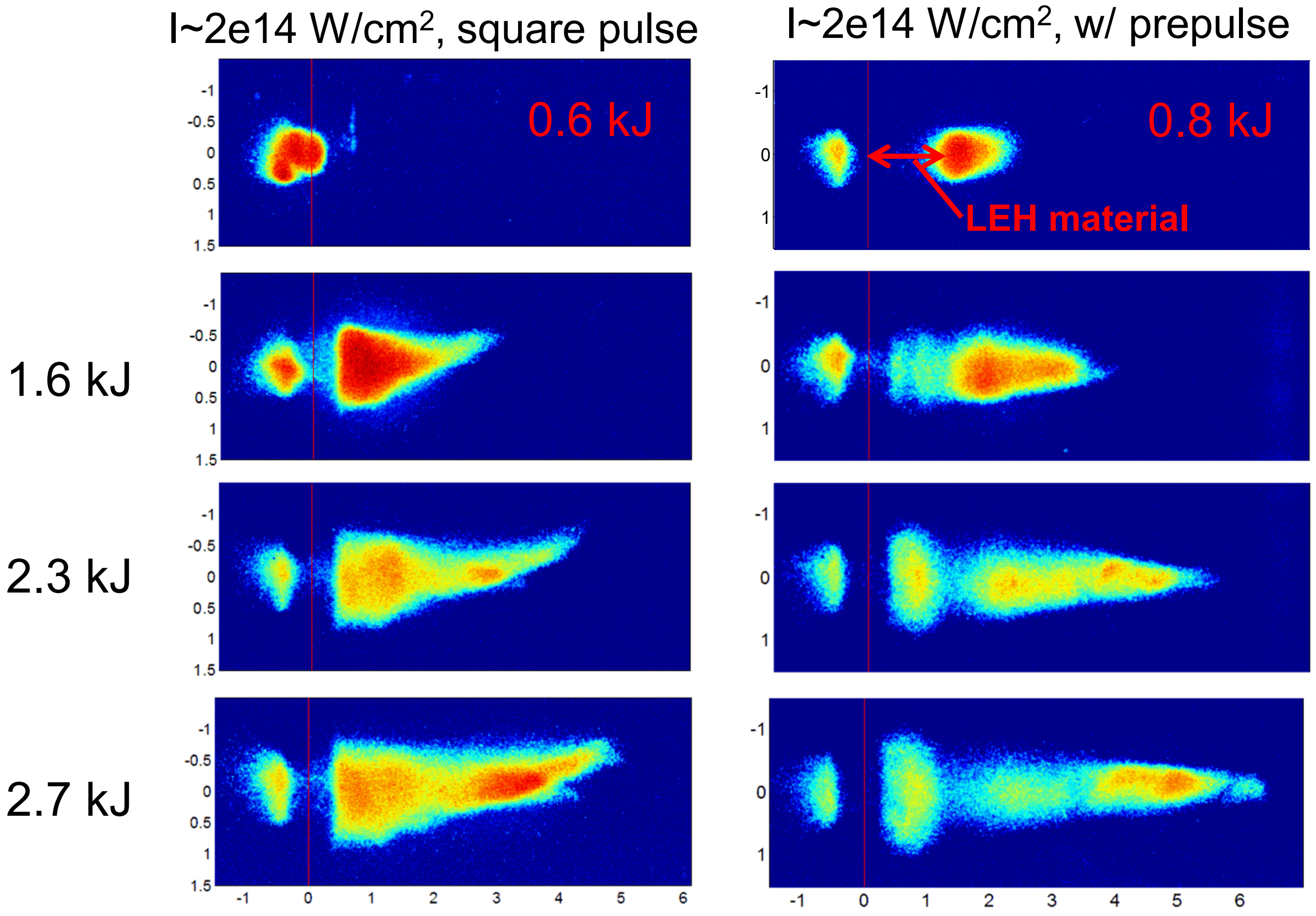
I~2e14 W/cm^2, square pulse



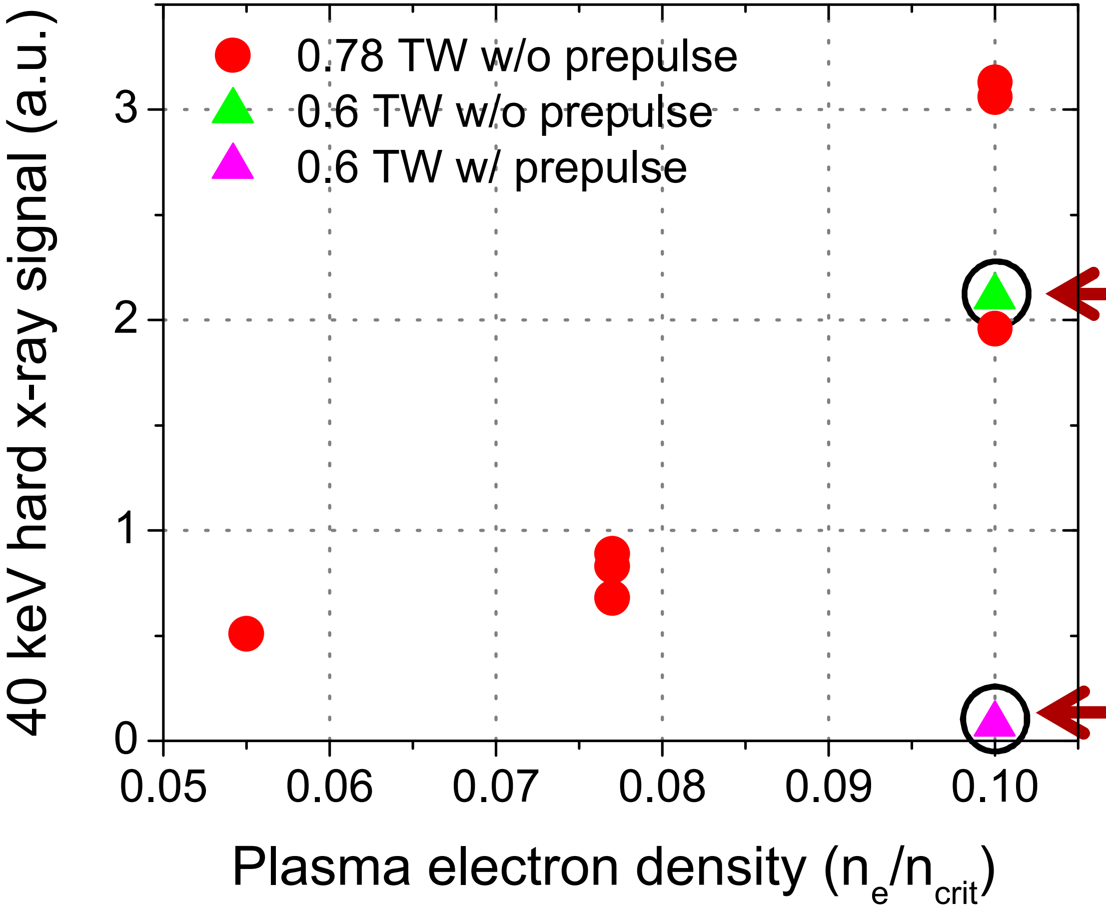
Emission after 1 ns prepulse



Propagation for pulse shaped beam is much smoother, emission profile changes significantly



Adding a prepulse significantly reduced hard x-ray signature



Reducing the power does not reduce hard x-rays

Adding a prepulse significantly reduces hard x-rays

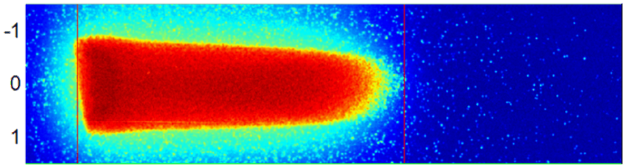
Adding a prepulse affects LEH window interaction
- LEH window disassembly may be responsible for LPI/bending

Summary: OMEGA-EP experiments are systematically testing laser heating of magnetized underdense plasmas

- OMEGA-EP experiments systematically test energy deposition at conditions relevant to MagLIF preheat
- Experiments tested inverse Bremms. absorption in Ar – results agree with MHD codes
- Experiments in D_2 show high densities (n_e=0.1n_c), thick laser entrance hole foils increases LPI
- Using a prepulse can reduce effect of thick laser entrance hole windows reducing LPI

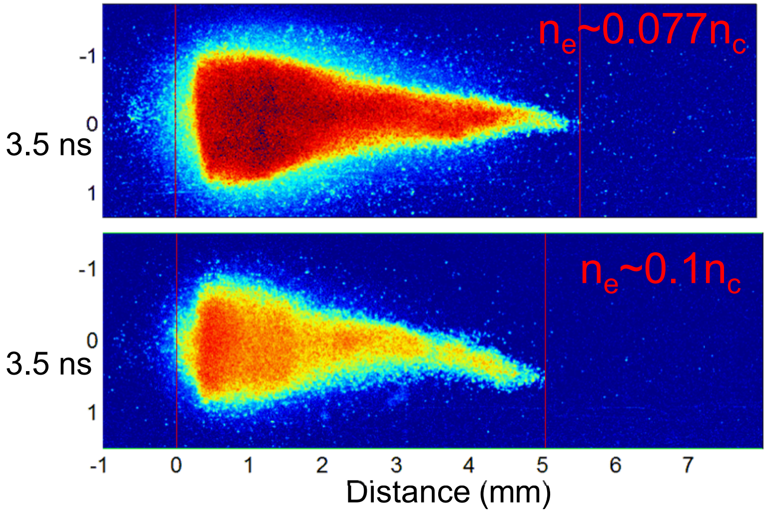
Propagation in Ar (n_e=0.047n_c)
P~0.75 TW, $\bar{I}$~ 2.3e14 W/cm^2

Experiment



Simulation

Propagation in doped D_2
B~5 T, P~0.78 TW, $\bar{I}$~ 2.3e14 W/cm^2



Extra slides

HYDRA simulations accurately model IB absorption – comparisons are ongoing

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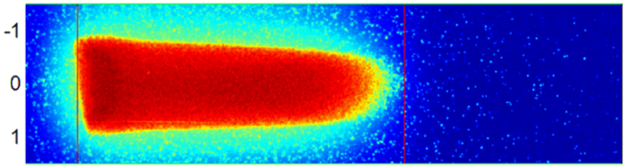

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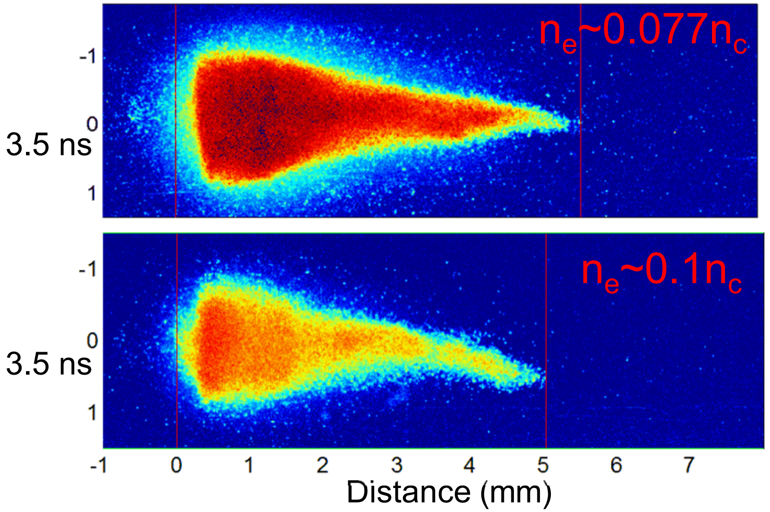
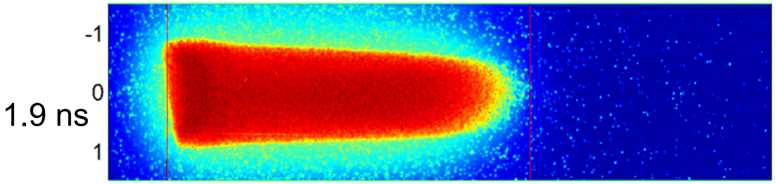


Summary: OMEGA-EP experiments are systematically testing laser heating of magnetized underdense plasmas

- OMEGA-EP experiments systematically test energy deposition at conditions relevant to MagLIF preheat
- In regimes where laser plasma instabilities are no significant, MHD codes accurately model inverse Bremmstrahlung absorption
- At high densities (n_e=0.1n_c) beam propagation bends and more hard x-rays are generated – laser entrance hole window appears to be a culprit
- Effort continues to map out parameter space where preheat is effective and predictable

Propagation in Ar (n_e=0.047n_c)
P~0.75 TW, $\bar{I}$~ 2.3e14 W/cm^2



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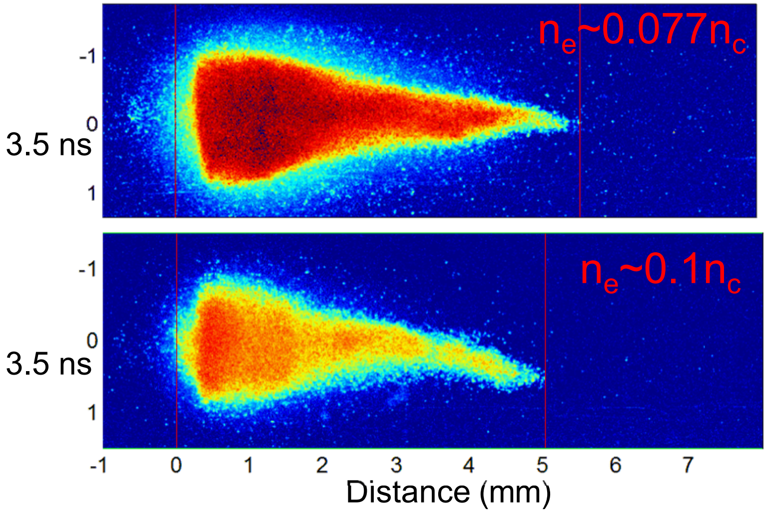

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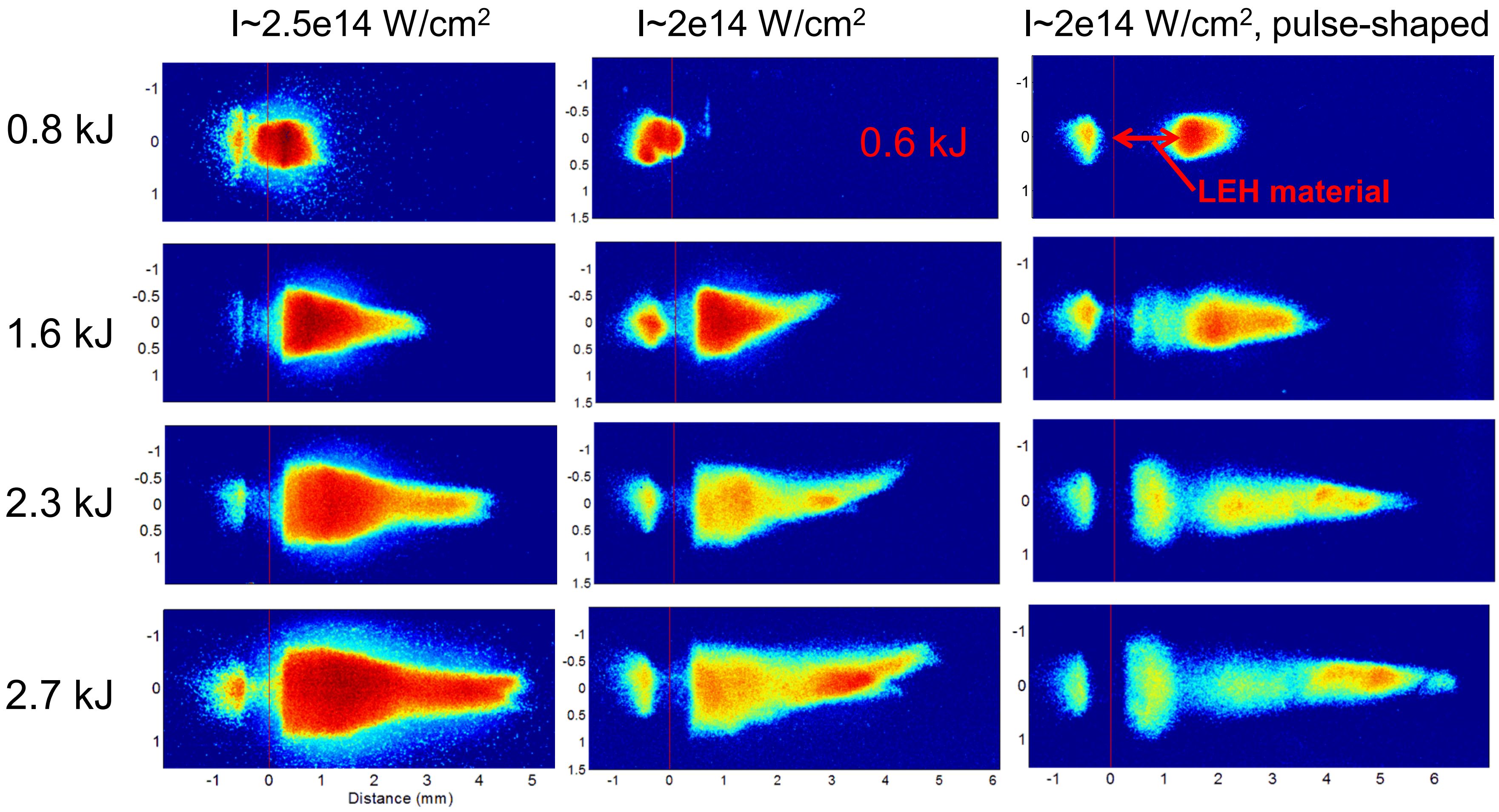
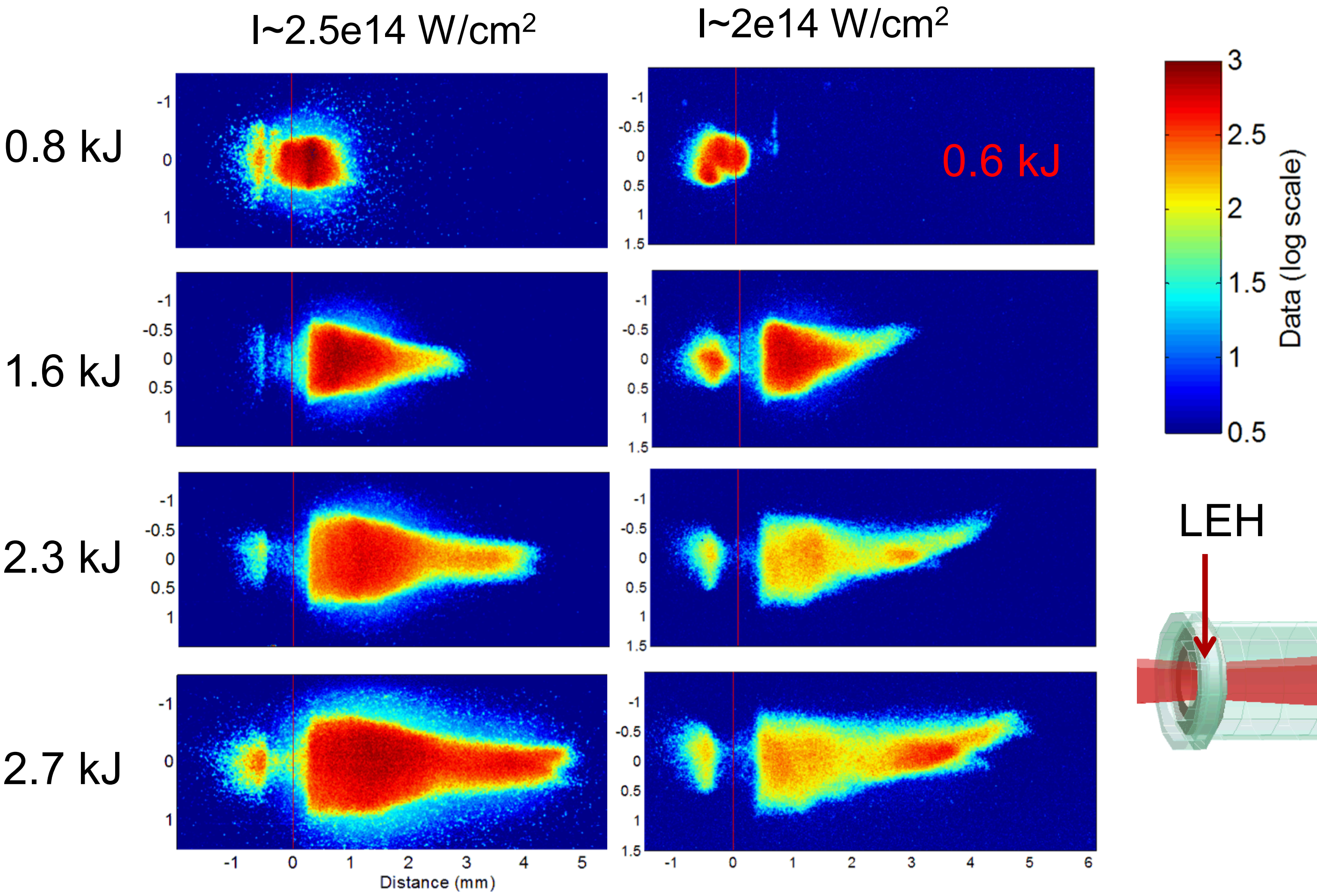
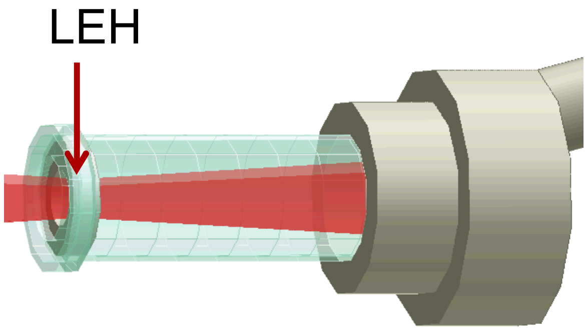
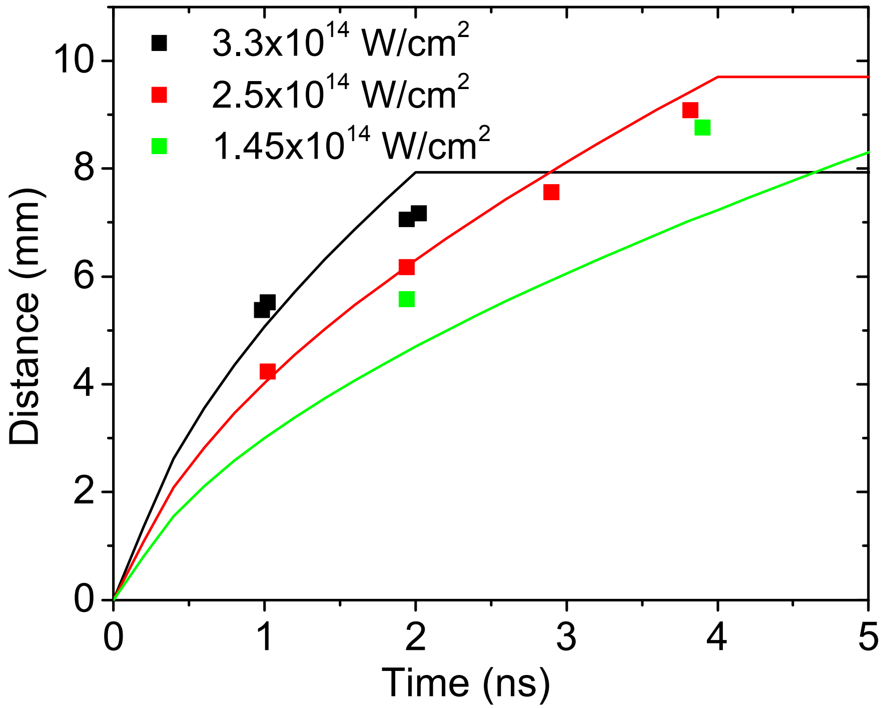


Propagation for 0.8 and 0.6 TW looks similar





At high intensities 1-D inverse Bremmstrahlung absorption model (SAMM) predicts propagation well

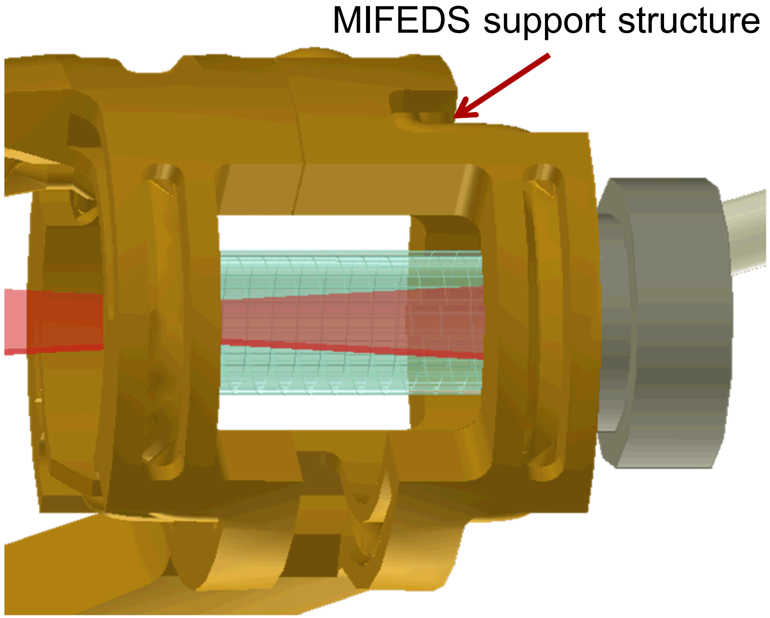


- SAMM[1] 1-D inverse Bremms. absorption model fails to capture low intensity propagation

Experiments tested energy deposition for D_2 gasses with $n_e = 0.055 – 0.1\ n_c$ and B=0 and 5T

Relevant D_2 densities based on MagLIF designs for initial targets

- 0.68 mg/cc (n_e=0.052 n_c for <u>527 nm</u> – current target design) to 2 mg/cc (n_e=0.15 n_c) D_2*



Propagation in 3 gas densities tested

- $n_e = 0.055\ n_c$ (10 atm pressure, 1.67 mg/cm^3)
- $n_e = 0.077\ n_c$ (14 atm pressure, 2.34 mg/cm^3)
- $n_e = 0.10\ n_c$ (18 atm pressure, 3.35 mg/cm^3)

Ar dopant (<0.25%) added to D_2

- Beam propagates through 3 µm thick LEH down axis of D_2 gas filled tube
- Propagation imaged using x-ray framing camera (250 ps frame times, ~150 µm resolution)– sensitive primarily to Ar He-α emission from dopant

The cause of the bending could be LPI or refraction

Beam intensity is very modest ($I\lambda^2$ = 2.9e13 Wμm^2/cm^2) – we weren't expecting LPI (SBS) in the gas to be an issue - one possibility is filamentation of the light

For a phase plate smoothed beam, the propagation is expected to filament when FFOM>1

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

Typical parameters (estimated):

- T_e ~ 600 eV
- f# = 6.7
- I_p = 2.3e14 W/cm^2
- n_e/n_c = 0.1

FFOM = 1 at these conditions
Detailed analysis by A. Schmitt (NRL) also suggests beam should not experience ponderomotive or thermal filamentation

Other possibilities include:

- Beam refraction by density gradients in the plasma (can be explored with MHD sims)
- Regions of the plasma reaching n_e~0.25n_c allowing TPD and SRS (would also produce hot electrons)
- Filamentation due to non-local thermal effects

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

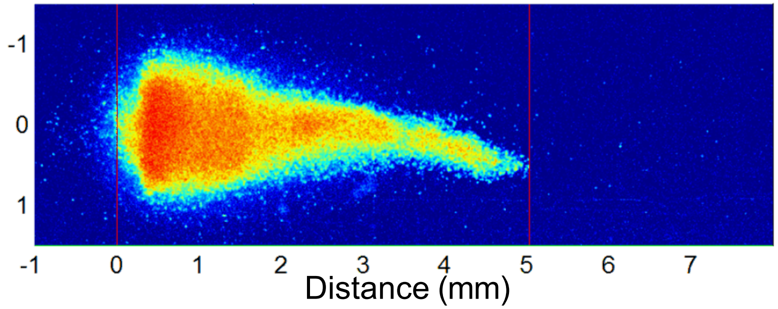
Summary: OMEGA-EP experiments are systematically testing our understanding of propagation in underdense plasmas

- OMEGA-EP experiments systematically test energy deposition at conditions relevant to MagLIF preheat

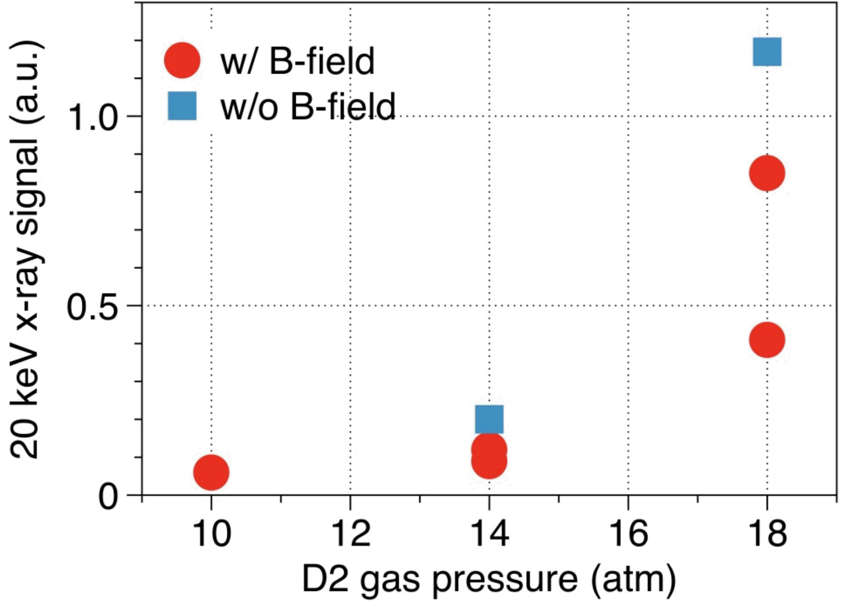
- At higher densities (n_e=0.1n_c) beam propagation bends and more hard x-rays are generated

- Effort continues to map out parameter space where preheat is effective and predictable

n_e~0.1n_c B~5 T, t=3.5 ns



20 keV x-ray signal



See T. Nagayama poster Mo.Po.48 for spectra from this series and analysis

Simulations suggest that filaments should not grow at these conditions

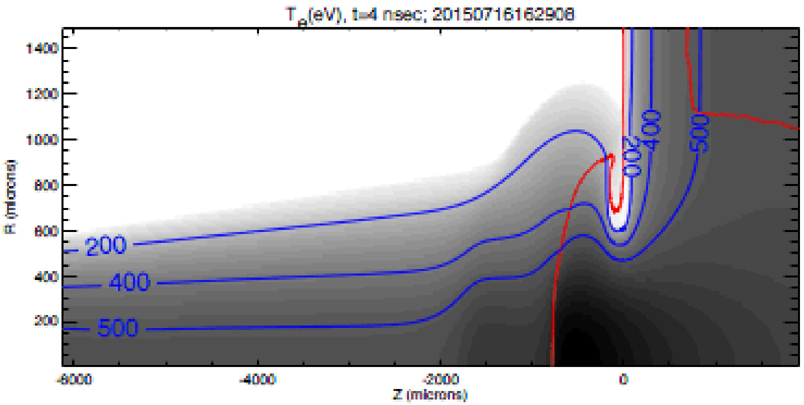
- Simulations and analysis done by Andrew Schmitt of NRL

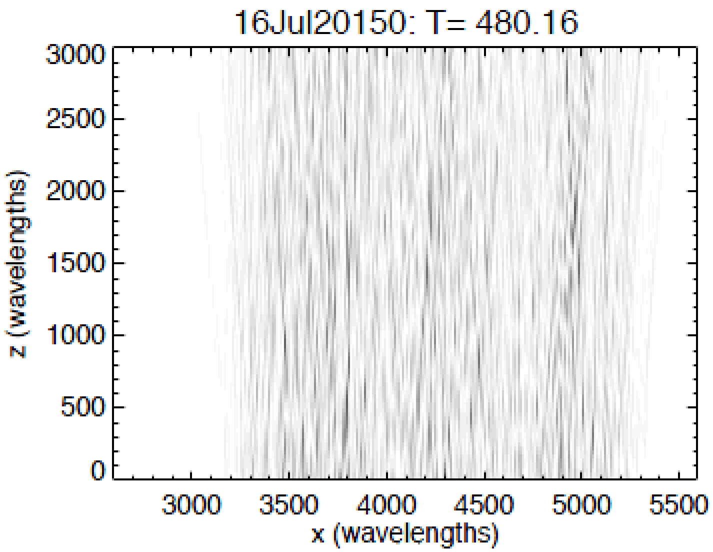
- Parameters from FAST3D simulation used in filamentation code – no filamentation observed

- Analytical analysis of simulated conditions suggests shortest growth lengths:
  - Ponderomotive growth length: L=3mm
  - Nonlocal thermal filamentation: L~680µm, wavelength λ~82µm

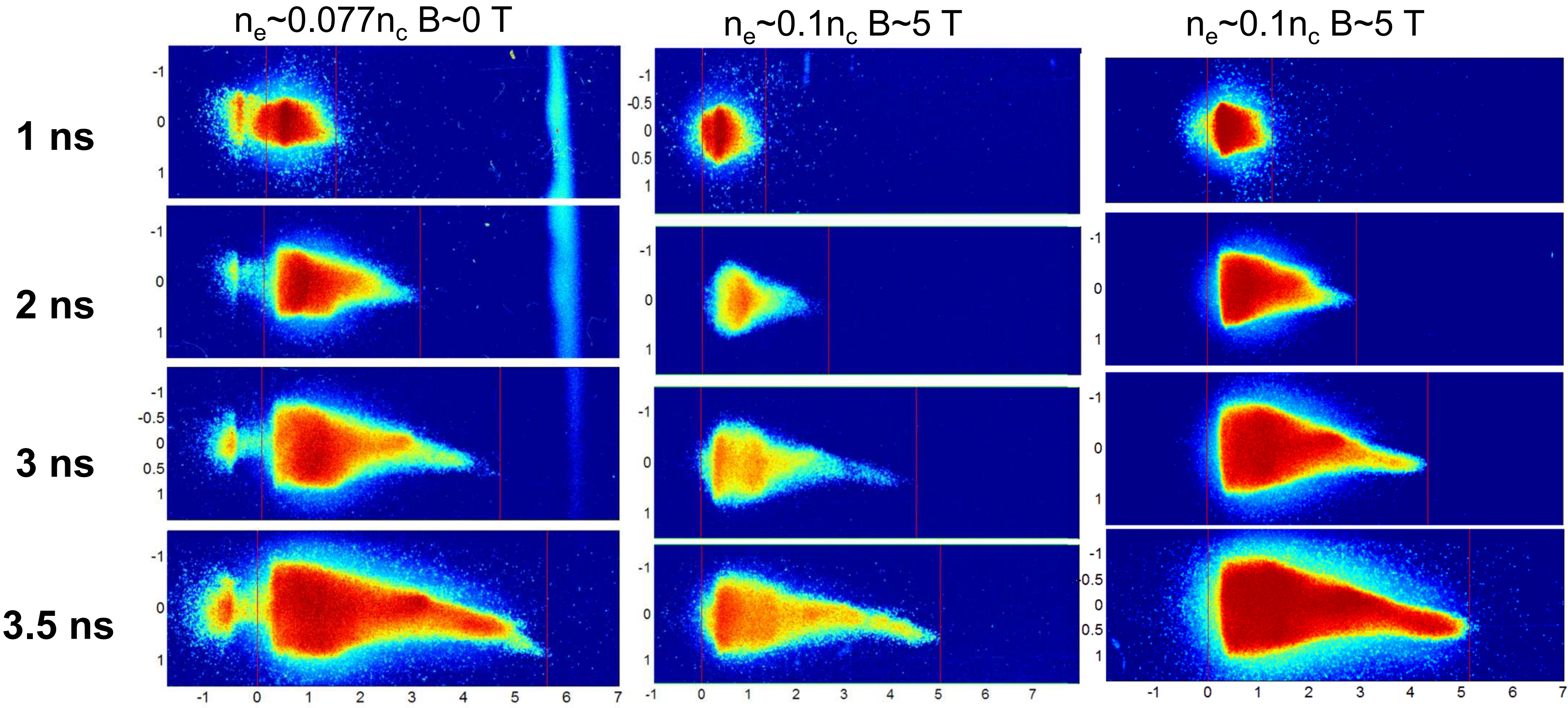
- Growth scales larger than speckle structure in the beam from DPP: 2 microns wide and 60 microns long

FAST3D sim at 4 ns for $n_e=0.1n_c$



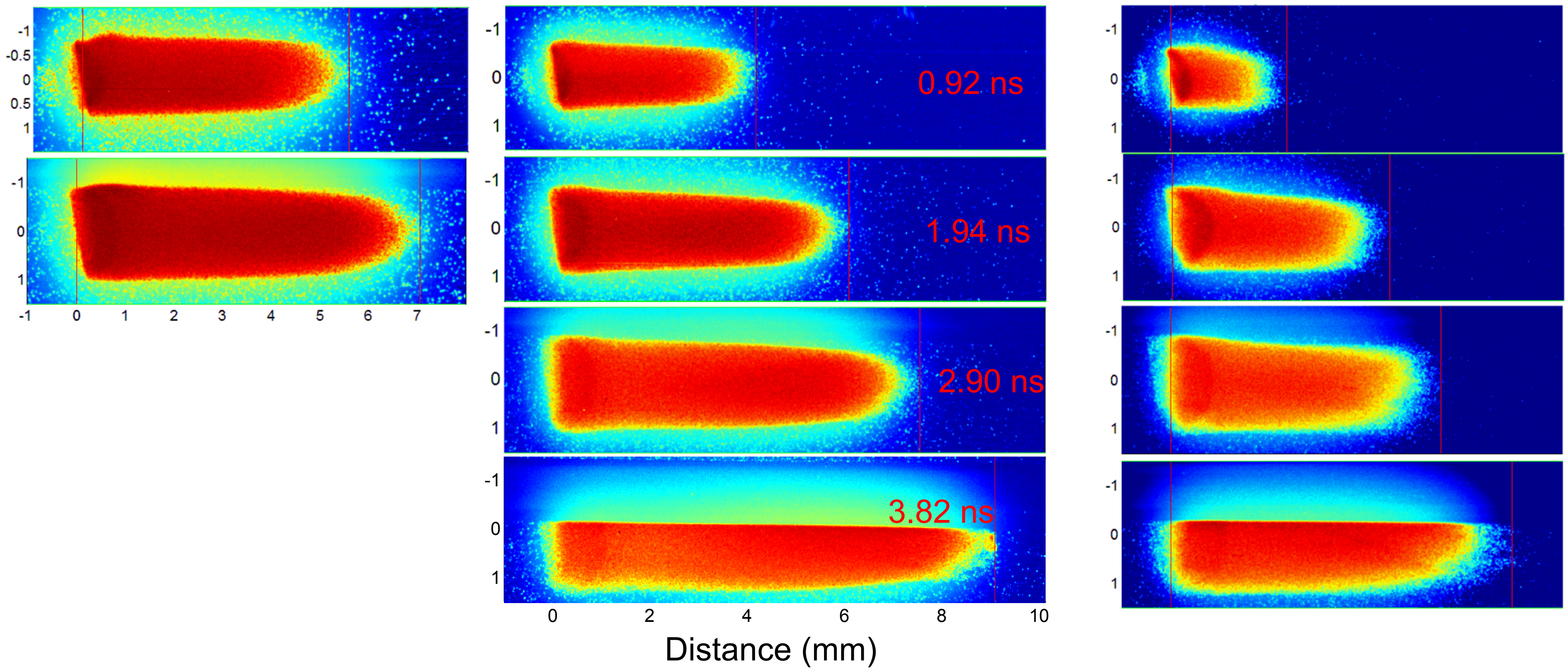


In all cases where the propagation bent, the bending was downwards – we don't know why



- Not clear why propagation bends downwards – no hotspot should be present (DPP smoothing) and pointing should be accurate – apparent bias could be due to low statistics?
- If initial conditions are responsible this has implications for preheating at Z – pointing of ZBL significantly less accurate

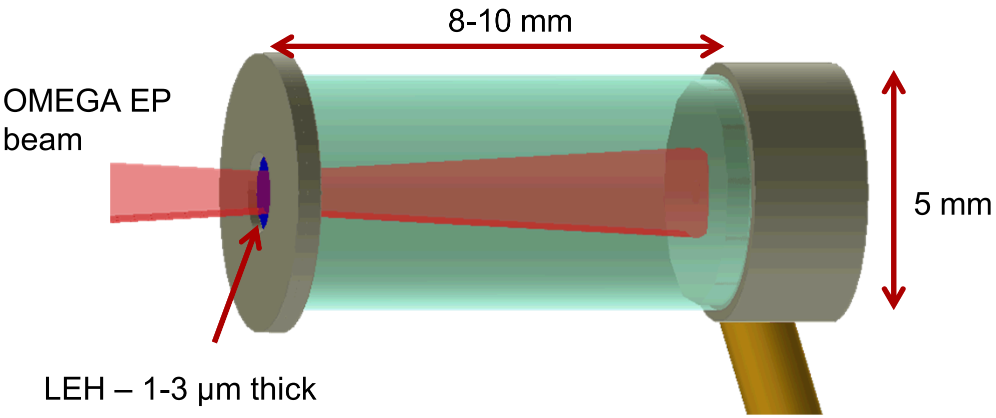
Changing the beam intensity alters the propagation velocity in pure Ar (n_e~0.047 n_c)



0.71 TW, I=2.5e14 W/cm^2

0.71 TW, I=2.5e14 W/cm^2

MagLIF-like targets are used to systematically investigate factors that affect laser preheat



Targets filled with pure Ar or Ar-doped D_2

- Pure Ar relaxes target requirements
  - Increased signal levels
  - Reduced pressure/LEH thickness
- Doped D_2 maximizes surrogacy

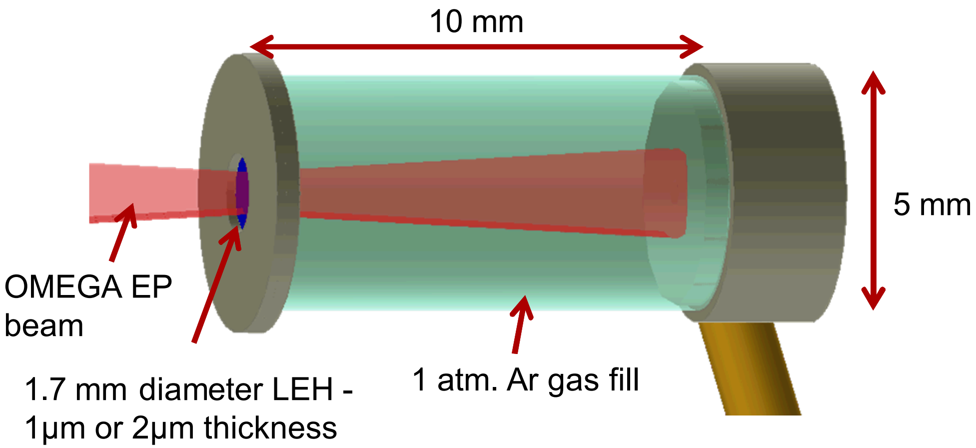
Systematic studies have investigated factors that affect energy deposition in MagLIF preheat

- Laser intensity (I= 1.45, 2.13 and 3.3e14 W/cm^2) (Ar)
- Beam smoothing (DPP vs. no DPP) (Ar)
- Effect of plasma density on energy deposition (n_e=0.05-0.1n_c) (D_2)
- Effect of magnetic field on energy deposition (B=0-4 T) (D_2)
- Effect of pulseshape on energy deposition (prepulse vs. no prepulse) (Ar and D_2)

OMEGA-EP laser has relevant energies and consistent performance to enable systematic studies

OMEGA-EP has characteristics ideal for MagLIF preheat studies

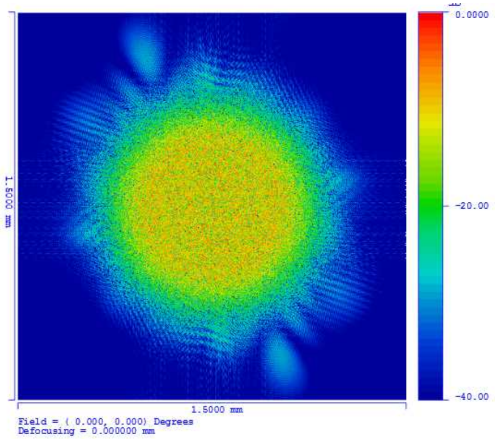
- Long duration (up to 10 ns), high energy beams (up to 5 kJ per beam)
- Good time gated diagnostics
- Up to 10T applied B fields provided by MIFEDS
- Beams are DPP smoothed with energy stability (~3-4%) and timing
- High shot rate – 7 shots per day per beam



Beam energies available on OMEGA-EP

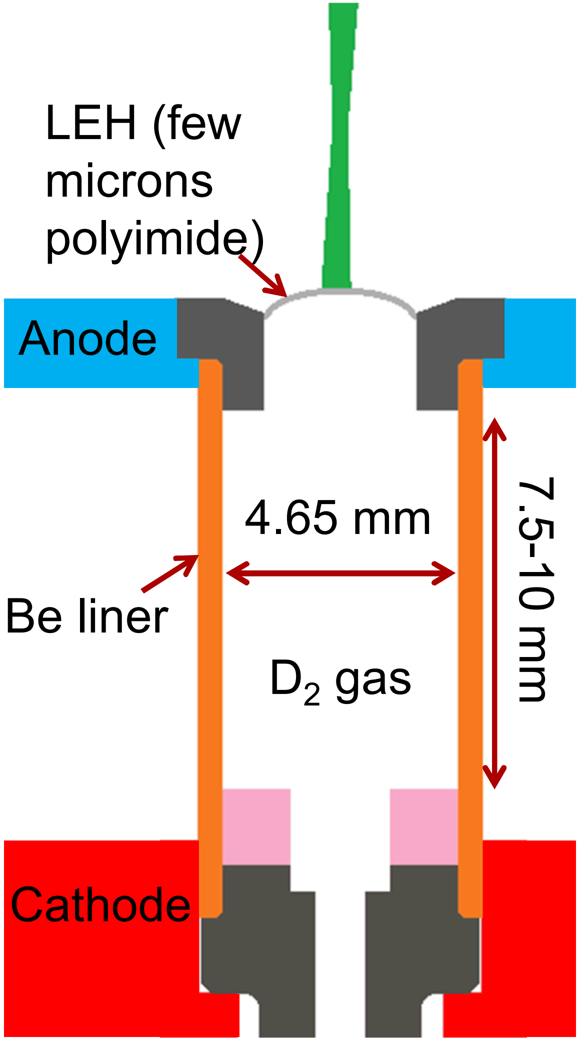
Duration	Beam 1	Beam 2	Beam 3	Beam 4
1 ns	1250 J	1250 J	1250 J	1250 J
2 ns	1950 J	1950 J	2250 J	2200J
4 ns	2800 J	2800 J	3150 J	3100 J
10 ns	4400 J	4400 J	5000 J	4900 J

750 um DPP point spread function



A. Harvey-Thompson et al., Phys. Plasmas, in review

MagLIF preheat challenge: Coupling 6-8 kJ of laser energy into an underdense D_2 gas in a MagLIF target without mix



- The scale length of MagLIF targets is well defined
  - Length of imploding region limited to 10 mm
  - Target ID limited to ~5 mm
  - Applied B field is 10-15T
- MagLIF is very sensitive to mix occurring during laser preheat – fuel has >50 ns to cool[1]

[1]: A. B. Sefkow et al., Phys. Plasmas 21, 072711 (2014)

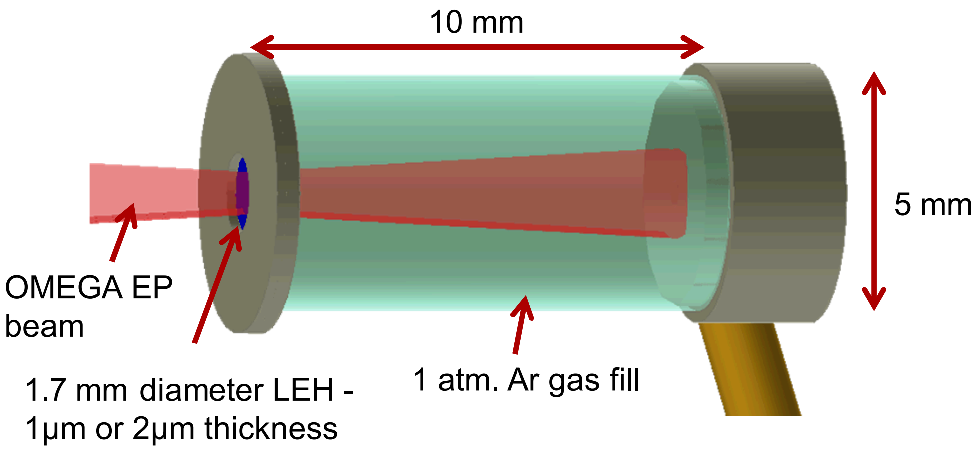
Systematic studies have investigated energy deposition in pure Ar, and D_2 doped with Argon

- Beam intensity varied
- and smoothing on energy deposition - intensities varied from 1.45-3.3e14 W/cm^2
- Effect of beam smoothing on energy deposition

- Effect of plasma density and applied magnetic field on energy deposition

OMEGA-EP laser is significantly different to Z-beamlet – experiments still needed on that laser

Experiments using targets filled with 1 atm. Ar show effect of beam intensity on energy deposition



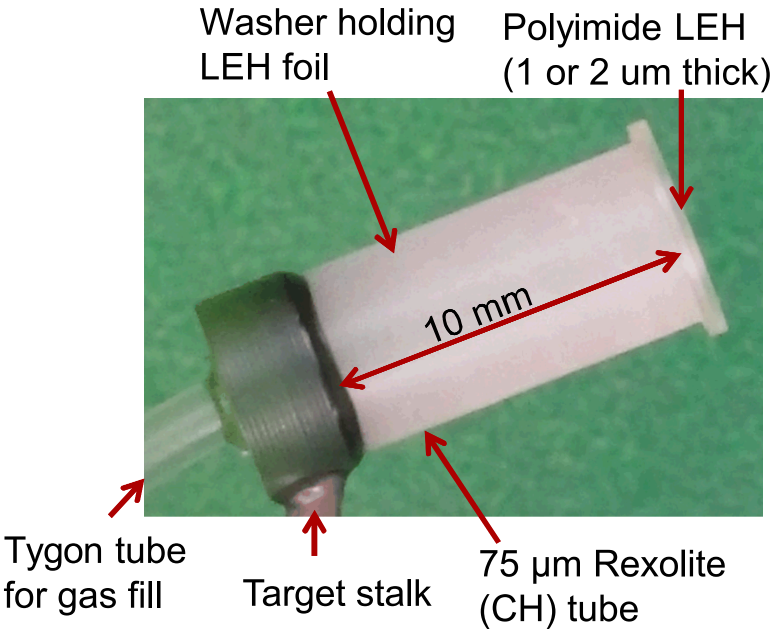
Experimental variables:

- Laser duration/power
- Phase plate smoothing vs. no phase plate smoothing
- 1 um and 2 um thick LEH windows
- Prepulse (250 J) vs. no prepulse

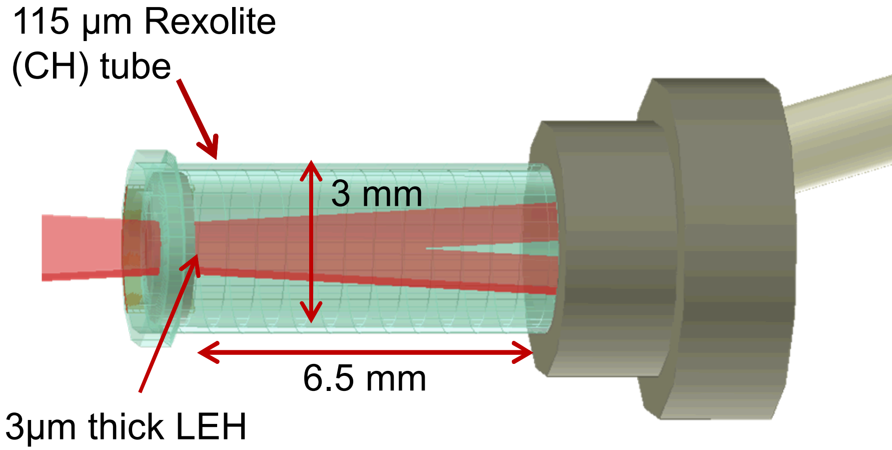
- Experiments tested beam propagation in 1 atm pure Ar ($n_e = 0.048\ n_c$ c.f. current MagLIF n_e~$0.05\ n_c$)
  - Ar allows for good diagnostic signatures and low pressures for a given n_e
- All beams used square pulses

Experiments used MagLIF-like CH tube targets filled with Ar or D_2

1 atm. Ar-filled targets



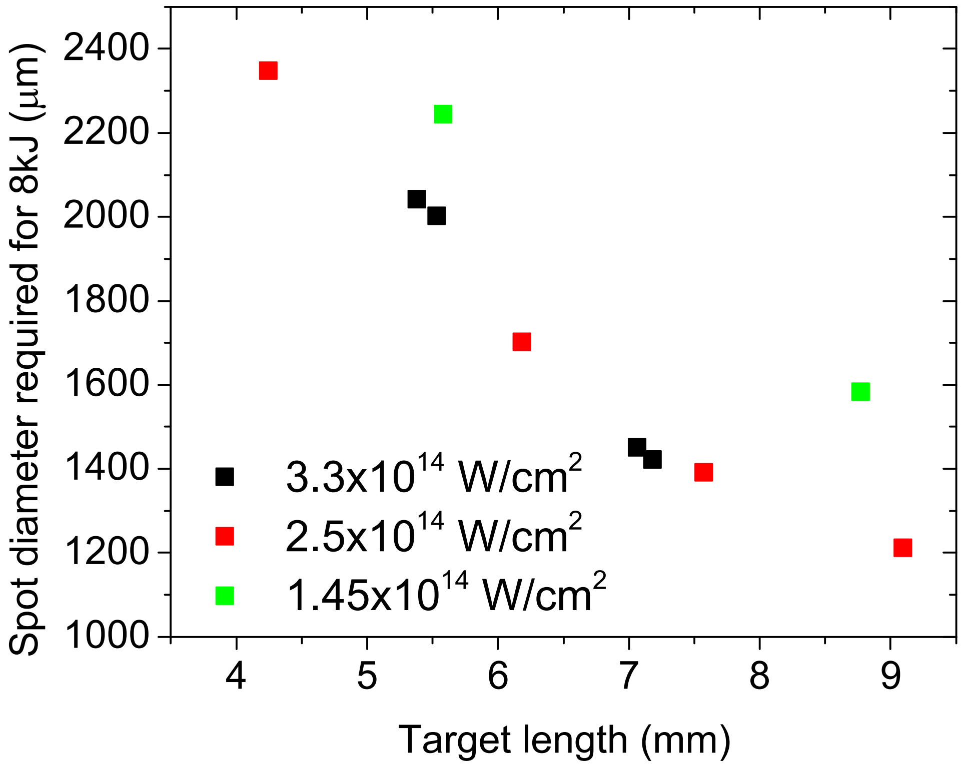
10-18 atm. D_2 -filled targets (VISRAD)



- Pure Ar decreases pressure required and increases signal levels – D_2 is more relevant for studies
- Densities studied are relevant to MagLIF: 1 atm Ar ≡ 0.047 n_c

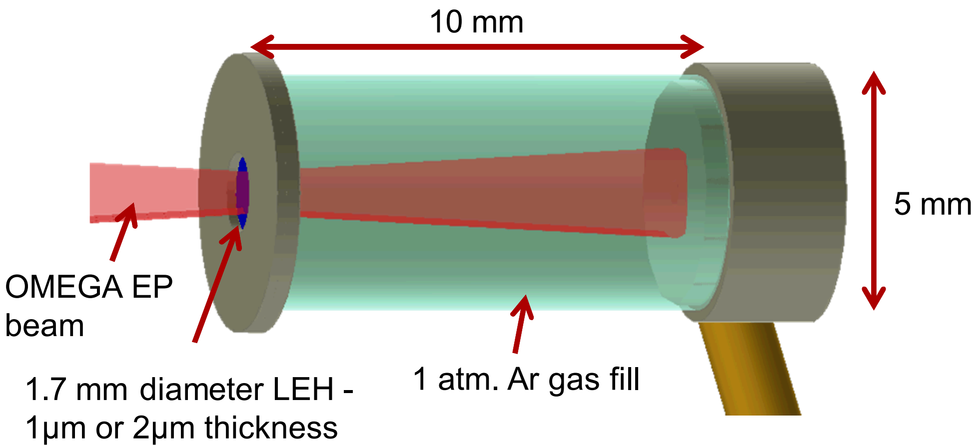
Extra slides

The data suggests that coupling 8 kJ is possible with a 1.2 mm spot size and 2.5x10^{14} W/cm^2



- Little difference in propagation velocity between 1.45 and 2.5x10^{14} W/cm^2
- 3 kJ is deposited into the target length for a modest spot diameter (750 µm), modest intensity (2.5x10^{14} W/cm^2) and low density (n_e/n_{crit}~0.05)
- If a 1.2 mm spot size is used 8 kJ can be easily coupled at these conditions (caveats apply)

Experiments using targets filled with 1 atm. Ar show effect of beam intensity on energy deposition



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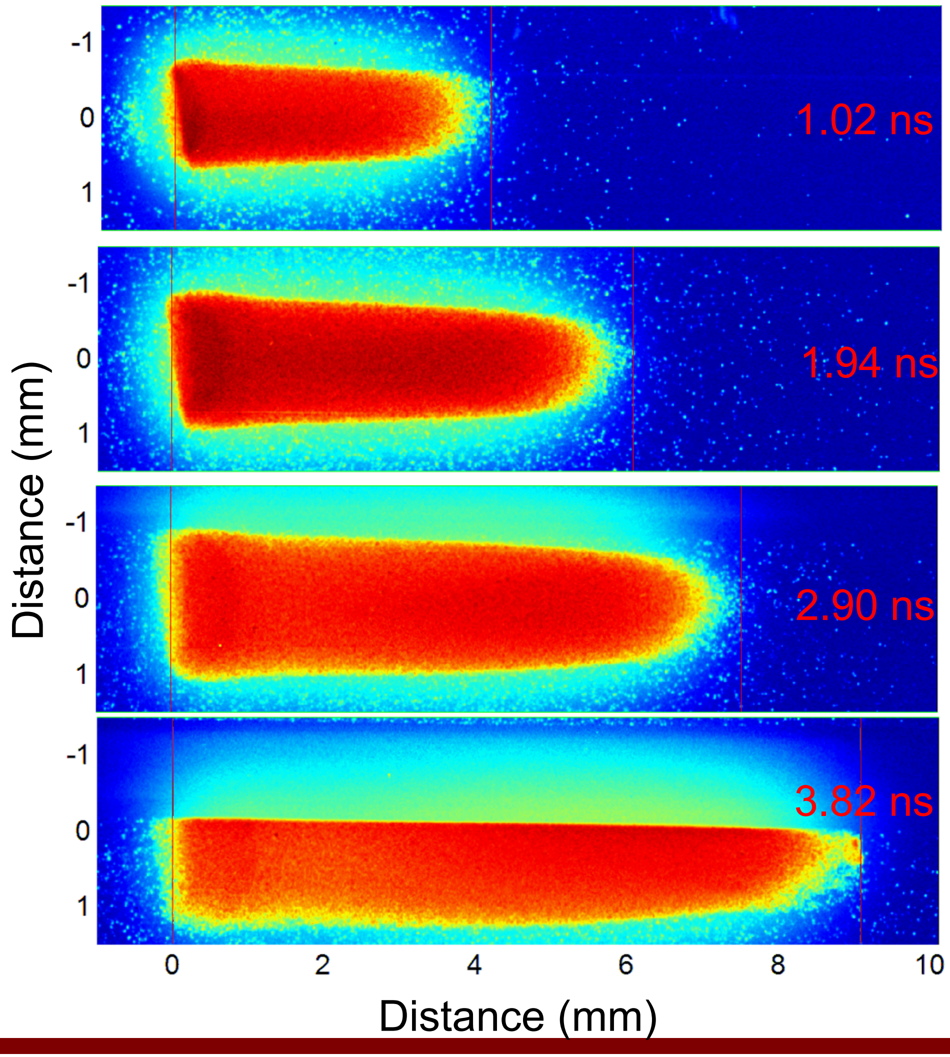
- Experiments tested beam propagation in 1 atm pure Ar ($n_e = 0.048\ n_c$ c.f. current MagLIF $n_e \sim 0.05\ n_c$)
  - Ar allows for good diagnostic signatures and low pressures for a given n_e
- All beams used square pulses

Xray framing camera images show beam propagation



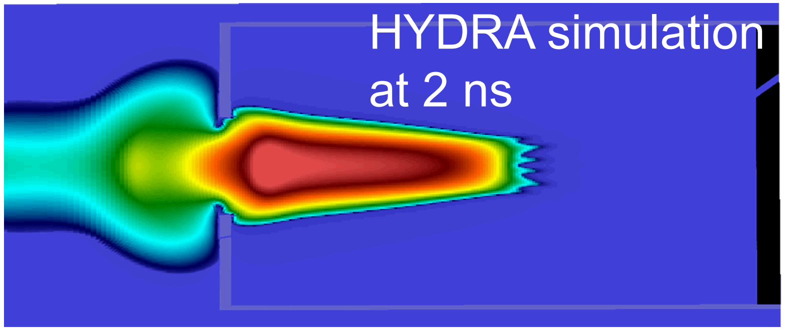
0.71 TW, I=2.5e14 W/cm^2

Experiments tested propagation for four beam powers (intensities)

- 1.1 TW (3.3e14 W/cm^2)
- 0.71 TW (2.13e14 W/cm^2)
- 0.46 TW (1.45e14 W/cm^2)

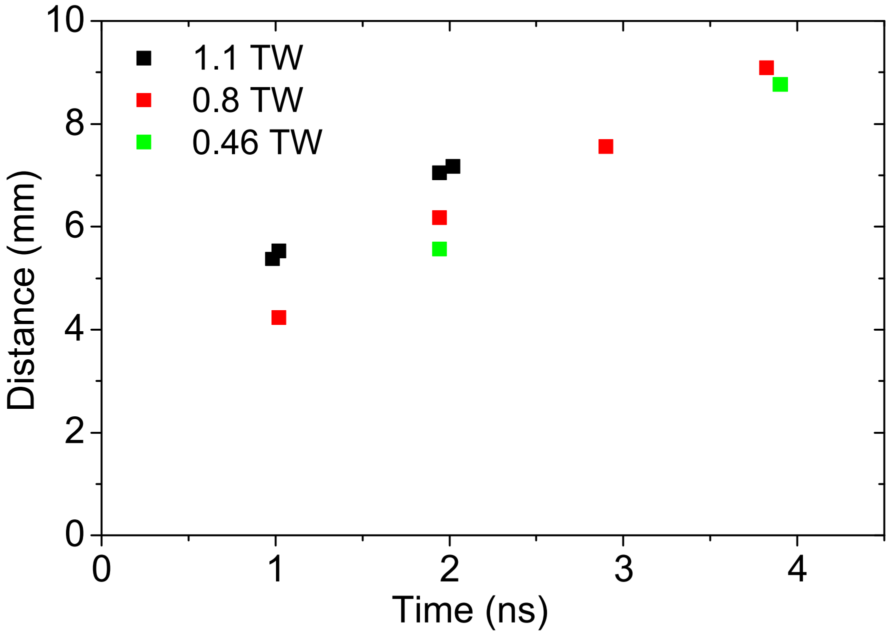
Gas density (1 atm ~0.048 n_c) and LEH thickness (1 µm) kept constant

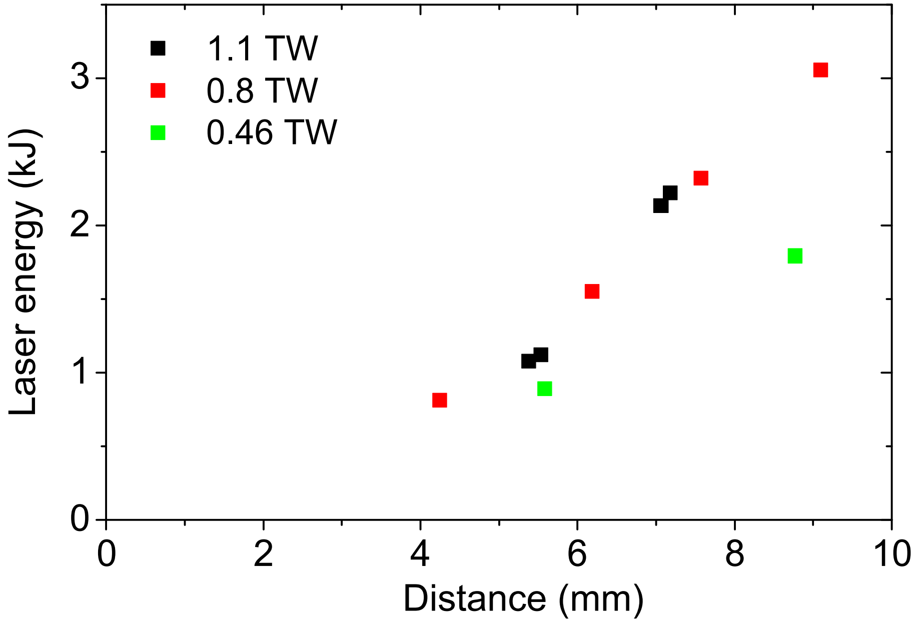
Results simulated using 2D HYDRA



HYDRA simulation at 2 ns

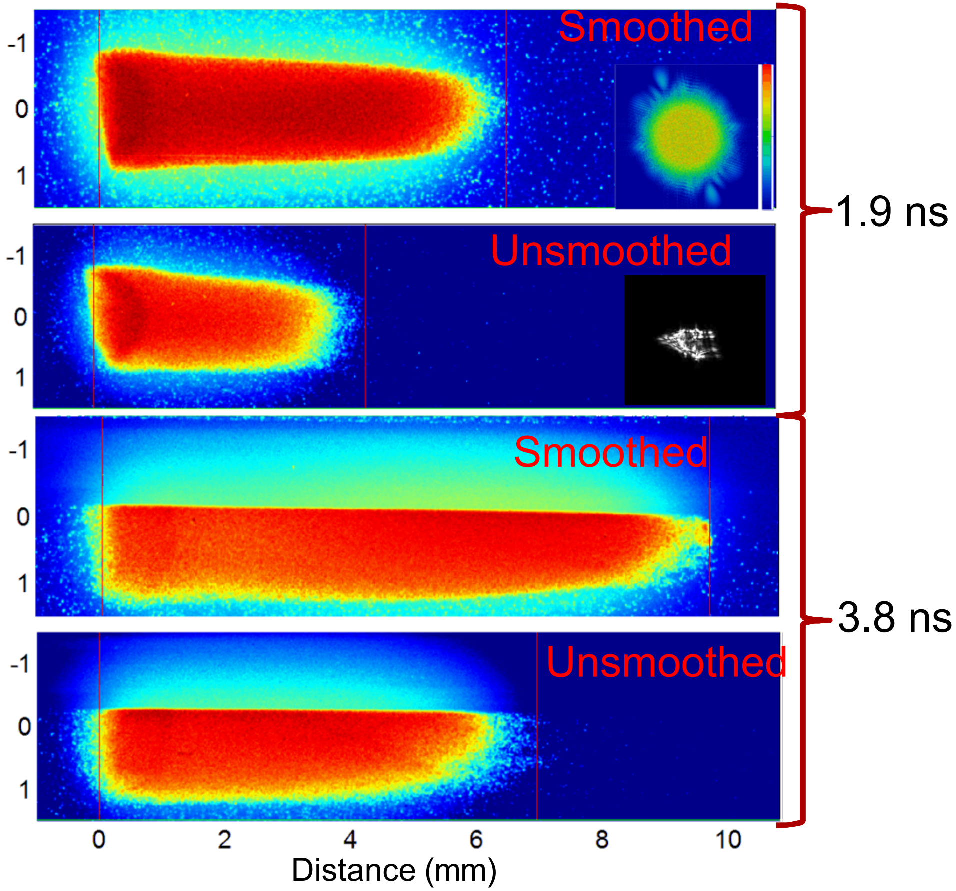
Effect of intensity on beam propagation

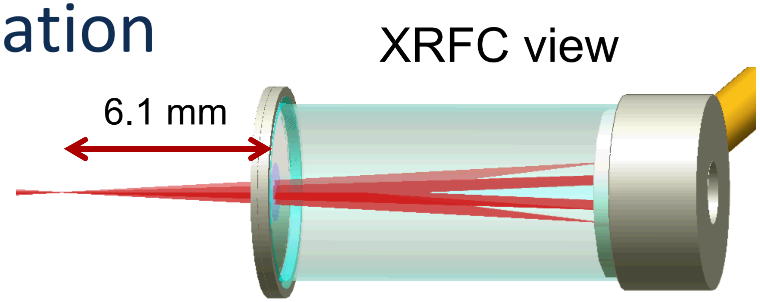


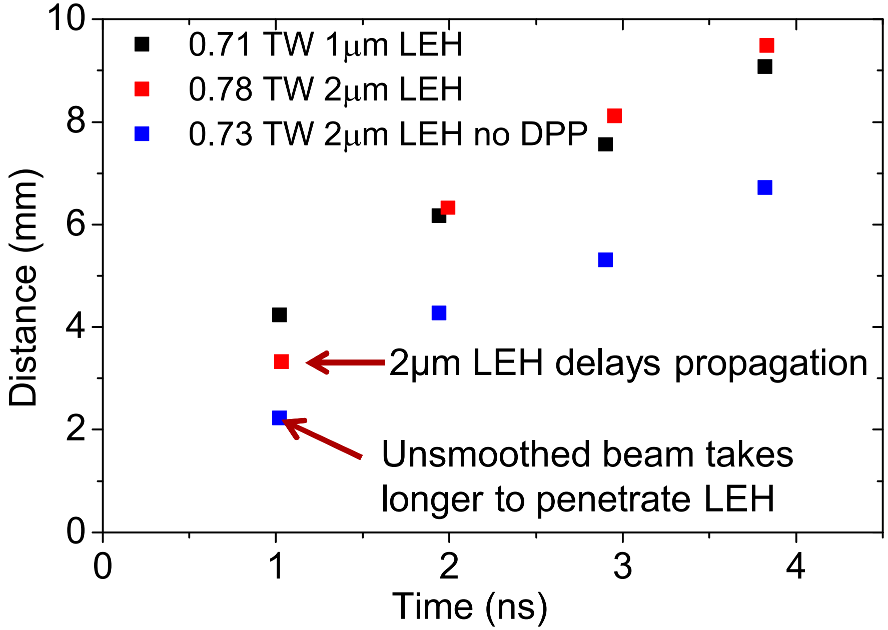


- Propagation begins rapidly before slowing in spite of energy lost to LEH
- Differences between intensities tested is not significant
- Plotting laser energy delivered to target vs. propagation distance down target shows how effectively target is heated

Data shows clear effect of smoothing and intensity/duration on beam propagation







- 2μm thick window delays propagation only slightly for DPP smoothed beam
- Removing phase plate results in more energy loss to LEH and slower propagation – energy being lost to LPI?

Previous experiments have investigated energy coupling at higher intensities, different scale lengths

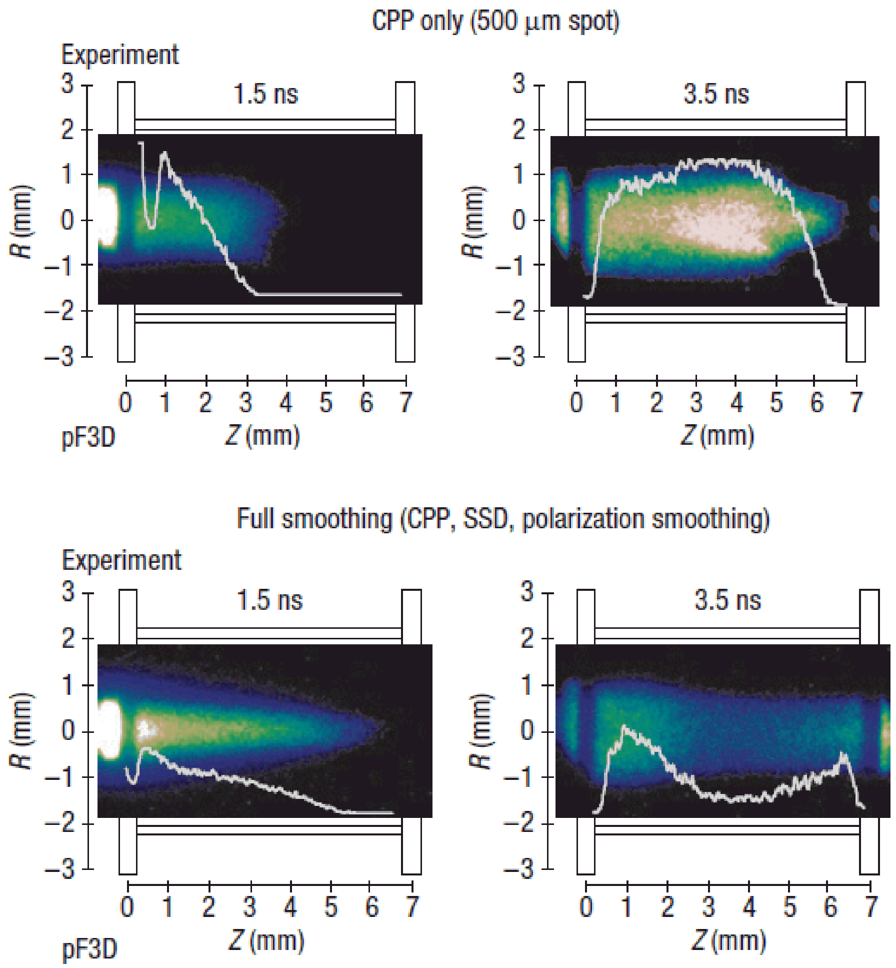
NIF hohlraums require laser propagation without significant scatter

Glenzer et. al., investigated propagation at conditions somewhat relevant to MagLIF in gas pipe targets

- CO_2 gas, n_e~$0.067n_c$ 7 mm long
- One NIF qaudrant (16 kJ, 3ω, 3.5 ns, I_0=2e15 W/cm^2)

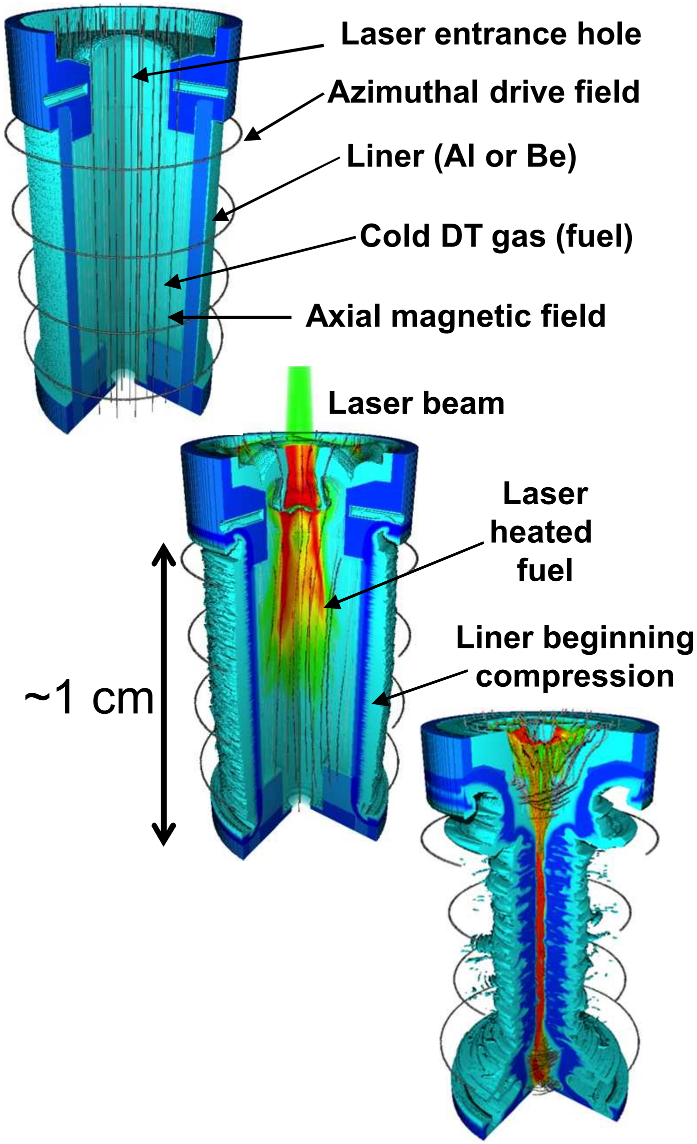
SSD and polarization smoothing was required to prevent filamentation and LPI allowing beam to propagate effectively

MagLIF requires that energy to be absorbed over a short distance, what beam and target parameters are required for this?



Glenzer et al., Nat. Phys. 3, 10, (2007)

The MagLIF[1] concept combines fuel preheating and magnetization to reduce fusion requirements



In addition to compressing the fuel with the Z current drive, MagLIF adds two extra elements:

- An initial 30 T axial magnetic field is applied produced by external Bfield coils
    - Inhibits thermal conduction losses
    - Confines alpha particles when compressed for greater self-heating
    - Appears to stabilize implosion at late times
- During the ~100 ns implosion, the fuel is heated using the Z-Beamlet laser (about 6 kJ in designs)
    - Preheating to ~300 eV reduces the compression needed to obtain fusion temperatures to $R_{initial}/R_{stagnation}$ ~ 23 on Z
    - Preheating reduces the implosion velocity needed to ~100 km/s, allowing us to use thick liners that are more robust against instabilities

Initial experiments have produced 2e12 DD neutrons[2]

[1] S.A. Slutz *et al.*, Phys. Plasmas 17, 056303 (2010). M. R. Gomez et al., PRL 113, 155003 (2014).