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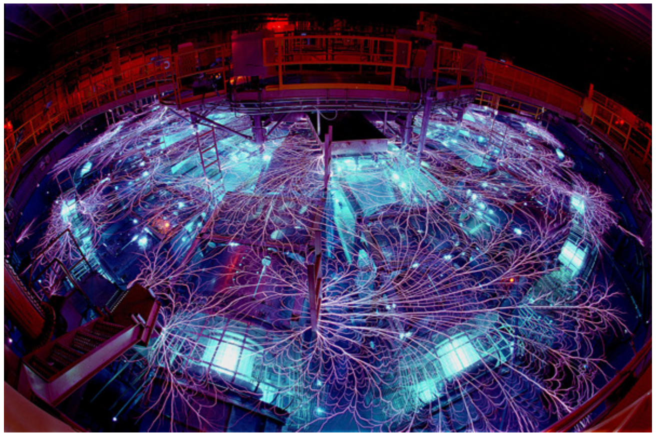

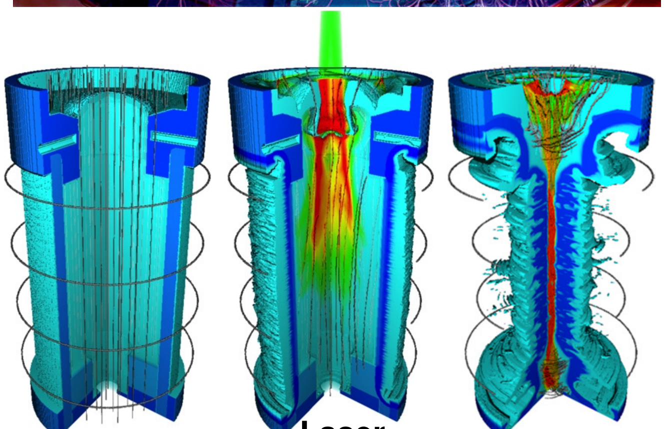

Progress in Magnetized Liner Inertial Fusion (MagLIF)

Stephanie Hansen

For the MagLIF team

Sandia National Laboratories

European Physical Society Conference on Plasma Physics
June 22-26, 2015

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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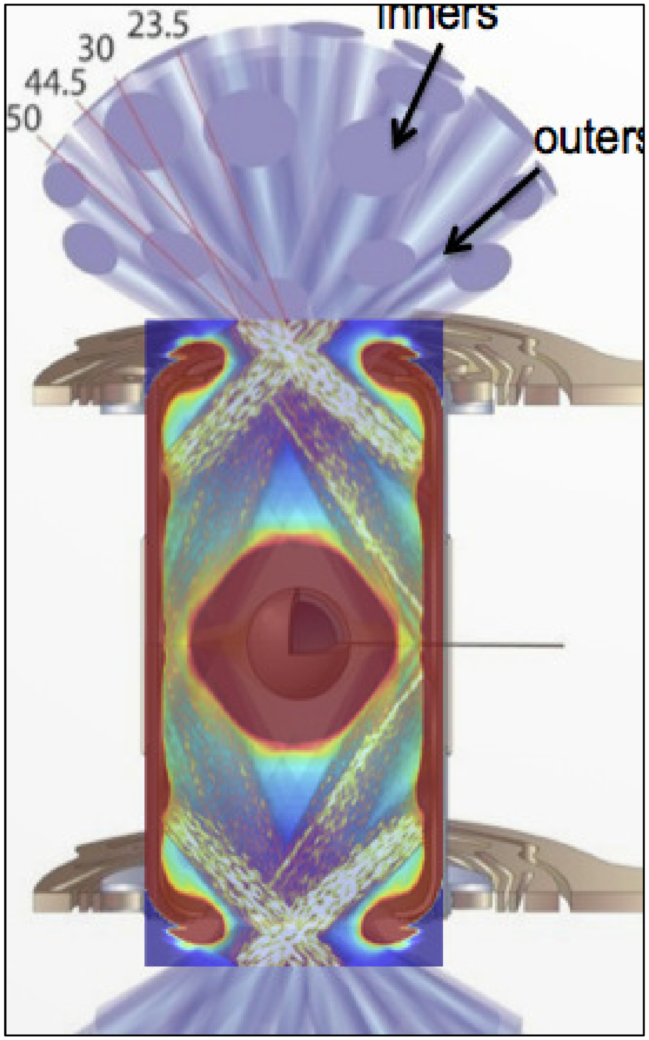
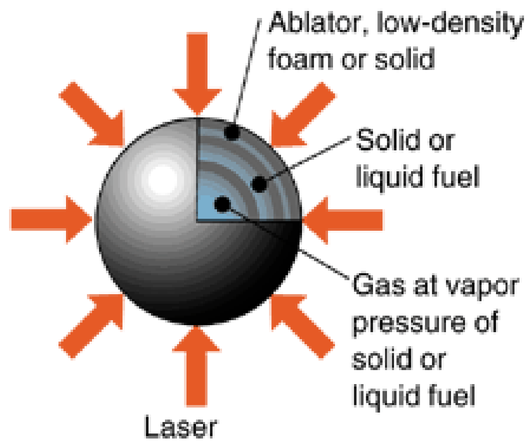
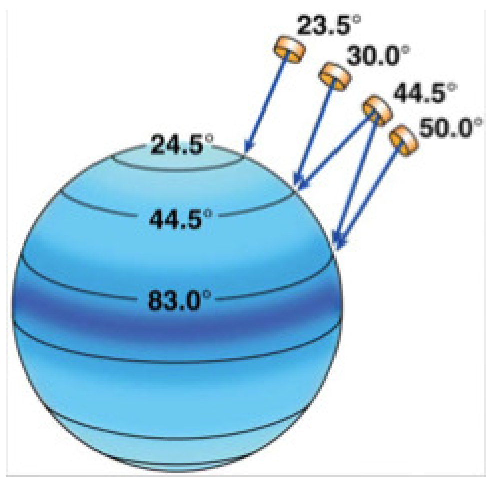
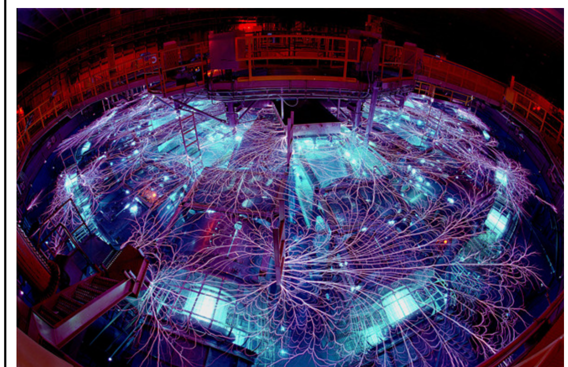
The United States ICF program has focused on three main approaches to ignition

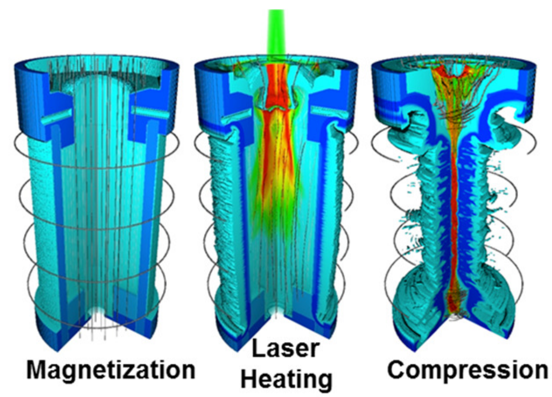
Indirect X-ray drive	Direct laser drive	Direct magnetic drive







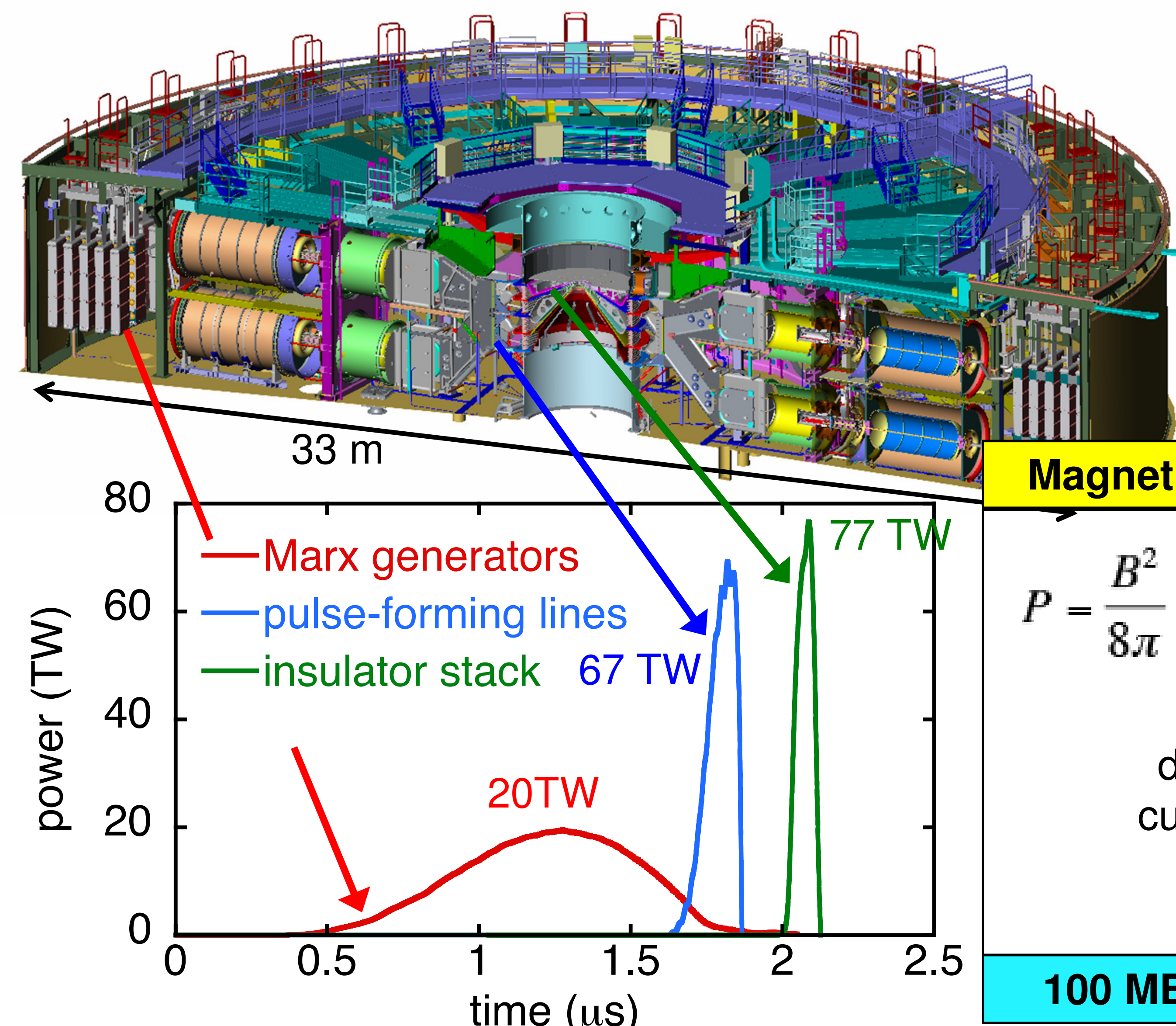




Focus of today's talk

Primary Approach	Alternative Approach	Alternative Approach

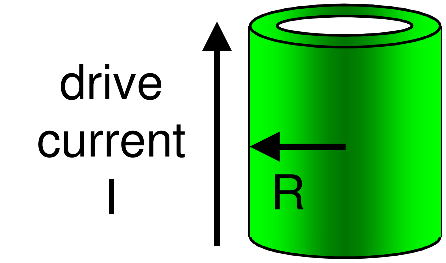
Magnetic direct drive is based on the idea that we can efficiently use large currents to create high pressures



Z today couples 0.5 MJ out of 20 MJ stored to MagLIF targets, delivering 0.1 MJ to DD fuel.

Magnetically-Driven Implosion

$$P = \frac{B^2}{8\pi} = 105\left(\frac{I_{MA}/26}{R_{mm}}\right)^2 \text{ MBar}$$

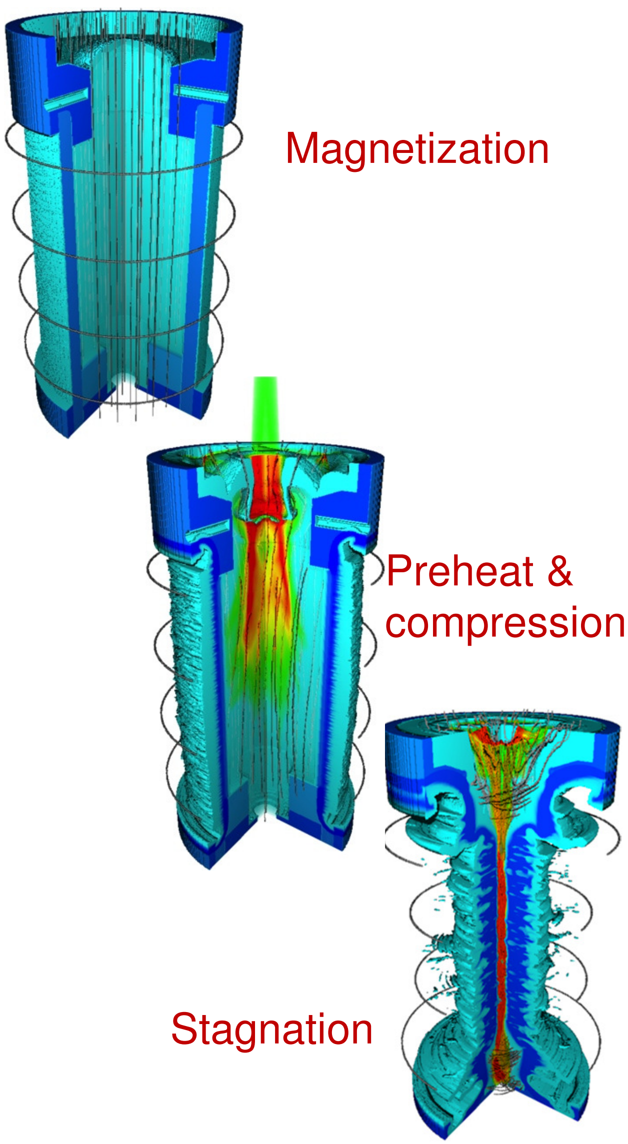


100 MBar at 26 MA and 1 mm

Implosion time ~50 ns; stagnation ~0.1-1 ns

(1 atm = 1 bar = 10^5 Pascals)

The Magnetized Liner Inertial Fusion (MagLIF)* concept is well suited to pulsed power drivers and may reduce inertial fusion requirements

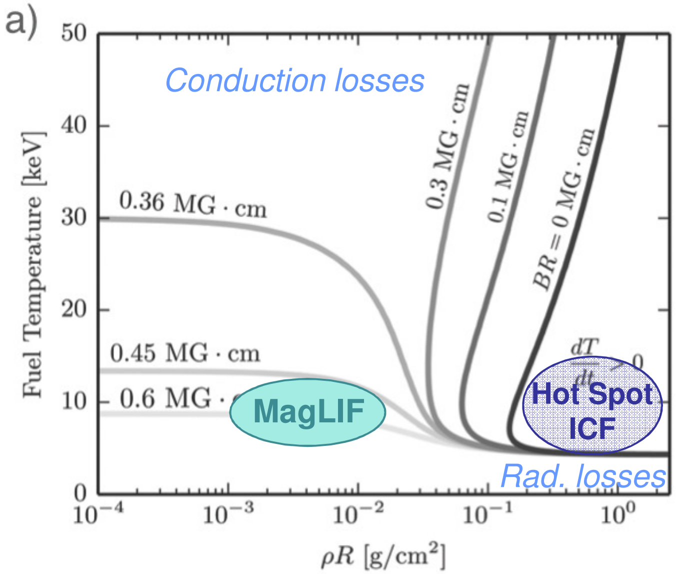


- <u>Axial magnetization</u> of fuel/liner (B_{z0} = 10-30 T)
  - Inhibits thermal conduction losses, may help stabilize liner compression, traps charged fusion products (β: 5~80; $\omega\tau$>200)
- <u>Laser preheat</u> (2-10 kJ)
  - Reduces amount of radial fuel compression needed to reach fusion temperatures (R_0/R_f = 23-35)
- <u>Liner compression</u> of fuel (70-100 km/s, ~100 ns)
  - "Slow", quasi-adiabatic compression of fuel
  - Low velocity requirements allow use of thick liners ($R/\Delta R$~6) that are robust to instabilities and provide sufficient ρR at stagnation to inertially confine fuel
- Combination allows fusion at ~100x lower fuel density than traditional ICF (~5 Gbar vs. 500 Gbar)
- DD equivalent of 100 kJ DT yield may be possible on Z with upgrades from our initial setup
  e.g., 10 T → 30 T; 2 kJ → >6 kJ; 19 MA → >24 MA

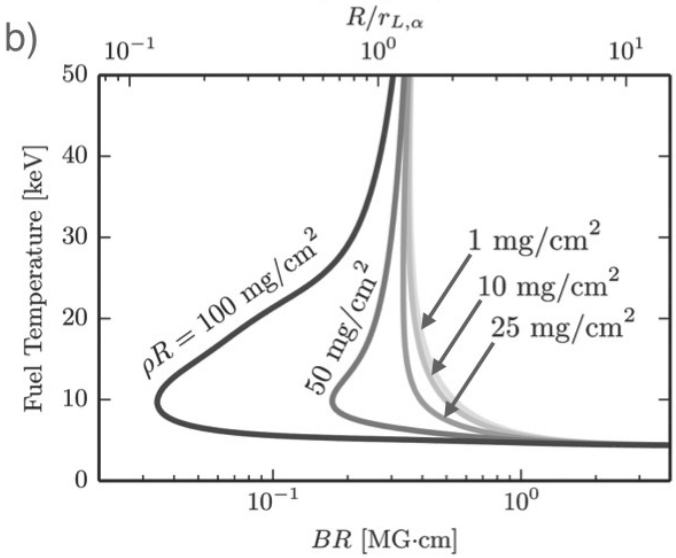
*S.A. Slutz *et al.*, Phys Plasmas (2010); S.A. Slutz and R.A. Vesey, Phys Rev Lett (2012); A.B. Sefkow *et al.*, Phys Plasmas (2014).

Magnetization can be used to reduce thermal conduction losses and ρR/pressure requirements

a)

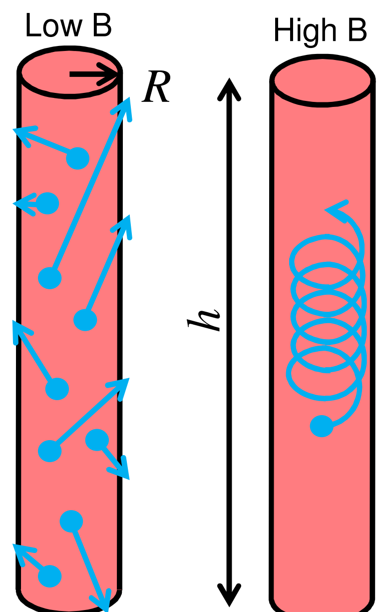


b)



- **Axial magnetization of fuel/liner (B_{z0} = 10-30 T)**
  - **Inhibits thermal conduction losses, may help stabilize liner compression, traps fusion products (β: 5~80; ωτ>200)**

$$\frac{R}{r_\alpha} = \frac{BR\ [T \cdot \mathrm{cm}]}{26.5} = \frac{BR\ [G \cdot \mathrm{cm}]}{2.65e5} \approx 4BR\ [MG \cdot \mathrm{cm}]$$



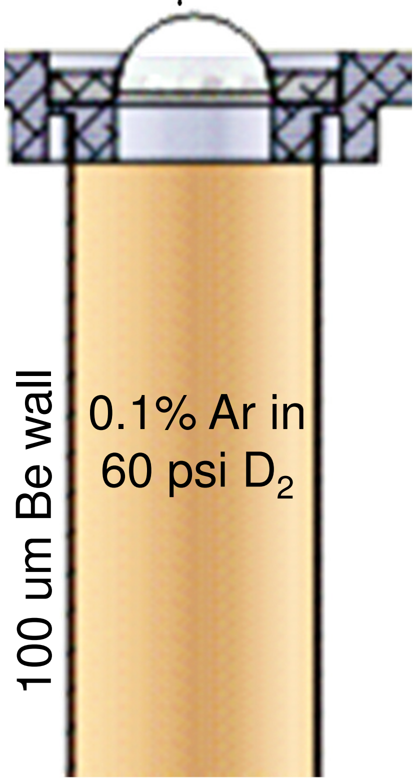
Fraction of trapped α's (tritons) is a function of ***BR*** only

Measurements to date suggest we are reaching 0.4 MG-cm: enough to return 40% of fusion product energy to the fuel.
Effects saturate at BR > 0.5 MG-cm

*S.A. Slutz *et al.*, Phys Plasmas (2010); S.A. Slutz and R.A. Vesey, Phys Rev Lett (2012); A.B. Sefkow *et al.*, Phys Plasmas (2014).

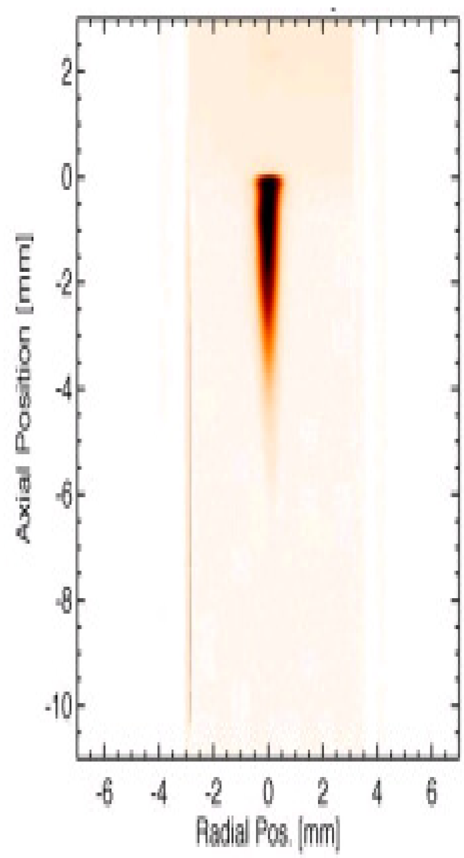
Magnetization and preheat: dedicated preheat experiments indicate that the external magnetic field effectively insulates the preheated plasma

2.5 kJ laser onto 1.5 μm foil:

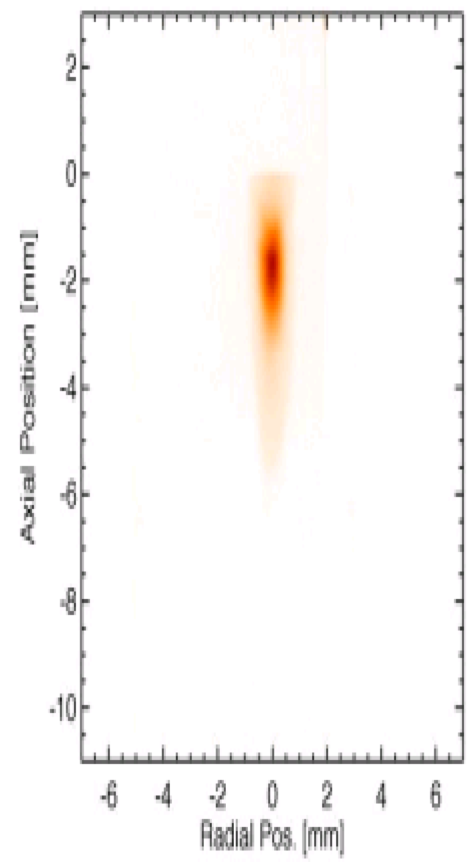


3.12 keV argon self-emission images

Bz = 8.5 T



Bz = 0 T

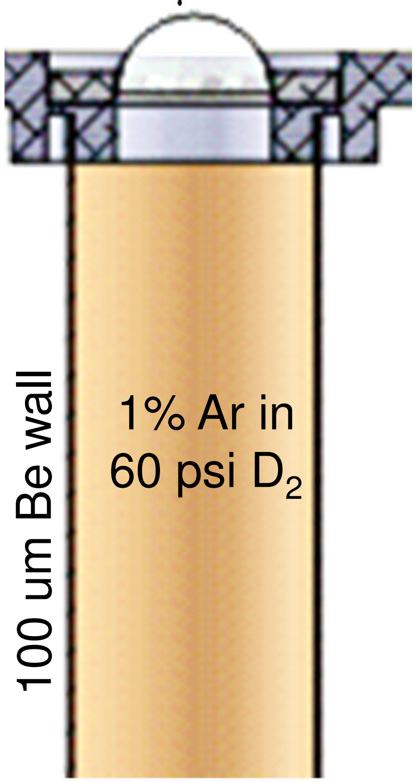


These data may help constrain models of thermal conductivities in high magnetic fields

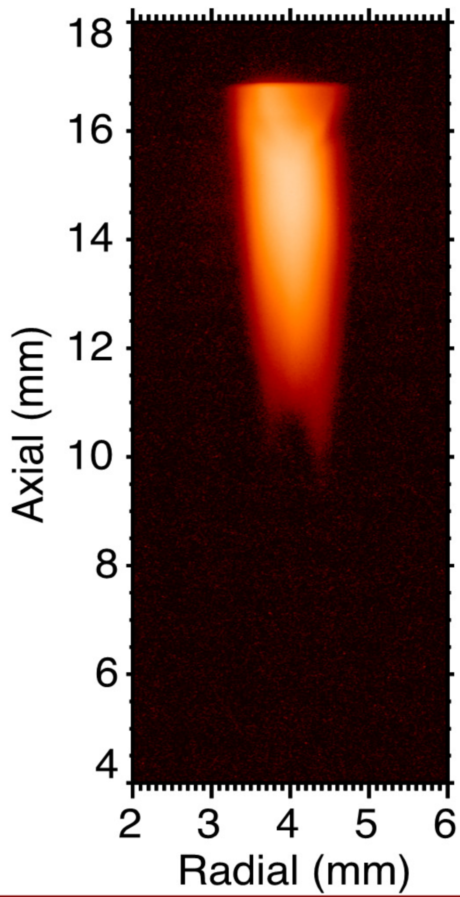
A. Harvey-Thompson, K. Peterson, M. Geissel

Preheat: Dedicated preheat experiments indicate poor laser coupling to the fuel (100-300 J from 2-4 kJ)

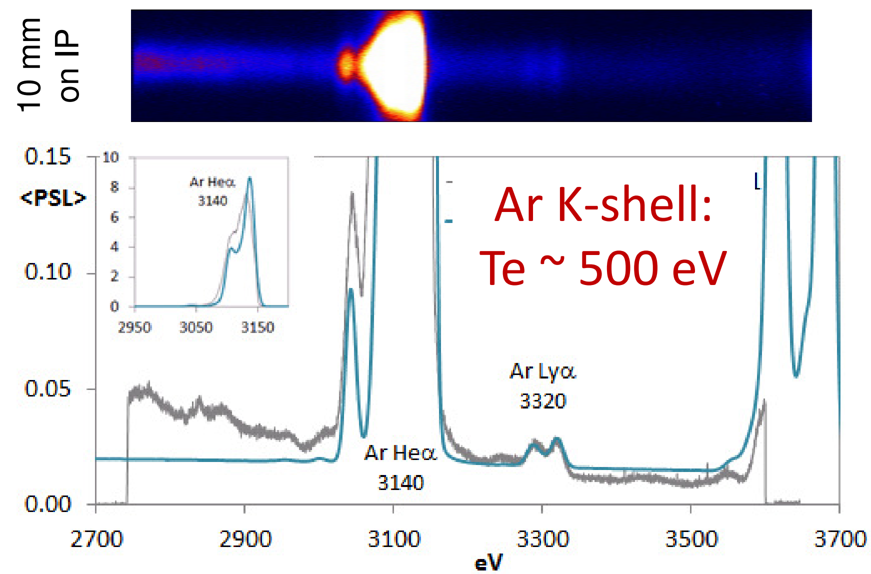
2.5 kJ laser onto 1.5 μm foil:



3.12 keV self-emission image



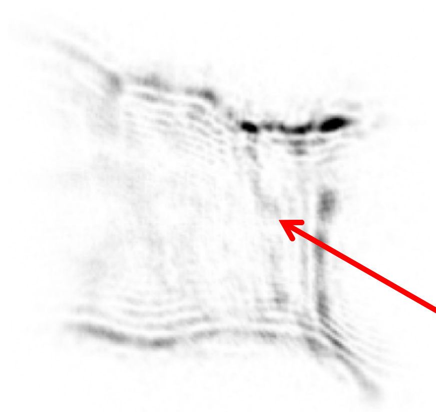
Radially resolved Ar emission spectrum



Spectra and imager data:
~500 eV temperature in ~mm^3 volumes → only ~10% of laser energy is coupled to the fuel – consistent with ~10^{12} DD yields in integrated experiments

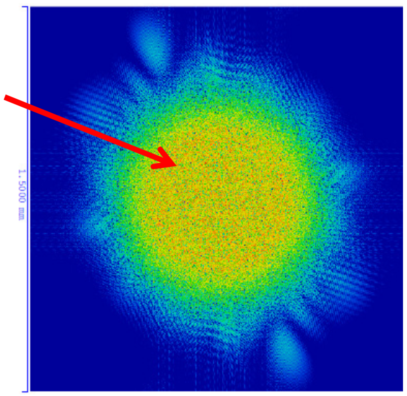
Preheat: Poor beam quality is contributing to poor laser-fuel coupling; future experiments will use conditioned beam

Z-Beamlet currently does not use any beam smoothing techniques adopted by the laser community

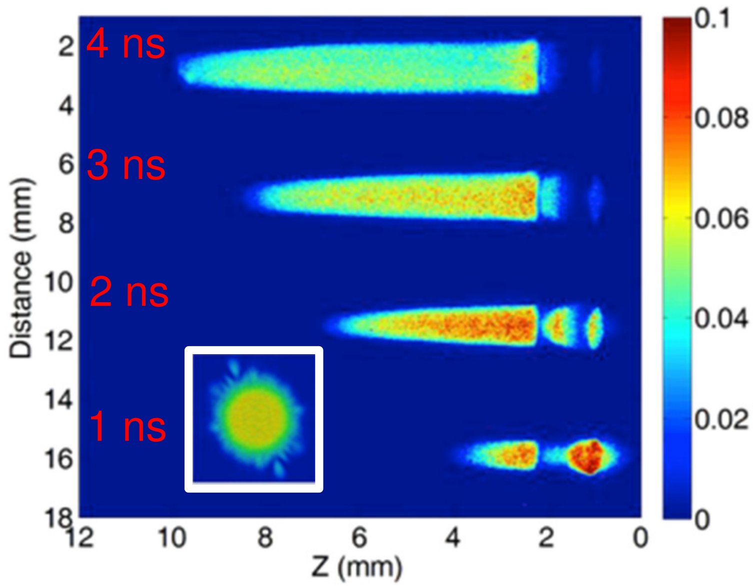


ZBL: No DPP (representative)

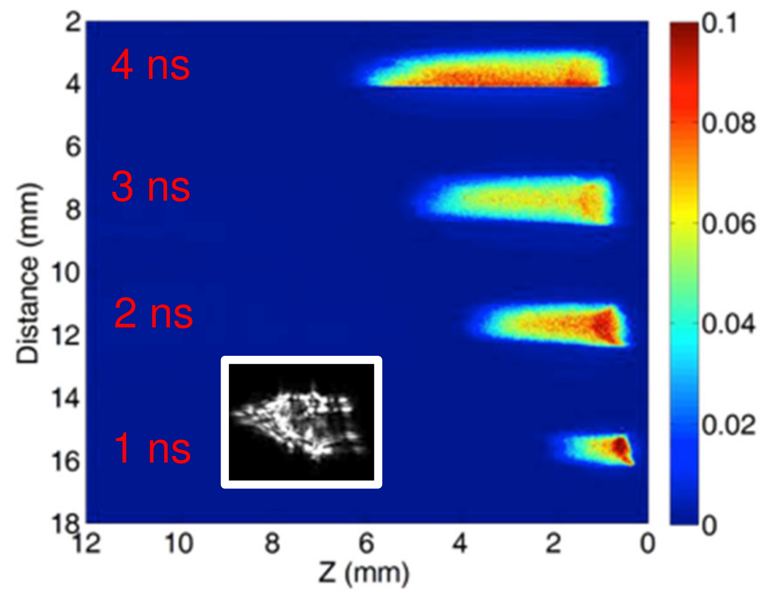
OMEGA-EP 750um DPP



4 ns/3.1 kJ, 2 µm LEH, no prepulse
with DPP (SNL Omega-EP data)

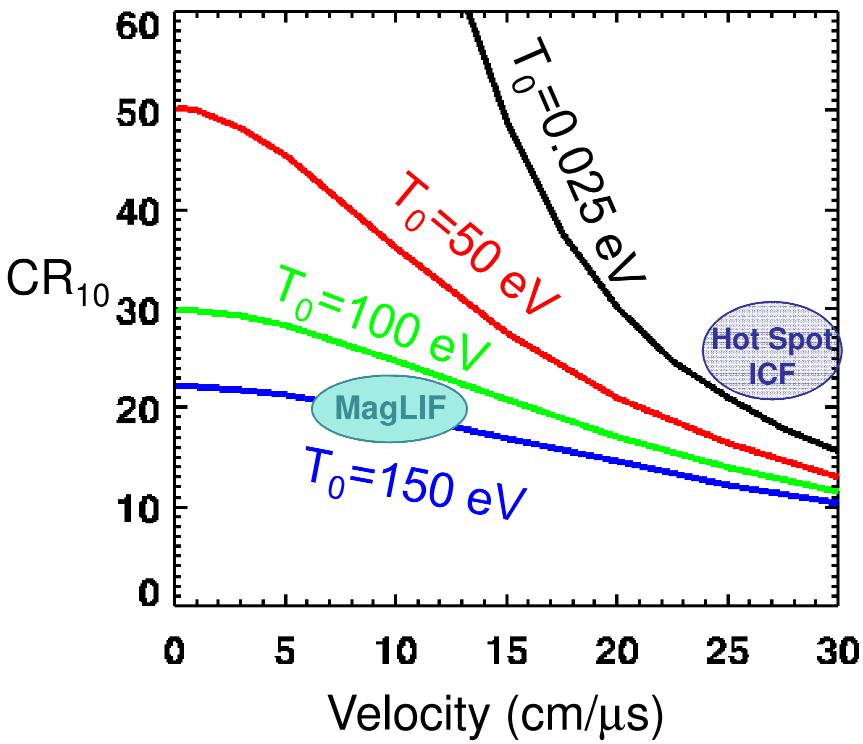


4 ns/2.93 kJ, 2 µm LEH, no prepulse
without DPP (SNL Omega-EP data)



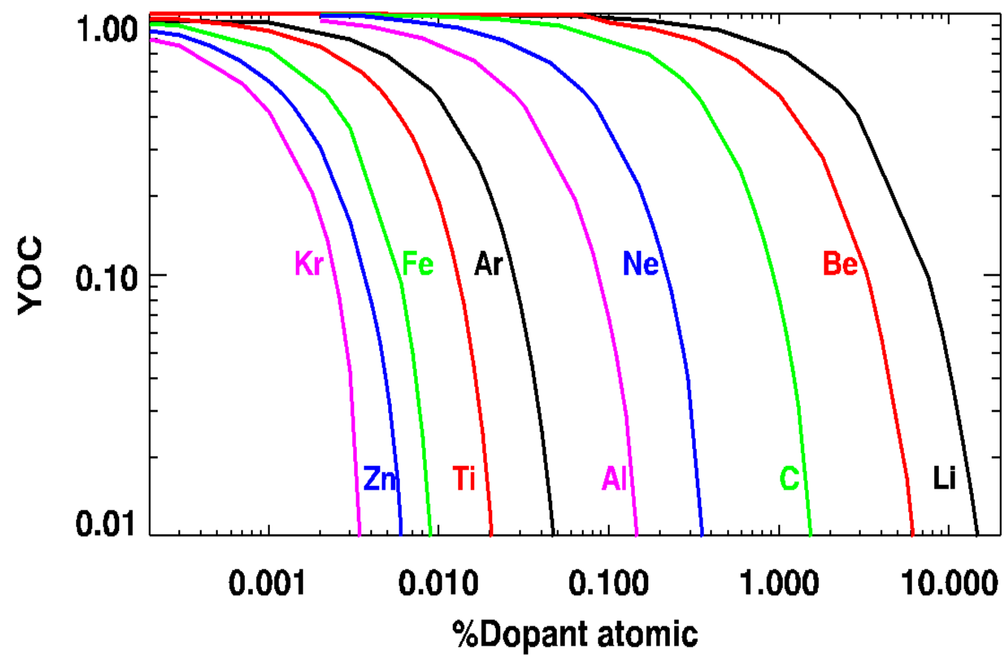
Preheat and implosion: Preheating the fuel allows slower, more stable implosions and lower convergence ratios than traditional ICF, but the preheated plasma is sensitive to mix

Simulations with constant velocity



CR_{10} = Convergence Ratio (R_0/R_f) needed to obtain T = 10 keV with no radiation or thermal conduction losses

Simulations with uniform mix

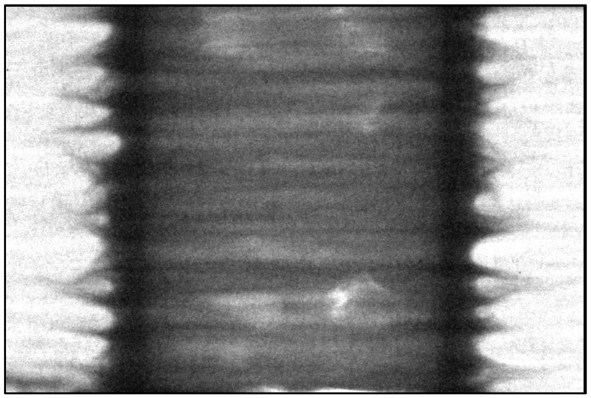


While magnetization reduces conduction losses, the long preheat stage is susceptible to radiative losses from mix, so we can't use dopants to diagnose preheat on integrated experiments.

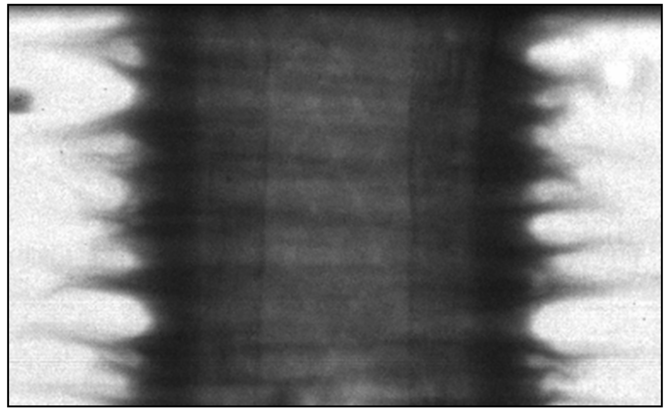
*S.A. Slutz *et al.*, Phys Plas. (2010); S.A. Slutz and R.A. Vesey, Phys Rev Lett (2012); A.B. Sefkow *et al.*, Phys Plas. (2014).

Magnetization and implosion: The axial magnetic field and dielectric coatings can effectively mitigate the growth of Magneto-Rayleigh-Taylor instabilities

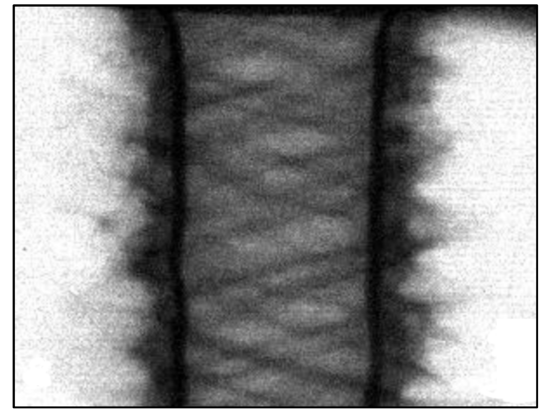
Axially-polished liner



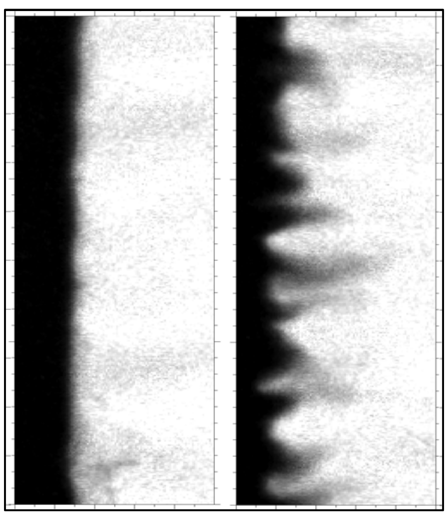
Helically perturbed liner



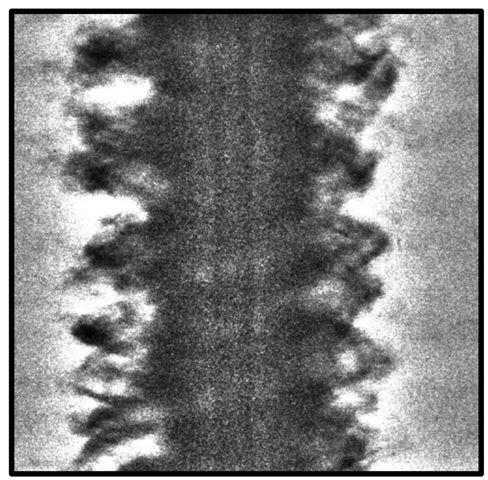
Magnetized liner



Coated Uncoated



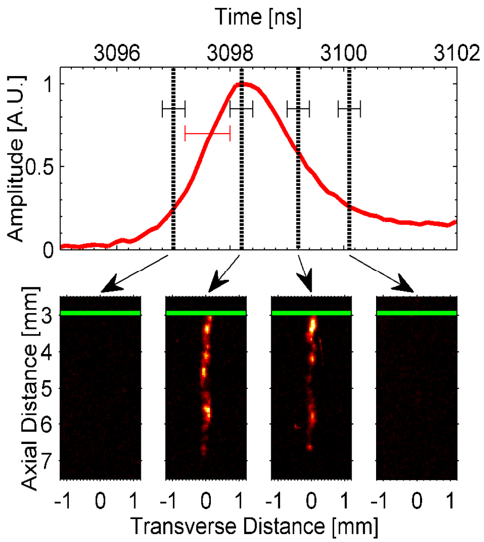
CH coatings on metal liners suppress the electro-thermal instability, the dominant MRT seed for MagLIF



A CH-coated, magnetized Be liner has a stable inner surface at CR ~ 20

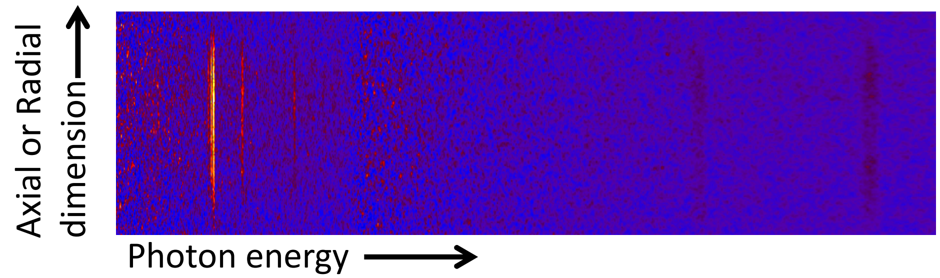
K. Peterson *et al., Phys Plas* (2014); T. Awe *et al. Phys Rev Lett* (2014)

Stagnation: Extensive x-ray and neutron diagnostics resolve plasma conditions in space, energy, and time

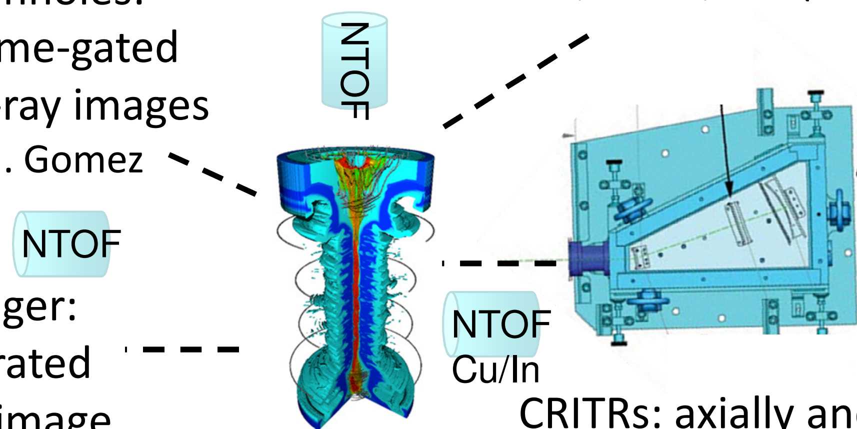


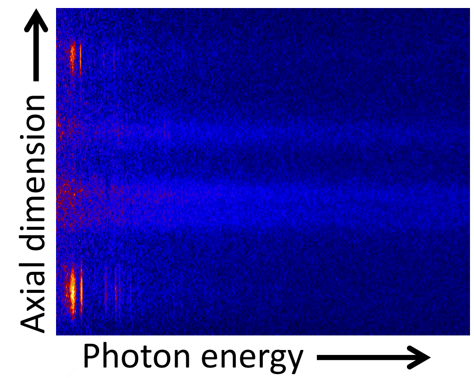
Filtered PCDs and SiDs: time-resolved x-ray powers

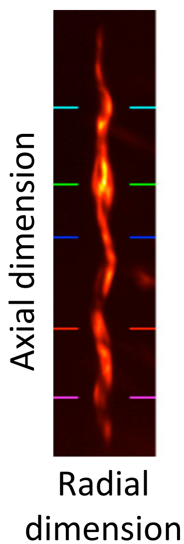
MLM/filtered pinholes: time-gated x-ray images
M. Gomez



TIXTLs: time-integrating spectrometers (1-10 keV)
T. Nash et al., RSI 70, 302 (1999)





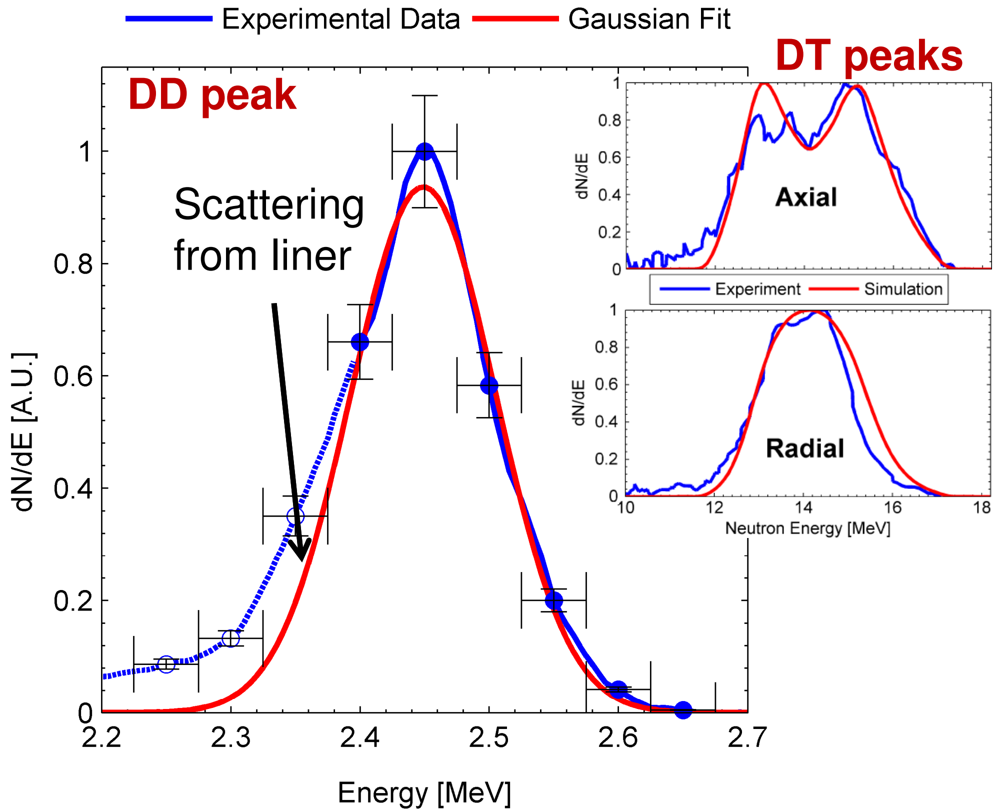


Crystal imager: time-integrated hard x-ray image
E. Harding

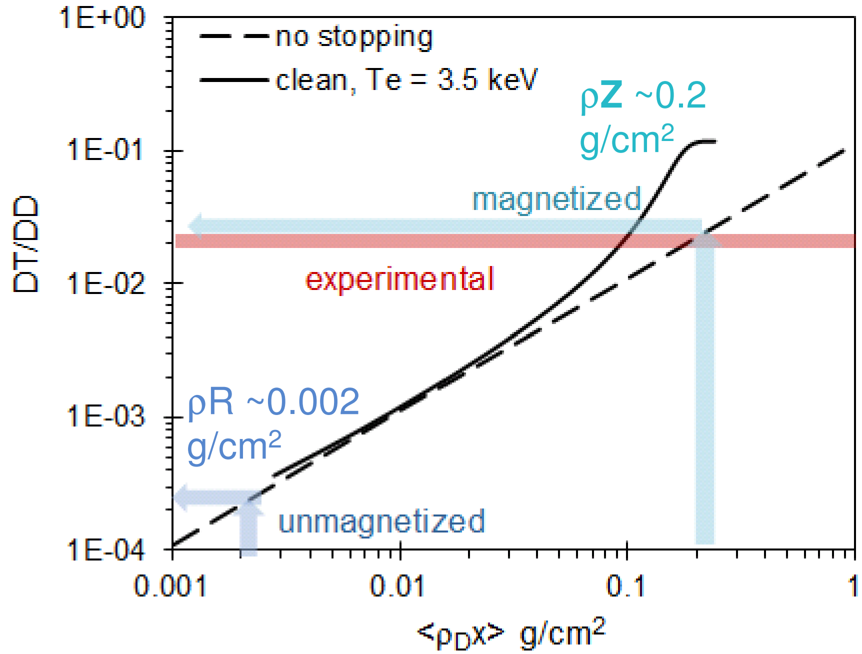
CRITRs: axially and radially resolving, time-integrating spectrometers (7-50 keV)
D. Sinars et al., RSI 82, 063113 (2011)

Measuring MagLIF's ~ 30 J x-ray yields is challenging compared to the few-MJ x-ray yields of many Z experiments

Stagnation: neutron data indicate T_{ion} ~ 2 keV and effective confinement of both fuel and 1 MeV tritons



Neutron time-of-flight data measure D-D neutrons, indicating T_{ion} ~ 2 keV and $\rho R_{liner} > 0.9\ cm^2/g$



High "secondary" DT neutron yields from the interaction of 1 MeV tritons generated by DD reactions – and asymmetry in the DT spectra – indicate BR ~ 0.4 MG-cm.

Stagnation: Combining information from all x-ray diagnostics constrains T_e, ρ_{fuel}, and ρR_{Be}

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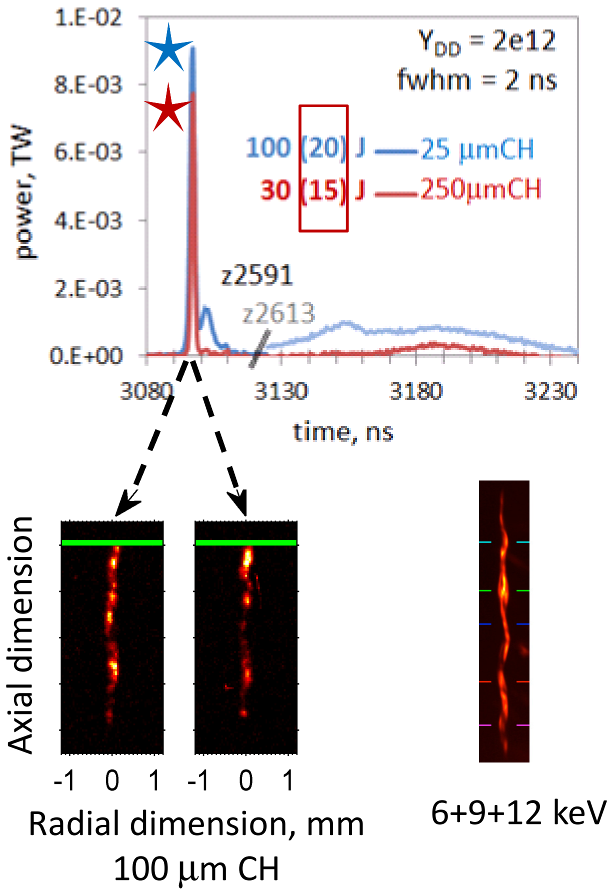
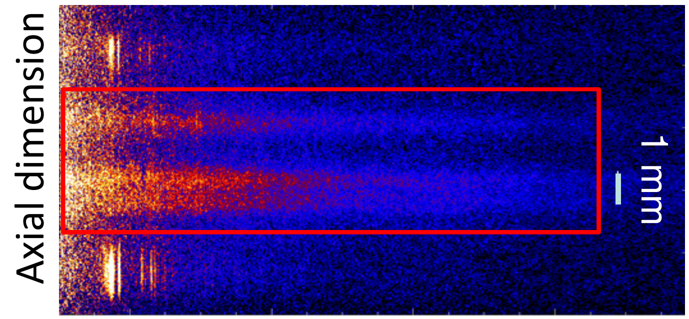
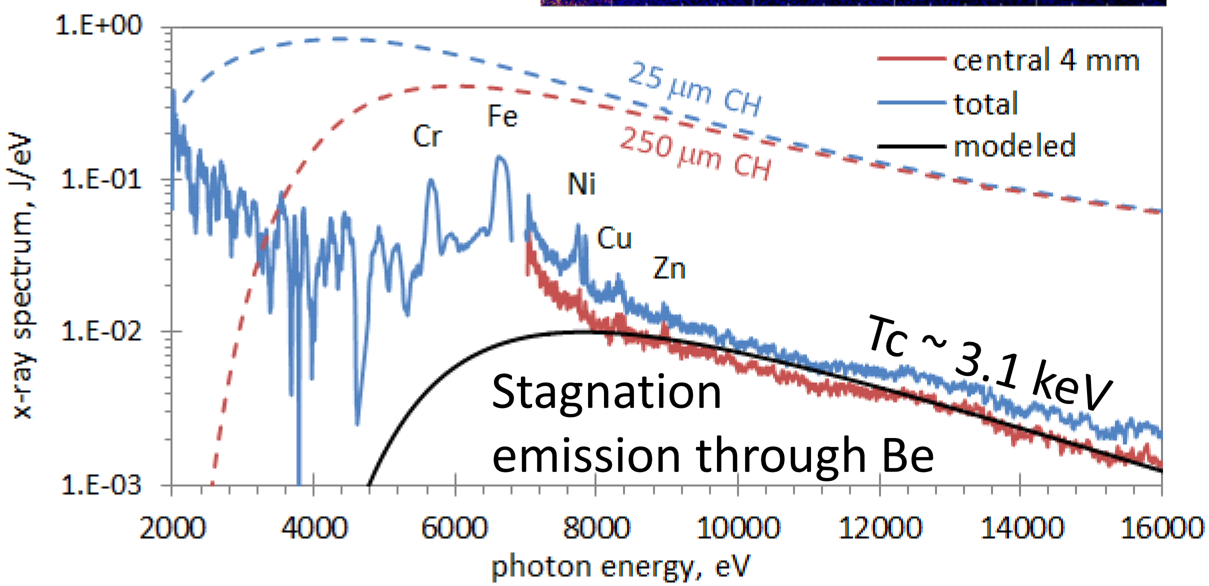


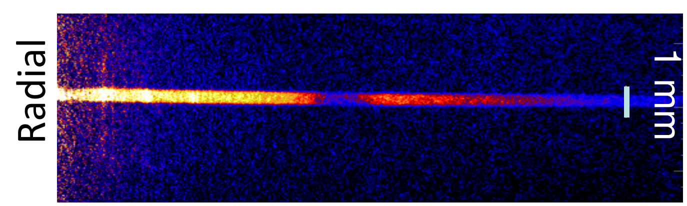
Powers constrain density and Be absorption:
ρ_D = 0.4 g/cm^3 (55%)
Be ρR ~ 0.9 g/cm^2





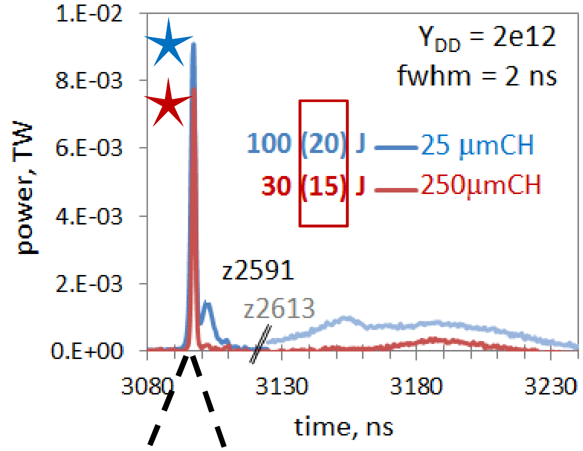
Images constrain stagnation volume:
R ~ 50 µm, Z ~ 4 mm

X_ray spectrum constrains stagnation temperature:
Tc ~ 3.1 keV



M. Gomez *et al*., *Phys. Rev. Lett*. **113**, 155003 (2014); S. Hansen *et al*. Phys Plas **22**, 056313 (2015)

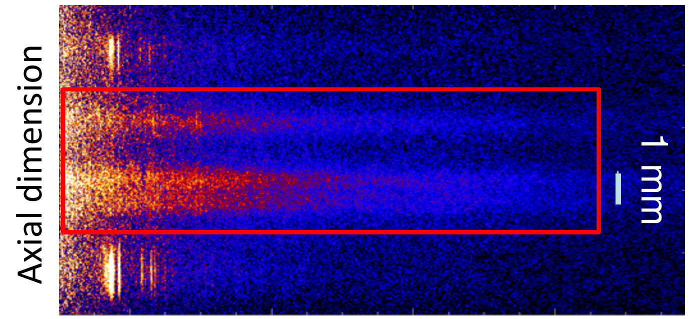
Stagnation: detailed spectroscopic measurements also constrain the amount of mix – but not yet its origin

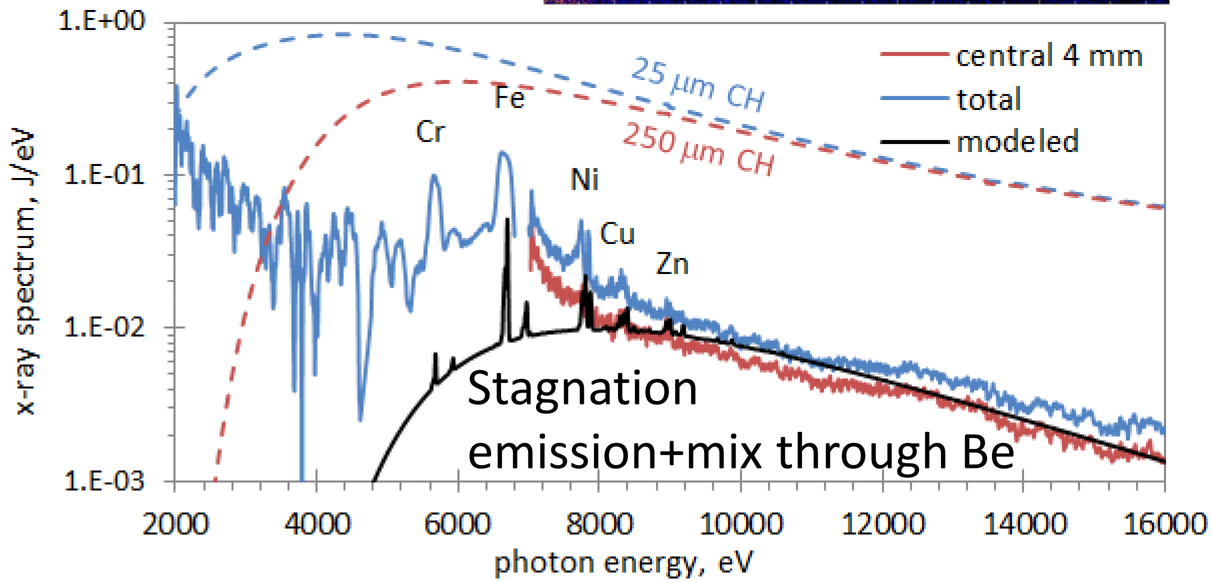


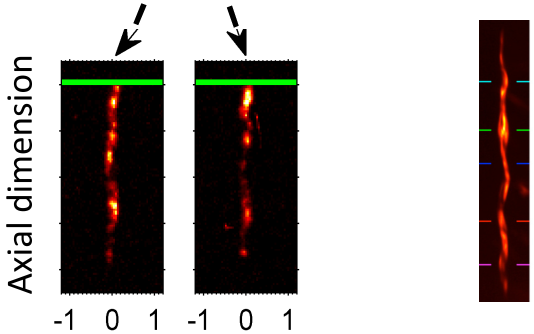
Powers constrain density and Be absorption:

ρ_D ~ 0.25 g/cm^3 (35%)

Be ρR ~ 0.9 g/cm^2







Radial dimension, mm

100 µm CH

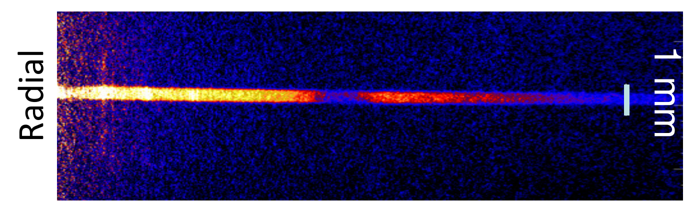
6+9+12 keV

Images constrain stagnation volume:

R ~ 70 µm, Z ~ 4 mm

Spectrum constrains mix:

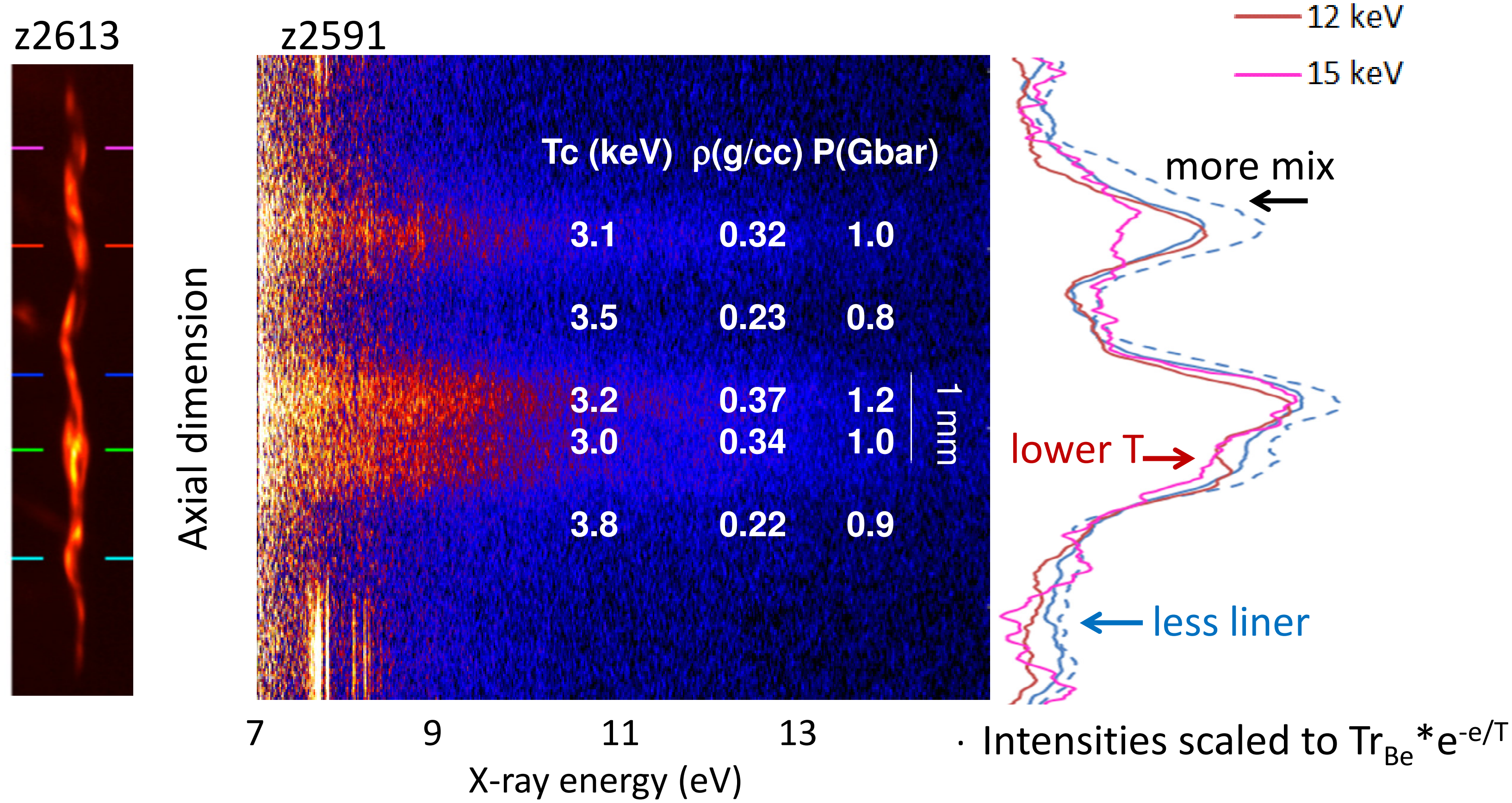
f_{Be} ~ 5% or f_{Al} ~ 0.04%



M. Gomez *et al.*, *Phys. Rev. Lett*. **113**, 155003 (2014); S. Hansen *et al*. Phys Plas **22**, 056313 (2015)

Stagnation: A closer look at axially-resolved x-ray spectra indicates ~20% axial pressure variations

Gross variations in axial intensities are most likely due to density variations along the column; under this interpretation, densities vary by factors of 2 while pressures are fairly uniform.



· Intensities scaled to $Tr_{Be} * e^{-e/T}$

S. Hansen *et al*. Phys Plas **22**, 056313 (2015)

Stagnation: An isobaric assumption for radial gradients improves agreement with the collection of x-ray and neutron data and is consistent with degraded-preheat simulations

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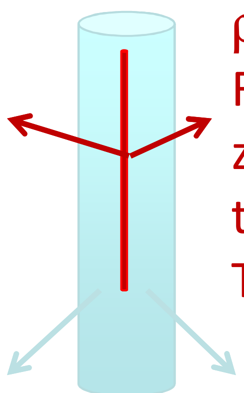
Degraded simulation: burn averages

$\rho_D = 0.4$ g/cm^3
R = 65 µm
z = 4 mm
$t_{burn} = 1.6$ ns
T ~ 3 keV



X-ray analysis with "cartoon" model

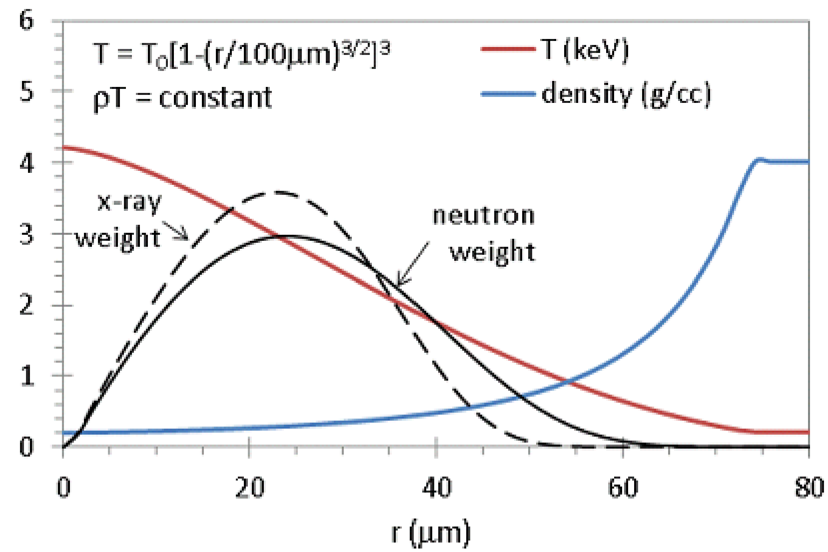
$\rho_D \sim 0.3$ g/cm^3
R = 70 µm
z = 4 mm
$t_{burn} = 2$ ns
$T_e = 3.1$ keV

$\rho r_{liner} = 0.9$ g/cm^2 (degraded simulation)
$Y_{DD} = 2\text{-}4 \times 10^{12}$

$\rho r_{liner} = 0.9$ g/cm^2 (x-ray analysis)
$Y_{DD} = 6 \times 10^{12}$

Measured neutron data:
$Y_{DD} = 2 \times 10^{12}$
$T_i = 2.5$ keV

Radial gradients in isobaric model*



Synthetic diagnostics:
Neutrons (sample $\sqrt{T_i}$) $\langle T_i \rangle = 2.5$ keV
X-rays (sample $\partial j/\partial \varepsilon$) $\langle T_e \rangle = 3.1$ keV
$Y_{DD} = 2\times10^{12}$

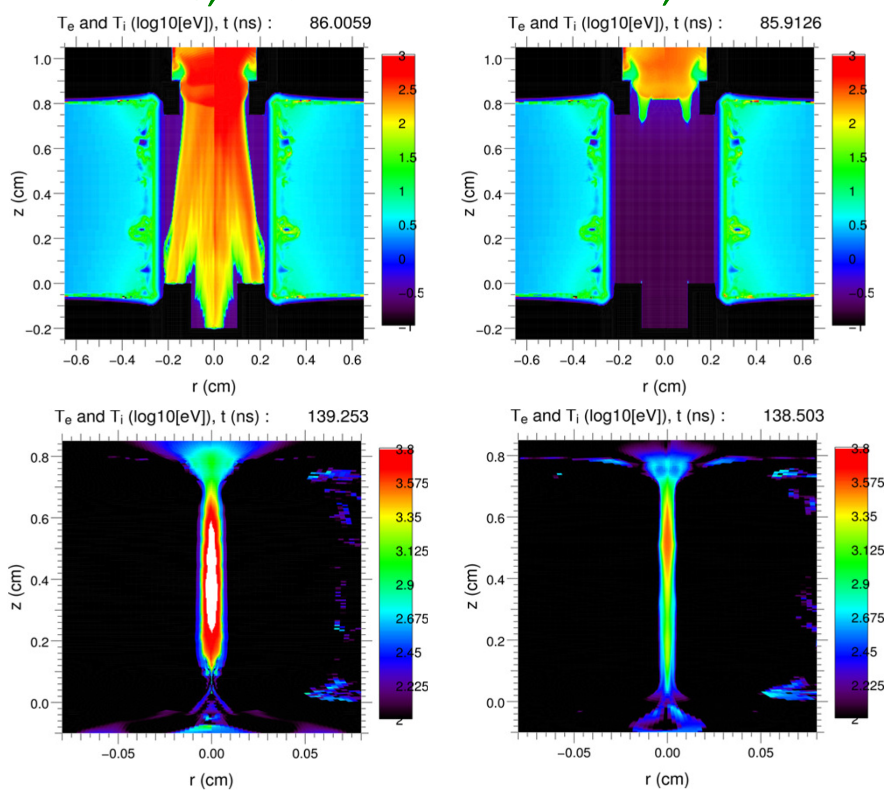
*P. Springer *et al.*, *EPJ Web of Conferences* **59**, 04001 (2013); A. B. Sefkow Hydra simulations

Simulations and scaling: Degraded-preheat simulations are consistent with 10^{12} DD yields; improving the preheat (without increasing mix) would increase yields > tenfold

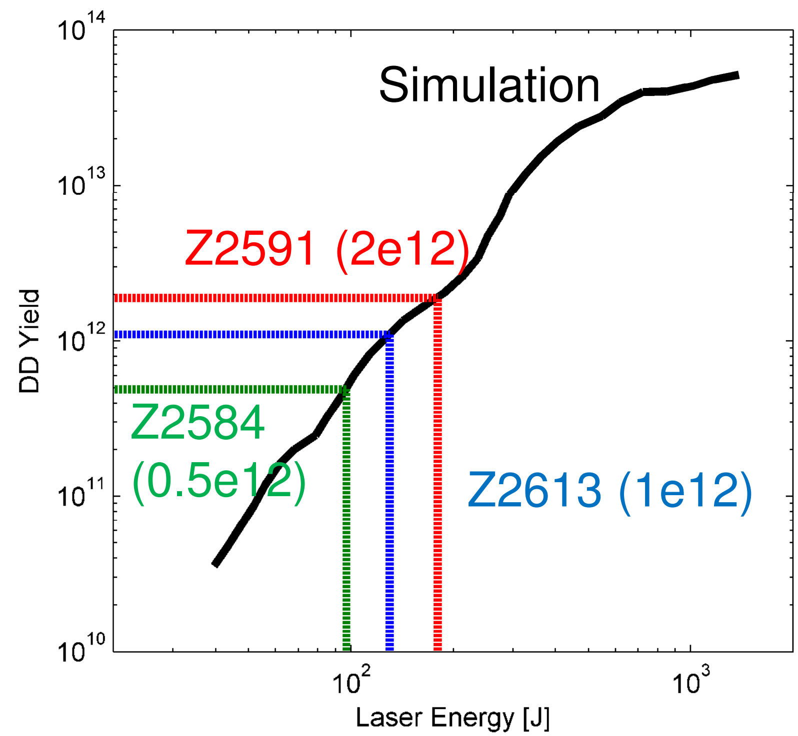
HYDRA Simulations

main pulse 2 ns, 2 kJ

main pulse 0.2 ns, 0.2 kJ

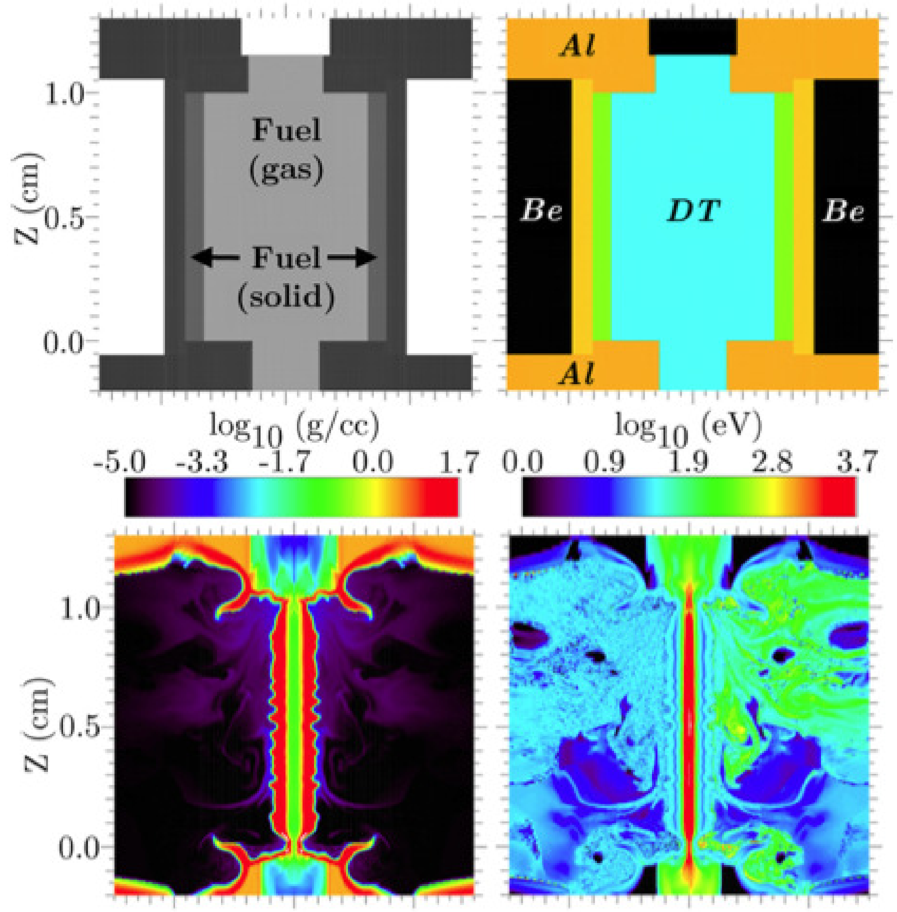


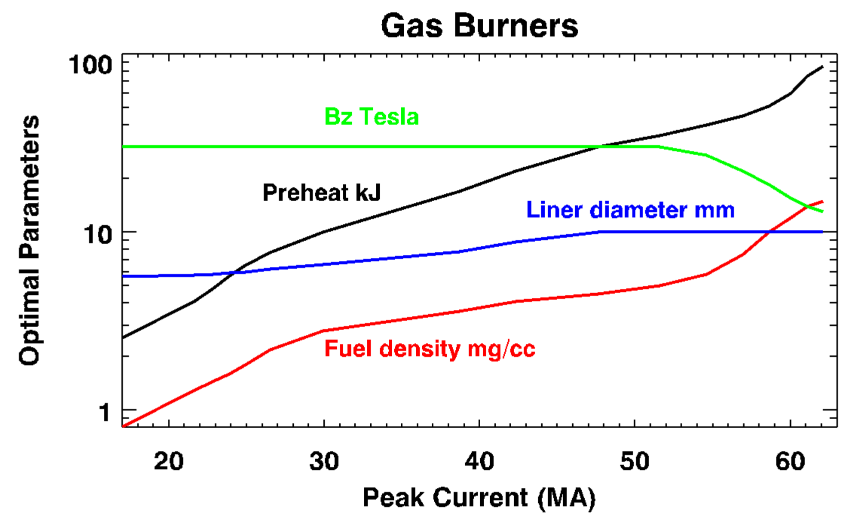
A.B. Sefkow *et al.*, Phys. Plasmas (2014).

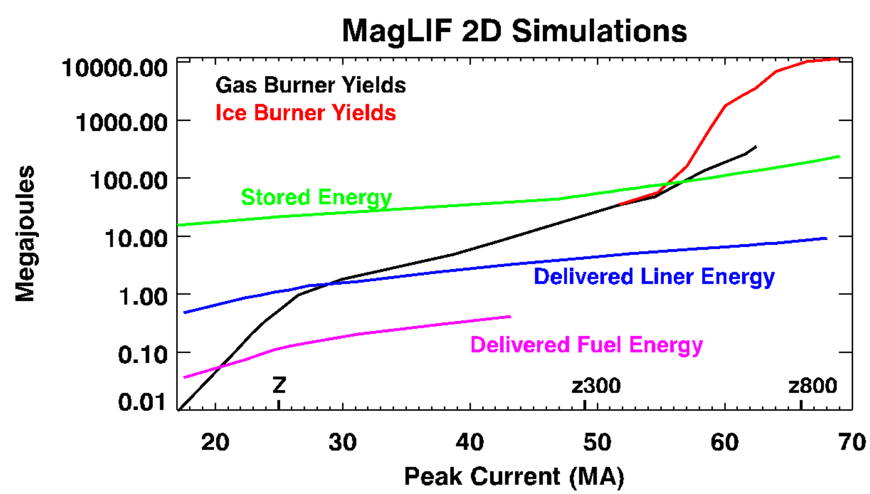


Simulations with 100-200 J preheat match both yields and the detailed parameters measured in the experiments (temperature, shape, BR)

Simulations and scaling: alpha heating and ignition are possible on a future facility using a cryogenic DT layer and substantial preheat—we are testing the physics of these targets on Z today



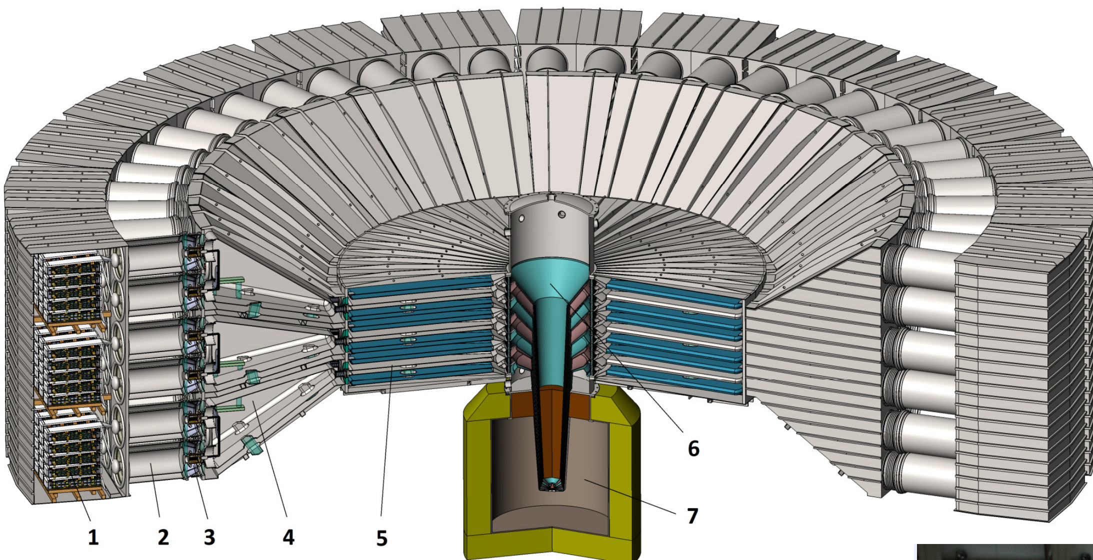




We are engaging with multiple collaborators to help us improve our understanding

- **U. Rochester**: Collaboration on "mini-MagLIF" will examine MHD modeling of magnetic flux loss; preheat studies are underway
- **LLNL**: Scaled preheat NIF experiments are planned along with code workshops and development; extensive collaboration on diagnostics
- **NRL:** Developing validation tools (Noh, Nernst) and radiation transport models
- **Universities** (Cornell, U. Mich, U. Nevada): Implosion validation experiments are underway along with active development of extended MHD models
- **Private companies:** Voss Scientific and Prism Computational Sciences are developing PIC/Hybrid PIC and experimental design and diagnostic tools
- **International Collaborators:** Fundamental work on transport properties at U. Kiel – more interaction would be welcome!

There is growing international interest in pulsed-power ICF



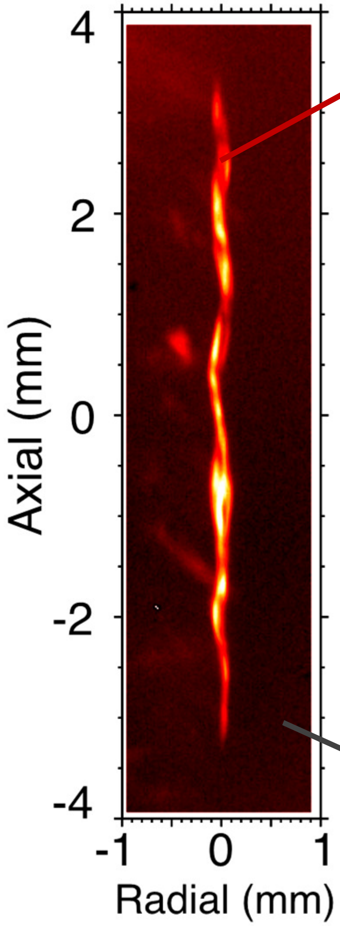
Operating Chinese Facility (PTS)

- 8 MA
- 100 ns
- 8 MJ (1/3 x Z)
- Successfully duplicating previous published work worldwide
- Building a 1 ns, 1 kJ laser facility like Z-Beamlet!
- Currently evaluating LTD and Marx-based architectures

Russian Facility (Baikal)

- 50 MA
- 150 ns
- 100 MJ (4 x Z)
- Stated goal: **25 MJ fusion yield**
- Scheduled for completion in 2019, funding is secured and there is activity
- If it works, they will have this capability before any realistic scenario for Z-300

MagLIF experiments are extensively diagnosed, demonstrating significant promise for Magnetized Inertial Fusion



X-ray image of a MagLIF plasma that produced 10^{12} DD neutrons

Stagnating plasma

$\langle T \rangle = 3 \pm 0.5$ keV

$T(r) = T_0[1 - (r/R)^2]$

$t_{burn} = 1.5 \pm 0.5$ ns

$f_{Be} = 5 \pm 3$ %

$z = 5 \pm 2$ mm

$R = 50 \pm 20$ μm

$\rho_D = 0.3 \pm 0.1$ g/cm^3

$P(z) = 1 \pm 0.2$ Gbar

$\rho R \sim 1.5$ mg/cm^2

$BR \sim 0.4$ MG·cm

Confining liner

$\rho r_{liner} = 0.9$ g/cm^2

Magnetized Liner Inertial Fusion (MagLIF) has the potential to produce high fusion yields by exploiting:

1) magnetic confinement that relaxes required pressures 100x (present experiments trap ~40% of fast fusion products)
2) a highly efficient driver delivering ~1% of its stored energy *to the fuel*
3) Symmetric drive and slow, low-convergence implosions that are robust against instabilities

M. Gomez *et al.*, *Phys. Rev. Lett.* **113**, 155003 (2014) and P.F. Schmit *et al.*, *ibid*. 155004

Many researchers are contributing to the MagLIF effort:

T.J. Awe, C.J. Bourdon, G.A. Chandler, P.J. Christenson, M.E. Cuneo, M. Geissel, **M.R. Gomez**, K.D. Hahn, S.B. Hansen, E.C. Harding, A.J. Harvey-Thompson, M.H. Hess, C.A. Jennings, B. Jones, M. Jones, R.J. Kaye, P.F. Knapp, D.C. Lamppa, M.R. Lopez, T. Nagayama, M.R. Martin, R.D. McBride, L.A. McPherson, J.S. Lash, K.J. Peterson, J.L. Porter, **G.A. Rochau**, D.C. Rovang, C.L. Ruiz, S.E. Rosenthal, M.E. Savage, P.F. Schmit, **A.B. Sefkow**, **D.B. Sinars**, **S.A. Slutz**, I.C. Smith, W.A. Stygar, R.A. Vesey, E.P. Yu
Sandia National Laboratories, Albuquerque, NM

B.E. Blue, D.G. Schroen, K. Tomlinson
General Atomics, San Diego, CA

M.C. Herrmann, D. Ryutov
Lawrence Livermore National Lab, Livermore, CA

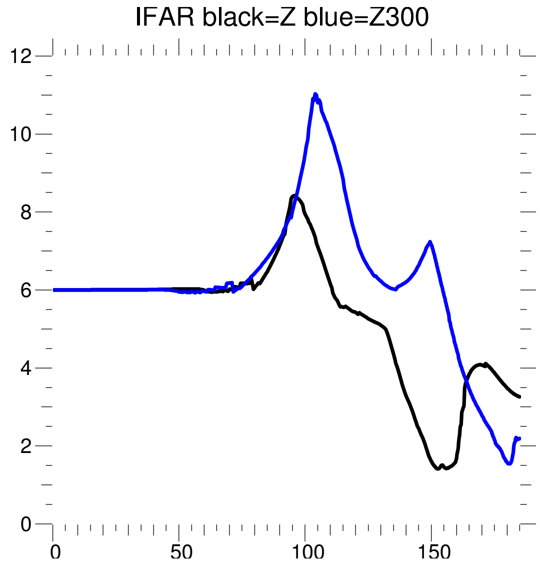
R. Betti, E. M. Campbell, J. Davies, M. Wei
Laboratory for Laser Energetics, U. Rochester

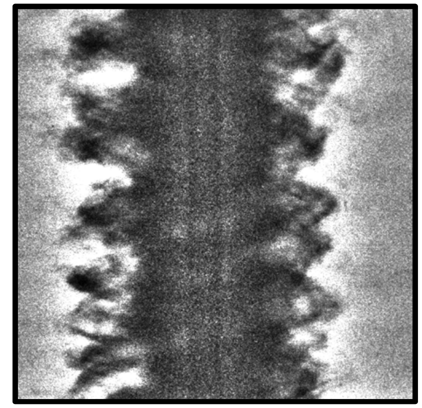
Questions?

Relative to the primary ICF approach, MagLIF uses a robust fuel compression method and (largely) untested magneto-inertial fusion principles

Sandia National Laboratories

Metric	X-ray Drive on NIF	100 kJ MagLIF on Z
Pressure	~140-160 Mbar	26 MA at 1 mm is 100 Mbar
Force vs. Radius	Goes as R^2	Goes as 1/R^2
Peak velocity	350-380 km/s	70-100 km/s
Peak IFAR	13-15 (high foot) to 17-20 (low foot)	8.5
Hot spot CR	35 (high foot) to 45 (low foot)	25
Volume Change	43000x to 91000x (high & low foot)	625x
Fuel rho-R	>0.3 g/cm^2	~0.003 g/cm^2
Liner rho-R	n/a	>0.3 g/cm^2
BR	n/a	>0.5 MG-cm
Burn time	0.15 to 0.2 ns	1 to 2 ns
T_ion	>4 keV	>4 keV

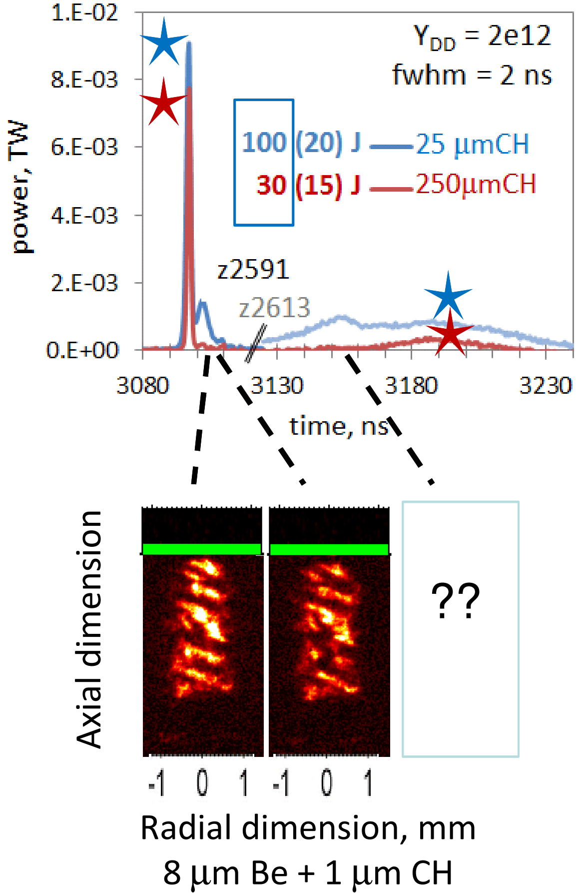




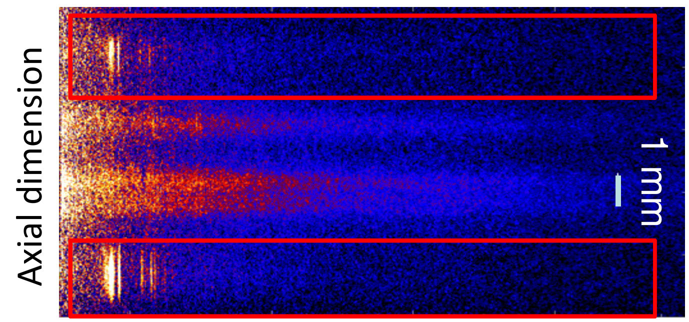
Plastic-coated, magnetized Be liner at CR of 13 to 25

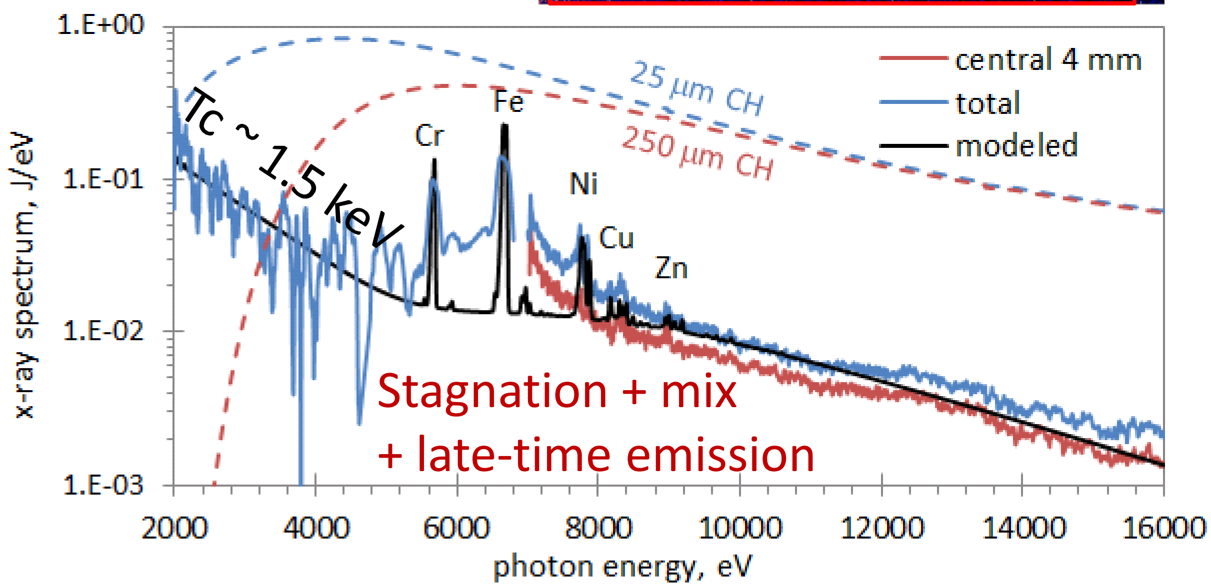
- Magnetic drive is fundamentally different than x-ray or laser-driven ablation
- By traditional ICF implosion metrics MagLIF is very conservative, though different physics
- Reaching fusion conditions relies on largely untested MIF principles
  - Long stagnation time (2 ns) → more susceptible to high-Z contamination
  - Magnetic suppression of heat transport

Late-time emission contributes to low-energy spectral region



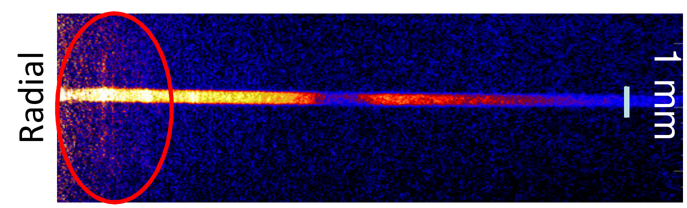
Powers constrain participating mass:
ρR_{Be} ~ 1 µg/cm^2
$\rho R_{stainless}$ ~ 10 ng/cm^2





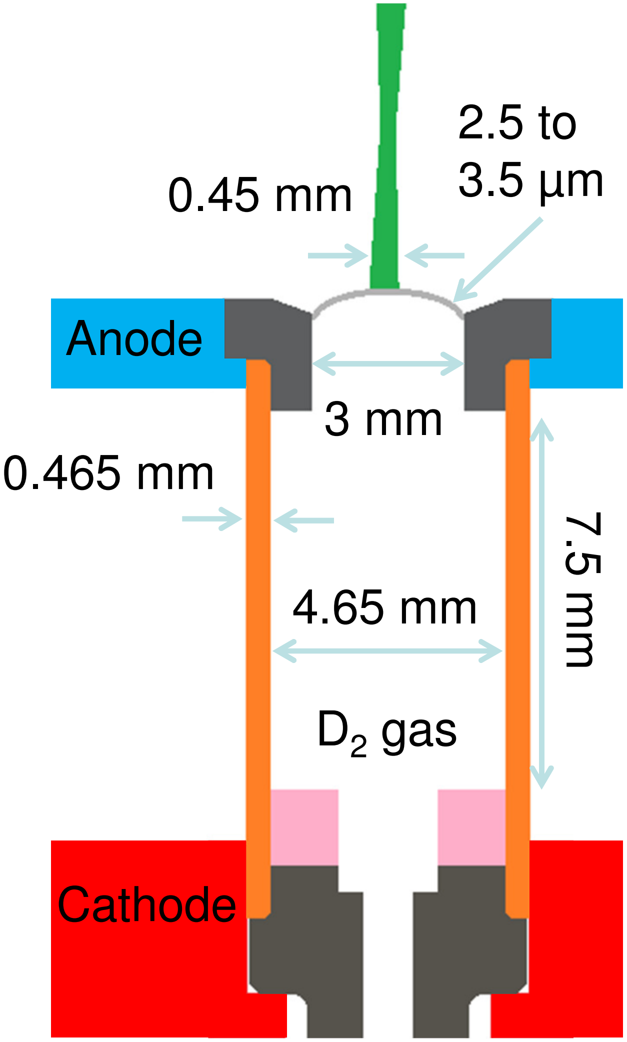
Images constrain
late-time emission area:
R ~ 1 mm, Z ~ 8 mm

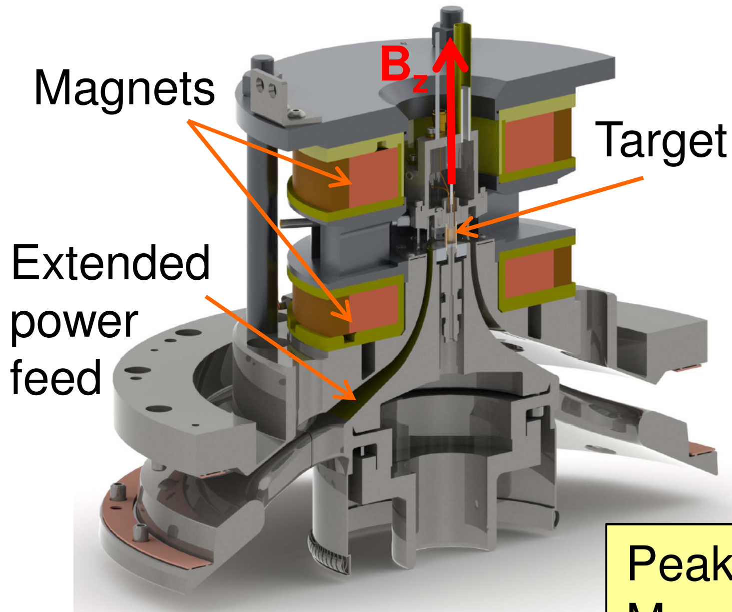
Spectrum constrains
temperature:
Te ~ 1.5 keV

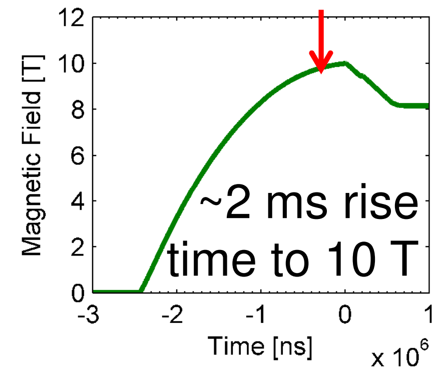


M. Gomez *et al*., *Phys. Rev. Lett*. **113**, 155003 (2014); S. Hansen *et al*. Phys Plas **22**, 056313 (2015)

The initial experiments used 10 T, 2.5 kJ laser energy, and 19-20 MA current to drive a D_2 filled (0.7 mg/cc) Be liner







Peak current is 19 MA
Magnetic field is 10 T
Total laser energy is 2.5 kJ