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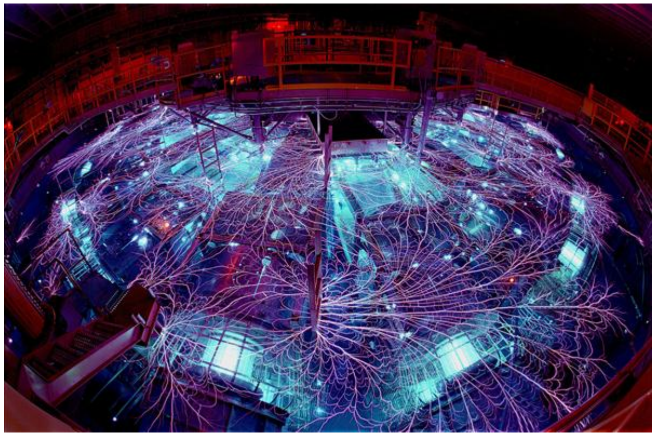

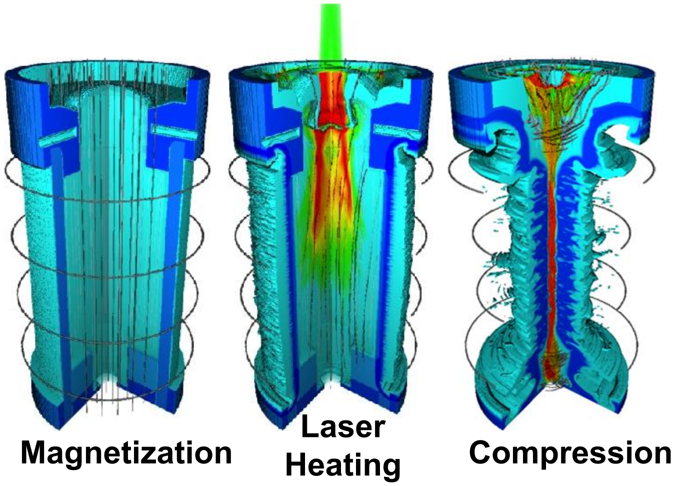

Diagnosing stagnation conditions, mix, and drive in MagLIF experiments

Stephanie Hansen
for the MagLIF team

Sandia National Laboratories

56th Annual Meeting of APS-DPP
New Orleans, LA
Oct 27, 2014

U.S. DEPARTMENT OF ENERGY
NNSA National Nuclear Security Administration

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Summary: Extensive x-ray diagnostics on Z are guiding our understanding of MagLIF plasmas

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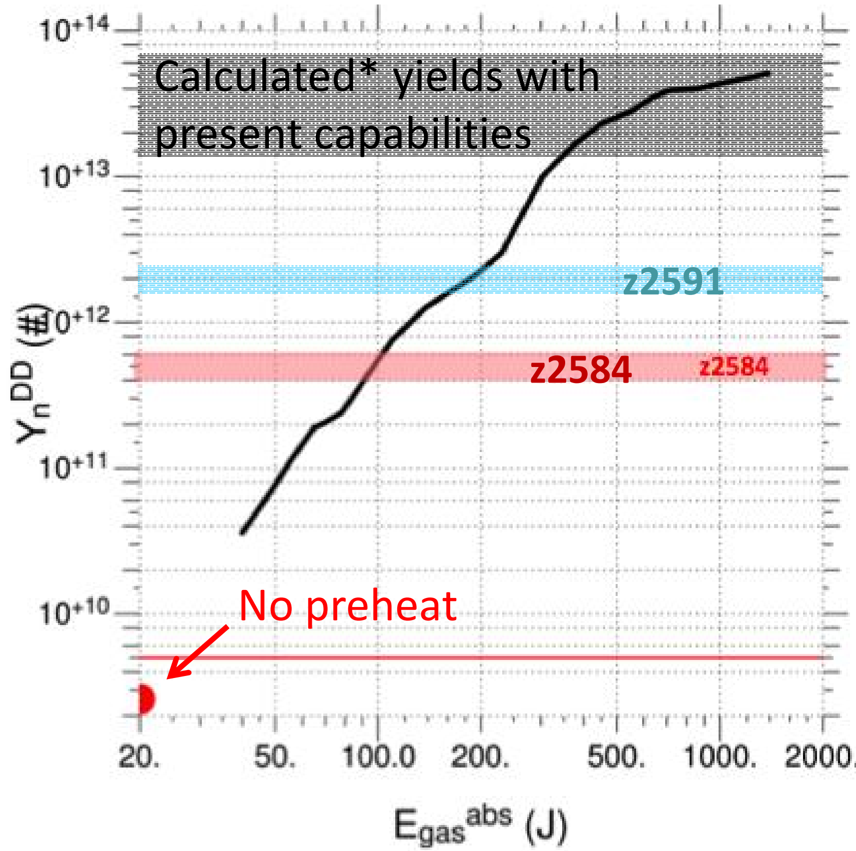
- Magnetized Liner Inertial Fusion (MagLIF) offers a promising alternative to traditional ICF schemes – if we can understand and control the complex interplay of magnetization, preheat, and stagnation
- Analysis of extensive neutron and x-ray data including imaging, power, and spectroscopic diagnostics are guiding our understanding of the plasma evolution and stagnation, helping to benchmark simulations
- Future experiments are planned to improve our understanding of preheat, mix, and scaling

Initial MagLIF results are promising but yields still fall well short of predictions

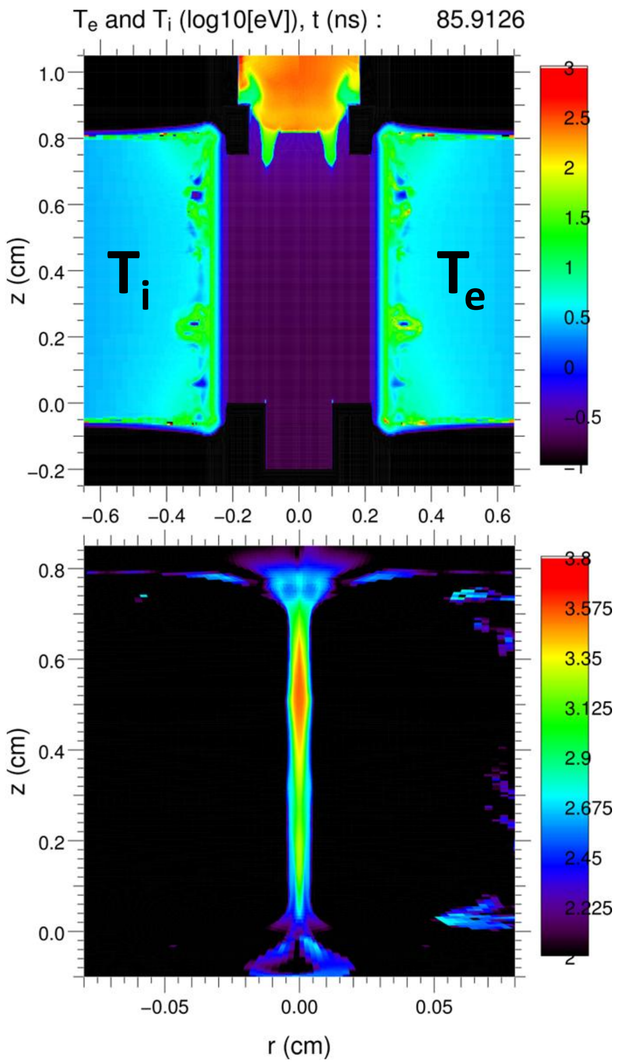
According to simulations, MagLIF has the potential to produce high fusion yields by exploiting:

1) a highly efficient driver delivering ~1% of its stored energy *to the fuel*
2) magnetic confinement that relaxes required pressures for ignition (to 5 Gbar from 500)
3) slow, low-convergence implosions robust against instabilities (10 km/s)



One hypothesis is that we are coupling only a small fraction of laser energy to the fuel (*2-D Hydra simulations by A.B. Sefkow)

Degraded simulations that match the measured yields provide a detailed picture of the stagnation



If the main laser pulse is truncated after depositing only 10% of its energy, it barely penetrates the LEH…

… but still produces significant yield from a plasma column with burn-averaged conditions:

ρ_D = 0.4 g/cm^3

R = 65 μm

z ~ 4 mm

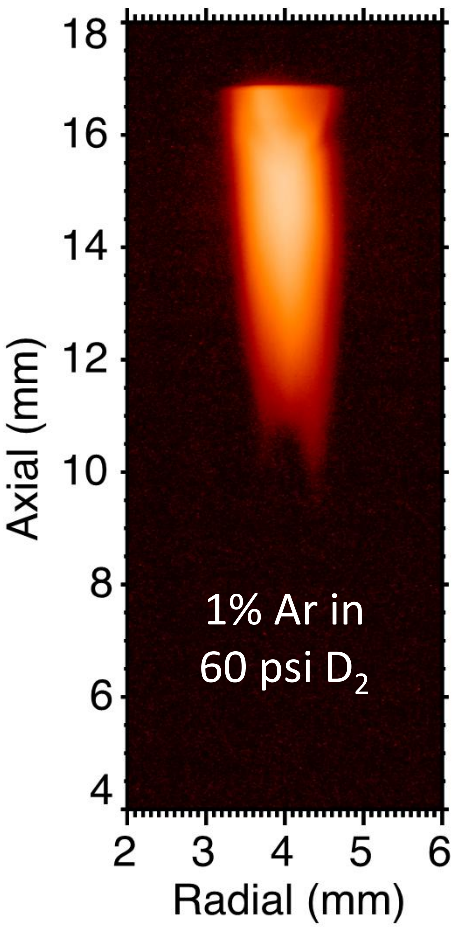
T ~ 3 keV

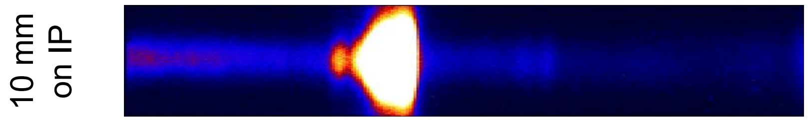
t_{burn} = 1.6 ns

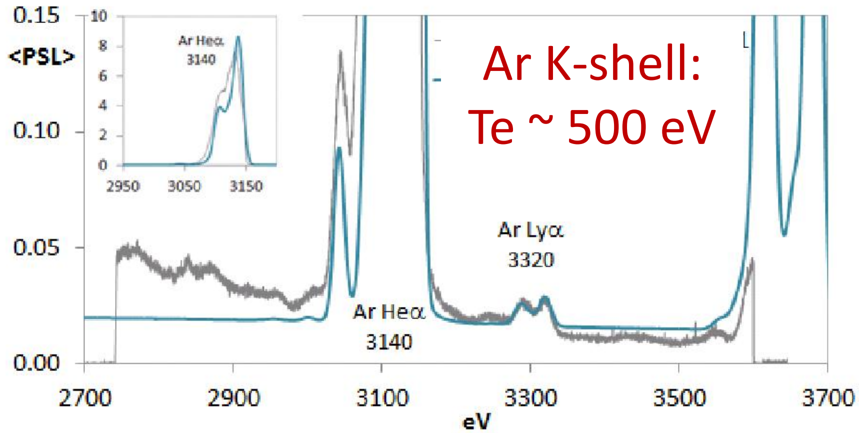
ρr_{liner} = 0.9 g/cm^2

Can we diagnose preheat directly and correlate it with measured yields?

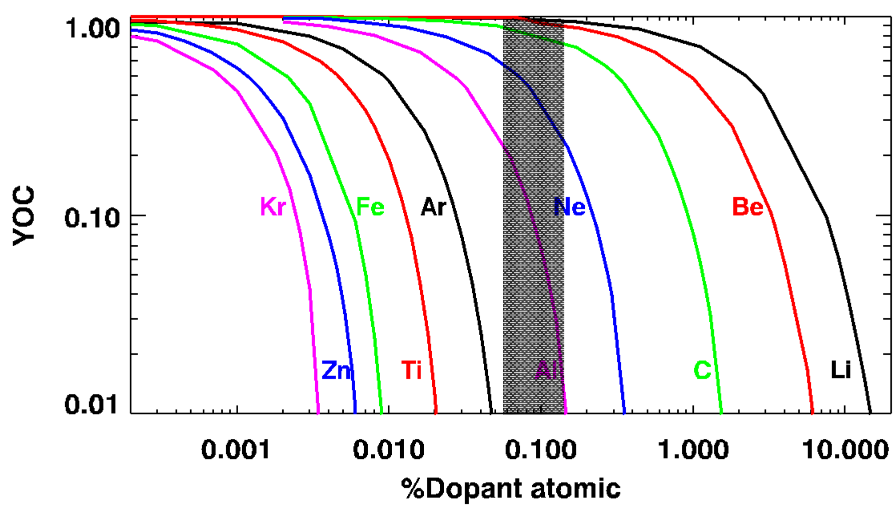
2.5 kJ of laser energy onto a 1.5 μm foil:







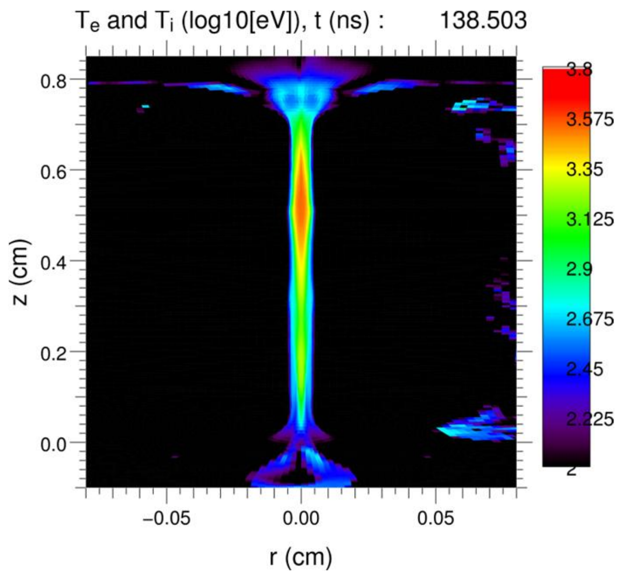
The extensive x-ray diagnostics on Z can provide preheat data from fuel fills doped doped with >0.1% Ar

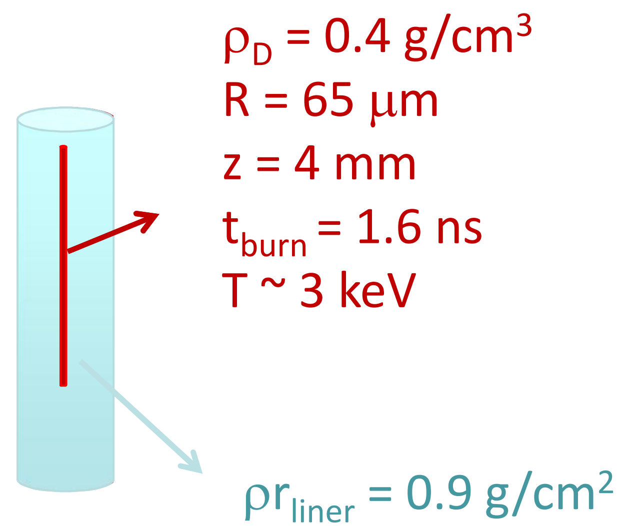


But even small high-Z fractions lead to catastrophic radiative losses during the long preheat stage (late-time mix is much less harmful)

Calculations by S. Slutz

Another approach: do the degraded simulations present a plausible picture of stagnation?





The calculated stagnation plasma produces Y_{DD}=2-4x10^{12} and T_i ~ 3 keV – consistent with neutron data – but many variations of ρ, R, z, and t_{burn} are consistent with Y_{DD}, and Y_{DT} does not constrain ρR

The simulations also provide detailed predictions for the plasma conditions at stagnation, which can be tested using x-ray diagnostics

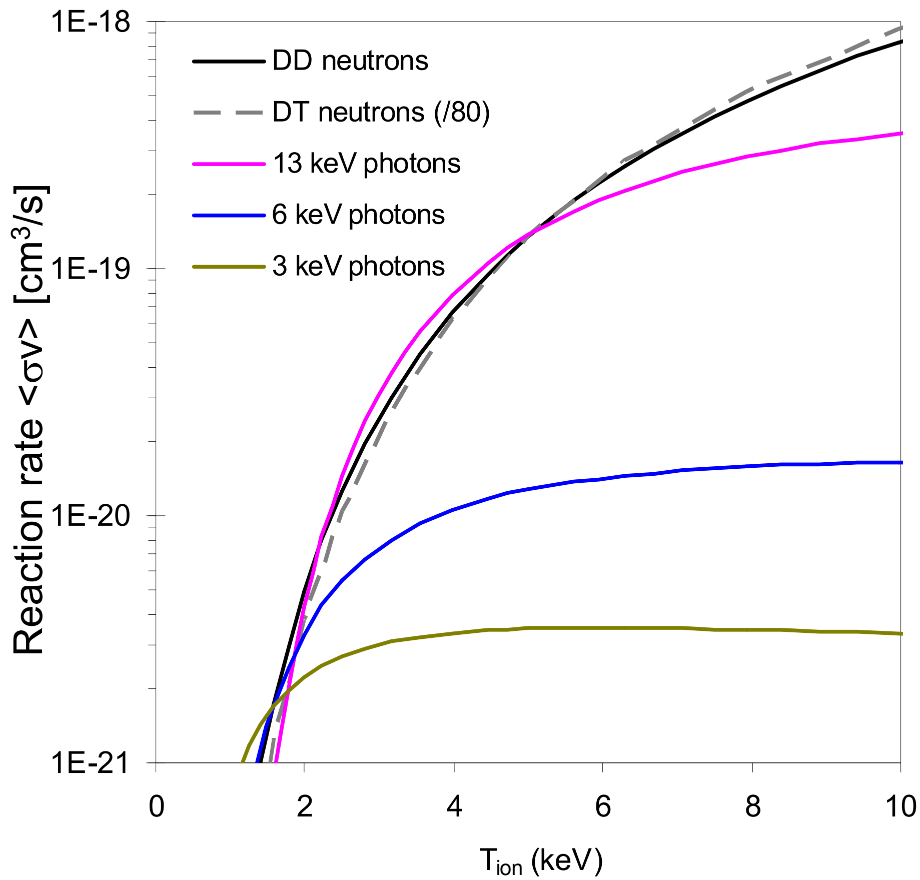
High-energy X-rays are reasonable proxies for thermonuclear neutrons

Neutron production rate:

$$R = n_T n_D < \sigma_{DT} v_{ion}(T) > Vol\ [n/s]$$

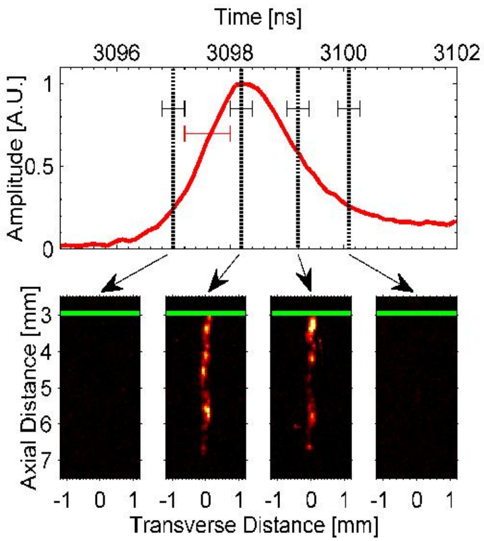
A given neutron yield can be generated by a multiplicity of burn plasmas whose density, volume, temperature and duration satisfy $Y = R\Delta t$

Detailed x-ray diagnostics can supplement neutron data, placing stringent constraints stagnation conditions.



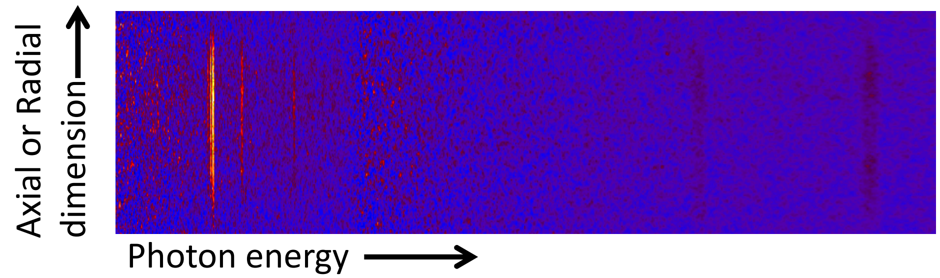
P. Springer *et al.*, *EPJ Web of Conferences* **59**, 04001 (2013)
S. Hansen, *Phys. Plas.* **19**, 056312 (2013)
T. Ma *et al.*, *Phys. Rev. Lett.* **111**, 085004 (2013)

Z has extensive x-ray diagnostics that witness the MagLIF experiments

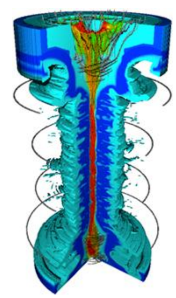


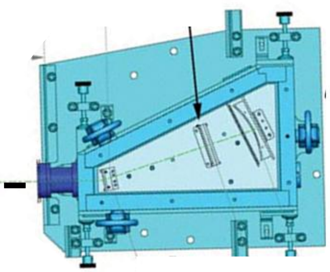
Filtered PCDs and SiDs: time-resolved x-ray powers

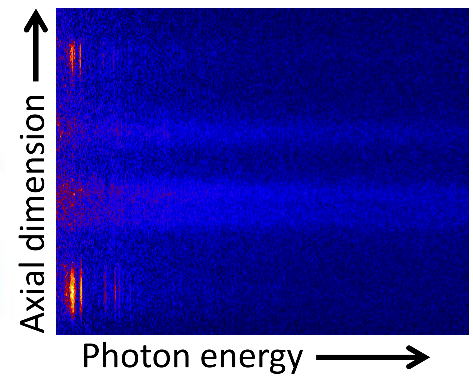
MLM/filtered pinholes: time-gated x-ray images
M. Gomez



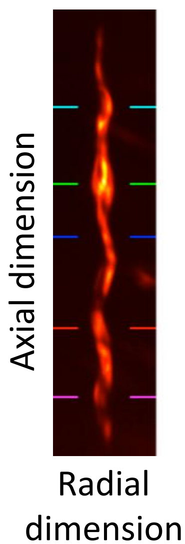
TIXTLs: time-integrating spectrometers (1-10 keV)
T. Nash et al., RSI 70, 302 (1999)







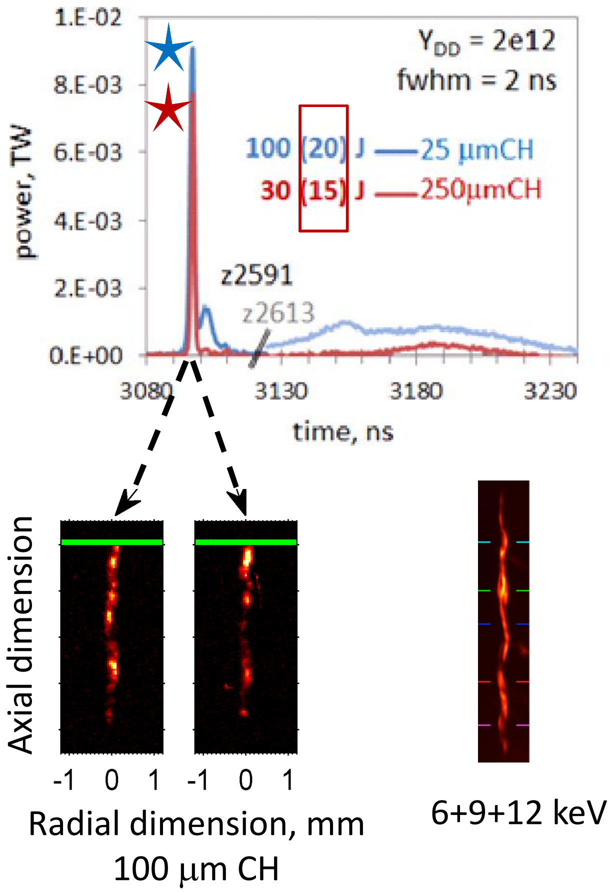
CRITRs: axially and radially resolving, time-integrating spectrometers (7-22 keV)
D. Sinars et al., RSI 82, 063113 (2011)



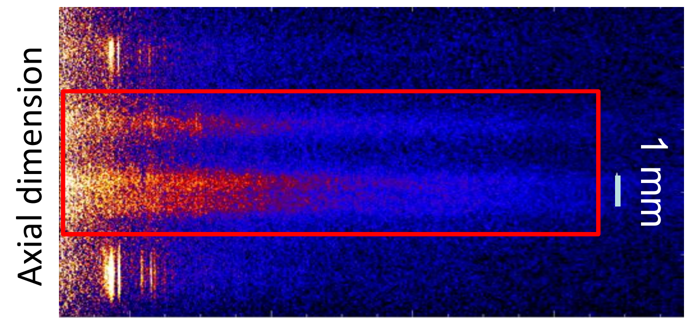
Crystal imager: time-integrated hard x-ray image
E. Harding

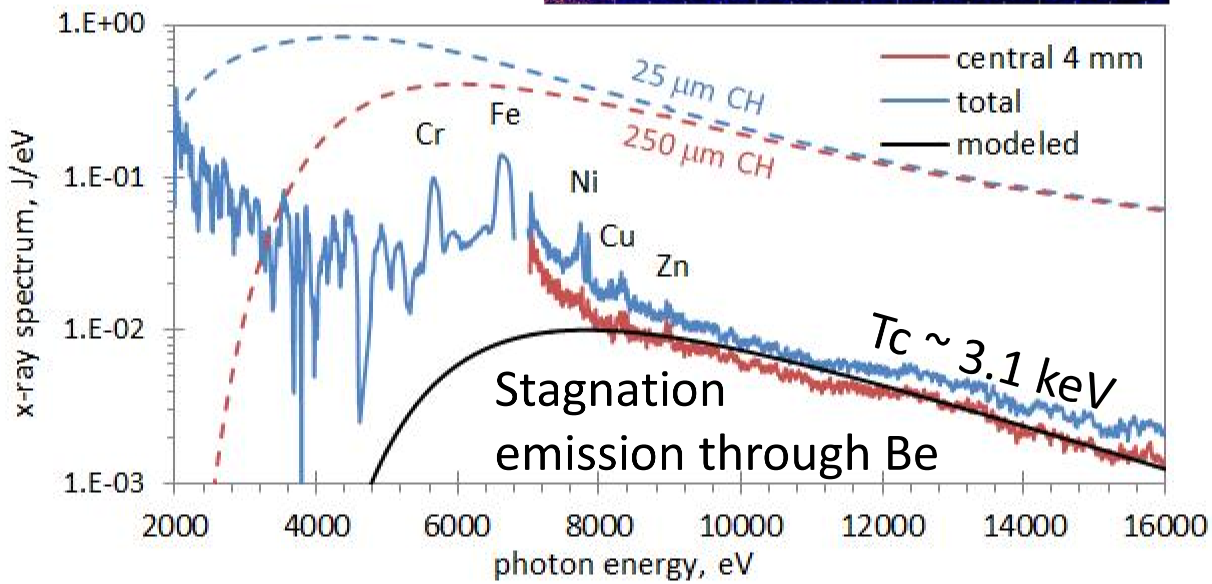
Measuring MagLIF's ~ 30 J x-ray yields is challenging compared to the few-MJ x-ray yields of many Z experiments

Combining information from all x-ray diagnostics provides a well-constrained picture of stagnation



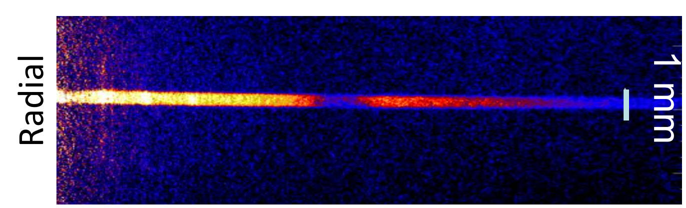
Powers constrain density and Be absorption:
ρ_D = 0.4 g/cm^3 (55%)
Be ρR ~ 0.9 g/cm^2





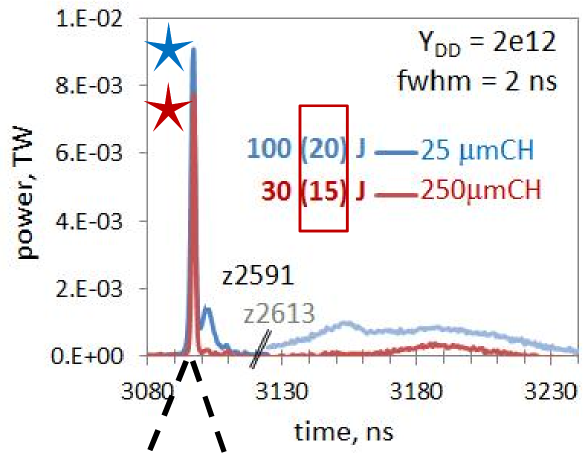
Images constrain stagnation volume:
R ~ 70 µm, Z ~ 4 mm

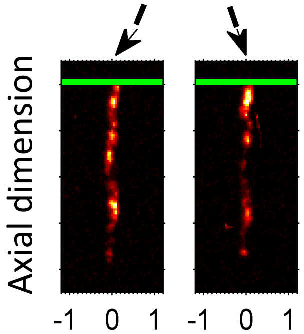
Spectrum constrains stagnation temperature:
Tc ~ 3.1 keV



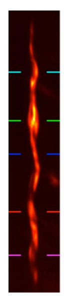
M. Gomez *et al.*, *Phys. Rev. Lett.* **113**, 155003 (2014)

Detailed spectral measurements also provide information about mix





Radial dimension, mm
100 µm CH

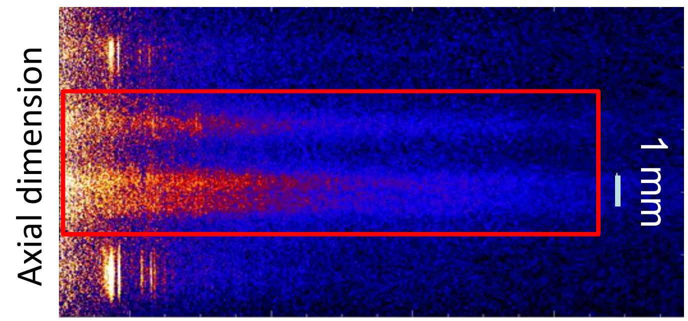


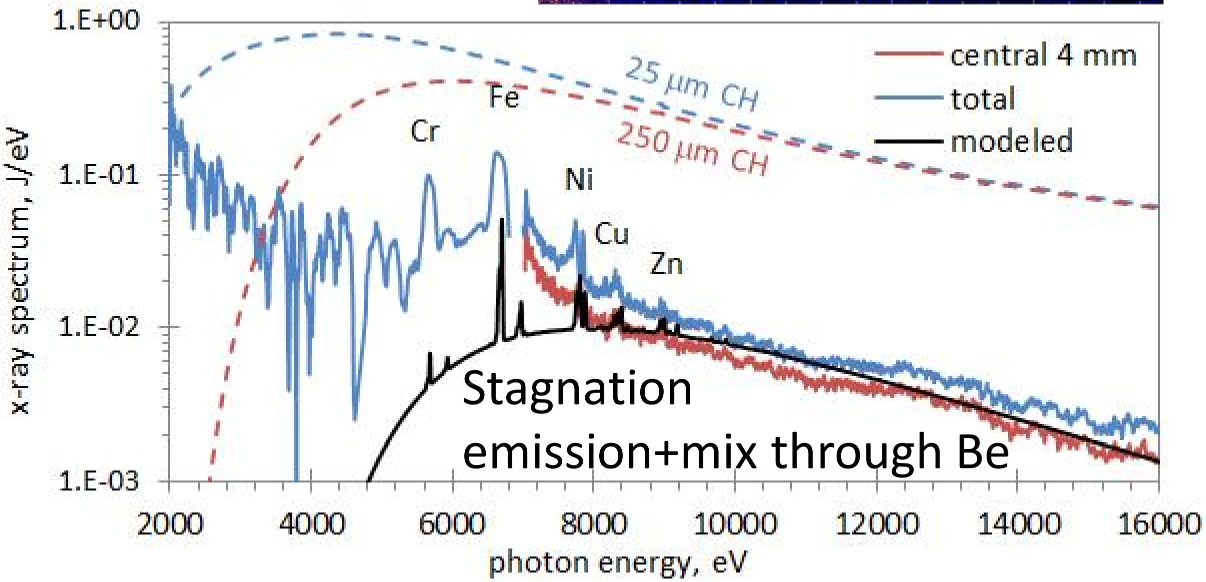
6+9+12 keV

Powers constrain density and Be absorption:

$\rho_D \sim 0.25\ g/cm^3$ (35%)

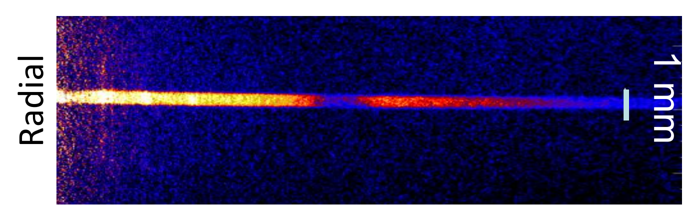
Be $\rho R \sim 0.9\ g/cm^2$





Images constrain stagnation volume: R ~ 70 µm, Z ~ 4 mm

Spectrum constrains mix: for typical Be transition metal impurities, $f_{Be} \sim 5\%$



M. Gomez *et al.*, *Phys. Rev. Lett.* **113**, 155003 (2014)

This picture of stagnation is broadly consistent with the degraded-yield simulation

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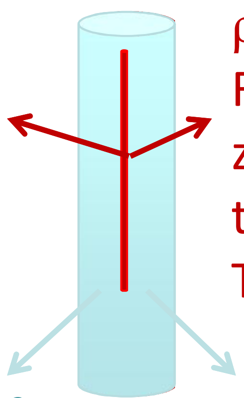
Degraded simulation: burn averages

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

ρr_{liner} = 0.9 g/cm^2

Y_{DD}= 2-4 x 10^{12}



X-ray analysis with cartoon model

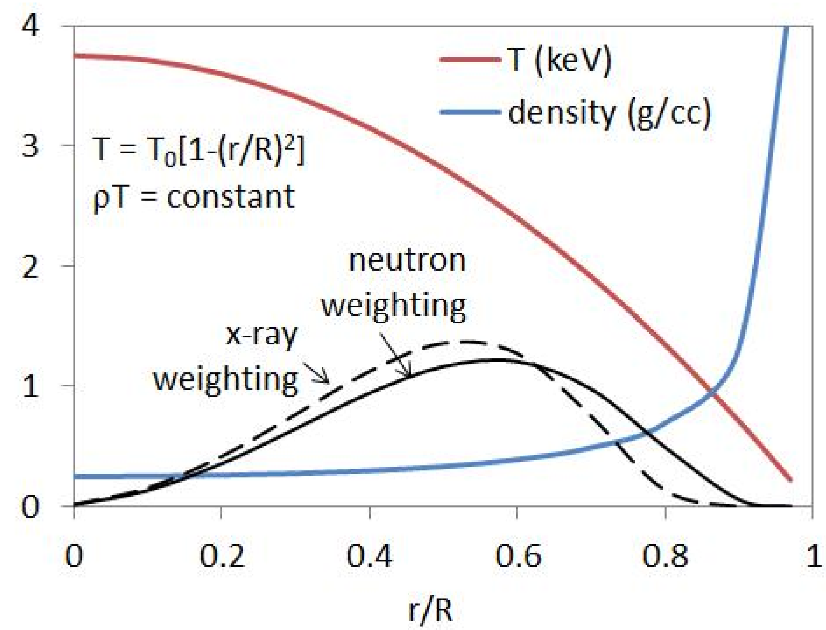
ρ_D ~ 0.3 g/cm^3
R = 70 μm
z = 4 mm
t_{burn} = 2 ns
T_e = 3.1 keV

ρr_{liner} = 0.9 g/cm^2

Y_{DD}= 6 x 10^{12}

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

Isobaric model* provides values even closer to neutron data

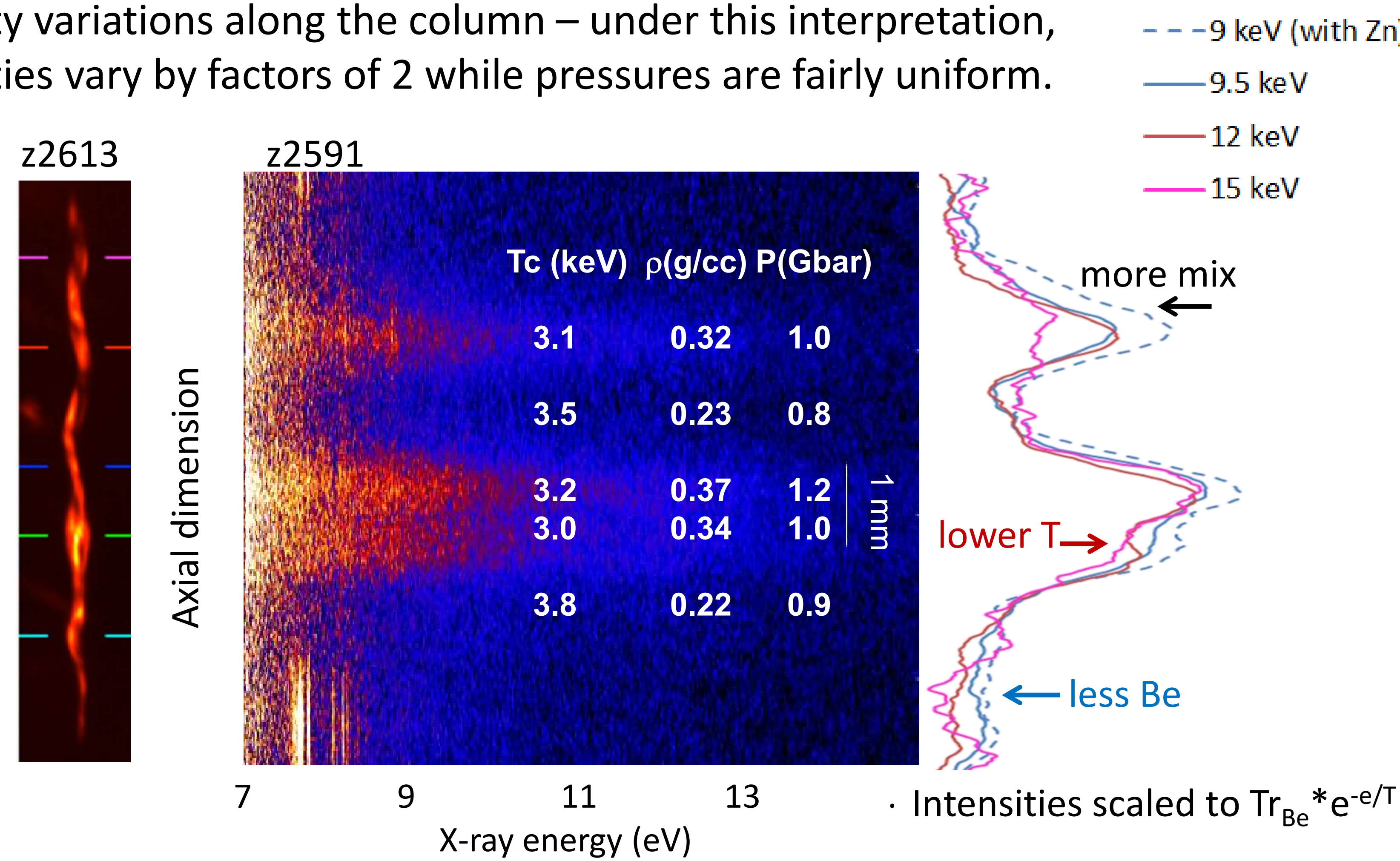


Synthetic diagnostics:
Neutrons (sample $\sqrt{T_i}$) $\langle T_i \rangle$ = 2.5 keV
X-rays (sample $\partial j/\partial \varepsilon$) $\langle T_e \rangle$ = 3.1 keV

*P. Springer *et al.*, *EPJ Web of Conferences* **59**, 04001 (2013)

Axially resolved spectra allow us to assess axial variations in ρ_{fuel}, T, ρR_{liner}, and mix

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.



Upcoming shots will use an interior tracer layer of ZnO to better characterize fuel-liner mix

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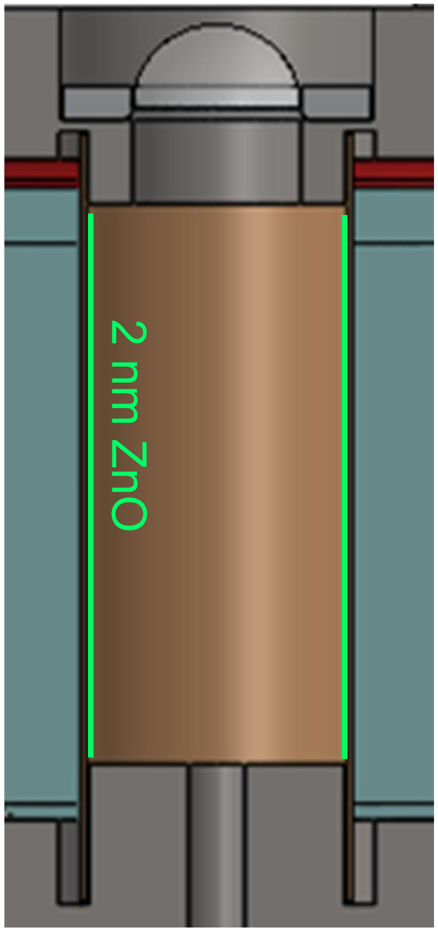
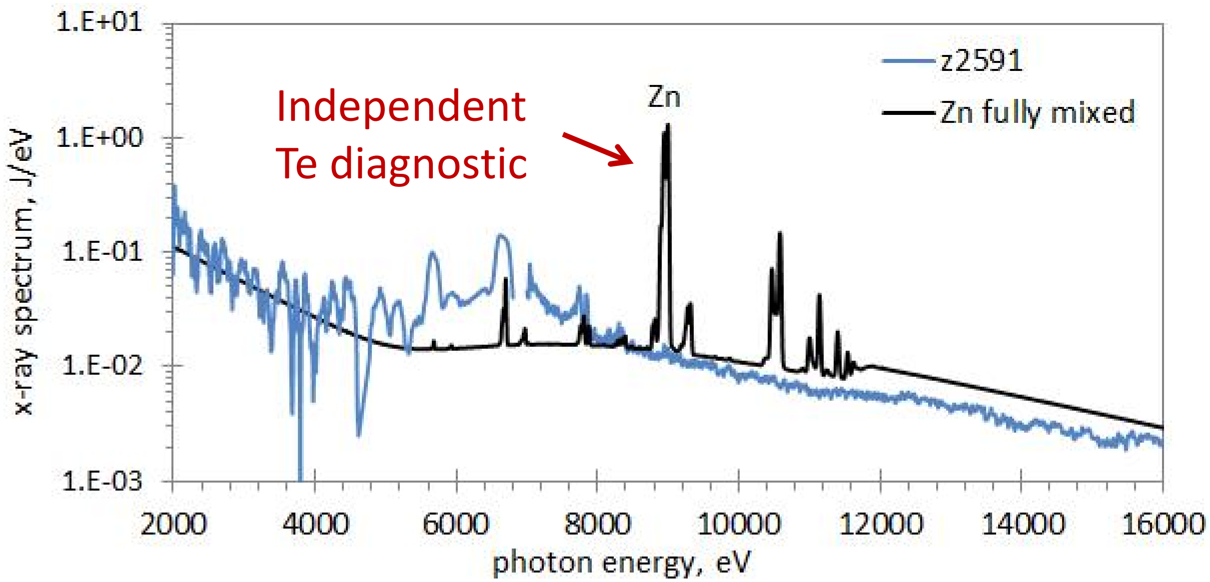
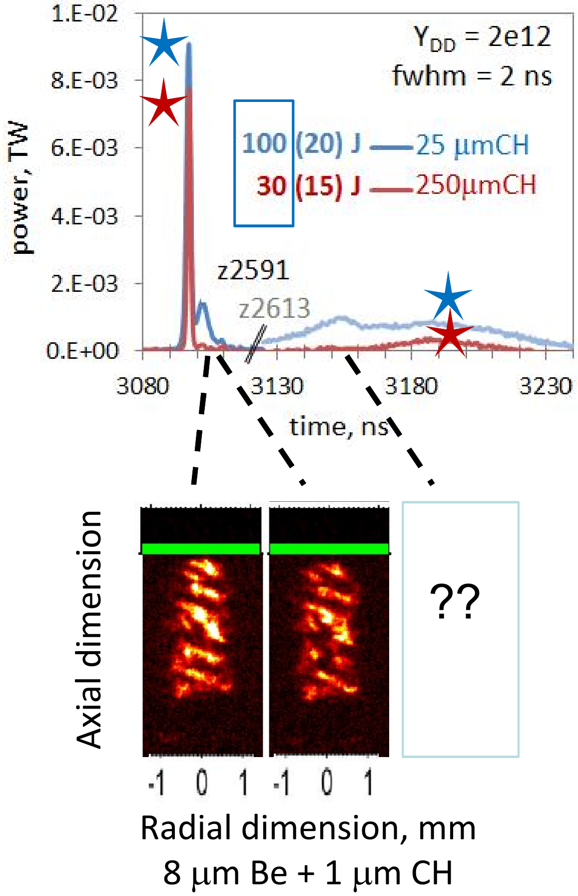


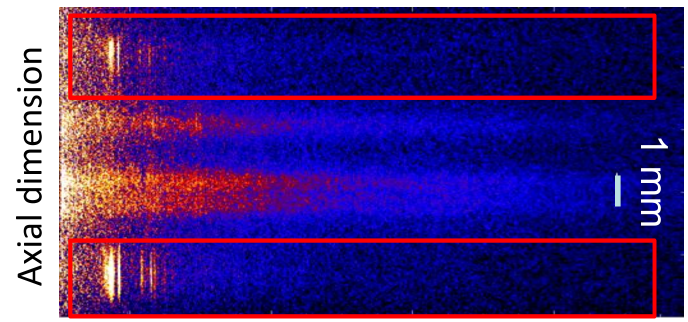


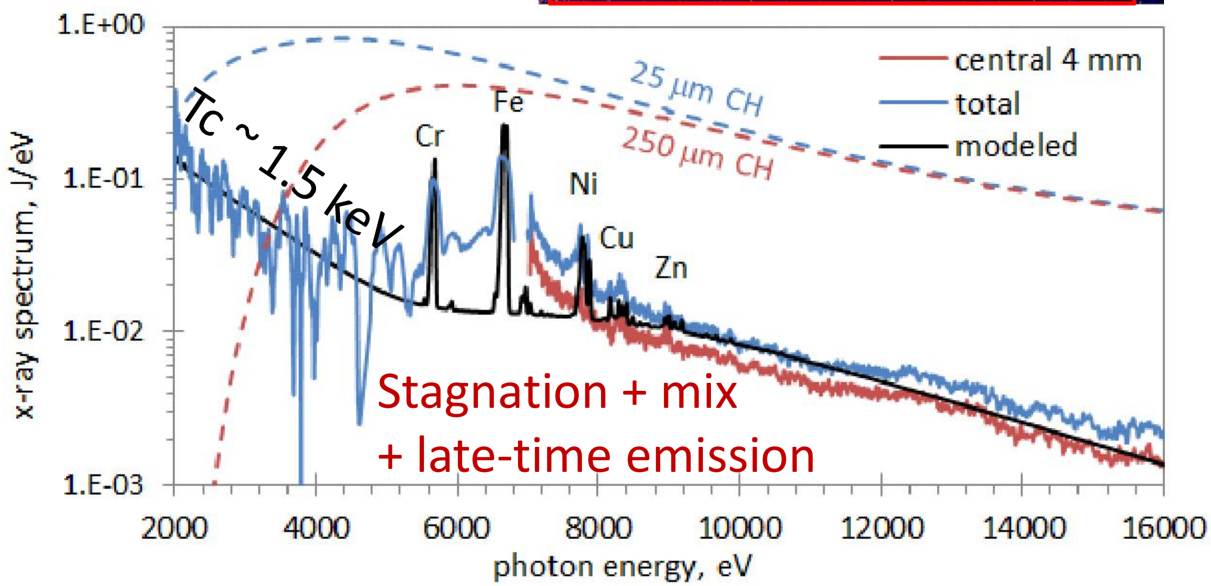
- Additional emitters will increase Zn signal by ~10^3
- Expect yield degradation of ~2x if mixed near stagnation, and ~10x if mixed by laser
- Provide a localized signal and independent temperature estimate from the mixed region

Combining information from all x-ray diagnostics also helps characterize late-time emission:



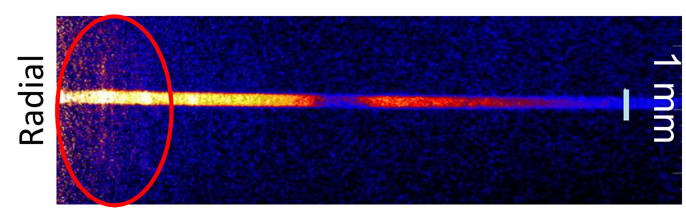
Powers constrain participating mass:
ρR_{Be} ~ 1 µg/cm²
$\rho R_{stainless}$ ~ 10 ng/cm²





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)

Can the late-time emission help us understand observed helical instabilities?

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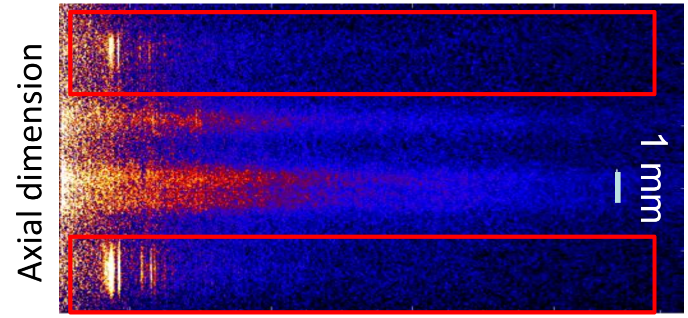
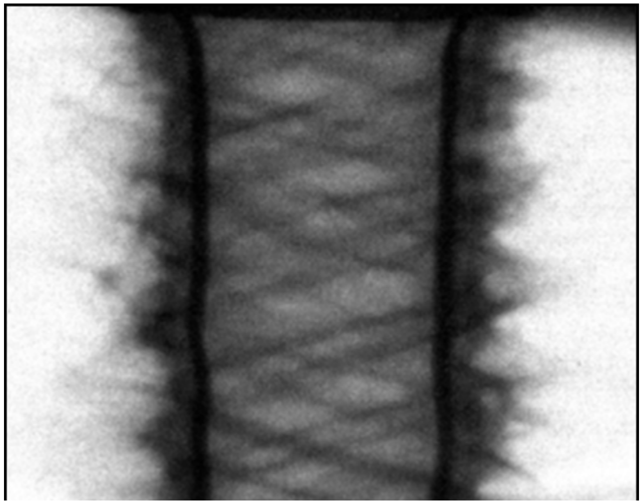
- Late-time stainless steel emission was not observed on shots where the stainless return can was replaced with aluminum

- The pitch of helical instabilities observed by Awe *et al*. on implosions with applied B_Z suggest instability seeding when $B_Z \sim B_\theta$

- For B ~ 10 T, this occurs well before the liner begins to implode, but a small amount of ionized mass swept onto the liner at early times (~ 1 μg/cm^2), could flux-compress the external B_Z to ~ 100 T ~ B_θ (Ryutov)

- The late-time emission suggesting ~ 10 ng/cm^2 from the return can could be supplemented with tracers in the current feed





T. Awe *et al.*, *Phys. Rev. Lett*. **111**, 235005 (2013), D. Ryutov *et al*. submitted to DZP proceedings

Caveats to the x-ray analysis

- The absolute power and spectral measurements which inform the density diagnostic depend PCD calibrations, which have ~30% uncertainties translating to ~50% uncertainties in ρ_{fuel} and ρR_{liner}
- Low S/N on the spectrometers at high photon energies leads to 10-20% uncertainties in the inferred electron temperatures
- The temporal evolution of the stagnating plasma has not yet been analyzed
- The data analysis was performed using a composite data set taken from two shots; in future experiments we hope to have complete data sets to enable analysis of every shot

We are building a rough but reliable picture of MagLIF stagnation conditions, providing detailed data to help validate our simulations.

High-fidelity radiation and thermal transport data will be critical for predictive simulations

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- Radiative losses during preheat can have a major effect on target performance: requires reliable non-LTE atomic models
  - H. Scott and S. Hansen, *High Energy Density Phys*. **6**, 39 (2010)
  - M. Rosen *et al*., *High Energy Density Phys.* **7**, 180 (2011)

- The efficacy of the magnetic field in inhibiting conduction losses is also key, but there is a dearth of data and benchmarked calculations of thermal conduction, particularly in high magnetic fields:
  - Y. Ping, Thermal conductivity measurements of CH and Be by refraction-enhanced x-ray radiography (last year's DPP)
  - T. Ott and M. Bonitz, *Phys. Rev. Lett.* **107**, 135003 (2011)
  - P. Grabowski, UC Irvine

- Optimizing laser preheat may require more sophisticated treatments of LPI

Summary: Extensive x-ray diagnostics on Z are guiding our understanding of MagLIF plasmas

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- Magnetized Liner Inertial Fusion (MagLIF) offers a promising alternative to traditional ICF schemes – if we can understand and control the complex interplay of magnetization, preheat, and stagnation

- Analysis of extensive neutron and x-ray data including imaging, power, and spectroscopic diagnostics are guiding our understanding of the plasma evolution and stagnation, helping to benchmark simulations

- Future experiments are planned to improve our understanding of preheat, mix, and scaling

The Magnetized Liner Inertial Fusion (MagLIF) effort on Z has many important contributors:

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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, 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

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B.E. Blue, D.G. Schroen, K. Tomlinson

General Atomics, San Diego, CA

M.C. Herrmann, D. Ryutov

Lawrence Livermore National Lab, Livermore, CA

+ Additional Collaborators at LLE, MIT, and LANL

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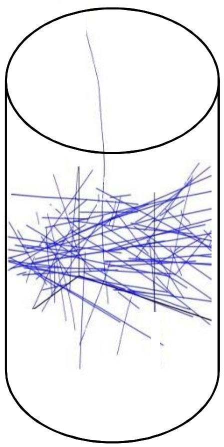
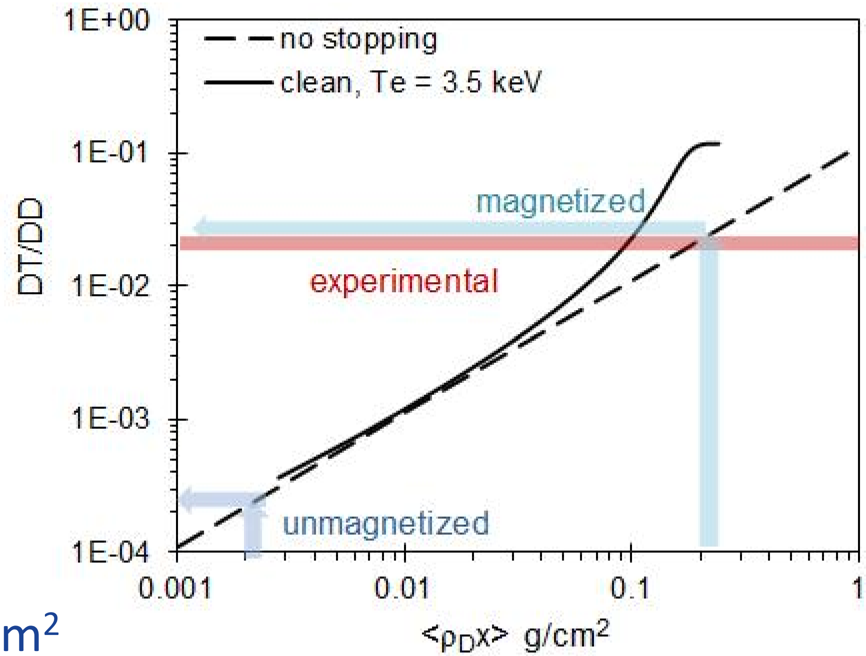
Initial experiments produced 2×10^{12} DD neutrons – and a remarkable 5×10^{10} DT neutrons

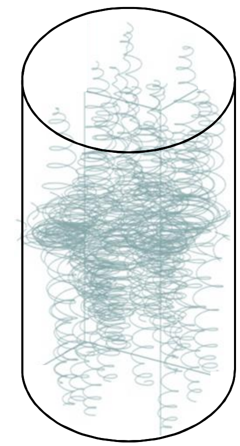
"Secondary" 14 MeV neutrons are produced by 1 MeV tritons interacting with D fuel:

D + D $\xrightarrow{50\%}$ **0.8 MeV He^3 + 2.5 MeV n**

D + D $\xrightarrow{50\%}$ **1.0 MeV T + 3 .0 MeV p**







In an unmagnetized plasma, $\rho R > 200$ mg/cm^2 is required for triton/α confinement ($\langle x\rangle \sim R$)

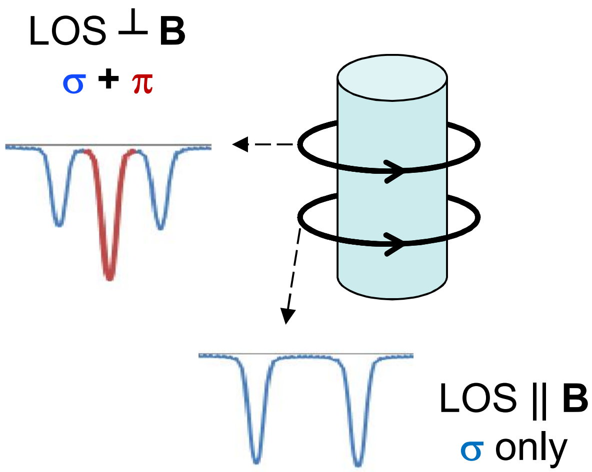
In a magnetized plasma, $\rho R \sim 2$ mg/cm^2 is sufficient to confine 1 MeV tritons ($\langle x\rangle \sim Z$)

A field that confines 1 MeV tritons will also confine thermal electrons (inhibiting conduction losses) and fast alphas (required for self-heating)

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

Zeeman splitting is being used to characterize Z's current drive and flux compression in Magnetized Liner Inertial Fusion (MagLIF) experiments

- Sodium deposits vaporized and backlit by current-carrying surfaces signal both the magnitude and direction of the local magnetic field:



The relative strength of σ and π components indicates field direction