SAND2016-6453PE

Mix in MagLIF Stagnation

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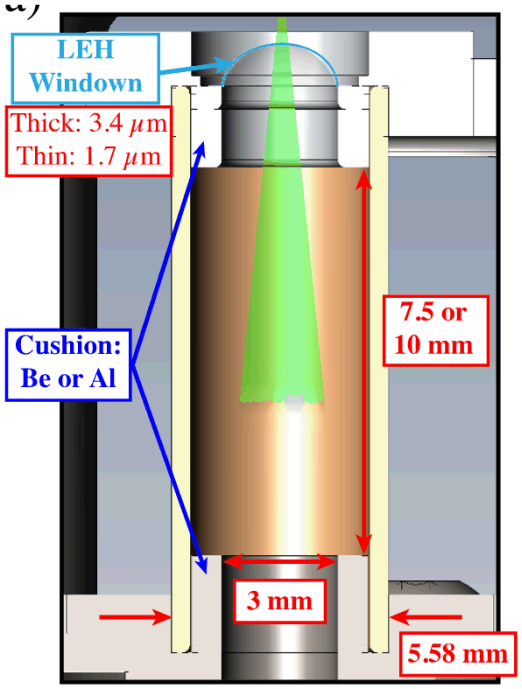
Questions to Address

- What do we know today and how do we know it (what measurements, model evidence)?
- How does our measurement knowledge differ from our models?
- What are the big questions we need to address?
- What experiments and/or simulations can we conduct to address these questions?
- What new measurements, diagnostics, and/or models are needed?

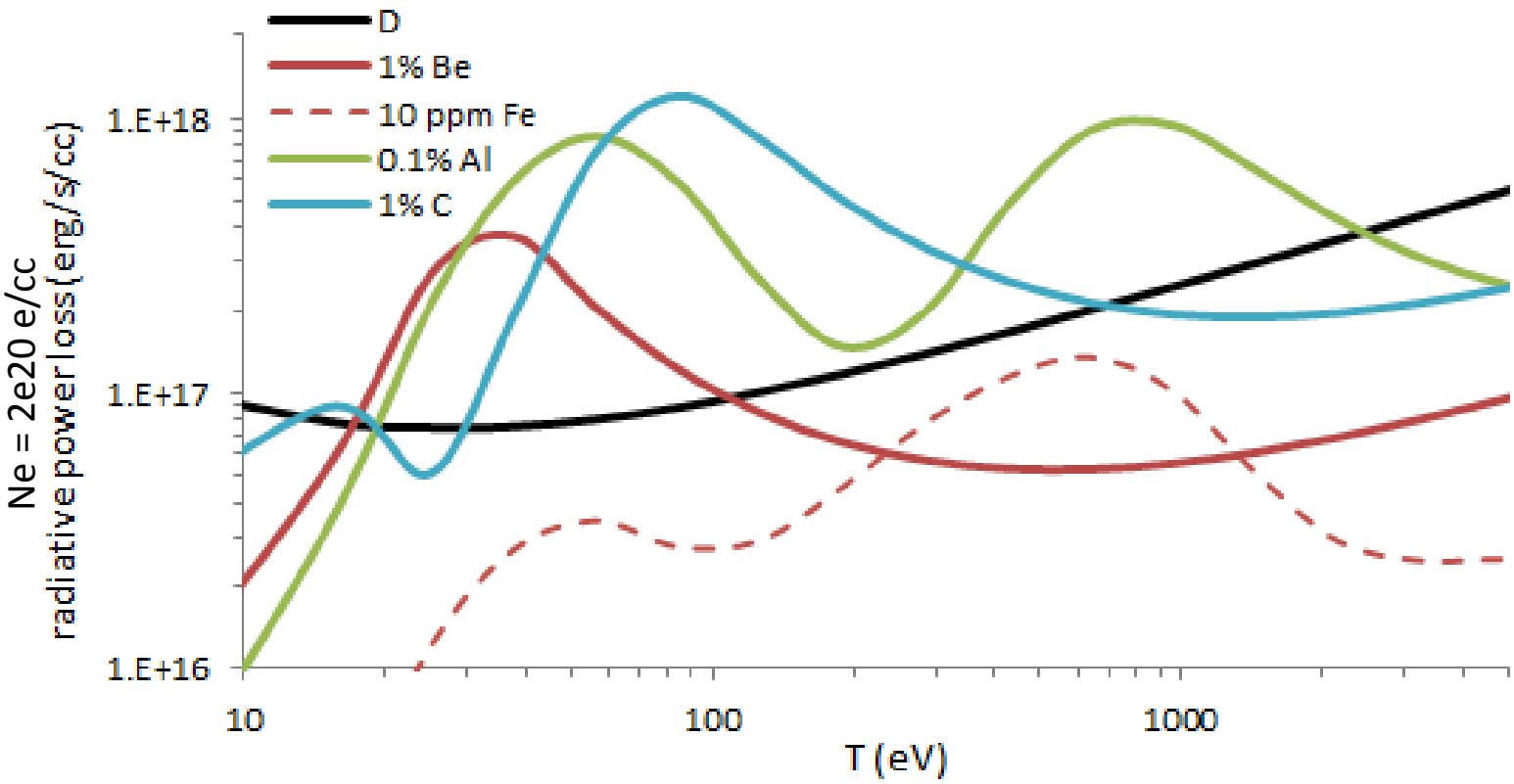
What do we know today and how do we know it (what measurements, model evidence)?

- Mix from the endcaps affects the yield
  - Be endcaps result in a ~10x higher yield than Al endcaps
- Be from the liner and/or endcaps end up in the hot stagnation plasma.
  - Fe He-like emission is seen in time-integrated spectra
- The intensity ratio of the Fe He-like lines to the continuum is consistent with a few % Be mix.
  - Assumes a lot…
- Early-time mix can significantly affect stag performance
  - 0.1% Ar in the DD duds the yield.
- Mix from the laser-heating phase is probably important
  - Trend of decreasing yield with increasing laser energy
- The LEH window may be a source of mix.
  - Shot with window on bottom of cushion had ~30x less yield
  - Shot using phase-plate had ~20x less yield



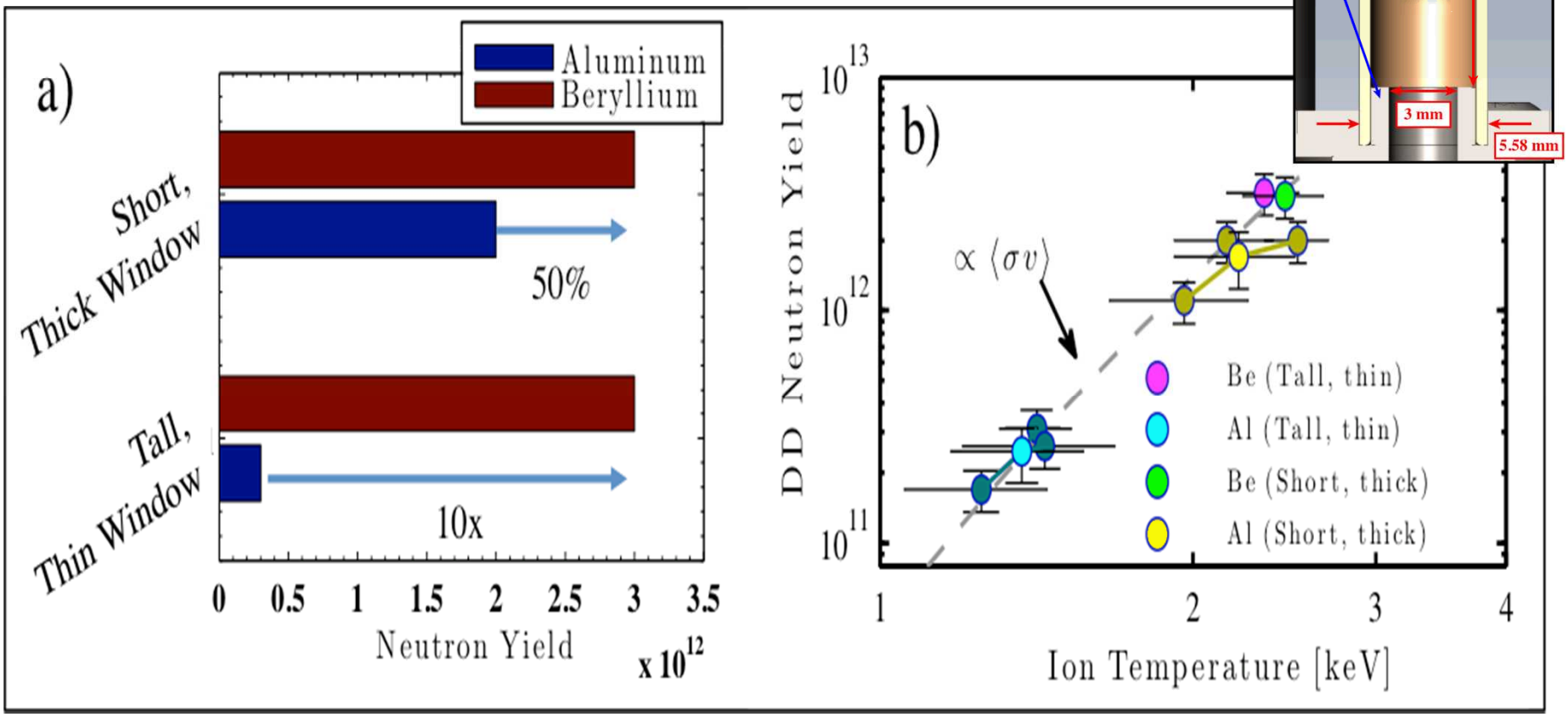
In Activation
-DD Yield
Crystal Spectrometers
-Lines and Continuum
Crystal Imager
-Hot plasma distribution

Radiative losses vary with material and charge state

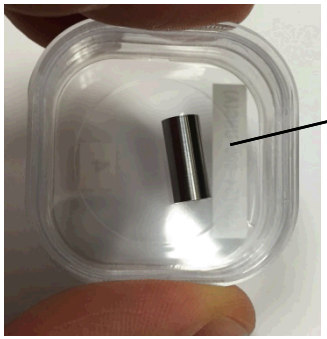


- Mix levels of ~1% Be are tolerable (~2x degradation)
- 0.1% Aluminum is devastating (~10x degradation)
- 1% carbon is devastating (~10x degradation)
  Note that uniform mix of half thin (thick) window mass gives ~3% (8%) C
- Mid-Z impurities in Be don't hurt at all, even at 10x detected levels

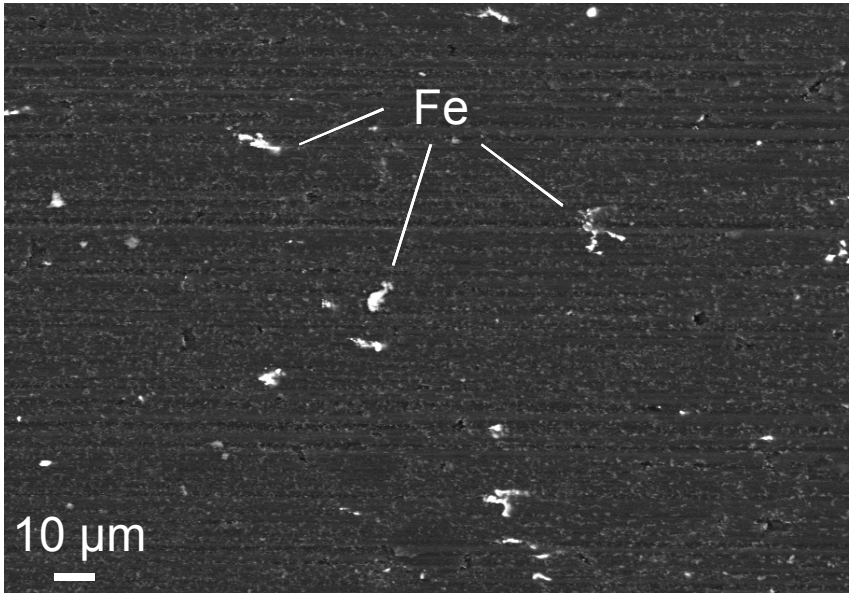
Yield and Ti are consistent with endcaps being a source of mix



Fe occurs “naturally” in our S-65 grade Be liners and endcaps.



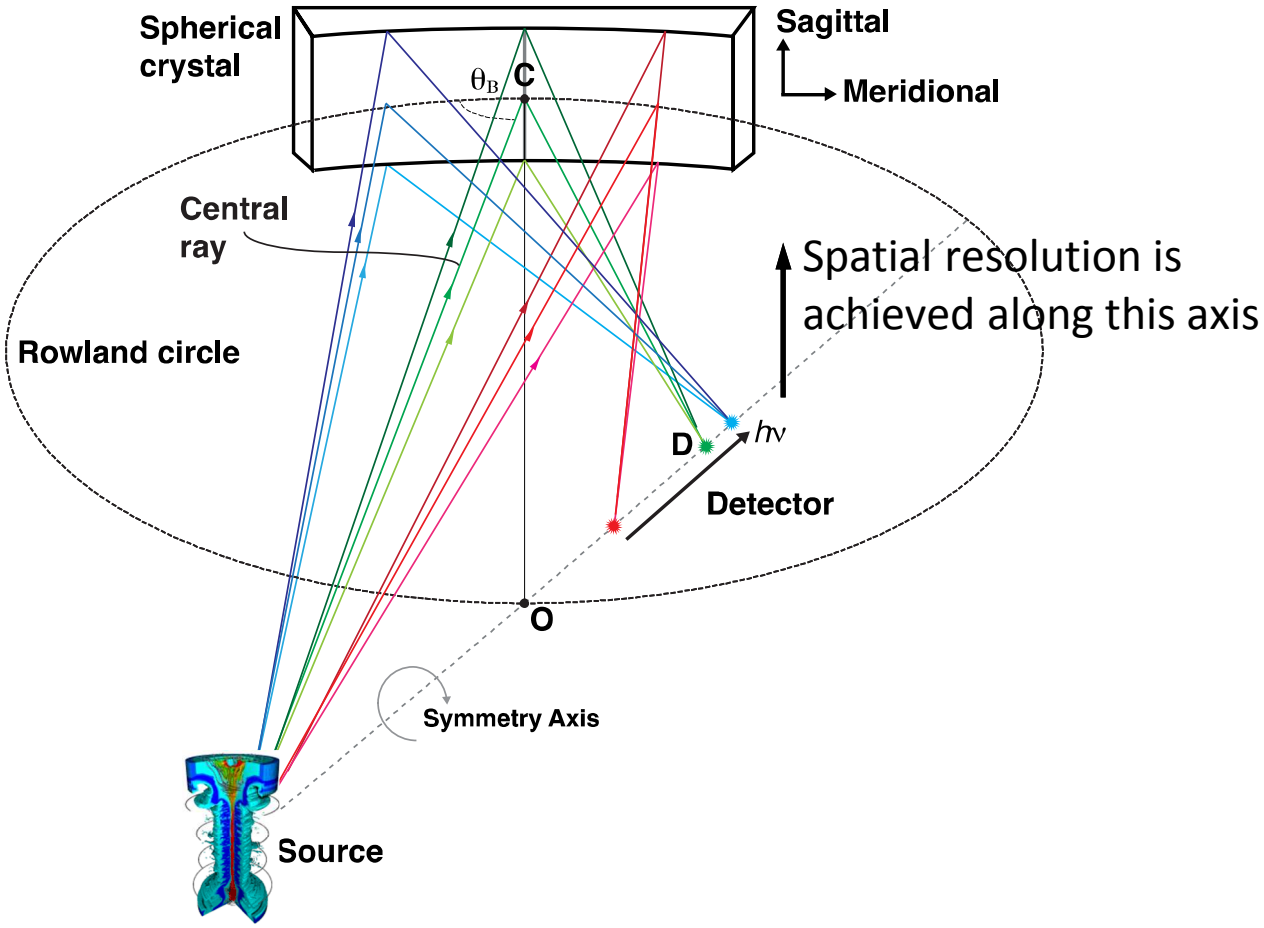
SEM image of the Be liner outer surface



- The Be stock material contains ~100 ppm (0.01% atomic) of Fe that originate from the manufacturing process.
- The Fe appears as micron-sized impurities that are uniformly distributed on the visible surfaces. We are assuming it is uniform in the bulk.

To resolve the Fe emission generated at stagnation we use a spherically-bent crystal spectrometer.

Spherical crystal spectrometer[1]

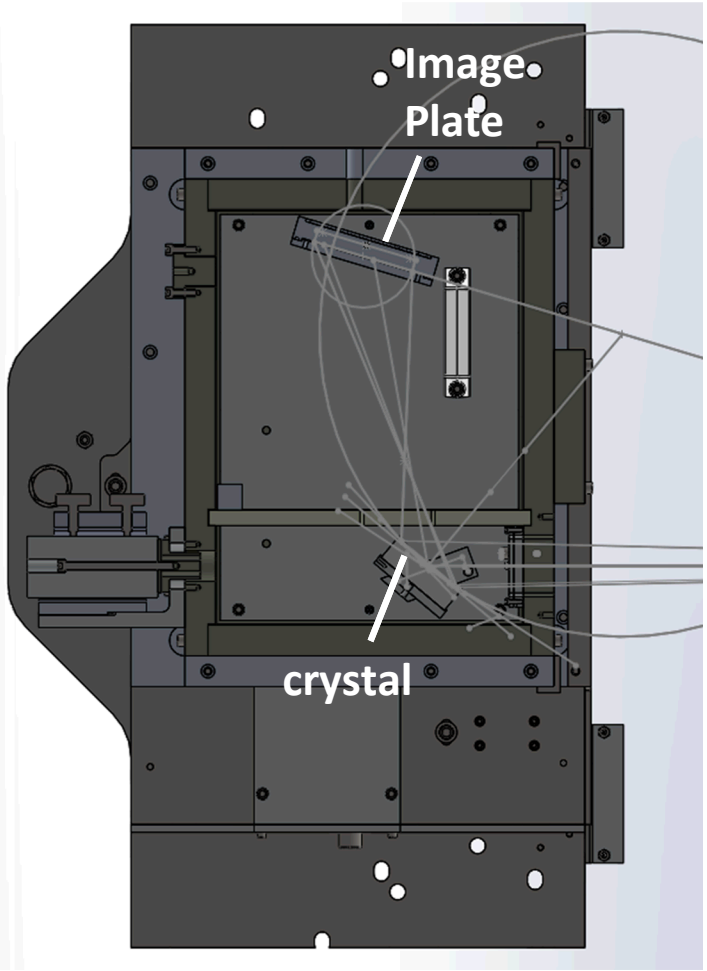


[1]E.C.Harding et. al., RSI (2015)
D. Sinars et. al. JSQRT (2006)
FSSR used on dynamic hohlraum capsule implosions

X-Ray Scattering Spherical Spectrometer (XRS3) Spectrometer

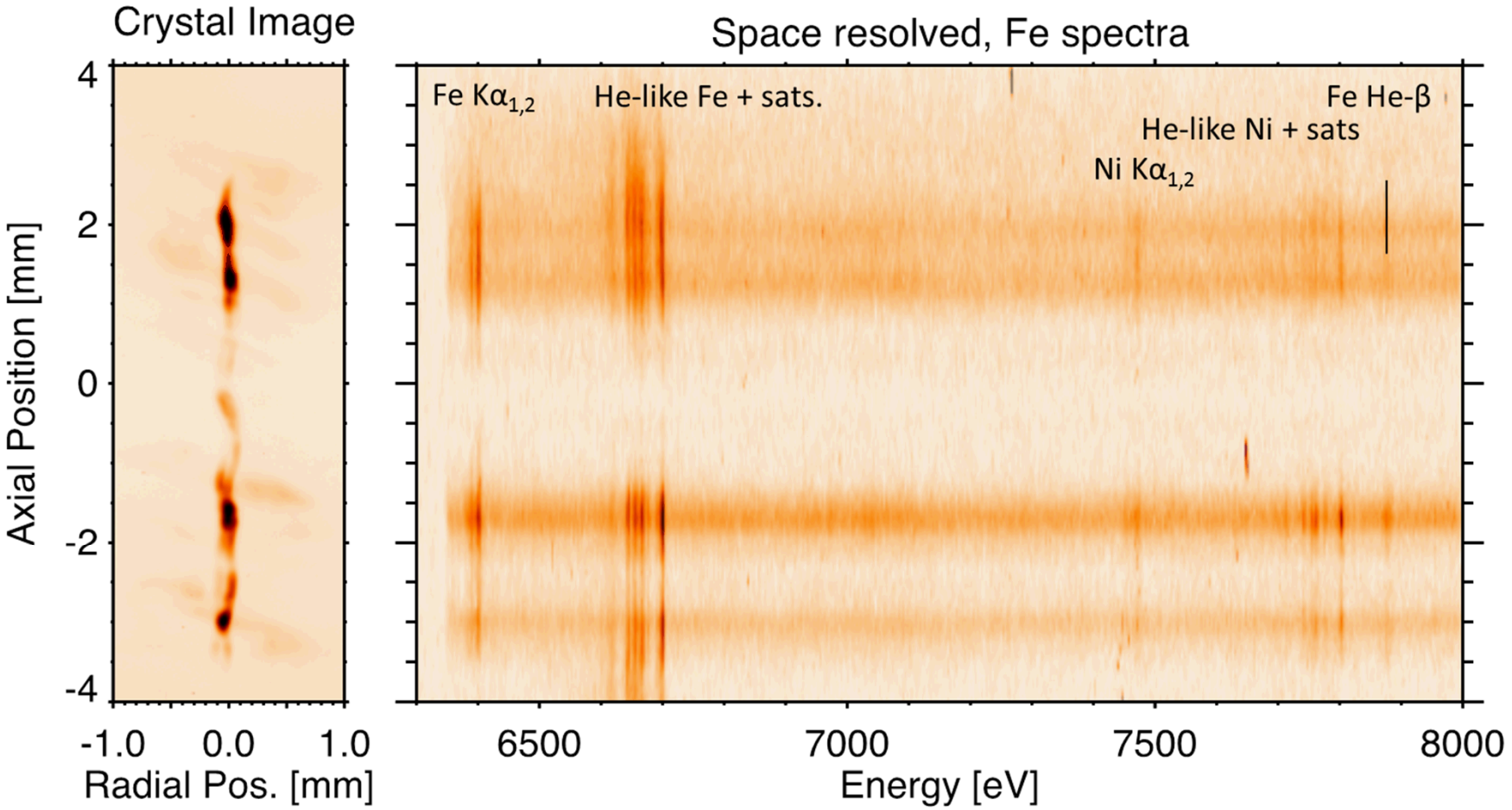
Spectrometer setup for He-like Fe emission

Crystal	Q20-23 (2d = 2.749 Å)
Source-to-crystal	800 mm
Crystal-to-detector	256.92 mm
Crystal Radius	250 mm
Center Bragg Angle	40°
Crystal size[1]	60 x 36 mm
Spectral Range[2]	6328 - 7977 eV
Spatial Mag. (M_{sag})	0.30x
Spectral Resolution[3]	2 eV
Spatial Resolution[3]	210 µm
Throughput	1.9e-7 steradians



[1]This is a tiled crystal consisting of 2 strips, each one is 60 x 18 mm
[2]Detector length must be 85 mm to capture entire spectral range.
[3]Limited by the Image Plate resolution of 63 microns.

We believe we are observing He-like Fe emission from stagnation.



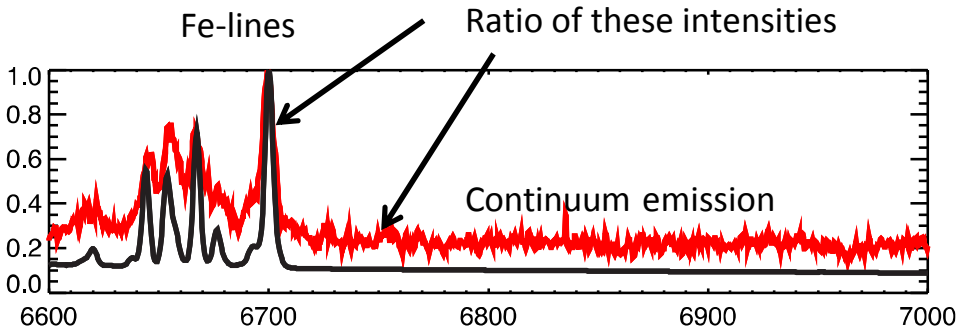
Z2850

Target: 7.5 mm tall Be AR6 liner with Be cushions and a 3.5 um LEH window

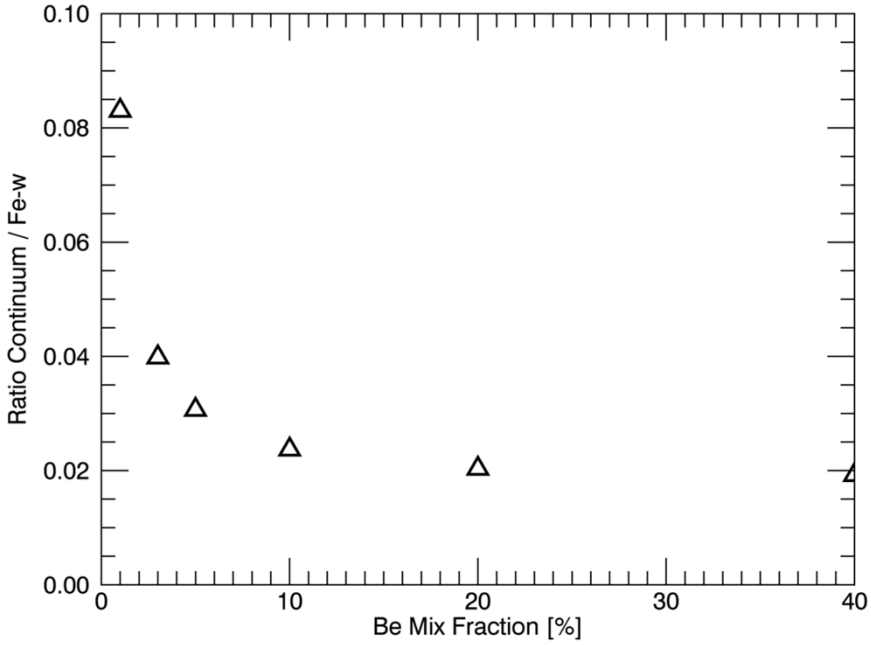
Yield: 3E12 DD (highest performing MagLIF shot to date)

Ratio of Fe line emission and nearby continuum emission is sensitive to mix fraction.

XRS3 data and PrismSPECT



Intensities Ratios vs. Be mix



<u>Key Assumptions:</u>

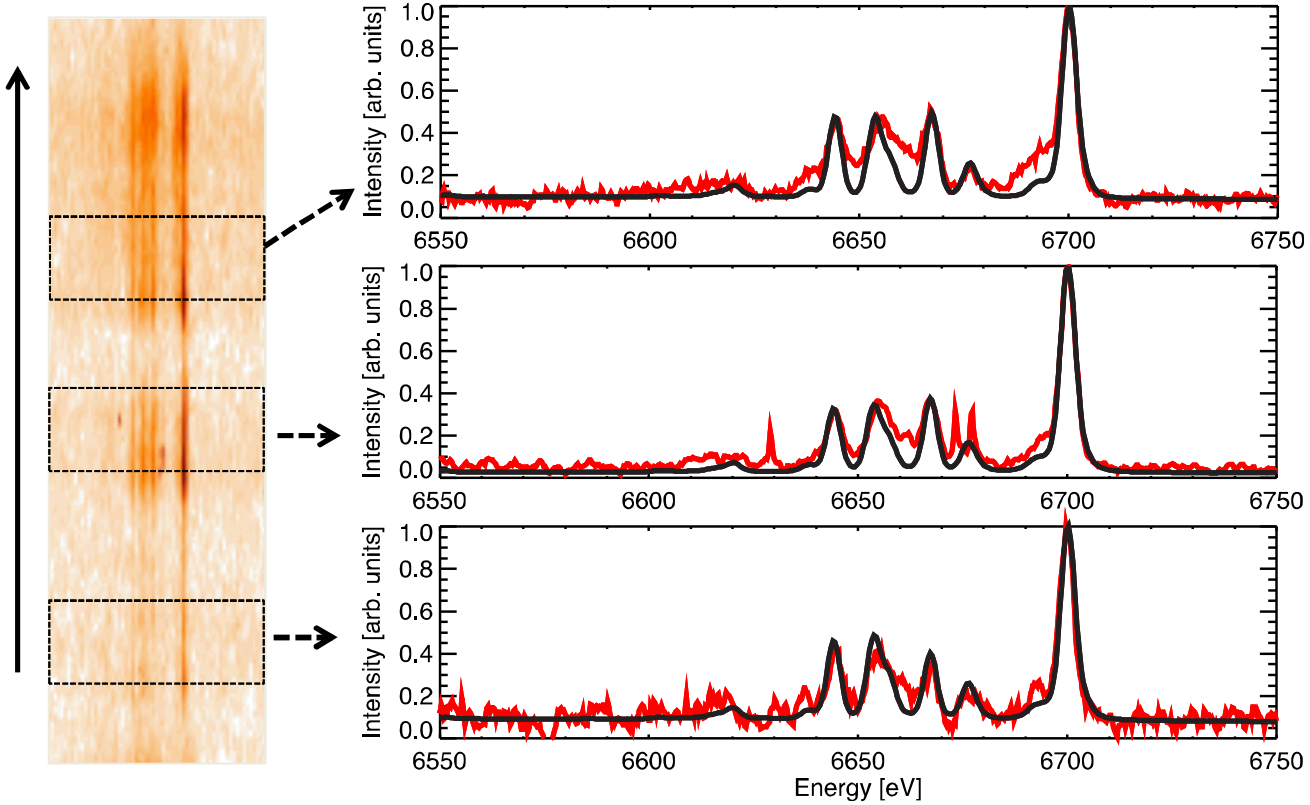
- Lines and continuum are from the same plasma at the same time
  - If continuum has other contributions, then this is a lower bound on mix
- Fe/Be ratio is fixed throughout the volume
- Others?

PrismSPECT runs use
D + Be + Fe

Relative amounts of each are varied w/ fixed total mass density and $T_{e.}$

Example: (Z2839) Be mix fraction appears to be 1-3%

Experimental spectra fitted with PrismSPECT simulations using E/ΔE = 3000.



Inferred values

T_e = 1.5 keV
n_e = 1.2e23 cm^{-3}
Be mix ~ 1%

T_e = 1.6 keV
n_e = 1.7e23 cm^{-3}
Be mix ~ 3%

T_e = 1.4 keV
n_e = 2.0e23 cm^{-3}
Be mix ~ 1%

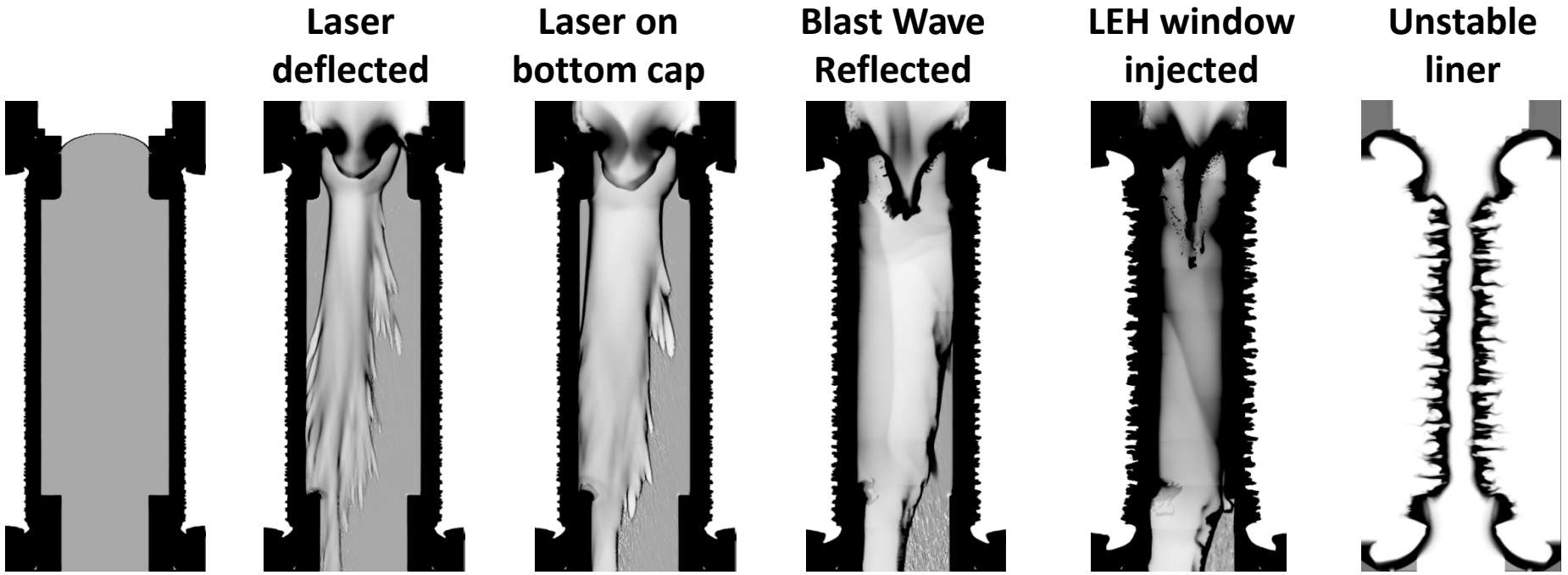
Z2839

Target: 10 mm tall Be AR6 liner with Be cushions and a 1.5 um LEH window

Yield: 3E12 DD (highest performing MagLIF shot to date)

How does our measurement knowledge differ from our models?

- Models indicate mix can occur from multiple origins:
  - Blast wave from laser preheat causes blowoff from liner wall and endcaps
  - Laser can pass through the gas and cause blowoff from the bottom end cap
  - Laser can deflect through LEH plasma and hit the liner/endcap causing blowoff
  - The exploded LEH window can mix into the gas
  - The liner is RT unstable

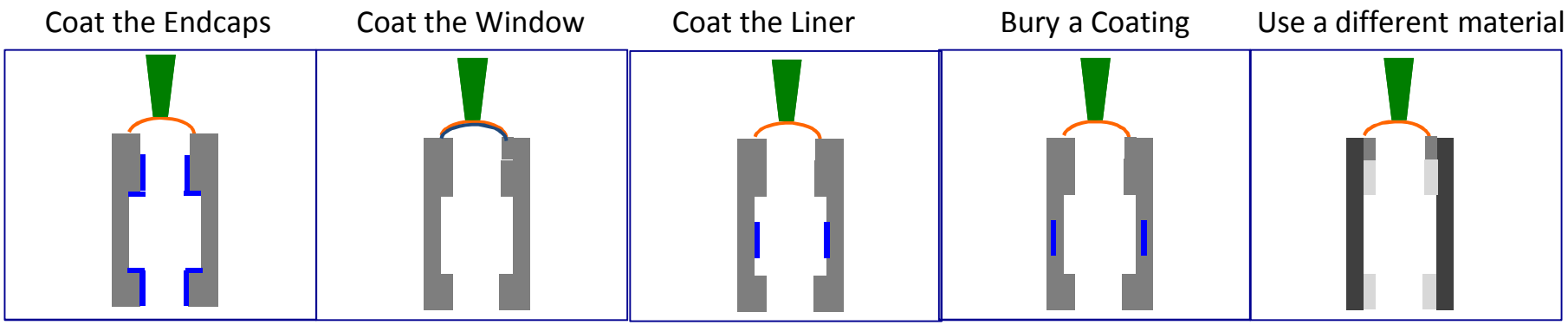


What are the big questions we need to address?

- What are the true origins of the Be mix and at what level of relative importance?
  - Present data is ambiguous on the source and simulations indicate it may come from multiple places.
- How is the Be mix distributed in space and time?
  - Present interpretation is that Fe emission all comes during stagnation
  - Spectrometers integrate over at least 2 spatial dimensions
- Is the LEH window a significant contributor to mix?
- How can we reduce the amount of mix from preheat where it has the largest impact?

What experiments and/or simulations can we conduct to address these questions?

- Use localized coatings/tracers to assess the origins of the mix.
  - Liner (Co), endcap (Co), window (Co, Cl)
  - This is our baseline approach; ~1 week per year of dedicated development on Z
  - Should use OMEGA-EP and Pecos (ZBL) to develop techniques for window coatings
- Use different liner/endcap materials and assess impact on yield and/or intensity of line emission.
  - Li (target development in progress), high purity Be
- Assess mix with different laser preheating.
- Asses yield with various LEH window positions.
  - A coupled problem

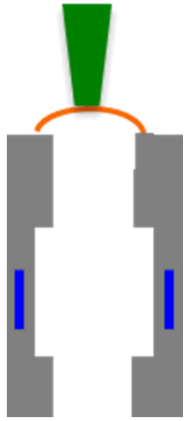


Future experiments and diagnostics

- Time-integrated x-ray emission lines from dopant, impurities, and tracers can unambiguously track material fractions at stagnation
  - Co coating on endcaps (and windows) will emit in range of XRS3
  - Ultra-pure and high-impurity Be can help isolate mix source
- In general, x-ray diagnostics must dance along multiple fine lines:
  - AR-6 liner is opaque to hv < 3 keV initially (and hv < 6 keV at stagnation) → Z ≥ 18 (26)
  - Detectable emission → T ≥ ~ hv/3 and ~100 ppm at preheat (~few ppm at stagnation)
  - Concentrations > 100 ppm of Z = 18 (or ~10 ppm of Z = 36) degrade neutron yields by 2-3x and decrease (or eliminate) x-ray signals →
  - Fuel dopants can be precisely fixed but are restricted to gases (Ar/Kr)
  - There are many good options for endcap/liner tracers (Ti/Co/Zn) but since we lack a predictive simulation capability for dynamic mix, we must rely on empirical data
  - Window tracers can be volumetric (Cl) or coated, but must not interfere with laser enrgy deposition
- With 500 J of preheat energy and AR12 liners, time-dependent K-shell spectroscopy of 100 ppm Ar in fuel and 1% Cl window could provide temporal evolution of fuel temperature and mix

What new measurements, diagnostics, targets, and/or models are needed?

- Time-resolved spectroscopy of tracers
  - Requires single line-of-sight gating…
- 2-D spatial imaging of tracers…
- Be liners with buried tracer layers
  - Assess depth of the liner that penetrates stag column
- High purity Be Liners…
- Li liners (in development)
  - Reduce impact of liner mix
  - Oxygen contaminants need to be controlled
- Cryo DD layers?

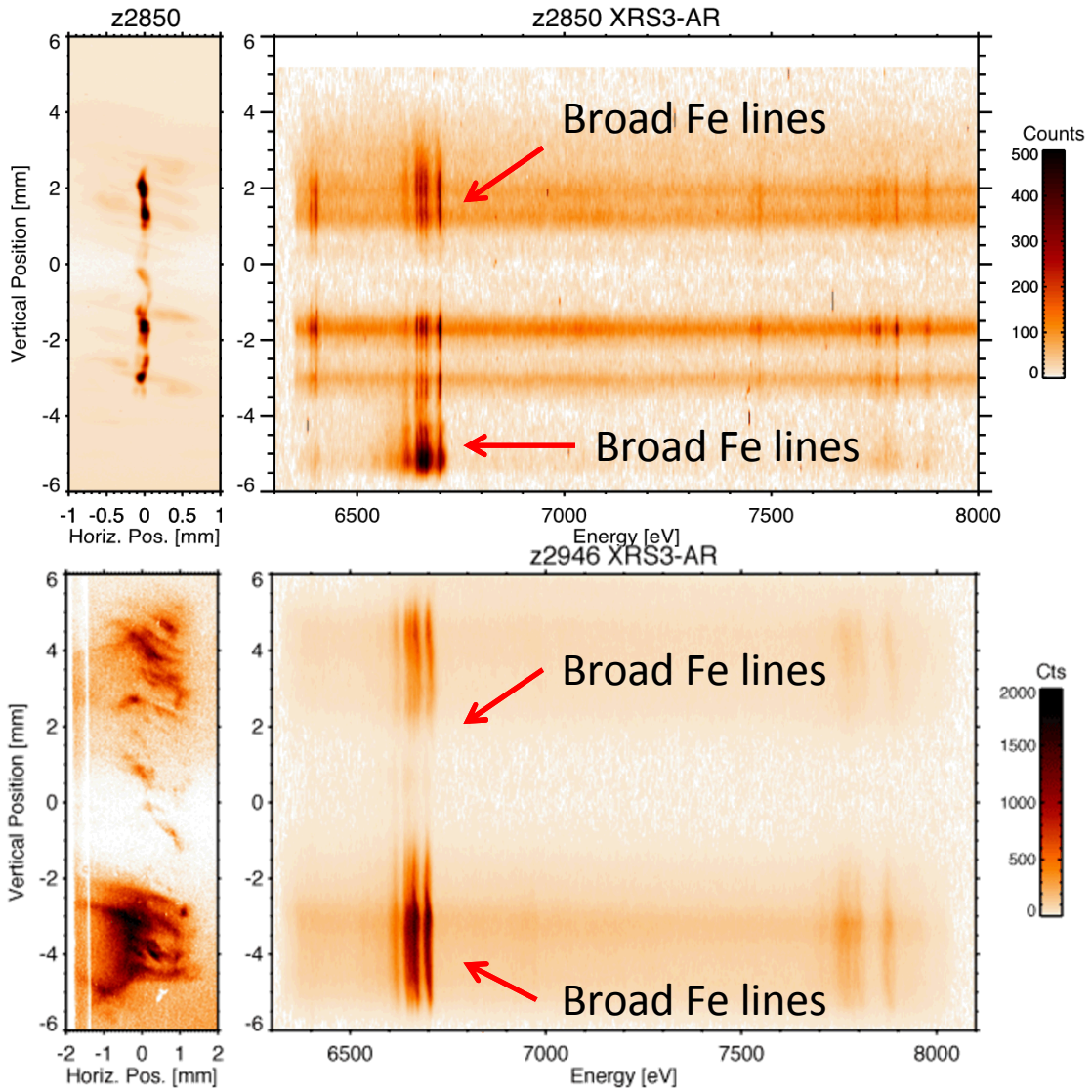


Li Liner picture

Materion's UHP9999 material is nearly a single crystalline piece of Be. This is the highest purity Be we can get.

Initial discussions with Don Hashiguchi and Jerry Holman (Materion Elmore, OH): UHP 9999 is fragile. Machining will likely require a careful EDM process and possibly diamond turning. EDM only (i.e., no SPDT) may yield Ra ~ 400nm. 1 liner is ~$8k.

Fe lines can come from somewhere other than the stagnation column

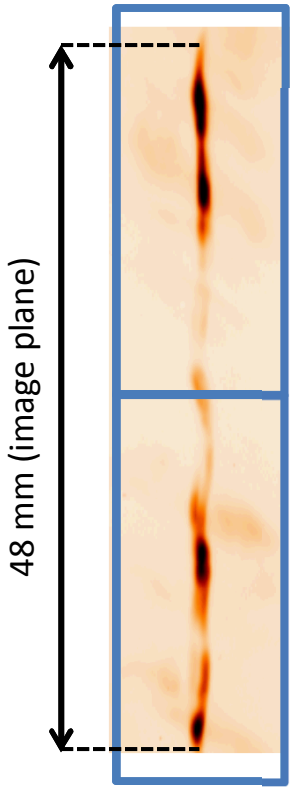


Full MagLIF shot (z2850),Y_{DD} = 3e12:
Fe spectral lines near the top and bottom of the target appear broadened.

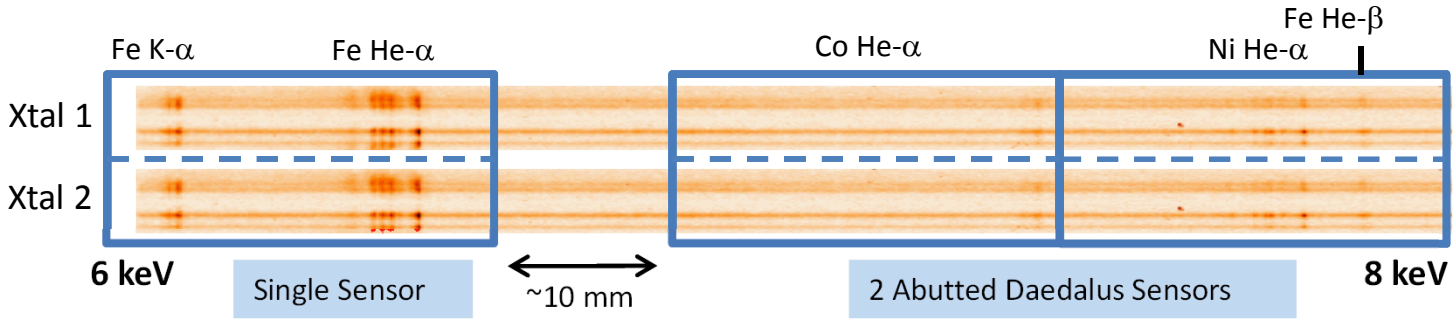
Implosion only shot (z2946), no laser heating:
No stagnation column but there are strong Fe signals appearing near the ends. This spatially broad source of Fe emission maybe contaminating other shots like z2850.

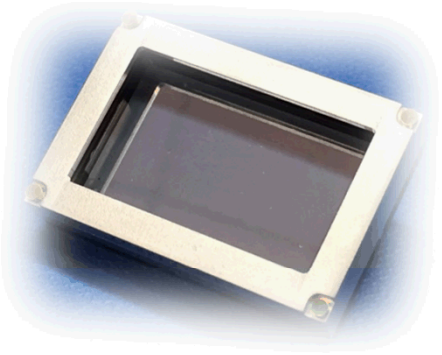
Fast gated CMOS sensors will be used to separate stagnation from other events

Spherical Crystal 2-D Imager (Mag 6)



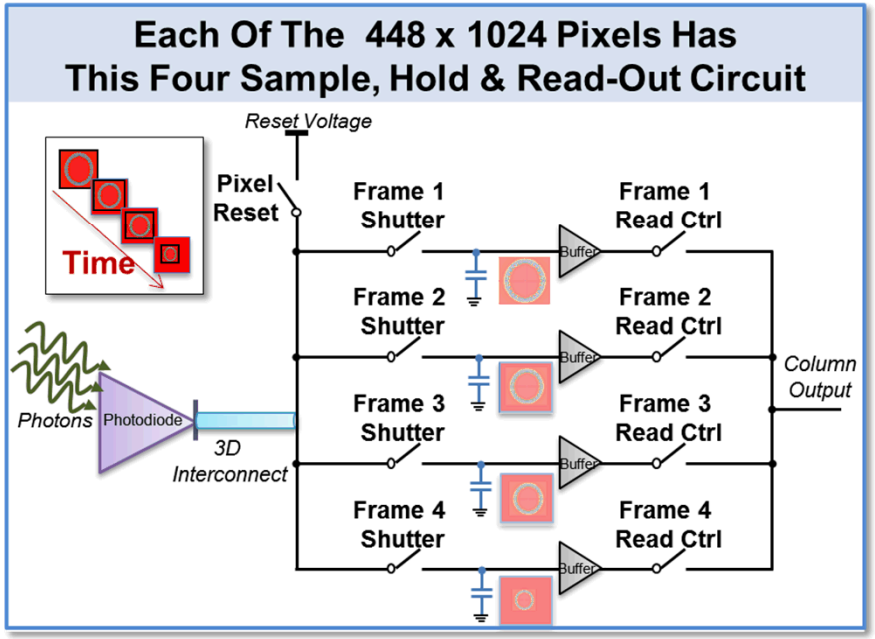
Dual Crystal Spherical Spectrometer w/ 1-D Resolution



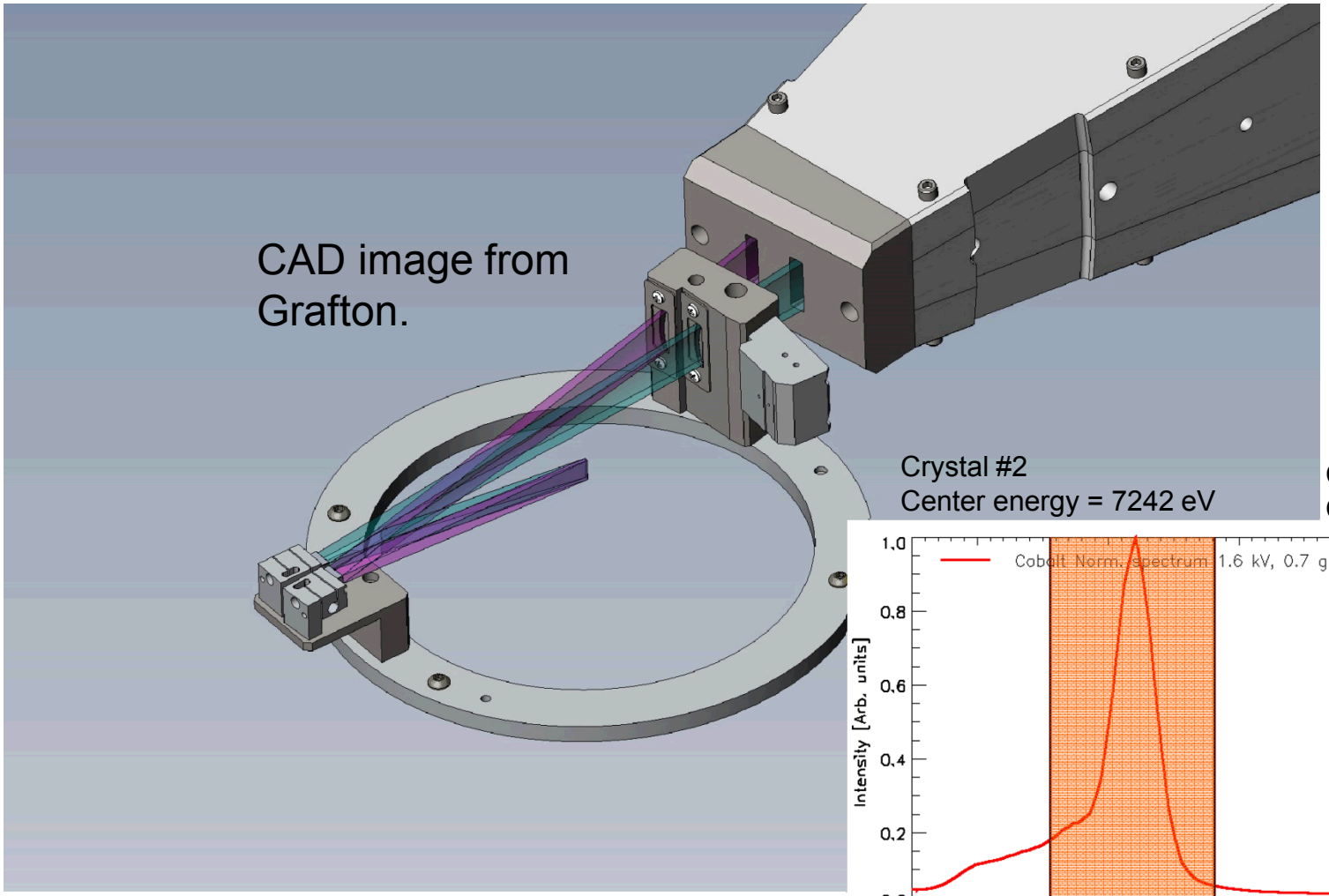


Next Generation Sensor (FY18)

- 3 – 9 frames per sensor depending on resolution requirements
- ~1 ns gate times
- Good dynamic range up to ~10 keV

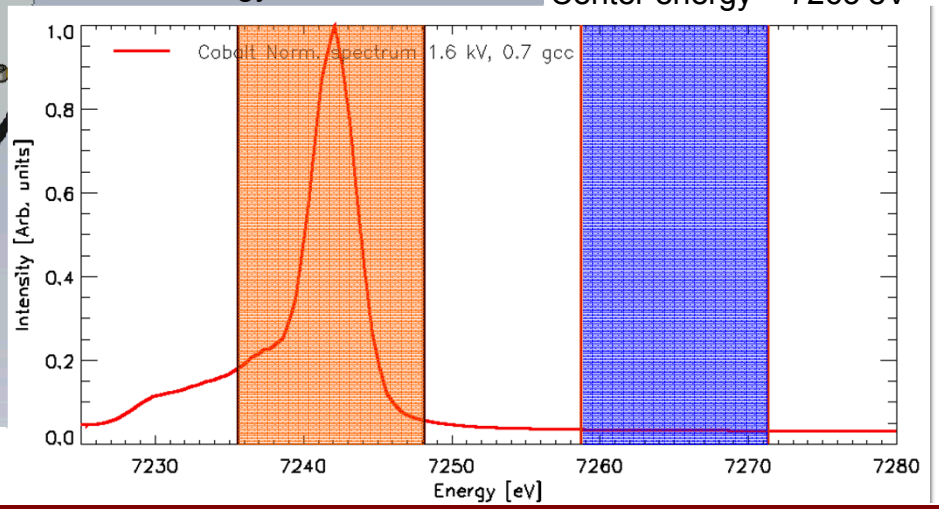


The new Dual crystal imager will capture two images of stagnation by using two side-by-side Ge 335 crystals.



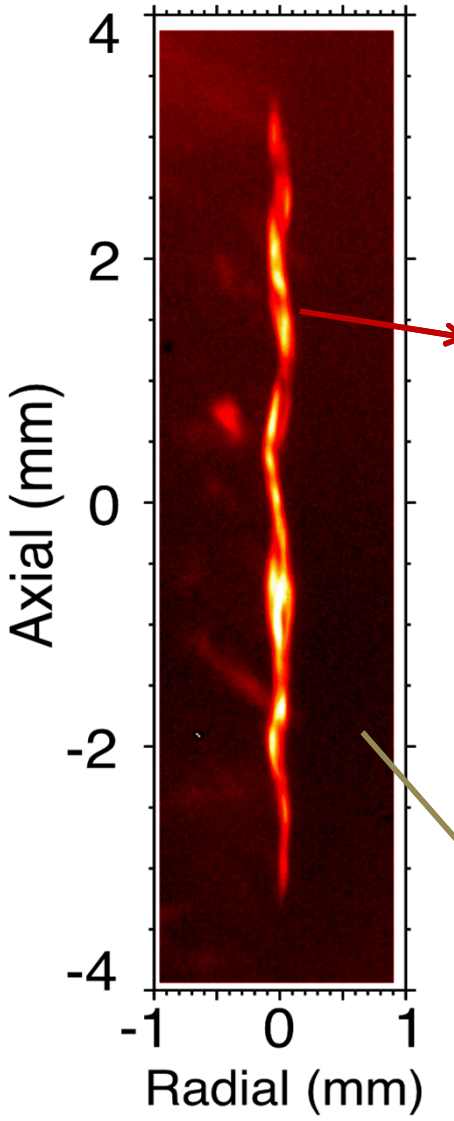
Crystal #2
Center energy = 7242 eV

Crystal #1
Center energy = 7265 eV



Backup

MagLIF stagnation is diagnosed with extensive neutron & x-ray diagnostics



X-ray image of MagLIF plasma

Stagnating plasma

<Te> = 3 ±1 keV

<Ti >= 2.5 +/- 0.5 keV

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

t_{burn} = 1.5 ± 0.5 ns

f_{mix} ~ 1 %

z = 5 ± 2 mm

R = 50 ± 20 μm

ρ_D = 0.3 ± 0.1 g/cm³

P(z) = 1 ± 0.2 Gbar

ρR ~ 1.5 mg/cm²

BR ~ 0.4 MG·cm

Confining liner

ρr_{liner} = 1 g/cm²

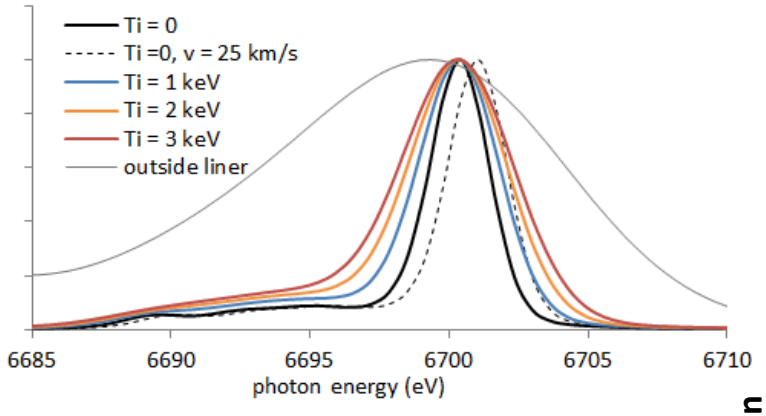
Magnetized Liner Inertial Fusion (MagLIF) has the potential to produce high fusion yields by exploiting:

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
4) Preheat and stagnation stages are both highly sensitive to radiative losses from impurities (mix)

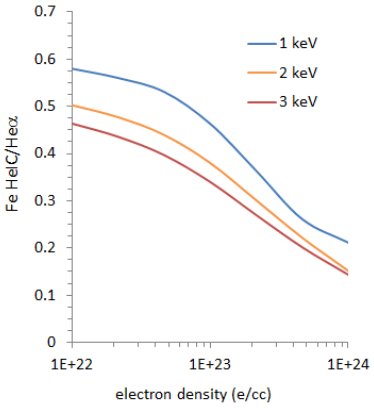
M. Gomez *et al.*, *Phys. Rev. Lett*. **113**, 155003 (2014) and P.F. Schmit *et al.*, *ibid*. 155004

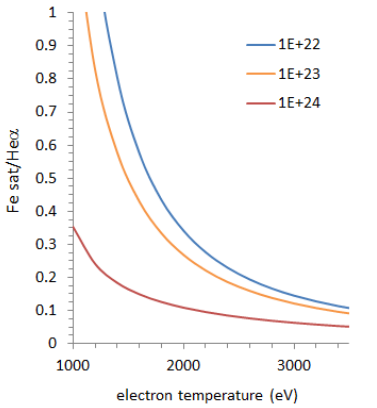
High-resolution, axially resolving spectrometer provides a wealth of information

Line shapes → T_{ion}, v_{bulk}, & r_{source}

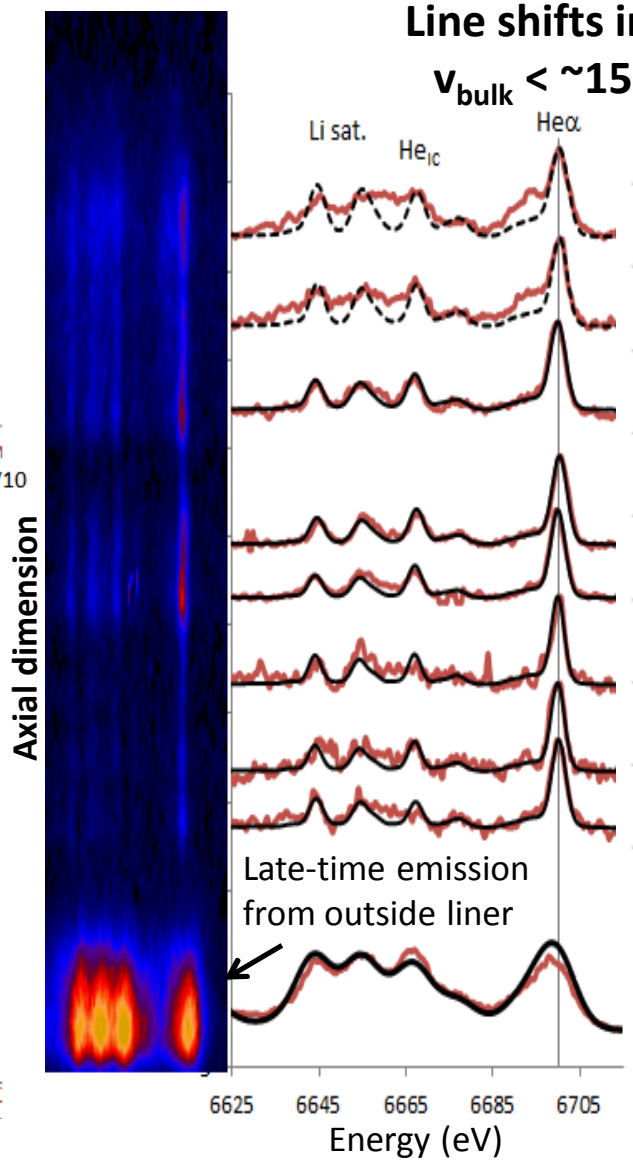


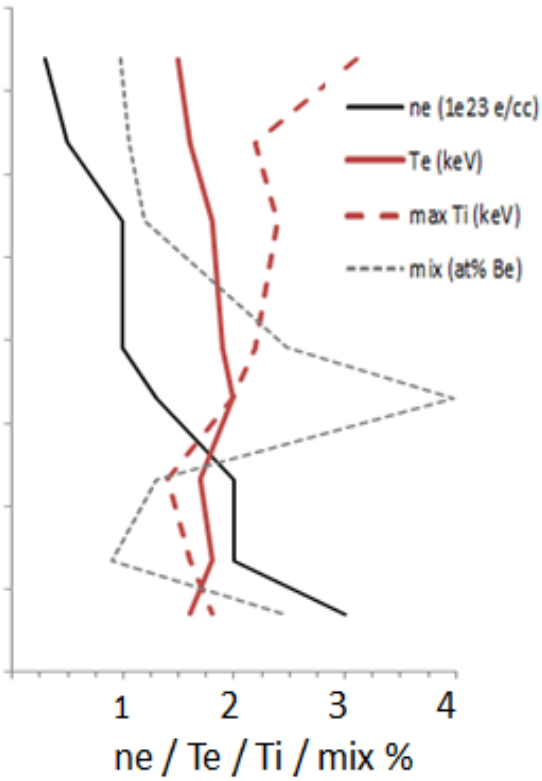
Intensity ratios → T_e, n_e, & mix





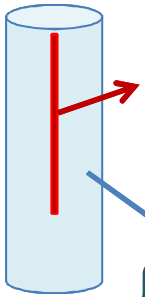
Line shifts indicate v_{bulk} < ~15 km/s





Data constrains some gradients as well as burn averages

"cartoon" stagnation distilled from x-ray images & continuur spectra



ρ_D = 0.25 g/cm^3

T_e = 3.1 keV

T_i = 2.5 keV

ρR_{liner} ~ 1 g/cm^2

Inferences from high-res line spectra

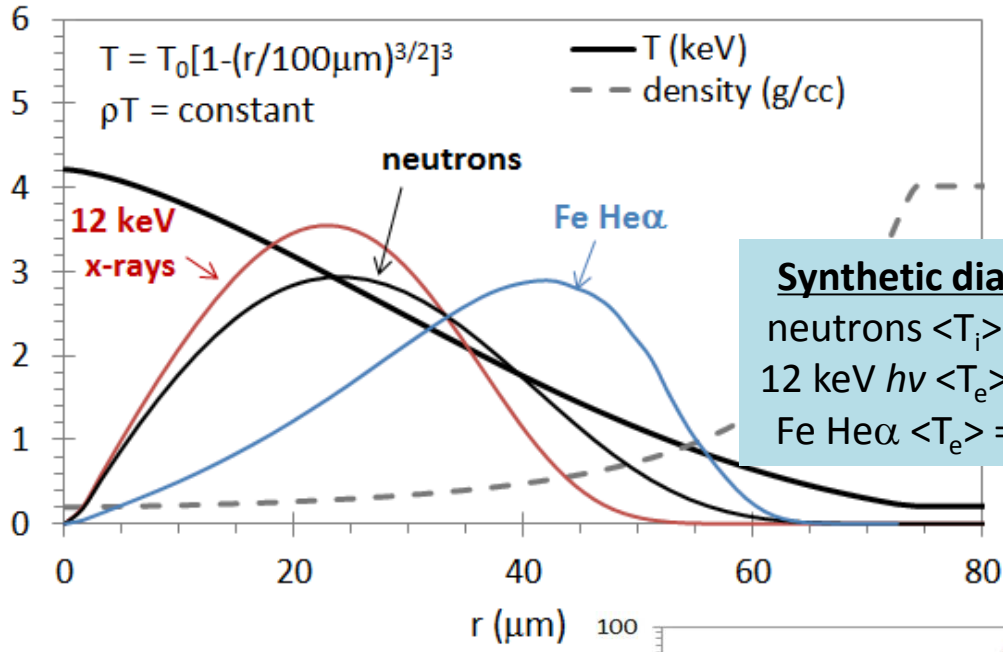
ρ_D = 0.33 g/cm^3

T_e = 1.8 keV

T_i = 2.3 keV

ρR_{liner} = 1.1 g/cm^2

Isobaric model* fits diagnosed Ti/Te



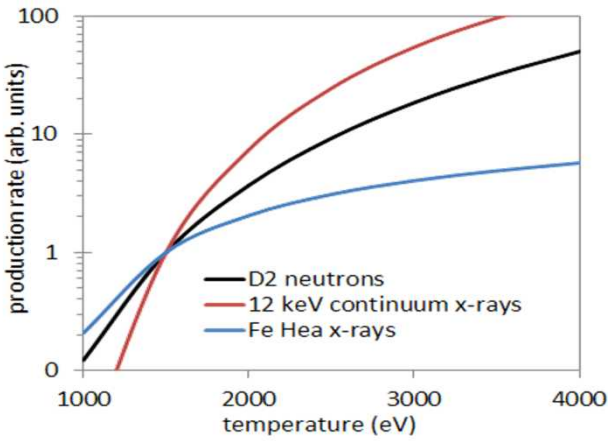
Synthetic diagnostics

neutrons <T_i>= 2.5 keV

12 keV *hv* <T_e>= 3.1 keV

Fe Heα <T_e> = 1.7 keV

High-energy (12-15 keV) continuum x-rays sample hotter portions of the plasma than Fe line emission (and even D-D neutrons)



*Springer et al., *EPJ Web of Conferences* **59**, 04001 (2013), and S. Hansen et al., Phys Plasmas (2014).

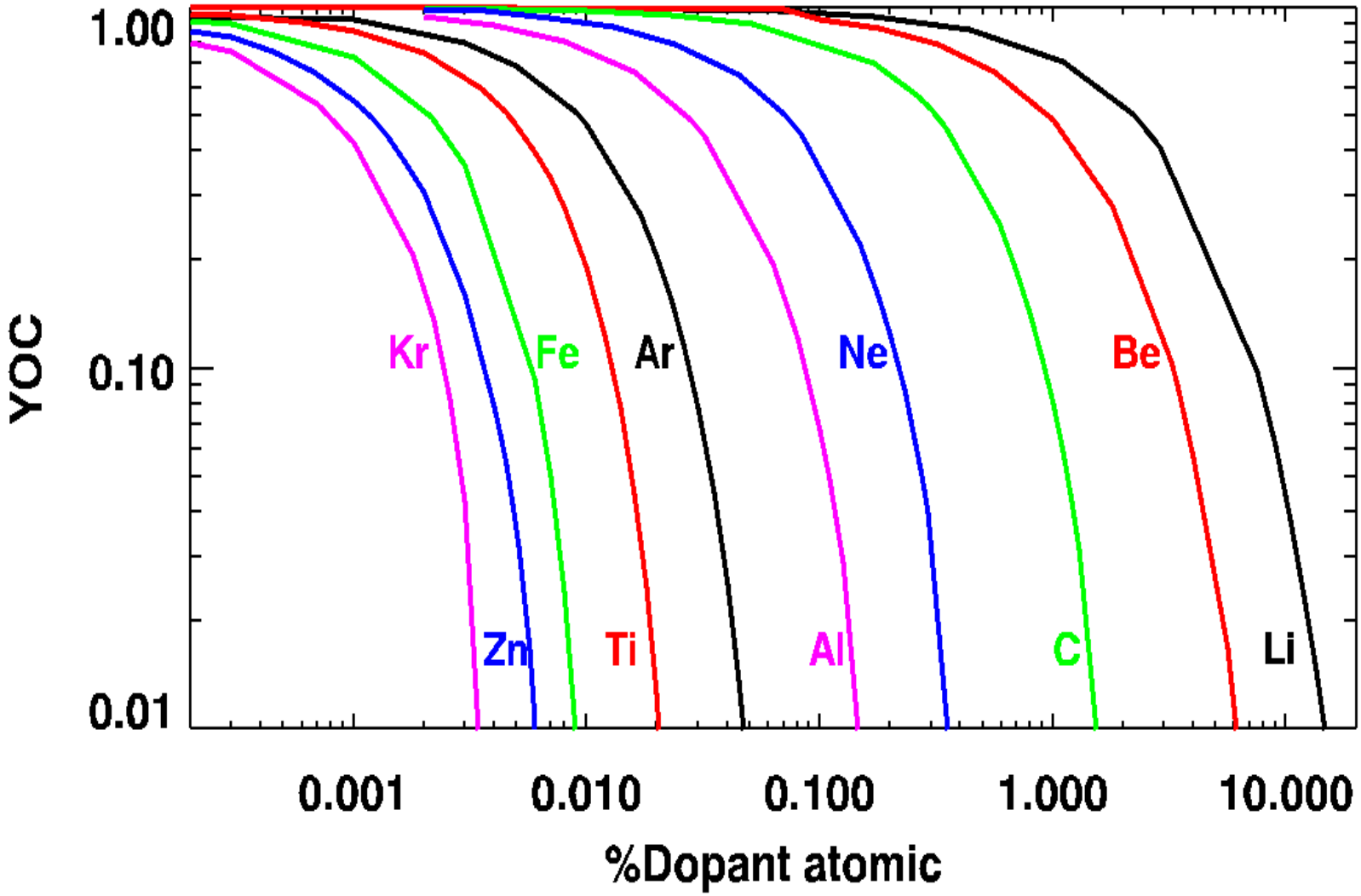
Stagnation data can constrain preheat energy and mix

- Neutron yields are highly sensitive to initial preheat energy (Slutz, Sefkow, Peterson, McBride) and radiation losses from mix (Slutz/McBride)
- Spectroscopy constrains mix (Be from Fe on XRS3; Al from Zn on CRITR)

Window thickness (μm)	Preheat energy (J)	Endcap mix (%)	Window mix (%)	Liner mix (%)
3.5	150	0.05	0%	1%
3.5	300	0.05	5%	1%
1.5	150	0.10	0%	1%
1.5	300	0.15	5%	1%

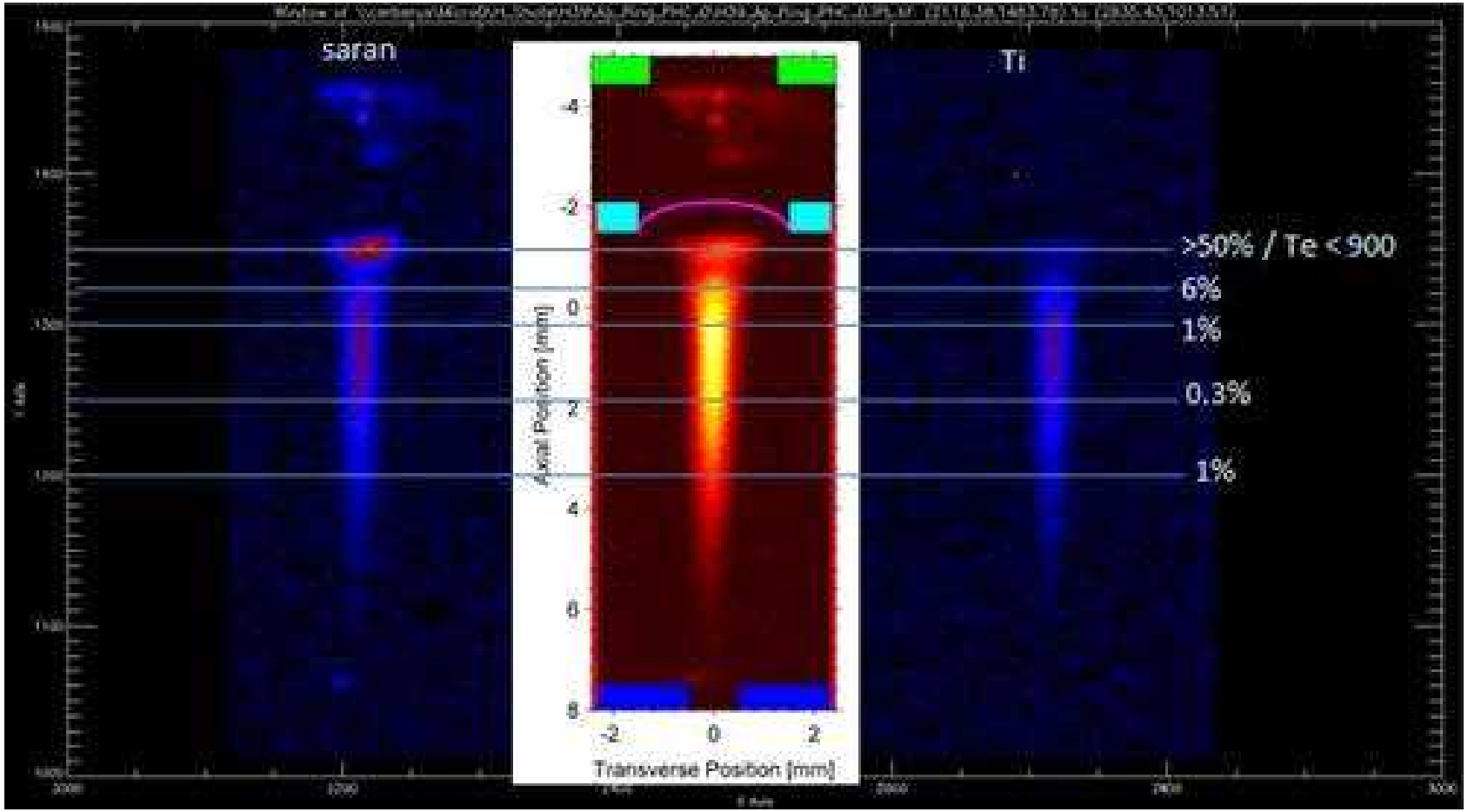
- Fitting yields from a very simple model to data from shots with Al & Be endcaps (and unconditioned beams) constrains preheat energy and mix
- Assumes that for a given laser energy and window thickness, the preheat energies and mix fractions must be the same regardless of endcap material
- Endcap mix fractions consistent with measured yields increase with laser energy under several plausible scenarios

Yield degradation from mix (LTE?)



Steve Slutz

Evidence for window mix from laser-only shot (H39)



- The ratio of TIPC intensities behind saran/Ti filters is sensitive to carbon fraction (which increases continuum over Ar line emission)

How can we measure window mix?

- Characteristic X-rays may be the only way we can track material
- Flash-coat window/endcaps? (Harding)
- Late-time measurements seem possible even with 160 J of preheat energy; earlier time require dedicated targets
- With 500 J of preheat, temperatures support high-energy emission that could escpar liner