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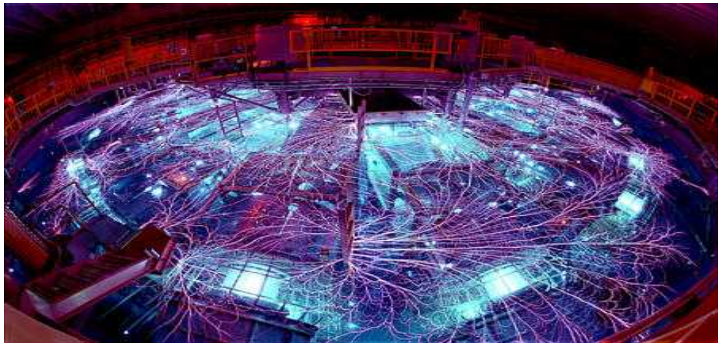

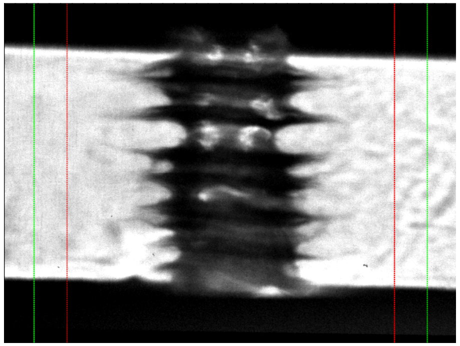

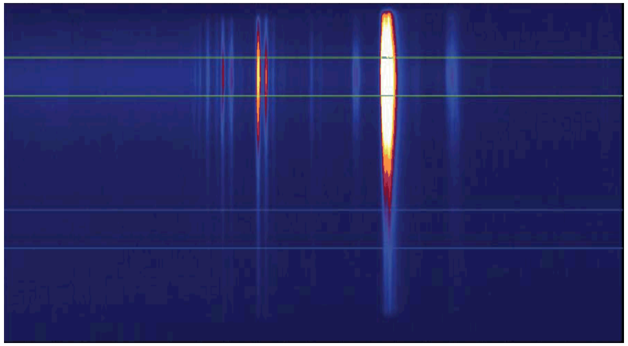

High Energy Spectroscopy for ICF on Z: Time Gated High Energy Radiation Spectrometer (TiGHER)

Patrick Knapp

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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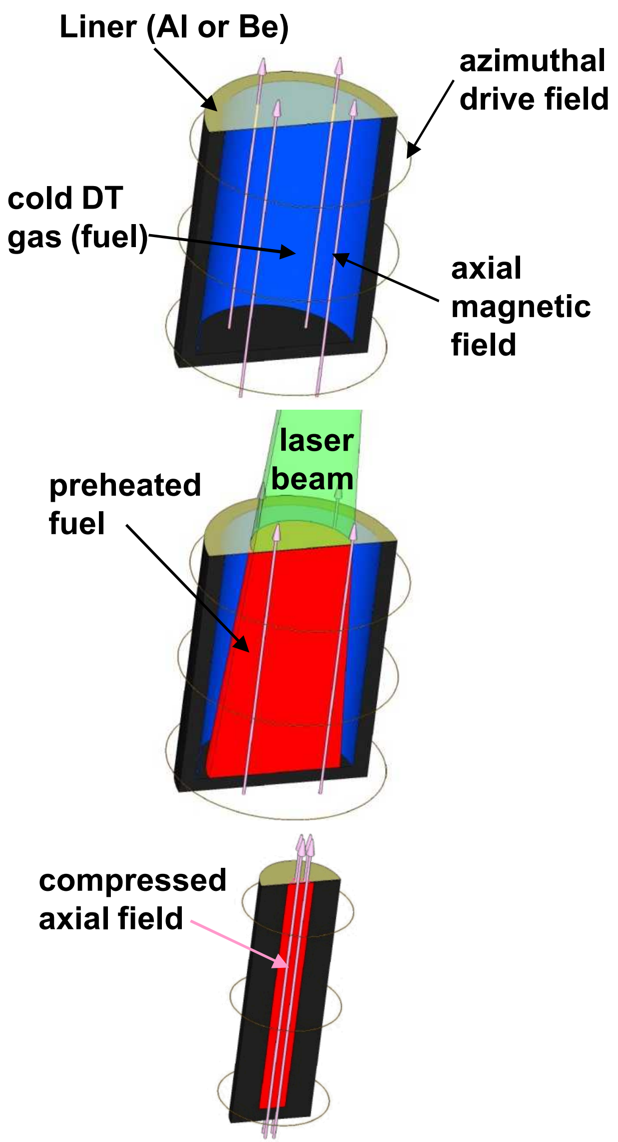
Outline

- Motivation and Needs
- Instrumental Requirements
- Preliminary Design
- Major Risks
- Conclusions and Ongoing Work

This diagnostic is a direct result of the Z gaps workshop

- High energy X-ray spectroscopy directly addresses at least 4 needs in the ICF program
  - 2.2.1.2. Ion and electron temperature of the burning plasma
  - 2.2.1.4. Density and rho-r of the burning plasma
  - 2.2.1.1. Burn history
  - 2.2.1.3. Spatial extent of the burning plasma
- Additionally, the RES program has several needs that we can help meet (probably can’t meet ALL requirements)
  - 3.1.1.5. Time- and space-resolved spectral line shapes with high spectral resolution
  - 3.1.1.9. Spatial structure of bright-spot generation in z-pinch implosions
  - 3.1.1.10. Fine-scale structure of K-shell line generation

We are working toward an evaluation of a new Magnetized Liner Inertial Fusion (MagLIF)* concept

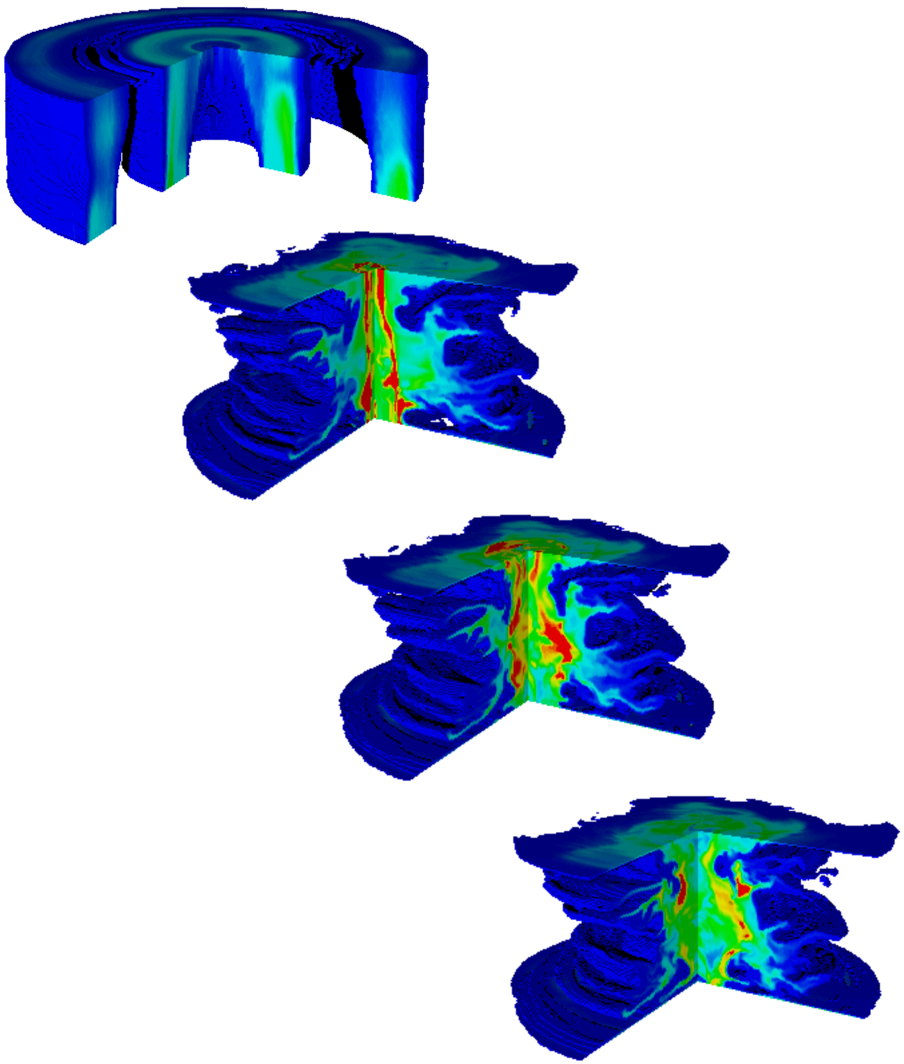


- Idea: Directly drive solid liner containing fusion fuel
- An initial ~10 T axial magnetic field is applied
  - Inhibits thermal conduction losses
  - Enhances alpha particle energy deposition
  - May help stabilize implosion at late times
- During implosion, the fuel is heated using the Z-Beamlet laser (<10 kJ needed)
  - Preheating reduces the compression needed to obtain ignition temperatures to 20-30 on Z
  - Preheating reduces the implosion velocity needed to "only" 100 km/s (slow for ICF)
- Simulations suggest scientific breakeven may be possible on Z (fusion yield = energy into fusion fuel), which is about 100 kJ

* S. A. Slutz *et al.*, "Pulsed-power-driven cylindrical liner implosions of laser preheated fuel magnetized with an axial field," Physics of Plasmas 17, 056303 (2010).

D2 Gas Puff is an attractive neutron source

- $3x10^{13}$ neutrons at 17 MA*
- Expected to do better than 10^{14} at 26 MA
- Many design variations to test
  - B Field
  - Gas density profile
  - Central jet
  - Etc.
- Need good diagnostics to assess impact of changes
- Want to assess viability of scaling for neutron RES

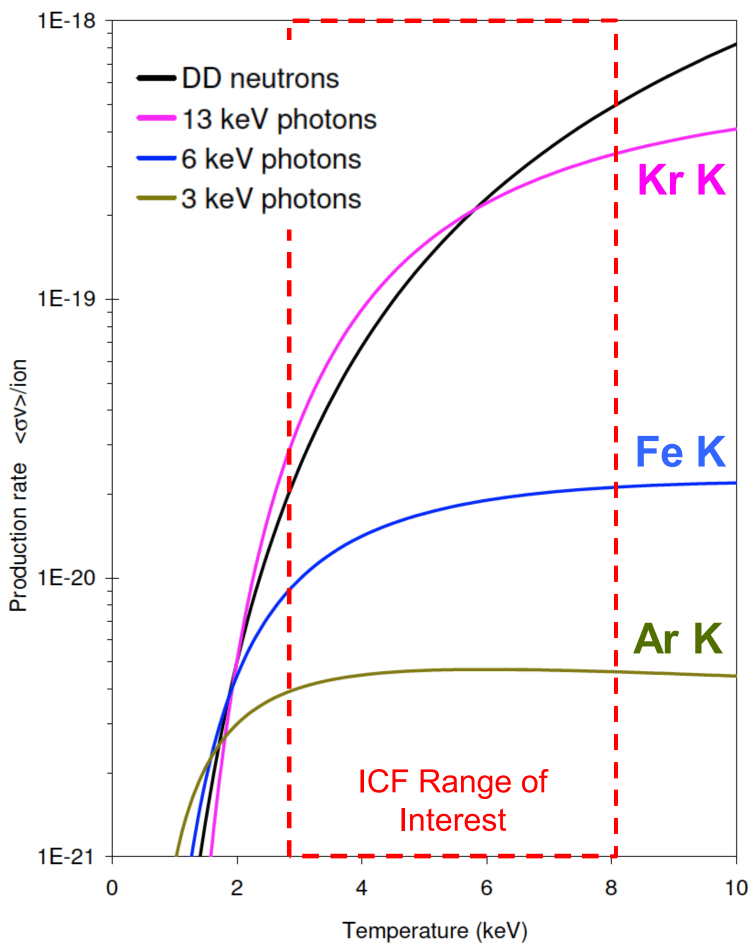


3D GORGON simulations (C.A. Jennings)

* C.A. Coverdale et al., Phys. Plasmas, 14, 056309 2007 and 14, 022706 2007

Kr is an ideal dopant for measuring thermonuclear conditions in ICF Experiments

Photon and Neutron Production Scaling



- Kr K-shell production scales well with DD neutron reactivity – Surrogate for burn
- K-shell production rate very sensitive function of T_e – sensitive to gradients
- 13 keV photons easily escape thick liner
- K-α production sensitive to beams
- K-shell production sensitive to thermal conditions

Kr is ideally suited for measuring quantities like $P\tau$, burn region dimensions and distribution as well as burn duration

*Figure courtesy Dr. Stephanie Hansen

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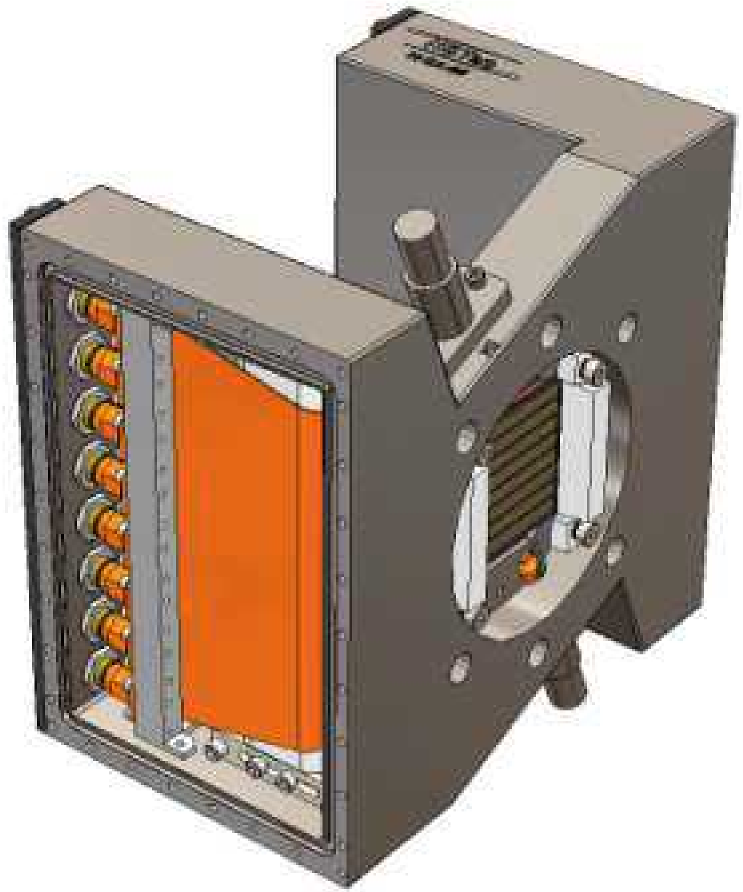
Detector technology has already been selected in order to facilitate design process

- Will use Gen II MCP*
  - We have lots of experience
  - Existing infrastructure
  - Flat gain response
  - Understand performance at low energy
  - 8 frames gives reasonable record length
- Motivated primarily by schedule and cost
- Ongoing effort to assess performance
  - At high photon energies
    - hν and θ dependent response (sensitivity, gain, dynamic range)
    - hν and θ dependent resolution
    - Preliminary data suggests Δx = 100 – 200 μm at detector
  - In Z shock and radiation environment

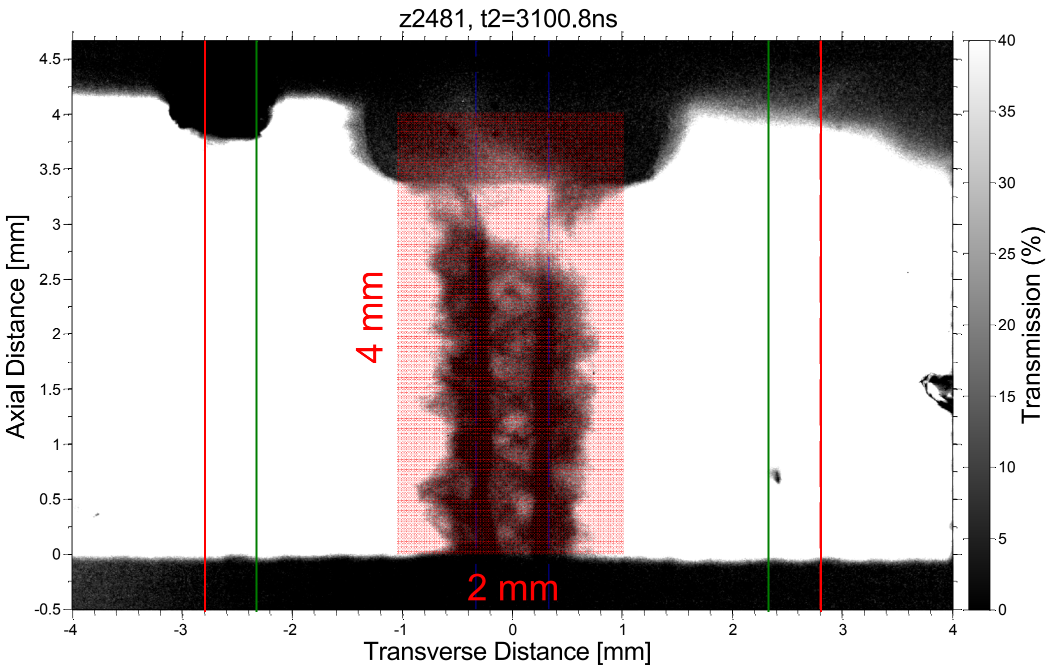


* Credit? Reference?

Field of View and Spatial Resolution are heavily constrained by detector technology

- Strip-lines are 4 mm tall
- effective resolution gives 20 – 40 resolution elements per strip
- Magnification determines FOV AND resolution
- Axially Resolved
  - 4-6 mm FOV
  - Requires M<1
  - Resolution ~ 200 – 400 μm
- Radially Resolved
  - ~2 mm or less
  - Requires M >2
  - Resolution < 100 μm

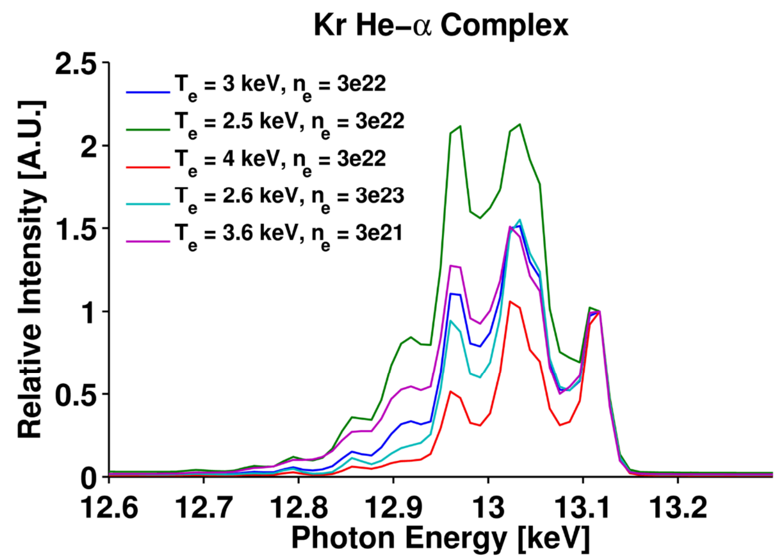
Experimental radiograph from a MagLIF liner, B_o = 10 T, taken at CR=7

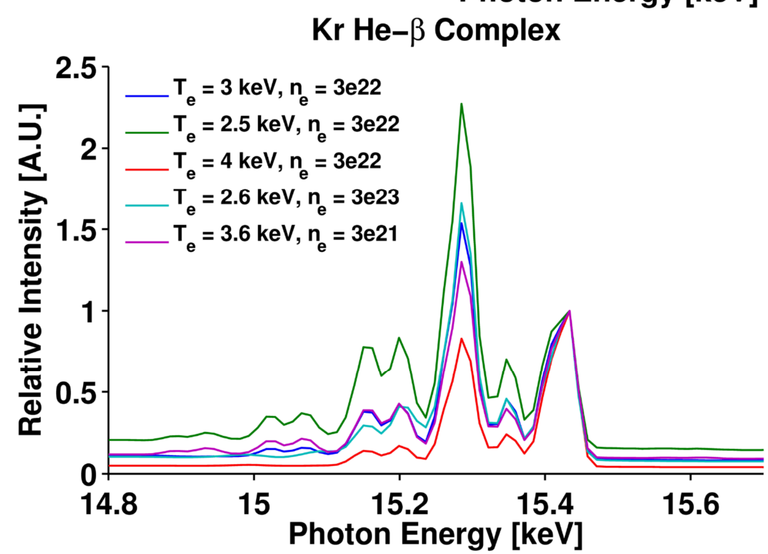


Courtesy Dr. T.J. Awe

Temporal and spectral requirements are motivated by calculations and experiments

- Temporal Requirements
  - Resolution < 1 ns (250 ps demonstrated)
  - Record length > 5 ns (detector has 8 frames)
- Spectral Requirements
  - Modeling done Using Scram□
  - Spectral resolution $\lambda/\Delta\lambda$> 600 to resolve T_e and n_e sensitive features
  - Able to simultaneously record Br K-α (11.9 keV) to Kr He-β (15.4 keV)
    - Near term Kr gas is ideally suited for D_2 gas
    - For future high-gain MagLIF* concept, levitated shell wicked foam can use Br dopant (cryogenic)





*S.A. Slutz and R.A. Vesey, Phys. Rev. Lett. (2012).

□S.B. Hansen

What measurement accuracy do we need to improve meet our objectives?

- MagLIF is a new concept, we need to be able to measure progress and quantify effects of target changes (i.e. preheat energy, Bo, liner material, pulse shape, etc.)
- We are not looking for few % level model validation
- T_e ~±20% - strong temperature dependence of K-shell lines
- n_e ~ 3x - Density dependence is fairly weak
- Remember
  - the purpose of this instrument is not simply to measure conditions
  - We want to measure
    - where those conditions are
    - How they are distributed
    - How long they persist
- Success of this instrument is measured in multiple ways

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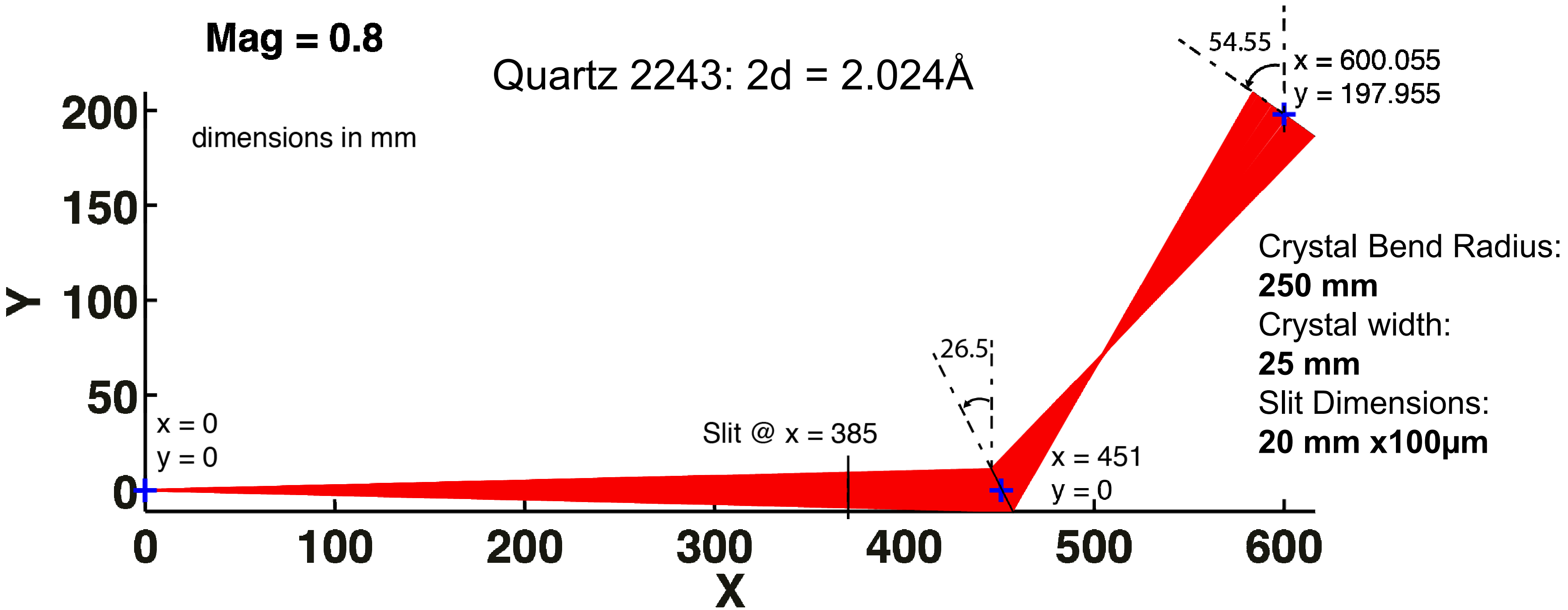
We have selected a Cauchois spectrometer with variable magnification



- Eliminates source broadening
- Efficient at high photon energies
- Simple alignment
- Flexible magnification
- Allows possibility to change crystal with only slight change in detector location
- We have lots of experience fielding, analyzing (CRITR)

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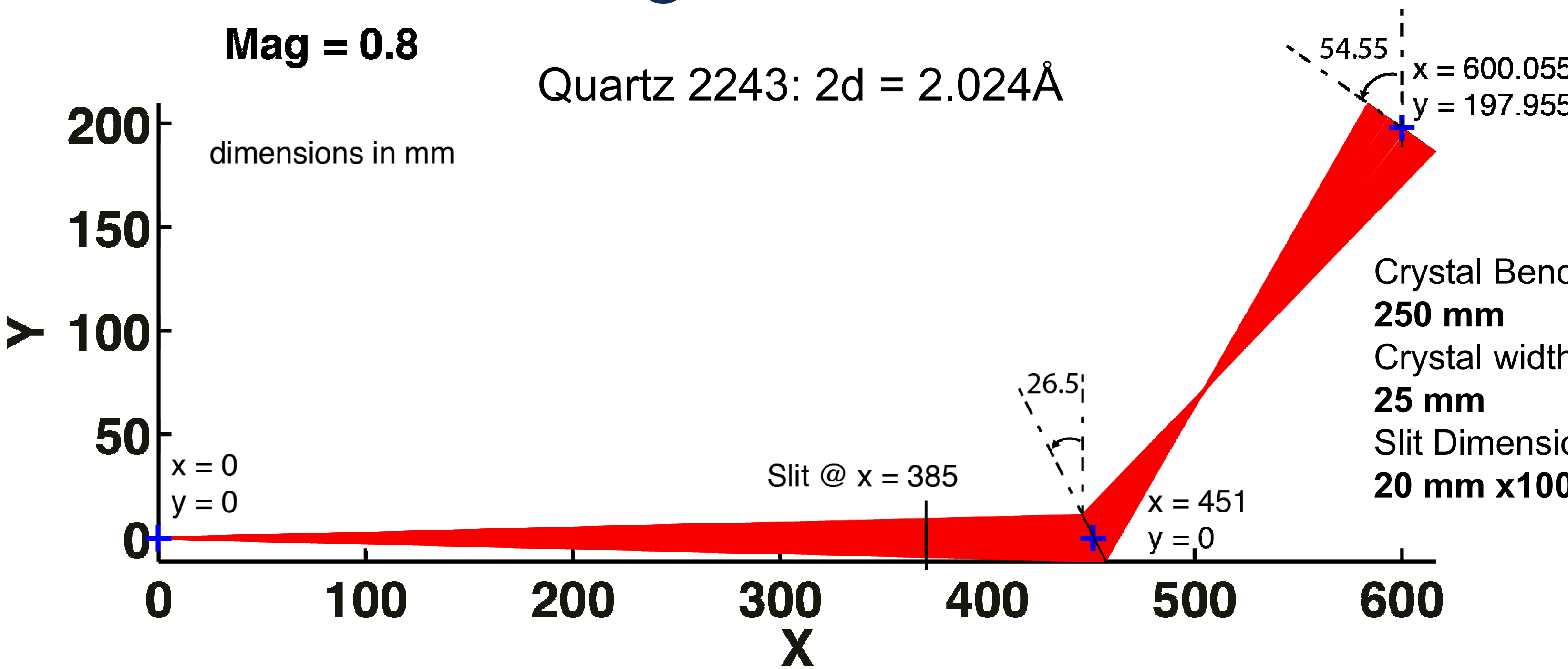


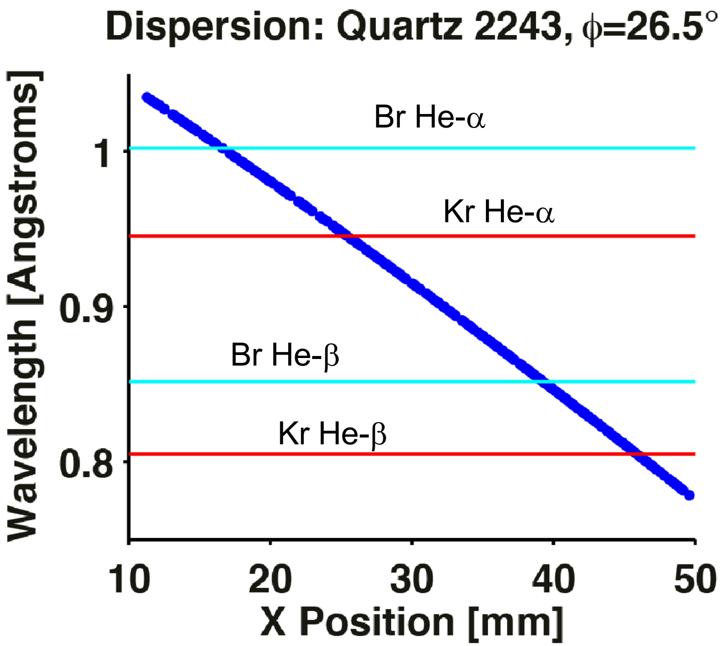
Crystal Bend Radius:
250 mm
Crystal width:
25 mm
Slit Dimensions:
20 mm x100μm

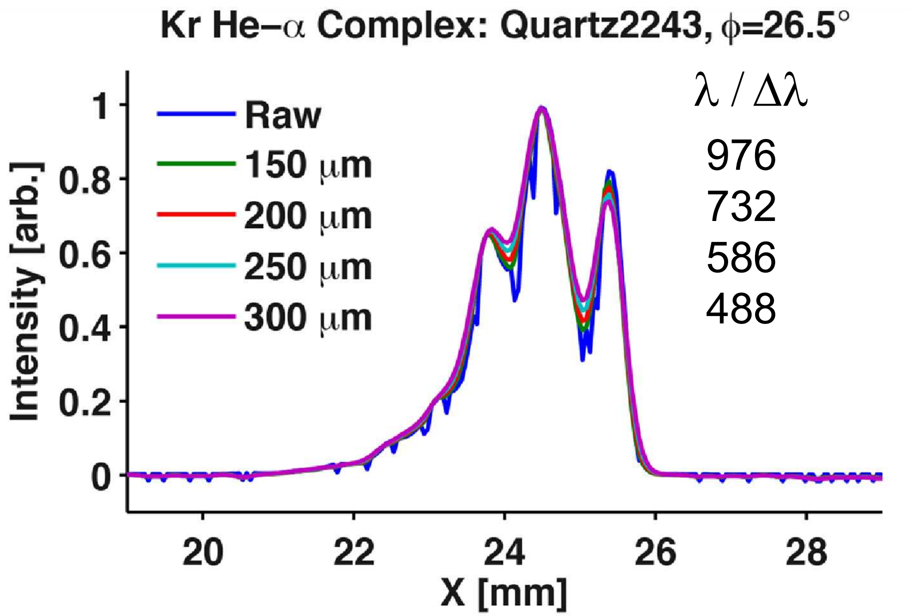
Mag.	X_{slit} (mm)	$X_{crystal}$ (mm)	FOV (mm)	Δx (μm)
0.35	770	800	11.5	570/300
0.5	590	650	8	400/200
0.8	385	451	5	250/125
1	350	451	4	200/100
2	230	451	2	100/50

Nominal Axial Configuration

Nominal Radial Configuration

Ray tracing used to determine spectral range and resolution



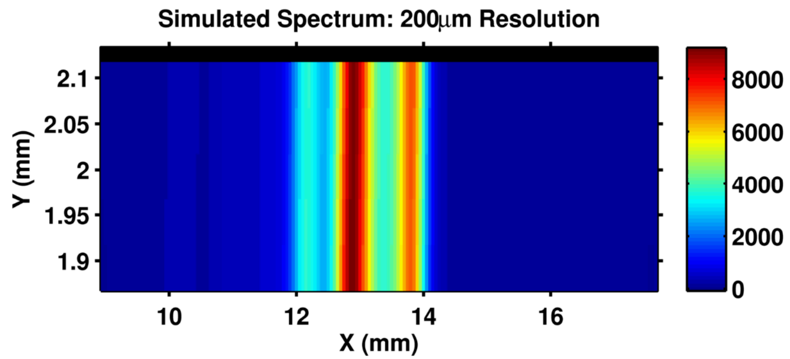


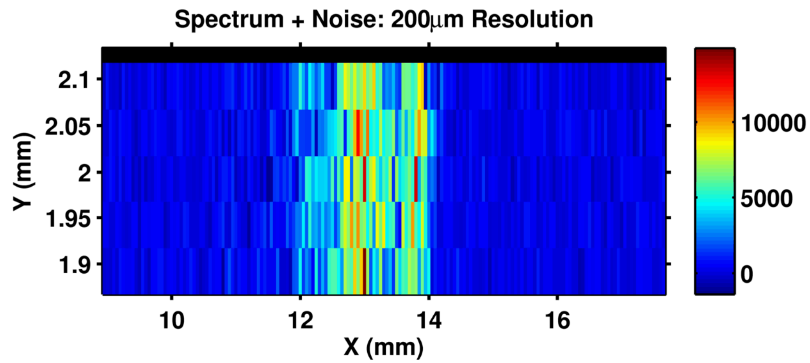
Features:

- Very nearly linear dispersion
- Covers Br K-α to above Kr He-β
- Desired resolution (> 600) is achieved with current detector (~200μm effective pixel size)
- Spectral resolution could be as high as 1000

Definition and Calculation of Signal to Noise Ratio

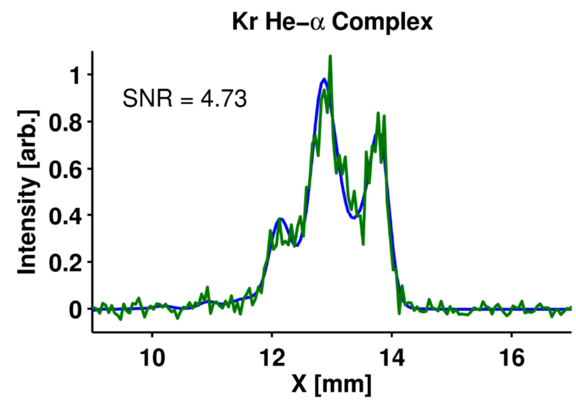
$$SNR = \frac{A_{sig}}{A_{noise}} = \frac{rms_{sig}}{\sigma_{noise}}$$





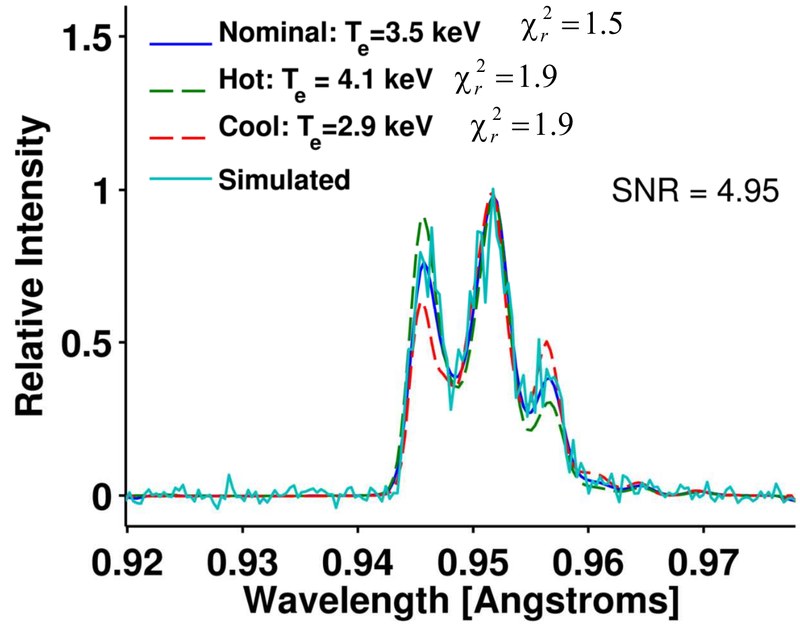
Calculating SNR:

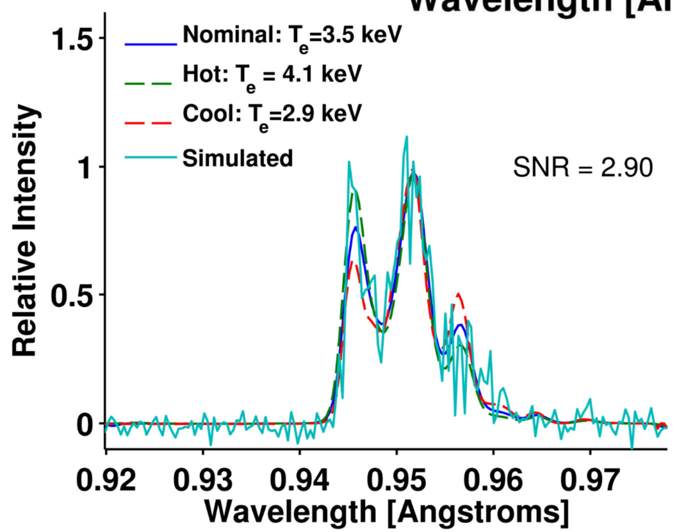
- Propagate spectrum through instrument (ray tracing)
- Blur detector according to effective resolution (crude approximation of MCP behavior)
- Add Gaussian distributed noise ($A \propto \sqrt{N}$)to detector at the true pixel level
- Average over appropriate number of detector pixels to acquire actual spatial resolution



Preliminary noise tolerance assessment

- Our desired measurement accuracy is ±20% in T_e
- Current analysis using only He-α complex suggests SNR=5 will give good confidence in the fit
- Less (SNR ~ 3) may be tolerable
- Use of He-β may improve confidence
- Analysis for density dependence in progress





Conceptual Instrument Design

- Hardware design is in progress – many things still to learn
  - Shielding
  - Shock and debris mitigation
- Considering a multi-spectrometer instrument
  - 1 radial TiGHER
  - 1 axial TiGHER
  - 1 radial time integrated spect.
  - 1 radial time integrated spect.
- All in one body, conserves real estate
- Saves on alignment time
  - pre-alignment for each instrument
  - One alignment performed in chamber
- Very complicated

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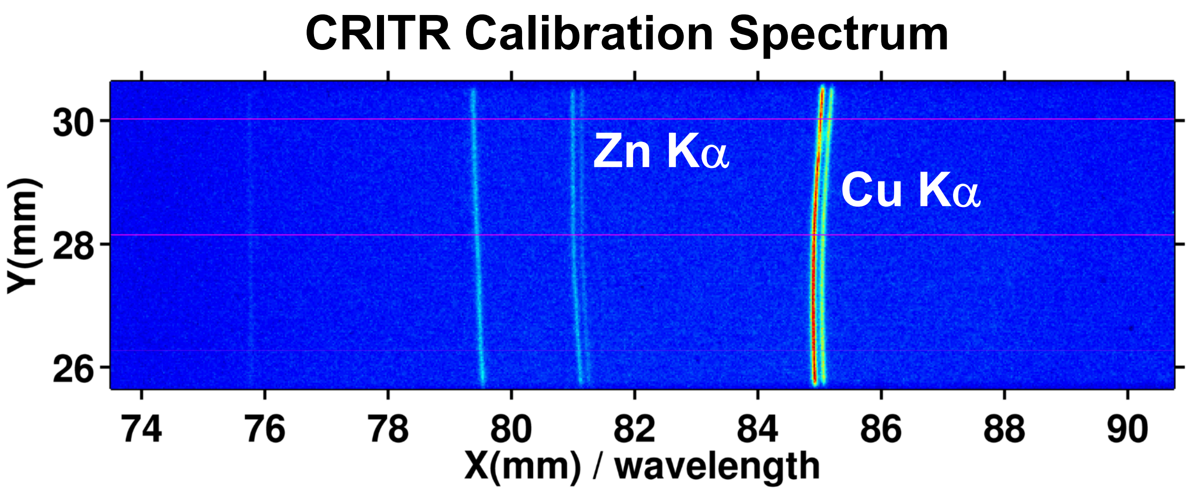
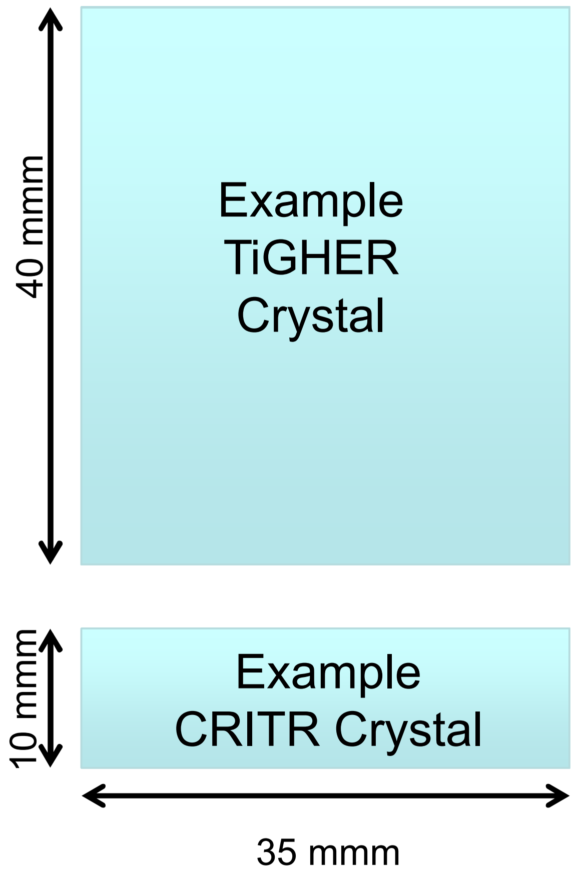
Crystal/Substrate system requires careful thought

- Crystal dimensions pose problems for uniform bending
  - Tile smaller crystals
  - Solid transparent substrate
    - Min. photon energy ~ 12keV
    - Can tolerate ~few mm of Be
- CRITR xtal is much smaller but we see defects in spectra

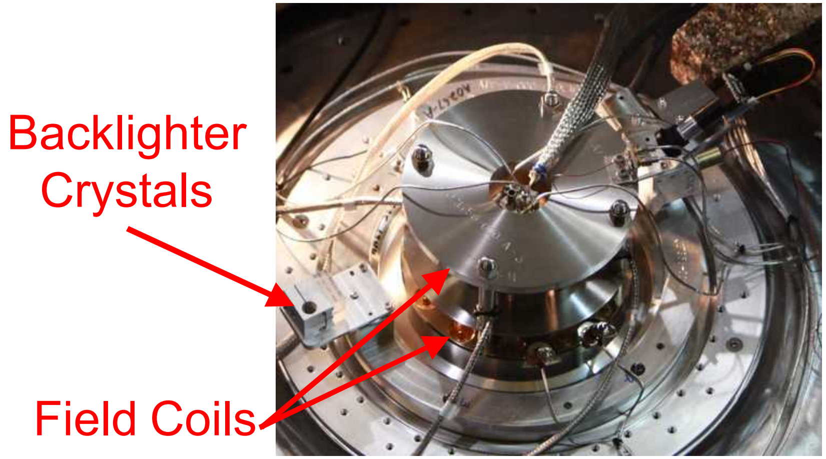


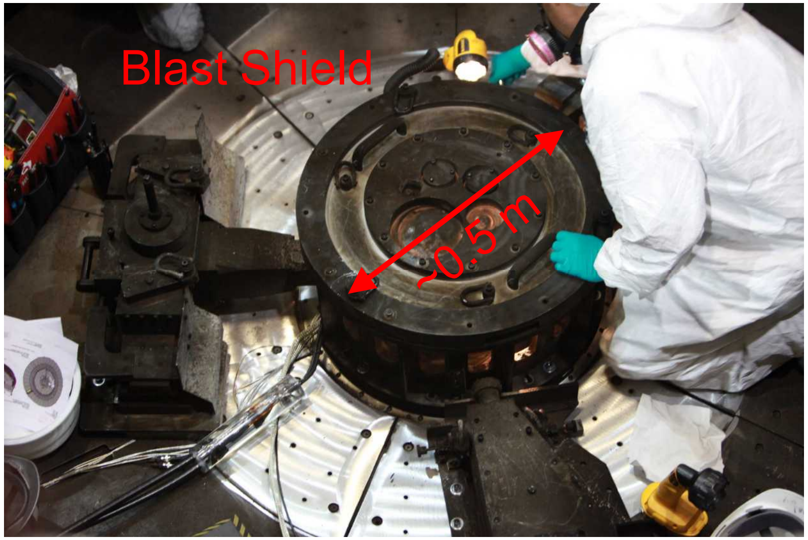


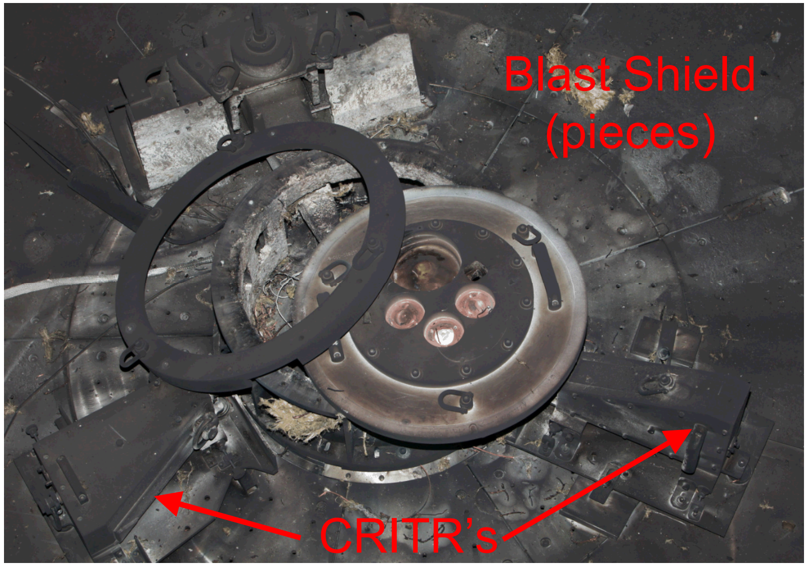
Mitigation of debris, shock damage and radiation are big risks on Z

Currently have a lot of uncertainty in the environment

- Have begun a concerted effort to make measurements relevant to each of these issues
- Modeling and measurements will be used to help mitigate effects
- Previous experience gives confidence we will be able to field this instrument (CRITR, gated radiography)







Pictures from first experiment with applied field coils

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Ongoing work

- Model MCP in instrument simulation
  - Need to learn more about MCP in range of interest
  - Realistic noise/gain/dynamic range information
  - Revisit SNR with more info.
- Photometrics
  - Again – need more MCP info
  - Also need measurements of crystal
    - Rocking curve, reflectivity, etc.
  - Assess what Intensities are needed to make measurements at specified SNR
- Couple instrument model to hydro-code outputs

Conclusions

- We have defined the requirements for a time-gated, space-resolved high energy spectrometer for ICF on Z
- We have outlined a preliminary design that meets these requirements
- Built in flexibility makes instrument useful over broad range of experiments
  - ICF – MagLIF, gas puff
  - RES (x-ray and neutron sources)