The Consortium for Enabling Technologies and Innovation

Virtual Summer Meeting for Young Researchers

Simultaneous imaging and ID of radioactive materials and devices

…from plasma physics & fusion to national security

Dr. Luis F. Delgado-Aparicio
Princeton Plasma Physics Laboratory

July 8th, 2020

National Nuclear Security Administration

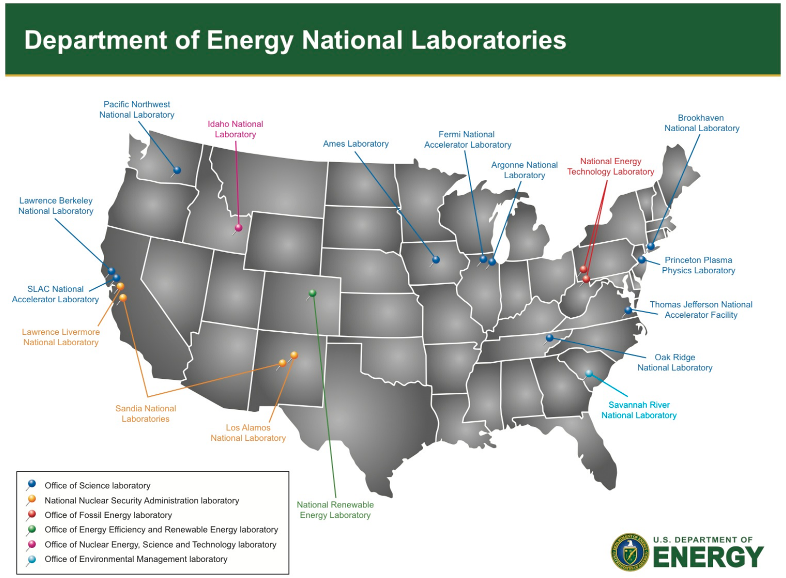
Acknowledgements to all my collaborators

P. vanMeter[2], E. Feibush[1], B. Stratton[1], D. Den Hartog[2], K. Hill[1], M. Bitter[1], N. Pablant[1], T. Barbui[1], O. Chellai[1], P. Efthimion[1], G. Ascione[1], J. Menard[1] and R. Goldston[1,3]

[1]Princeton Plasma Physics Laboratory, Princeton, NJ, 08540
[2]University of Wisconsin, Madison, WI, 53706
[3]Princeton University, Princeton, NJ, 08540

Princeton University Plasma Physics Laboratory (PPPL)

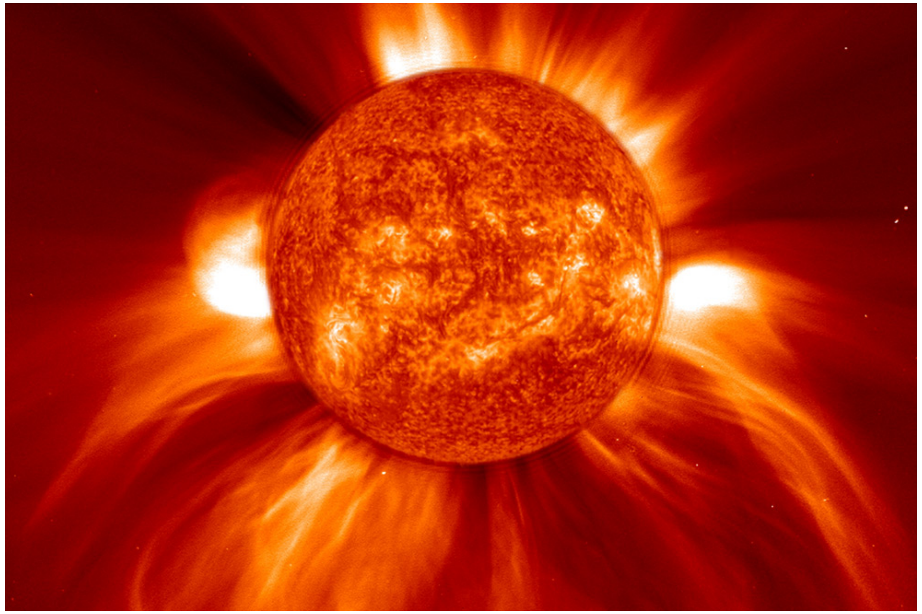
- PPPL is one of 17 DoE national laboratories.
- We are managed by PU but have a government mandate that focuses on fusion energy research and basic plasma science.



Nuclear Fusion is an ideal alternative to solve the energy challenge – the sun's energy comes from FUSION

Fusion energy is:

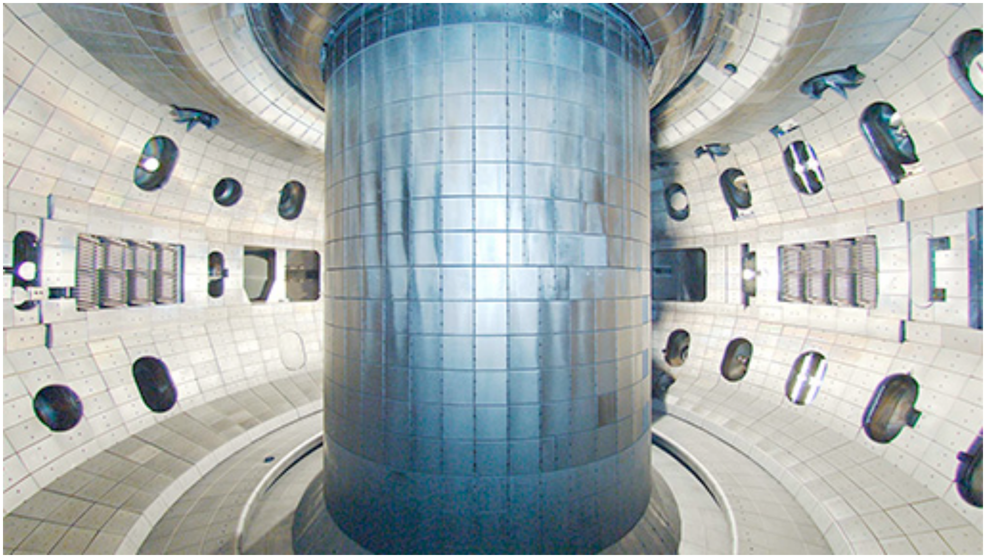
1. Clean
   - No greenhouse-gas production
   - No smog and no acid rain
   - Only short-lived radioactive wastes (due to neutron bombardment of vessel material)
2. Safe
   - No possibility of runaway "chain" reaction/meltdown
   - No proliferation threat (not a credible bomb factory)
3. Nearly inexhaustible (~10^9 year supply)
4. Efficient and independent of geographical location
5. In the future, available 24/7



When small hot ions combine (usually hydrogen: H, D, T) …. there is a lot of ENERGY produced!

ldelgado@pppl.gov

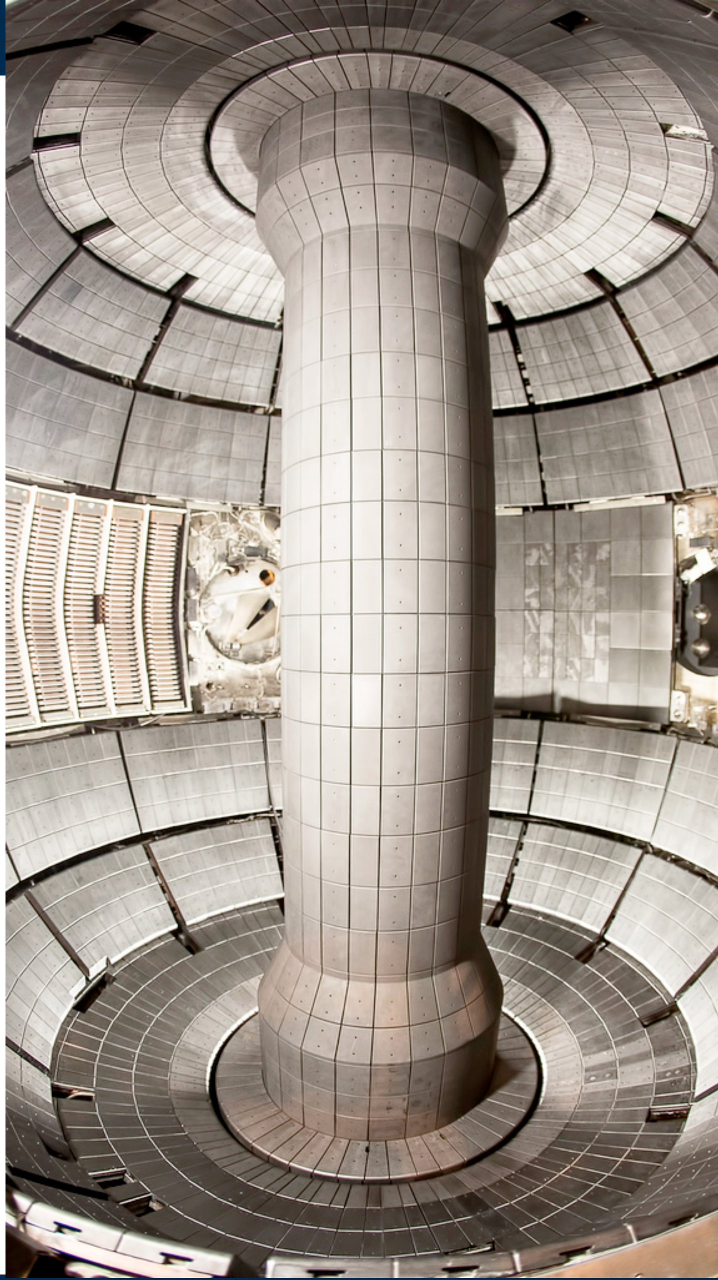
Main systems in the US are in General Atomics (CA), MIT (MA) & PPPL (NJ)



DIII-D in General Atomics, San Diego, CA

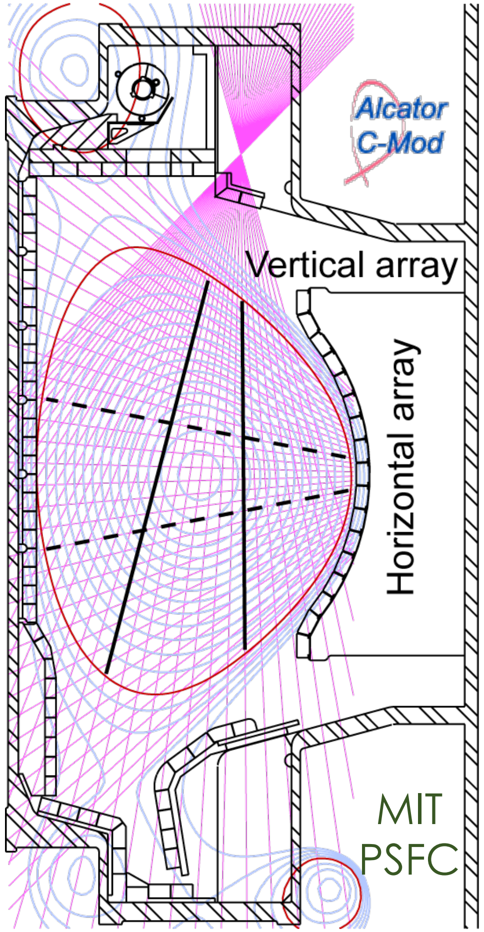
Alcator C-Mod @ PSFC, MIT, Cambridge, MA

$T_{e,0}$~1→6 keV (>10^6 °C)
⇒ naturally emits x-rays



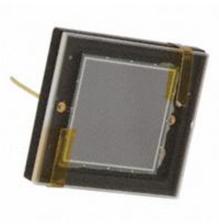
NSTX-U @ PPPL, Princeton University
Princeton, NJ

Conventional tomography integrates in photon-energy using a metallic filter & photodiode arrays



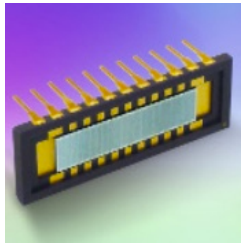
DIRECT EXAMPLES (e.g. Si)

AXUV-100

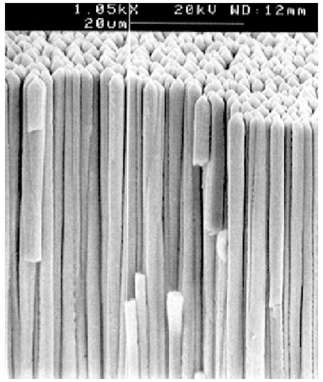


or

AXUV-20

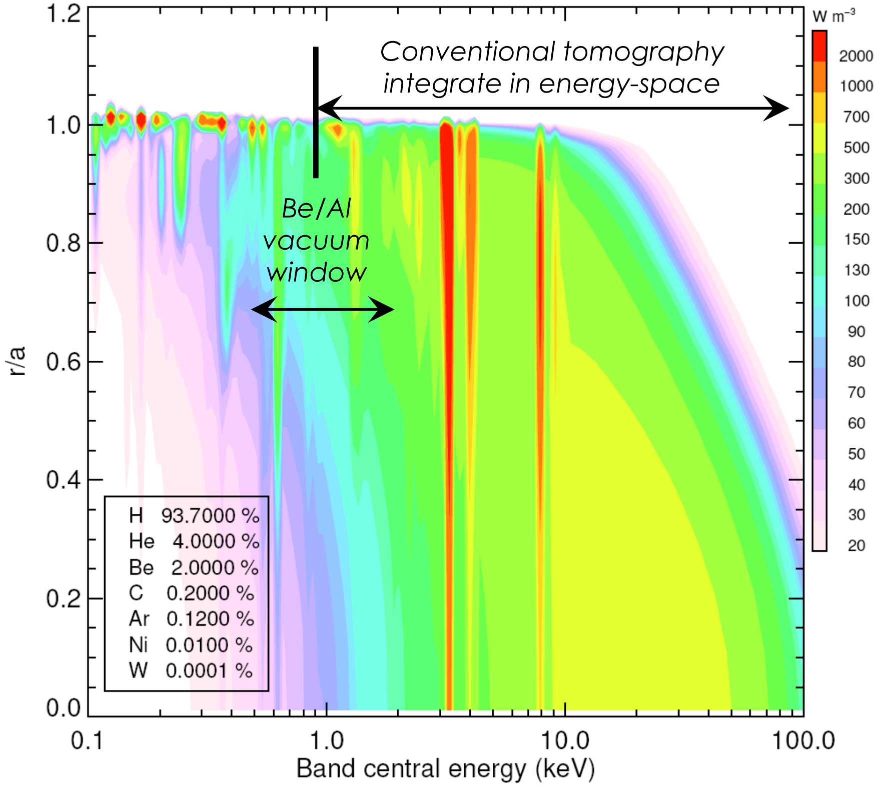


INDIRECT EXAMPLE (e.g. CsITl)

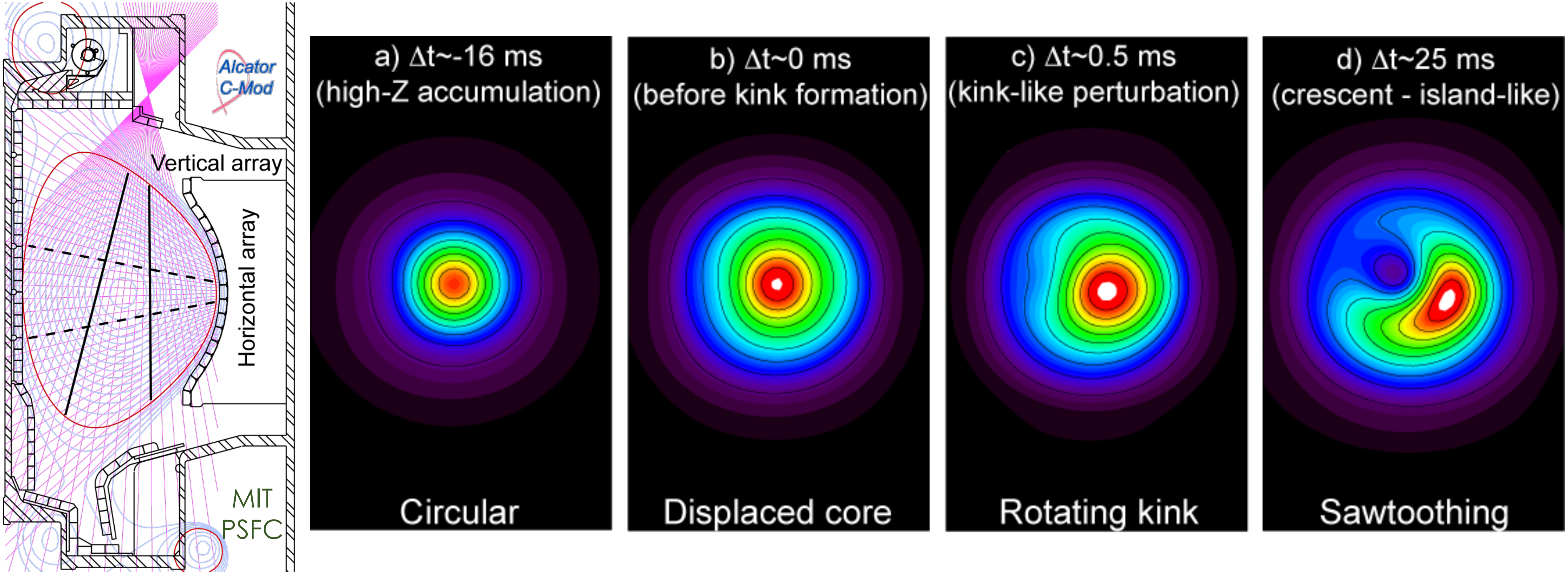


+ PMT and/or Si-diodes

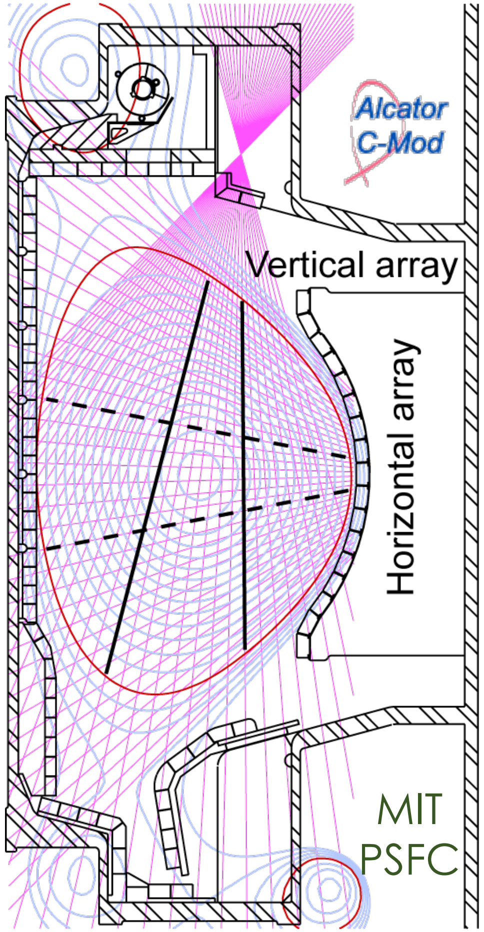
Example of spatially resolved soft & hard x-ray (SXR & HXR) spectra from ITER



Conventional SXR tomography is still being used for stability, MHD and transport studies



Its extremely difficult to extract plasma quantities from integrated emission using conventional tomography



Tomographic systems measure the line-integrated continuum & line-emission

Plasma variables

n_e: electron density
n_i: ion (H, D/T) density
n_Z: impurity density (He, B, C, O, Ar, Mo, W)
T_e: electron temperature
"Maxwellian" distributions $f(E_e/k_BT_e)$

θ-asymmetries as F[v_f: toroidal velocity, M_Z: ion mass]
(vertical or tangential views are needed)

L: Length of integration, θ: poloidal angle
(radial and poloidal coverage)

Energy response

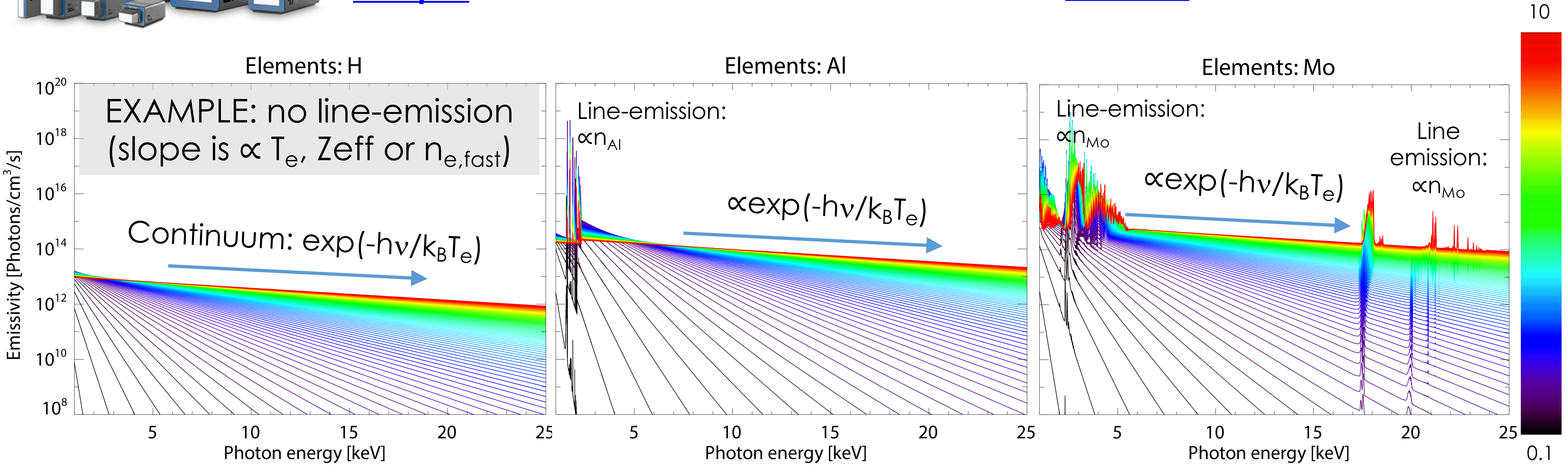
$T_{filter}(E_{ph})$: transmission function of filter
Detector response: $S(E_{ph})$

How to circumvent this difficulty ?

Novel x-ray detectors are able to take simultaneous images of the plasmas at different energy ranges

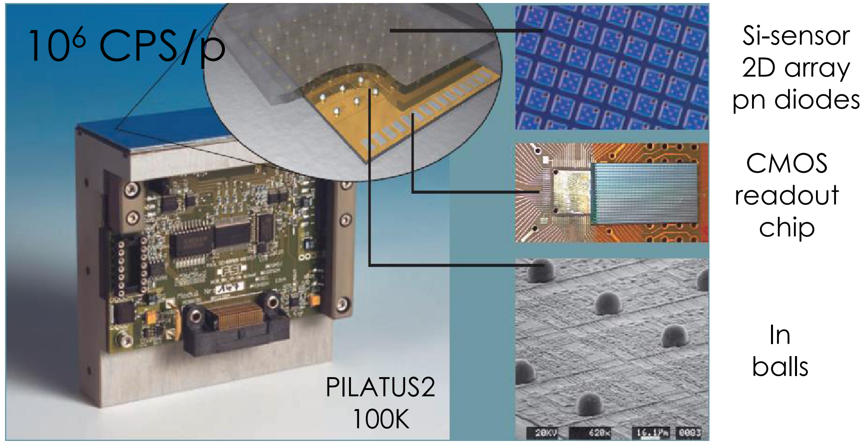
1) Obtain T_e, Z_{eff}, & $n_{e,fast}$ by ***sample*** the continuum-radiation

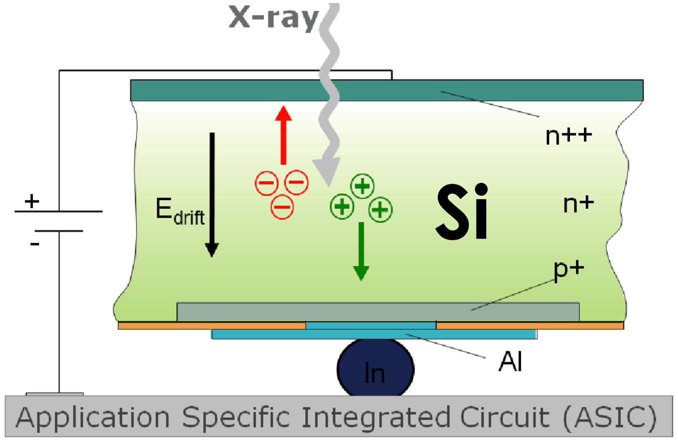
2) Obtain n_Z & ΔZ_{eff} by sample or ***bracket*** line-radiation

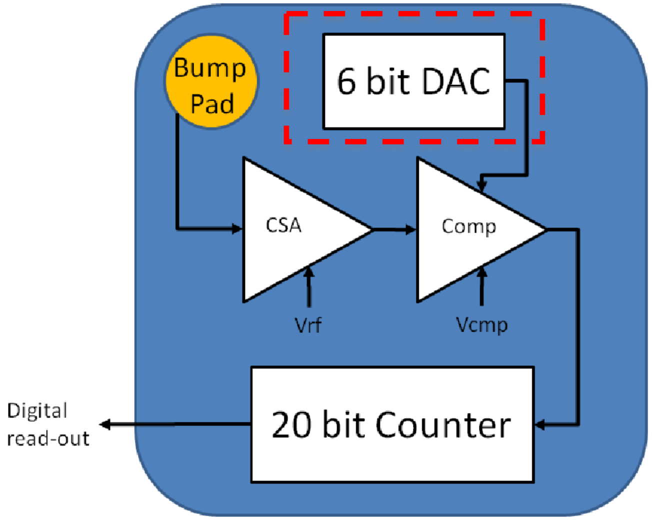


PILATUS detectors enable breakthrough of 100k pixels (minimum) working at multiple energy ranges!

Operates in single photon counting mode

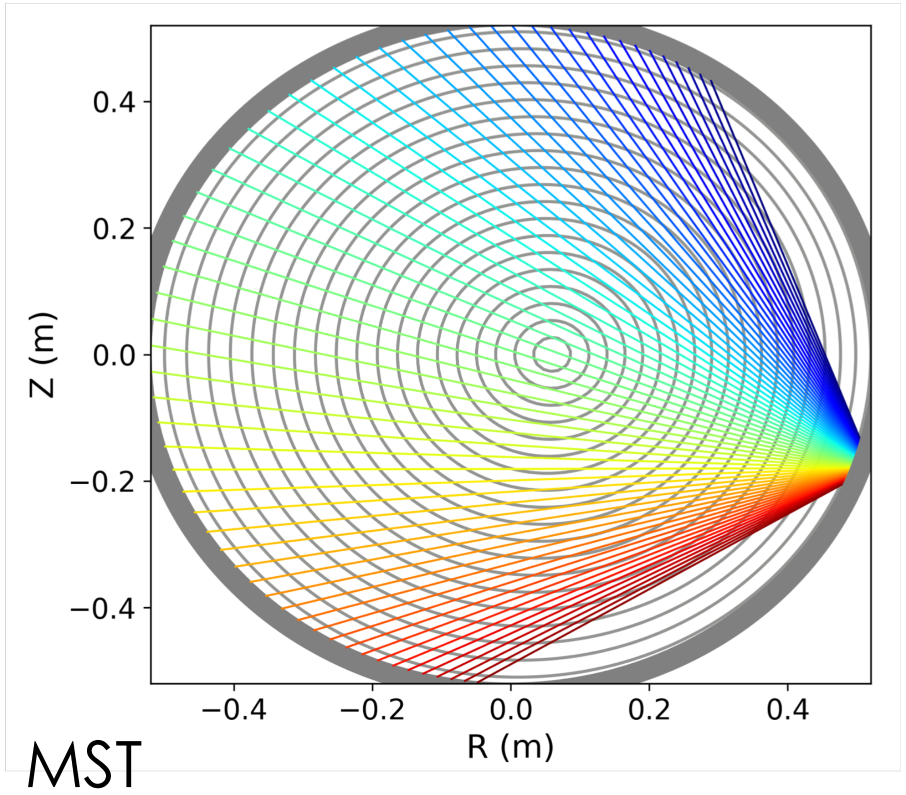




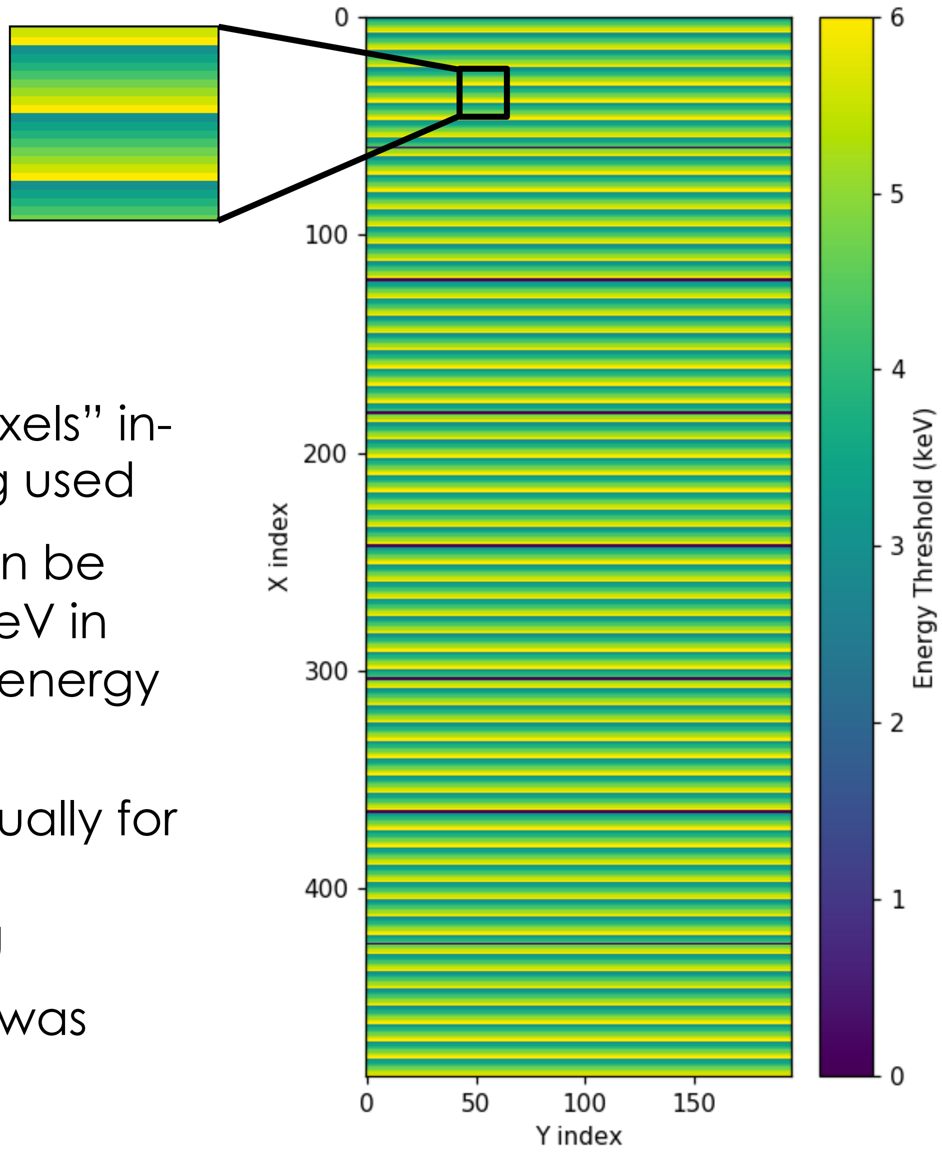


- CMOS hybrid pixel technology developed originally for synchrotrons
- The comparator voltage of the readout chip (V_{cmp}) controls the *global* threshold energy.
- The threshold energy can be individually *refined/trimmed* using a built-in 6-bits DAC (V_{trim}).
- Maximum frame rate is 500 Hz (1ms integration + 1 ms readout); 10^7 CPS/p for PILATUS3

Eight (8) "color" measurement at MST is possible using 60-chord photon detector



- 487 pixels vertically; 7-"pixels" in-between chips not being used
- 8-color measurement can be selected from 1.8 to 22 keV in low-, medium- and high-energy ranges
- Thresholds are set individually for each pixel adjusting the associated trimbit setting
- In-situ spatial calibration was done using Fe55 source

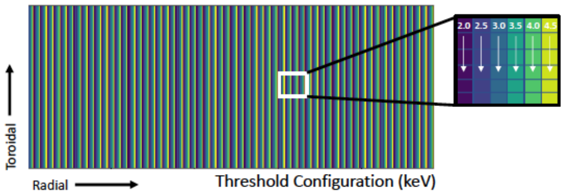


Diagnostic tested at UW-Madison has demonstrated unprecedented flexibility in the design of x-ray systems

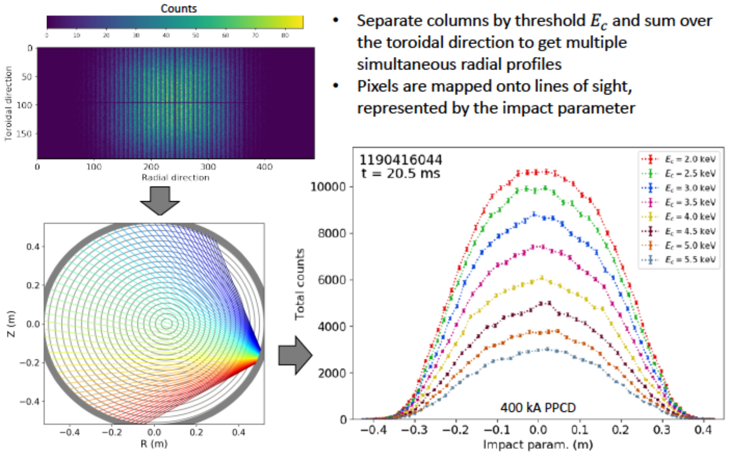
Configuration #1: Horizontal Stripes

Multi-energy high SNR 1D profile measurements

- Thresholds vary in the radial direction and stay constant in the direction of symmetry
- 8 repeating thresholds gives 60 effective lines of sight
- For MST this is a resolution of ~1 cm in the core



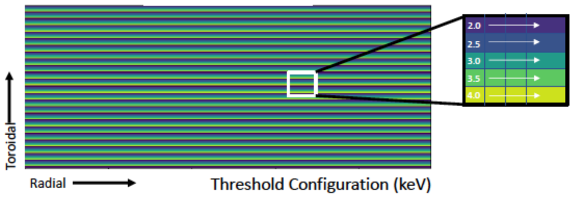
- Separate columns by threshold E_c and sum over the toroidal direction to get multiple simultaneous radial profiles
- Pixels are mapped onto lines of sight, represented by the impact parameter



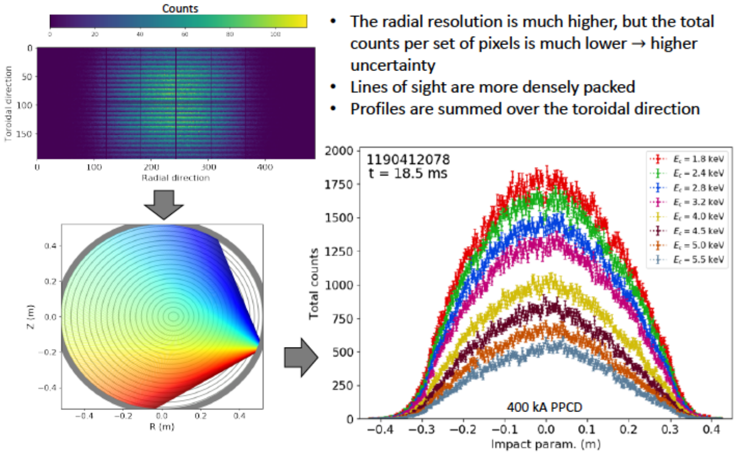
Configuration #2: Vertical Stripes

Multi-energy high resolution 1D profile measurements

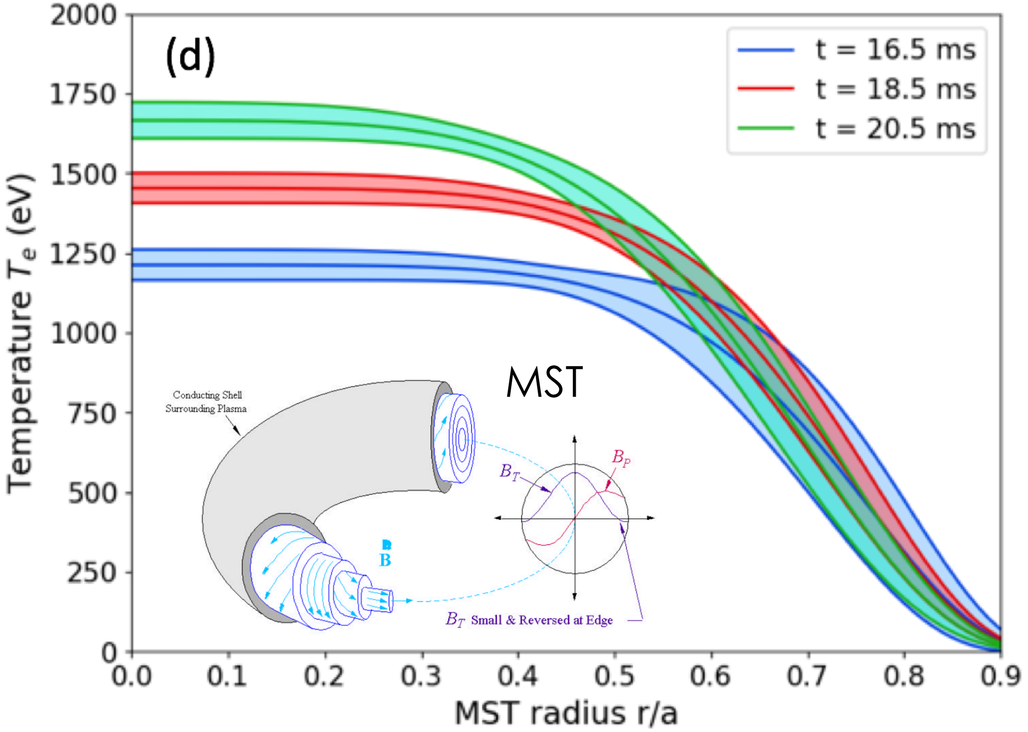
- Thresholds to vary in the toroidal direction and stay constant in the radial direction
- Improved radial resolution with 480 lines of sight, but lower total photon count
- Oversamples MST, but may be important in future installations



- The radial resolution is much higher, but the total counts per set of pixels is much lower → higher uncertainty
- Lines of sight are more densely packed
- Profiles are summed over the toroidal direction

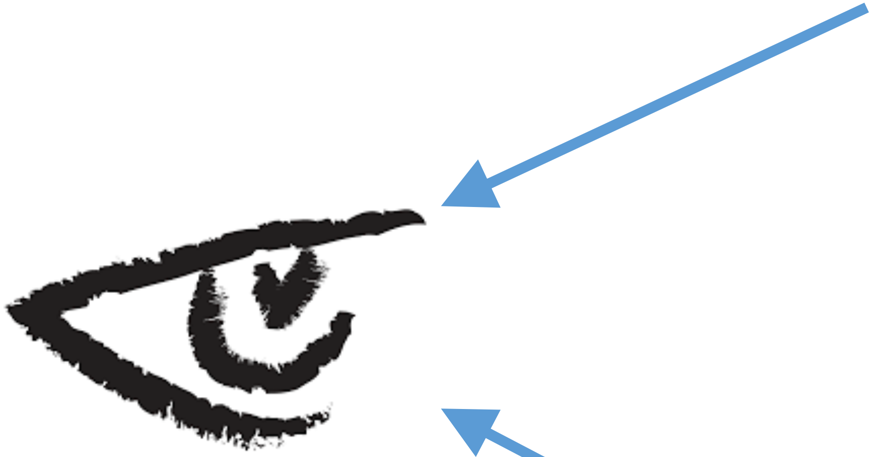


SXR-inferred $T_e(r,t)$ measurement @ MST (dr~1 cm and dt~1 ms)



Motivation for developing capability for simultaneous imaging and ID of radioactive materials and devices

Develop a 6D imaging concept that is capable of identifying the position (x,y,z), time-evolution (t) and nature of active radio-nuclei (intensity [I] ,energy [E]) which can be found or used in the medical field, physical and chemical sciences, military bases, decontamination sites, nuclear reactors and nuclear proliferation probes.



GOAL: Develop 6D technology (x,y,z,t,I,E)

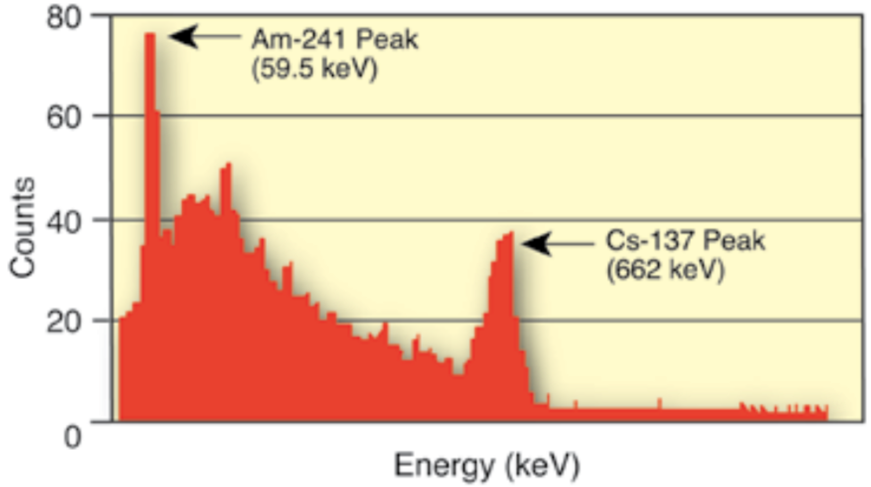
Special Atomic Demolition Munition

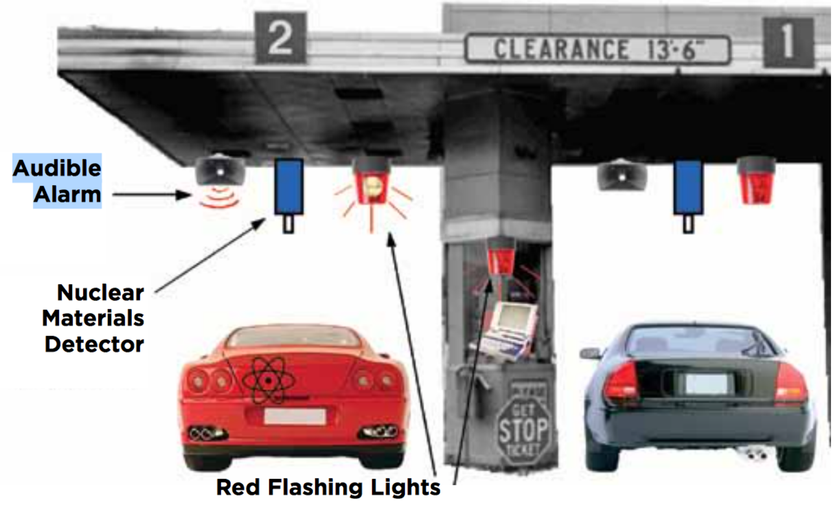
The 2D option (e.g. intensity, energy) was developed @ PPPL

Miniature Integrated Nuclear Detection System (MINDS)

- Three U.S. patents have been issued
- Licensed to InSitech
- Sub-licensed to VeriTainer Corporation
- Undergoing testing in Singapore
- Operational @ U.S. military base and rail @ bus commuter centers in the NE-US.

MINDS detection system consist of a scintillator, a PMT, an amplifier & a MCA

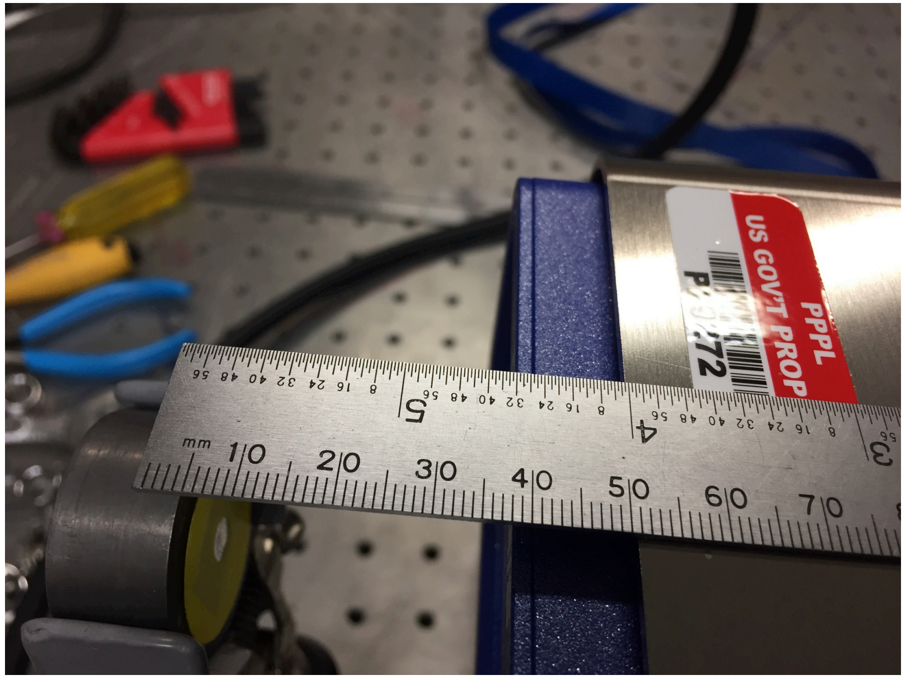




MINDS tollbooth application.

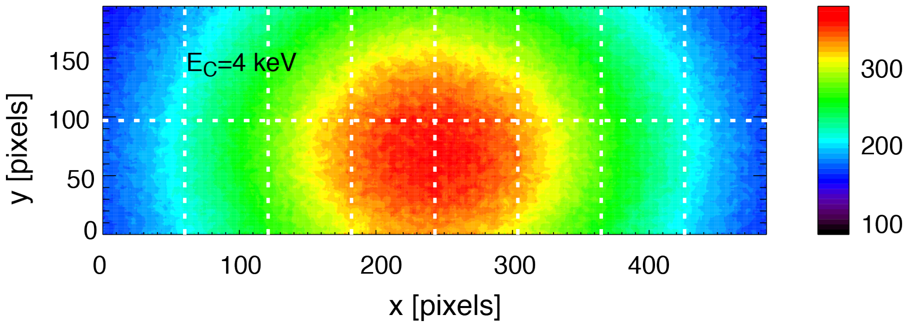
1st GOAL: Examine 4D (x,y,intensity,energy) option

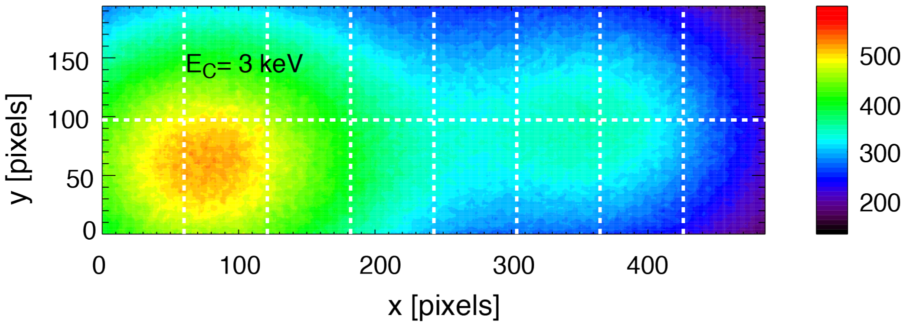
Test #1:
PILATUS3
+ Fe55



Test #2:
PILATUS3
+ Fe55 +
Am241

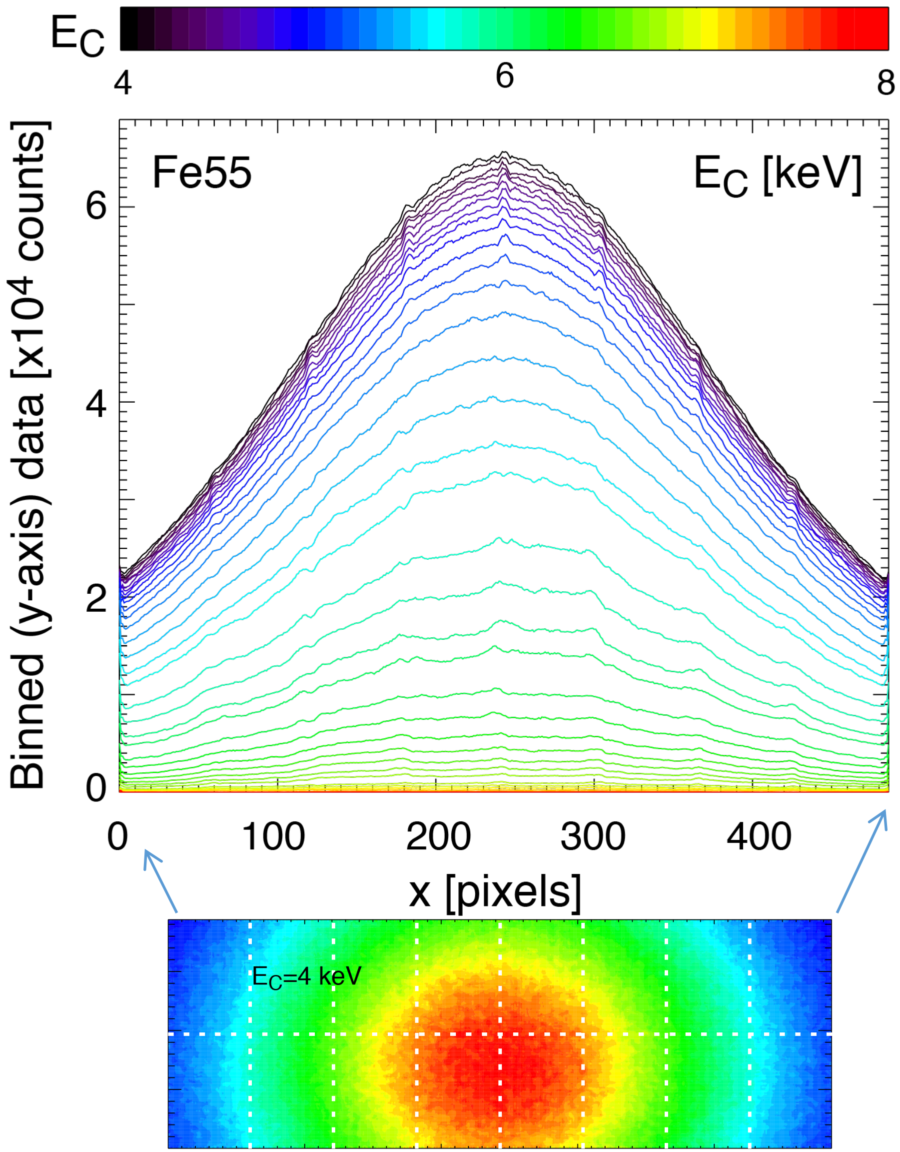
Fe55

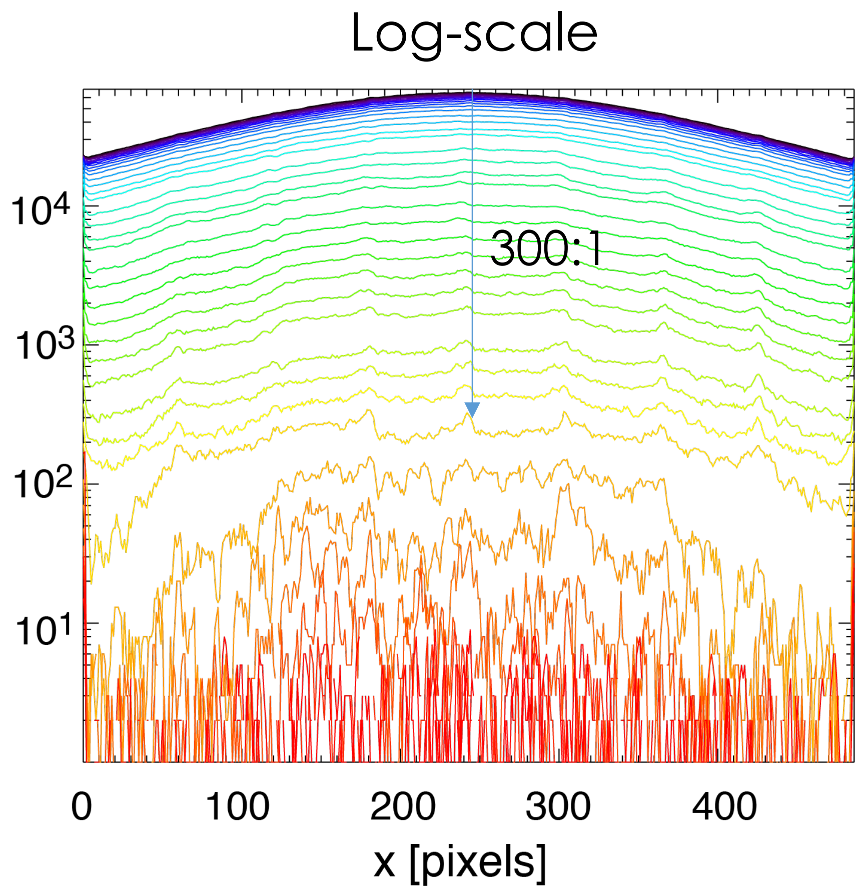




Fe55 +
Am241

Scan of Fe55 reveal its location, intensity & energy-dependence

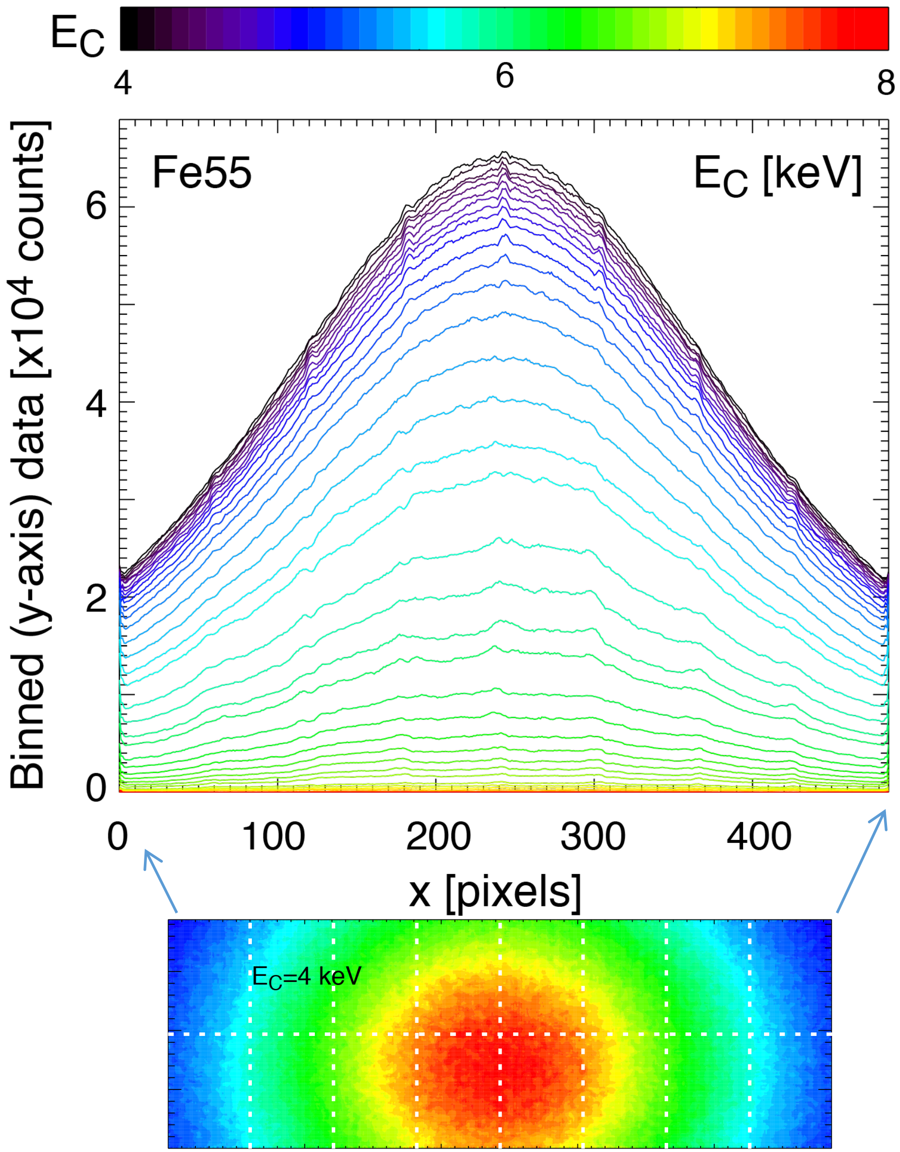


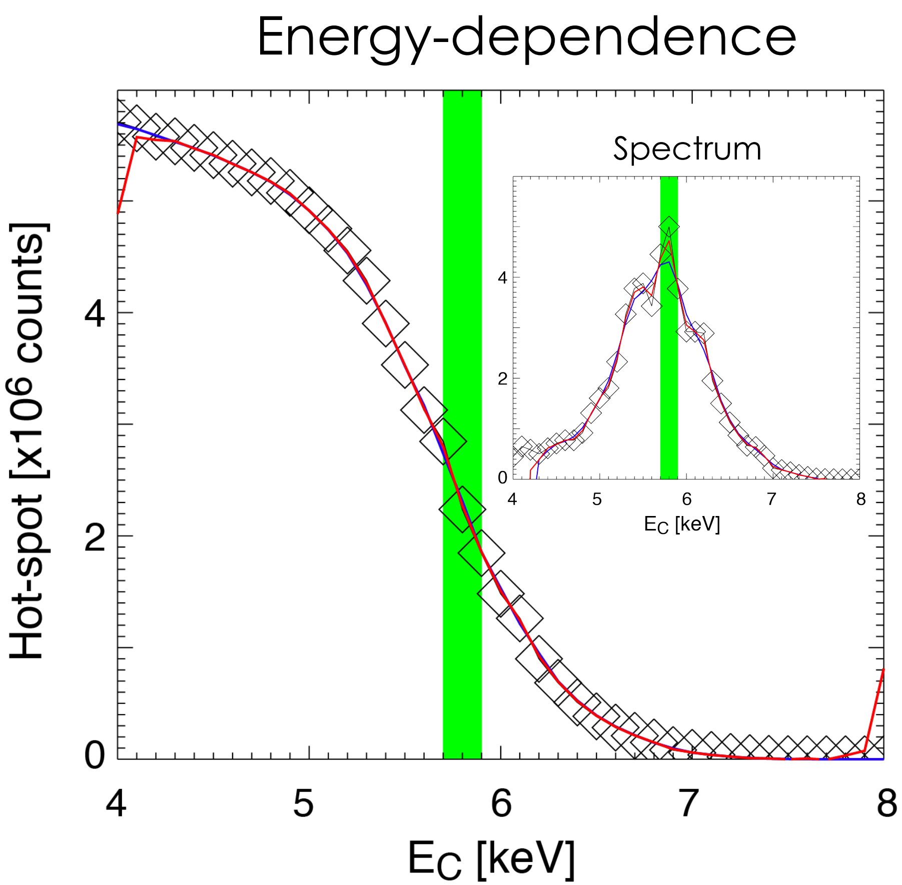


- Fe55 used was weak
  $\Delta t_{integration}$~3 mins
  ~1c/pix/s
- PILATUS3 has larger dynamic range: $5x10^6$ c/pix/s
  (good option for strong sources)
- Emission drops quickly between 4 & 6 keV)

ldelgado@pppl.gov

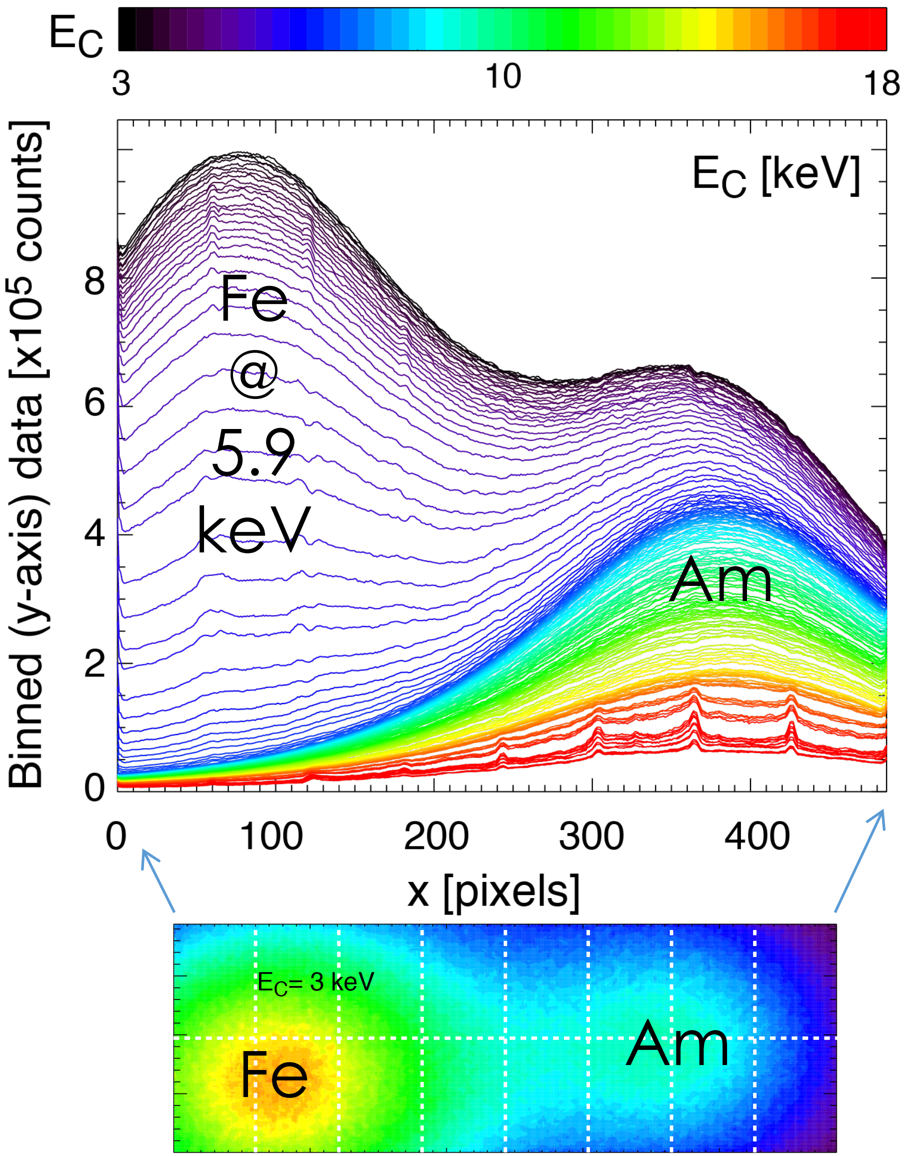
E-dependence of emission reveals characteristic Fe55 energy

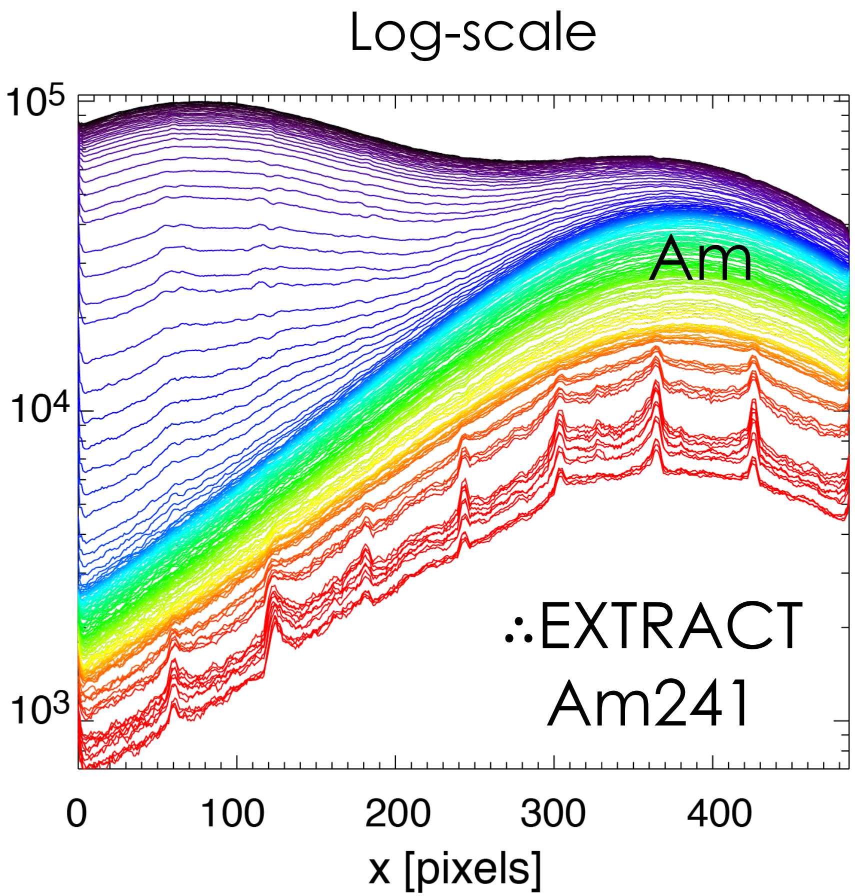


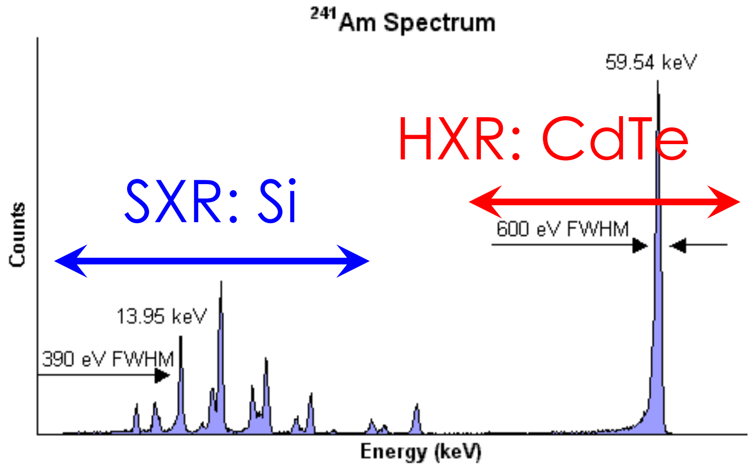


- Low-resolution spectroscopy with $\Delta E=0.1$ keV is enough to reveal the source
- Future step: deal with stronger sources and $\Delta E=0.05$ keV

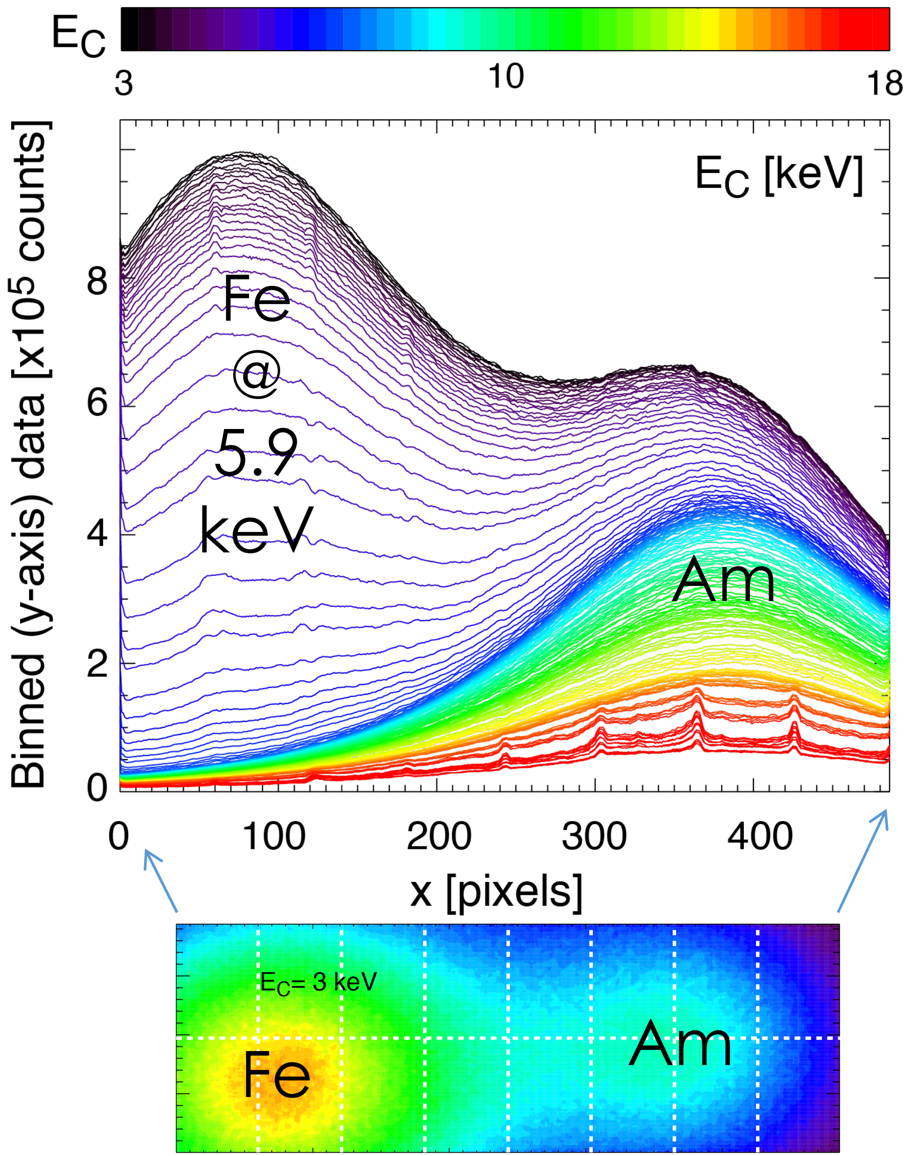
Scanning of Fe55+Am241 reveals & energy-dependent features





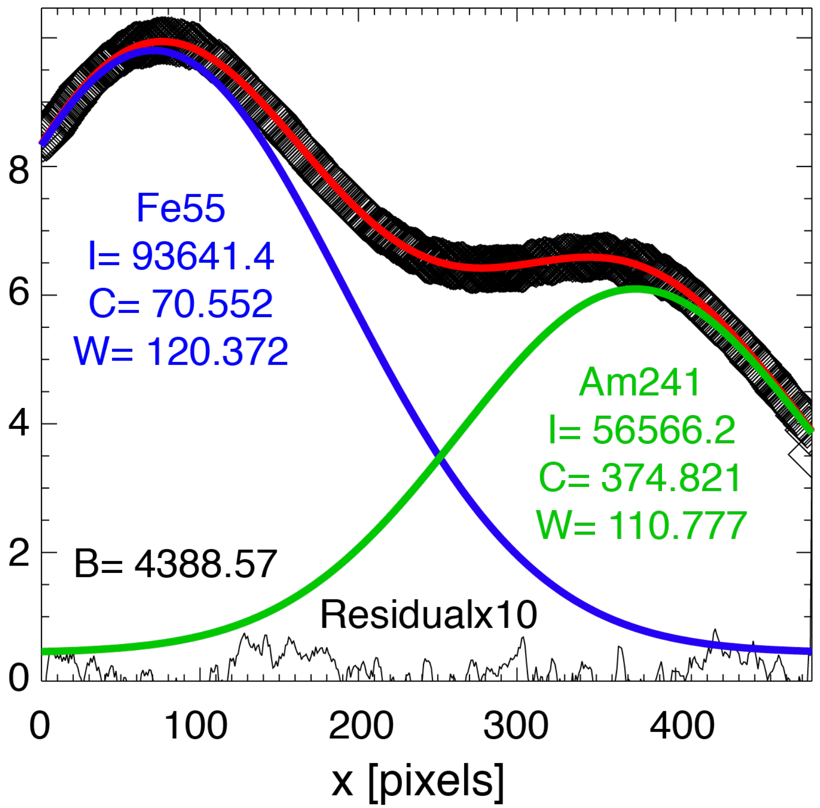


- For E_C>6 keV: Fe55 “disappears” and basic Am241 signatures are still visible
- For E_C>18 keV only the ~60 keV Am241 signature is left (opportunities for CdTe)



Multi-Gaussian profile fit can be obtained with high-accuracy

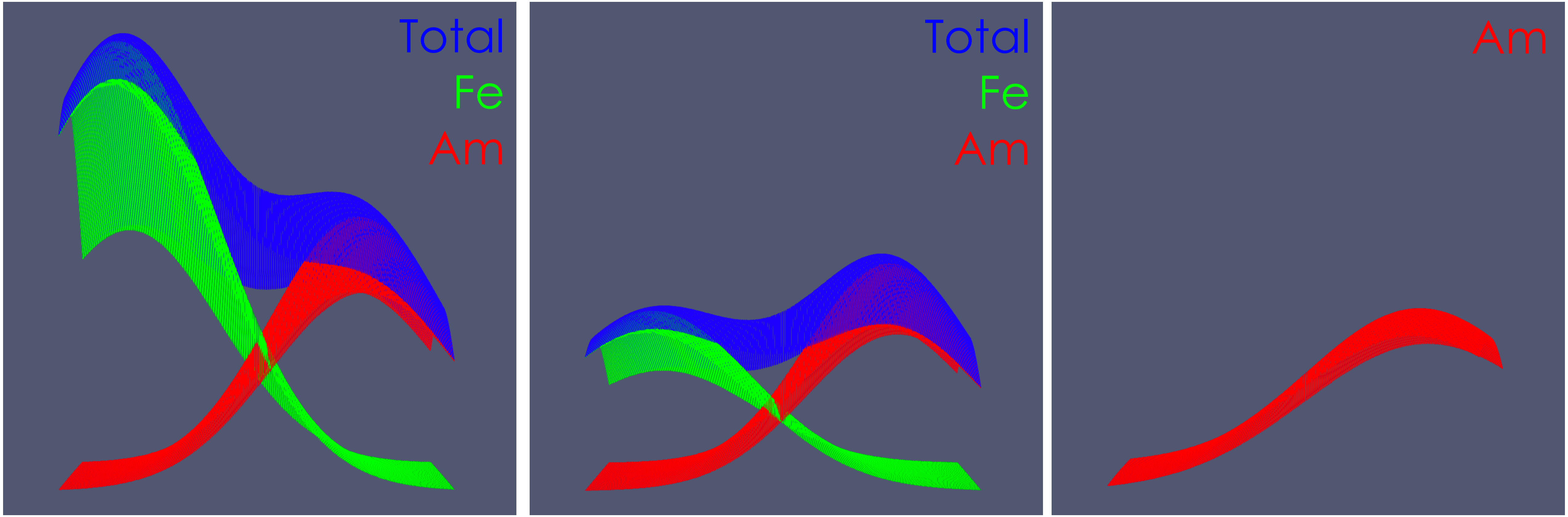
Two Gaussian fit for E_C=3 keV



Automatic procedure capable of:

- 2D localization
- Intensity
- Energy-dependence

2D fits were done for all energy-scan resolving 4D option (e.g. x,y,I,E): extracting Fe & Am emission



ldelgado@pppl.gov

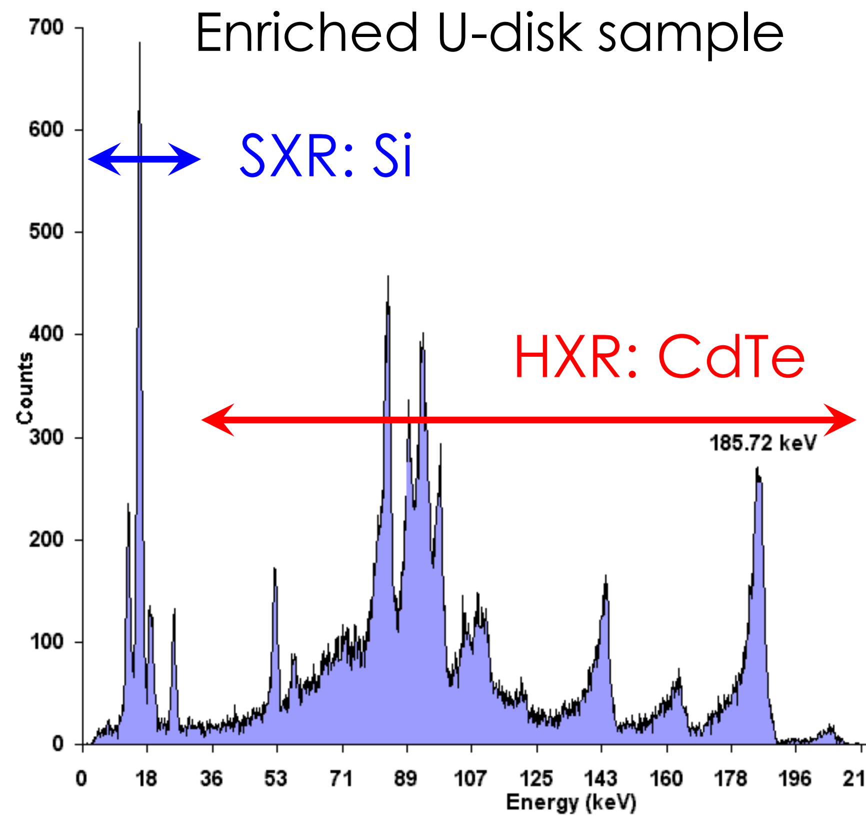
Conclusion and future work

① Using novel technology developed for nuclear fusion studies we aim to develop a 6D capability for Simultaneous IMaging and Identification of RAdioactive Materials & Devices (SIMIRA^{MD})

② Tested 4D option (e.g. x,y,I,E) using Si-PILATUS3 technology and low-intensity Fe & Am sources

③ Custom visualization tool to locate & ID sources and the nature of their unstable nuclei

④ Use stronger sources and radiation fields with moving-parts (max. fr~500 Hz)



⑤ Use of HXR imagers fielded with CdTe sensors working with Am/Co, as well as depleted and enriched Pu- & U-samples.

Acknowledgement

This material is based upon work supported by the Department of Energy/National Nuclear Security Administration under Award Number DE-NA0003921.

This work was performed under U.S. DoE Contracts No. DE-AC02-09CH11466 and OFES 2015 Early Career Award No. AT-10-20-10-1 at PPPL

ldelgado@pppl.gov