U.S. DEPARTMENT OF ENERGY | Office of Science

NSTX-U

Multi-energy x-ray cameras for T_e and n_Z profile measurements in NSTX-U

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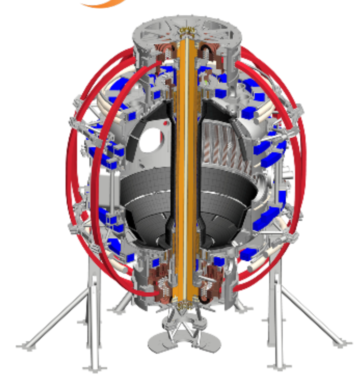
PPPL

MIT PSFC

Alcator C-Mod

JOHNS HOPKINS UNIVERSITY



New technology for developing multi-energy soft x-ray diagnostics is now available

Thanks to important advances in the x-ray detector technology it is now possible to simultaneously record high resolution images of x-ray photons at multiple energy ranges through direct x-ray detection.

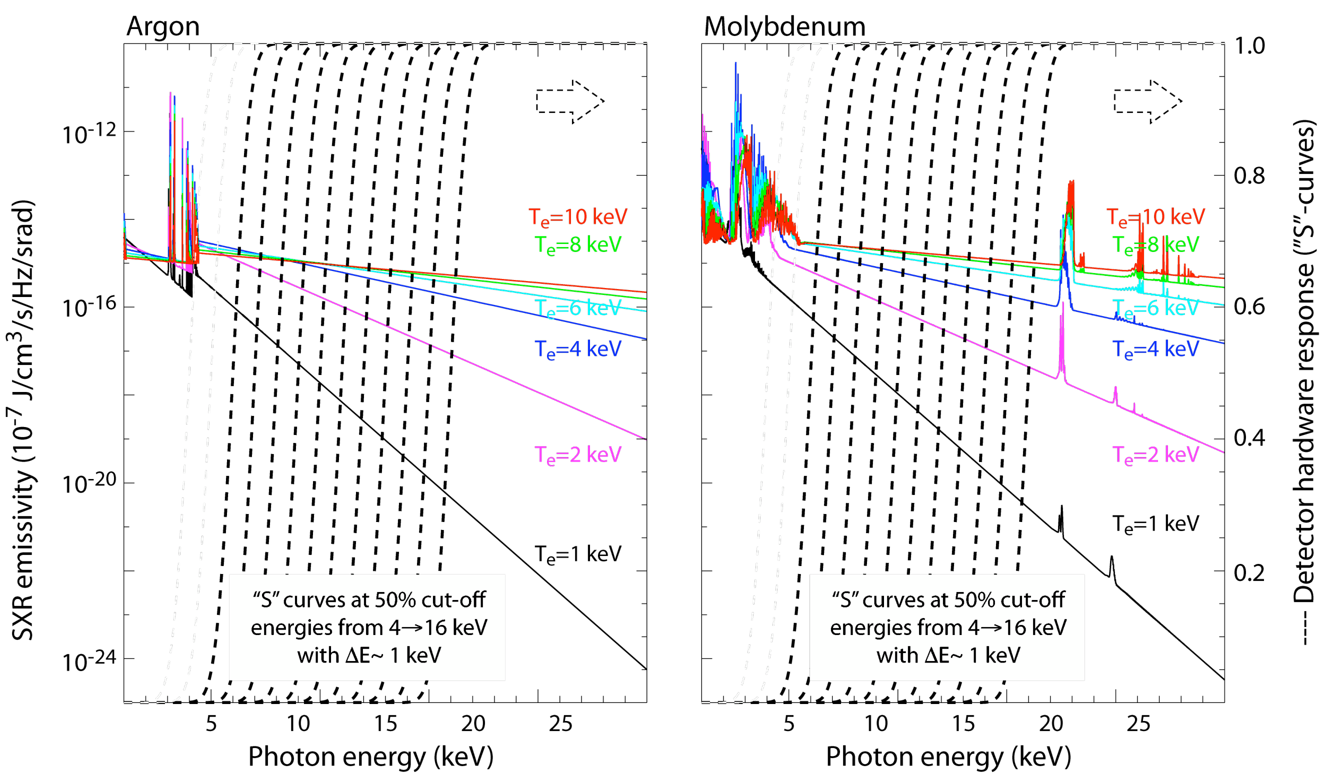
CMOS hybrid pixel technology

① Good efficiency

GOALS:

② Obtain T_e & $n_{e,fast}$ ***sampling*** the continuum.

③ Sampling or ***bracketing*** line radiation: n_Z, ΔZ_{eff}.



Motivation: Develop ME-SXR imaging for MCF plasmas with a unique capability

A unique opportunity of measuring, *simultaneously*, a variety of important plasma properties:

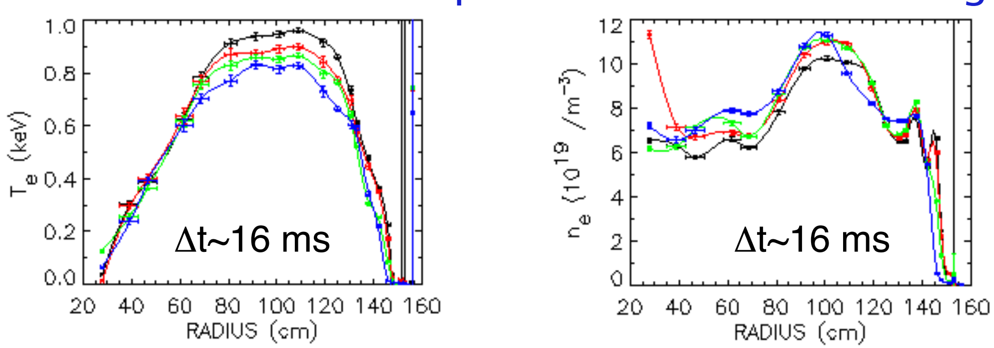
a) central electron temperature ($T_{e,0}$) and profiles ($T_e(R,t)$)
b) medium- to high-Z impurity concentrations (n_Z and ΔZ_{eff})
c) the birth of suprathermal e⁻ ($n_{e,fast}$)

Especially applicable for:

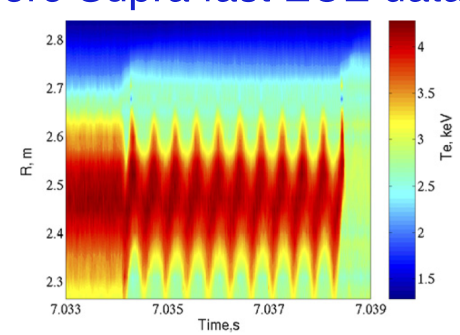
Spherical tokamaks: No T_e ECE-measurements in STs due to low-B_ϕ

Burning plasmas: Complement other techniques such as TS and ECE

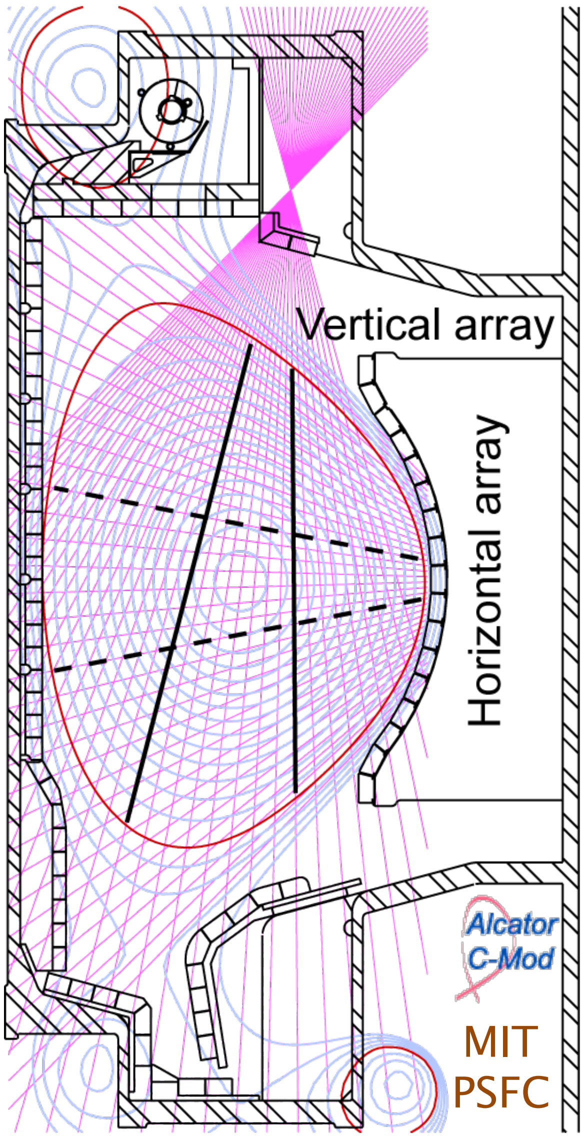
NSTX's 60 Hz Multi-point Thomson Scattering



Tore Supra fast ECE data



GOAL: Extract local parameters from the SXR emission in tokamak plasmas



SXR tomographic systems measure the line-integrated continuum & line-emission from MCF plasmas

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 $f(E_e/k_B T_e)$

L: Length of integration, θ: poloidal angle

v_ϕ: toroidal velocity, M_Z: ion mass

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

Detector response: $S(E_{ph})$

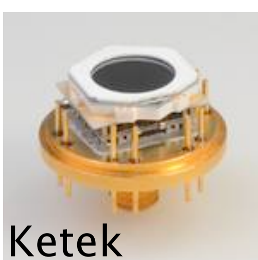
Photon counting ME-SXR systems use Si(Li), HgI_2, Si-Ge-CdTe diodes and SDDs

① Detectors in photon-counting mode

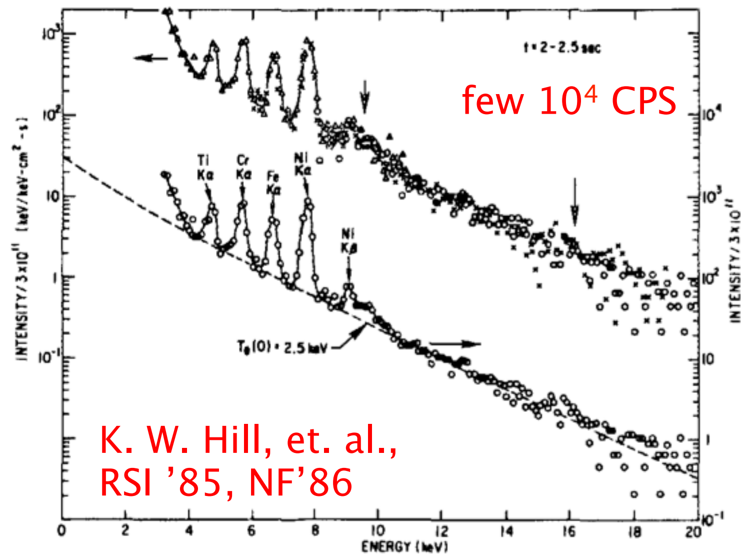
($\langle T_e \rangle$, $\langle Z_{eff} \rangle$, $\langle n_{e,fast} \rangle$, $\langle n_Z \rangle$)

- Pulse height analysis (PHA)
- Good energy resolution (100-200 eV)
- Slow time-response (20-50 ms)
- Low efficiency at high-energies
- Very poor profile definition
- Still used in our community (HT7, TCV, HL-2A)

Y. Shi-RSI'04, Z. Y Chen - NIMA'04, PST'05, T. Madeira-EPS'05, P. Xu-PST'09, Y. Zhang-RSI'09

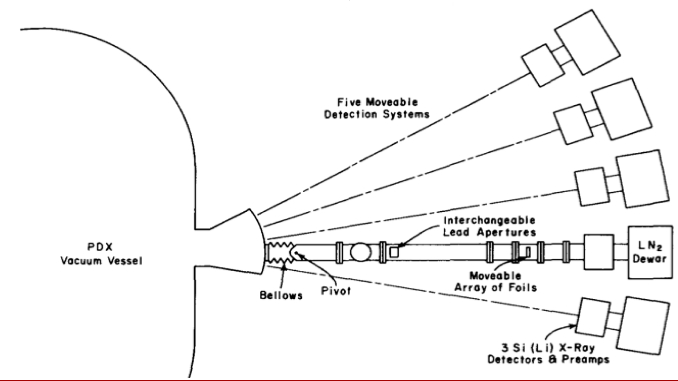


Single-chord spectrometers



One spectrum per instrument

E. H. Silver-RSI'82, J. E. Rice-PRA'82



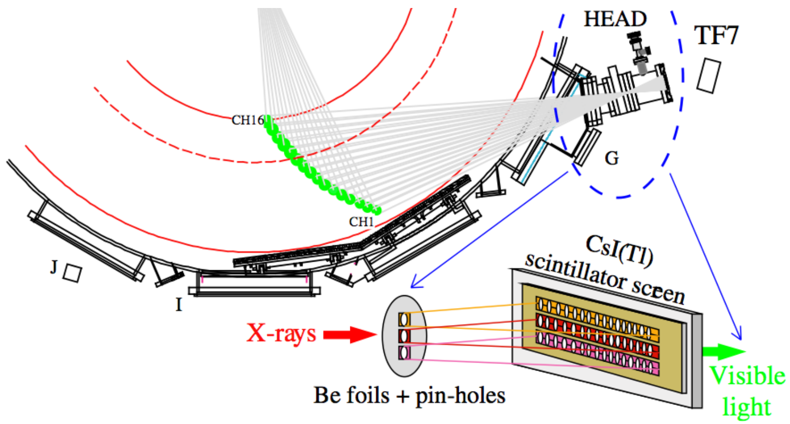
ME-SXR concepts in current mode used various filters, scintillators+PMTs, Si-diodes

② Multi-foil arrays in current-mode

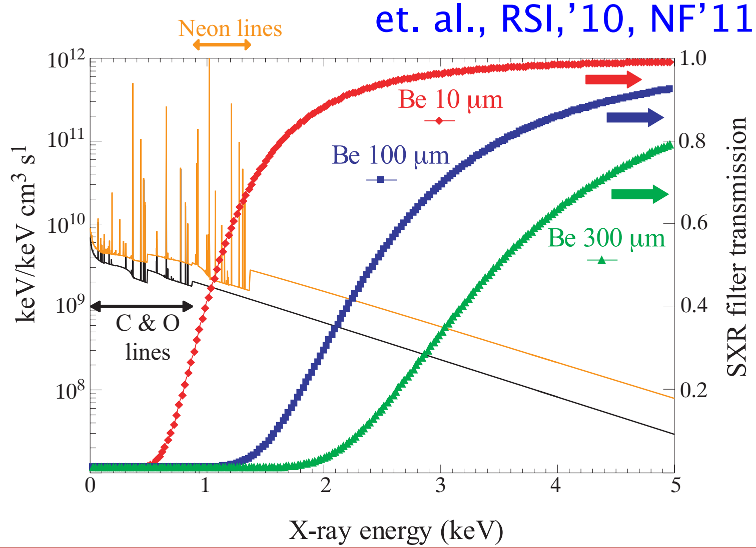
(T_e and n_Z profiles)

- Better profile definition:
  - Line integrated measurements
  - Tomographic reconstructions
  - Tangential view is preferable
- Fast time-response (1 ms to 1 μs)
- Low efficiency at high-energies
- Easy to avoid low-Z emission.
- Poor energy resolution (1-5 keV)
- Difficult to interpret in the presence of medium- to high-Z impurities
- Still, good T_e measurements!

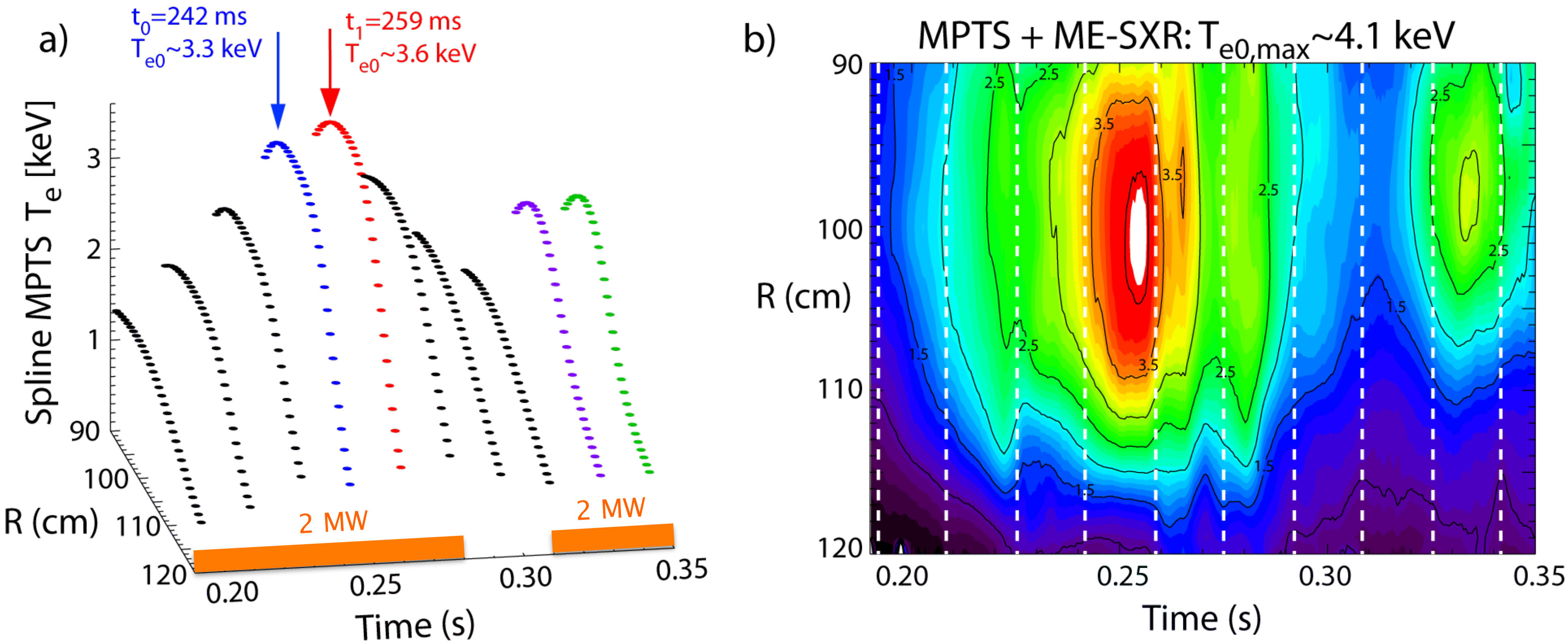
L. Delgado-Aparicio, et. al., JAP'07, PPCF'07,'11, NF'09, '11



L. Delgado-Aparicio, et. al., RSI,'10, NF'11



ME-SXR & Thomson Scattering “combo” provided fast $T_e(R,t)$ measurements in NSTX



“Fast” SXR temperature measurements done in:

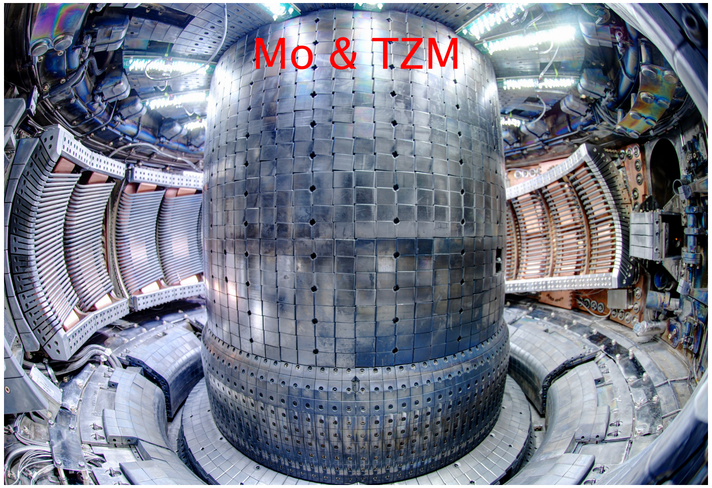
i. Steady state in Ohmic and NBI-heated scenarios (L. Delgado-Aparicio, et al., PPCF’07, D. J. Clayton, PPCF’13)

i. RF heated plasmas using HHFW waves (L. Delgado-Aparicio, et al., JAP’07)

ii. Plasmas with slow MHD [e.g. RWMs (L. Delgado-Aparicio, et al., PPCF’10)]

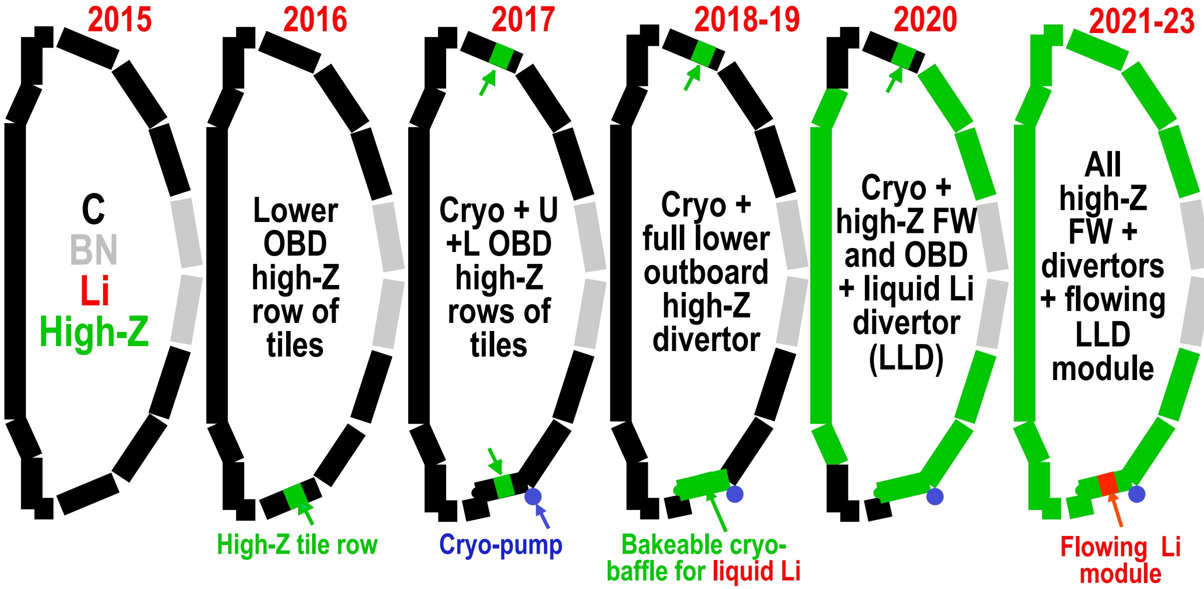
Line-emission from high-Z metals introduces challenges to the multi-foil technique

C-Mod (MIT), WEST (France), JET (UK), ASDEX (DE), EAST(China) have metallic PFCs



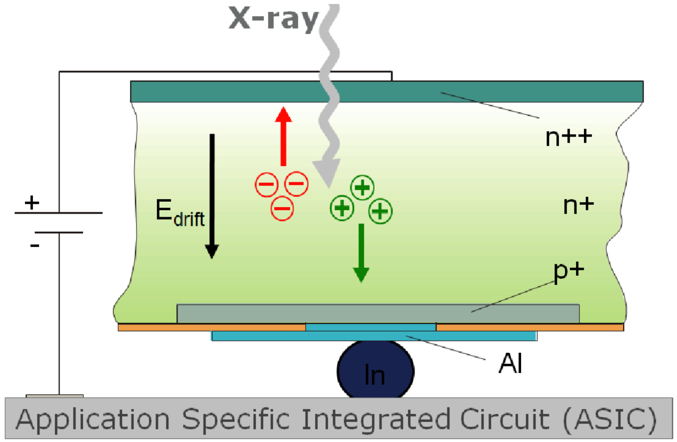
- Low-Z
  Boron (fully stripped)
  Carbon (fully stripped)
- Medium-Z
  Argon (He- and H-like)
- High-Z
  Molybdenum (Ne-like)

Nominal 5-7 year plan for implementation of high-Z wall in NSTX-U

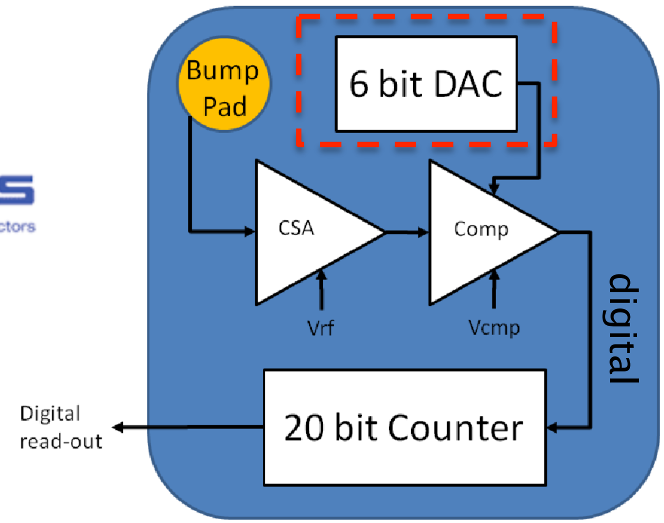


Pilatus cameras enable breakthrough of 100k pixels (minimum) at multiple energy ranges

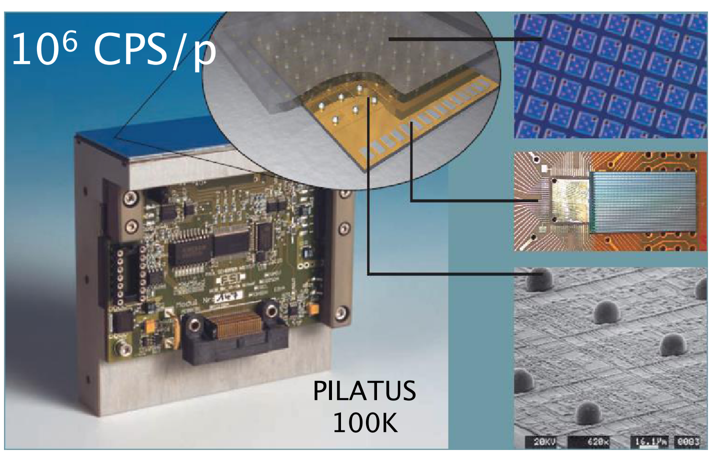
Operates in single photon counting mode



Photon counting circuit in **each pixel**



CMOS hybrid pixel technology developed originally for synchrotrons



Si-sensor 2D array pn diodes

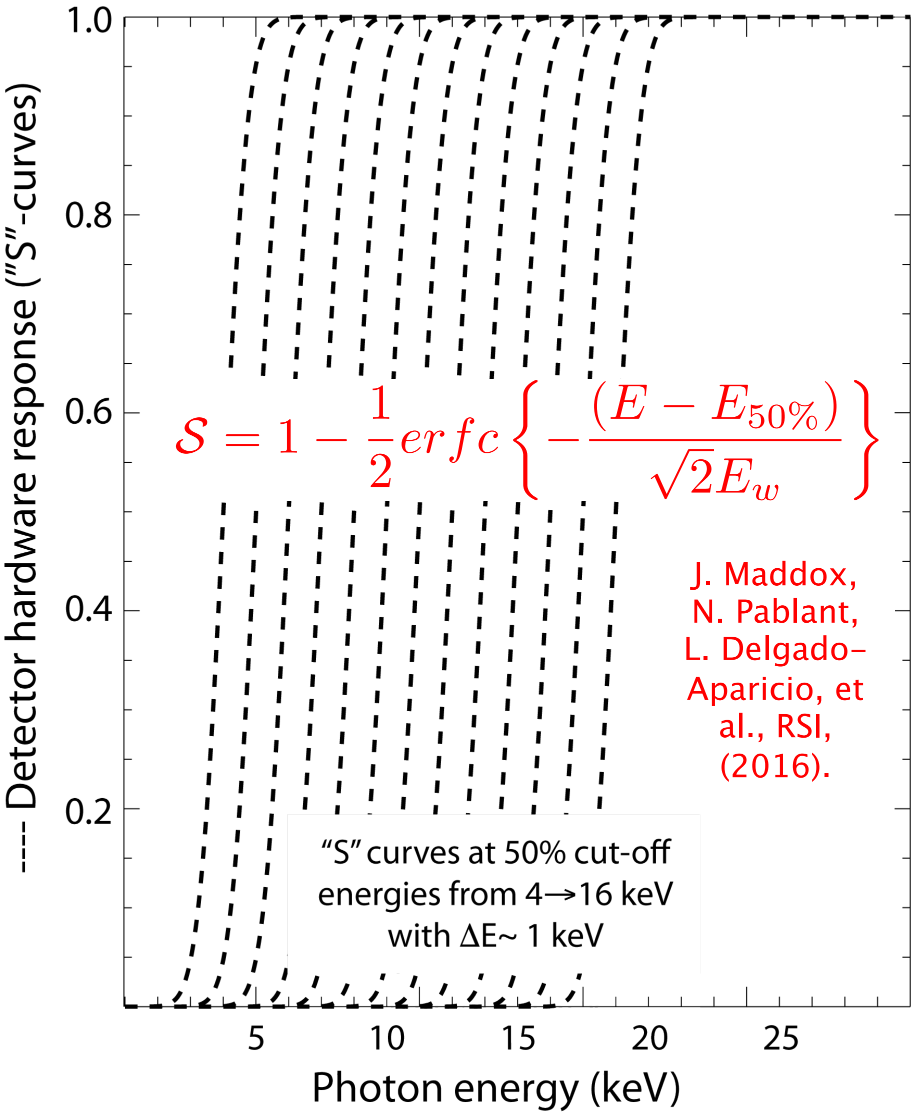
CMOS readout chip

In balls

- The comparator voltage of the readout chip (V_{cmp}) controls the *global* threshold energy.

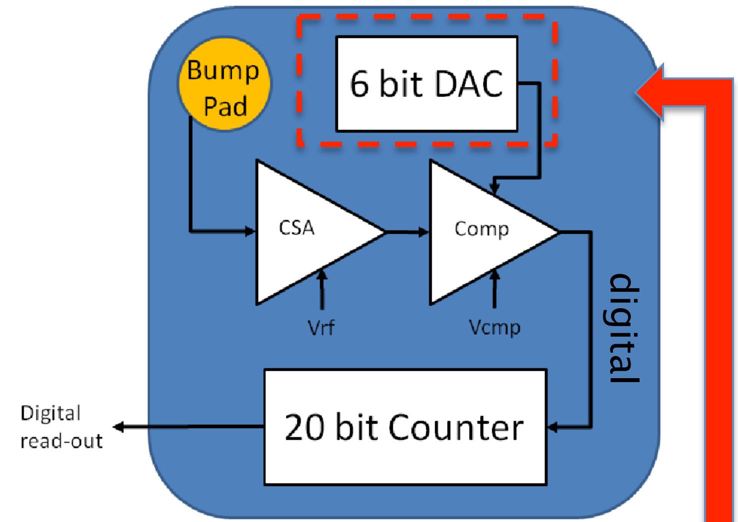
- The threshold energy can be individually *refined/trimmed* using and in-pixel 6-bits DAC (V_{trim}).

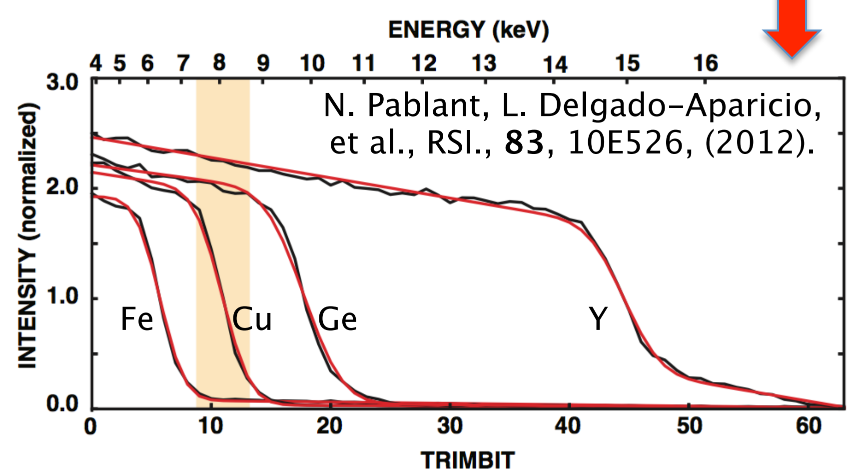
V_{Comp} & V_{trim} allows individual coarse & fine tuning of energy range with E_{width}=0.6 keV



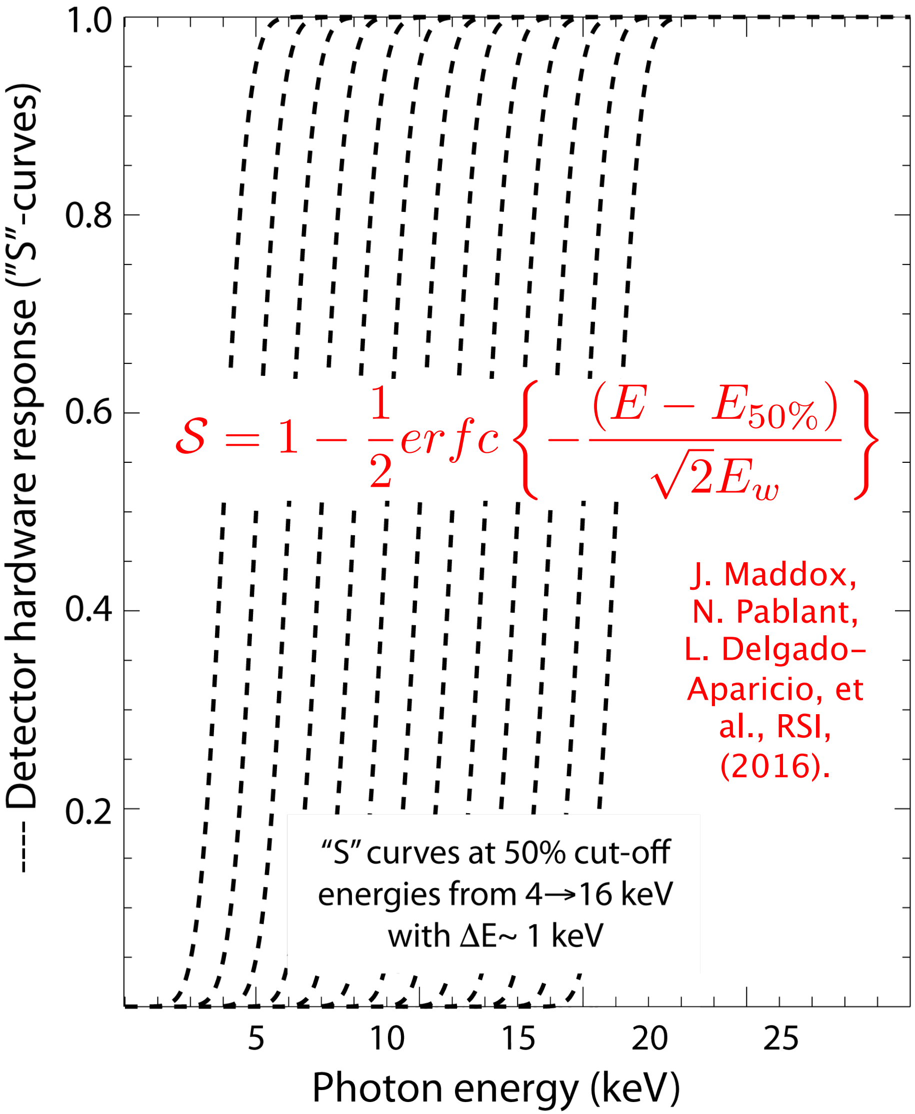
$$S = 1 - \frac{1}{2} erfc\left\{ -\frac{(E - E_{50\%})}{\sqrt{2}E_w} \right\}$$

Photon counting circuit in **each pixel**





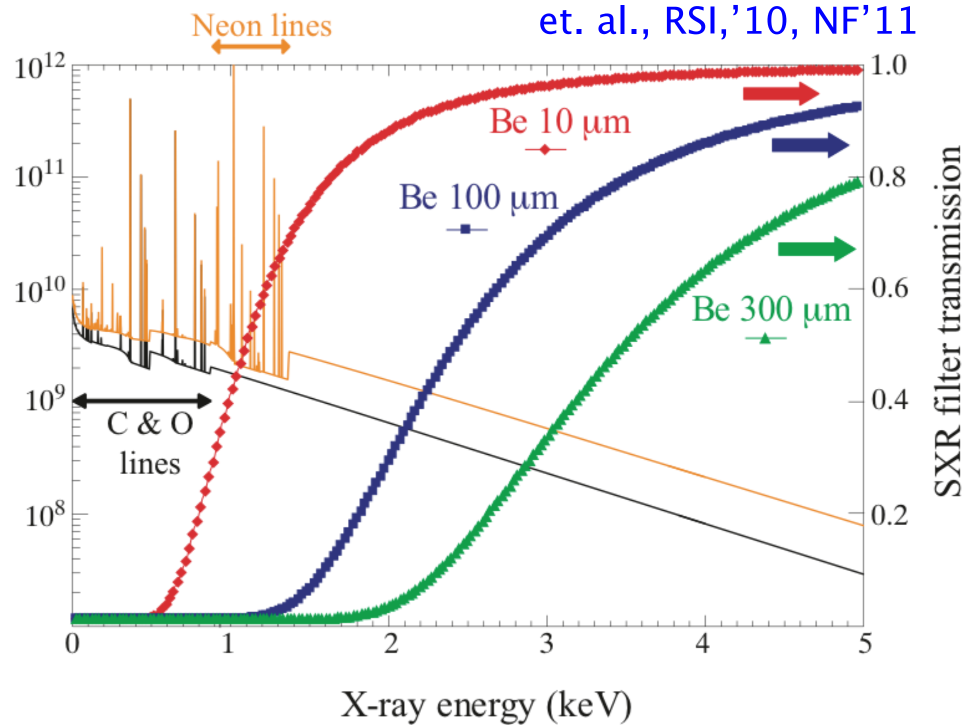
"Constant" width of electronic response is a great improvement over the use of filters



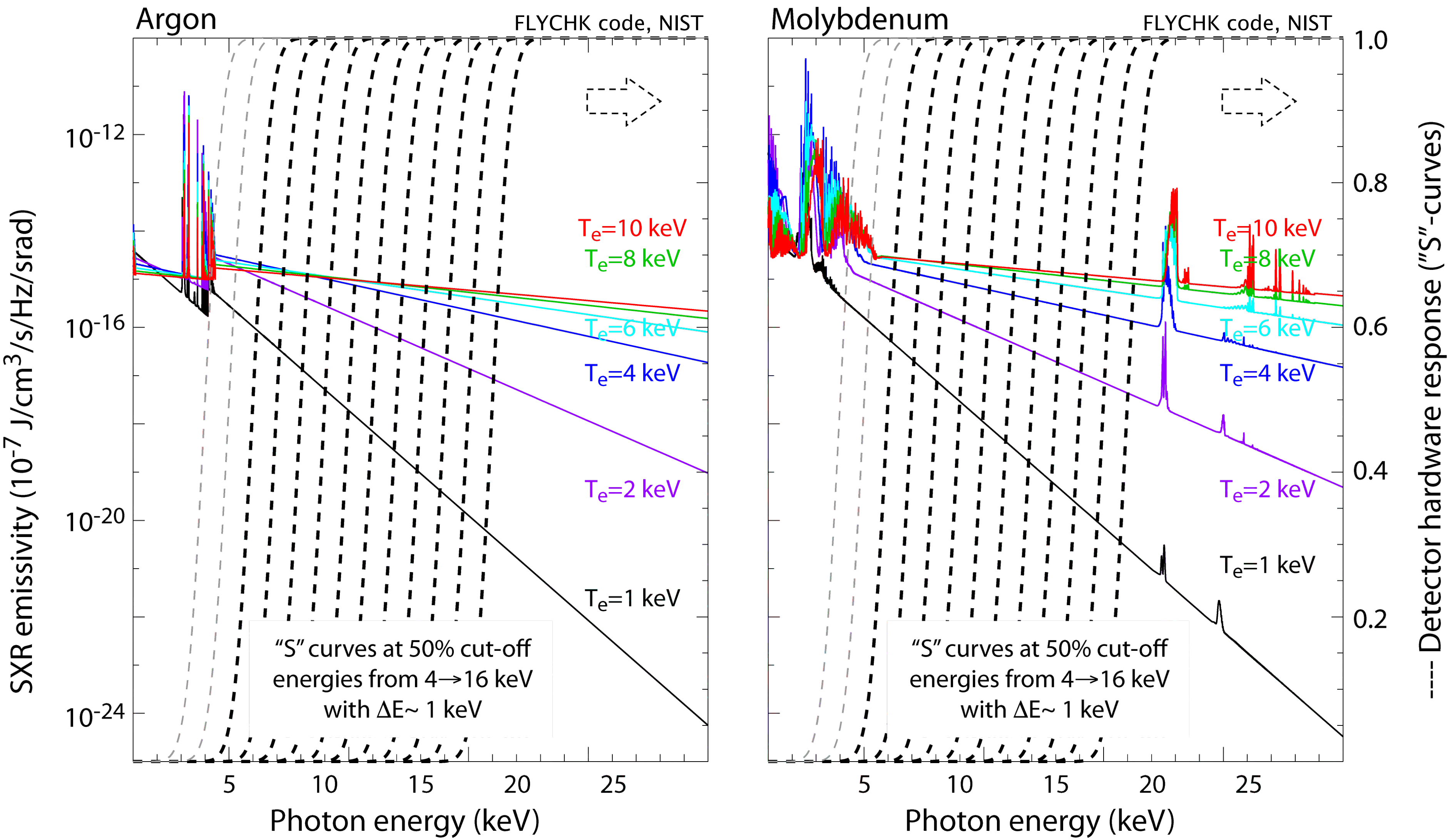
Filters: $\mathcal{T}(E) = \exp\left(-\frac{E_0^3}{E^3}\right)$

$$\Rightarrow \frac{d\mathcal{T}}{dE}\Big|_{E_0} \sim \frac{1}{E_0}$$

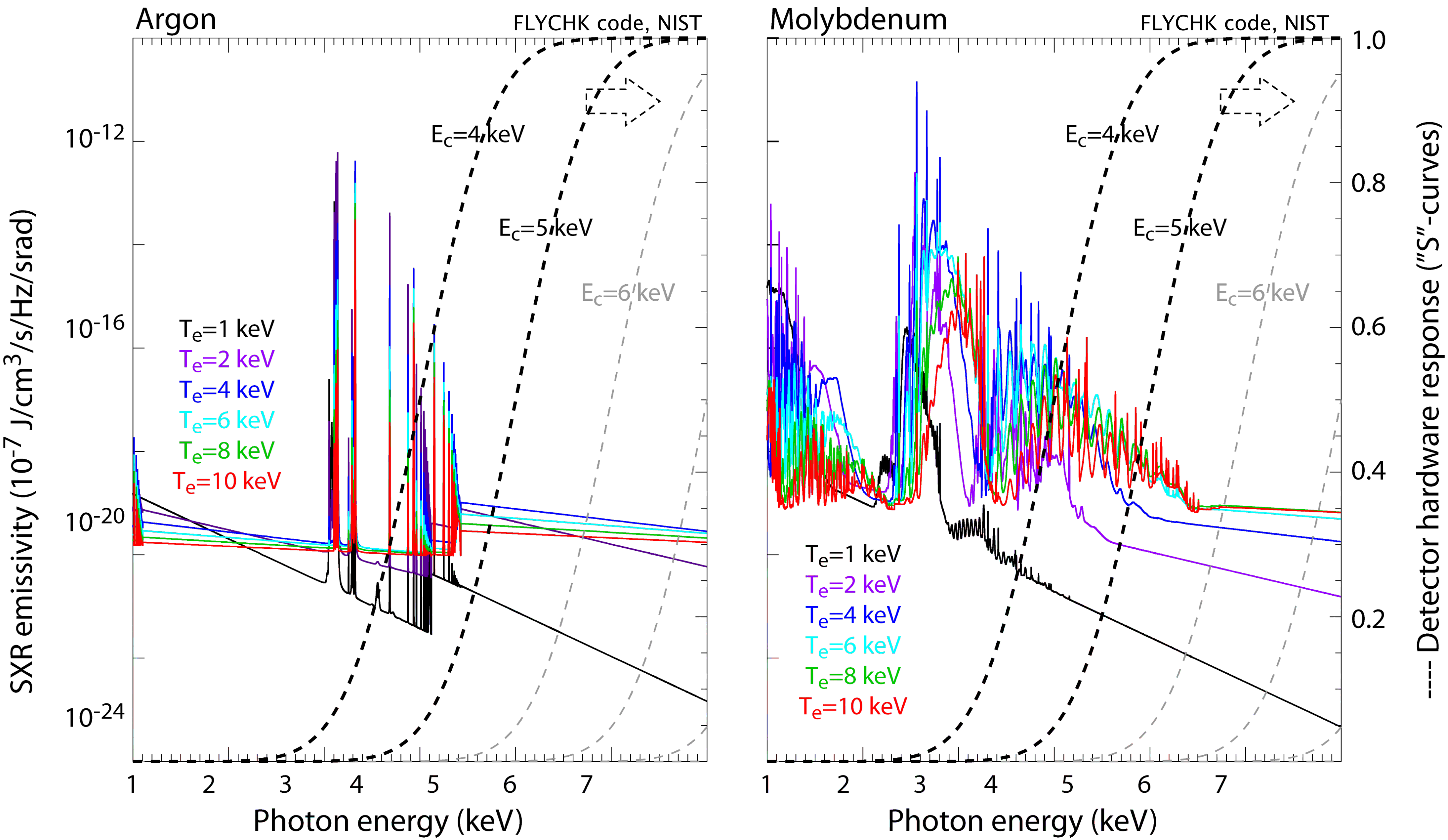
L. Delgado-Aparicio, et. al., RSI,'10, NF'11



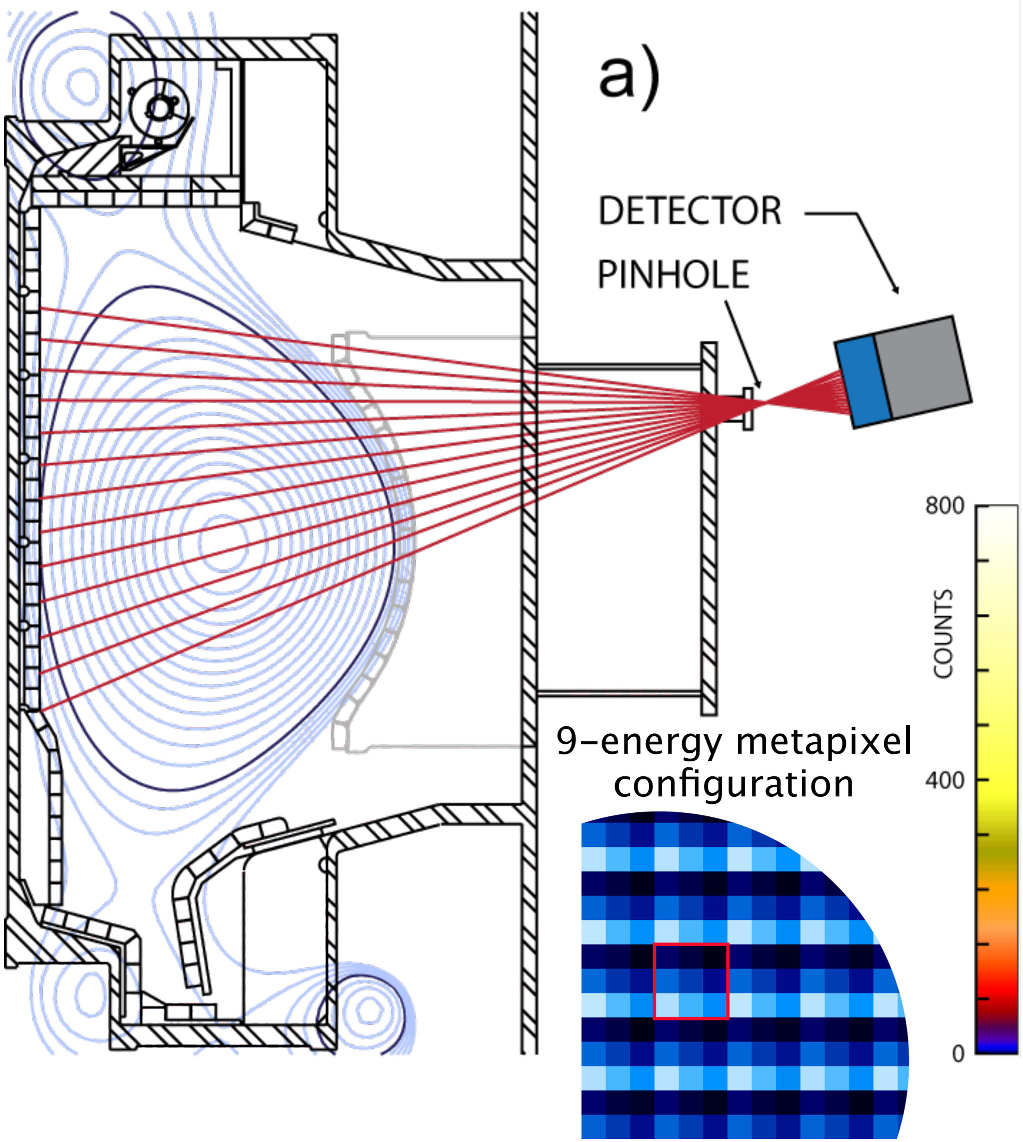
From sampling the continuum radiation from Ar & Mo one can measure T_e & $n_e^2 Z_{eff}$

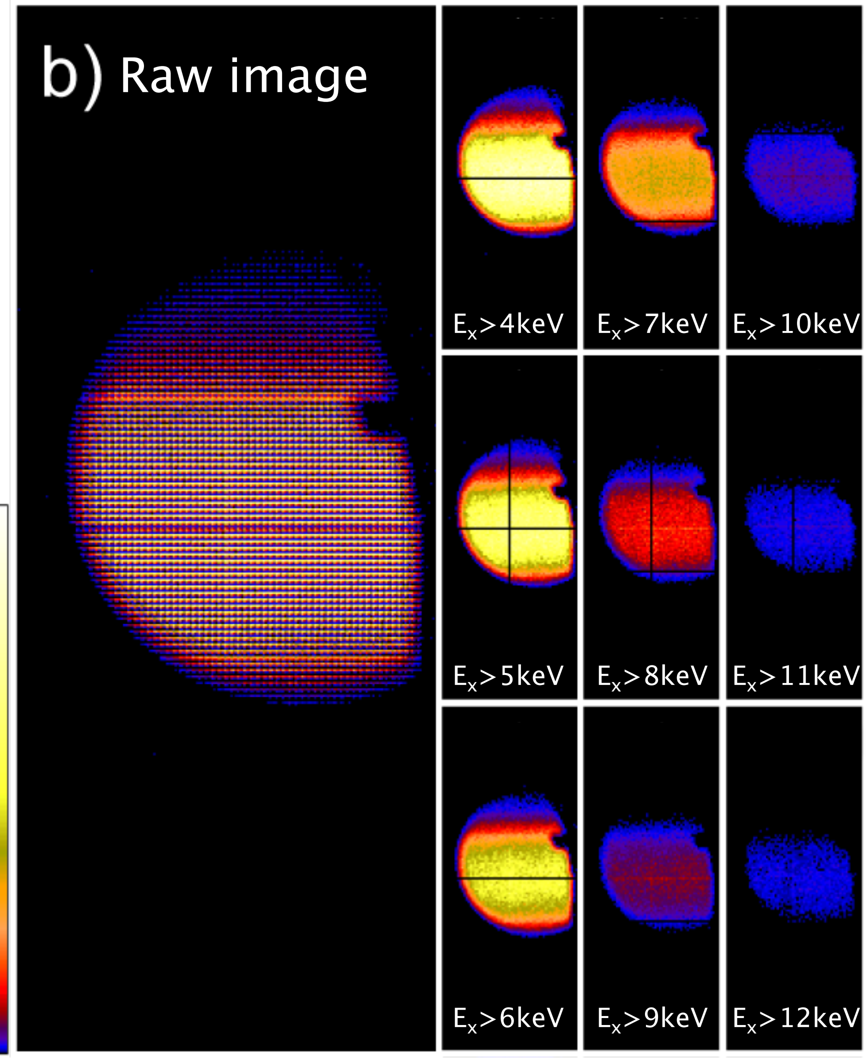


Detector response with 2≲E_{cut}≲6 keV can be used to constrain Ar and Moly density



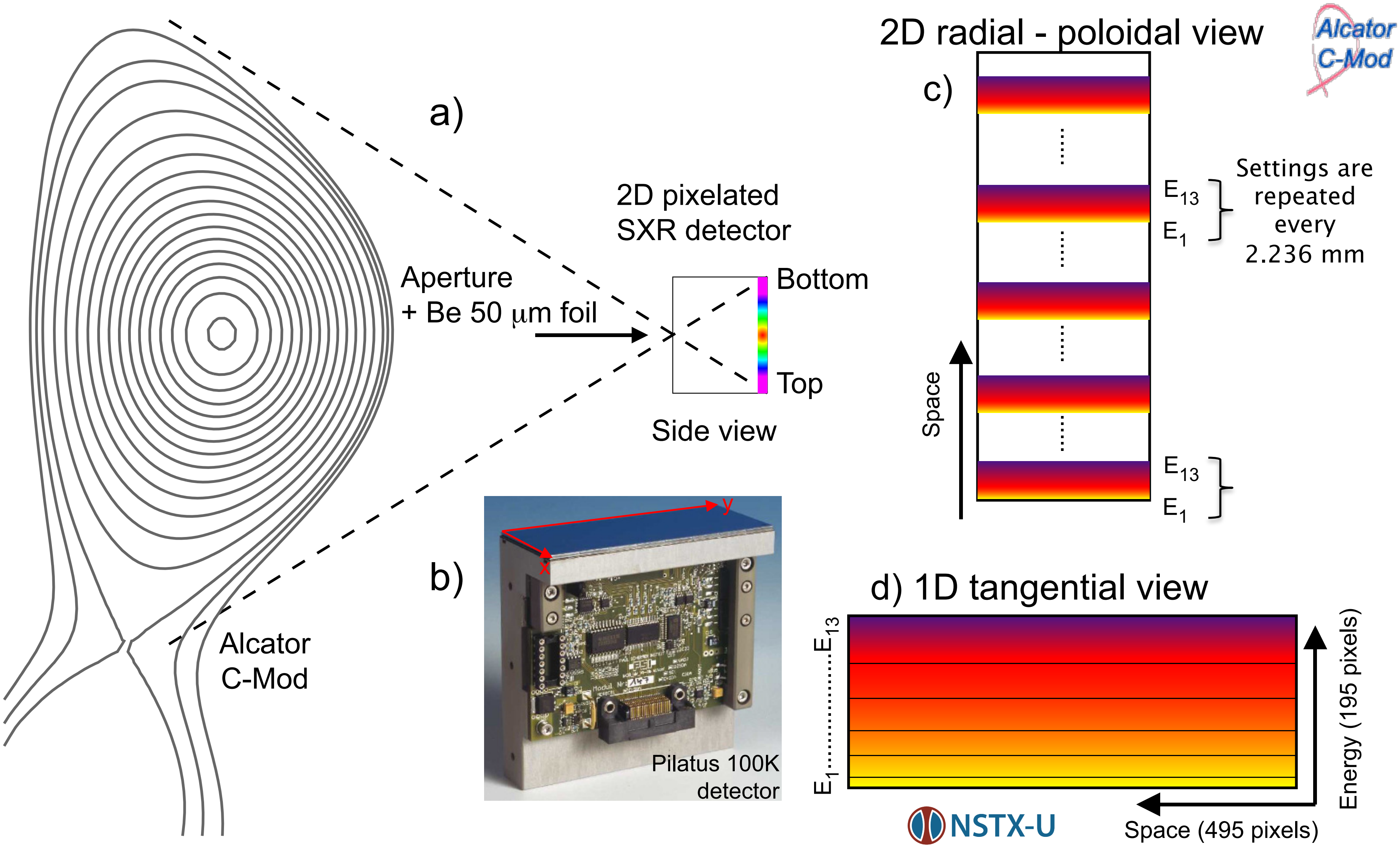
First multi-energy Pilatus tests were conducted at C-Mod @ MIT-PSFC in 2012





N. Pablant, L. Delgado-Aparicio, et al., RSI., **83**, 10E526, (2012).

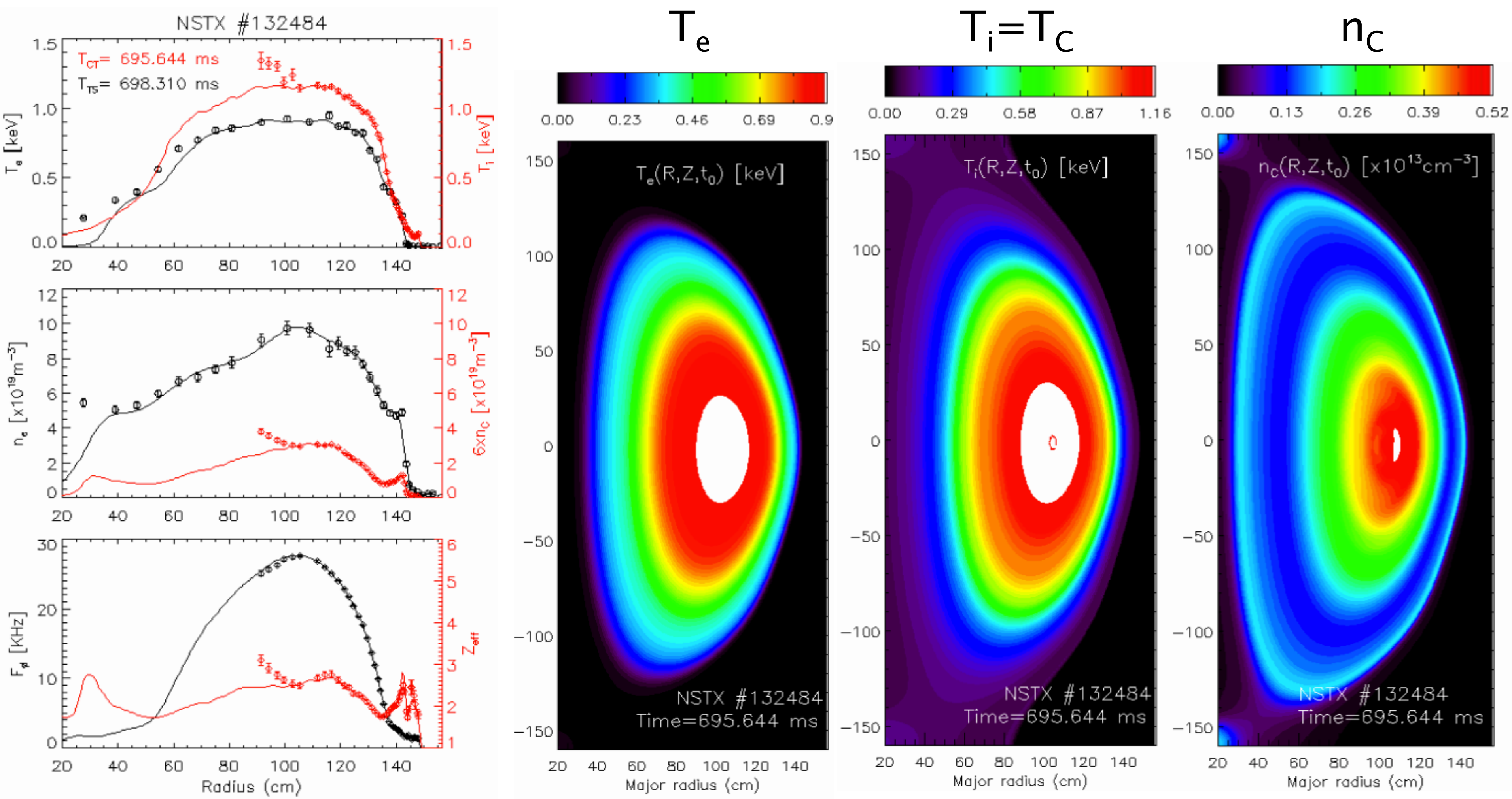
Imaging tests at Alcator C-Mod combined the best features from PHA & foil methods



Mapping of mid-plane data is needed to account for centrifugal asymmetries in n_Z

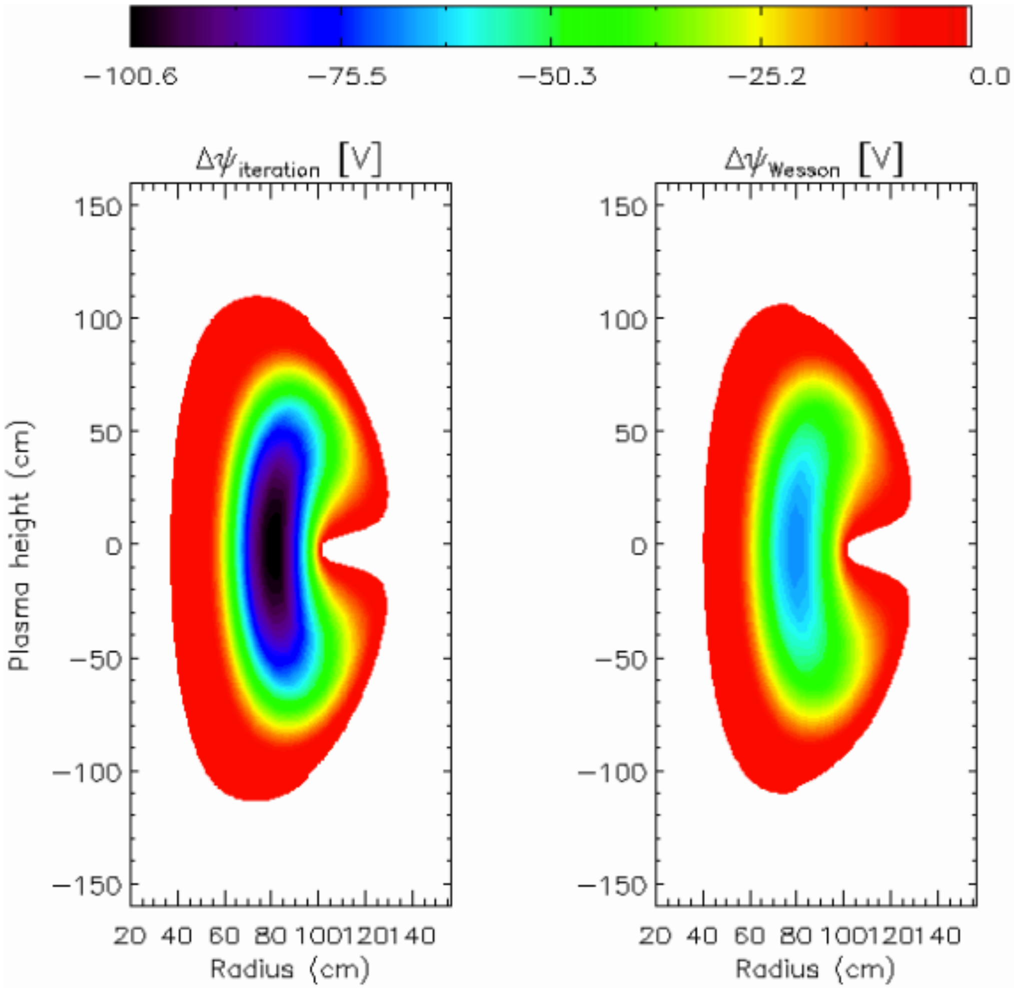
Mid-plane mapping

2D mapping of T_e, T_i and n_C ($Z_{eff,max}$~2.8)

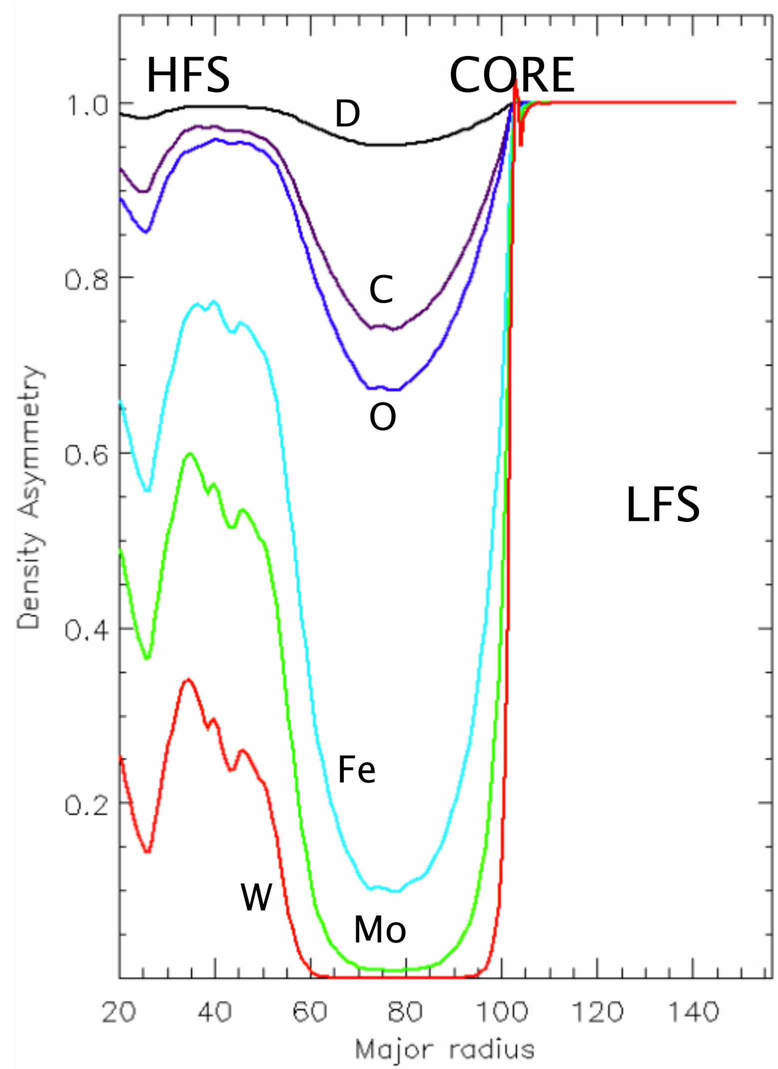


Solutions for electrostatic potential (Δϕ) and impurity density show in/out asymmetries

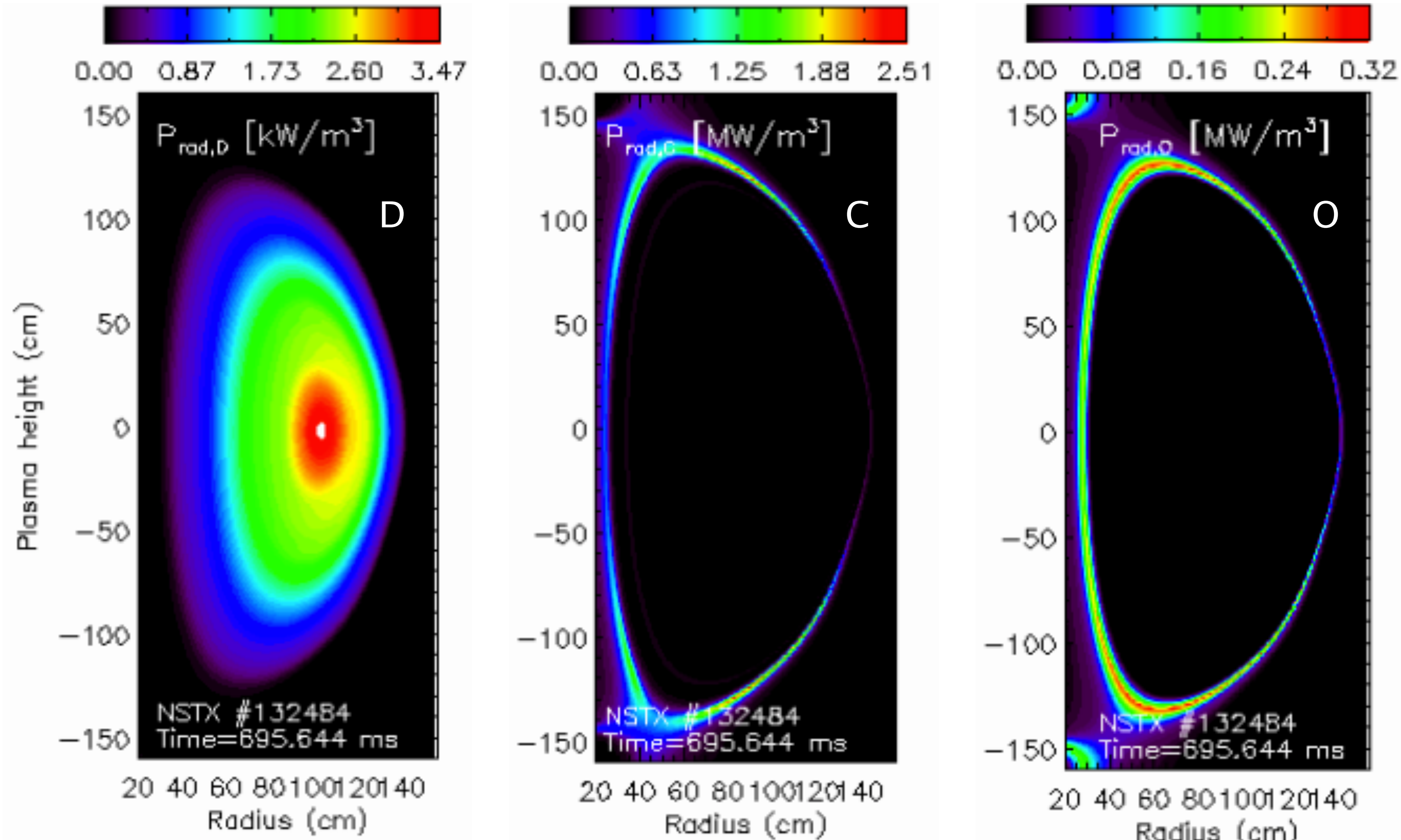
2D solution for the electrostatic potential



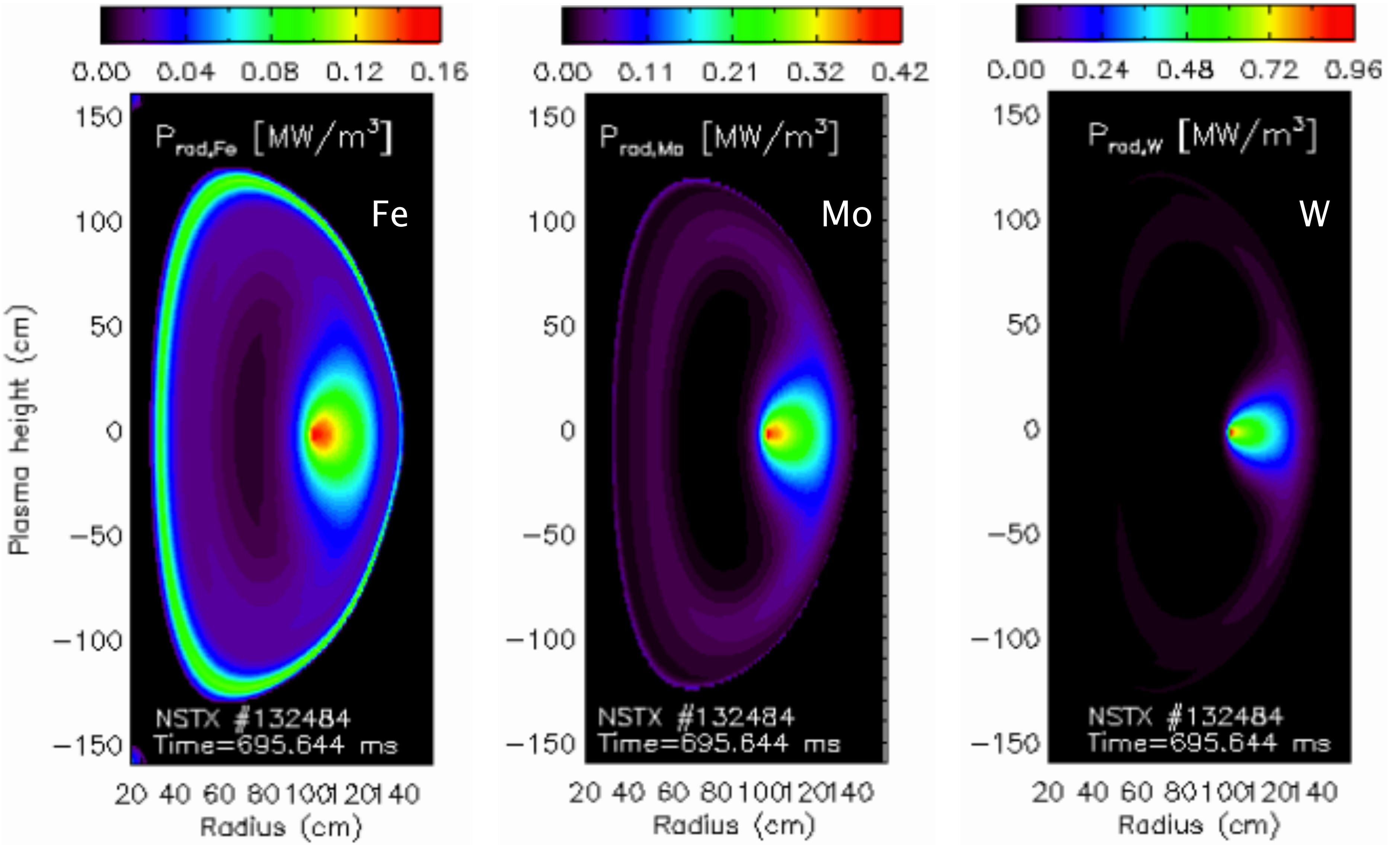
Ion density in/out asymmetries



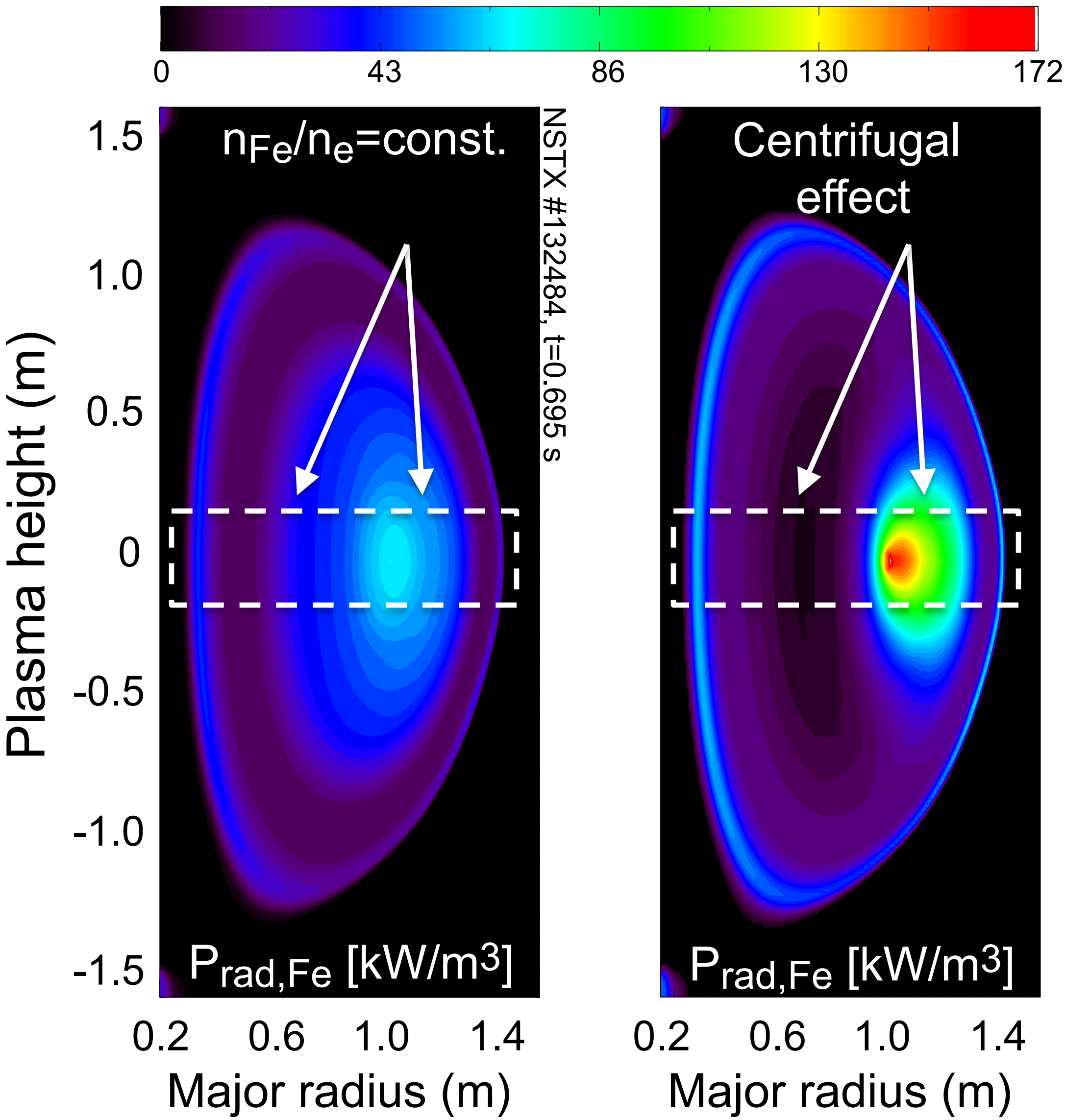
Core bremsstrahlung emission from main ion and fully stripped low-Z impurities is small



Core radiation from high-Z impurities will be affected by centrifugal forces in NSTX-U

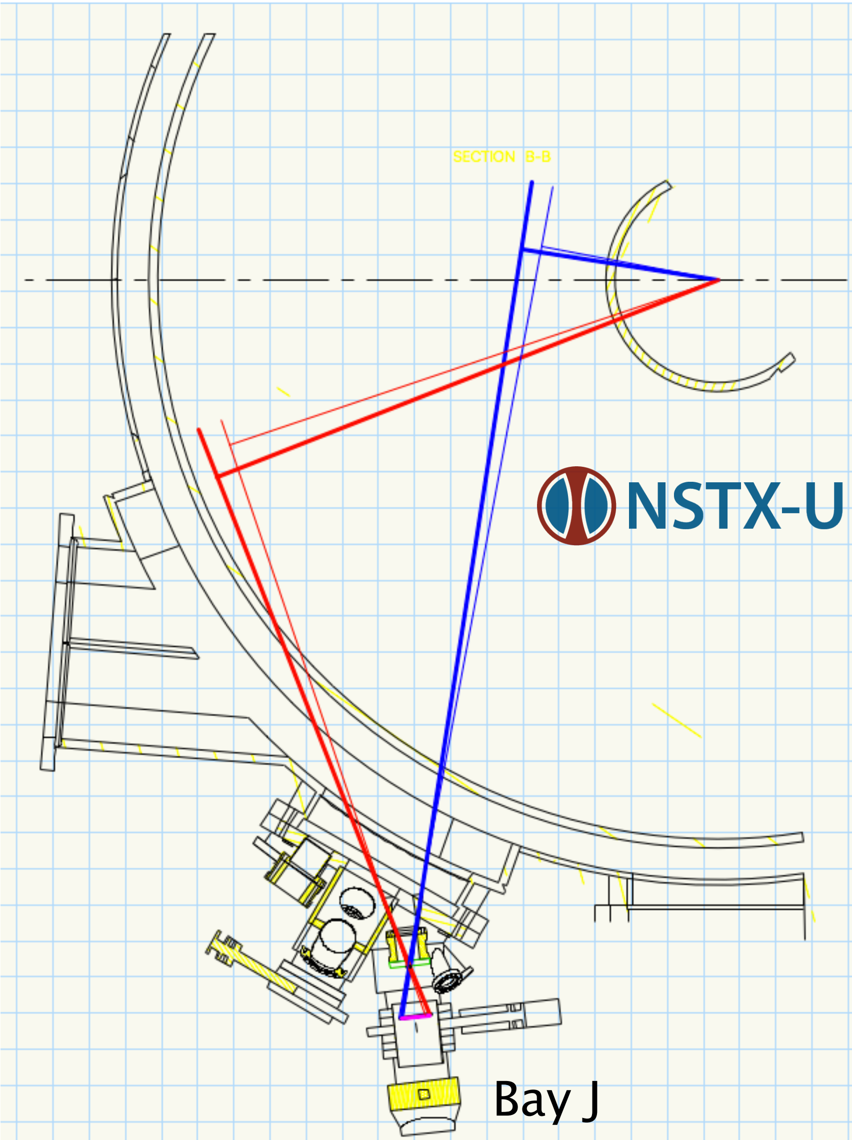


Tangential and vertical ME-SXR views are crucial to study impurity asymmetries and transport



- Tangential view will facilitate inversion at mid-plane using matrix-based Abel-reconstruction.
- Radial/vertical view will be useful to estimate level of poloidal asymmetry.
- Different energy ranges will be helpful for discriminating between Ar, Fe & Mo.

New tangential view for ME-SXR camera is available after redesigning port cover



- Include in the model an 11/16" thick 4-1/2" CF-flange for vacuum filter/ wall + pin-hole combo

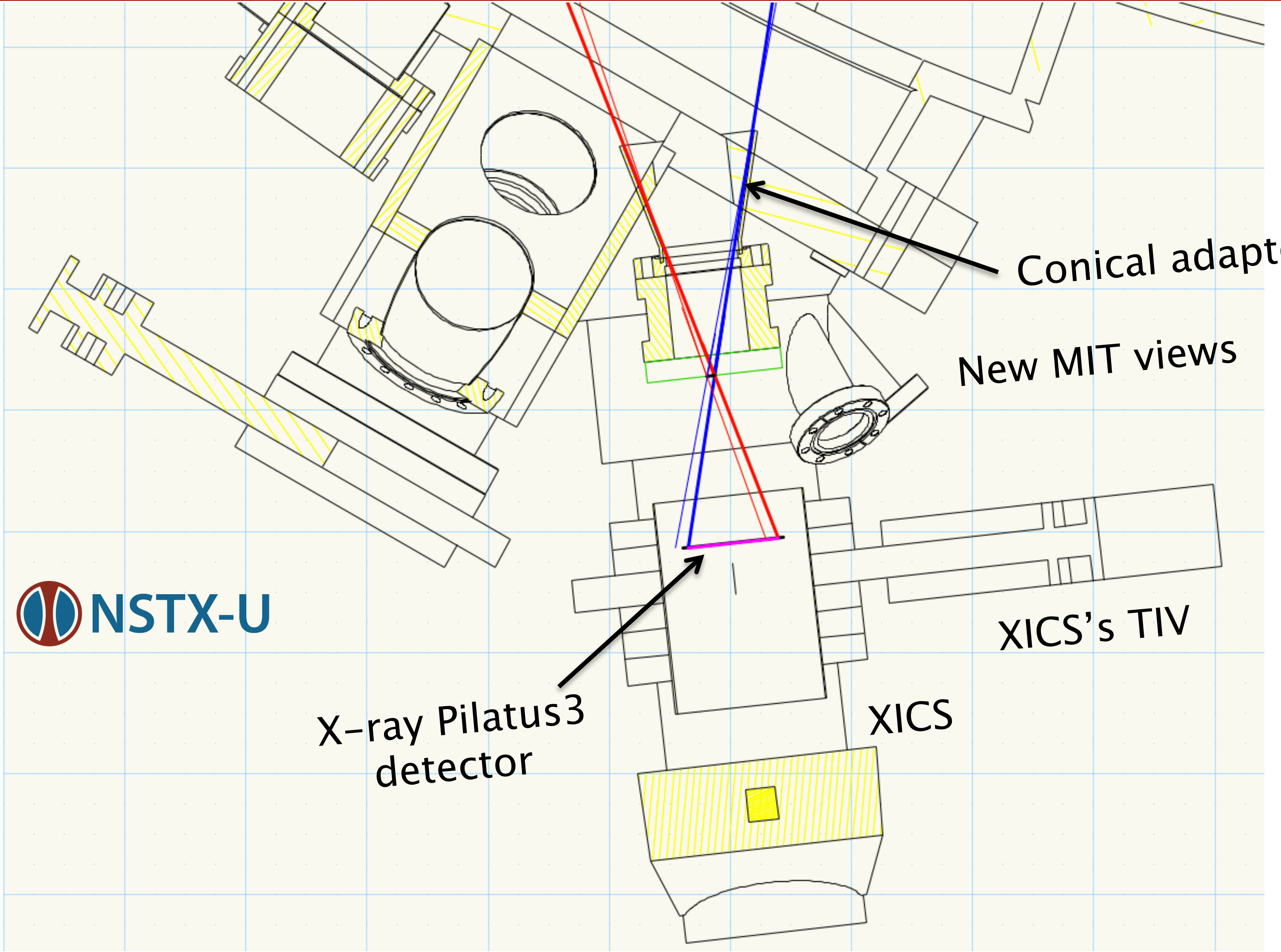
<u>Centered pinhole option (thick lines)</u>

- $R_{tg,max}$~151.38 cm
- $R_{tg,min}$~55.84 cm
- 90% of the detector will be used
- Mid-plane coverage ~ 95.5 cm
- ΔR~0.2 cm/pixel

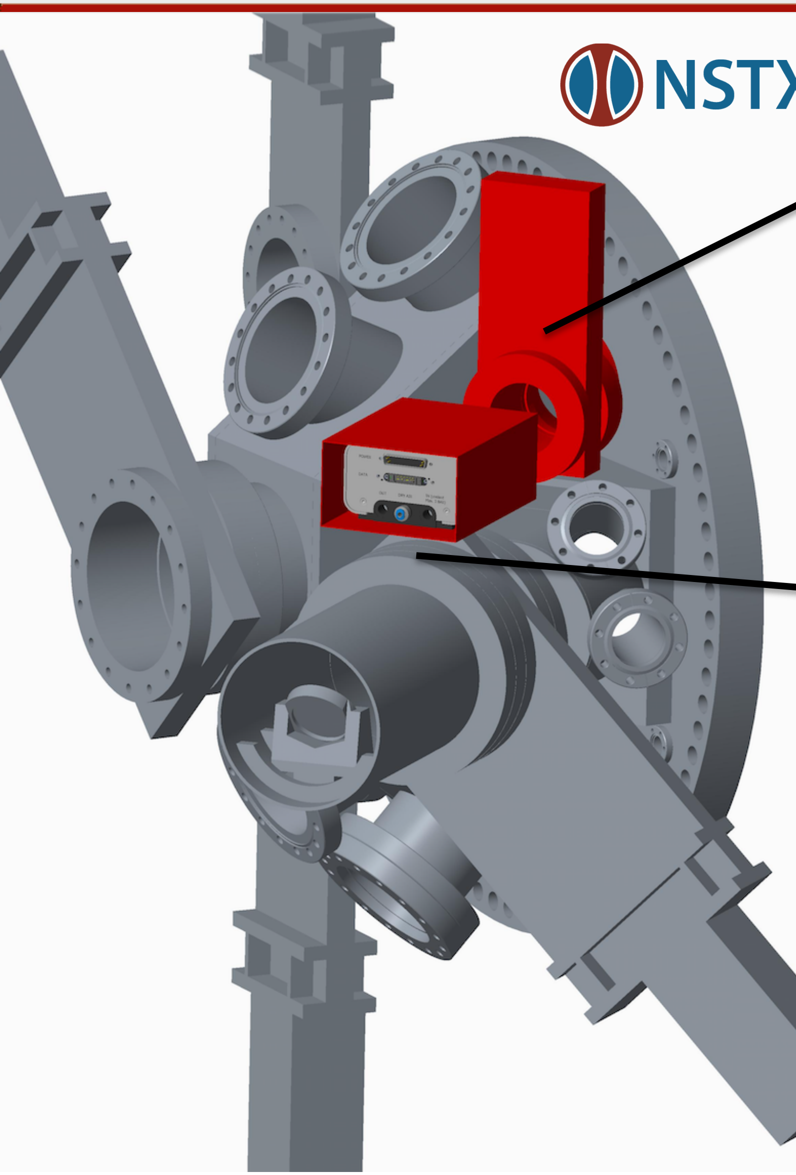
<u>Off-centering the pinhole ¼" (thin lines)</u>

- $R_{tg,max}$~144.9 cm
- $R_{tg,min}$~50.43 cm
- Mid-plane coverage ~ 94.5 cm

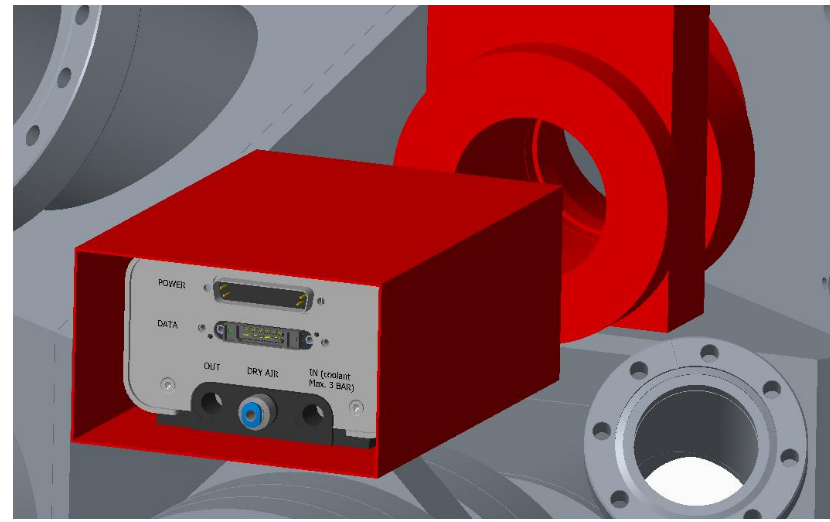
New conical adapter was included in the design to get a viewing angle of ~30^o



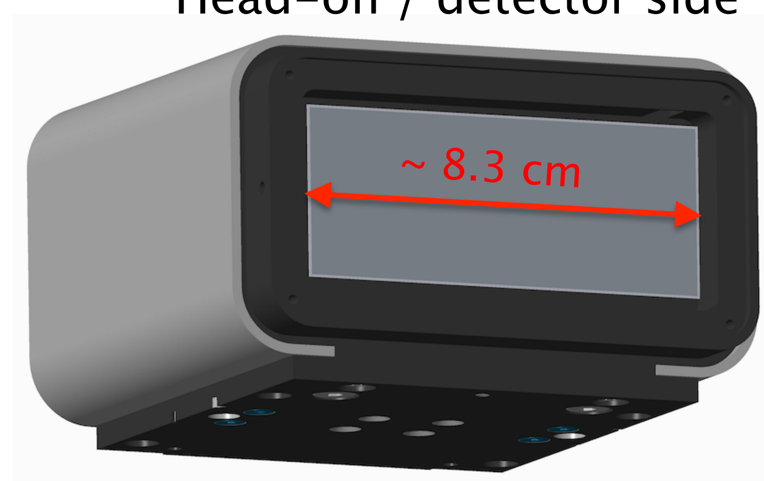
Tangential multi-energy camera will resolve SXR emission from low- to high-field sides



Pilatus3 front-end prepared for vacuum

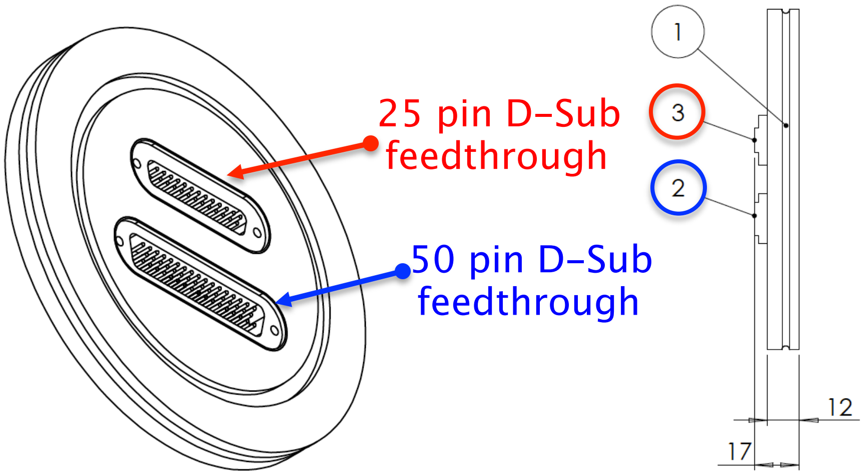


Head-on / detector side

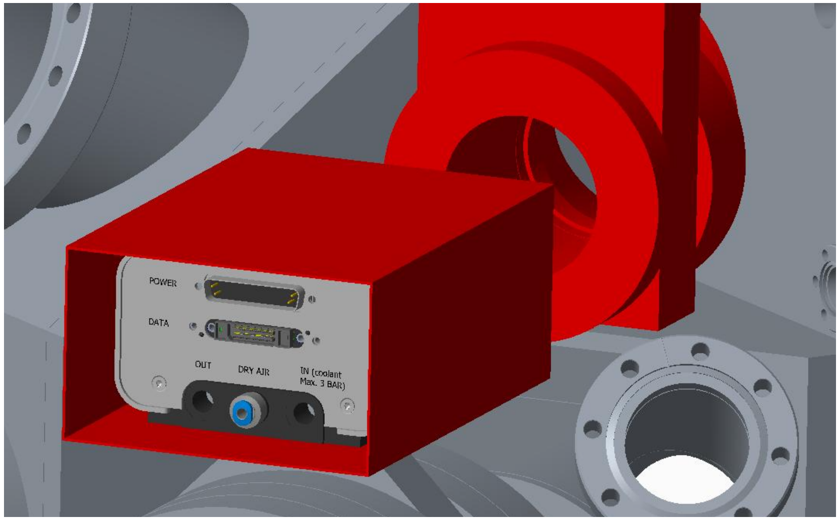


Small vacuum enclosure will house Pilatus3 detector to ensure low-energy sensitivity

Modified Flange DN100 ISO-K

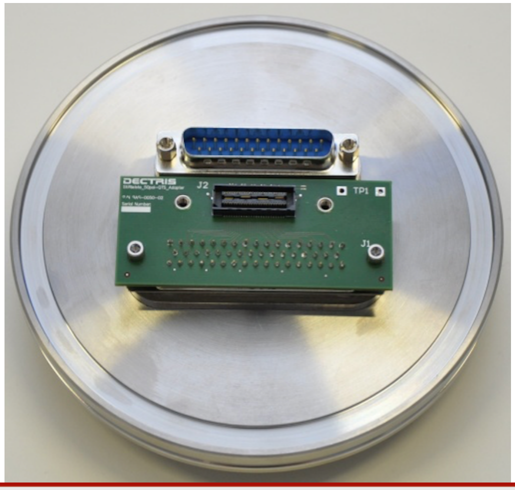


Pilatus3 front-end prepared for vacuum



Vacuum-side

Air-side



a) He-atmosphere inside the detector housing can also be used to avoid attenuation in air.

b) Rough-vacuum will minimize risks of He around port.

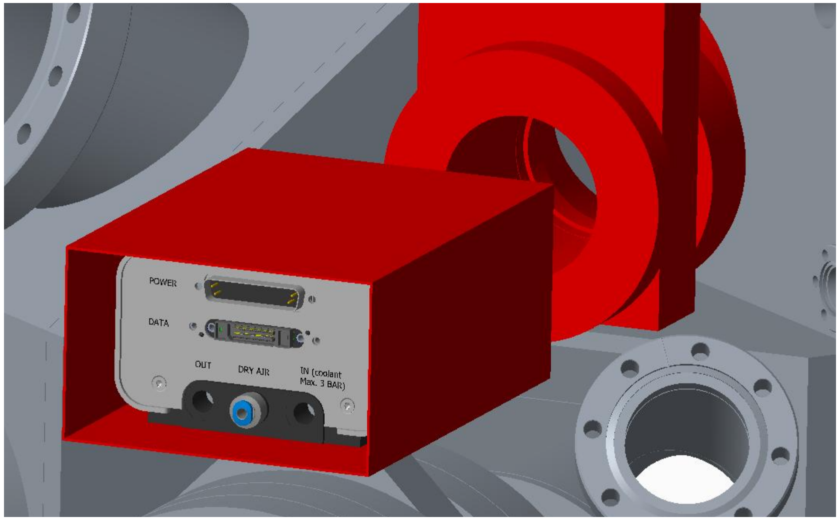
Custom made electronics box solution will be taken out of the magnetic field

Pilatus3 back-end

a) Back-end electronics is sensitive to toroidal and poloidal fields (recently tested for ITER-XICS).

b) 2m data cable will connect camera and back-end electronics.

Pilatus3 front-end prepared for vacuum



Pilatus3 cooling feedthrough

Vertical view is excellent complement but design and installation impose challenges

Umbrella

LITER's electrical box was installed in Bay G

Toroidal field coils

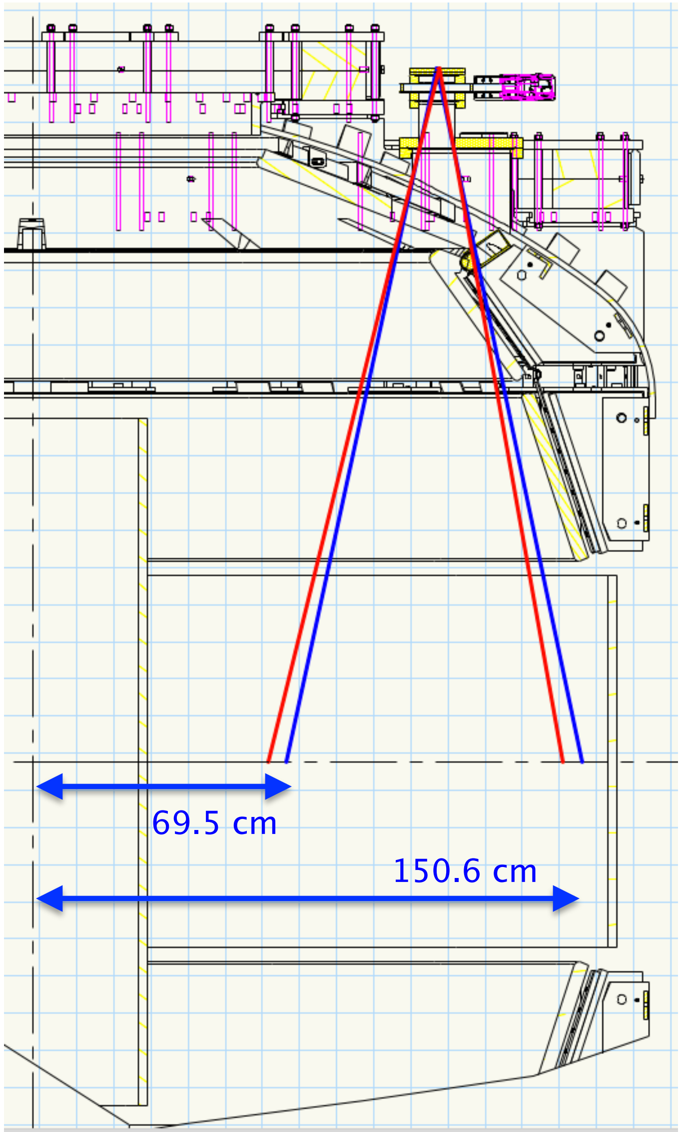
Water lines

Electrical lines

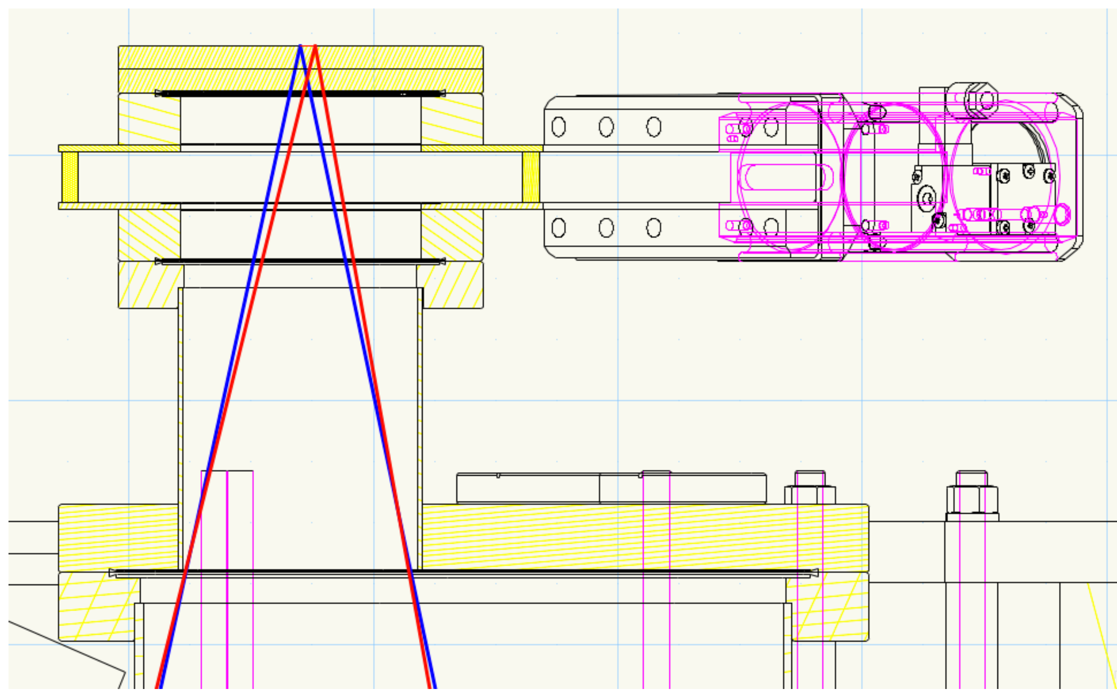
Equilibrium coils

6" conflat flange

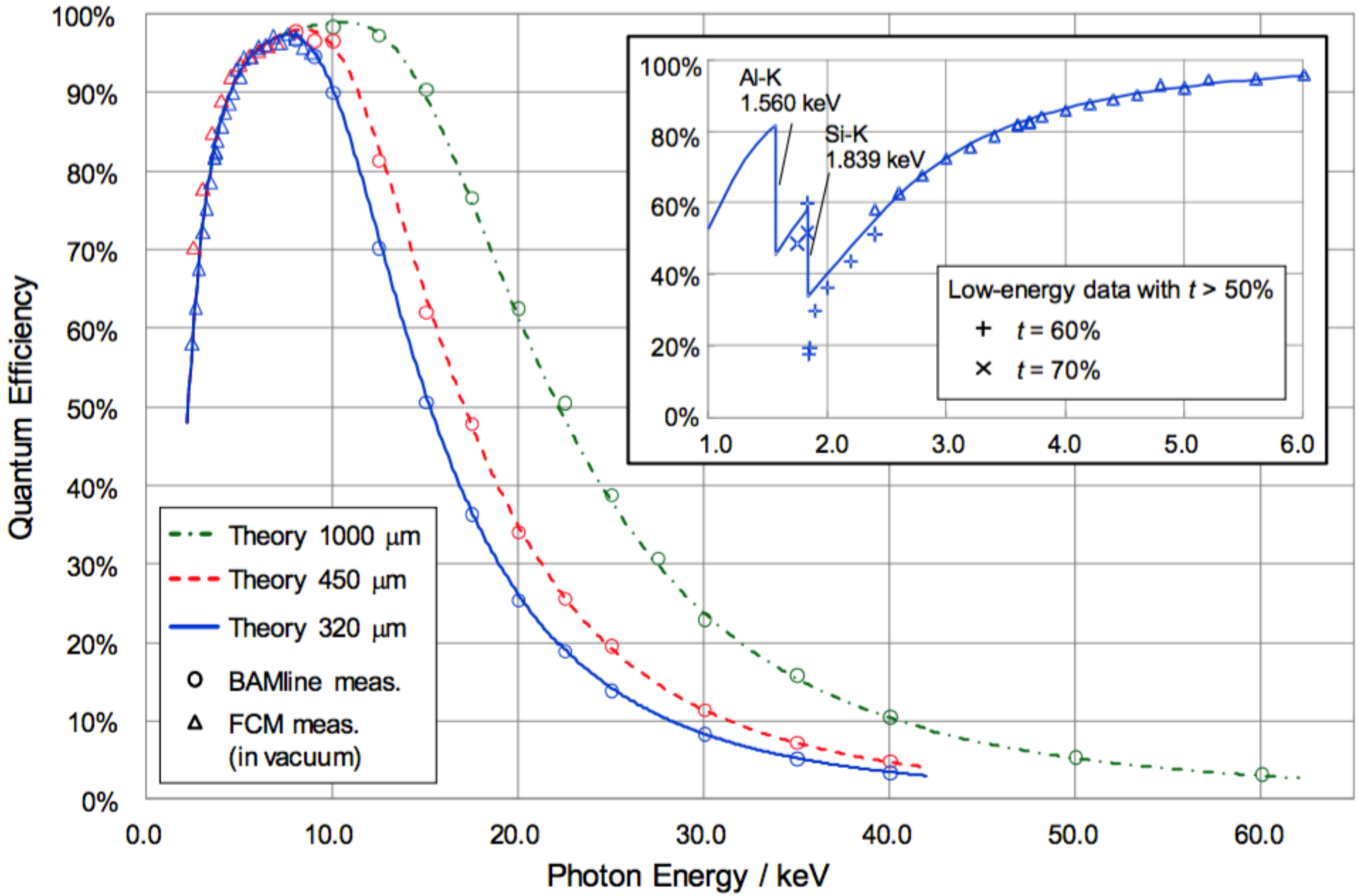
Top view allows x-ray coverage from both LFS and HFS (R_{min}~0.7 to R_{max}~1.5 m)



- Displacing the pinhole 6 mm to the LFS results in a sightline displacement of ~ 5 cm
- Drawing may not reflect blockage from NSTX-U's umbrella and and support plate.
- Re-entrant solution is being considered.



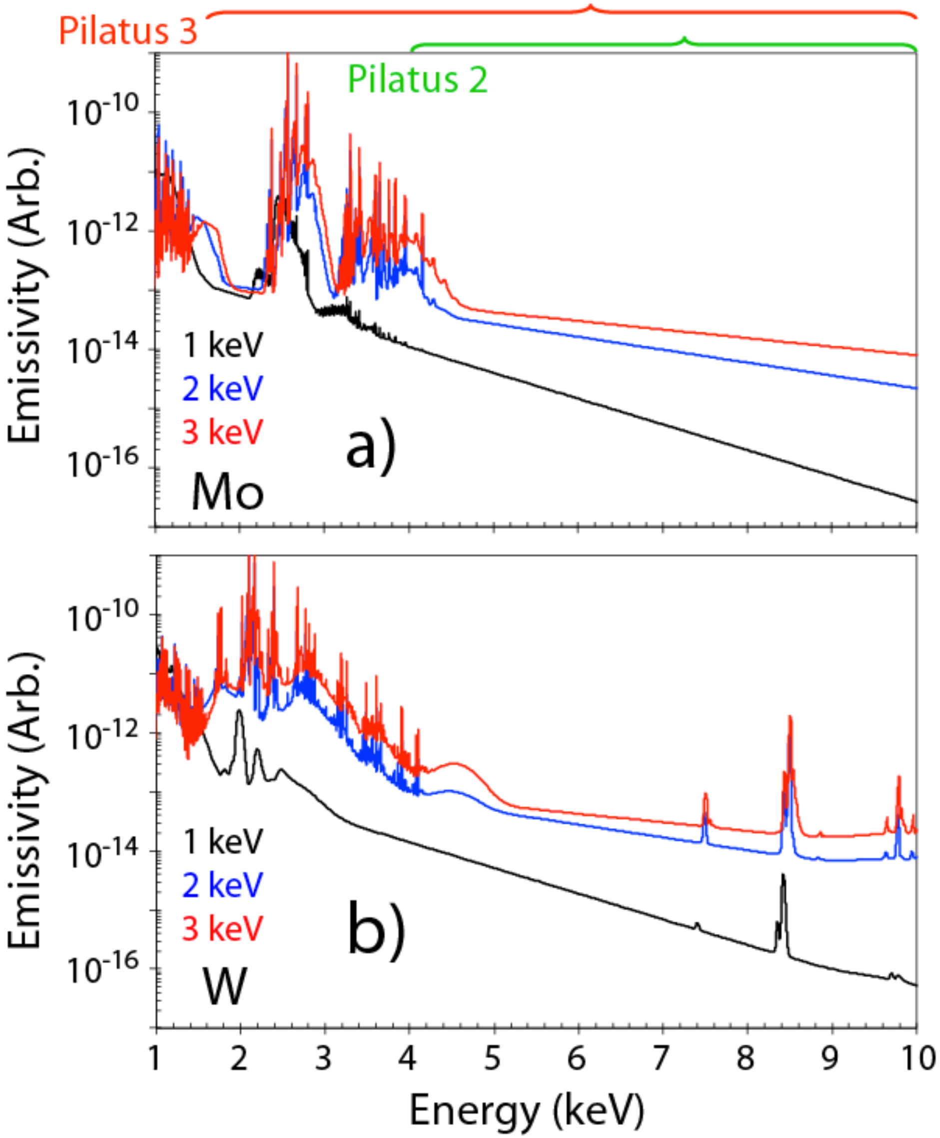
New PILATUS3 detector technology allows SXR detection from 1.6-1.8 to 10-20 keV



Pilatus3 detector technology will be used in NSTX-U for impurity transport research

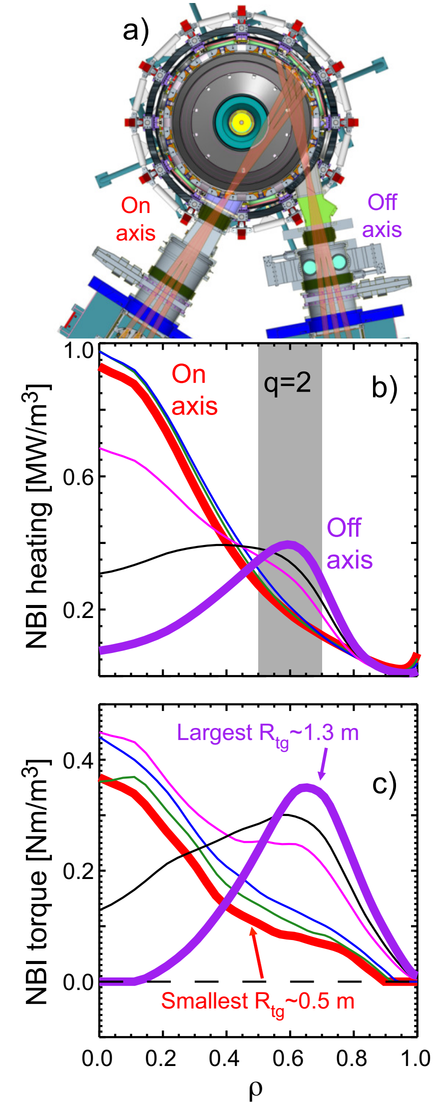
Pilatus3 enhanced sensitivity:

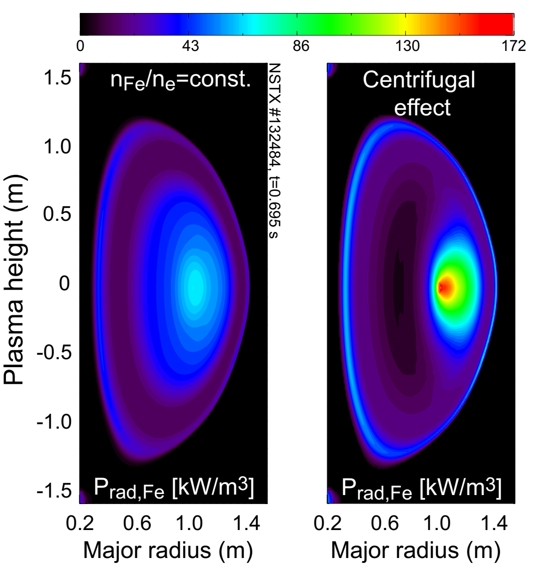
- Sensitive to Mo-emission (PFCs).
- Ca, Fe, Mo & W emission (laser-blow-off injection)
- Non-parallel photon counting technology > 10^7 ph/s/pixel
- Optimization of energy ranges
- ME-SXR tomography
- B_{max}: B_{DC}~2.5 T, dB/dt~3T/s
- Neutron fluence up to 10^{14} n_{eq}/ cm^2

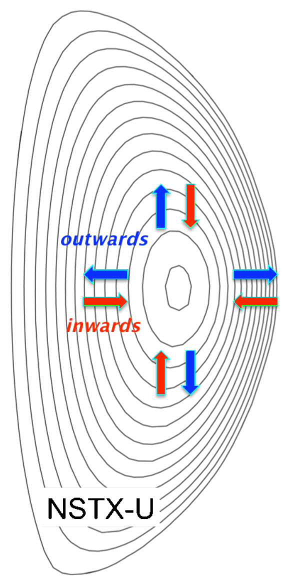


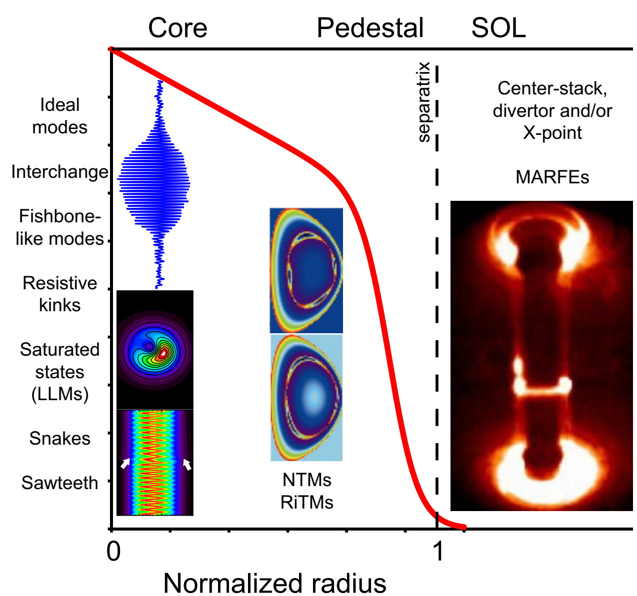
Physics program considers also the study & control of Z-transport and Z-induced-MHD

1. Study the role of neoclassical (including rotation effects) and turbulent impurity transport (TEP, TD and || compressibility).
2. Impurity peaking vs rotation and heating.
3. Effects of impurities on MHD at q=1 and q=2
4. Control using NBI, RF, RMPs, droplets, LBO, Li









Summary

1. ME-SXR imaging provides a unique opportunity of measuring, simultaneously, a variety of important plasma properties (T_e, $n_{Z\text{ (e.g. Ar, Ca, Fe, Mo, W)}}$, ΔZ_{eff} and $n_{e,fast}$).

2. Pilatus2 and Pilatus3 technology allows for individually selecting (64) energy ranges for all its 10^5 – nearly 10^7 pixels.

3. Two views are being considered for NSTX-U.

4. Test validity of ME-SXR analysis for L-mode and H-modes [inversion, Ω effects & impurity mix].

5. Limitation of Si above 20 keV for study of non-Maxwellian tails. Use higher-Z materials such as Ge, GaAs or CdTe (~100 keV).