U.S. DEPARTMENT OF ENERGY | Office of Science

NSTX-U

Multi-energy soft x-ray (SXR) cameras for NSTX-U [DOE-ECRP]

Luis F. Delgado-Aparicio

Princeton Plasma Physics Laboratory (PPPL)

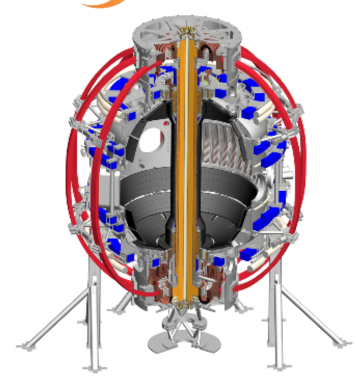
Presented at the NSTX-U diagnostic research planning meeting
Princeton, NJ 05/27/16

MIT

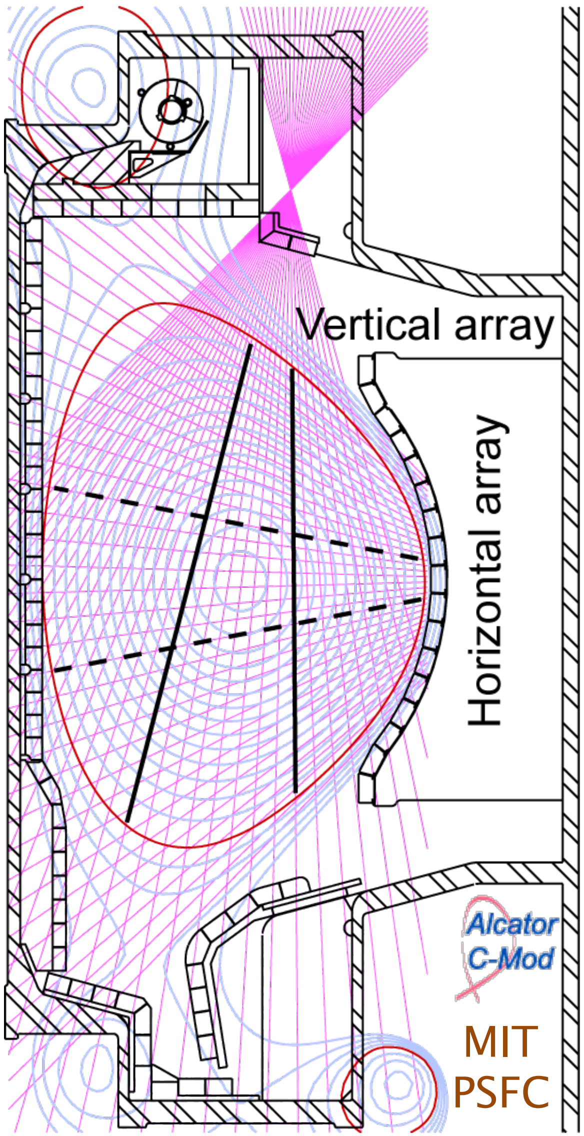
PSFC

Alcator C-Mod

PPPL



MOTIVATION: To 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: $S(E_{ph})$

GOAL: Develop ME-SXR capability for MCF plasmas (w/o metallic plasma facing components)

A multi-energy soft x-ray (ME-SXR) imaging capability provide 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 used in:

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

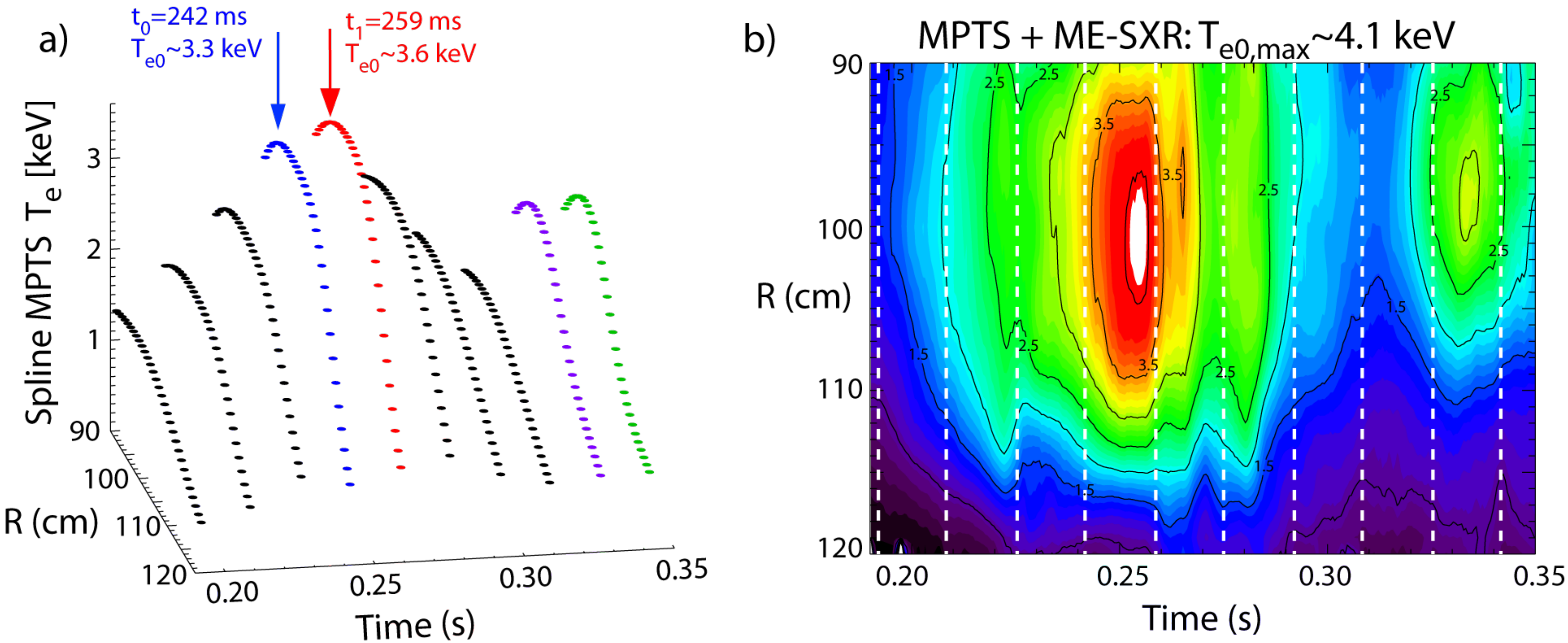
Applicable to/for:

Stability: Plasma positioning, low-freq. MHD phenomena, 3D RMP effects and runaway e^-.

Transport: Impurity particle- & electron thermal-transport.

Heating: RF deposition (e.g. T_e, HHFW & LHCD$\Rightarrow$non-maxwellian e^-).

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 (Delgado-Aparicio, et al., PPCF'07, RSI'10, D. J. Clayton, PPCF'13)

ii. RF heated plasmas using HHFW waves (Delgado-Aparicio, et al., JAP'07)

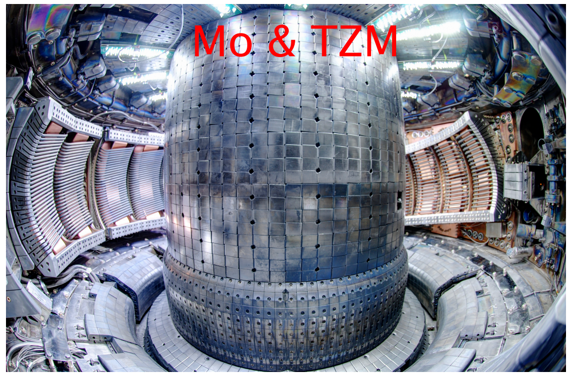
iii. Plasmas with slow MHD (RWMs) using RMPs (Delgado-Aparicio, et al., PPCF'10)

CHALLENGE: Line emission from high-Z metals difficult the use of the multi-foil technique

C-Mod (MIT), NSTX-U (PPPL), WEST (France), JET (UK), ASDEX (DE) and ITER will have metallic PFCs

PSFC MIT

Alcator C-Mod



Low-Z
Boron (fully stripped)
Carbon (fully stripped)

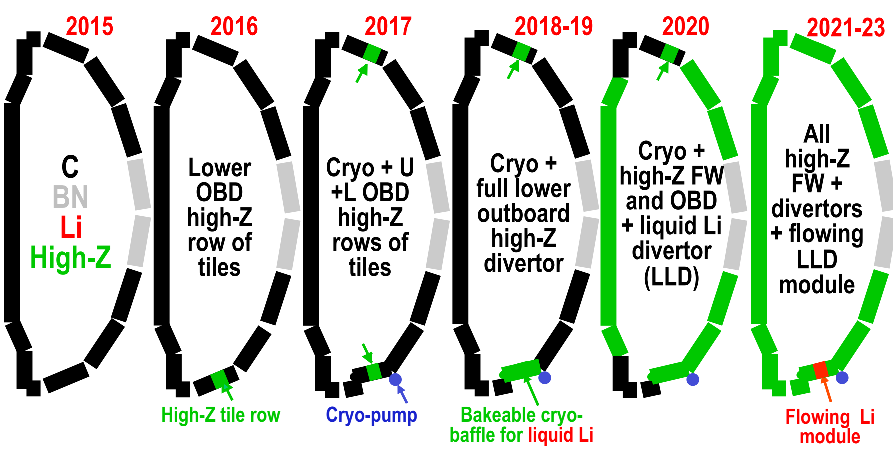
Medium-Z
Argon (He- and H-like)

High-Z
Molybdenum (Ne-like)

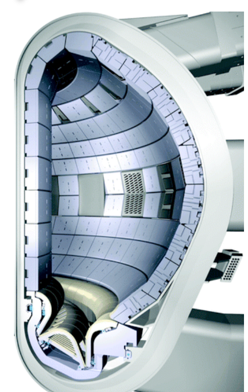
Nominal 5-7 year plan steps for implementation of high-Z wall in NSTX-U

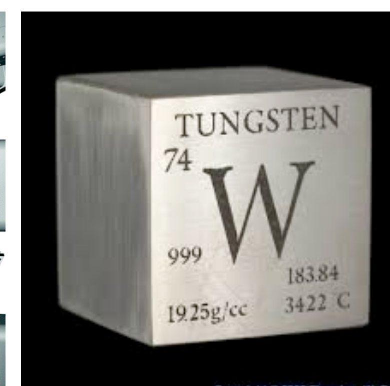
PPPL

NSTX-U



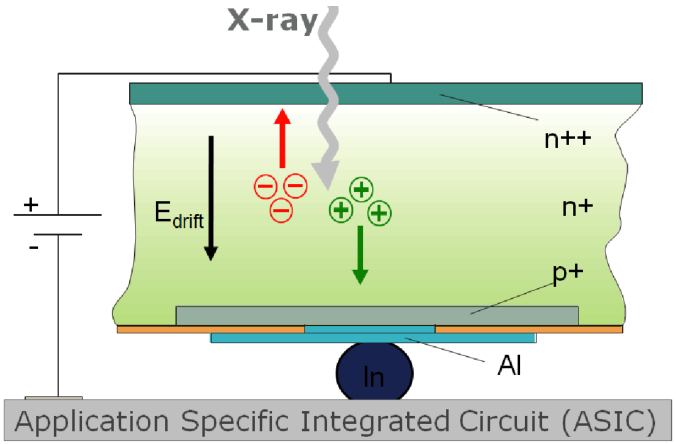
ITER will have Be & W PFCs



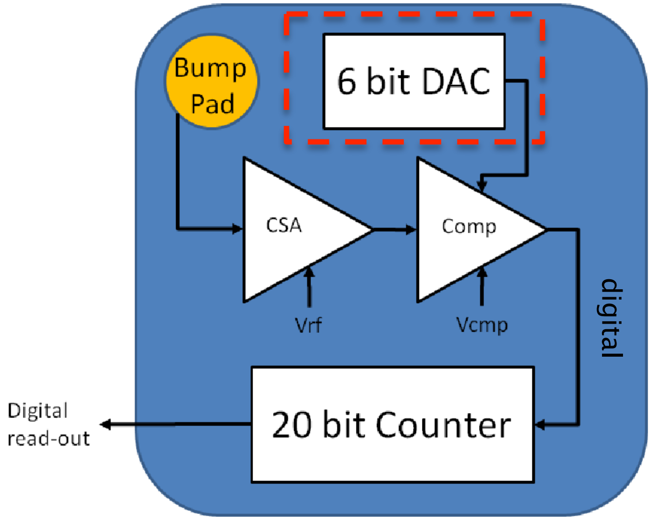


Pilatus cameras enable breakthrough of 100k pixels (minimum) at multiple energy ranges

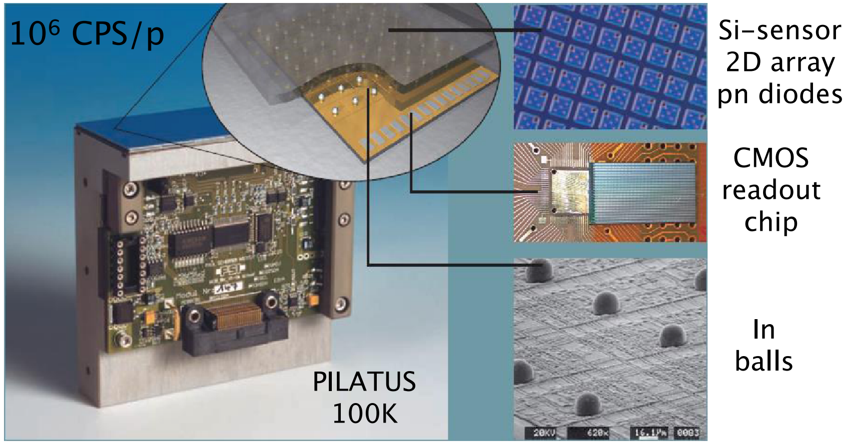
Operates in single photon counting mode



Photon counting circuit in **each pixel**



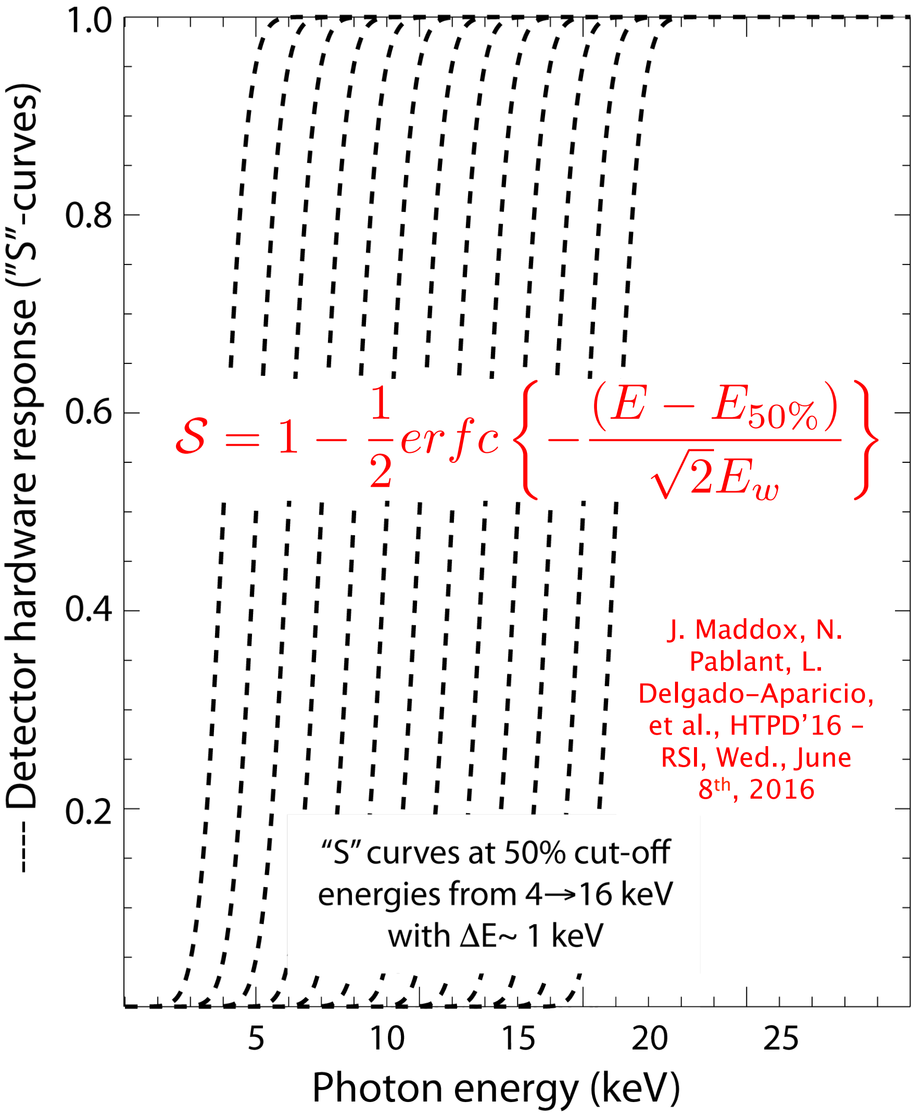
CMOS hybrid pixel technology



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

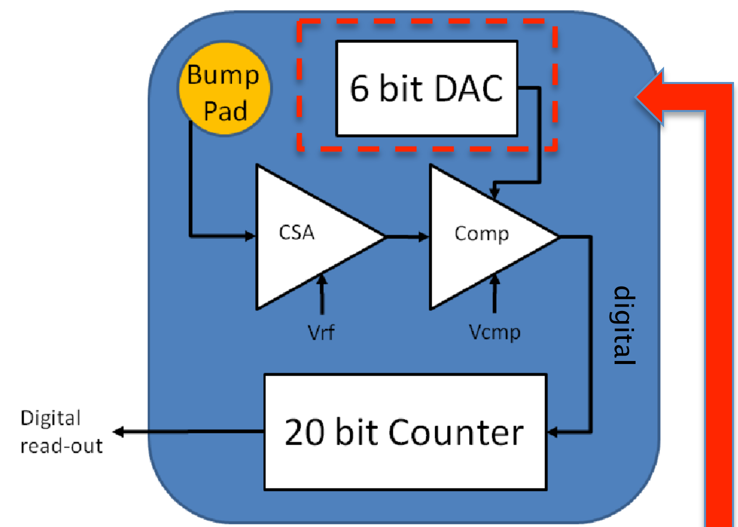
- The threshold energy can be individually *refined/trimmed* using and in-pixel 6-bits DAC (V_{trim}).

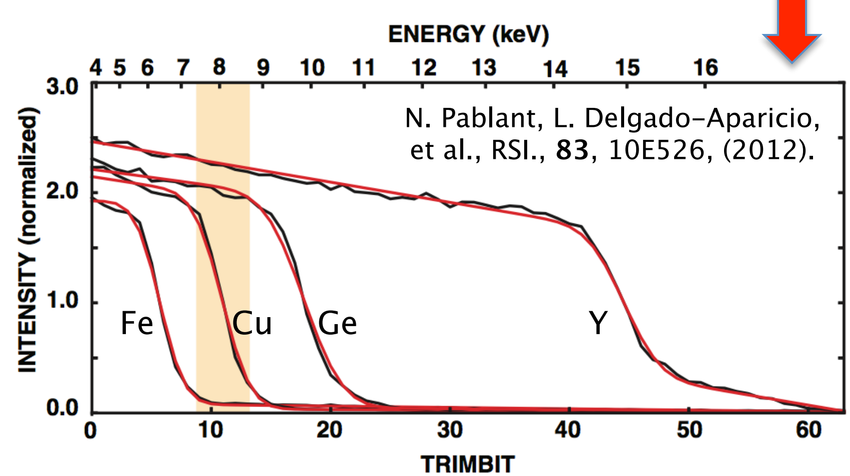
V_{Comp} & V_{trim} allows individual coarse & fine tuning of energy range with E_{width}=0.6 keV



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

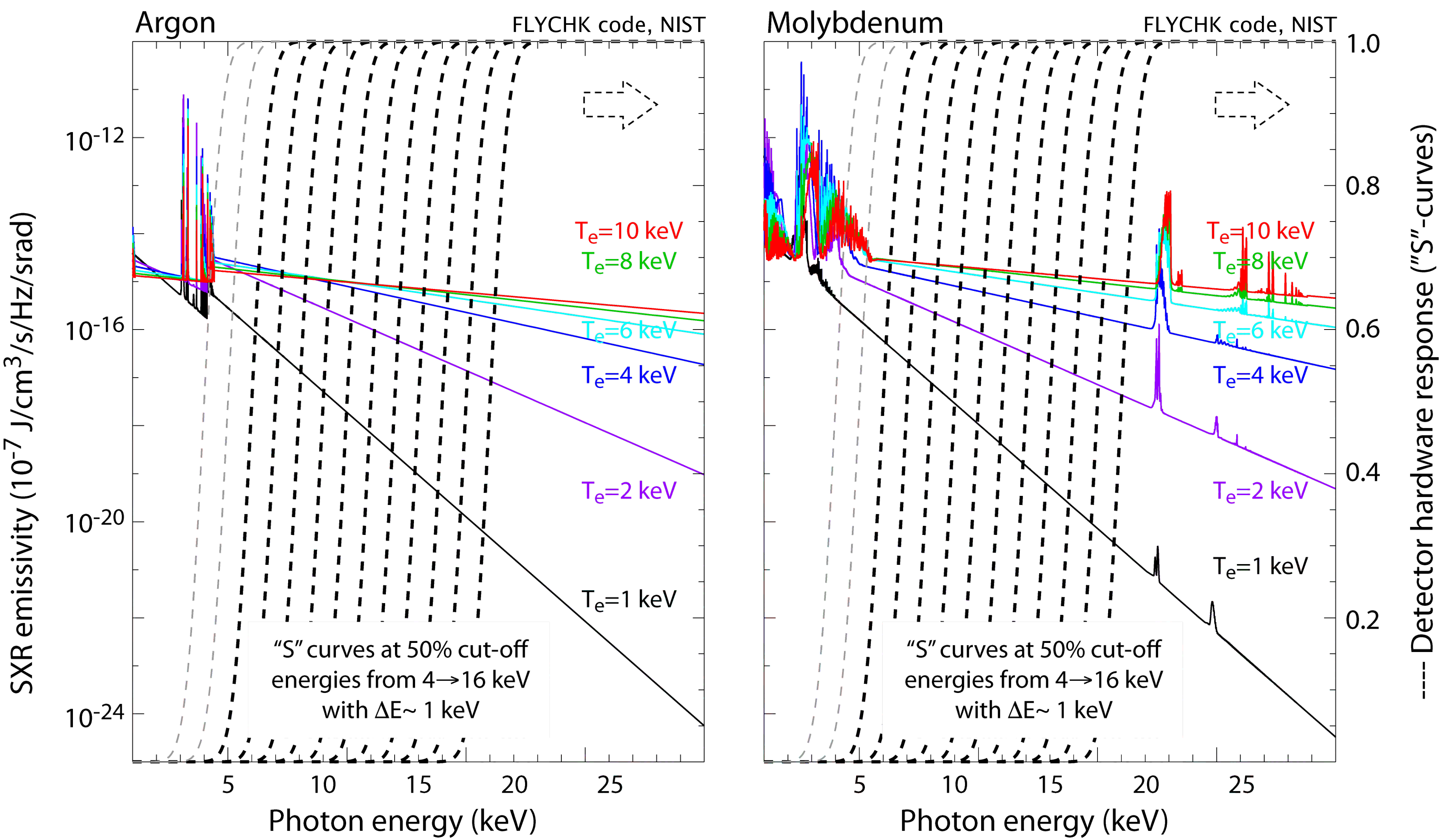
Photon counting circuit in **each pixel**





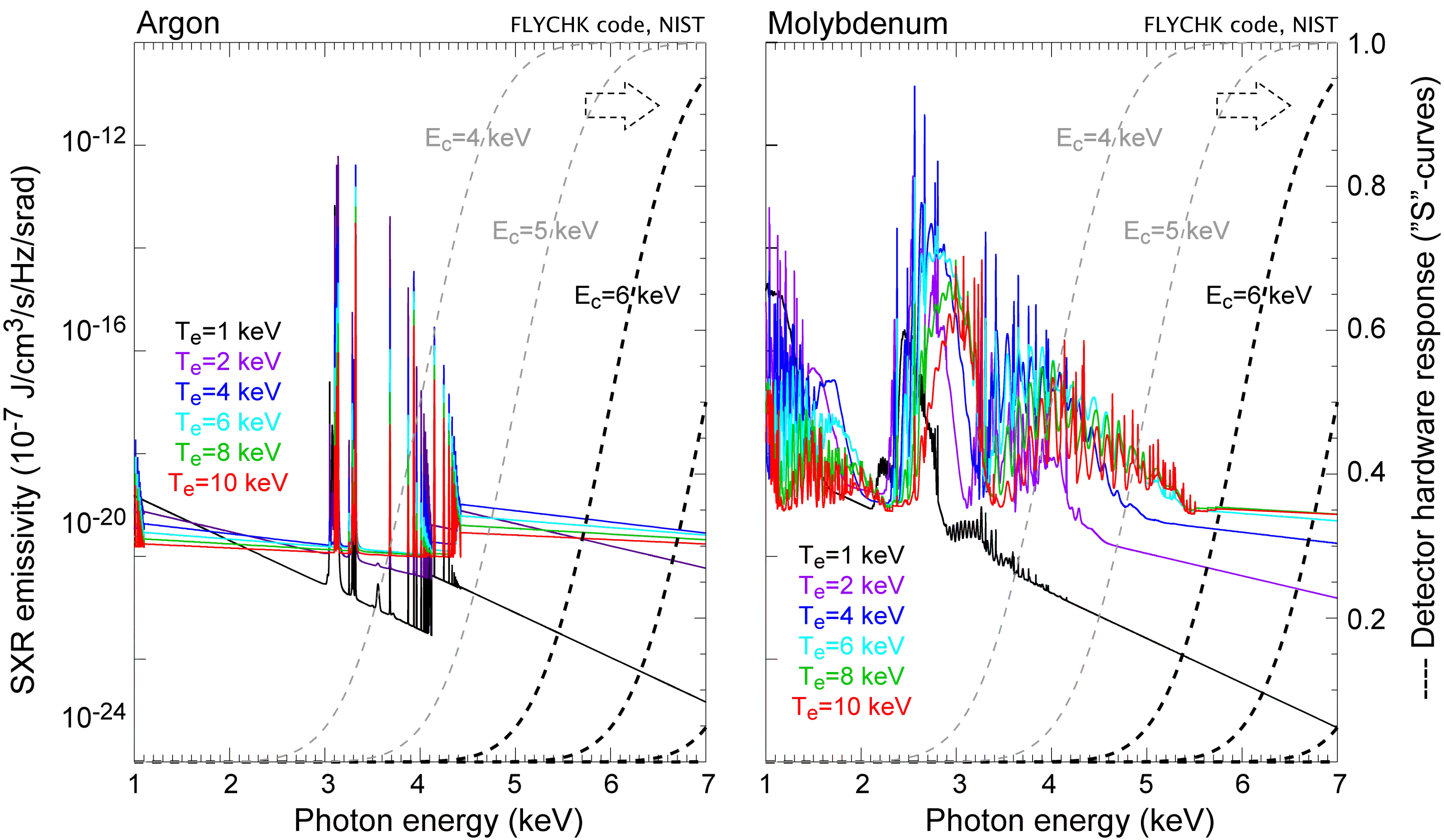
Multiple detector thresholds allow “sampling” ONLY the continuum radiation from Ar and Mo

“Filtered” continuum radiation from Ar & Mo can be used to measure $T_{e,0}$ & $n_e^2Z_{eff}$

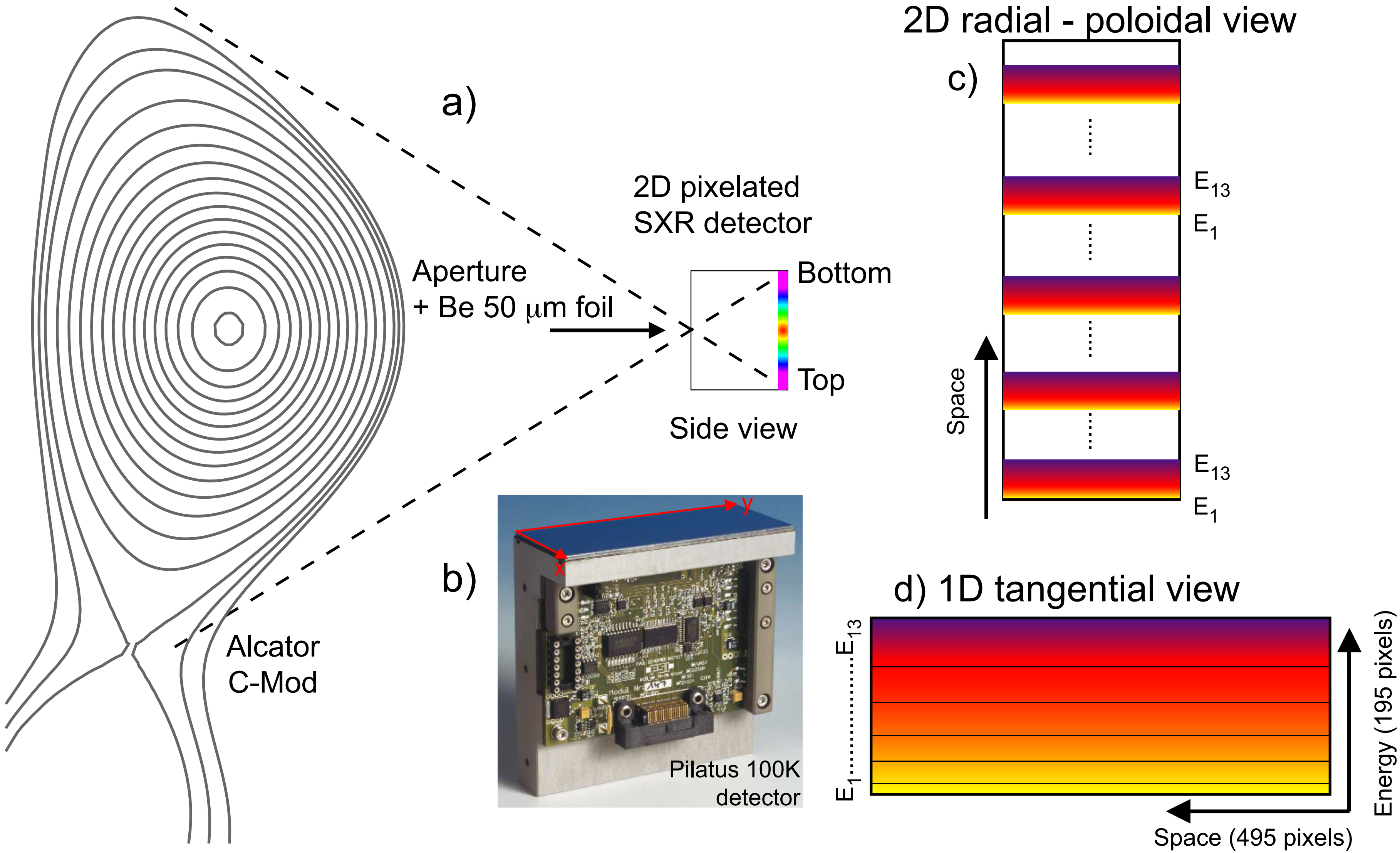


Detector response with 4≲$E_{cut-off}$≲6 keV will be sensitive to <u>**low-E**</u> line-emission

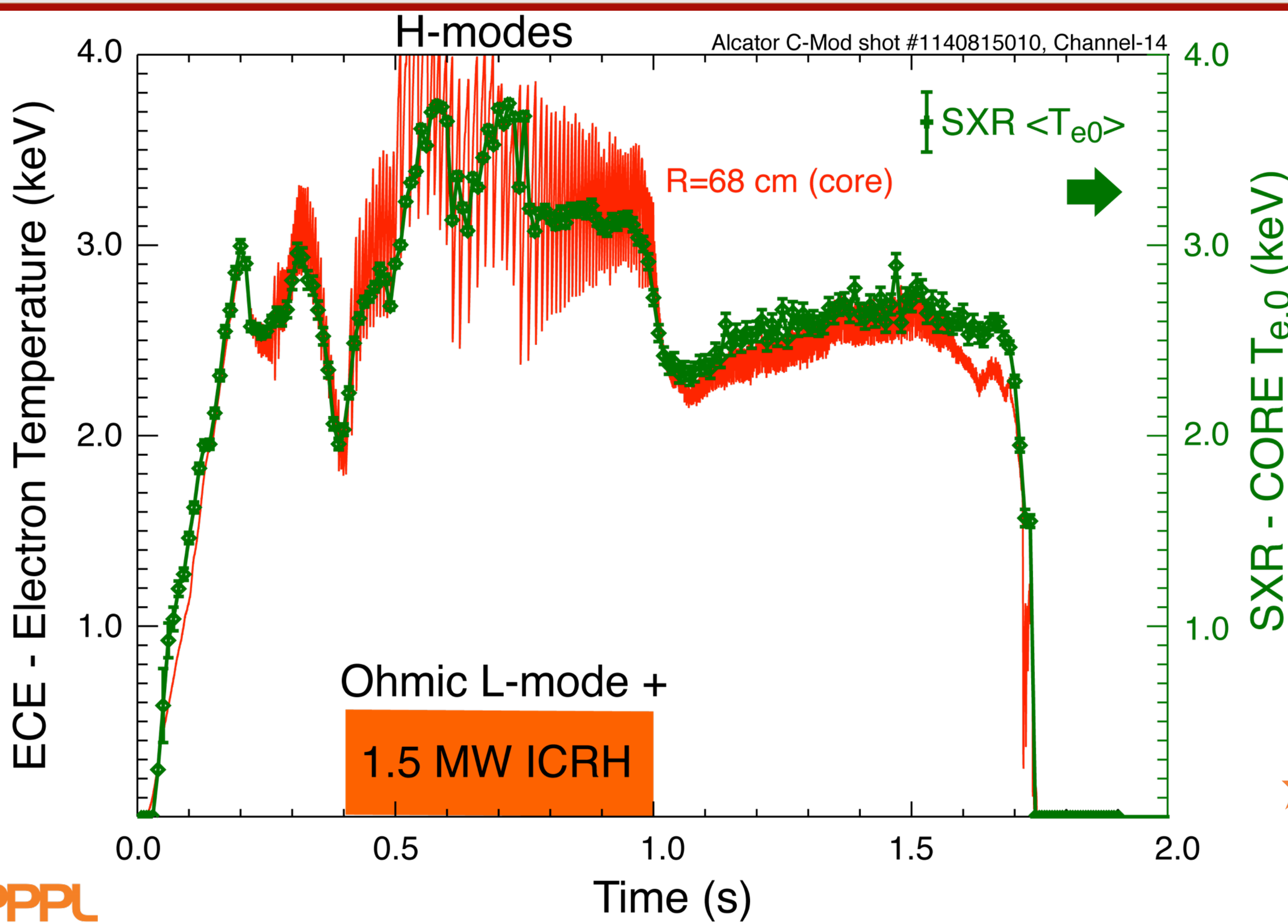
Line-emission from Ar & Mo <u>**can be used**</u> to constrain n_{Ar} & n_{Mo}



Imaging tests optimized in FY14-15 combined the best features from PHA & foil methods



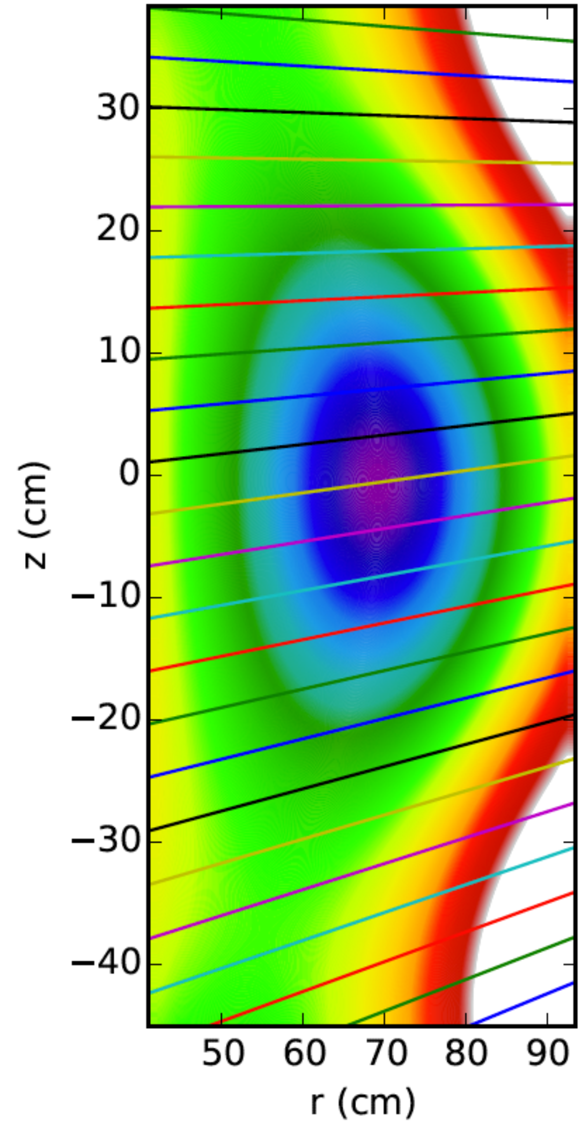
$T_{e,0}$ fits from core ME-SXR brightness measurements are in agreement with ECE



Work flow– Reconstruction and analysis

1. ME-SXR tomography:

- Use magnetic flux surface reconstruction
    - i. Include the effect of centrifugal forces
    - ii. Tangential view will facilitate inversion
- Measurement of local emmisivities (B=MxE)



2. Use FLYCHK for continuum and line emission:

Bremsstrahlung:

$$\frac{d\mathcal{P}_{ff}^{ij}(T_e,E)}{dE} \propto \frac{n_e^2 C_i (n_{ij}/n_i) Z_{ij}^2}{T_e^{1/2}} \mathcal{G}_{ff}(Z,T_e,E)\exp(-E/T_e)$$

Radiative recombination:

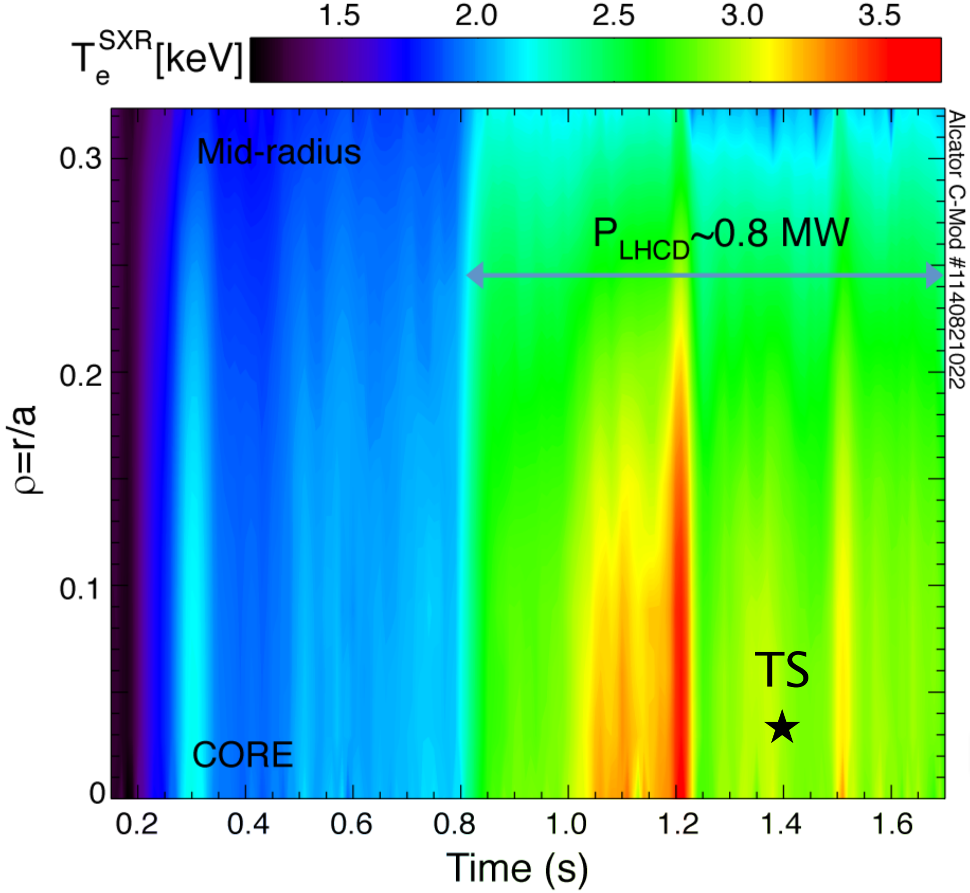
$$\frac{d\mathcal{P}_{fb}^{ij}(T_e,E)}{dE} \propto \frac{n_e^2 C_i (n_{ij}/n_i) Z_{ij}^2}{T_e^{1/2}} \beta_{ij}(T_e,E)\exp(-E/T_e)$$

Line emission:

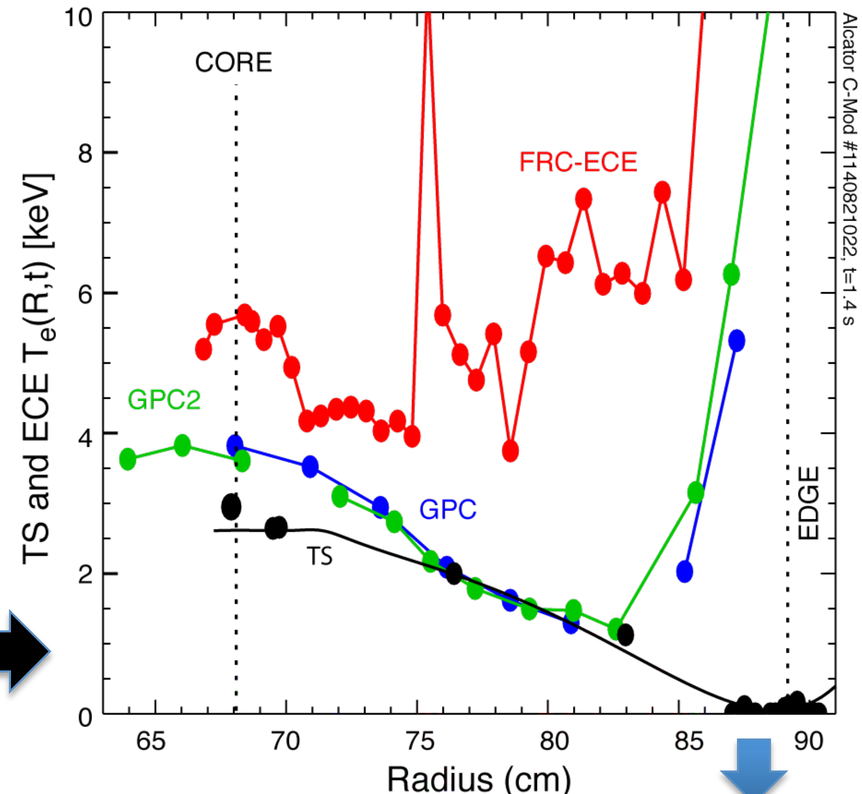
$$\frac{\mathcal{P}_L^{ij}(T_e,E)}{E_L} \propto n_e^2 C_i \,(n_{ij}/n_i)\,\langle \sigma v(T_e,E)_{ij}\rangle$$

T_e^{SXR} in agreement with Thomson Scattering temperatures in RF ICRH & LHCD scenarios

ME-SXR inferred $T_e(r,t)$

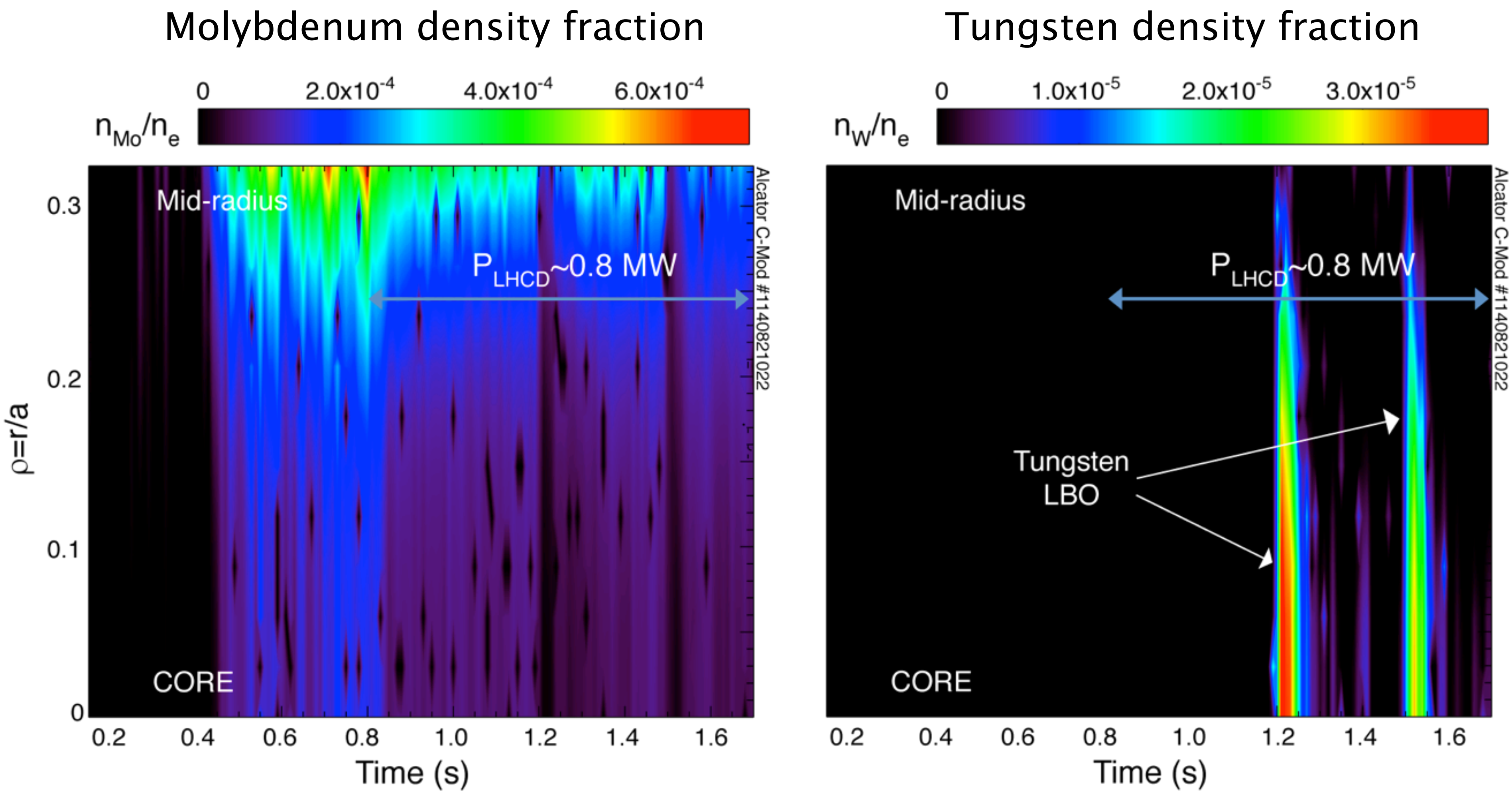


Thomson Scatterring (TS) and ECE $T_e(r,t)$ profiles during LHCD



Lower-hybrid current drive pulls non-Maxwellian tails inducing a downshift in the electron gyrofrequency ($\Omega=eB/\gamma m_e$) which "pollutes" the ECE measurements

ME-SXR technique can measure the background Mo and W-LBO contributions simultaneously



Measurements are consistent with other diagnostics (Bolometer and XTOMO)

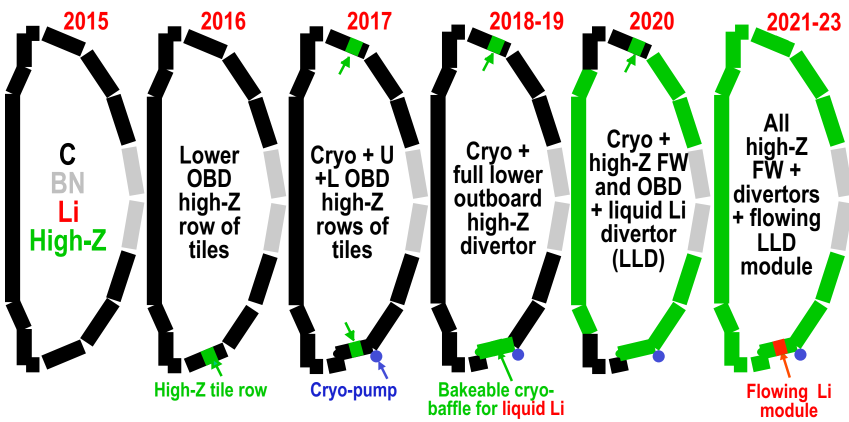
Future work in NSTX-U (FY17 onwards)

① New detector response calibration of Pilatus3 system (FY16)

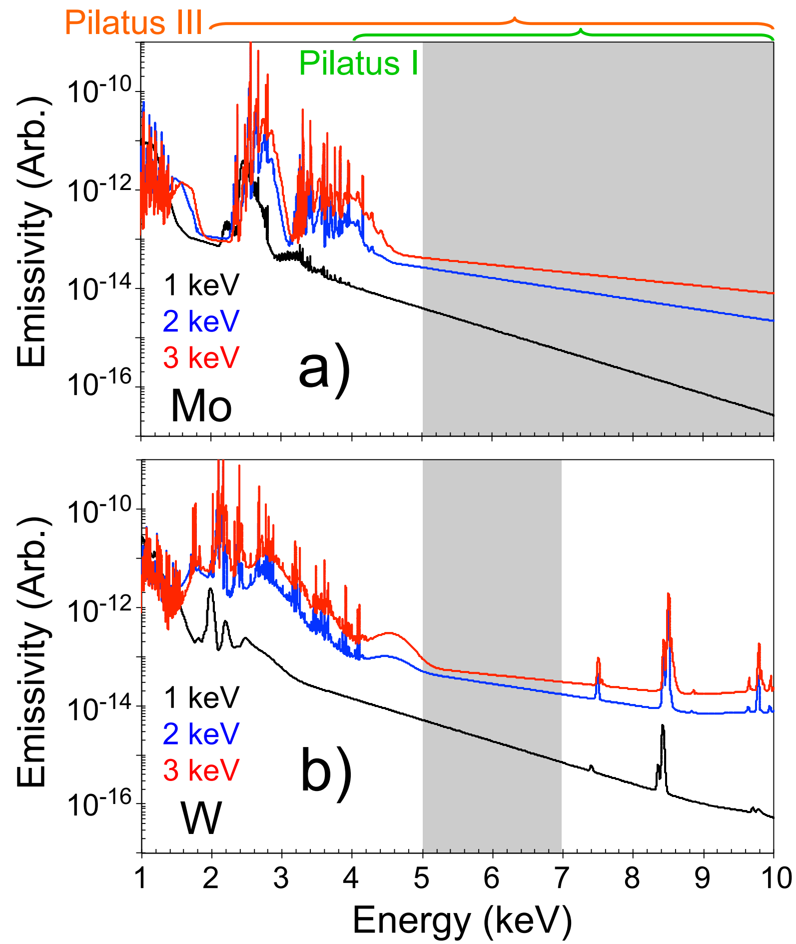
- Recently done at DECTRIS.
- Repeat with new NSTX-U detectors

② Pilatus3 detectors in NSTX-U:

- Sensitive to Ar, Ca, Fe, Mo & W emission
- Non-paralyzable photon counting technology allows > 10^7 ph/s/p
- Post-doc and students



Pilatus III technology will enhance imaging capabilities



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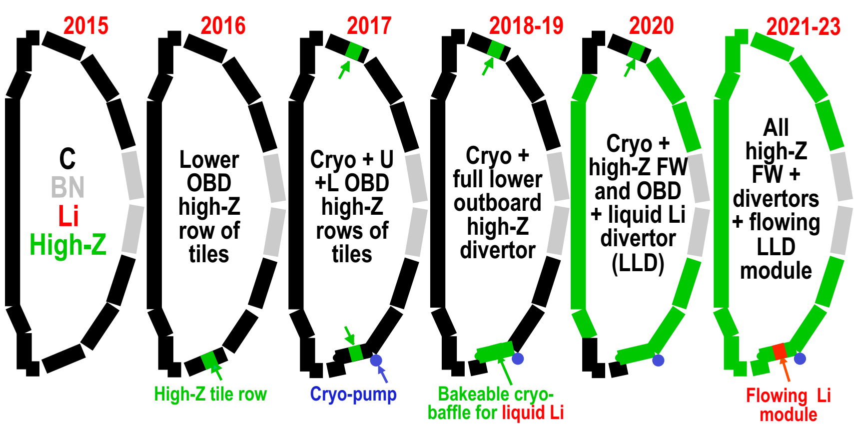
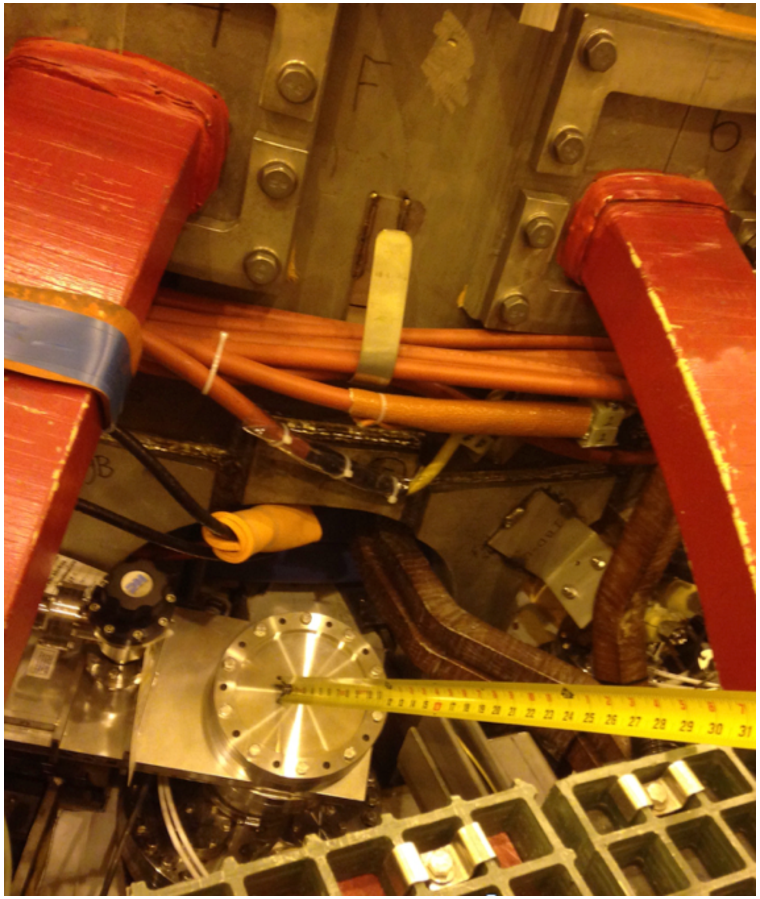


③ Integrate pol. & tang. views (FY17) => Engineer support!

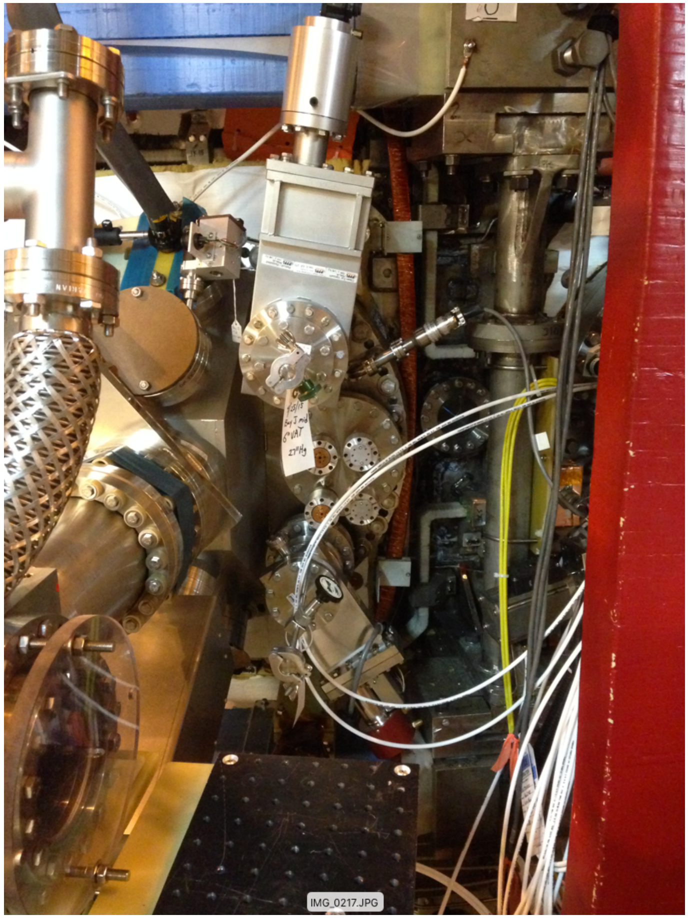
Bay G top



Options for tangential installation

1st choice – Bay K
(off 2nd NBI)

2nd choice – Bay J
(New mother flange!)



Bay I
(midplane-radial)

Awarded DOE-ECRP considered also 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