Adaptive energy-sensitive x-ray cameras for the record long-pulse at WEST

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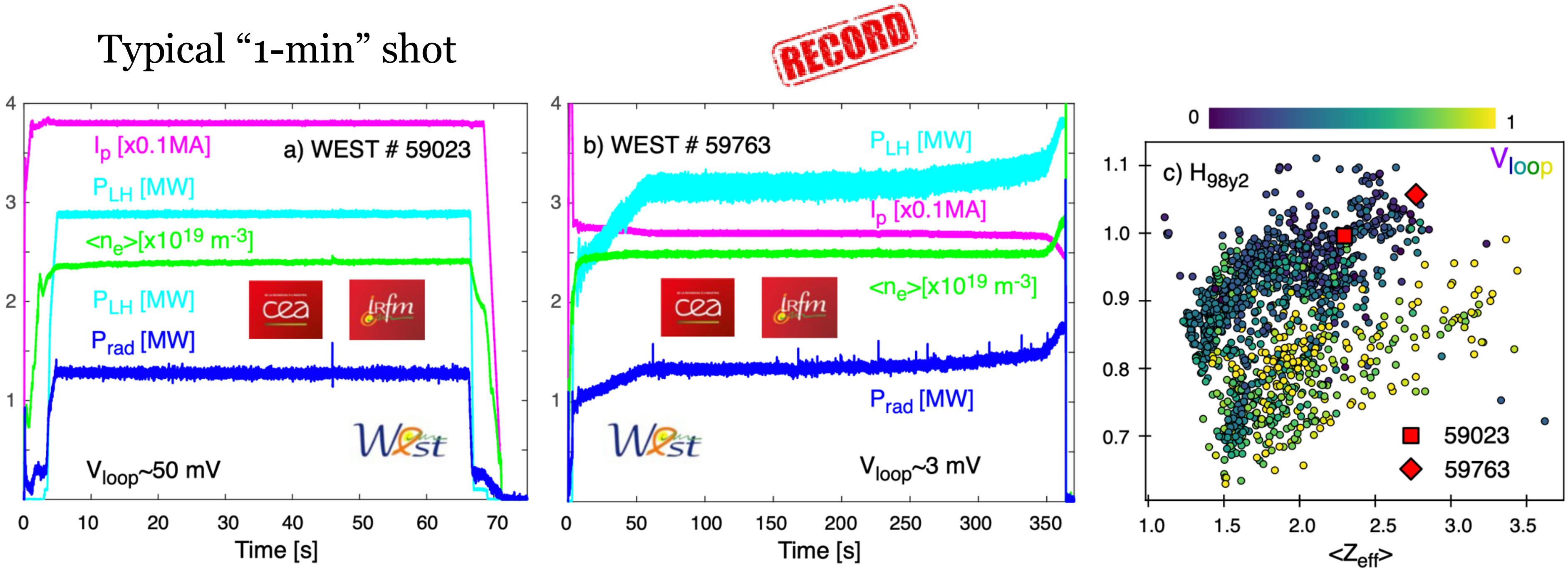
Agenda

1) Long Pulse operation @ WEST
2) X-ray spectroscopy…back to the basics!
3) Goals & challenges of multi-energy program
4) Circumventing the “W-challenge” at WEST
5) Few results and physics
6) Implementation of RT detection of W-UFOs @ WEST
7) Future tasks
8) Summary

Long pulse operations (LPO) open a new era of expertise, training (e.g. physics and engineer) & collaborations

Typical "1-min" shot



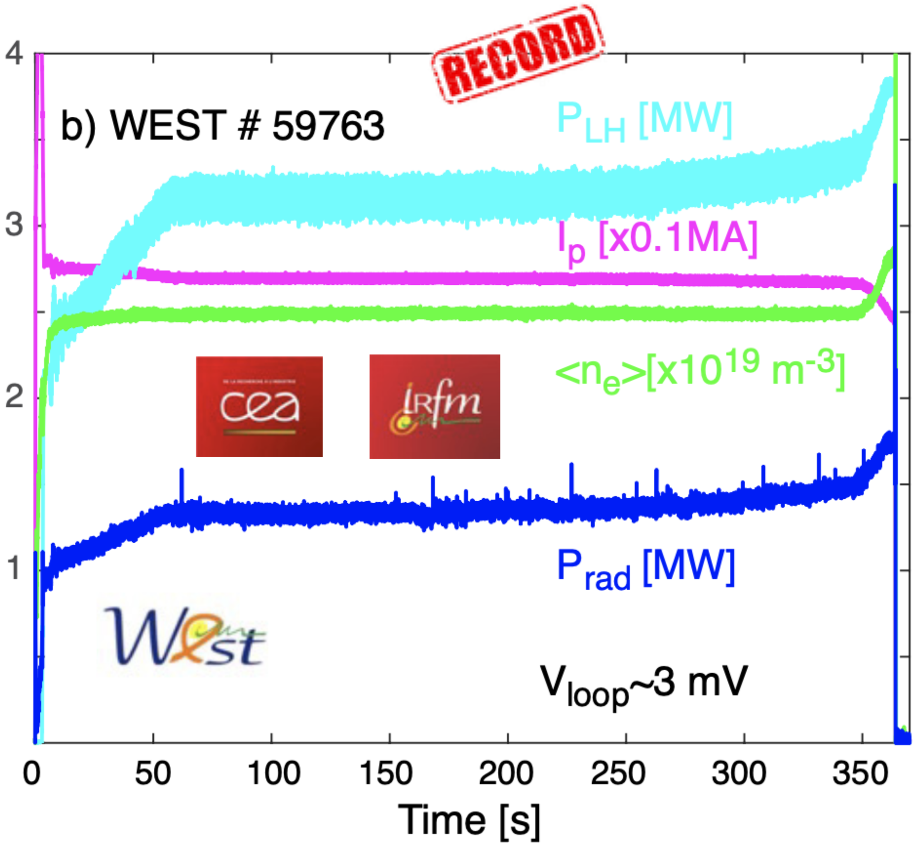
- Hot temperature branch @ 4-5 keV with density nearly a factor 2 compared to its predecessor
- Non-inductive ($V_{loop} \rightarrow 0$) long-pulse discharges with no external input torque and particle source
- Resilience to tungsten UFOs and an improved L-mode confinement ($H_{98y,2} \sim 1.0$, $\beta_p \sim 1.6$ & $\beta_N \sim 0.7$) lasting 6 mins
- Without W-wall conditioning and using a total of 1.146 GJ of injected energy.

Long pulse operations (LPO) open a new era of expertise, training (e.g. physics and engineer) & <u>collaborations</u>

Long pulse operation (LPO) redefines all our <u>diagnostic timescales</u> over eight-nine orders of magnitude

$\times(10^8\text{-}10^9)$

- $\tau_{MHD} \sim 1 - 100\ \mu s$
- $\tau_{ELM} \lesssim 1$ ms
- $\tau_{UFO} \sim 20\text{-}50$ ms
- $\tau_{Transport} \sim 1\text{-}20$ ms
- $\tau_E \sim 50\text{-}70$ ms
- $\tau_{Ex:e,i} \sim 250$ ms
- $\tau_{Ip} \sim 100$ s
- $\tau_{PMI} \sim 100\text{'s}$ s



Diagnostic community continues exploring innovative x-ray techniques for fusion

① Important % of the P_{in} is lost as radiation (~50%).

② $P_{rad,X}$ is subset of P_{rad} … high as 50-90%

③ Easier to get the signals out than the visible range !!!

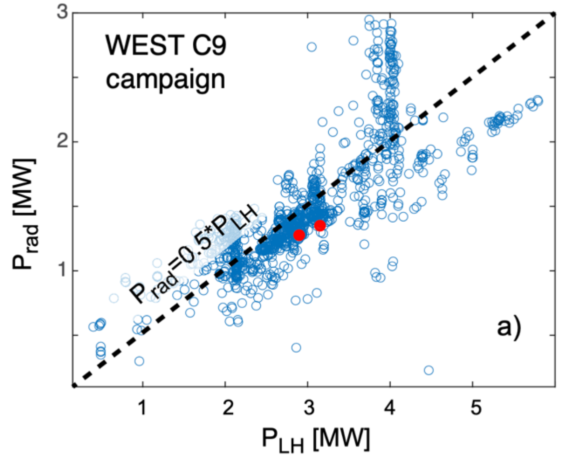
④ X-rays: dominant source of radiation ($h\nu = hc/\lambda \sim T_e$):
- 100 eV$<T_e<$20 keV ⇒ 0.5 Å $< \lambda <$130 Å ⇒ X-rays!
- 20 keV$< E_e <$ 200 keV ⇒ SXR to HXR

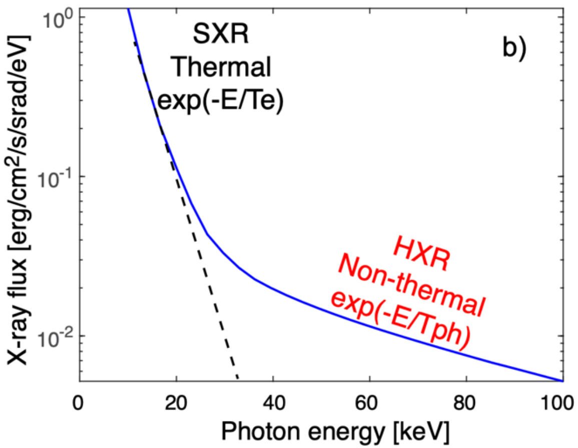
⑤ Measurement of $P_{rad,x}$ will enable:

⇒ Emiss[ph/cm²s, W/cm²], n_e, n_Z, T_e, T_Z, V_ϕ, V_θ & n_{RE}

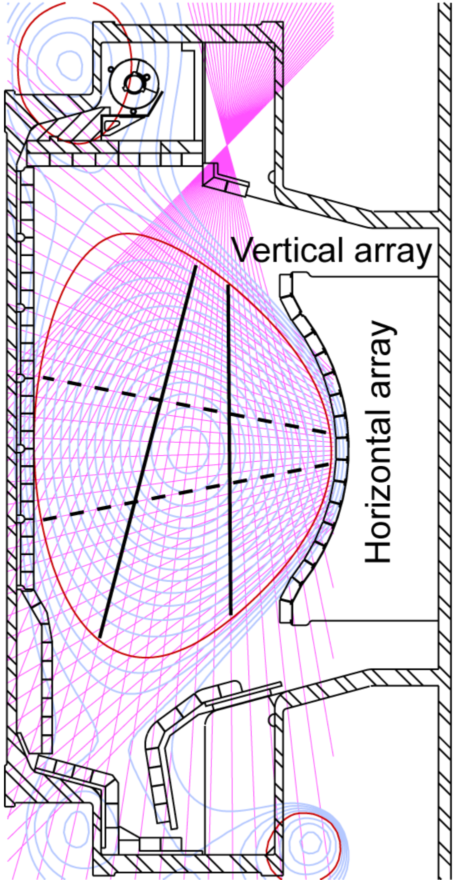
⑥ Ensure vacuum compatibility and in-situ calibration

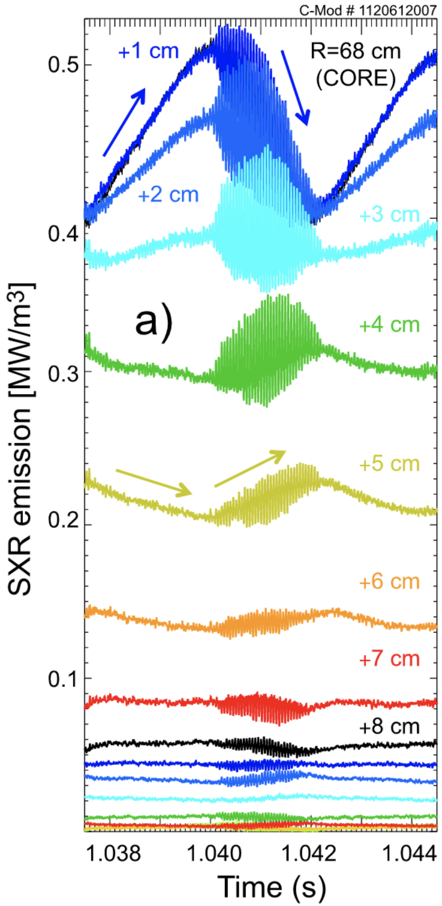
⇒Important technological & engineer development

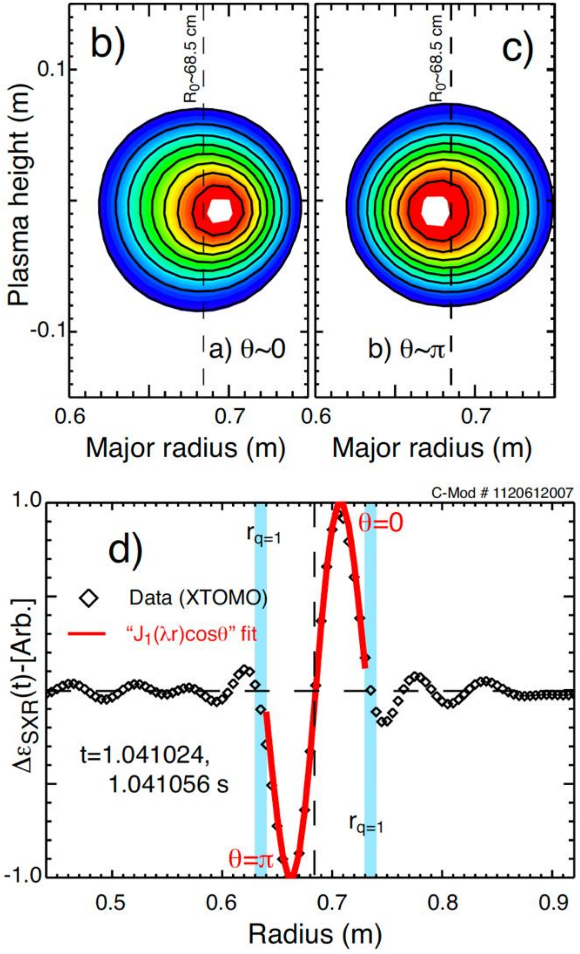




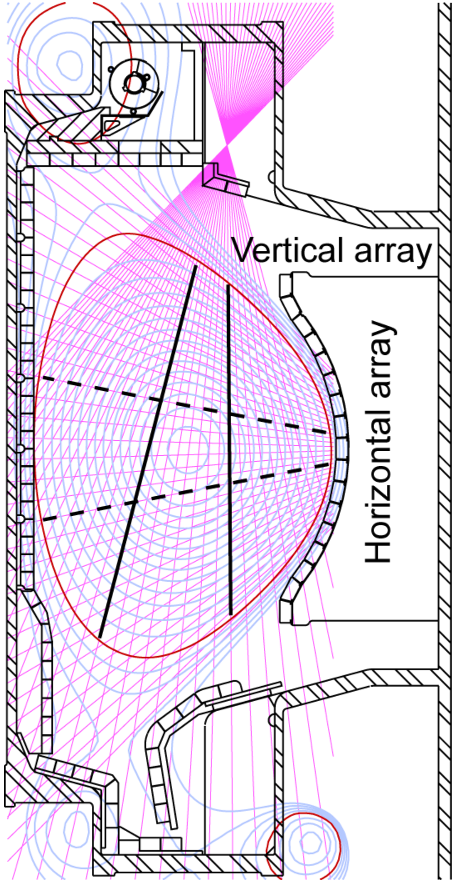
Conventional SXR tomography helps to study MHD:
e- and ion fishbones



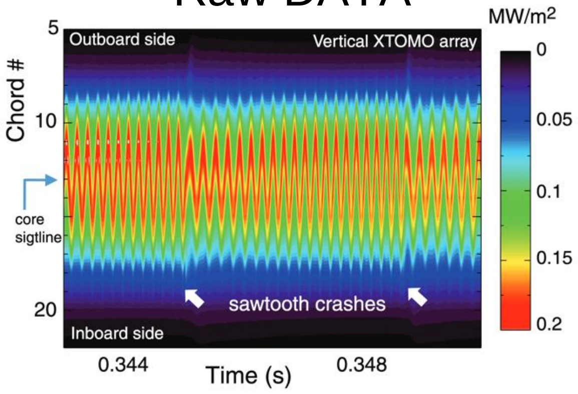




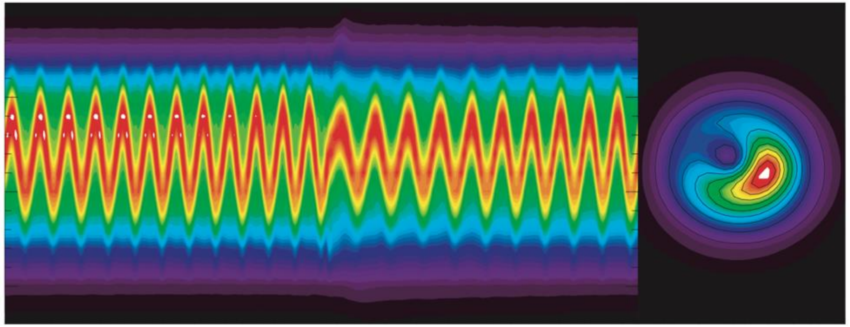
Conventional SXR tomography helps to study MHD:
(1,1) kinks, islands and LLMs



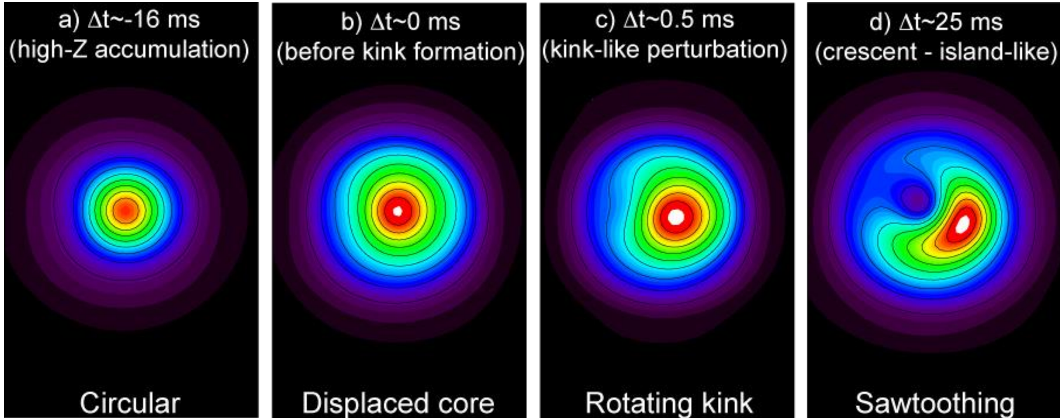
Raw DATA



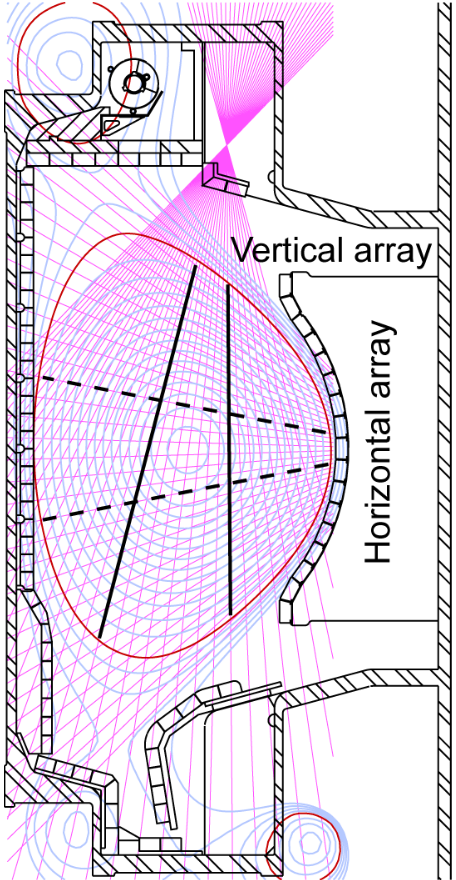
DATA + reconstruction

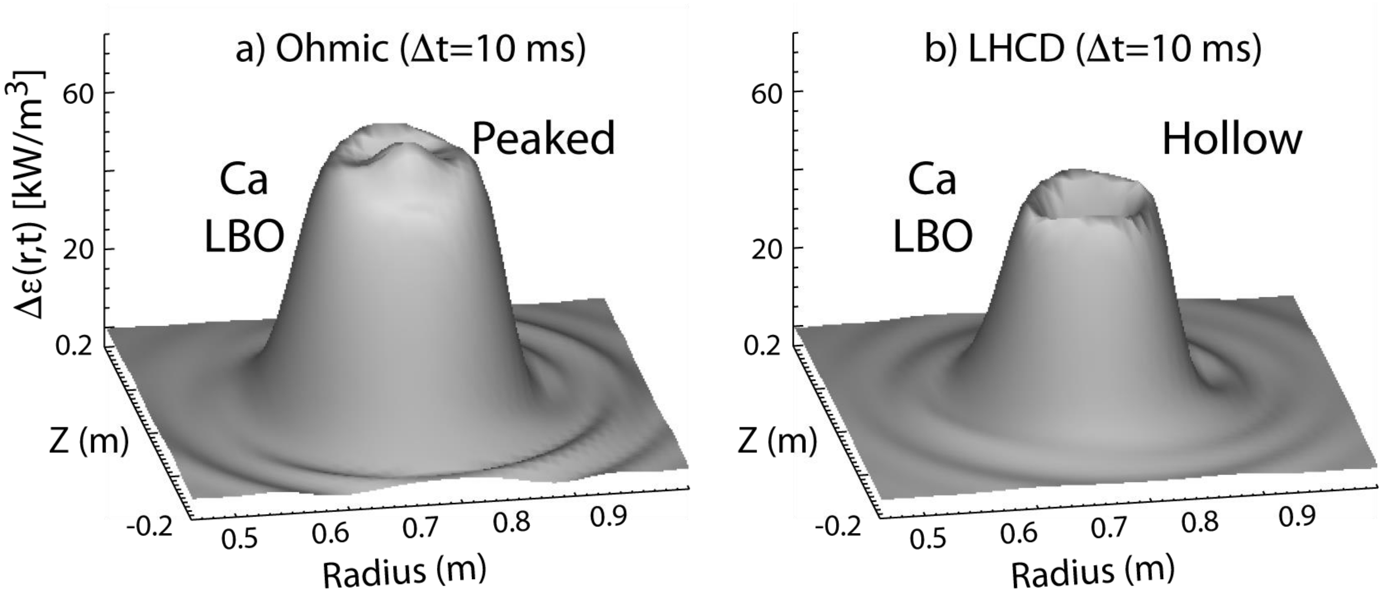


Time history of mode-formation



Conventional SXR tomography helps to study transport: particle (n_e) and medium- to high-Z (n_Z)





$$\Gamma_Z = -D_Z \nabla n_Z + V_Z n_Z$$

Programmatic GOALs:

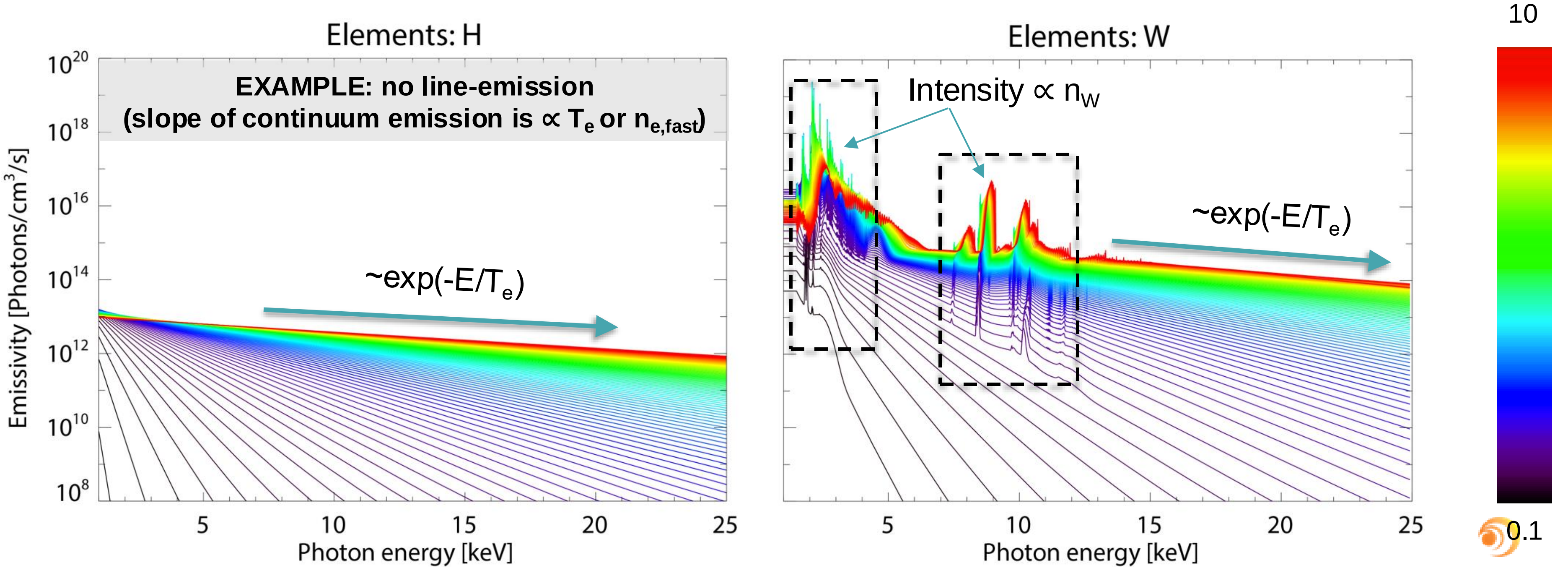
① RT-centroid (R_0, Z_0) and shape (Ψ) through Shafranov-shift (Δ_{SS})

② Real-time detection of UFOs which impact performance

③ n_Z & ΔZ_{eff} ***bracketing*** line radiation (BB)

④ T_e & $n_e^2 Z_{eff}$ ***sampling*** continuum (FF + FB)

⑤ $n_{e,nM}$ (e.g. ECCD, LHCD, runaways)



Programmatic Challenges:

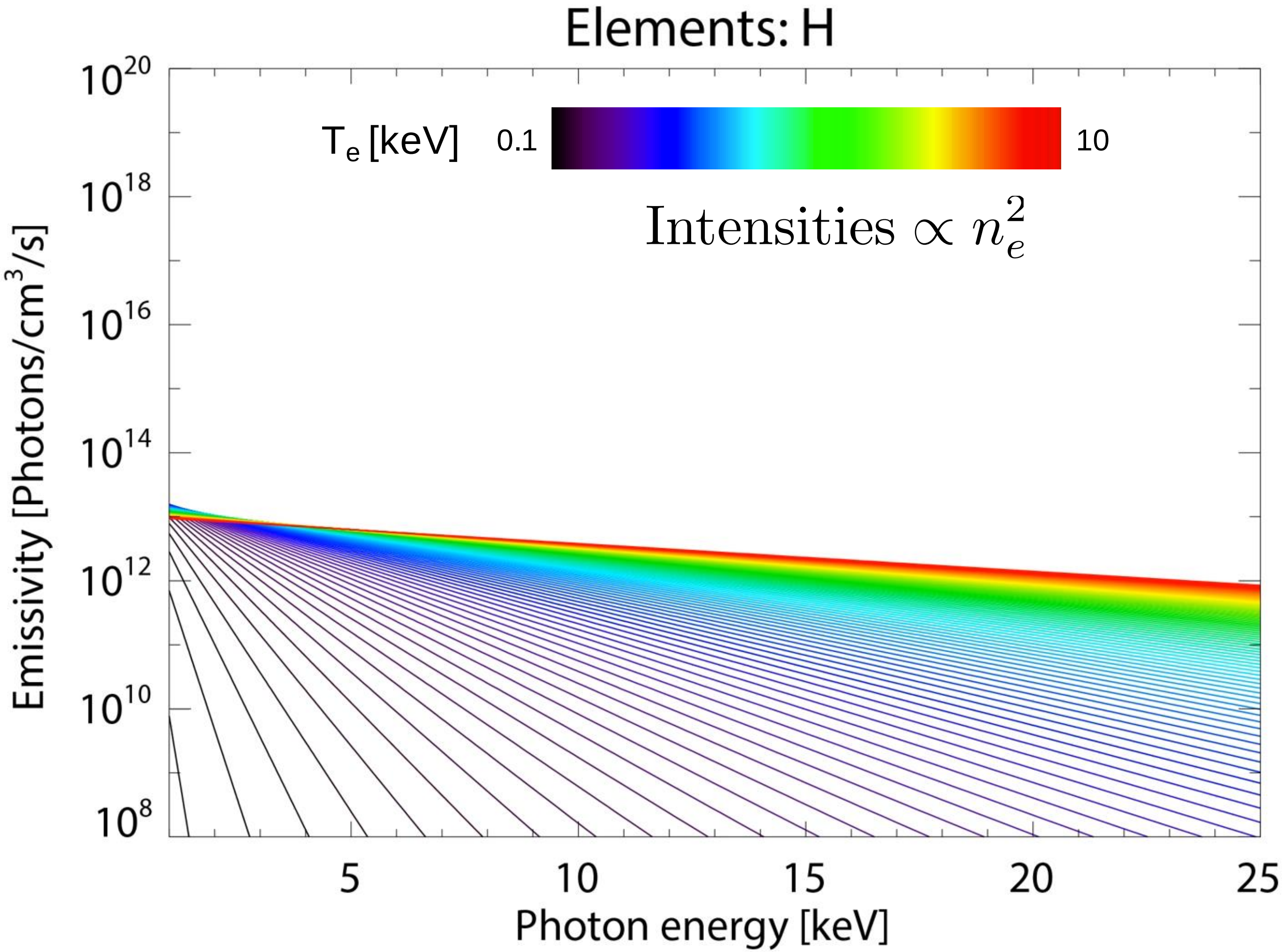
① Z-challenge (radiative recombination and line emission): ✓

② Neutrons

③ Gammas

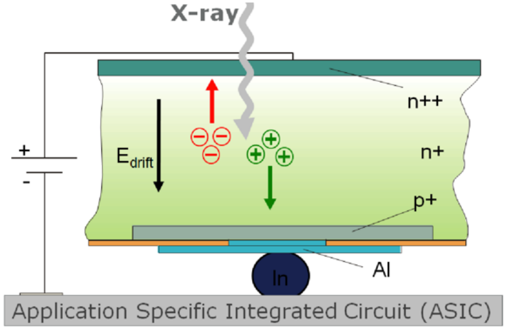
④ EM

⑤ Vacuum

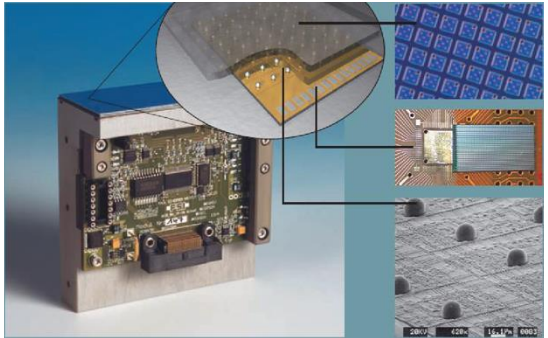


Novel x-ray detectors enable breakthrough of 100k pixels (minimum) at multiple energy ranges from 2-300 keV

Operates in single photon counting mode



CMOS hybrid pixel technology developed originally for synchrotrons

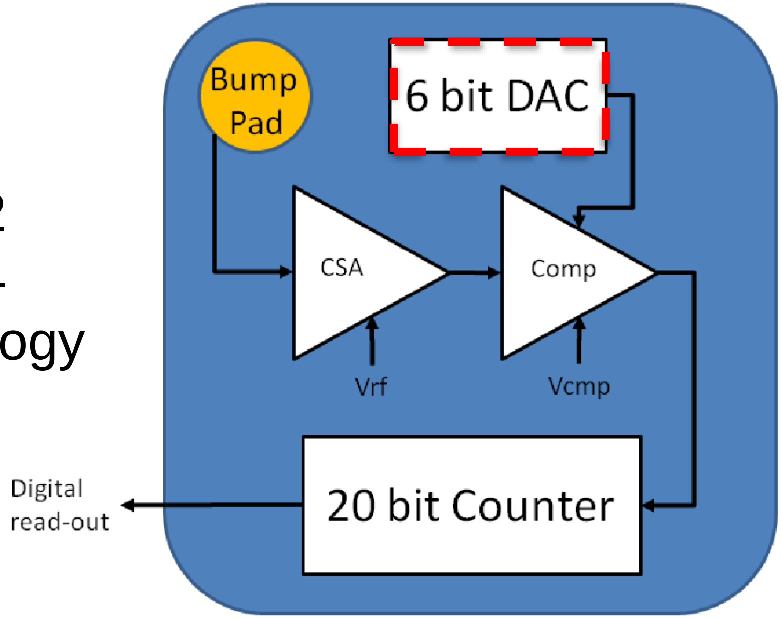


Si-sensor 2D array pn diodes

CMOS readout chip

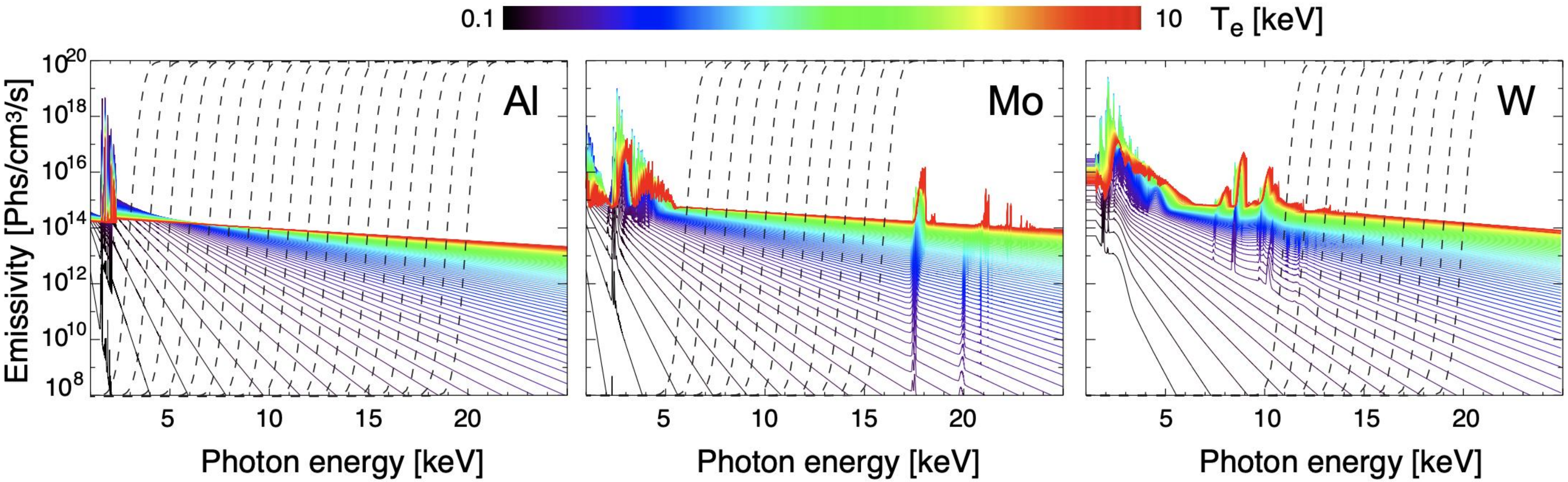
In balls

2012
2024
Technology

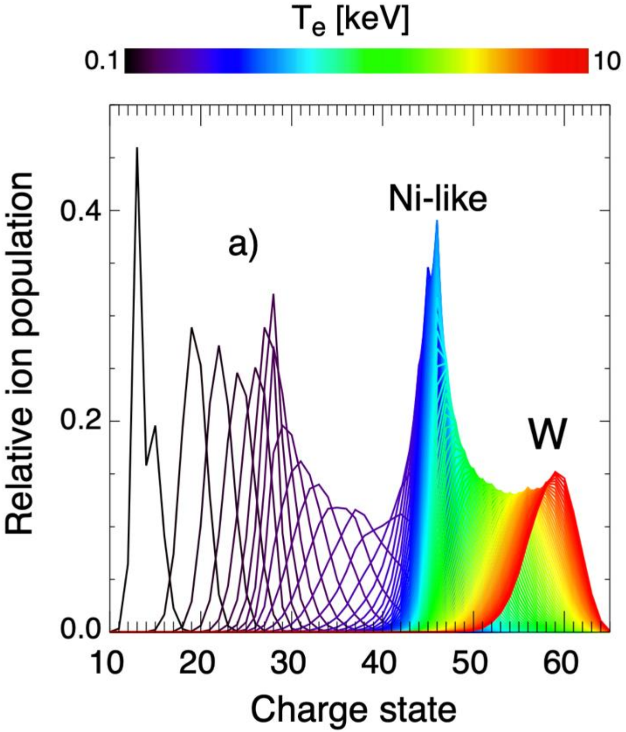


- The comparator voltage of the readout chip (V_{cmp}) controls the *global* threshold energy.
- The threshold energy can be individually *refined/trimmed* using and in-pixel 6-bits DAC (V_{trim}).

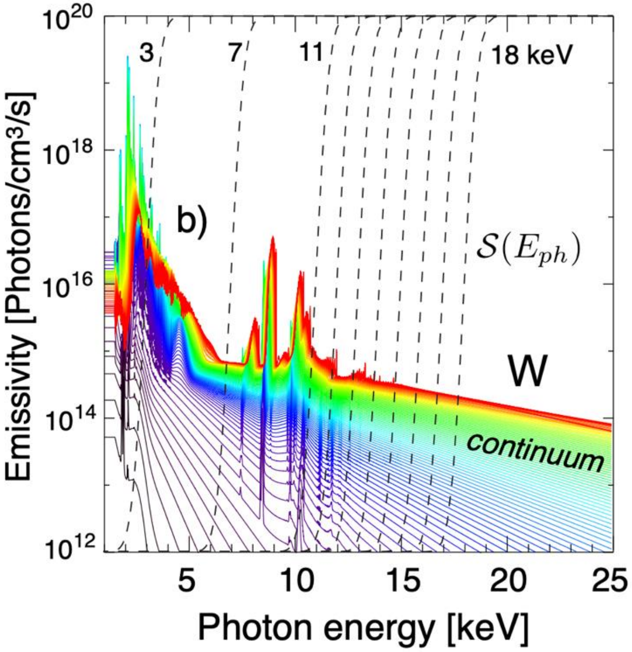
Smart pixel-technology allows filtering spectra to measure line-emission and/or the continuum

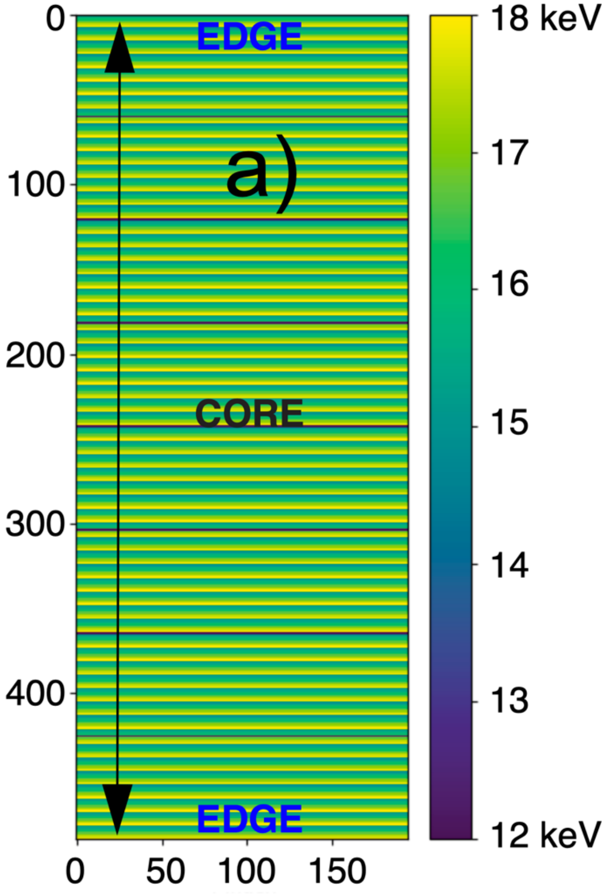


Main diagnostic challenge at WEST is to disentangle n_W and T_e-effects in recorded spectra



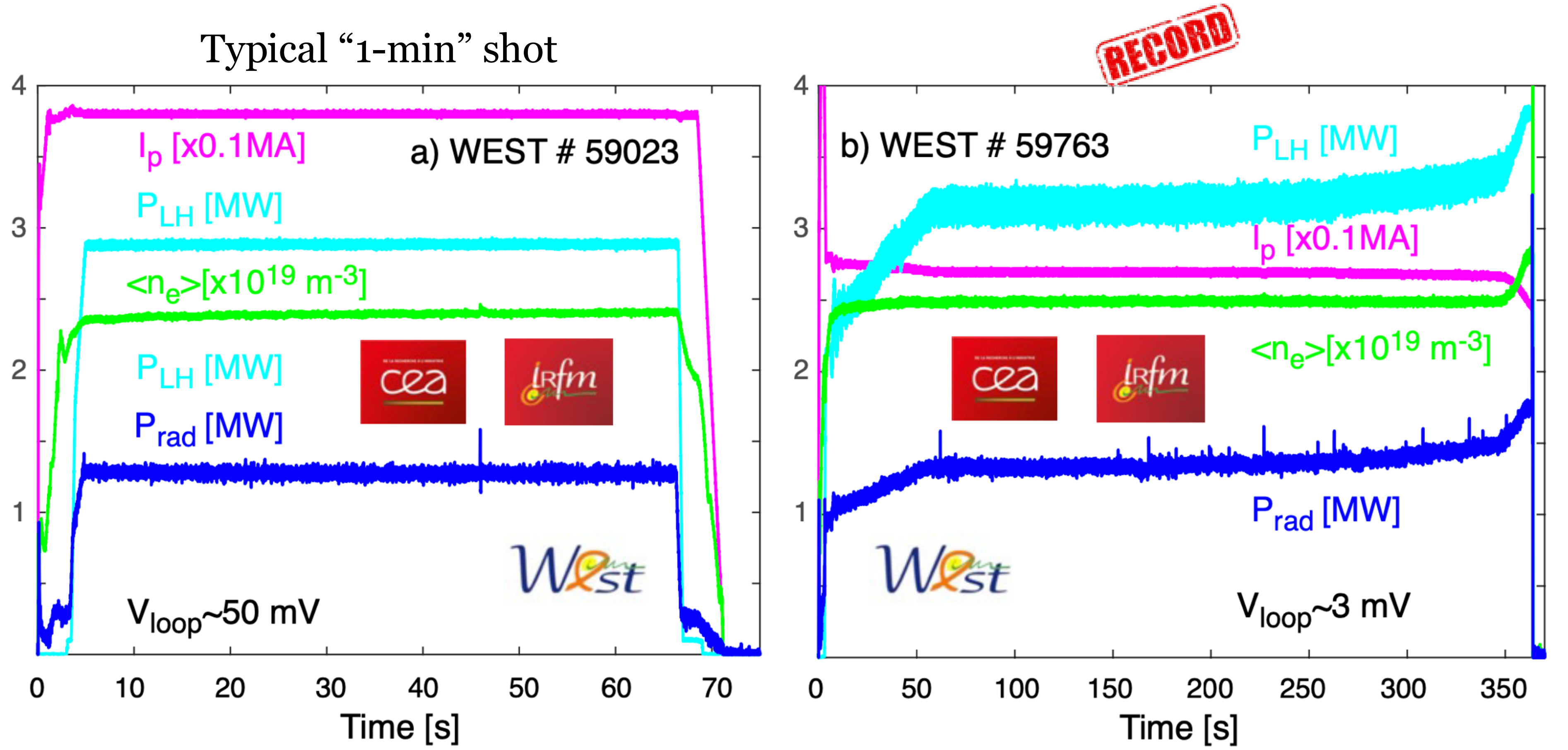
"Filtering the spectra"





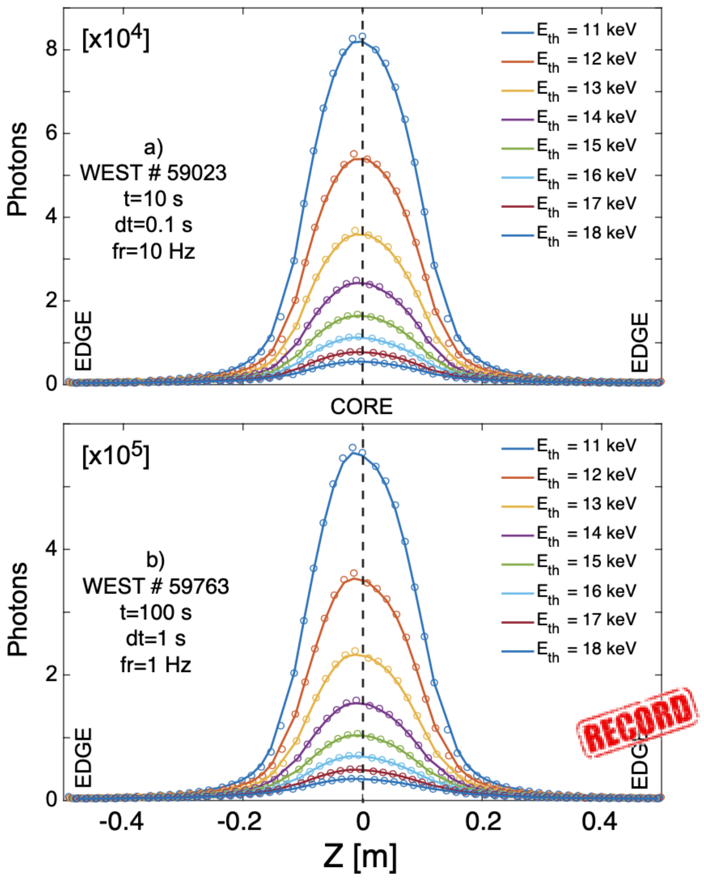
Long pulse operations (LPO) open a new era of expertise, training (e.g. physics and engineer) & collaborations

Typical "1-min" shot

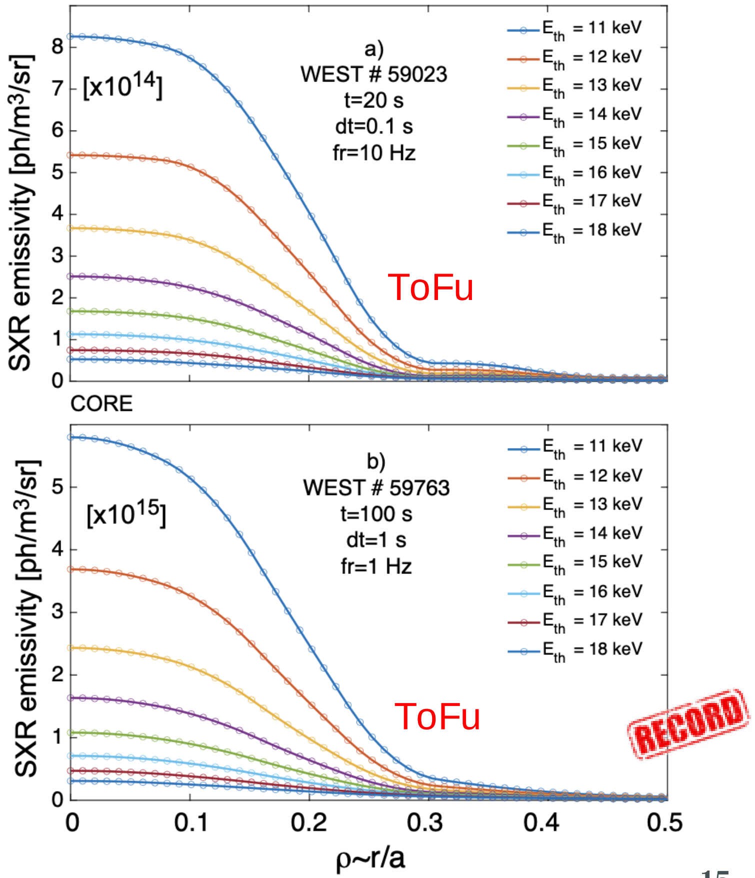


Tungsten multi-energy brightness and emissivities measured for the first time at WEST

Line-integrated brightness



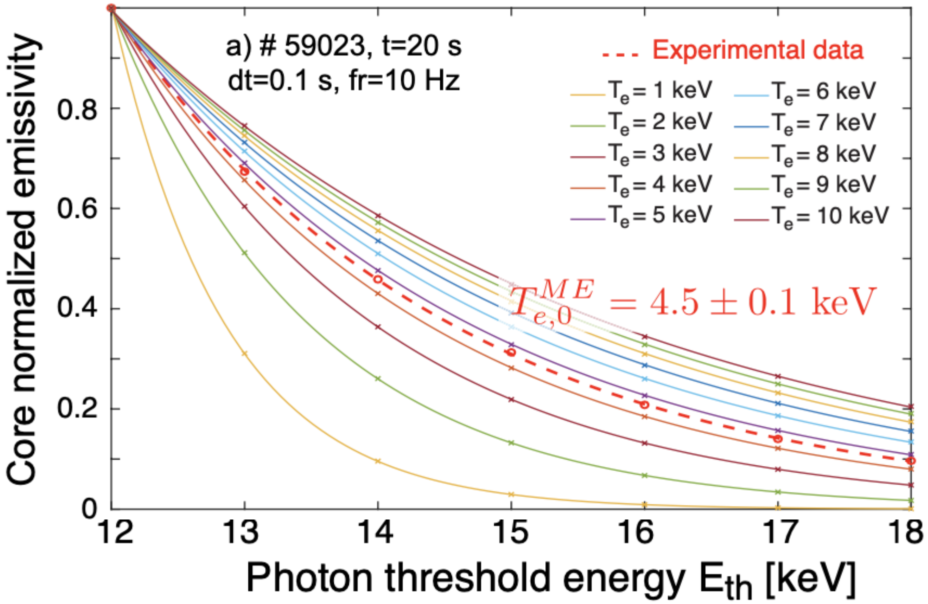
Local reconstructed emission

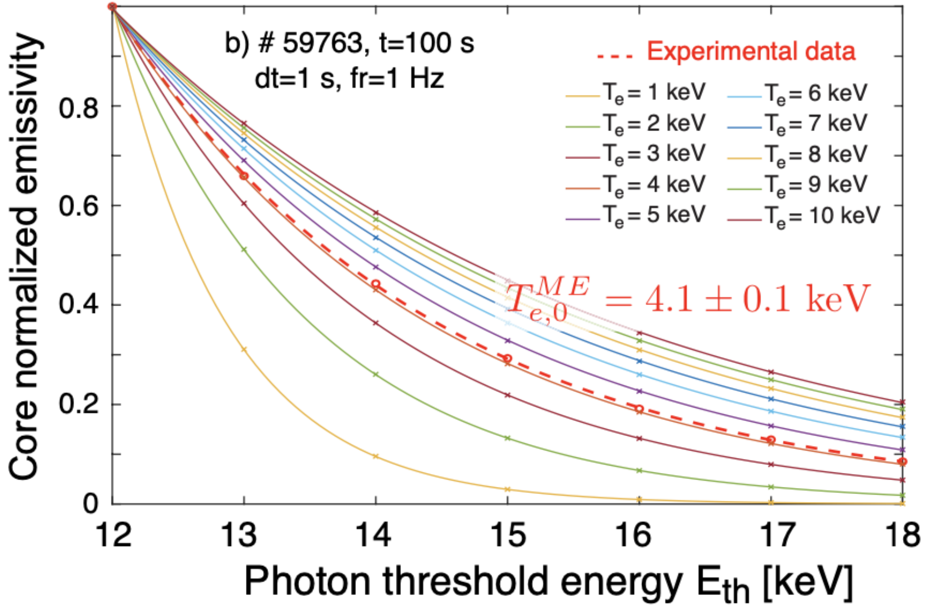


Core multi-energy (ME) fits capture the Maxwellian part of the electron energy distribution function

RECORD $\Rightarrow T_{e,0}$ ✓

Typical "1-min" shot



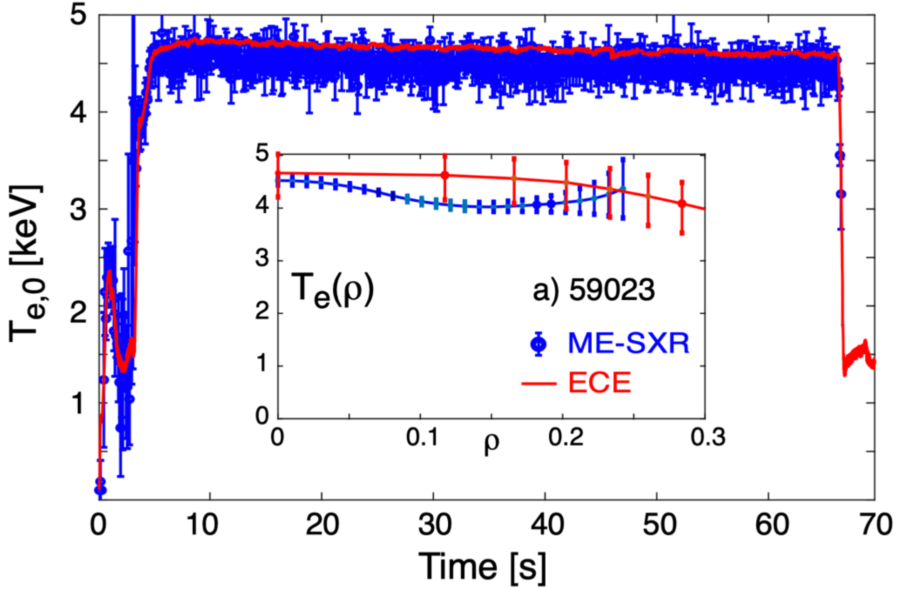


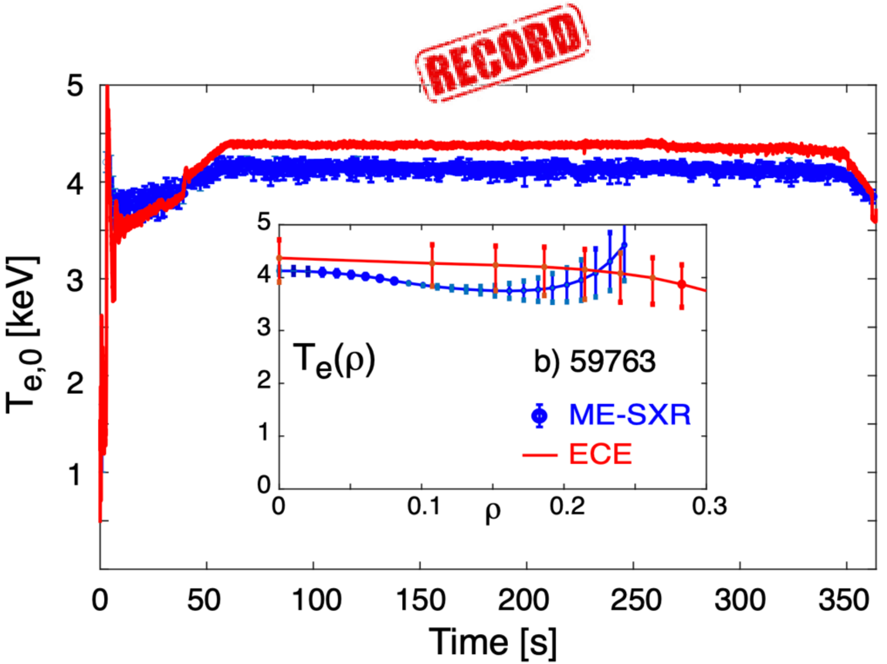
$\langle Z_{eff} \rangle$~2.2, $T_{e,0}$~4.5 keV and H_{98y2}~1

$\langle Z_{eff} \rangle$~2.7, $T_{e,0}$~4.1 keV and H_{98y2}~1.05

Steady-state non-inductive hot-electron branch with $T_{e,o}$ of the order of 4-5 keV obtained for $(10^2\text{-}10^3)\times\tau_E$

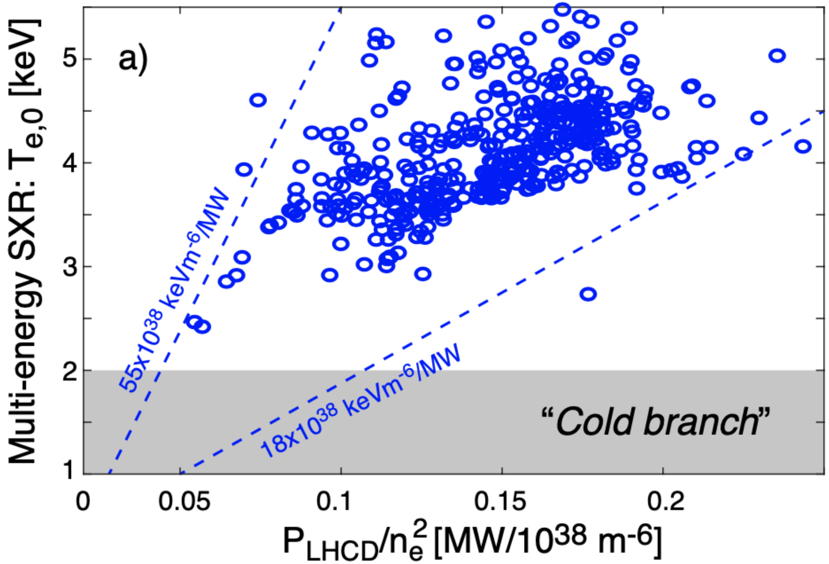
Typical "1-min" shot

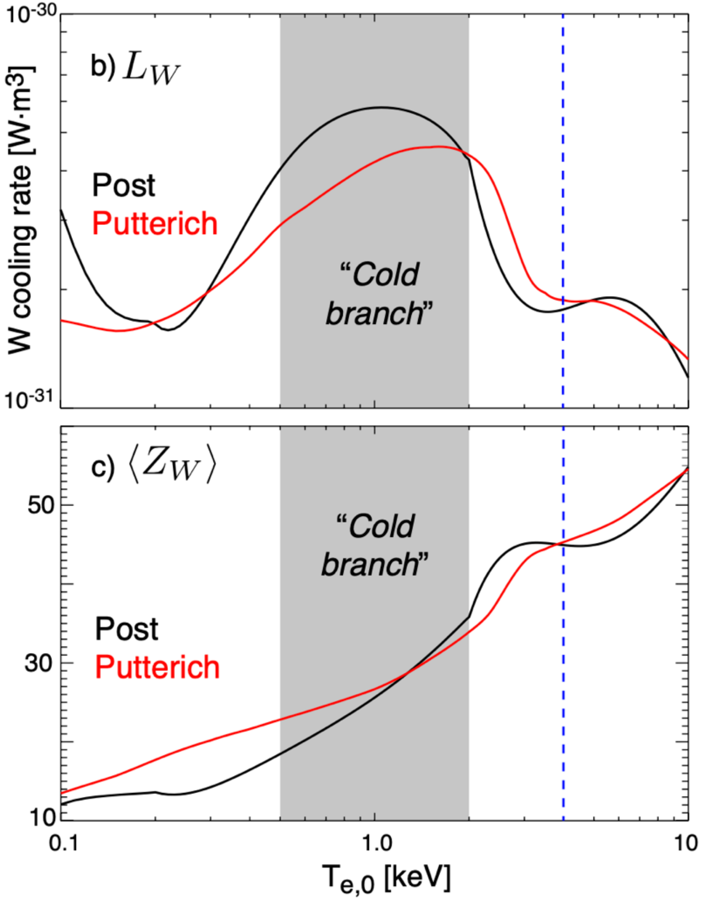




- T_e-measurement from tungsten-resolved spectra
- Error bars vary between 0.1-0.2 keV
- Very good agreement with ECE (recalibration performed on WEST database)
- **Next**: RT effort for control-room visualization (1-10 Hz)

Steady-state non-inductive hot-electron branch with $T_{e,o}$ of the order of 4-5 keV obtained for $(10^2\text{-}10^3)\times\tau_E$

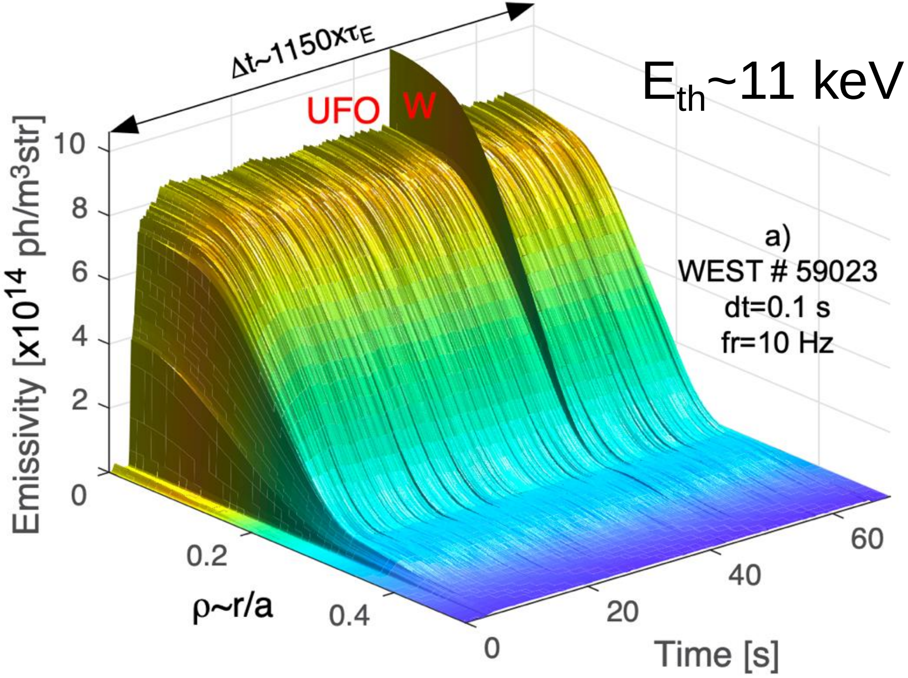




$$18 \lesssim \frac{n_{e,0}[10^{19}\ \mathrm{m}^{-3}] \cdot T_{e,0}[\mathrm{keV}]}{P_{LH}[\mathrm{MW}]/n_{e,0}[10^{19}\mathrm{m}^{-3}]} \lesssim 55$$

$$1 \times 10^{-4} \lesssim \mathcal{C}_{W,0} \lesssim 4 \times 10^{-4}$$

X-ray diagnostics open the window to diagnose it all! …including UFOs!



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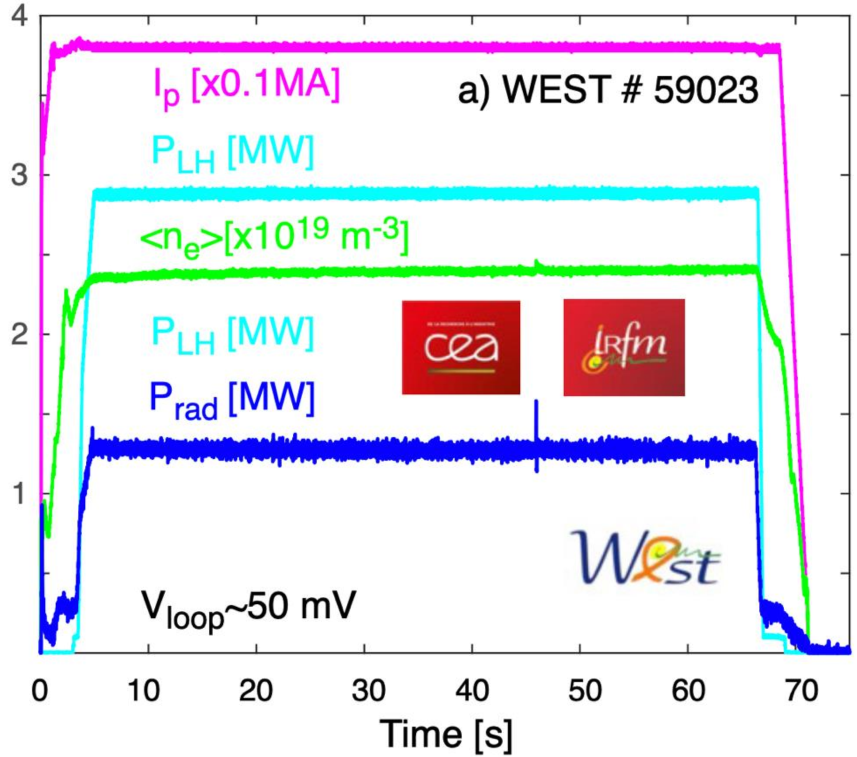
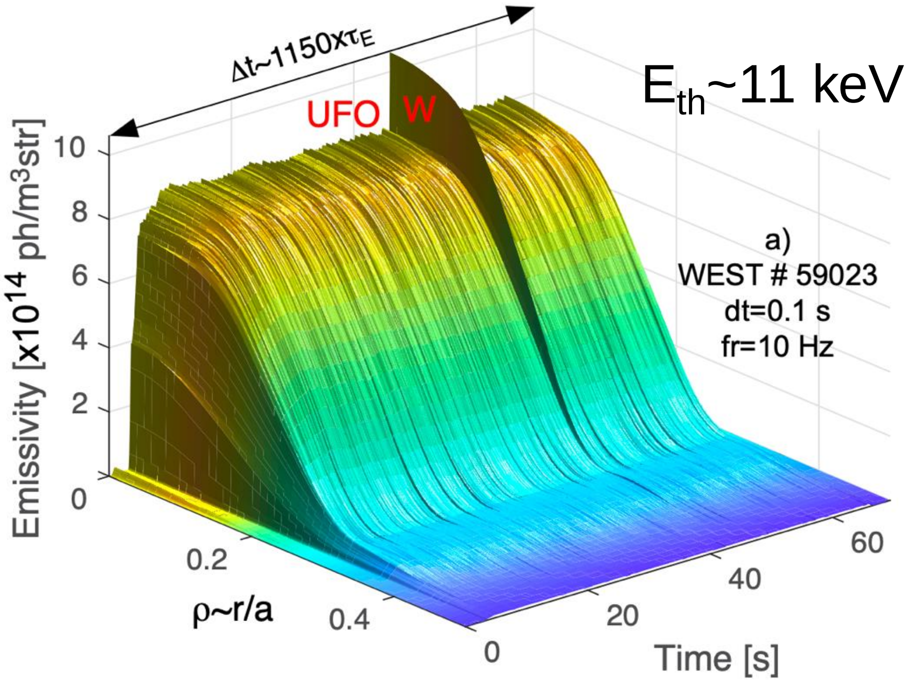


- $\tau_{MHD} \sim 1 - 100\ \mu s$
- $\tau_{ELM} \lesssim 1$ ms
- $\tau_{Transport} \sim$ 1-20 ms
- $\tau_{UFO} \sim$ 20-50 ms
- $\tau_E \sim$ 50-70 ms
- $\tau_{Ex:e,i} \sim$ 250 ms
- $\tau_{Ip} \sim$ 100 s
- $\tau_{PMI} \sim$ 100's s

X-ray diagnostics open the window to diagnose it all! ...including UFOs!



E_{th}~11 keV

- $\tau_{MHD} \sim 1 - 100$ μs
- $\tau_{ELM} \lesssim 1$ ms
- $\tau_{Transport} \sim$ 1-20 ms
- $\tau_{UFO} \sim$ 20-50 ms

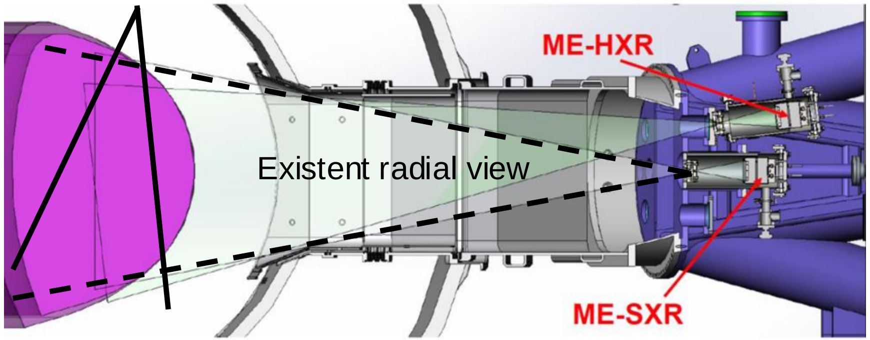
- $\tau_E \sim$ 50-70 ms
- $\tau_{Ex:e,i} \sim$ 250 ms
- $\tau_{Ip} \sim$ 100 s
- $\tau_{PMI} \sim$ 100's s

What is next:

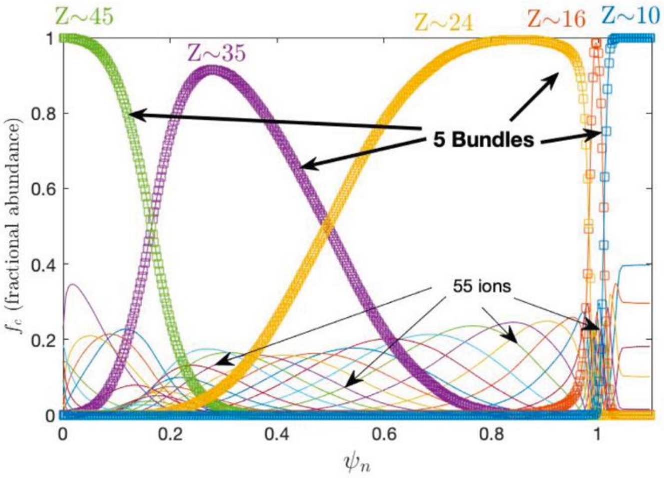
- Study WEST database
- Strengthen signal using low E_{th}~3 keV ⇒×(10-100)
- Sample faster 100-200 Hz
- Test detection latency~10 ms
- Implementation real-time detection of W-UFOs @ WEST
- Use P_{ECRH} @ core or q=2

TASK #1: Constrain W-transport in steady sate without perturbative experiments regardless of H & CD

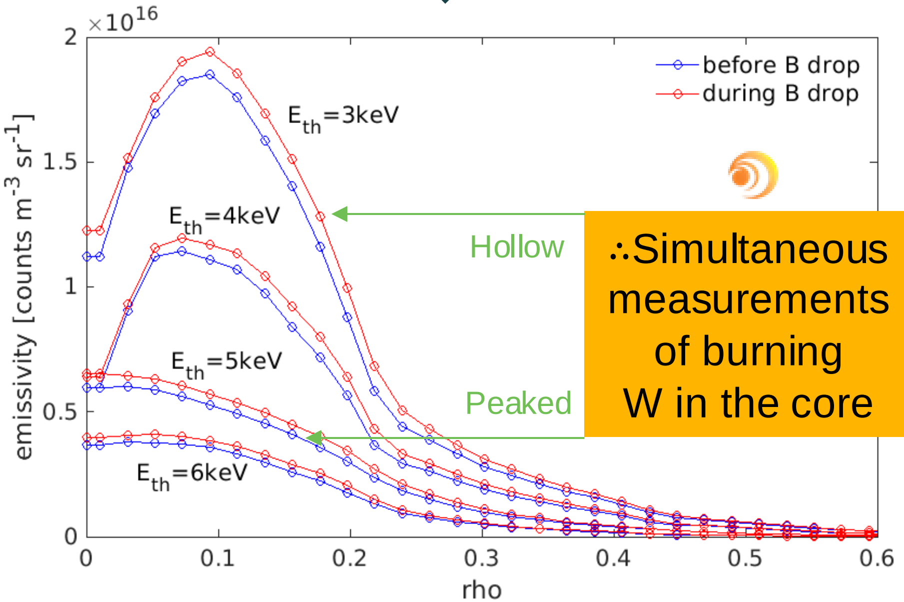
Ideal addition



$$\frac{1}{n_Z}\frac{\partial n_Z}{\partial r}(r,t) = \frac{V_Z}{D_Z}(r,t)$$

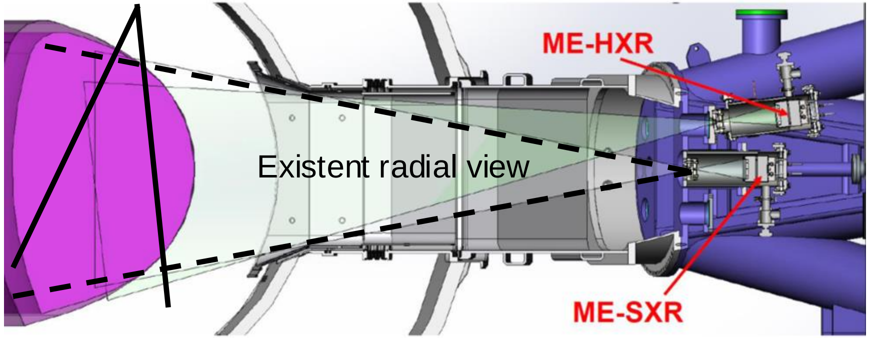


Courtesy of Parra & Dominski

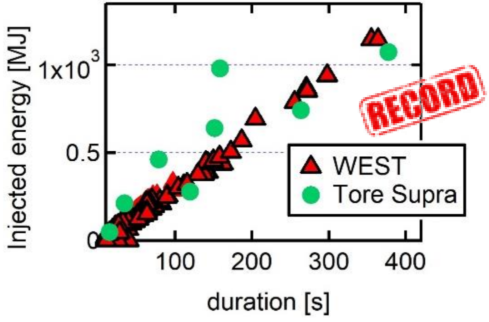


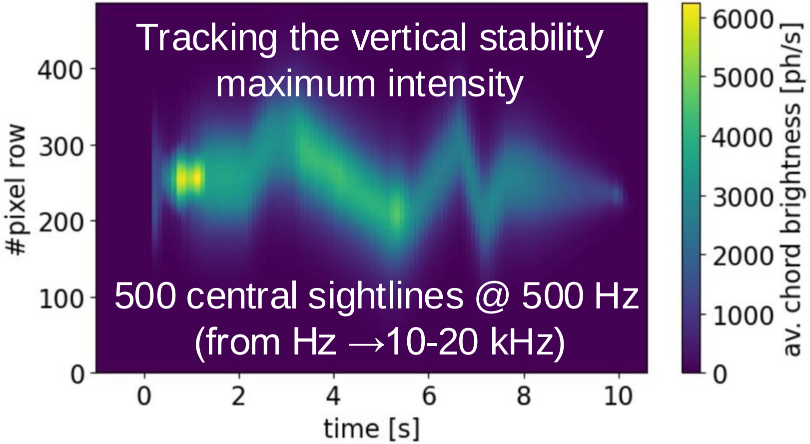
TASK #2: Complete tomography with to provide novel <u>non-magnetic internal measurements</u> of R_o, Z_o and Δ_{SS}

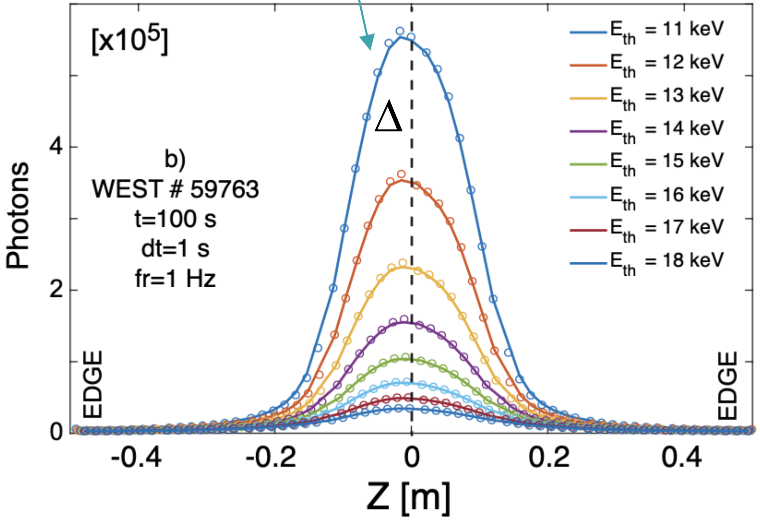
Ideal addition



Small vertical displacements currently under review

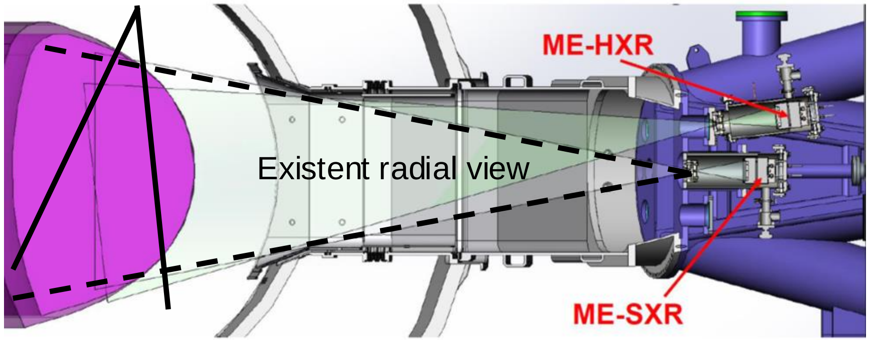


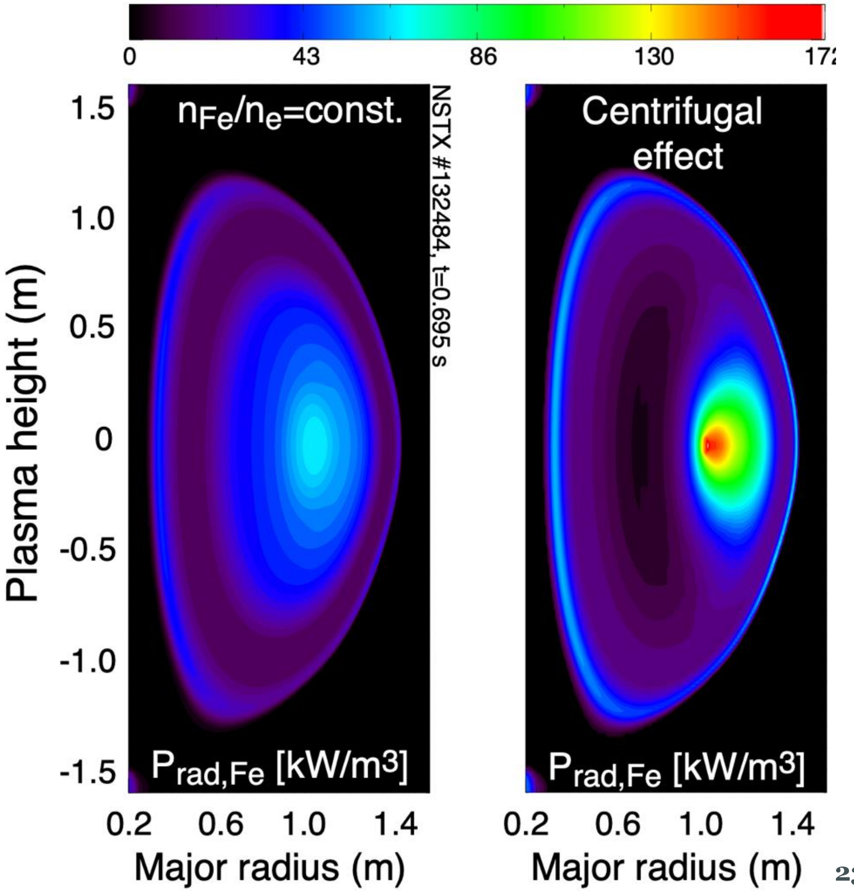




TASK #3: Complete tomography with vertical view to constrain W-transport asymmetries

Ideal addition



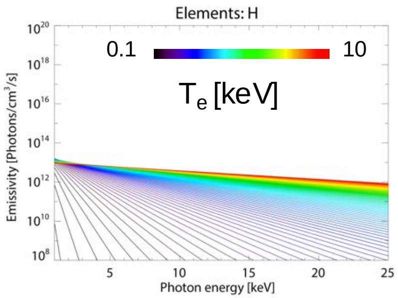


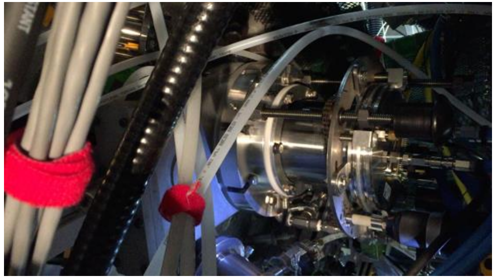
<u>Possible sources of Z-asymmetries</u>

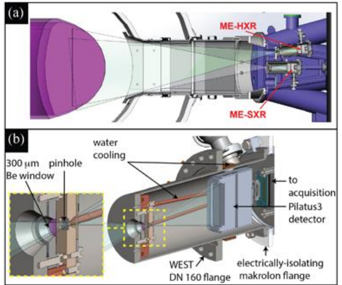
1. Rotation-induced asymmetries
   - L-mode: low rotation
   - H-Mode: higher rotation as $V_{\phi,RICE} \propto W_{MHD}$
2. ICRH-induced asymmetries @ high-field-side (ion $V_{\perp}$ vs $V_{||}$ effects)

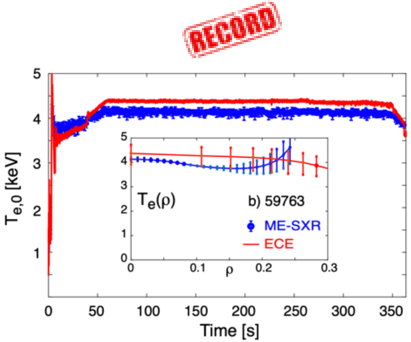
Summary

1) It is now possible to simultaneously record HR images of x-ray photons at **single** OR **multiple energy ranges**.
2) Solved main challenges of multi-energy technique circumventing radiative recombination steps and line-emission from medium to high-Z impurities
3) Tested multi-energy systems at Alcator C-Mod, MST and WEST (long-pulse)
4) Latest results @ WEST:
   - $T_{e,0}(t)$ and $n_W(t)$ at 1-100 Hz in L-mode long-pulse operation at WEST
   - Detection of W-UFOS
5) What is next? a) RT b) 2D tomography, c) W-transport and d) measure J and q.







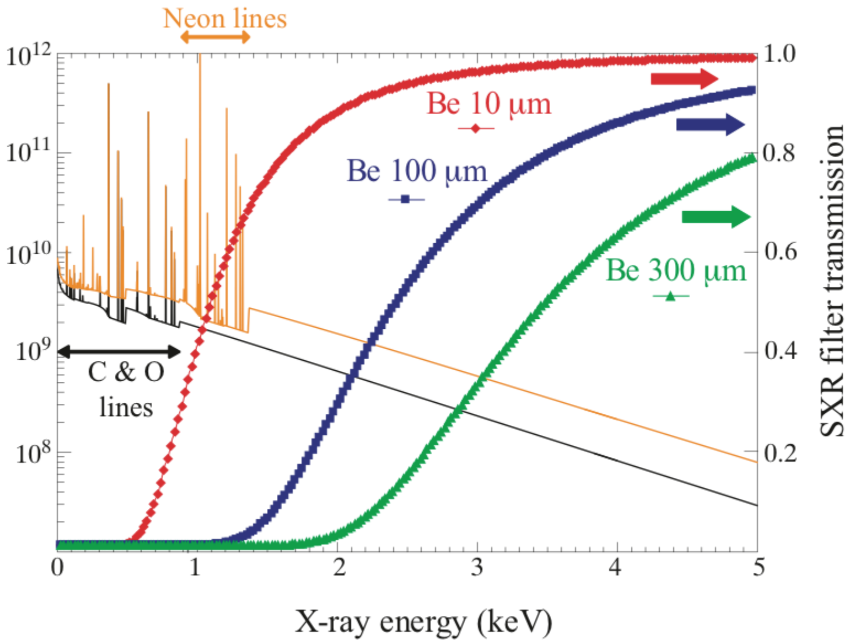


T_{e0} (t)
@
1 Hz

EXTRA

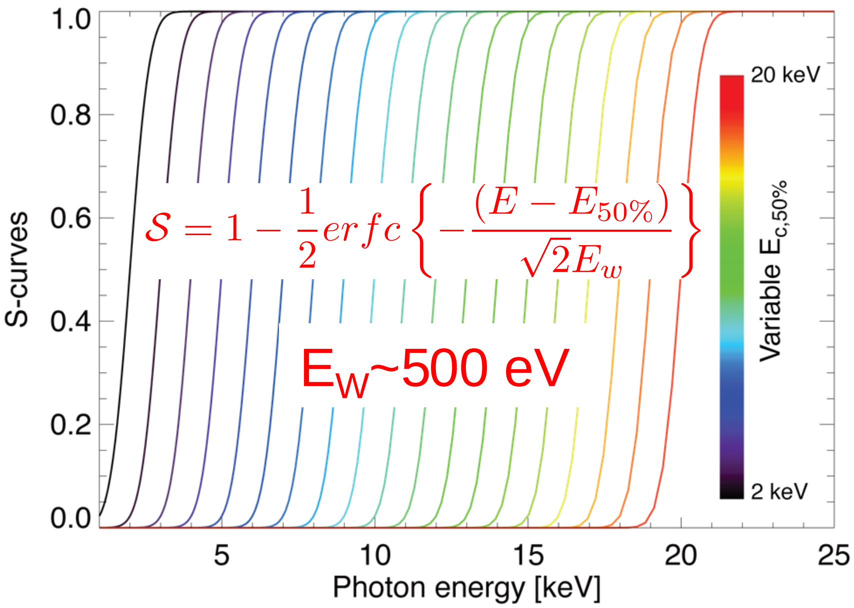
Novel x-ray detectors enable breakthrough of 100k pixels (minimum) at multiple energy ranges from 2-300 keV

Old technology: metal filters



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

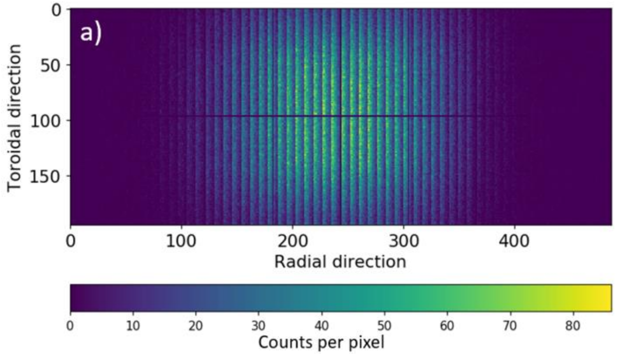
New technology electronics

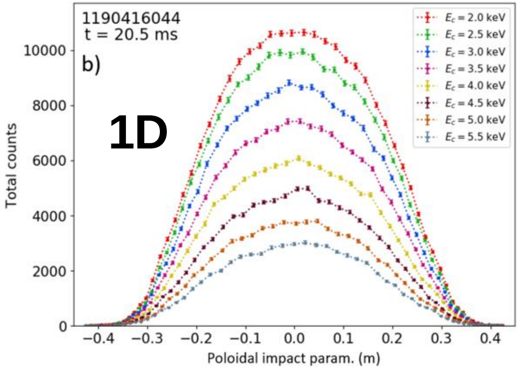


"Constant" width of electronic response is a great improvement over the use of filters

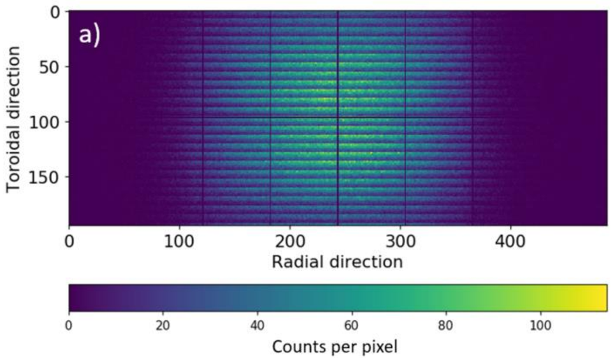
Technology tested at MST & WEST enables different options upon arrangements of threshold energies

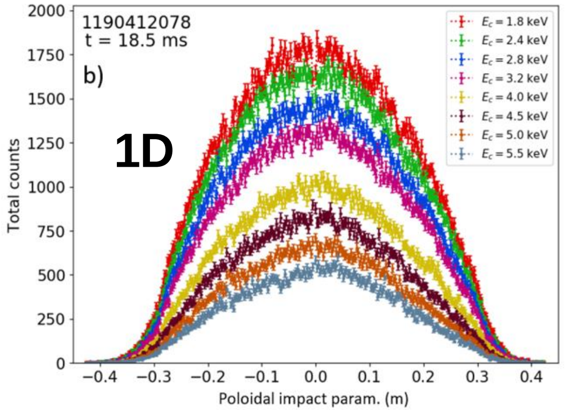
<u>In rows</u>: good spatial resolution



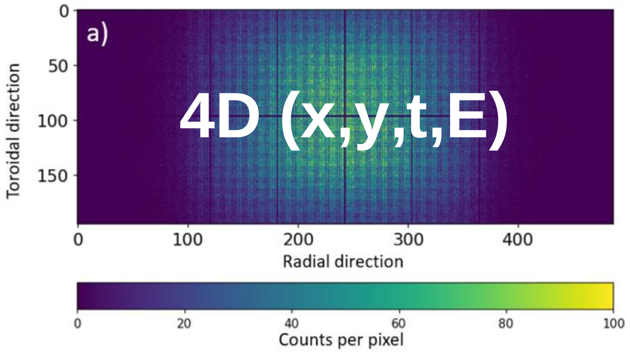


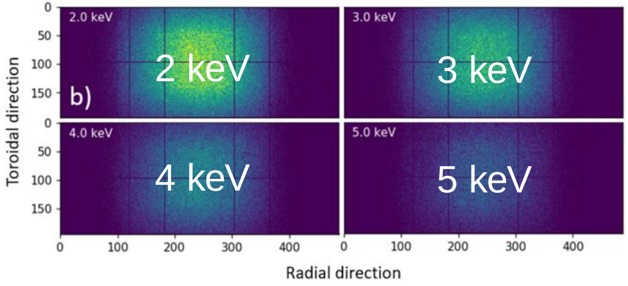
<u>In columns</u>: higher spatial resolution





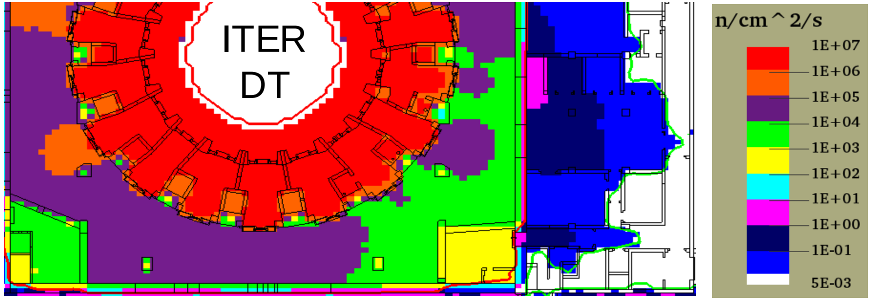
“Meta”-pixel: 2D distribution



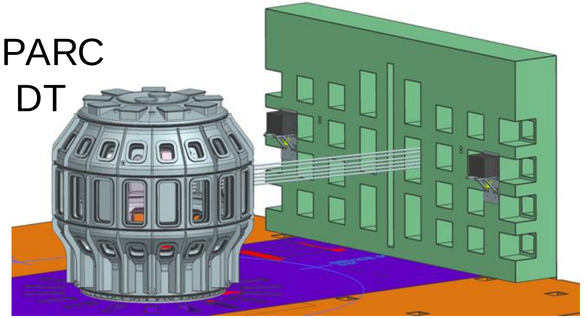


Meta-pixel configuration can be useful for long-range measurements using small openings

- Neutron-flux for ITER-DT and SPARC-DT scenarios can be as high as 10^{19}-10^{20} n/s
- **ALARA**: **A**s **L**ow **A**s **R**easonably **A**chievable
- D=10m ⇒ $F_n \sim 8\times(10^{11}-10^{12})$ n/cm²/s



SPARC
DT



1 MW of DT neutrons

~4.4×10^{17} n/s

Assuming, D=15 m

⇒ $F_n \sim 1.5\times10^{10}$ n/cm²/s

Δt=5-10 s

Fluence ~ 10^{11} n/cm²/shot

$\text{Fluence}_{max} \sim 10^{13\text{-}14}$ n/cm²/MeV

"Meta"-pixel