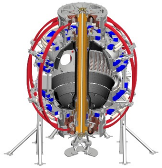
The high-Z challenge and advances in core x-ray spectroscopy

Luis F. Delgado-Aparicio (PPPL), Advanced Projects Department

Princeton, PPPL, 06/21/2024



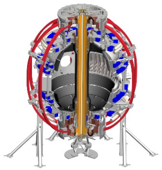
Outline

① Magnetically confined fusion (MCF) plasmas and the Z-challenge

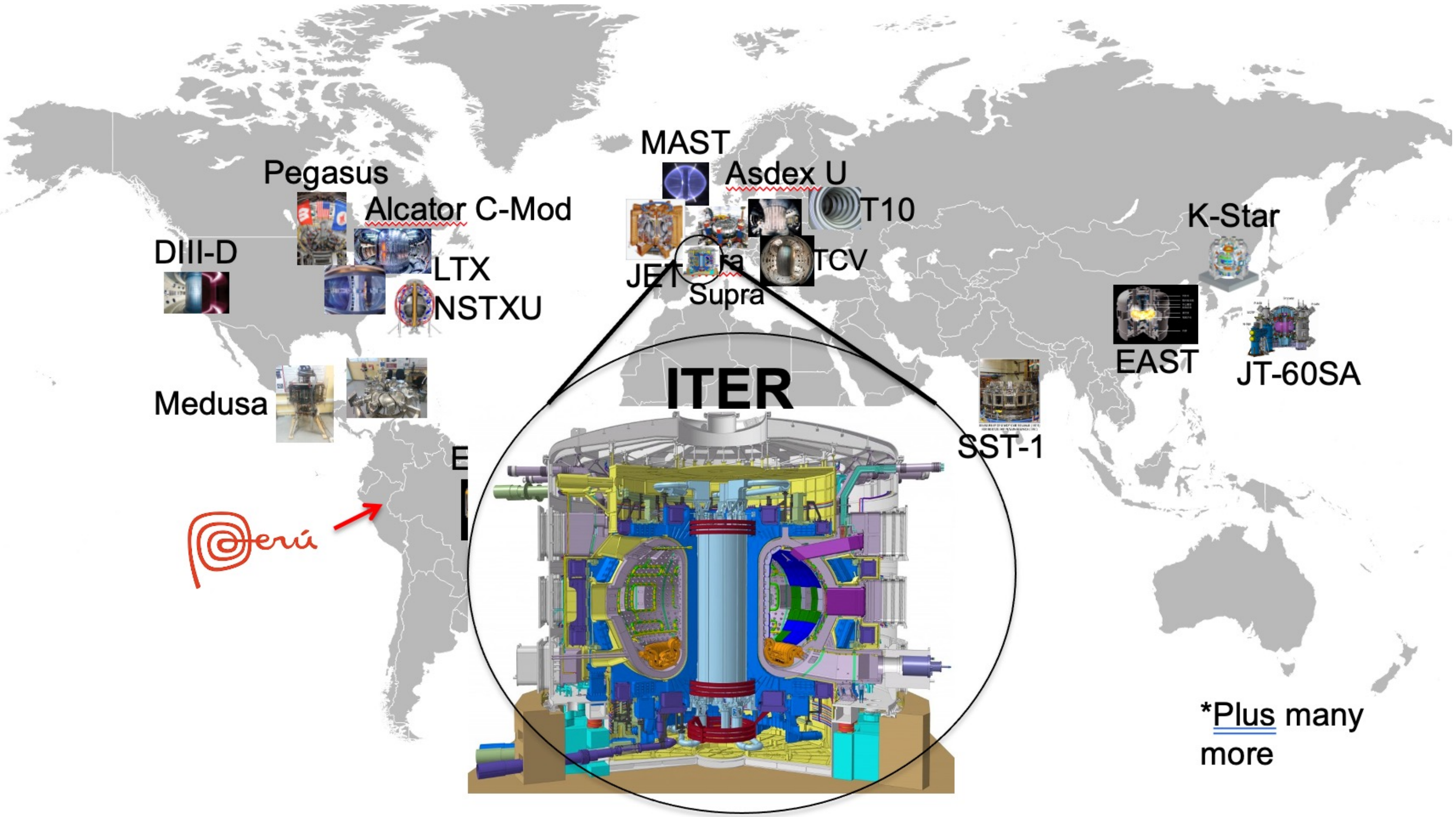
② Radiation and the basic need of x-ray spectroscopy?

③ Take home message: three types of x-ray diagnostics

④ Summary



Tokamaks (and stellarators) spread around the world study different plasma parameters and shapes



*Plus many more

ITER will be the first time we have net energy (more energy OUT than IN)

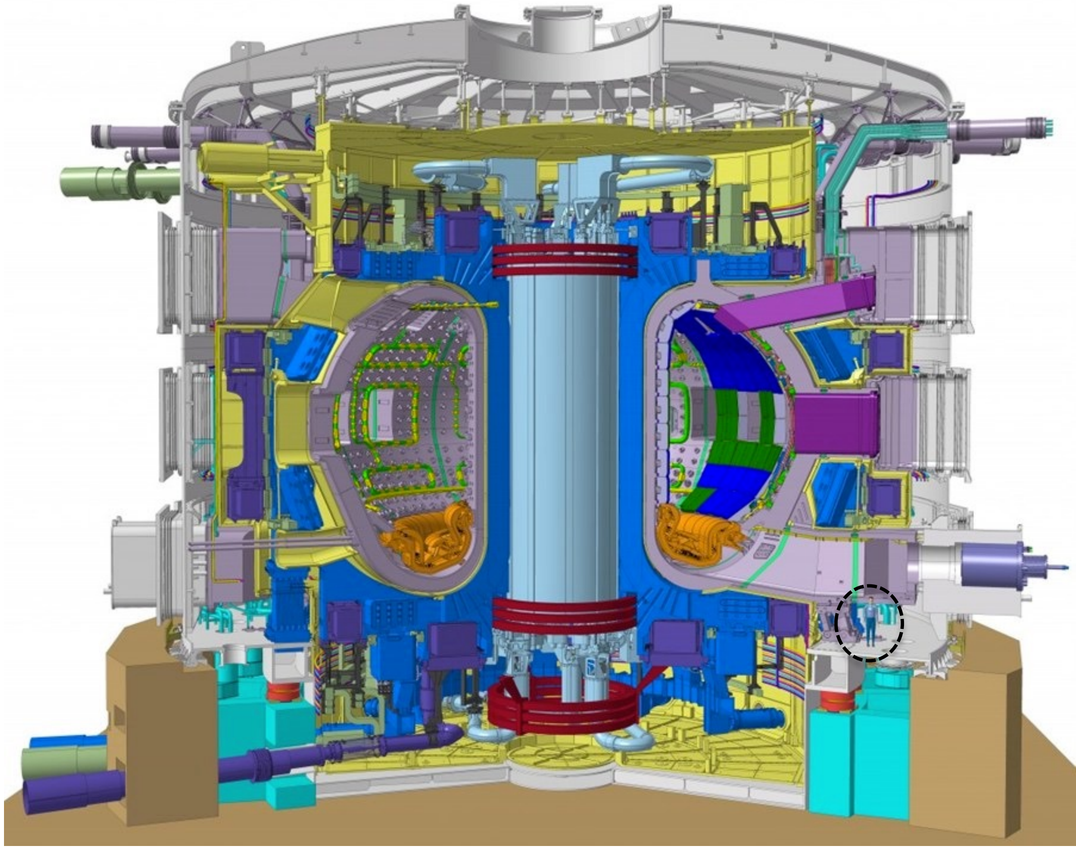
- ITER is a collaboration between USA, EU, China, Japan, Korea, India and Russia

- It's expected to produce 500MW of power using 50MW to run …this is the 1st time in history where $\mathbf{P_{out}>P_{in}}$

- First plasmas "expected" by 2025

  - Many challenges ahead!

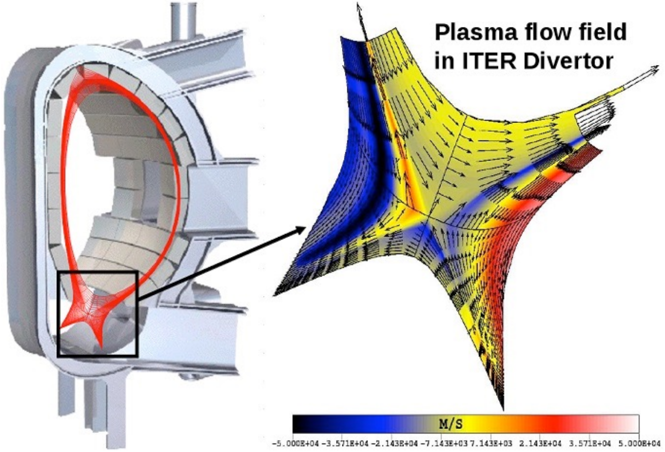
    - The Z-challenge? (low-Z vs high-Z)

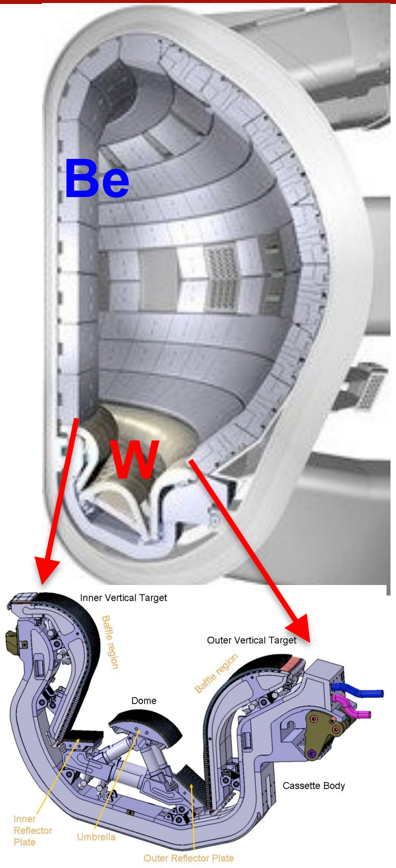


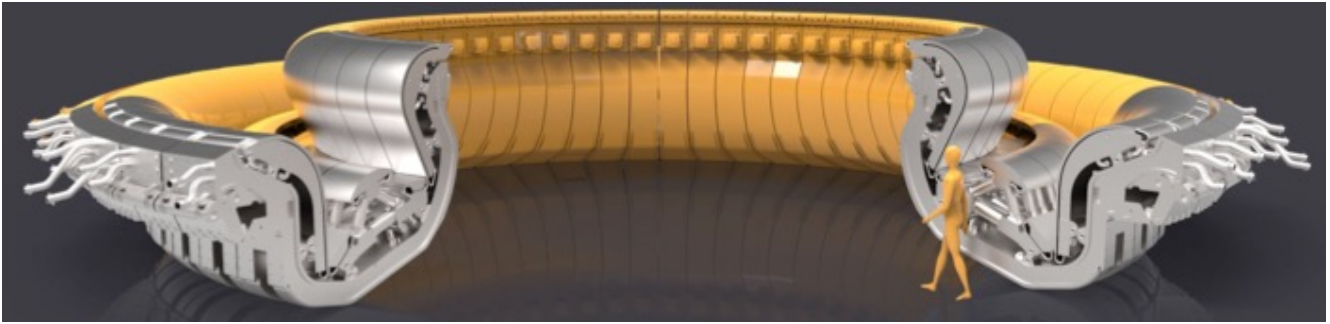
With the help of detailed simulations ITER scientists "decided" on a wall covered with low- and high-Z PFCs

Simulations of plasma flows and plasma-wall interaction have had a decisive influence on the design of ITER wall

⇒ It's a decision on the edge conditions which will alter core performance







Edge localized modes (ELMs) and disruptions can impact integrity of divertor cassettes

The low-Z (Li, Be, C, B) vs high-Z (Fe, Mo, W) plasma facing component (PFC) challenge - IDEAL

Both low- & high-Z materials are currently being used for the **PFCs**, but each has technological hurdles.

① Low-Z materials:

a) Typically have higher erosion rates

b) Their injection into the main chamber will result in an increase of Z_{eff} and collisionality ($\nu_{e,Z}$).

c) H-, D- & T-retention is a difficult issue!

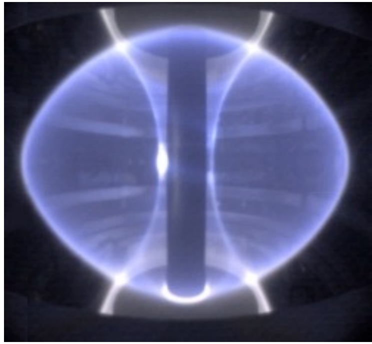
② Augment of Z_{eff} will lead to:

a) Reduce fuel purity (n_D/n_e) and reactivity ($S_n \propto n_D^2$ or $n_D n_T$).

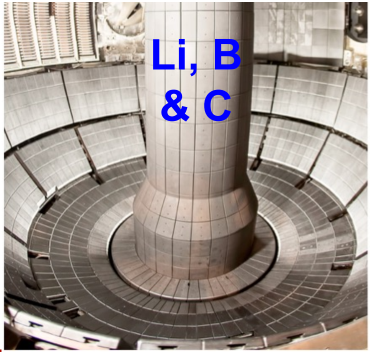
b) But contributing less to radiated power density:

$P_{rad}=n_e n_D L_D+n_e n_C L_c+\Sigma n_e n_Z L_Z$

MAST, CCFE, Oxfordshire, UK



NSTX-U @ PPPL, Princeton, NJ



The low-Z (Li, Be, C, B) vs high-Z (Fe, Mo, W) plasma facing component (PFC) challenge - **REAL**

③ Conversely, high-Z materials have good properties as a PFCs:

a) Low H/D/T retention.

b) High-heat tolerance (e.g. high melting points)

c) Low erosion (sputtering) rates.

d) Small contribution to Z_{eff}:

$$Z_{eff}=n_D/n_e+36n_C/n_e+\Sigma(n_Z/n_e)Z^2$$

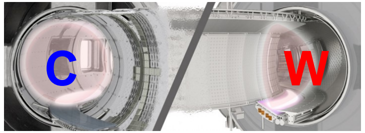
④ However, if high-Z impurities accumulate to any substantial level (e.g. high-n_Z/n_e), this will lead to:

a) Exponentially enhance the radiation power losses ($\propto Z^4$): $P_{rad}=n_e n_D L_D+n_e n_C L_C+\Sigma n_e n_Z L_Z$

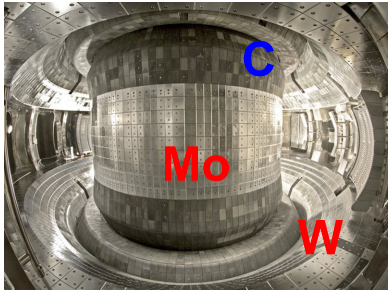
b) Reduce the heating efficiency and modifying the overall power balance

c) Radiation collapse

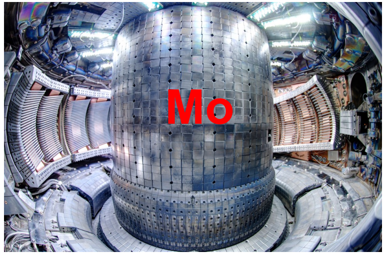
Tore Supra/WEST in France



EAST in China



C-Mod @ MIT, USA



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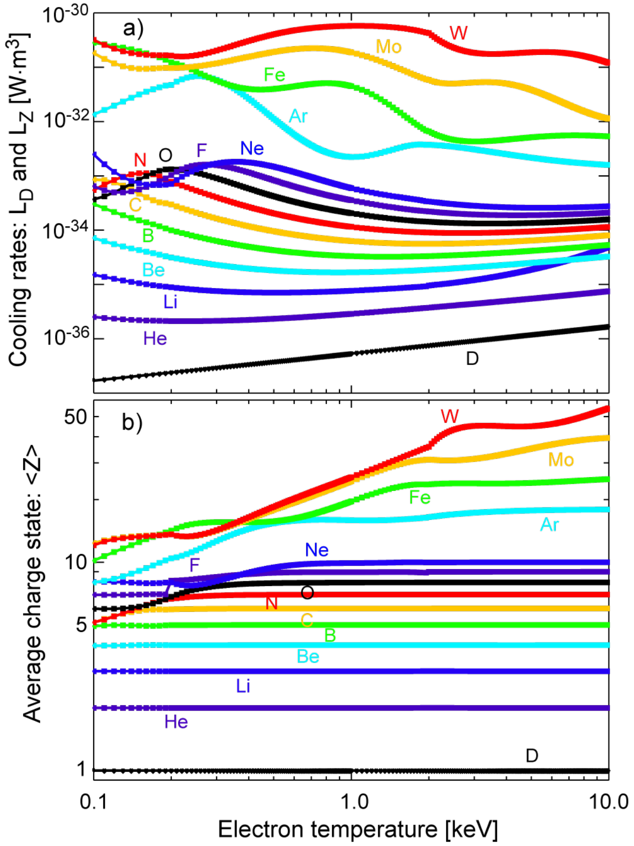


Radiative power densities (vis/UV/x-ray) & charge state <Z> can be obtained using coronal equilibrium

Parameterizing equations of interest for two-impurity plasma

Quasi-neutrality:

$$1 = \frac{n_D}{n_e} + \langle Z_1 \rangle \frac{n_{Z1}}{n_e} + \langle Z_2 \rangle \frac{n_{Z2}}{n_e}$$

Effective charge:

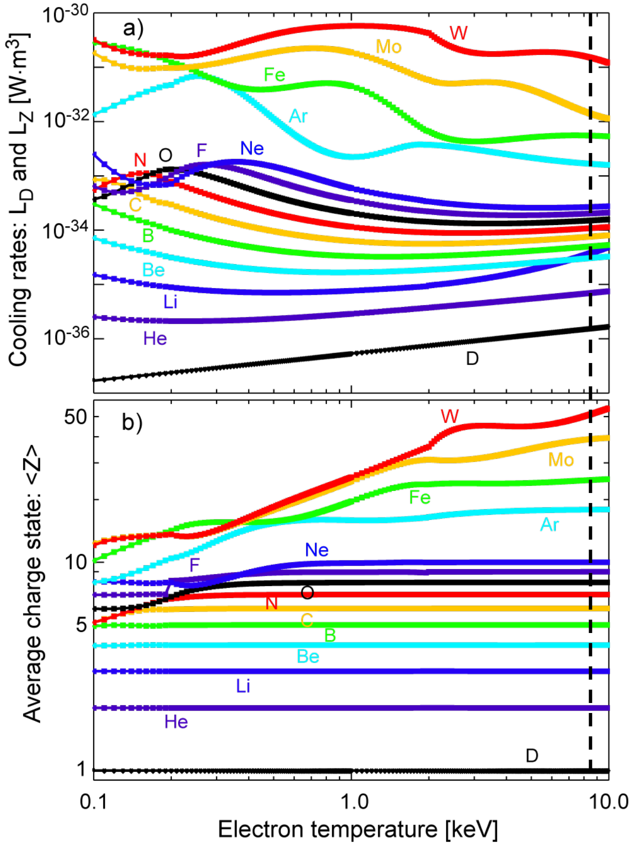
$$Z_{eff} = \frac{n_D}{n_e} + \langle Z_1 \rangle^2 \frac{n_{Z1}}{n_e} + \langle Z_2 \rangle^2 \frac{n_{Z2}}{n_e}$$

Normalized radiated power density:

$$\hat{P}^V_{rad} \equiv \frac{P^V_{rad}}{n_e^2 L_D} = \frac{n_D}{n_e} + \frac{n_{Z1}}{n_e}\frac{L_{Z1}}{L_D} + \frac{n_{Z2}}{n_e}\frac{L_{Z2}}{L_D}$$

Hydrogenic cooling rate:

$$L_D = 5.35 \times 10^{-37} T_e^{1/2}[\mathrm{keV}]\ \mathrm{W \cdot m^3}$$



Why is important to measure x-rays emitted from tokamak and stellarator fusion-grade plasmas ?

① A significant fraction of the power delivered to the plasma is lost in the form of radiation [even in an ideal pure H plasma].

② A subset of P_{rad}: In real conditions could be as high as 90%.

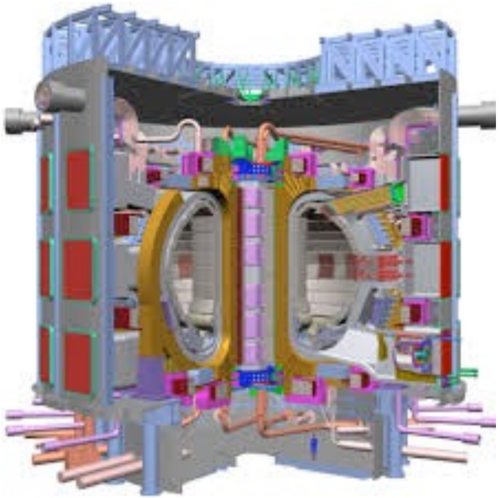
③ X-rays are the most dominant source of radiation from hot plasmas: $h\nu \sim T_e$:
Exercise: For 100 eV $< T_e <$ 20 keV $\Rightarrow$ $0.5 < \lambda < 130$ Å $\Rightarrow$ X-rays!

④ Measurement of power losses in the x-ray range enable the characterization of parameters such as, n_e, n_Z, T_e, T_i, v_ϕ, v_θ, to be used in describing/studying:

a) MHD and reconection events (from hot core to cold edge).
b) Transport coefficients (e.g. diffusivity and pinch velocity).
c) Radial electric field (E_r)
d) Magnetic flux-surface reconstructions: $T_e(\psi) \Rightarrow J$ and q

THE X-RAY CASE: …how to diagnose x-rays from thermonuclear plasmas ?

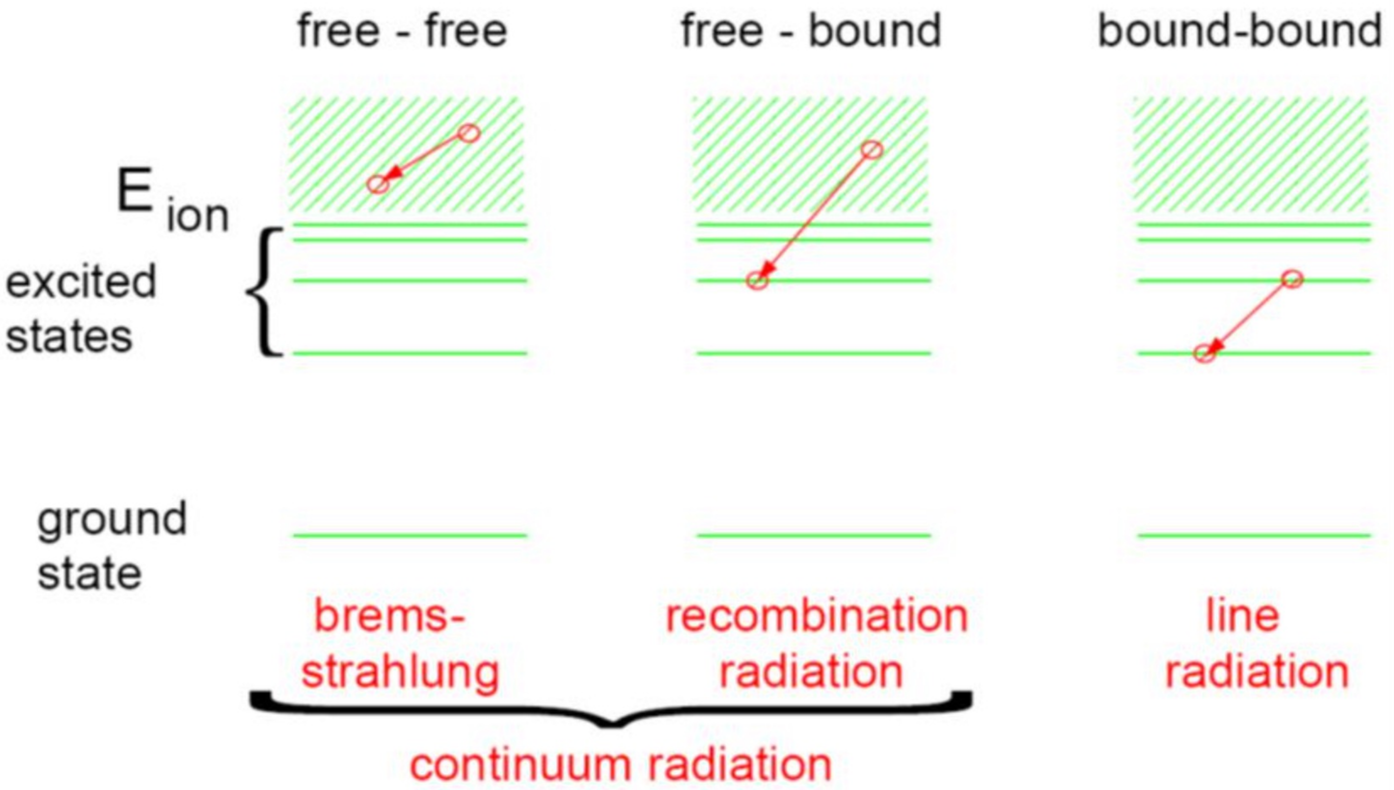
Nearly 90% of the radiated power in ITER will be in the x-ray range (V_{ITER}~840 m3)



SXR: 1<E<20 keV

HXR: 20<E<400 keV

Main radiation mechanisms: Bremsstrahlung (ff), radiative recombination (fb) & line-emission (bb)



Coronal equilibrium (ionization charge balance)

- Commonly used in fusion plasmas and in the solar corona
- Assumes three body-recombination rate is small
- Balance between electron-impact ionization & radiative recombination

$$\underbrace{n_e n_Z \mathcal{S}_{Z\rightarrow(Z+1)}(T_e)}_{Ionization} = \underbrace{n_e n_{(Z+1)} \alpha_{Z+1\rightarrow Z}(T_e)}_{Recombination}$$

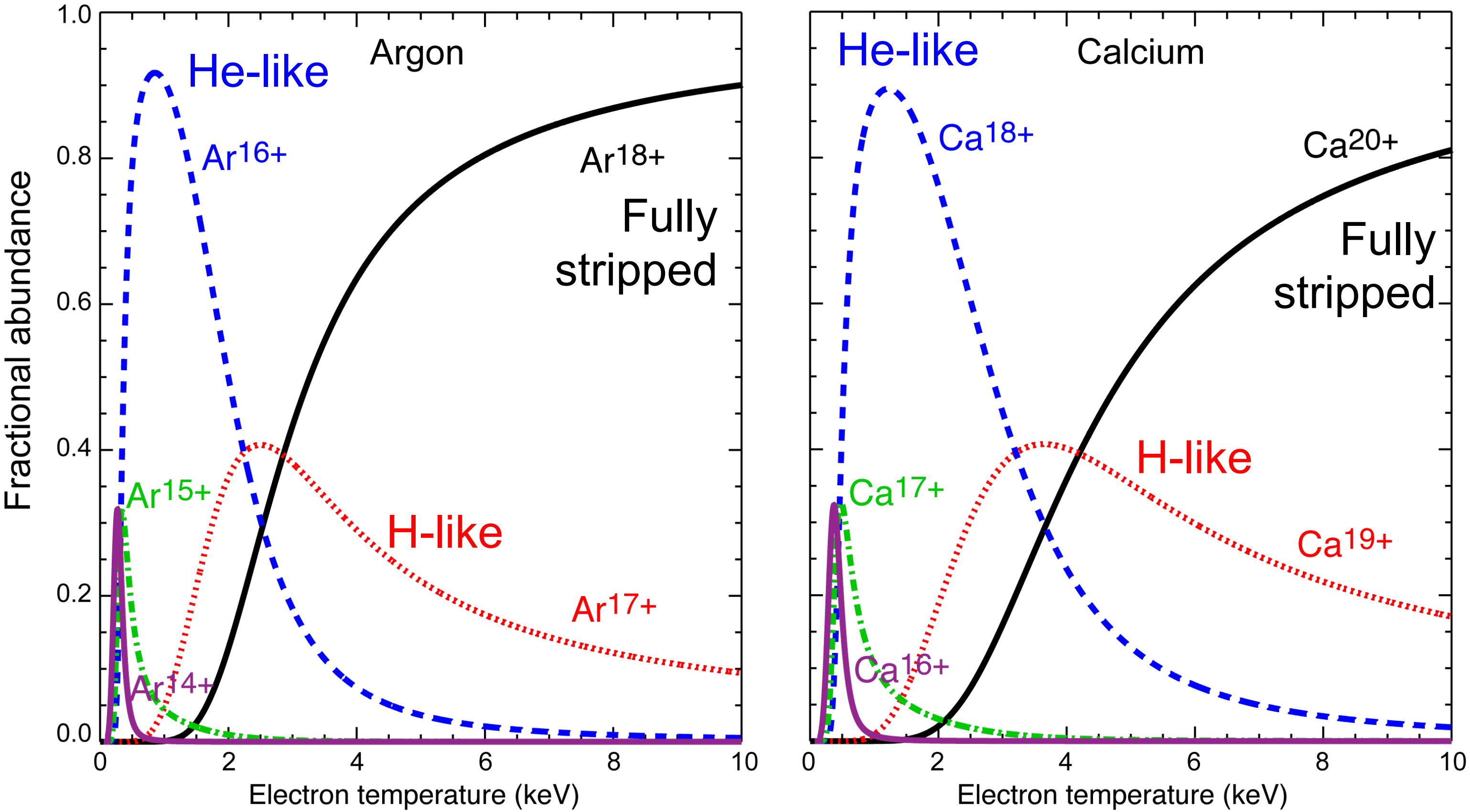
$$\Rightarrow \frac{n_{(Z+1)}}{n_Z} = \frac{\mathcal{S}_{Z\rightarrow(Z+1)}(T_e)}{\alpha_{Z+1\rightarrow Z}(T_e)}$$

- Result: Ionization degree is independent of density and increases with T_e
  - Low-Z ions (Be, B, C) are often fully stripped

Fractional abundance calculations (n_{ij}/n_i) depend only on the local electron temperature (issues with nomenclatures ???)

Argon
Z=18
A~40
18 protons
22 neutrons

Calcium
Z=20
A~40
20 protons
20 neutrons



Local emission **has** to be calculated on plasma parameters [T_e, n_e, $n_Z(R,t)$]

1. Continuum and & line emission:

Bremsstrahlung (ff):

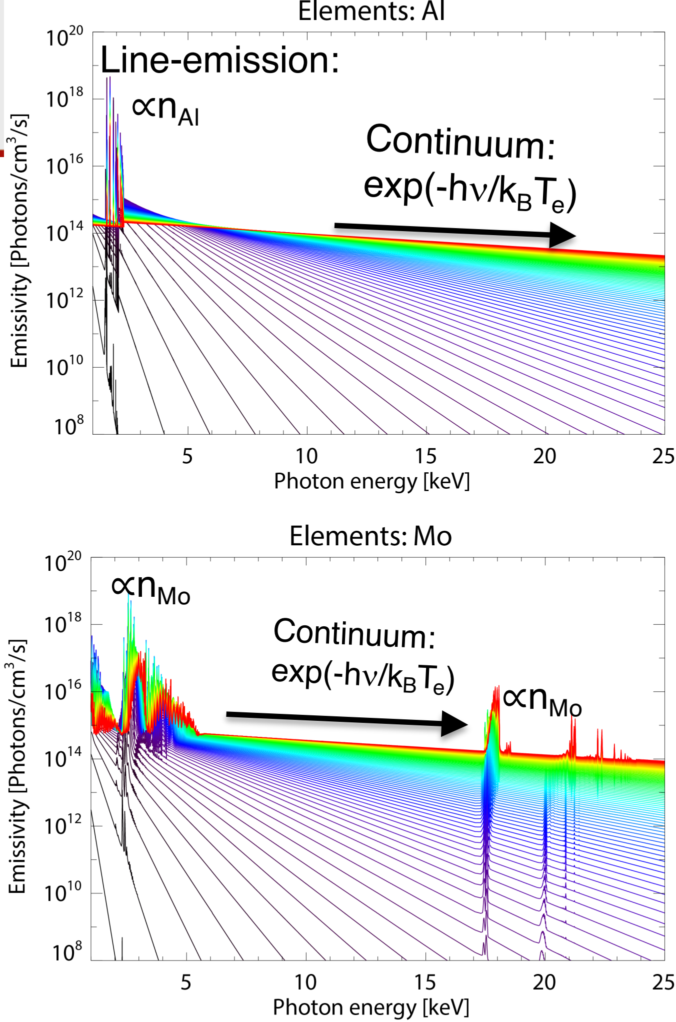
$$\frac{d\mathcal{P}^{ij}_{ff}(T_e,E)}{dE} \propto \frac{n_e^2 C_i (n_{ij}/n_i) Z_{ij}^2}{T_e^{1/2}} \mathcal{G}_{ff}(Z,T_e,E)\exp(-E/T_e)$$

Radiative recombination (fb):

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

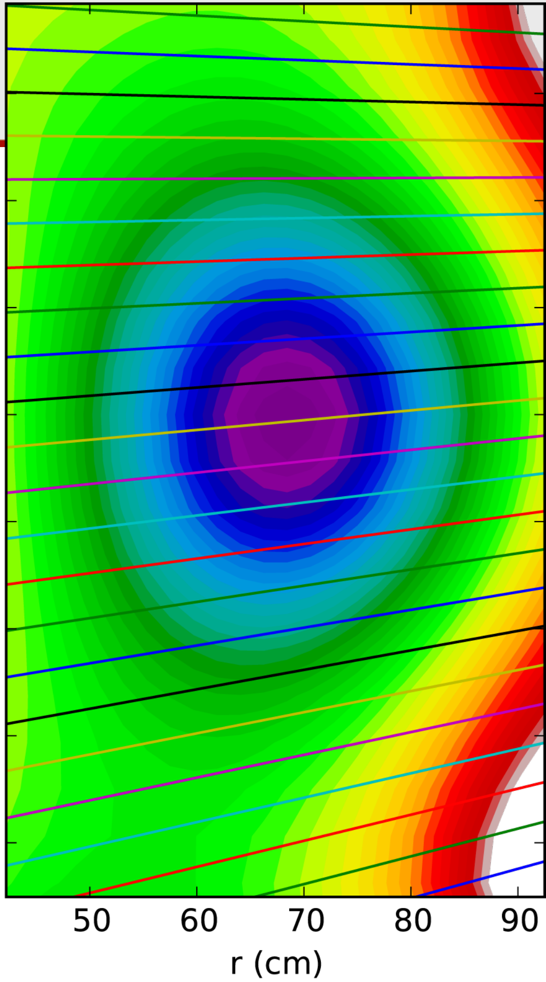
Line emission (bb):

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



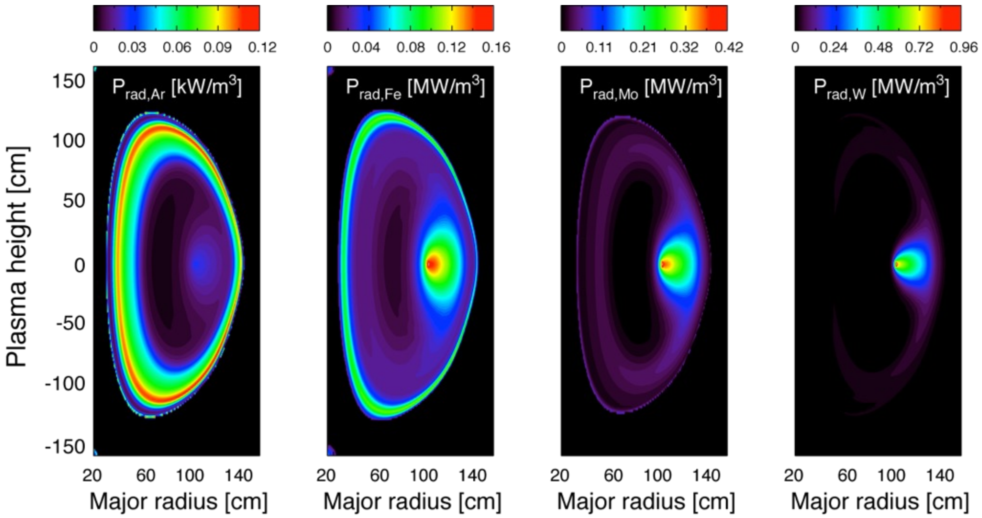
SXR brightness measurements are line-integrated along detection sightlines

2. Visible/UV/x-ray tomography:
- Emmisivity is a flux-surface function
- Inversion ($B = M \times E \Rightarrow E = M^{-1} \times B$)



3. Transport/heating asymmetries (warning):

Example:
Core radiation from medium- to high-Z will be affected by centrifugal forces



Take home message: You have three alternatives (…but with multiple detection options) in the x-ray range !

① Conventional broadband x-ray measurements
(e.g. SXR tomography ⇒ confinement, MHD, equilibrium)

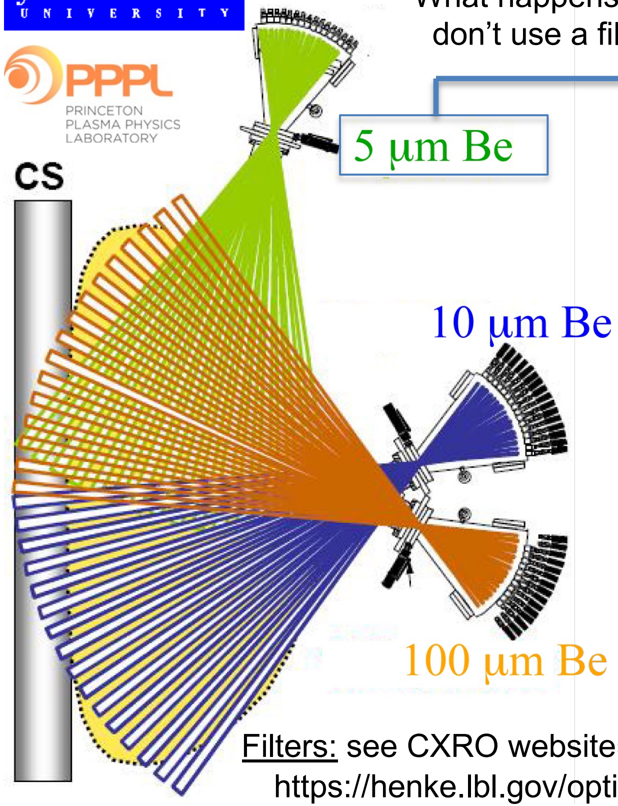
② Doppler line-radiation x-ray measurements
(e.g. n_Z, T_e, T_i, v_ϕ, v_θ, ⇒ calculation of E_r)

③ Modern broadband PHA & multi-energy measurements
(e.g. Z_{eff}, n_Z, T_e, $n_{e,fast}$)

1.- Conventional SXR tomography consists of an array of diodes/detectors integrating the local plasma emissivity

JOHNS HOPKINS UNIVERSITY

PPPL PRINCETON PLASMA PHYSICS LABORATORY



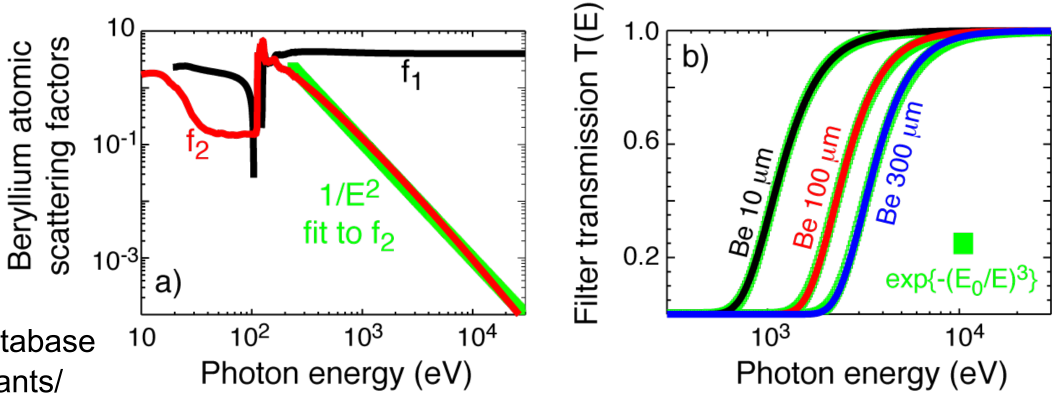
What happens if we don't use a filter?

① Essential elements:

a) Pinhole (radial resolution vs integration)
b) Thin vs thick metallic filters
c) Current mode: SXR Si-based diode or diode-array
d) Current mode: X-ray scintillator + FoP + FO + PMT
e) Transimpedance amplifier (10^4-10^7 V/A) + DAQ

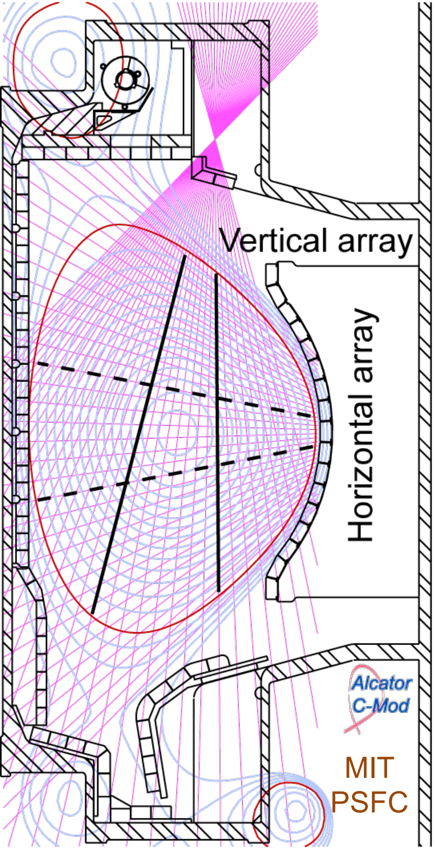
② Metal filters discriminate edge/core effects

(peeling the "onion")

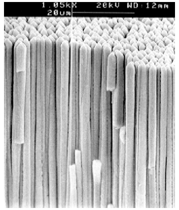


Filters: see CXRO website⇒x-ray database
https://henke.lbl.gov/optical_constants/

Conventional SXR tomography integrates in photon-energy using metal filters diode arrays and TIAs



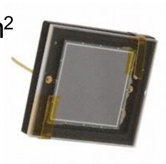
Indirect detection with scintillator (e.g. CsITl - green)



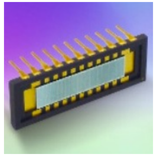
Direct x-ray detection (e.g. Si diodes)

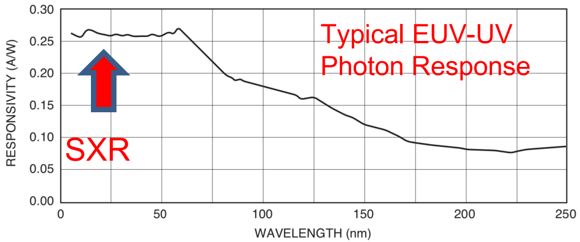
AXUV-100

1 cm^2

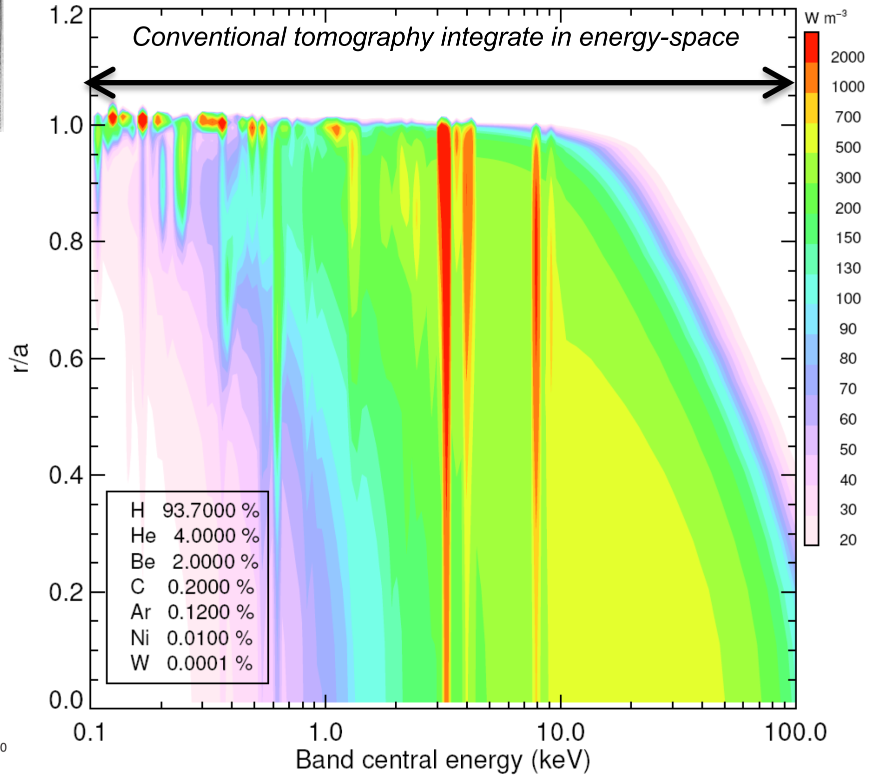


AXUV-20

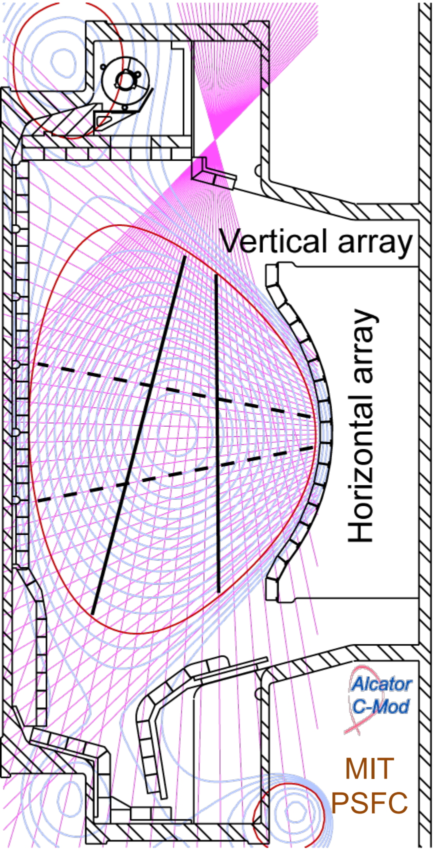




Example of spatially resolved x-ray spectra from ITER



Spatial and energy integration means also that it is very difficult to extract local plasma parameters from emission



SXR systems measure line-integrated continuum & line-emission

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_ϕ: toroidal velocity, M_Z: ion mass]
(vertical or tangential views are needed)

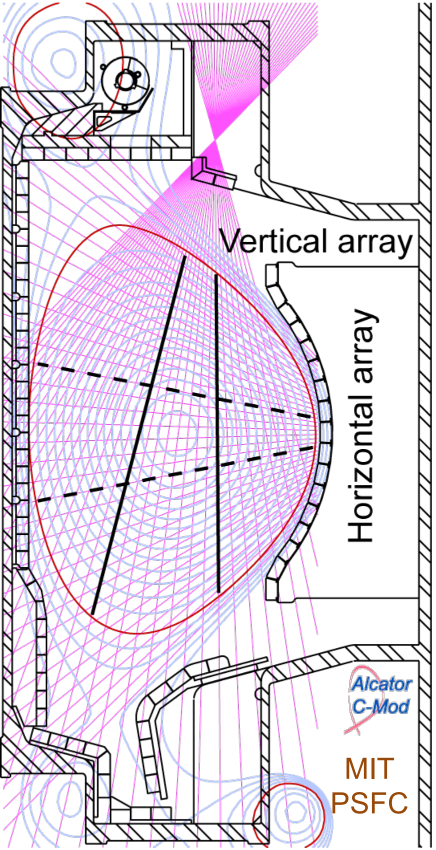
L: Length of integration, θ: poloidal angle
(radial and poloidal coverage)

Energy response

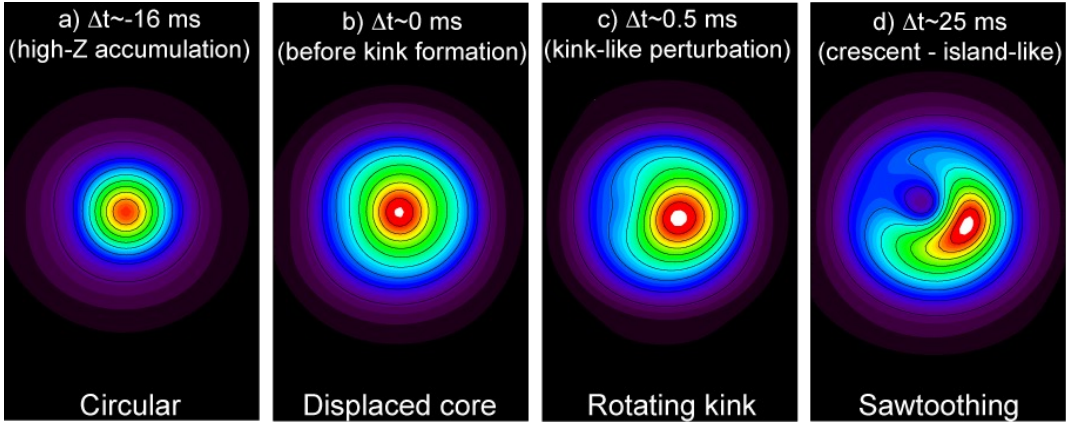
$T_{filter}(E_{ph})$: transmission function of filter

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

However, conventional SXR tomography is still being used for stability, MHD & transport studies

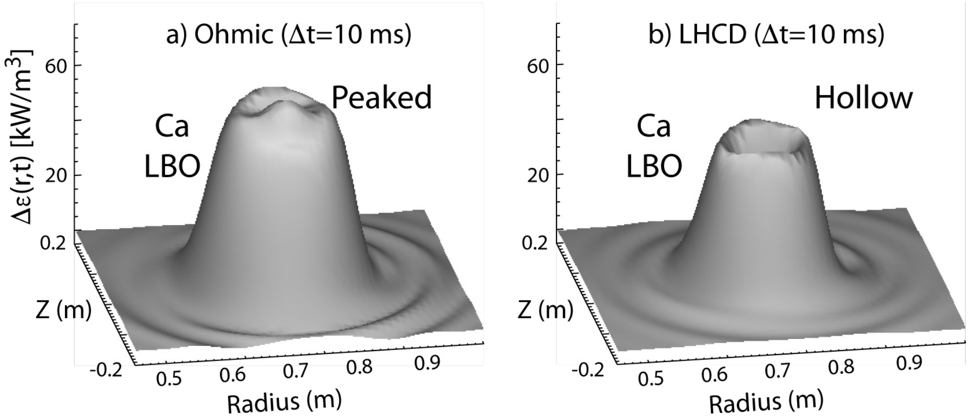


a) Stability and MHD [e.g. (m,n) modes and sawteeth]



b) Impurity transport (e.g. using gas injection or LBO)

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



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(e.g. Z_{eff}, n_Z, T_e, $n_{e,fast}$)

We also need to extract local plasma information !!!

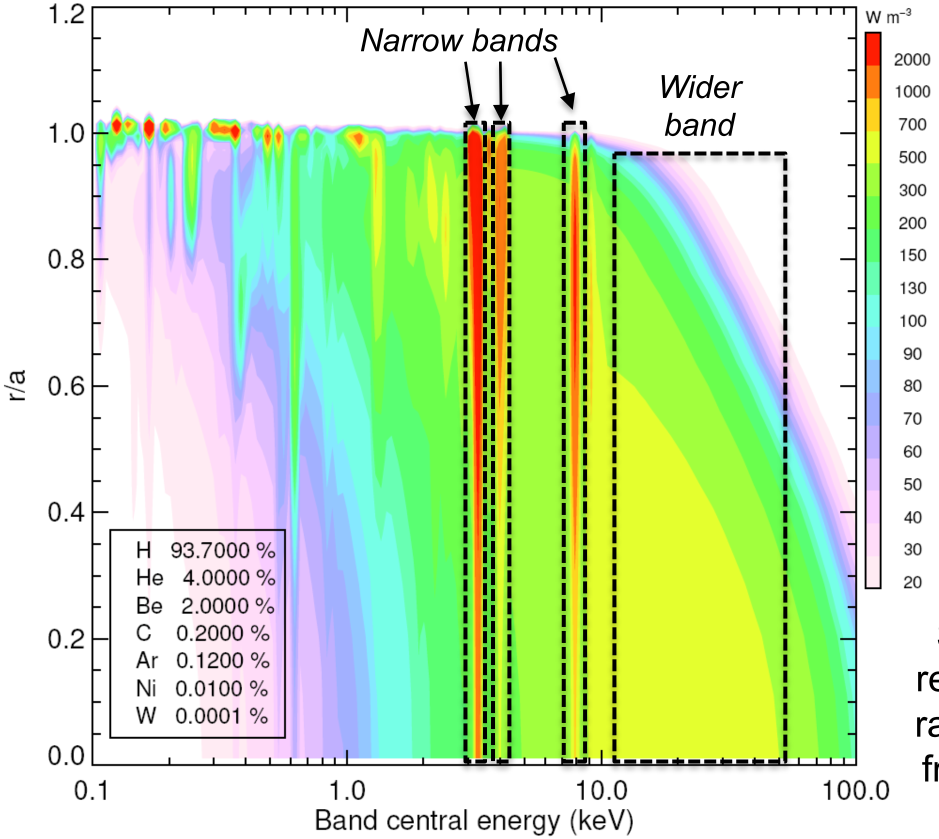
How to extract plasma physics parameters from narrow and/or wider SXR and HXE energy bands ?

Narrow energy bands

- Doppler spectroscopy
- High-resolution spectrometers
- $E/\Delta E \sim 5000\text{-}200000$
- Probes mainly the ion-channel
- T_i, $V_{\phi,\theta}$, n_Z… T_e (line-ratios)

Wider energy bands

- Multi-energy spectroscopy
- Low-resolution spectrometers
- $E/\Delta E \sim 10\text{-}50$
- Probes e^- and ion channels
- T_e, n_Z, ΔZ_{eff}, Z_{eff}
- $n_{e,fast}$ (e.g. LHCD, runaways)



Spatially resolved x-ray spectra from ITER

X-ray crystal imaging spectrometers enable $T_{i,e}$, $v_{\phi.\theta}$ and $n_{Z's}$ measurements via Doppler broadening & line shifts.

① Not all reactor concepts consider NBI's (CXRS). Spontaneous rotation ($\propto W_{MHD}$) may provide the solution for stabilization.

② Measurement of ion-temperature (T_i), toroidal and poloidal velocity ($v_{\phi,\theta}$) and impurity density ($n_{Z's}$) are important for understanding and optimizing confinement:

a) ∇T_i driven turbulence (ITG) is a leading candidate for explaining anomalous ion thermal transport.

b) V_ϕ and dV_ϕ/dr play important roles in the H-mode transition, ITB-formation, and RWM-stabilization.

c) Radial electric field ($\propto n_Z$, T_i, $v_{\phi,\theta}$)

d) Z-transport/accumulation needs to be studied & controlled/avoided

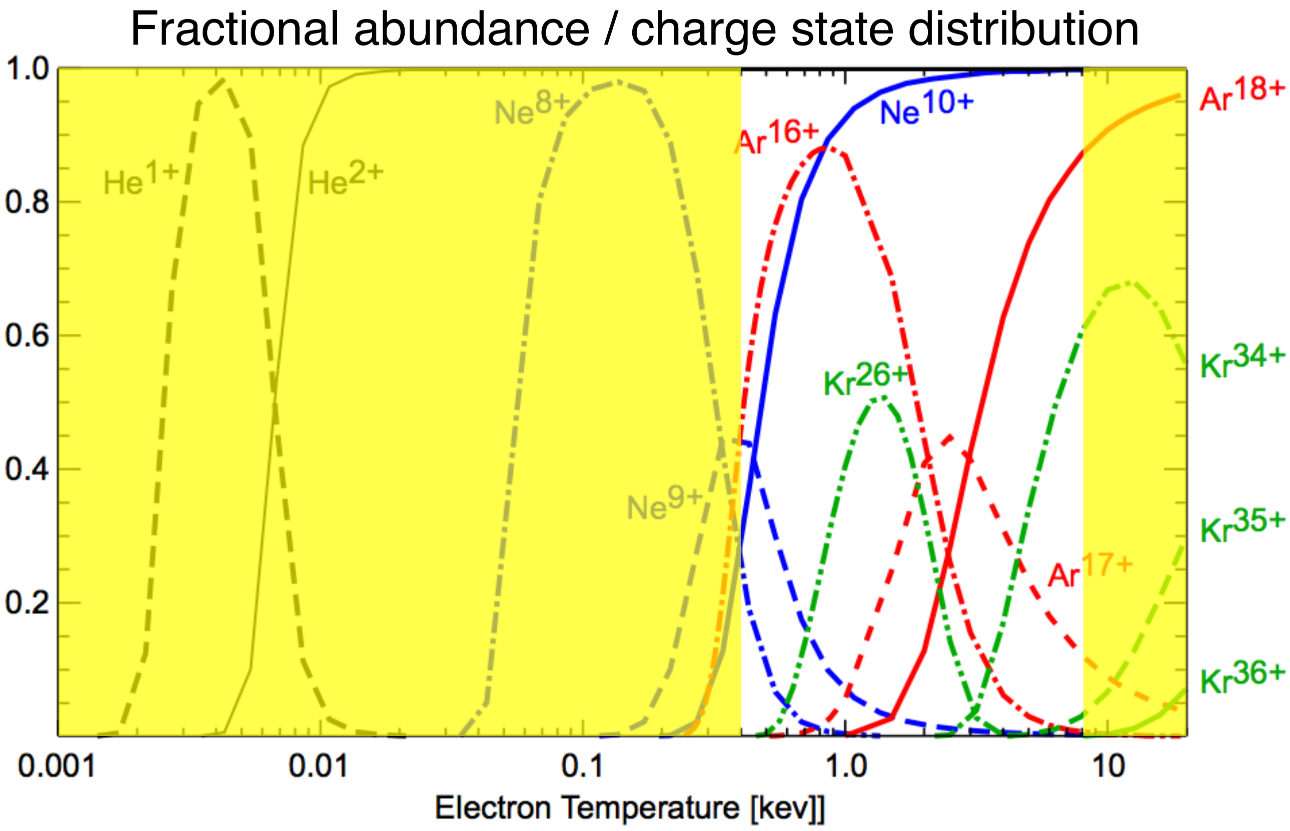
Choosing the appropriate (non-perturbative ⇒ low n_Z & P_{rad}) extrinsic impurity gas-puff to do x-ray spectroscopy

① For the T_e∈[0.5,5] keV, He & Ne are fully stripped except in the cool edge region.

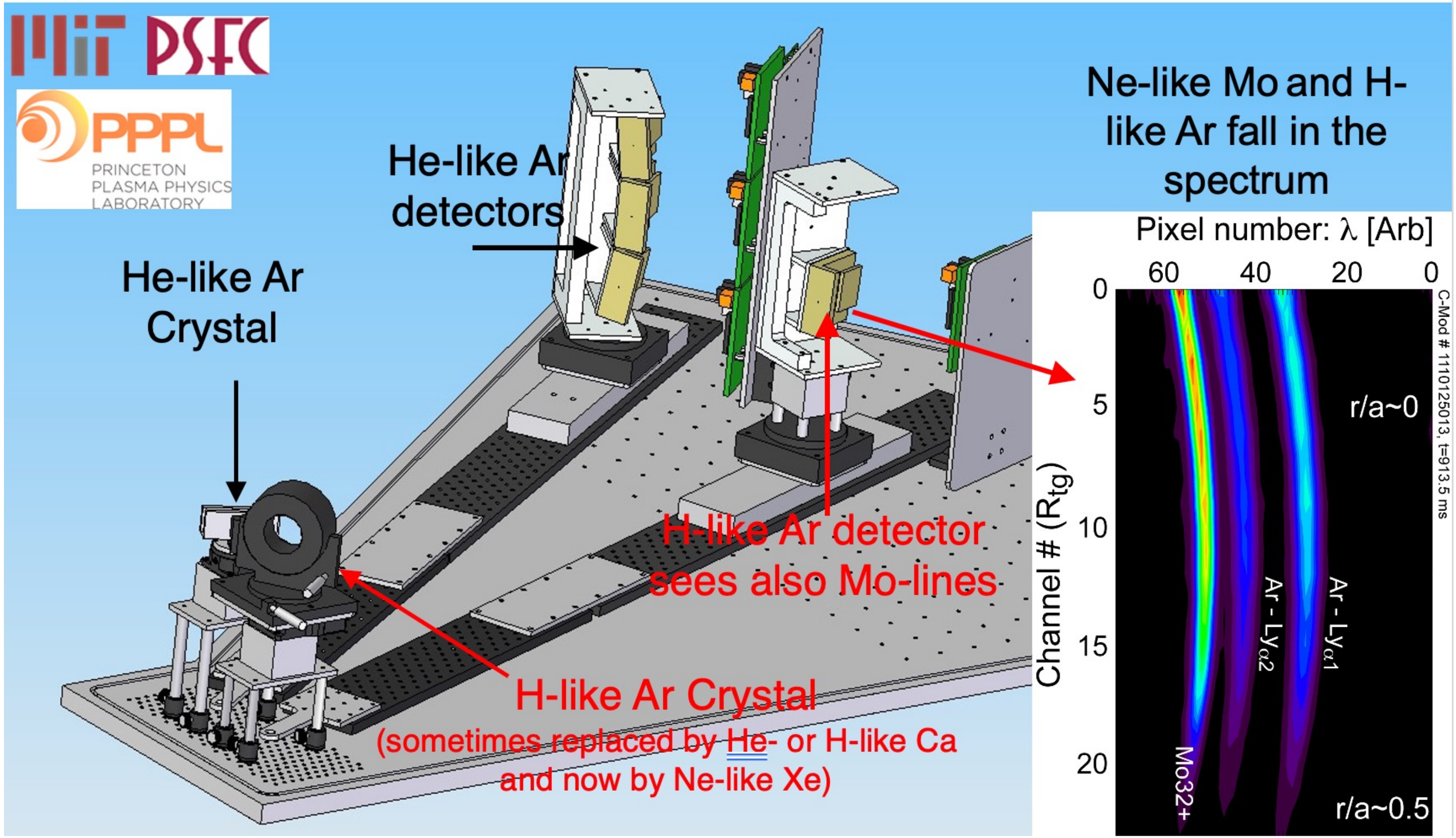
② H- and He-like Ar are dominant T_e∈[0.5,5] keV

③ Kr or Xe could be used for diagnosing the core T_e∈[4,20] keV, but they are more "*perturbative*" than Ar for the same absolute density,

⇒puff less Kr/Xe



X-ray crystal imaging spectrometers revolutionized our field with T_i and $V_{\phi,\theta}$ profile measurements



Similar systems have been installed in NSTX, KSTAR, EAST, LHD, W7 and in the future, NSTX-U, WEST, JT60SA & ITER

Focusing properties of spherical x-ray crystal

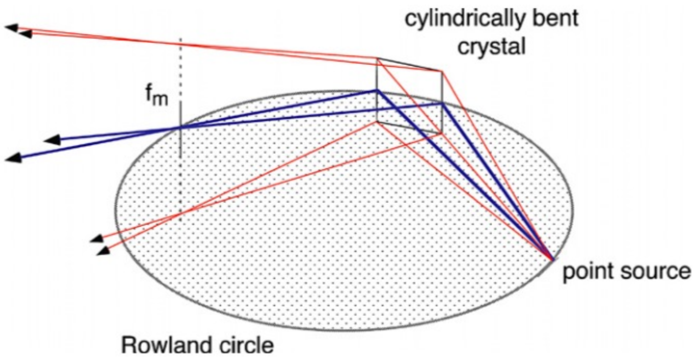


Figure 6. Focusing properties of a cylindrically bent crystal illustrating the divergence of sagittal rays.

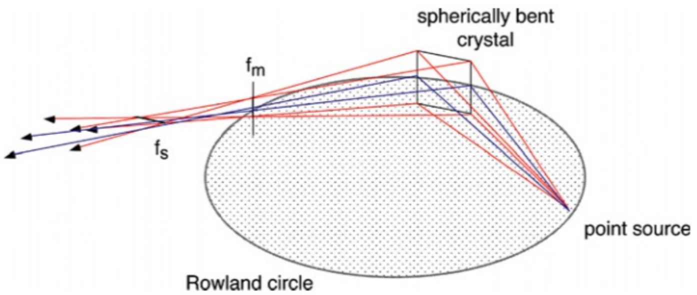
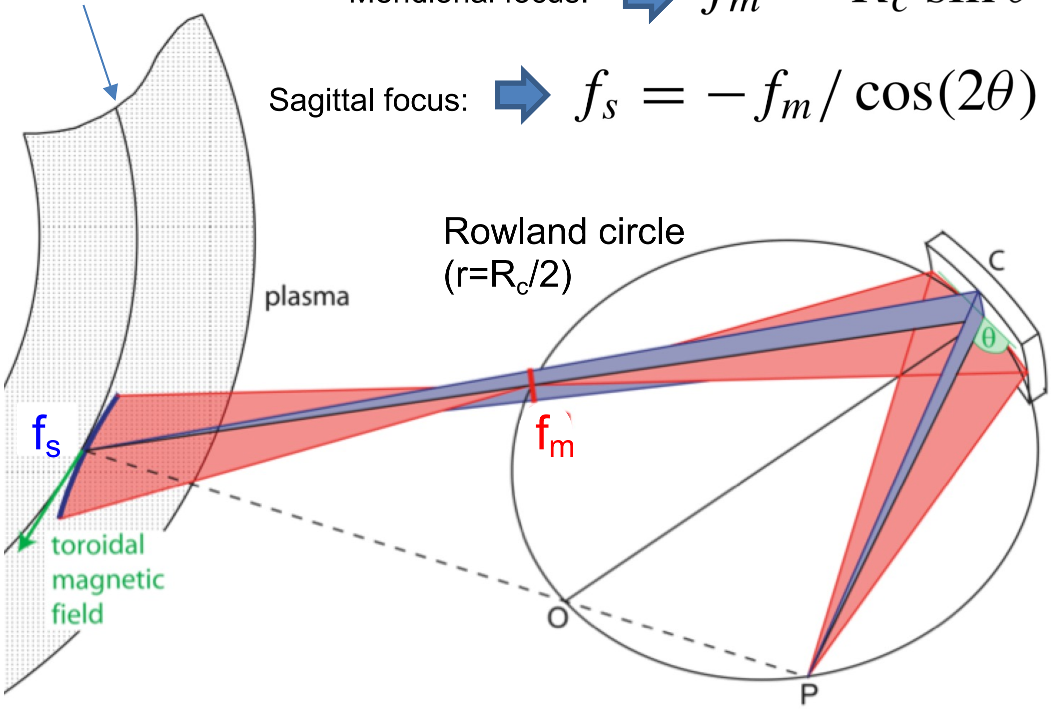


Figure 7. Focusing properties of a spherically bent crystal illustrating the focusing of sagittal rays.

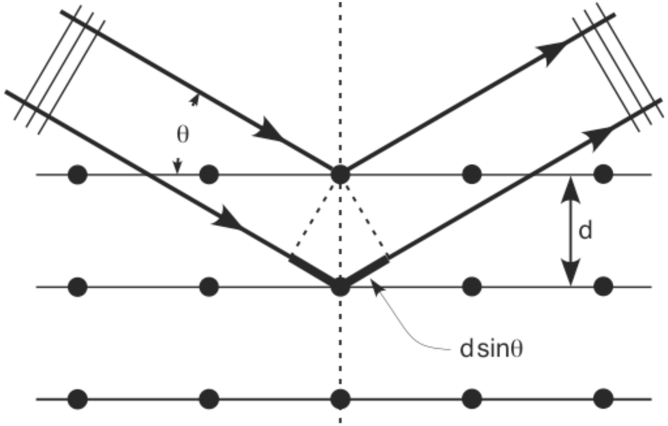
Typical distances from the crystal:

Meridional focus: $f_m = R_c \sin\theta$

Sagittal focus: $f_s = -f_m / \cos(2\theta)$



Crystals help achieving high-spectral response ($E/\Delta E>10^4$) for high-resolution $T_{e,i}$ & $v_{\phi,\theta}$ measurements



① Bragg diffraction: ➡ $$2d\sin\theta = n\lambda$$

② Assuming a constant "d", the observed relative wavelength shift (DS: Doppler shift) is given by:

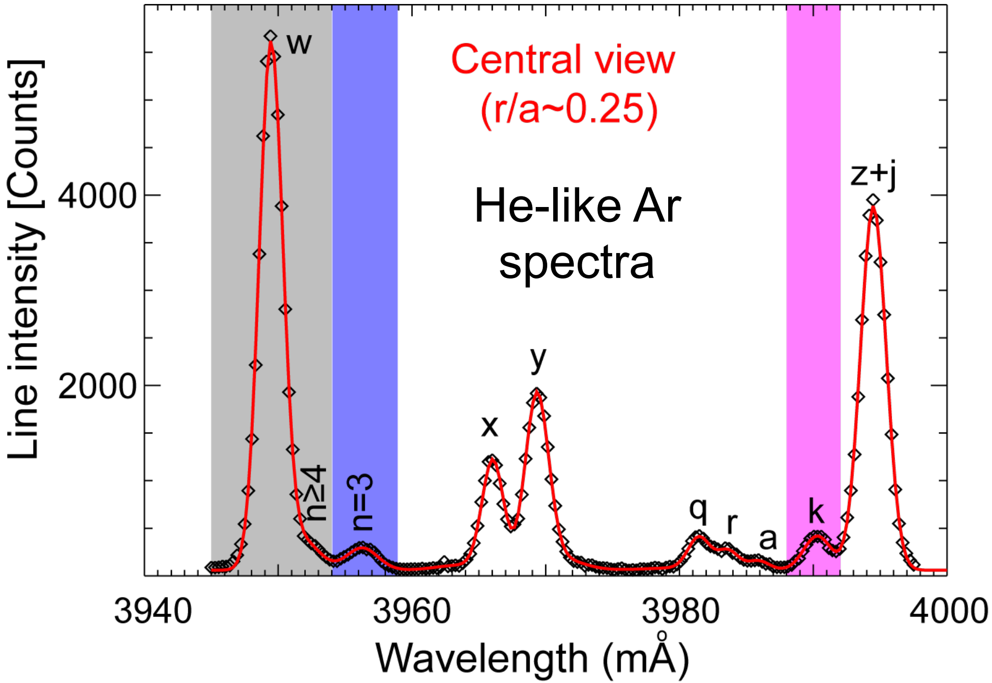
$$\frac{\Delta\lambda}{\lambda_0}\Big|_{DS} = \sqrt{\frac{1+v/c}{1-v/c}} \approx \frac{v}{c} \approx \frac{\Delta\theta}{\tan\theta}$$

v is the relative velocity between the source & detector

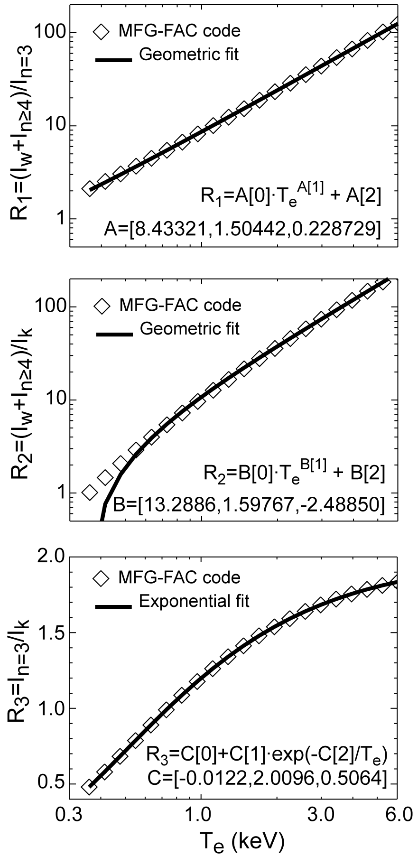
③ The value of $\Delta\theta_{max}$ from Johann error (*Je*): $$(\Delta\theta)_{Je} = l_c^2/8R_c^2\tan\theta$$

④ Resolving power: ➡ $$\frac{\lambda}{\Delta\lambda} = 8\frac{R_c^2}{l_c^2}\tan^2\theta$$

Electron temperature T_e-profiles can also be obtained using line-ratios between resonance and satellite lines



Te-measurements based on the ratio of the resonance line-w and the dielectronic satellites "n=3" and "k"



(L. Delgado-Aparicio, un-published)

Considered to be a secondary diagnostic technique for the electron temperature (T_e) JT60SA and ITER.

Take home message: You have three alternatives (…but with multiple detection options) in the x-ray range !

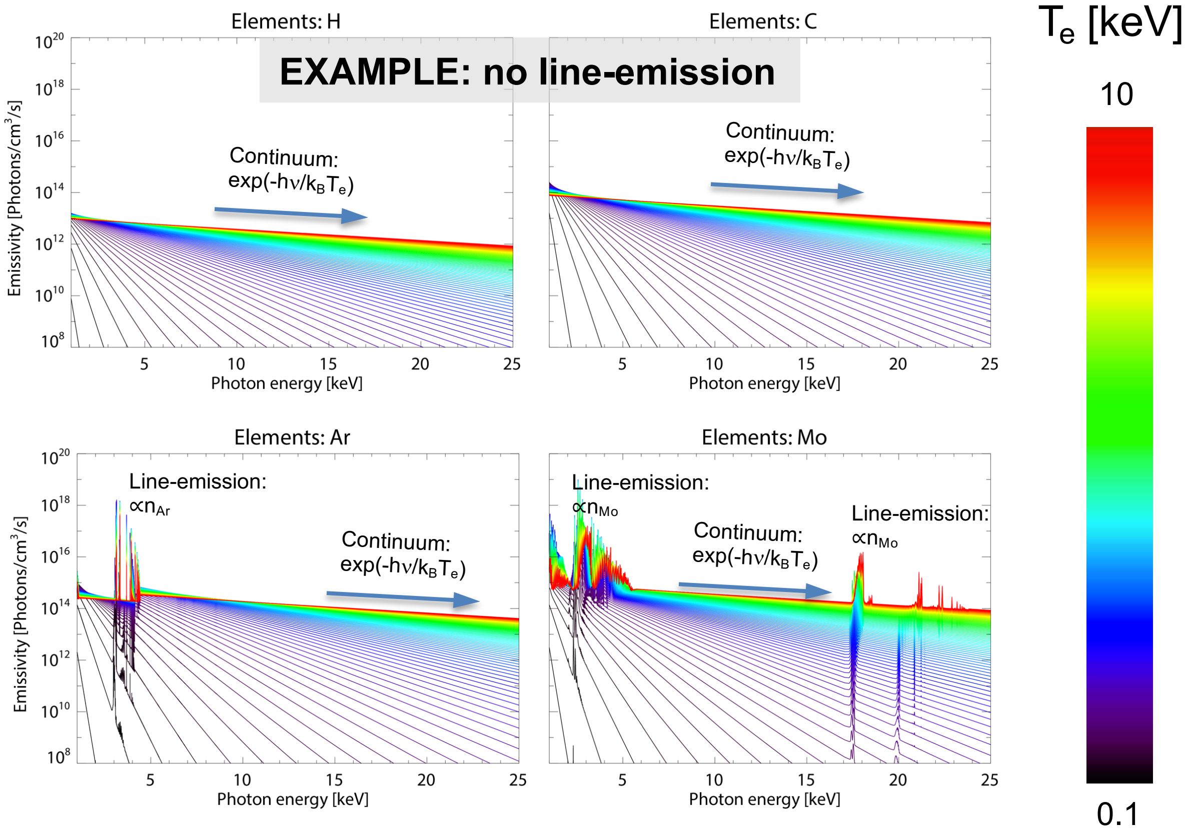
① Conventional broadband x-ray measurements
(e.g. SXR tomography ⇒ confinement, MHD, equilibrium)

② Doppler line-radiation x-ray measurements
(e.g. n_Z, T_e, T_i, v_ϕ, v_θ, ⇒ calculation of E_r)

③ Modern broadband PHA & multi-energy measurements
(e.g. Z_{eff}, n_Z, T_e, $n_{e,fast}$)

We also need to extract local plasma information !!!

Motivation #1: "spatially" resolve continuum & line-emission to derive local plasma physics parameters



?????

Simultaneous:

- Time resolution
- Spatial resolution
- Energy resolution
- In real-time…

Motivation #2: Develop ME-SXR imaging for magnetically confined fusion plasmas with a unique capability

Unique opportunity of measuring, *simultaneously*, a variety of plasma quantities:

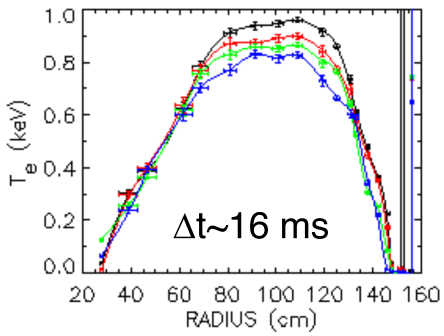
a) electron temperature profiles ($T_e(R,t)$)
b) medium- to high-Z impurity concentration profiles (Z_{eff}, $n_Z \Rightarrow \Delta Z_{eff}$)
c) the birth of suprathermal e$^-$ ($n_{e,fast}$)
d) plasma position (R_0, Z_0)

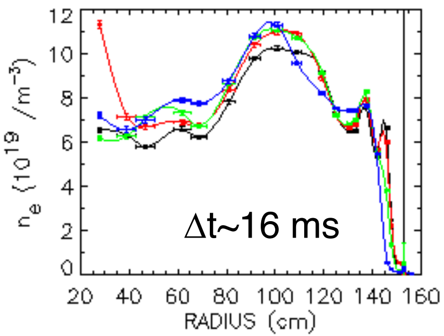
Especially applicable for:

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

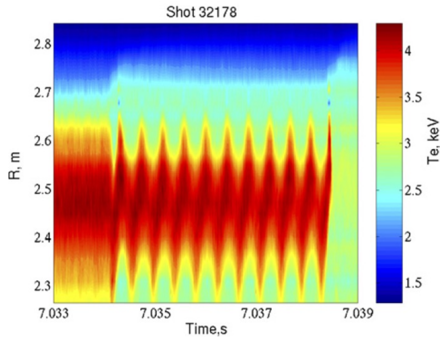
Burning plasmas: Complement other techniques such as TS and ECE

NSTX's 60 Hz Multi-point Thomson Scattering





Tore Supra fast ECE data

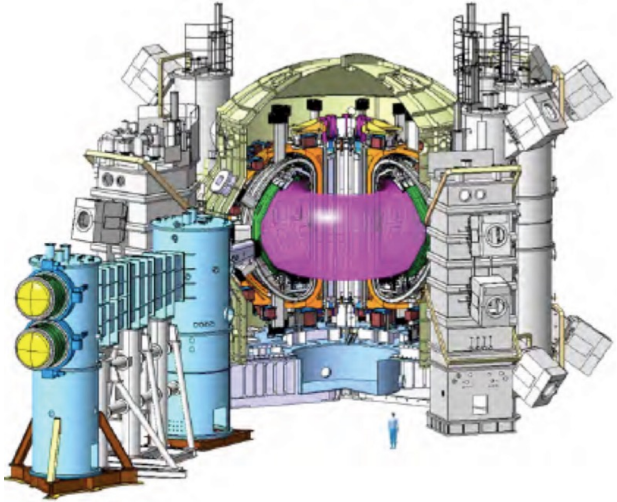


Motivation #3: … think really large (burning plasmas) !!!

Unique opportunity of measuring, *simultaneously*, a variety of plasma quantities:

a) electron temperature profiles ($T_e(R,t)$)
b) medium- to high-Z impurity concentration profiles (Z_{eff}, $n_Z \Rightarrow \Delta Z_{eff}$)

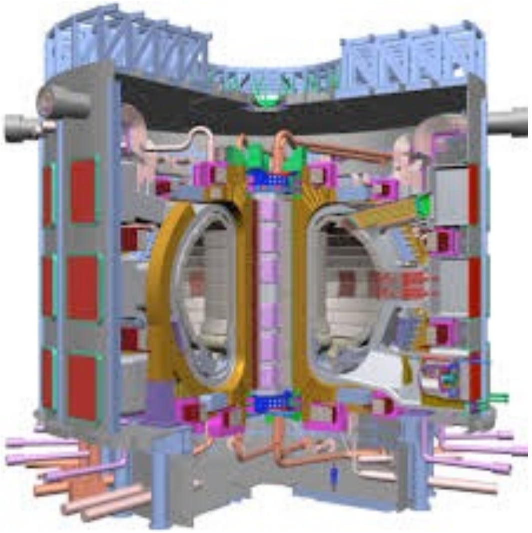
c) the birth of suprathermal e^- ($n_{e,fast}$)
d) plasma position (R_0, Z_0)



JT60SA, ITER & DEMO!

This technique should be explored also as a burning plasma diagnostic in-view of its simplicity and robustness.

e) $T_e(R,Z) \Rightarrow \Psi$, J & q

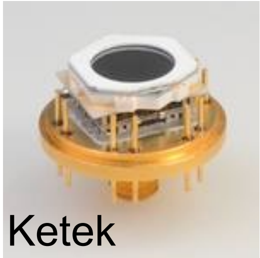


Background: Conventional photon counting ME-SXR systems use Si(Li), HgI_2, Si-Ge-CdTe diodes and SDDs

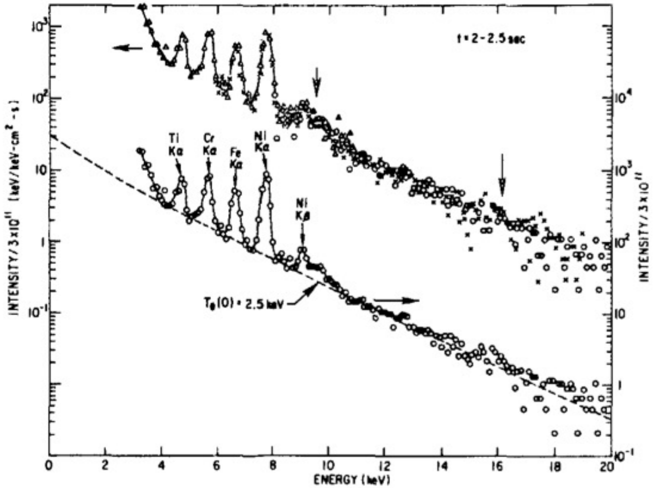
① Detectors in photon-counting mode

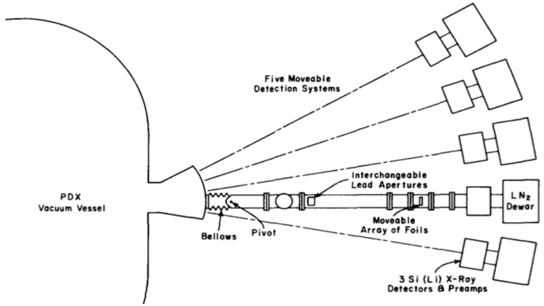
($\langle T_e \rangle$, $\langle Z_{eff} \rangle$, $\langle n_{e,fast} \rangle$, $\langle n_Z \rangle$)

- 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)



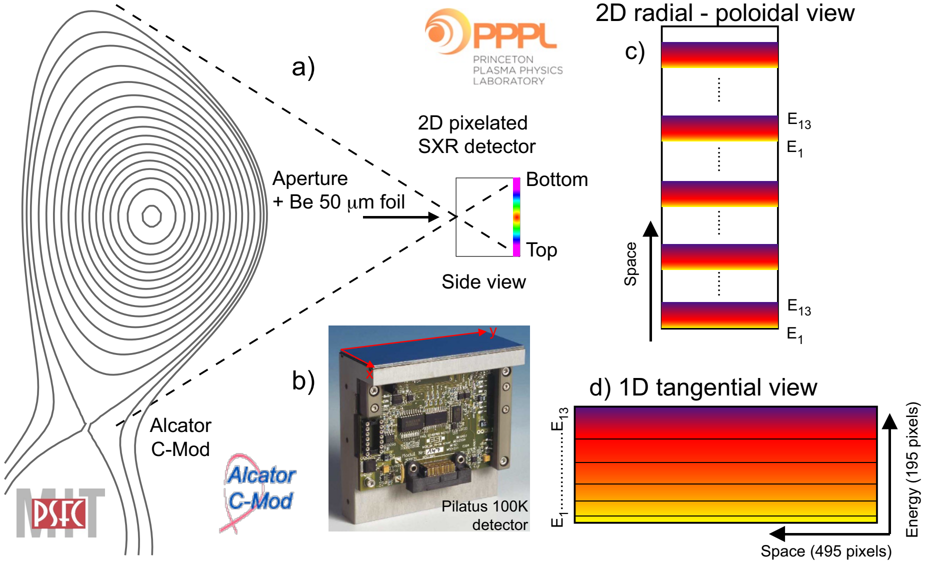
Single-chord spectrometers

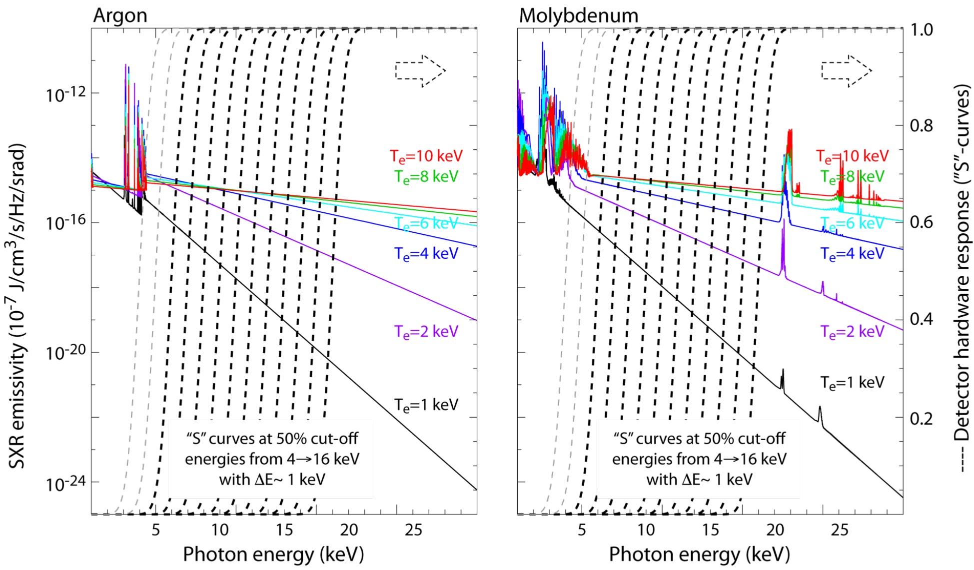




One spectrum per instrument

Initial ME-SXR imaging tests in C-Mod (@MIT) combined the best features from PHA & multi-foil methods

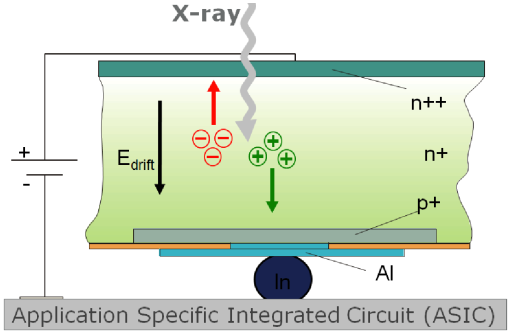




Pin-hole camera with multi-energy pixels allowed simultaneous spatial and energy resolution

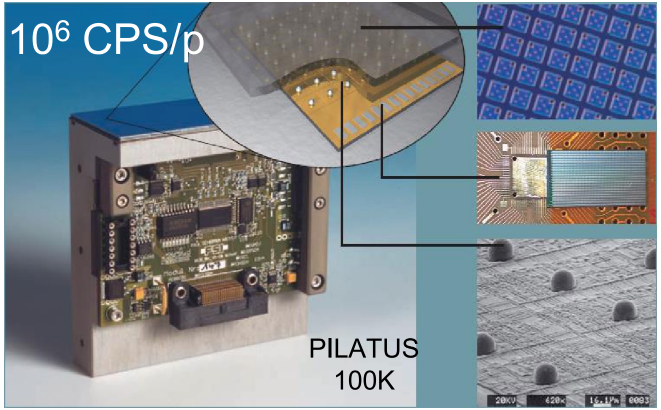
From sampling the continuum radiation from Ar & Mo one can measure T_e & $n_e^2 Z_{eff}$

Pilatus silicon detectors enables breakthrough of 100k pixels (minimum) at single or multiple energy ranges



Operates in single photon counting mode

CMOS hybrid pixel technology developed originally for synchrotrons (CERN + PSI + DECTRIS)



Si-sensor 2D array pn diodes

CMOS readout chip

In balls

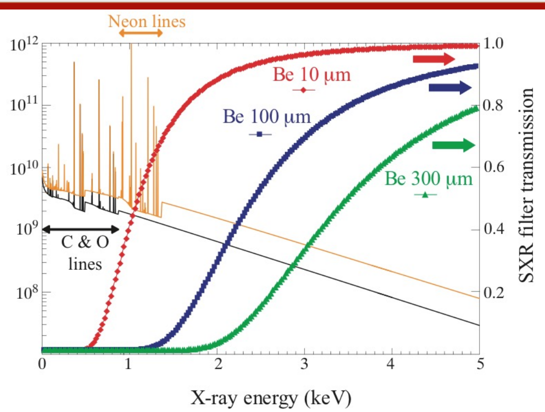
Thanks to important advances in the x-ray detector technology it is now possible to simultaneously record high resolution images of x-ray photons at single OR multiple energy ranges through direct x-ray detection.

100K to 12M pixels (PILATUS: 172 μm, EIGER: 75 μm)

PILATUS3 900K-IPP in-vacuum detector for x-ray plasma spectroscopy

(dimensions of a 100K system: 487x195 pixels)

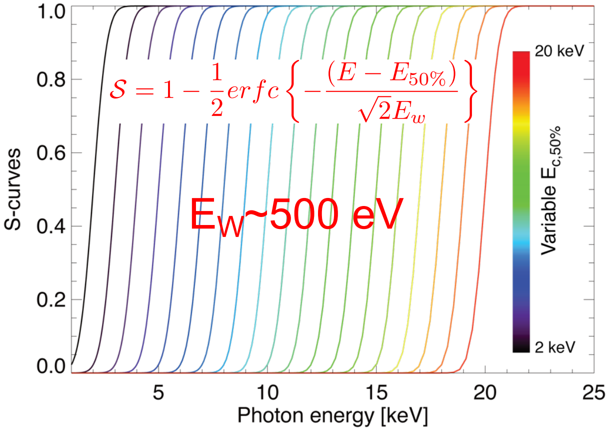
Comparator and triming voltages on each pixel allow individual coarse & fine tuning of energy range



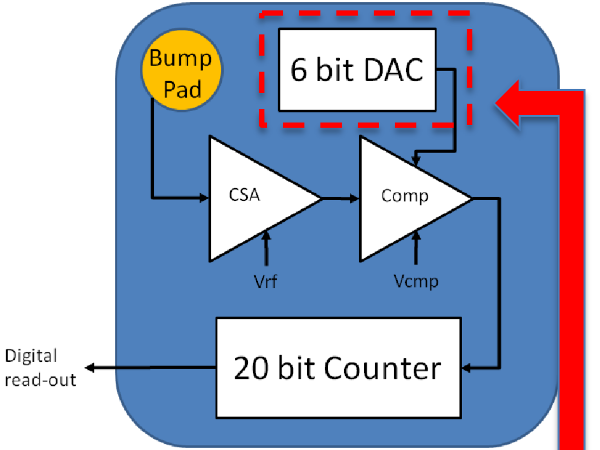
Filters: CXRO website:
X-ray database

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

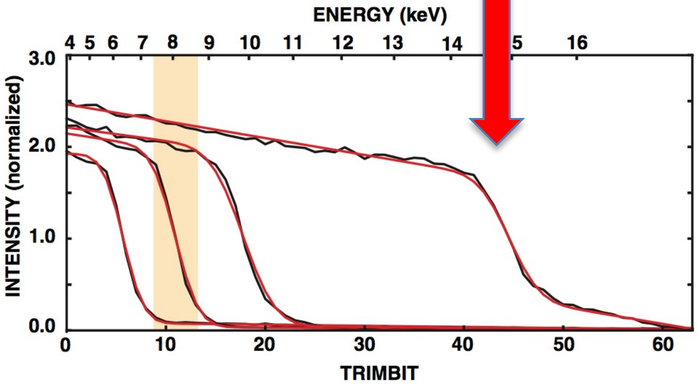
$$\Rightarrow \frac{d\mathcal{T}}{dE}\Big|_{E_0} \sim \frac{1}{E_0}$$



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

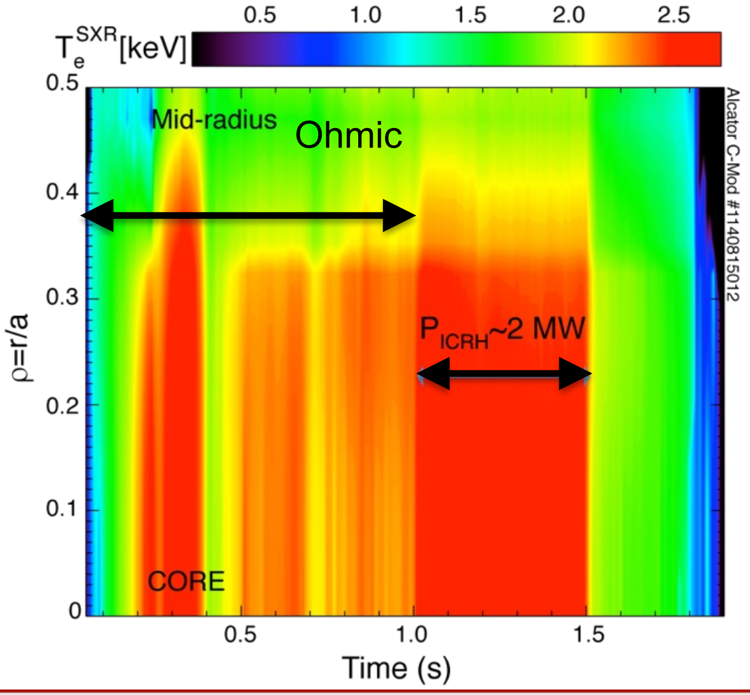


PILATUS technology: photon counting circuit in **each pixel**

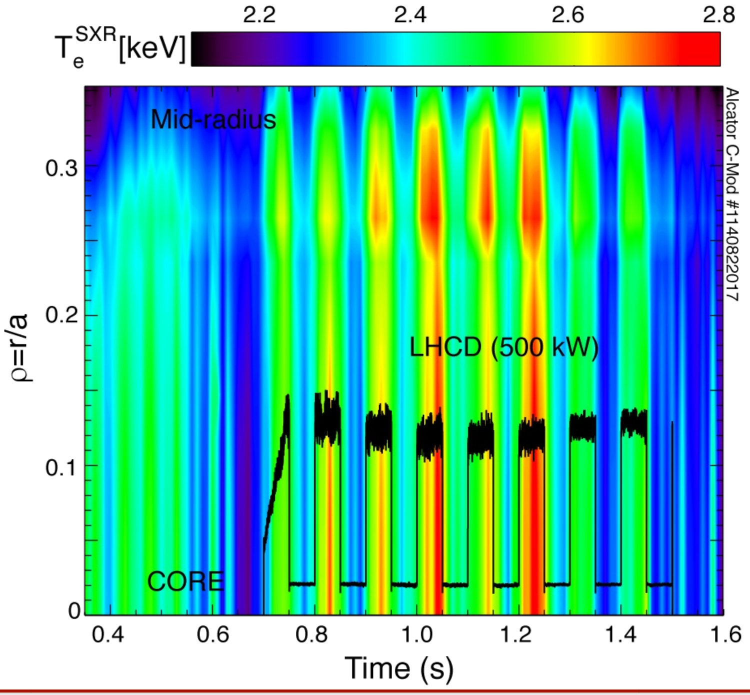


Goals #1&2: SXR-inferred T_e profiles can be obtained during Ohmic, ICRH & LHCD scenarios

- ICRH heats up ions & electrons
- EEDF function is still Maxwellian

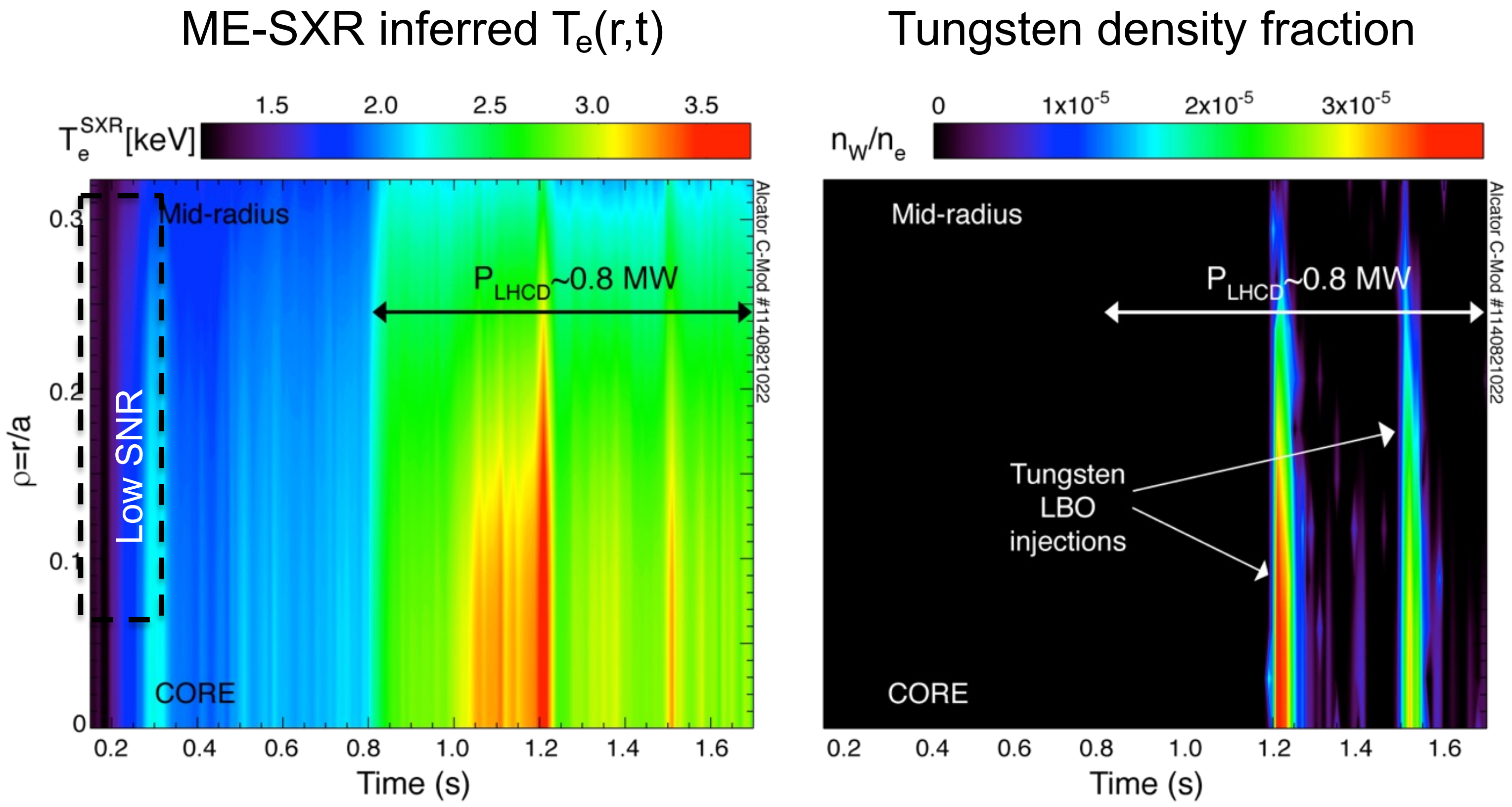


- LHCD drives current and heat e⁻
- LHCD present challenges for ECE



Note:
Thin Si detectors are sensitive mostly to the Maxwellian part of the electron distribution function

Goal #3: separate dynamic evolution of $T_e(R,t)$ from transient laser-blow-off contributions during LHCD

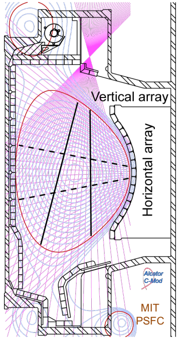


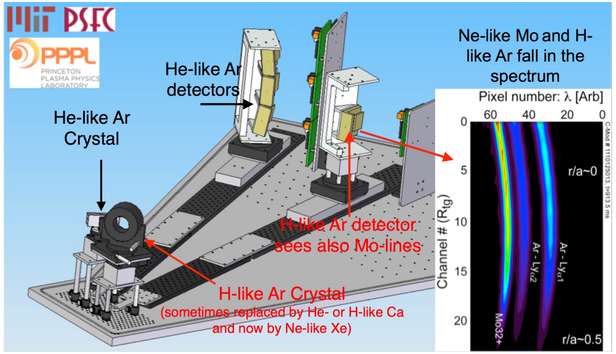
To-do:

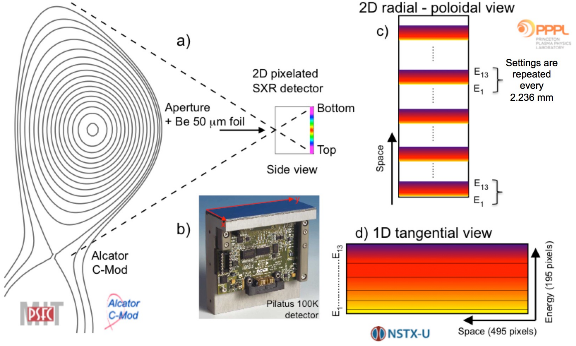
- Estimate n_Z/n_e using other diagnostics and compare

- Test Mo and W impurity transport in inductive & non-inductive scenarios

Summary: Modern x-ray diagnostics can help study MHD and resolve n_Z, $T_{e,i}$, $V_{\phi,\theta}$, Z_{eff} & $n_{e,fast}$ profiles





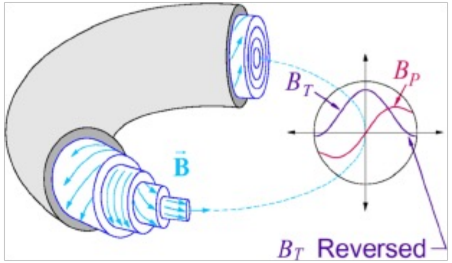


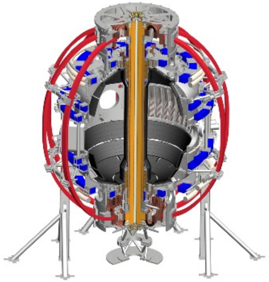
① With the selection of W for the divertor in ITER, understanding the sources, transport and confinement of high-Z impurities is crucial to ITER success.

② A significant fraction of the power delivered to the plasma is lost in the form of radiation. In the x-ray range (subset of P_{rad}) could be as high as 90%.

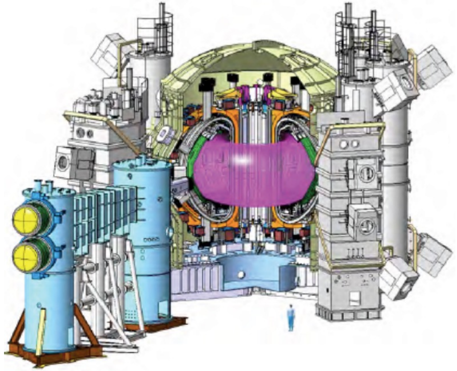
③ Modern diagnostics in x-ray range allow us to probe n_Z, $T_{e,i}$, $V_{\phi,\theta}$, Z_{eff} & $n_{e,fast}$ and their profiles!

New core x-ray diagnostic systems (US-lead) will be installed in NSTX-U, MST, WEST, JT60SA to ITER

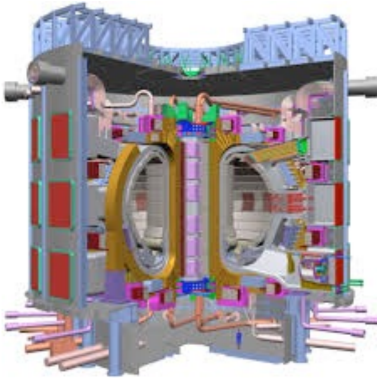




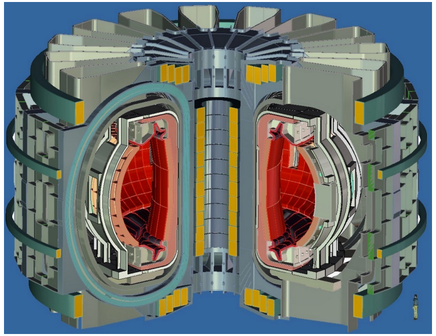
WEST - France



JT60SA
Japan



ITER
France



DEMO ?