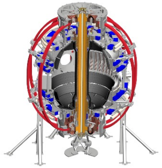
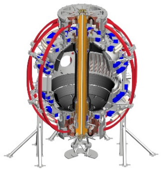
The Z-challenge, radiation & diagnostics

Luis F. Delgado-Aparicio (PPPL)

06/15/2023



Outline



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

② Radiation losses and the basic need of spectroscopy

③ Take home message: radiated power and x-ray diagnostics

④ Summary

Class-Homework #1 …on the “fly”

https://forms.gle/W6cmsJsyrpWvwRf16

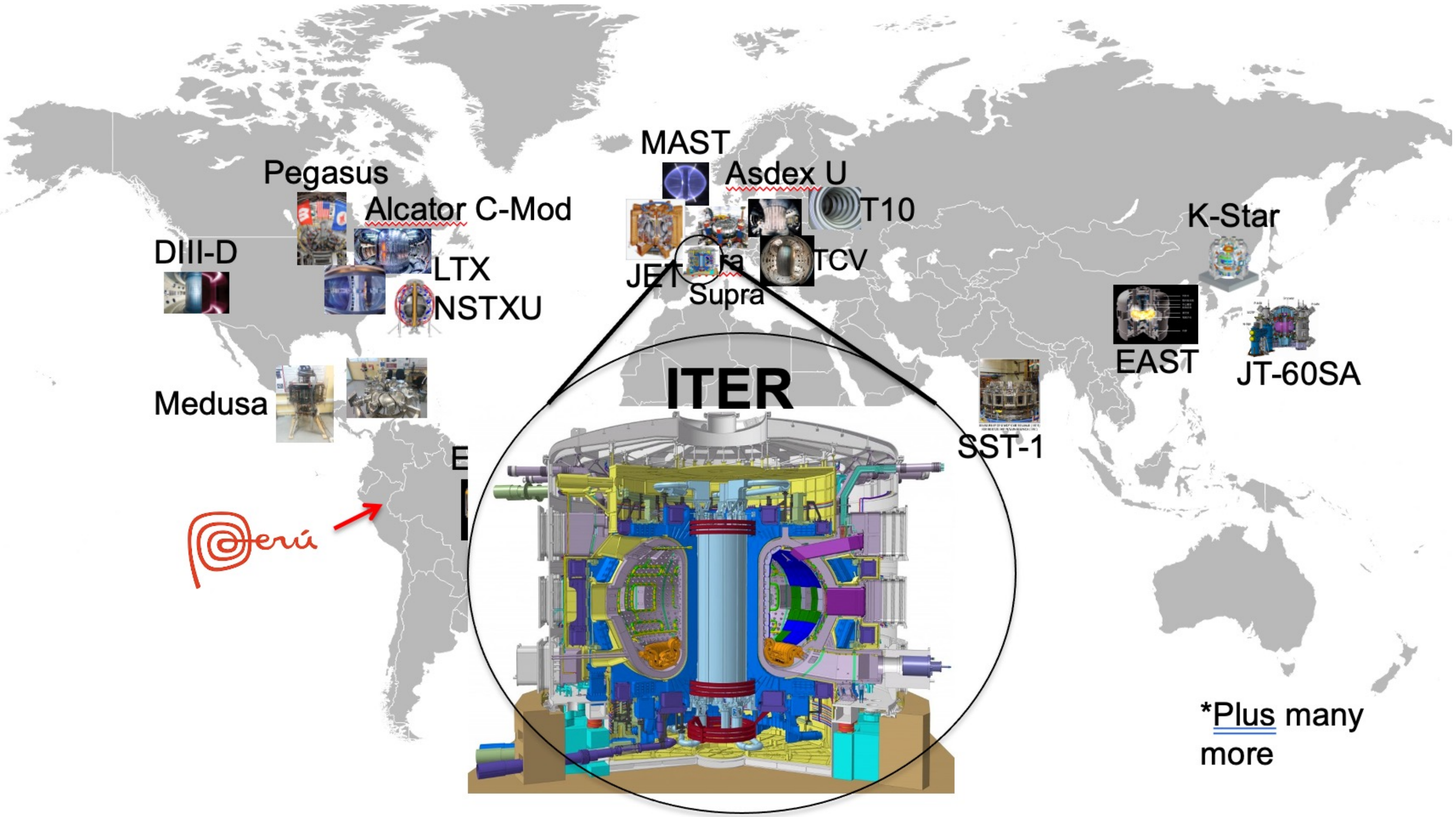
2023 Intro Fusion Energy Diagnostic poll

Author: Luis F. Delgado-Aparicio (PPPL)

After a good "couple-dozen” lectures in plasma physics and fusion, what do you think are the most important plasma quantities you need to diagnose in your experiments? Remember, diagnostics are "the key” to your access inside the plasma !!!

Challenge: Pick your top 10 (ONLY 10)
Time: Three minutes
Note: Responses cannot be changed after submitted

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



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

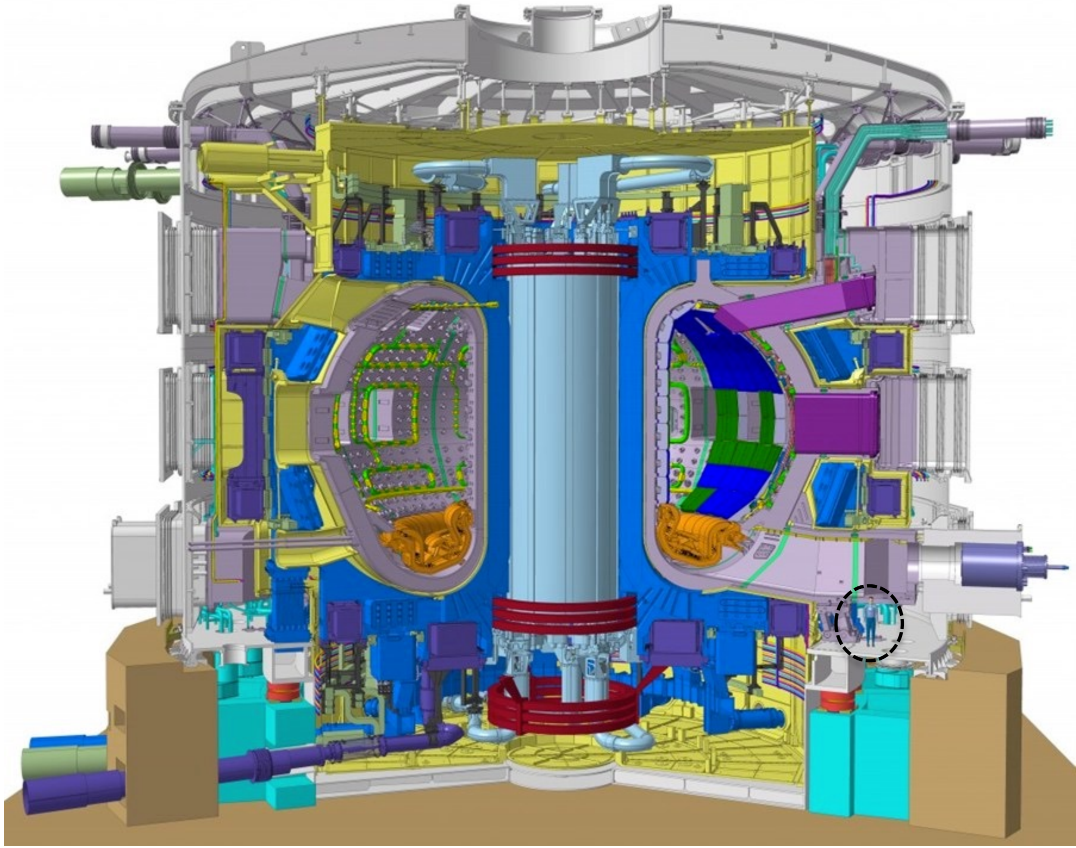
- ITER is a collaboration between USA, EU, China, Japan, Korea, India and Russia

- 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!

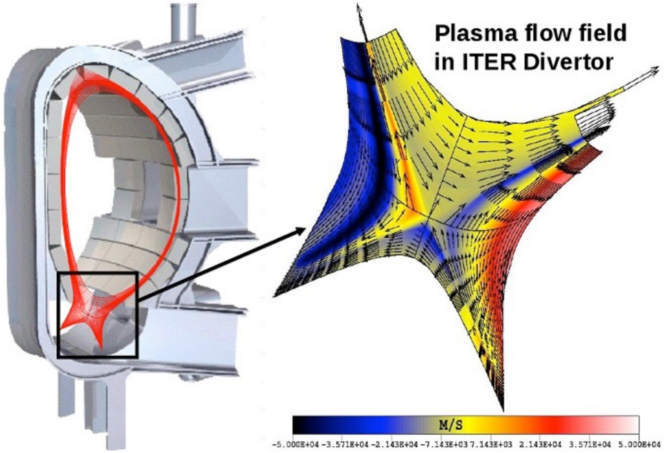
    - The Z-challenge? (low-Z vs high-Z)

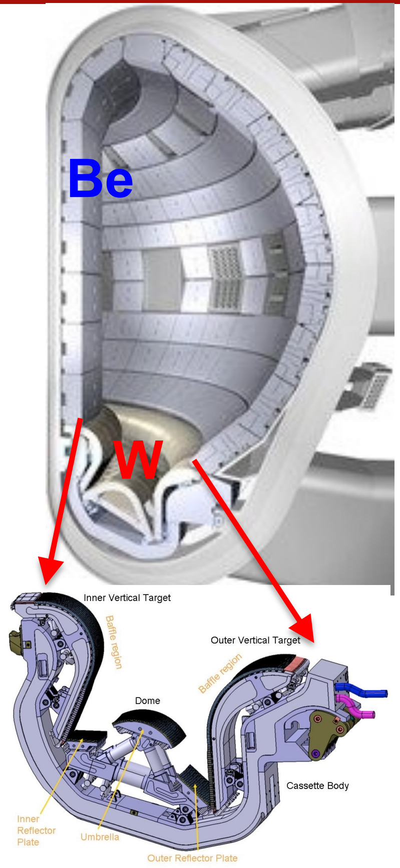


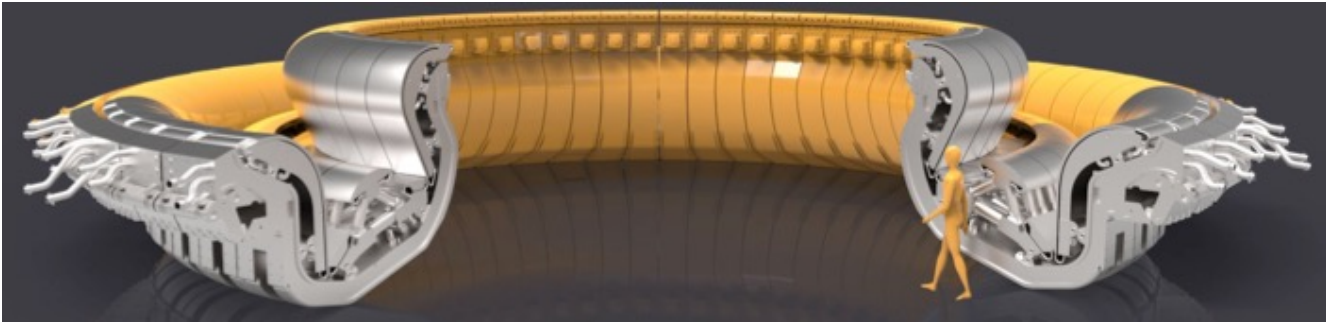
With the help of detailed simulations ITER scientists decided on a wall covered with low- and high-Z PFCs

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





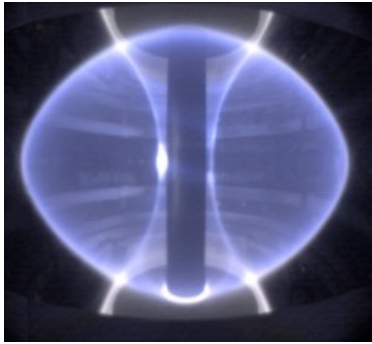


Edge localized modes (ELMs) and disruptions can impact integrity of divertor cassettes

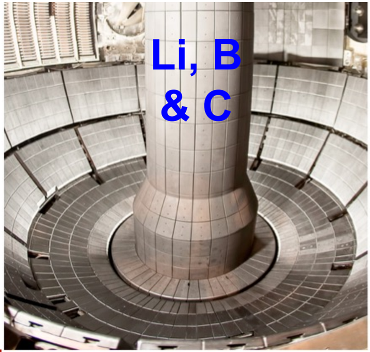
The low-Z (Li, Be, C, B) vs high-Z (Fe, Mo, W) plasma facing component (PFC) challenge

Both low- & high-Z materials are currently being used as plasma facing components (PFCs), but each has technological hurdles.

MAST, CCFE, Oxfordshire, UK



NSTX-U @ PPPL, Princeton, NJ



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! Physics or politics? Both?

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:

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

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

③ 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}:

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

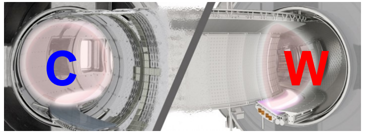
④ However, if high-Z impurities accumulate to any substantial level (e.g. high-n_Z/n_e), this will lead to:

a) Exponentially enhance the radiation power losses ($\propto Z^4$):

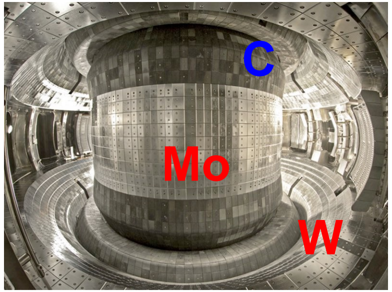
$$P_{rad} = n_e n_D L_D + n_e n_C L_c + \Sigma n_e n_Z L_Z$$

b) Reduce the heating efficiency and modifying the overall power balance and possibly even a radiative collapse

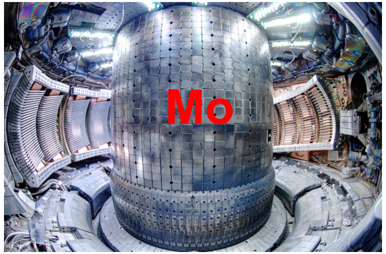
Tore Supra/WEST in France



EAST in China



C-Mod @ MIT, USA



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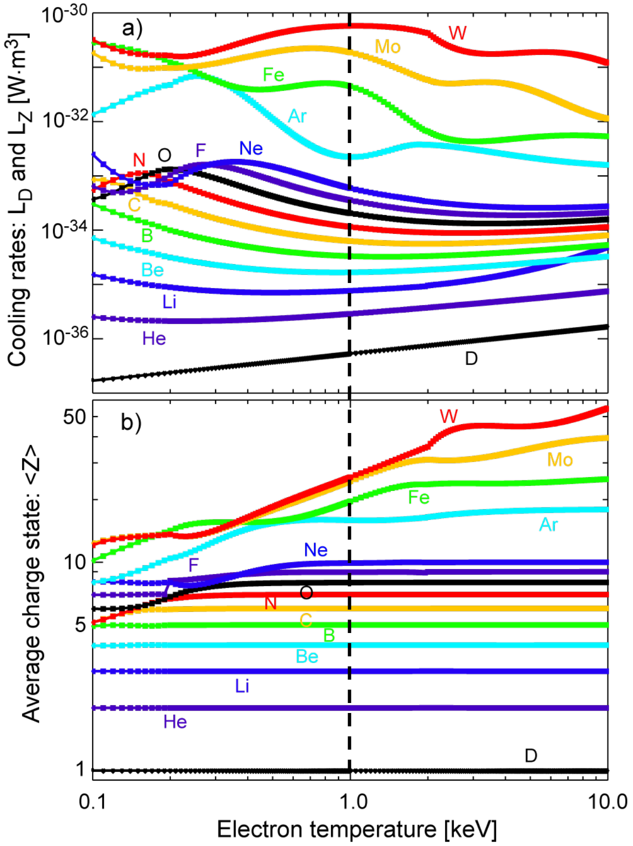
$$Z_{eff}=n_D/n_e+36n_C/n_e+\Sigma(n_Z/n_e)Z^2$$

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 ($\propto Z^4$):

$$P_{rad}=n_en_DL_D+n_en_CL_c+\Sigma n_en_ZL_Z$$

b) Reduce the heating efficiency and modifying the overall power balance and possibly even a radiative collapse

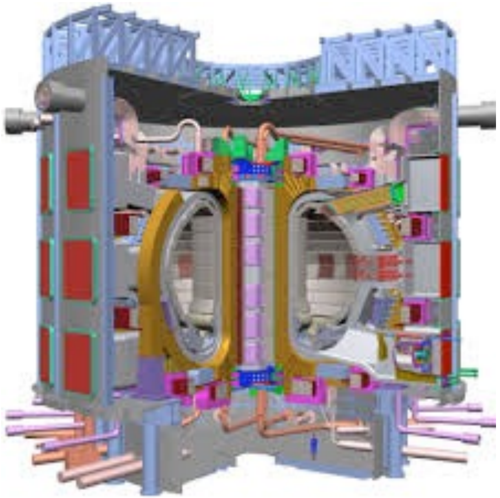


Target of opportunity: diagnose radiation from thermonuclear plasmas

X-Ray Goggles

- A significant fraction of the ITER input power (50 MW) will be radiated away

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



UV: 10eV < E_{photon}< 200 eV

SXR: 200 eV< E_{photon}< 20 keV

HXR: 20 keV < E_{photon}< 400 keV

Class-Homework #2: Nature…on the "fly"

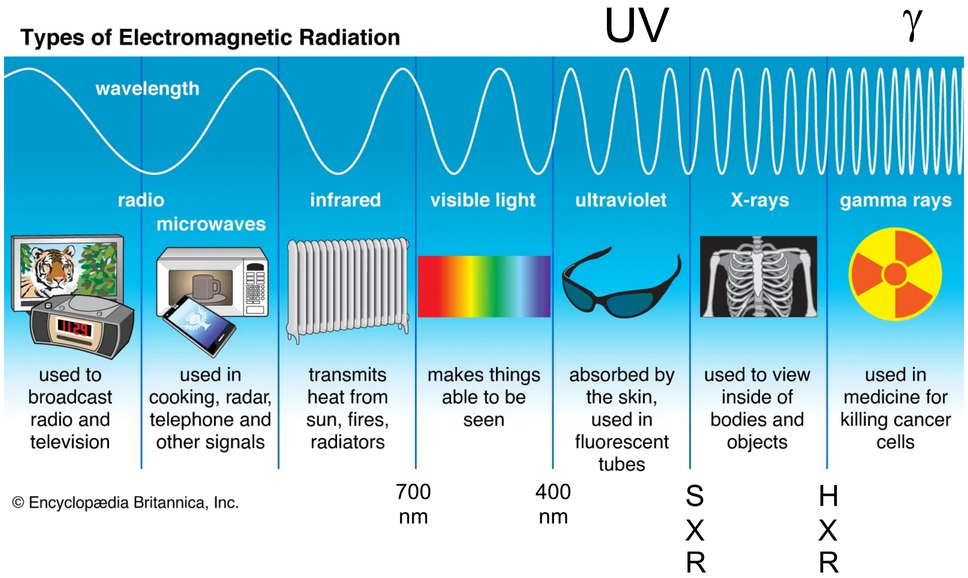
3) Can you estimate the mean wavelengths λ (…or type of light) emitted by cold, war, hot and burning plasmas (HINT: assume the photon energy emitted by the plasma scales roughly with its thermal energy… $E_{photon}=h\nu\sim T_e$, with h=Plank's constant and $\nu=c/\lambda$ with $c=3\times10^8$ m/s; or maybe λ_{photon} [Å]~12398/E_{photon} [eV])?:

a) Cold plasma: T_e=2 eV

b) Warm plasma: T_e=200 eV

c) Hot plasma: T_e=2000 eV

d) Burning plasma: T_e=20000 eV



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

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

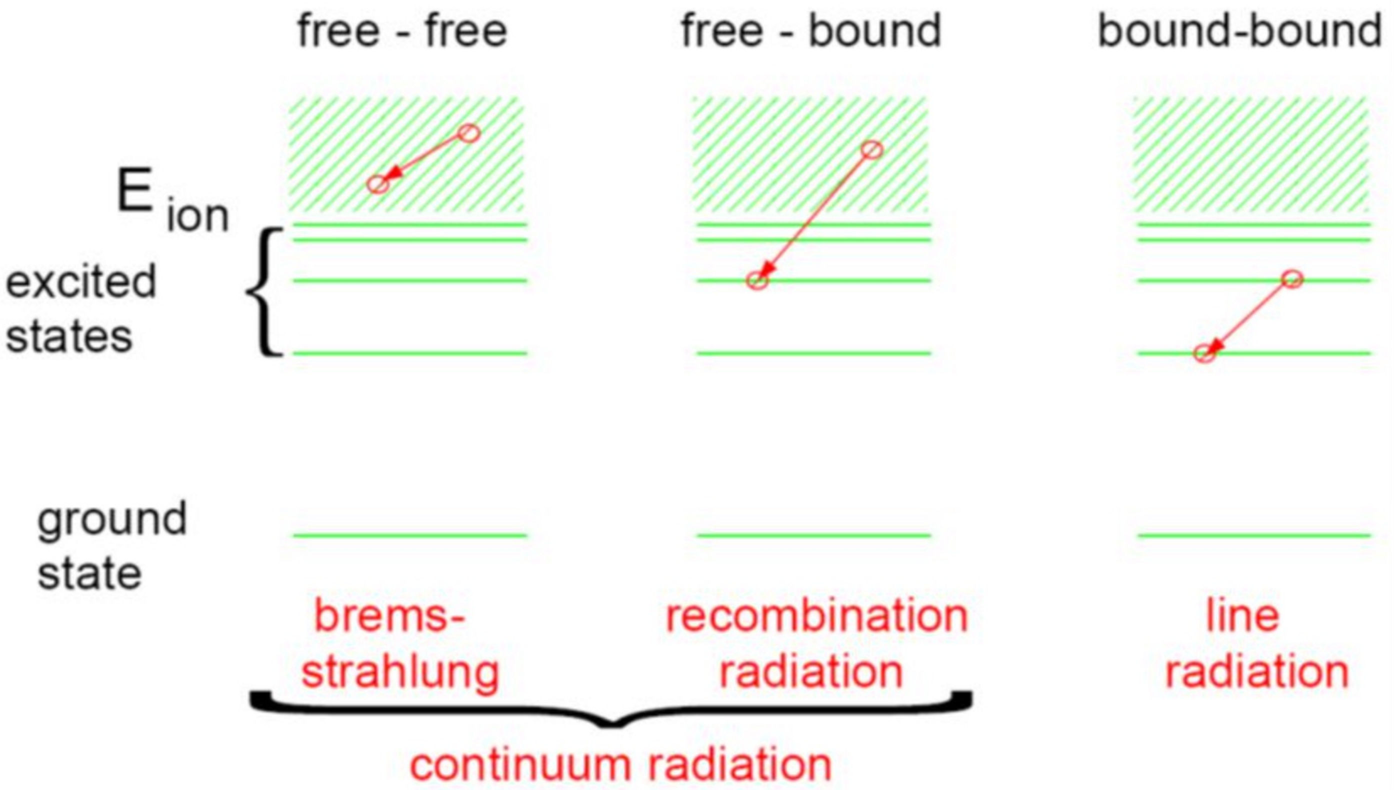
② In real conditions could be as high as 90%.

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

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

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

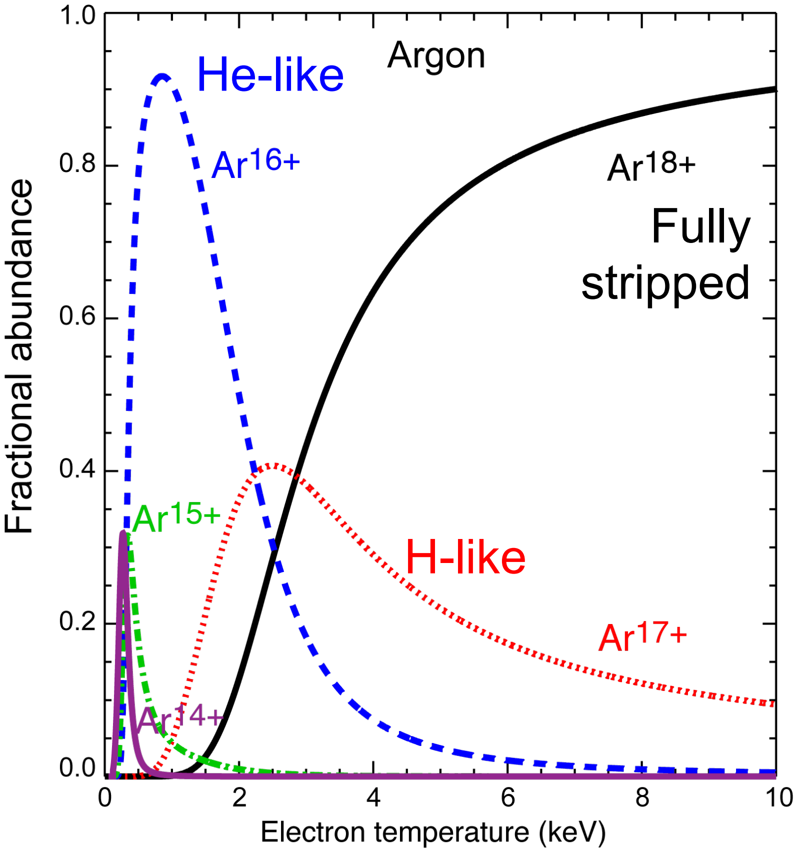
$$\Rightarrow \frac{n_{(Z+1)}}{n_Z} = \frac{\mathcal{S}_{Z\rightarrow(Z+1)}(T_e)}{\alpha_{Z+1\rightarrow Z}(T_e)}$$

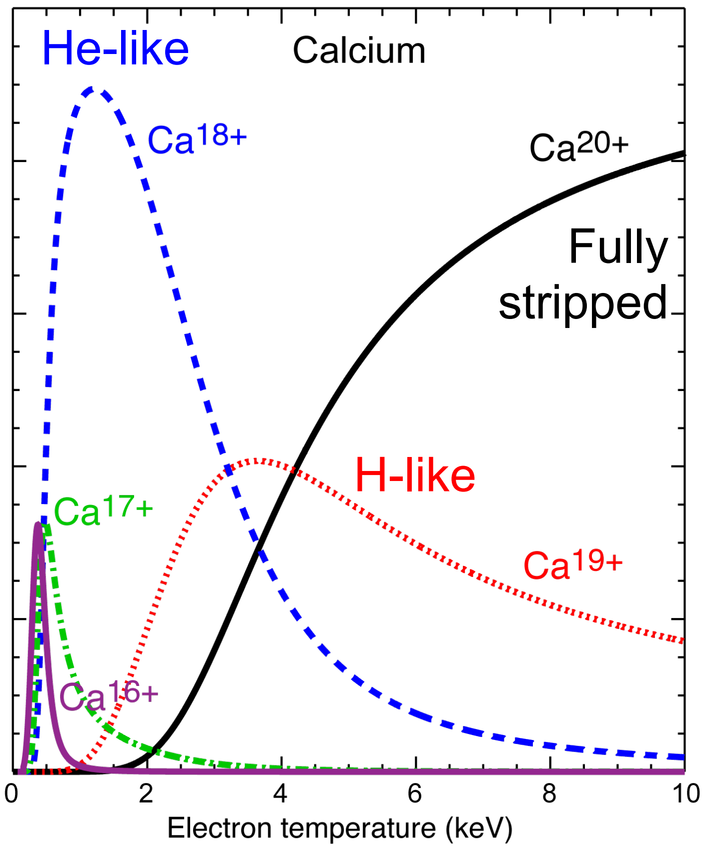
- Result: Ionization degree is independent of density and increases with T_e
  - Low-Z ions (Be, B, C) are often fully stripped

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, $n_Z(R,t)$]

Continuum and & line emission:

Bremsstrahlung (ff):

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

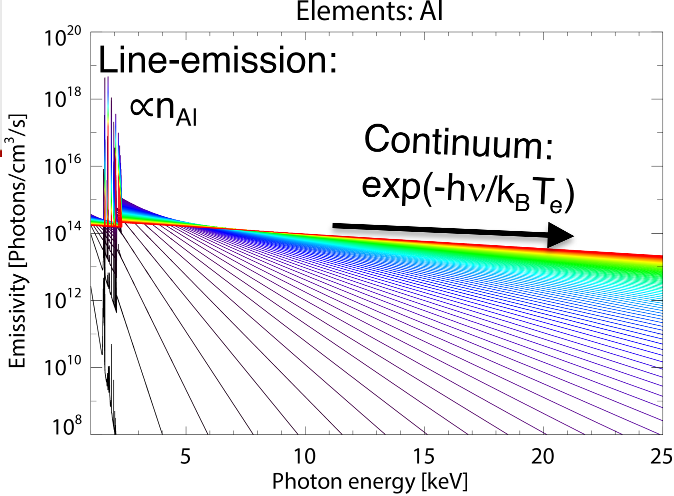
Radiative recombination (fb):

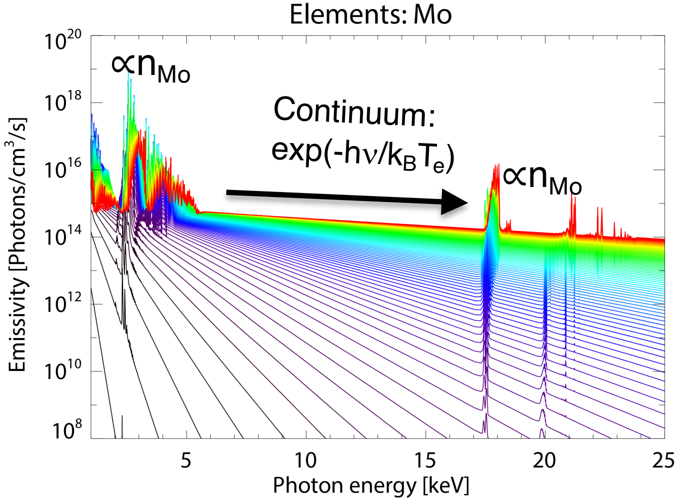
$$\frac{d\mathcal{P}^{ij}_{fb}(T_e,E)}{dE} \propto \frac{n_e^2 C_i (n_{ij}/n_i) Z_{ij}^2}{T_e^{1/2}} \beta_{ij}(T_e,E)\exp(-E/T_e)$$

Line emission (bb):

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

0.1 T_e [keV] 10





Take home message: You have four basic alternatives to measure radiation from plasmas

① **Conventional radiated power measurements** (integrate all) (e.g., radiated power density ⇒ power balance)

② **Conventional "broadband/filtered" x-ray measurements** (e.g., SXR tomography ⇒ confinement, MHD, equilibrium)

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

④ **Doppler line-radiation x-ray measurements** (e.g., n_Z, T_e, T_i, v_ϕ, v_θ, ⇒ calculation of E_r)

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

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:

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

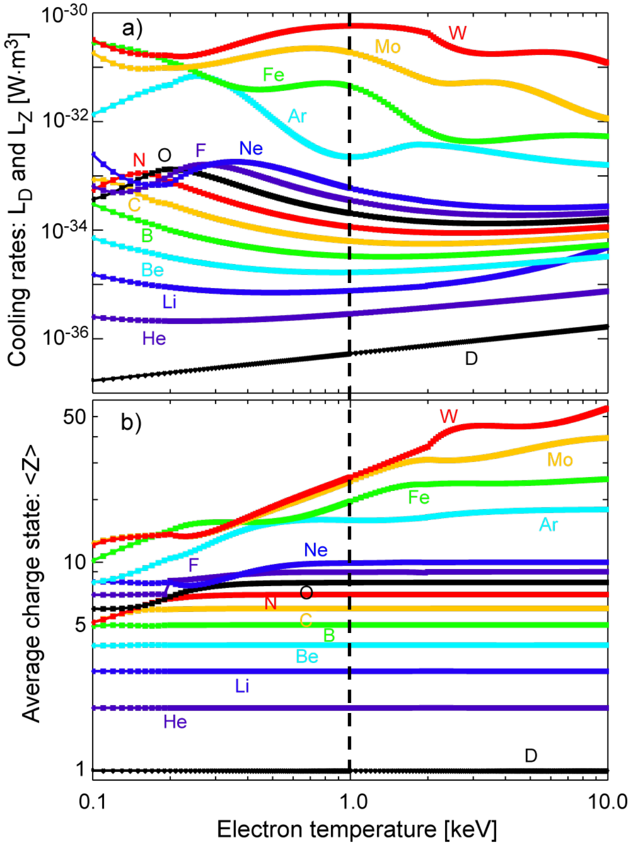
Normalized radiated power density:

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

Radiated power in the purely hydrogenic case (Z_{eff}=1)

Hydrogenic cooling rate:

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



Class-Homework #3: NSTX-U…on the "fly"

1) For a core DD NSTX-U plasma of 1 keV and a typical $n_{e,0}$ of 8.0×10^{19} m^{-3}, calculate:
   a) The deuterium concentration (n_D/n_e), plasma effective charge (Z_{eff}) and radiated power density P_{rad} [W/m^3] assuming a carbon concentration of 2% (HINT: no other impurities)
   b) How large is P_{rad} if one compares to the purely "ideal" hydrogenic value?

Quasi-neutrality:

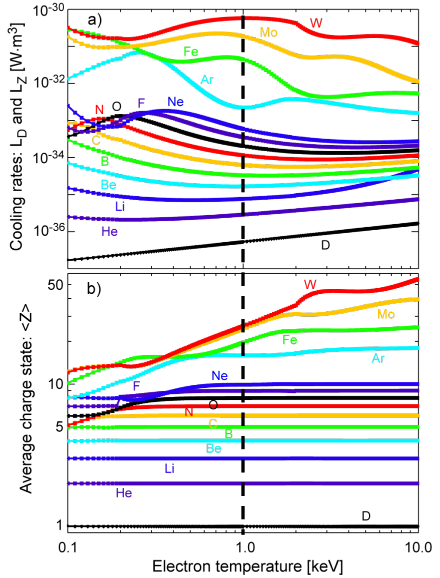
$$1 = \frac{n_D}{n_e} + \langle Z_1 \rangle \frac{n_{Z1}}{n_e} \quad \Rightarrow \frac{n_D}{n_e} = 1 -$$

Effective charge:

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

Normalized radiated power density:

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



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b) How large is P_{rad} if one compares to the purely “ideal” hydrogenic value?

EXTRA

c) The n_D/n_e, Z_{eff} and P_{rad} if one includes also 0.5% of oxygen

d) Now, how large is the new P_{rad} if one compares to the purely “ideal” hydrogenic value?

EXTRA

e) Now, add iron at $n_{Fe}/n_e \sim 0.1\%$, and repeat calculations for n_D/n_e, Z_{eff} and P_{rad}

f) How large is the new P_{rad} if one compares to the purely “ideal” hydrogenic value?

EXTRA

g) The change in neutron flux from the ideal case ($n_D=n_e$) when adding carbon, oxygen and iron cases (HINT: $S_n=n_D n_D \sigma_{DD}(T_i)$) and use dilution results from a), c) and e))

Class-Homework #4: ITER…for "home"

2) For a typical ITER DD plasma with an average electron density of 1.0×10^{20} m^{-3} and an average electron temperature of 8.8 keV (see http://fusionwiki.ciemat.es/wiki/ITER) calculate:

a) n_D and Z_{eff} assuming Be and W concentrations of 10% and 0.001%, respectively.

b) Increase the C_W to a more realistic 10^{-4} and repeat the calculation in 2-a).

c) The change in neutron rate when changing the tungsten concentration from 10^{-5} to 10^{-4}

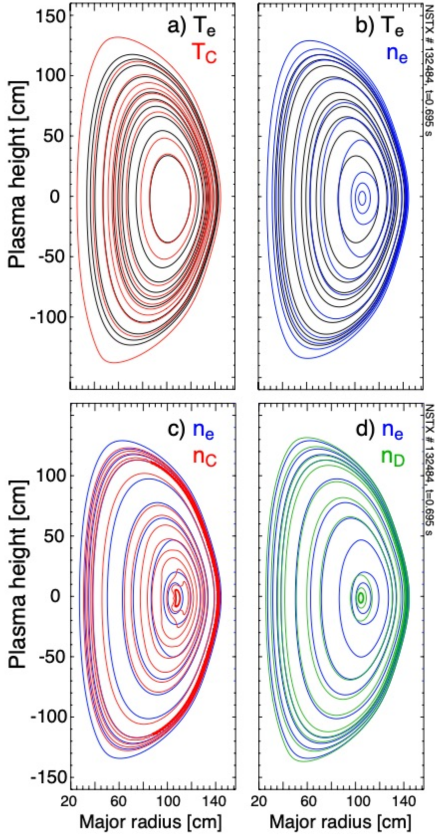
d) Calculate the core radiated power density [W/m^3] from all the ion constituents [e.g. H or D and Be for both cases of c_W @ 10^{-5} and 10^{-4}].

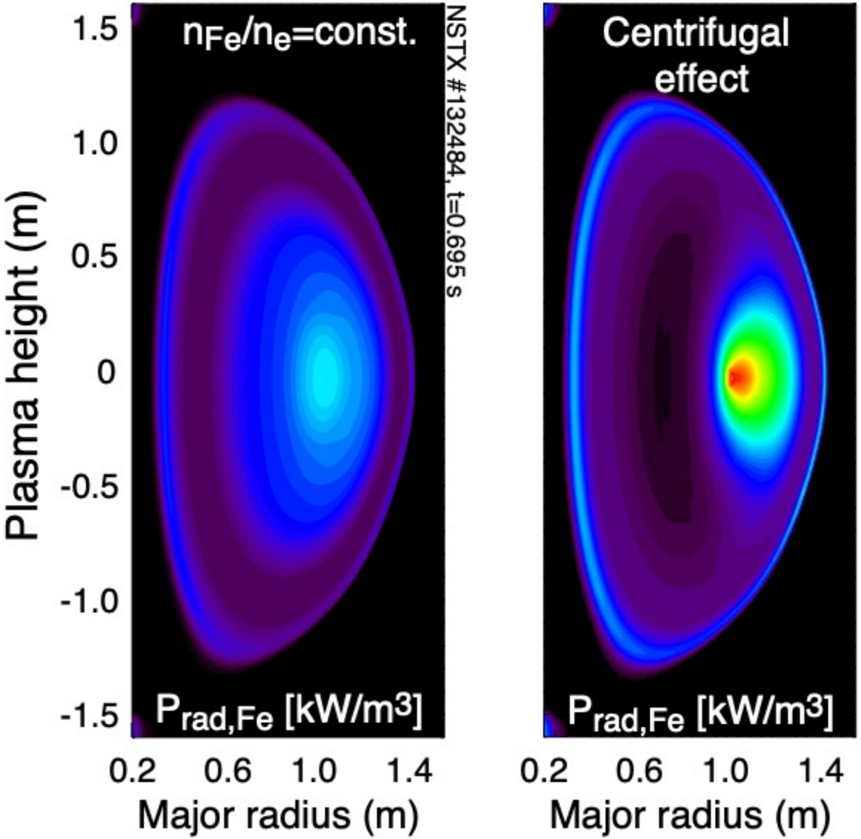
EXTRA

e) What fraction of the total input power is radiated away for the case of 10^{-1} of Be and 10^{-4} of W? Consider an average volume for ITER with an elliptical cross section of the order of $V_{ITER}\sim\pi ab\times2\pi R_0$, where "a" is the minor radius (~2m), "R_0" is the major radius of about 6 m and we consider an ellipticity (b/a) of about 1.5.

Let's get real…why is this important?

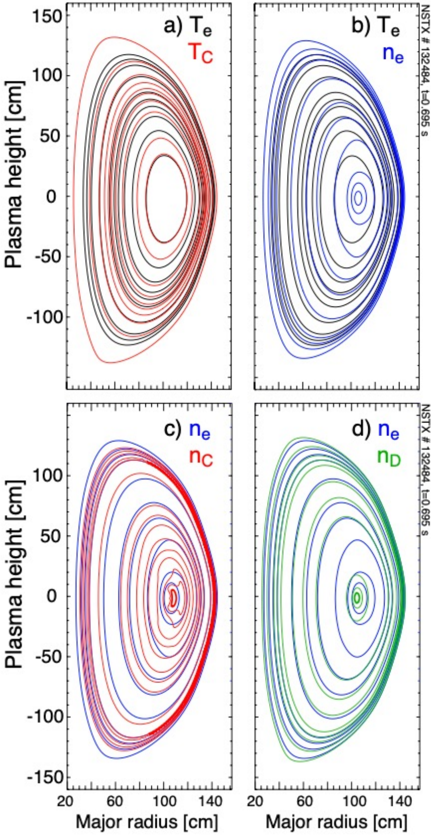
Rotation-induced $\Delta\varphi$, Er, n_Z, Z_{eff} and P_{rad} asymmetries in NSTX

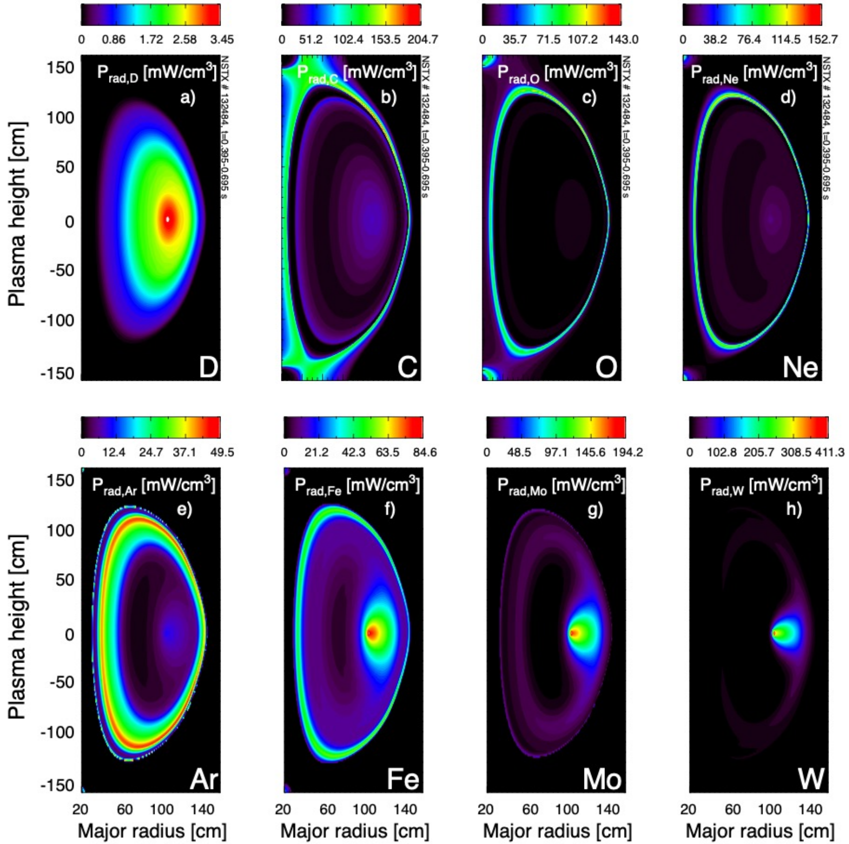




Let's get real…what do we conclude?

Rotation-induced $\Delta\varphi$, Er, n_Z, Z_{eff} and P_{rad} asymmetries in NSTX



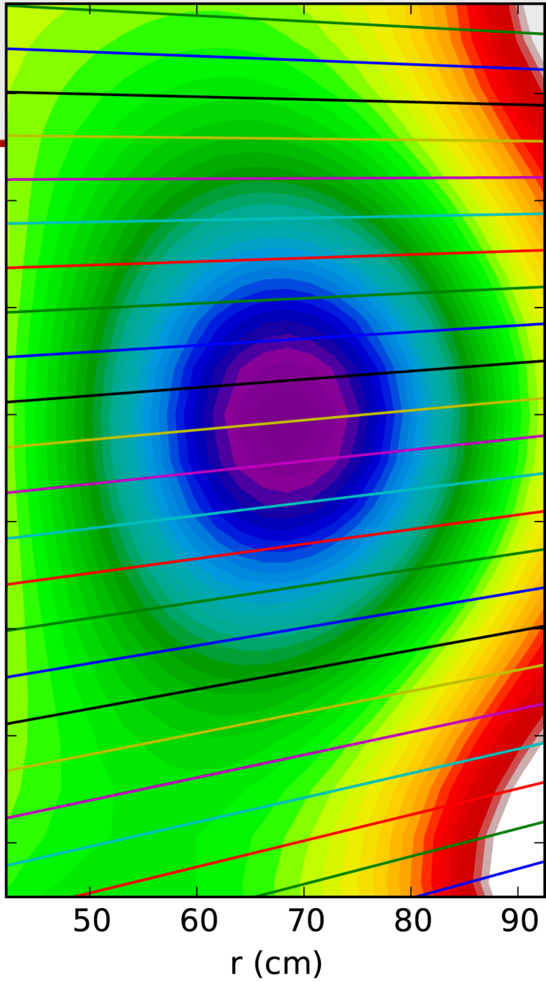


While the asymmetry in the core radiated power density from low-Z ions is relatively small, the 2D radiation profiles from medium- to high-Z's are strongly affected by centrifugal forces.

Radiation measurements are line-integrated along detection sightlines

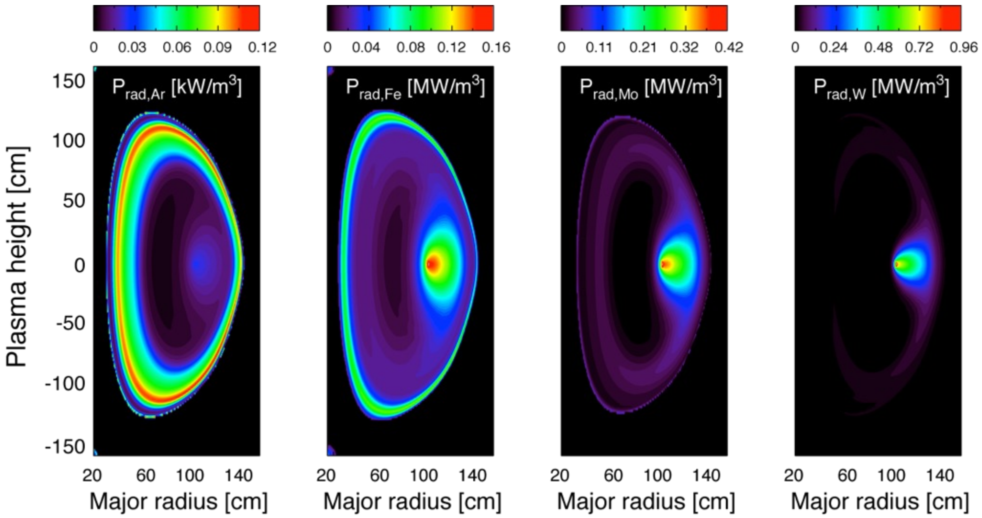
Visible/UV/x-ray radiated power tomography:

- Emissivity is a flux-surface function
- Inversion ($B=M \times E \Rightarrow E=M^{-1} \times B$)

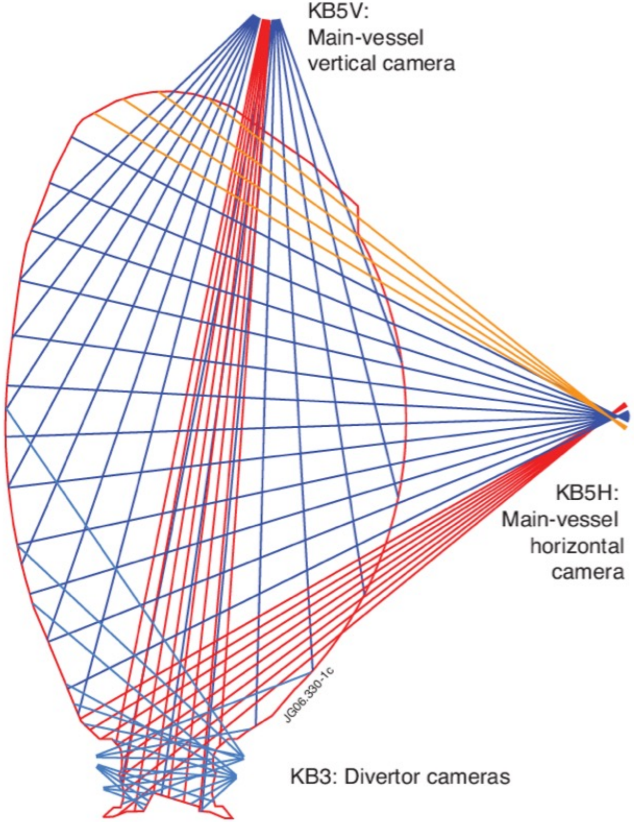


Transport/heating asymmetries (warning):

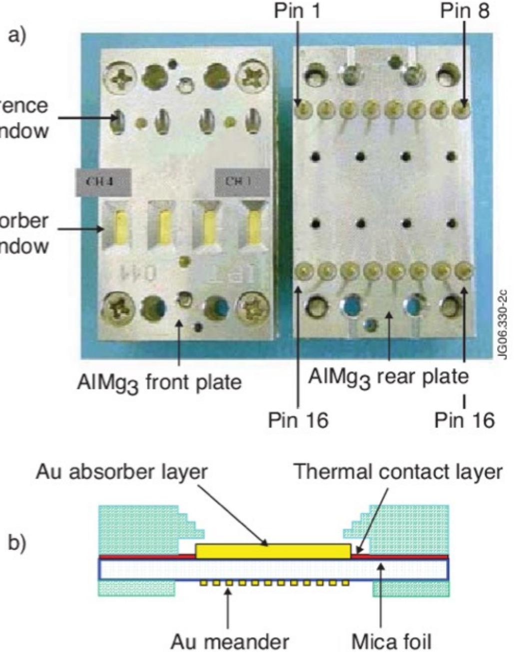
Example:
Core radiation from medium- to high-Z will be affected by centrifugal forces



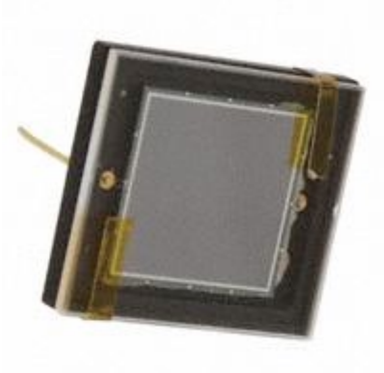
Radiated power density measurements (no spectral resolution) use metal-foils or Si-diodes + electronics

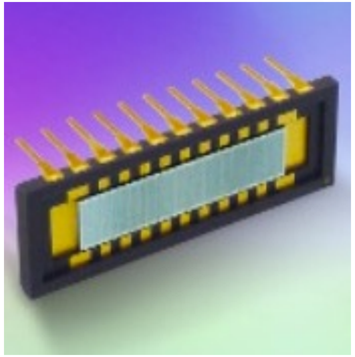


Metal foil bolometers

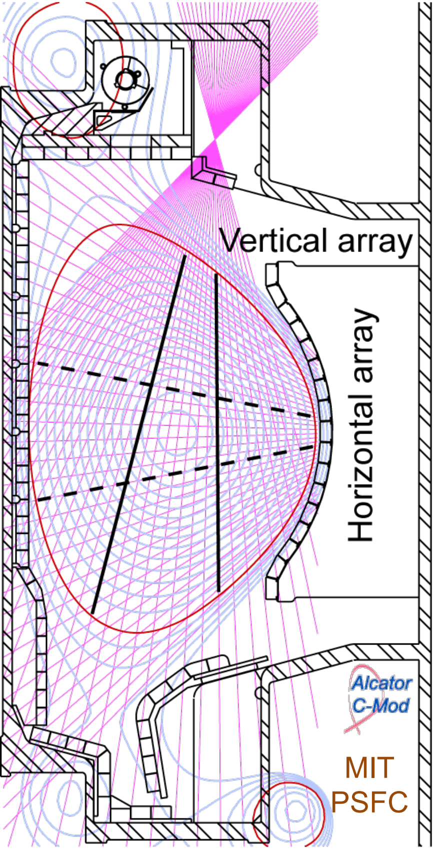


Si diodes

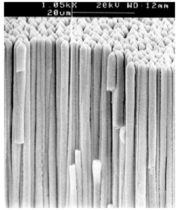




2) Conventional tomography integrates in photon-energy using metal filters, diode arrays and TIAs



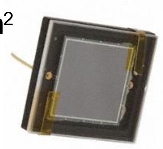
Indirect detection with scintillator (e.g. CsITl - green)



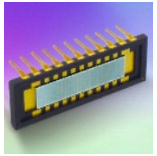
Direct x-ray detection (e.g. Si diodes)

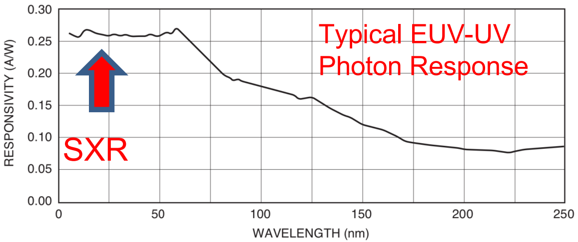
AXUV-100

1 cm^2

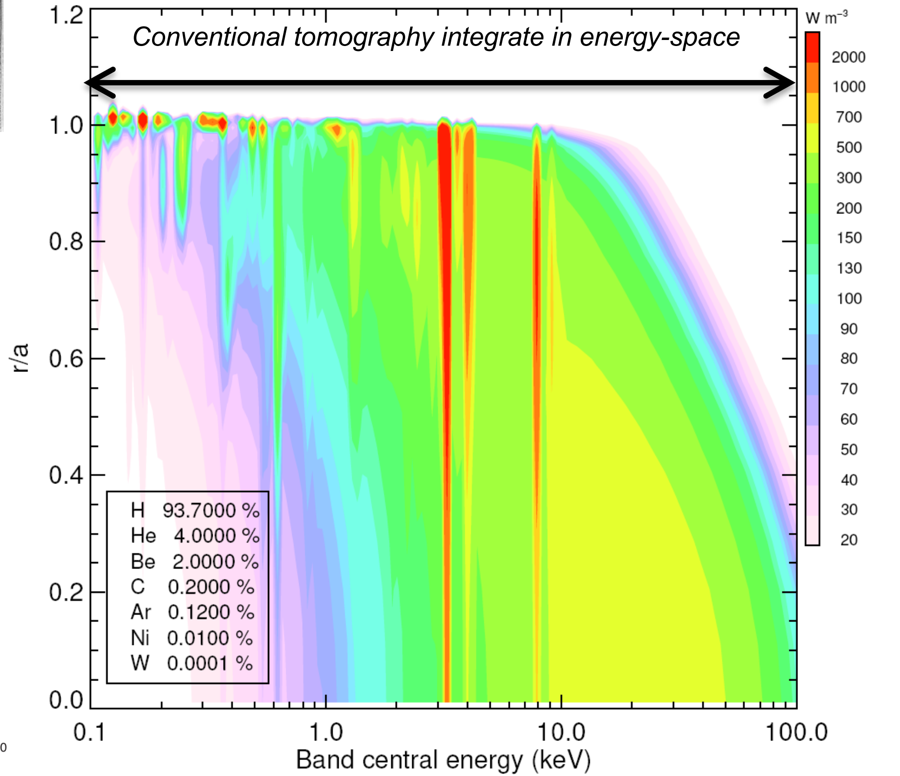


AXUV-20





Example of spatially resolved x-ray spectra from ITER

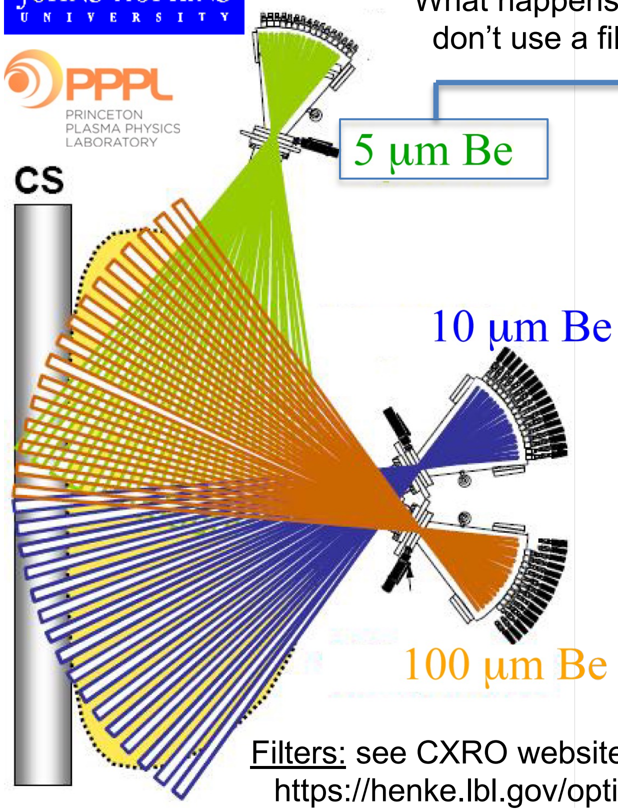


Conventional SXR tomography consists of an array of diodes/detectors integrating the local plasma emissivity

JOHNS HOPKINS UNIVERSITY

PPPL PRINCETON PLASMA PHYSICS LABORATORY

What happens if we don't use a filter?



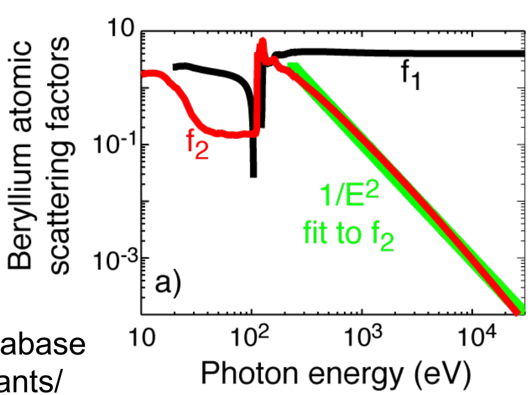
Filters: see CXRO website x-ray database https://henke.lbl.gov/optical_constants/

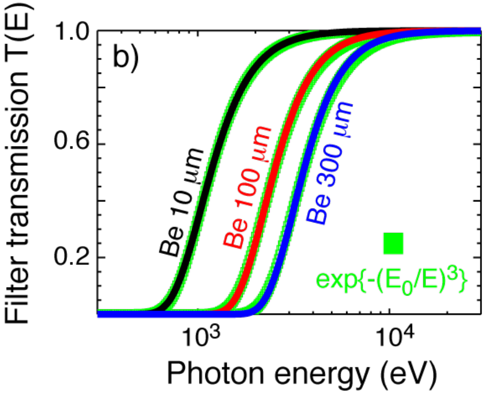
① Essential elements:

a) Pinhole (radial resolution vs integration)
b) Thin vs thick metallic filters (e.g., Be)
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

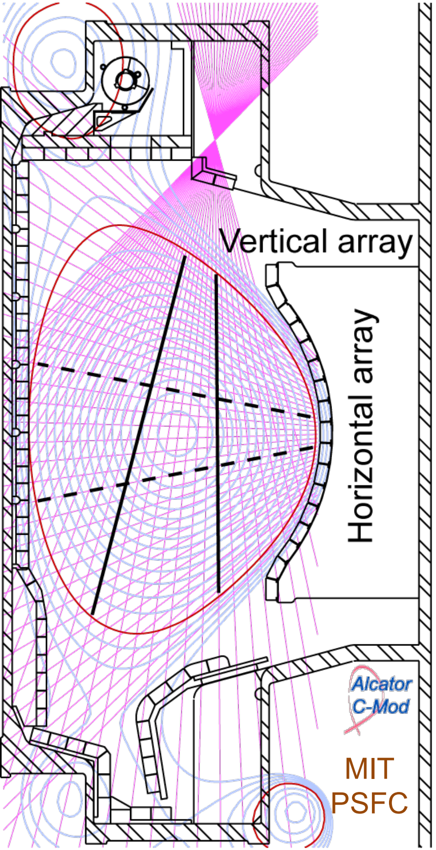
② Metal filters discriminate edge/core effects

(peeling the "onion")

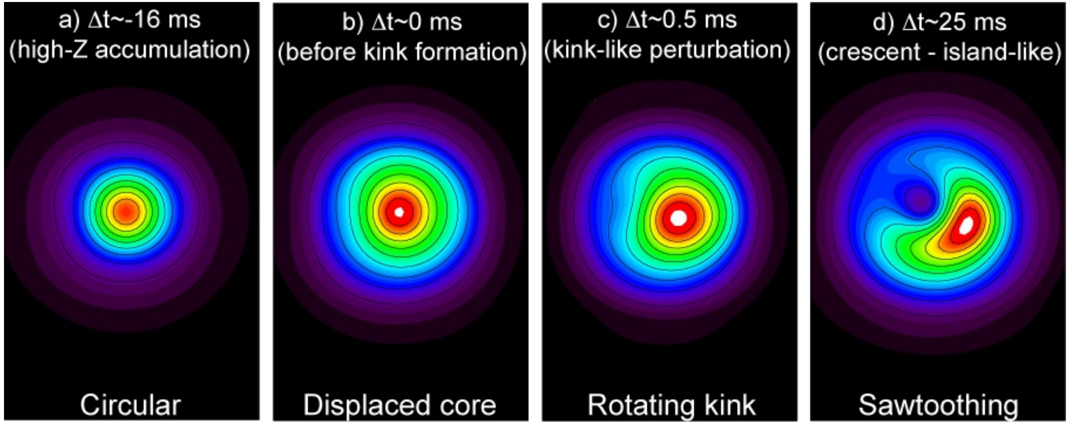




Conventional soft x-ray (SXR) tomography is still being used for stability, MHD & transport studies

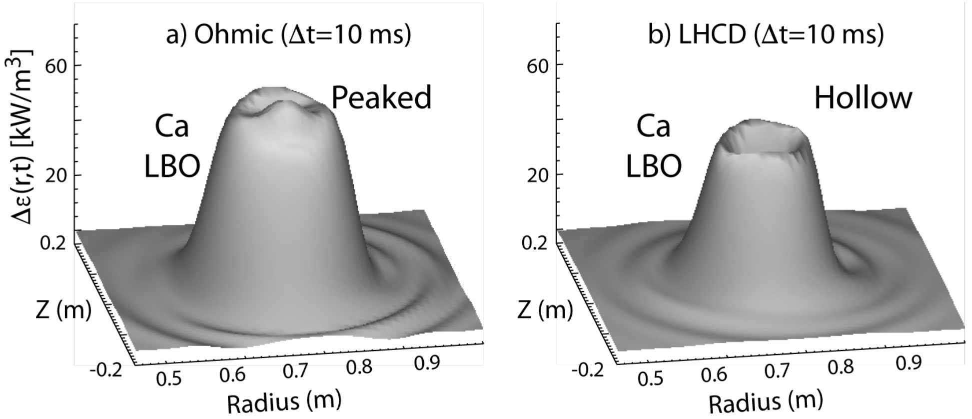


a) Stability and MHD [e.g. (m,n) modes and sawteeth]



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

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



Take home message: You have four alternatives to measure radiation from plasmas

① Conventional radiated power measurements (integrate all) (e.g., radiated power density ⇒ power balance)

② Conventional "broadband/filtered" x-ray measurements (e.g., SXR tomography ⇒ confinement, MHD, equilibrium)

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

④ Doppler line-radiation x-ray measurements (e.g., n_Z, T_e, T_i, v_ϕ, v_θ, ⇒ calculation of E_r)

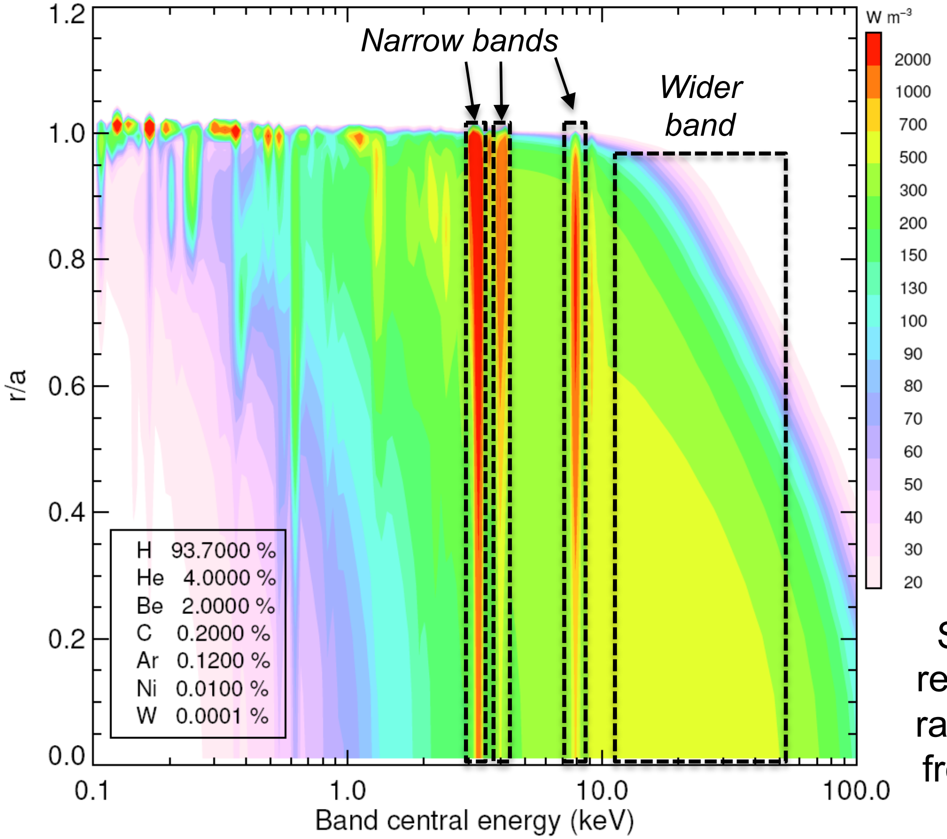
How to extract plasma physics parameters from wide and narrow energy bands ?

3) 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)

4) 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)



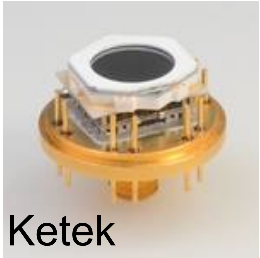
Spatially resolved x-ray spectra from ITER

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

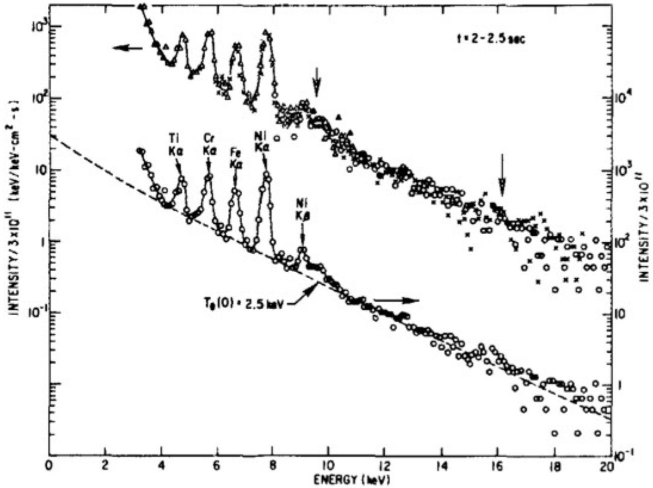
Detectors in photon-counting mode

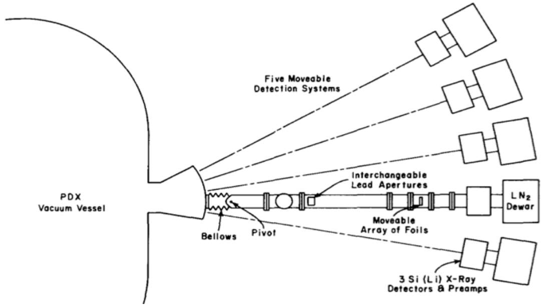
$(\langle T_e \rangle, \langle Z_{eff} \rangle, \langle n_{e,fast} \rangle, \langle n_Z \rangle)$

- 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)



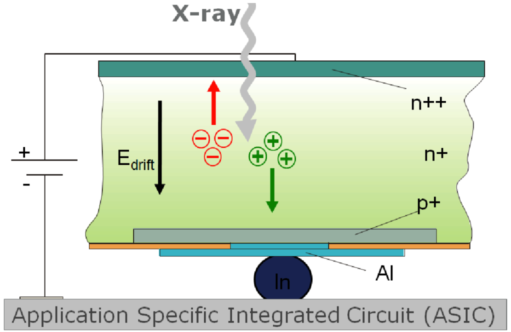
Single-chord spectrometers





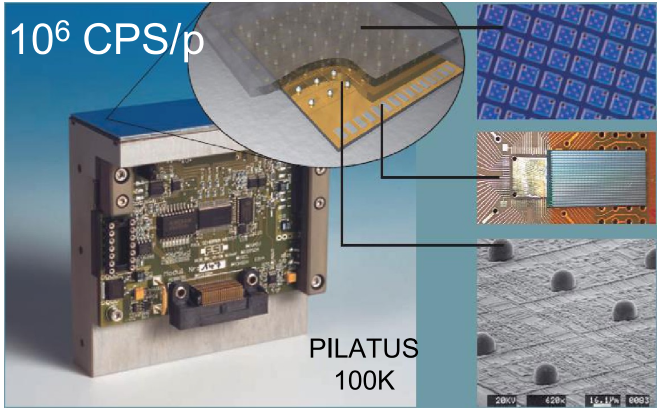
One spectrum per instrument

New PILATUS 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

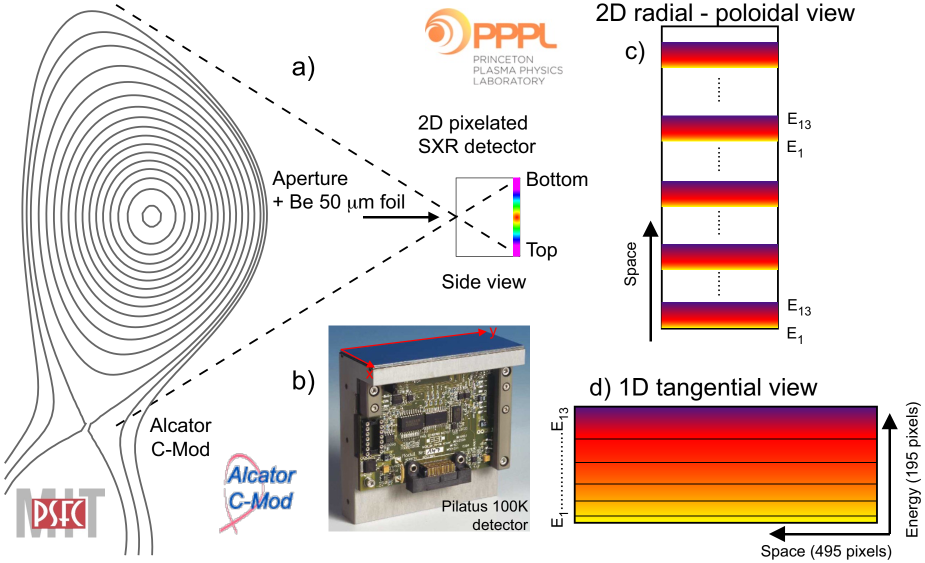
Thanks to important advances in the x-ray detector technology it is now possible to simultaneously record high resolution images of x-ray photons at single OR multiple energy ranges through direct x-ray detection.

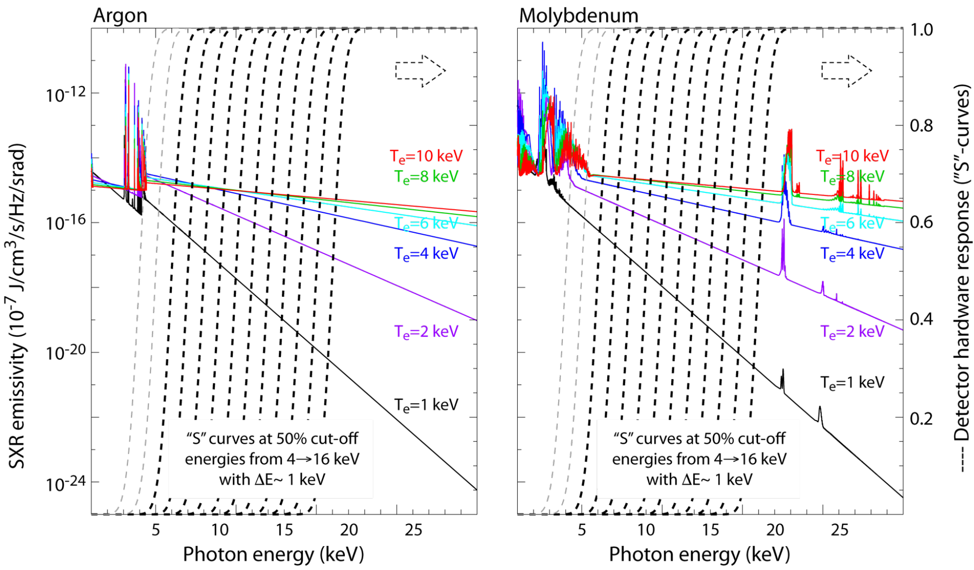
100K to 12M pixels (PILATUS: 172 μm, EIGER: 75 μm)

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

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

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

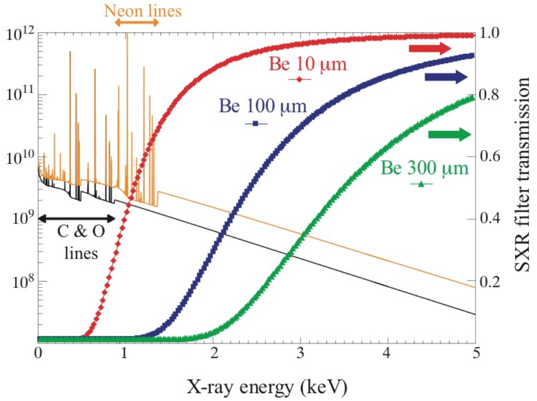




Pin-hole camera with multi-energy pixels allowed simultaneous spatial and energy resolution

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

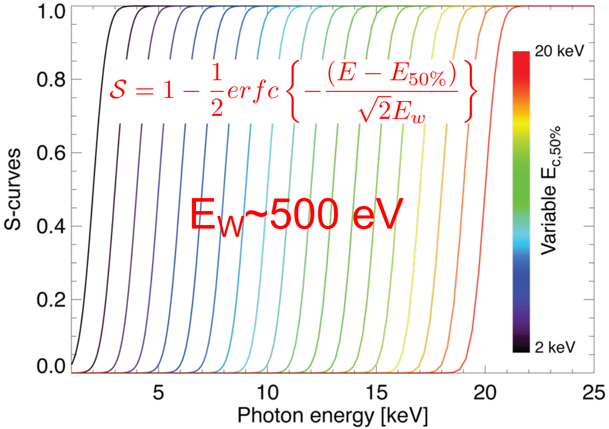
Comparator and triming voltages on each pixel allow individual coarse & fine tuning of energy range



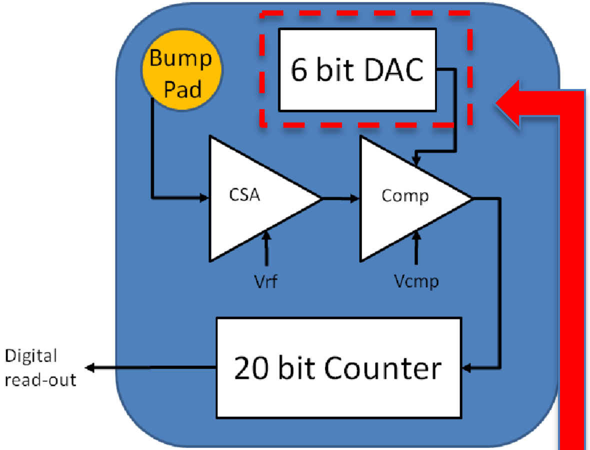
<u>Filters: CXRO website</u>:
X-ray database

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

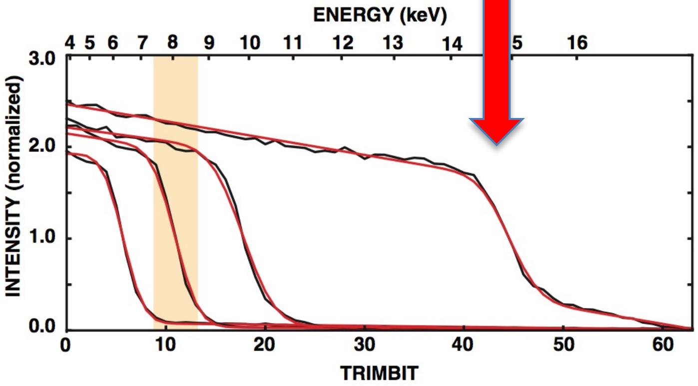
$$\Rightarrow \frac{d\mathcal{T}}{dE}\Big|_{E_0} \sim \frac{1}{E_0}$$



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



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



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3) Wider energy bands

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- Low-resolution spectrometers
  - $E/\Delta E \sim 10\text{-}50$
- Probes e^- and ion channels
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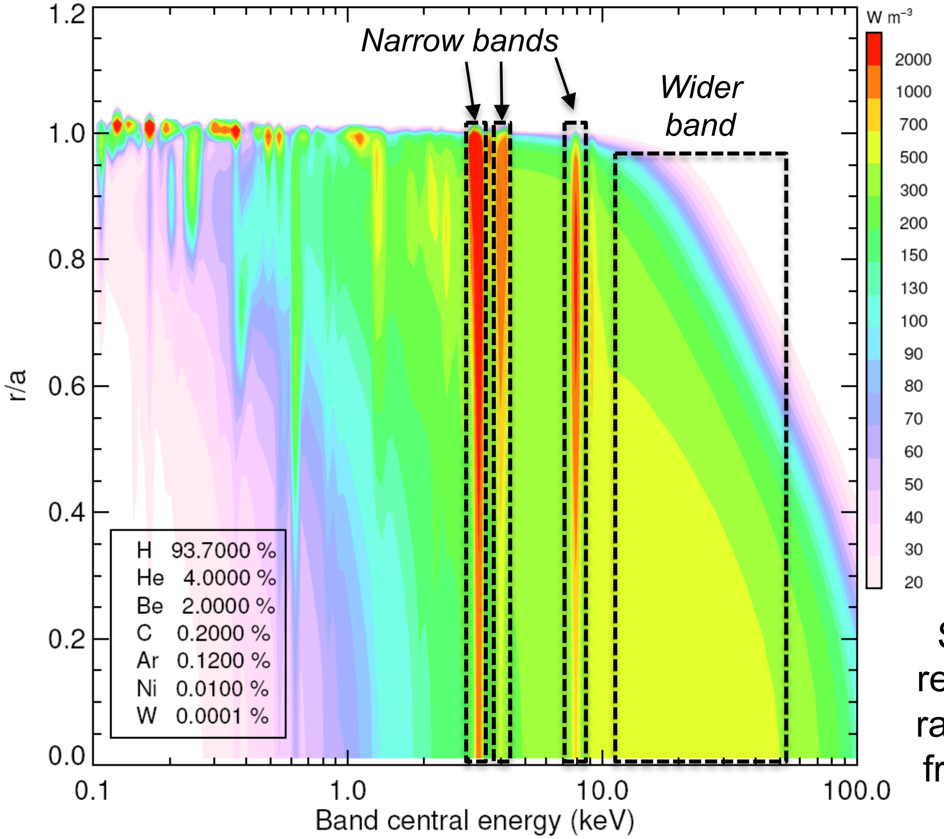
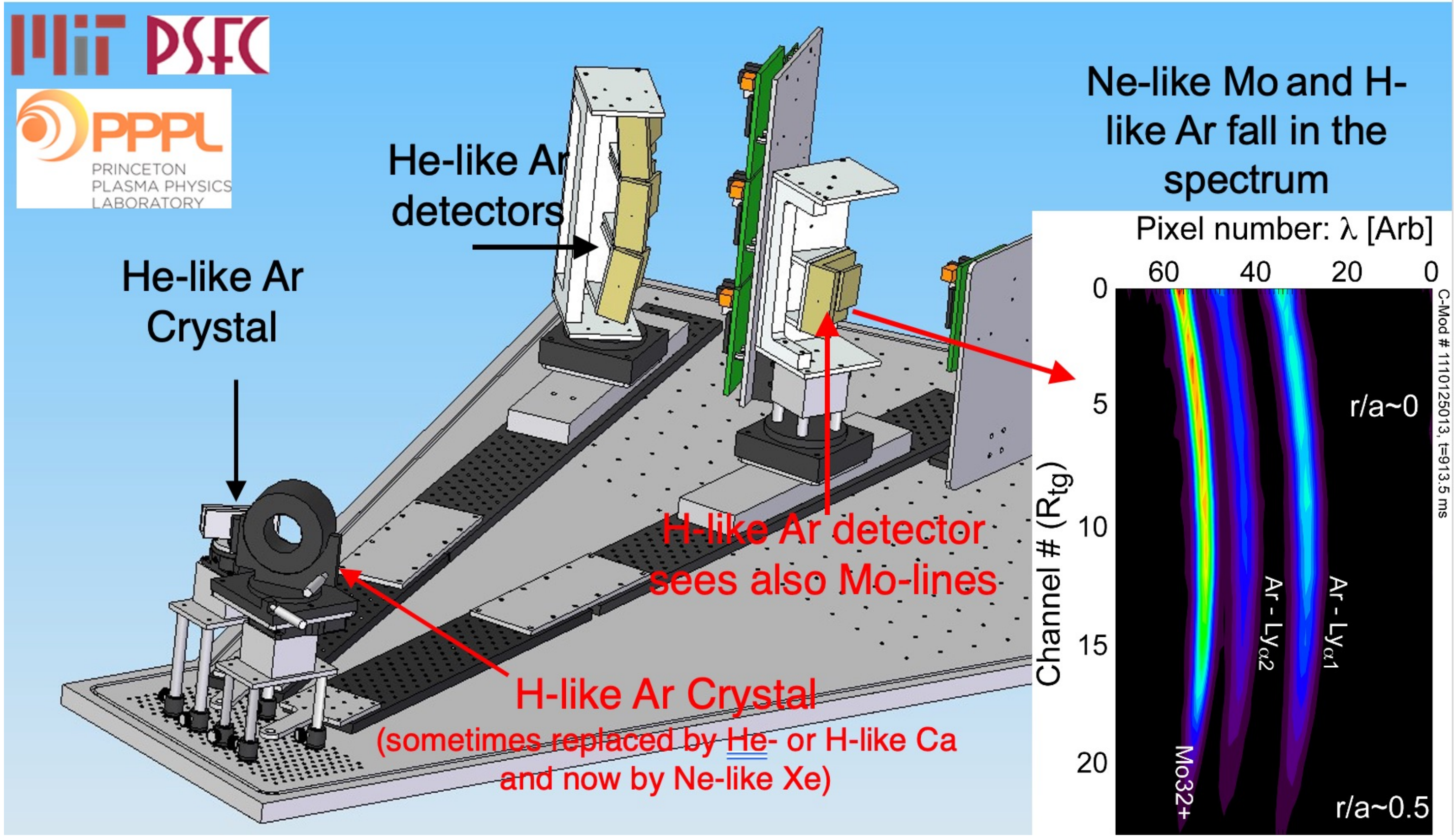


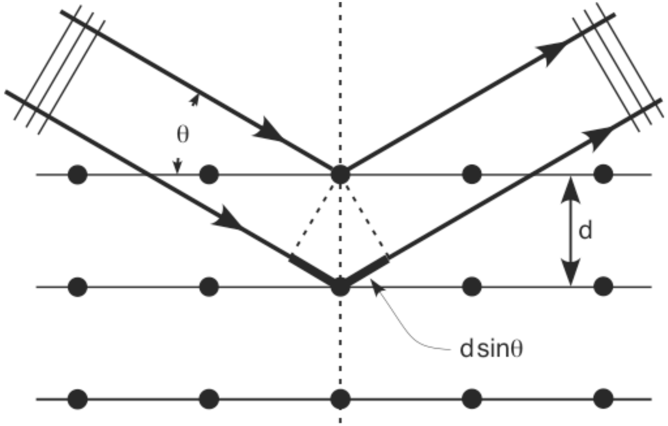
Spatially resolved x-ray spectra from ITER

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

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

Focusing properties of spherical x-ray crystal

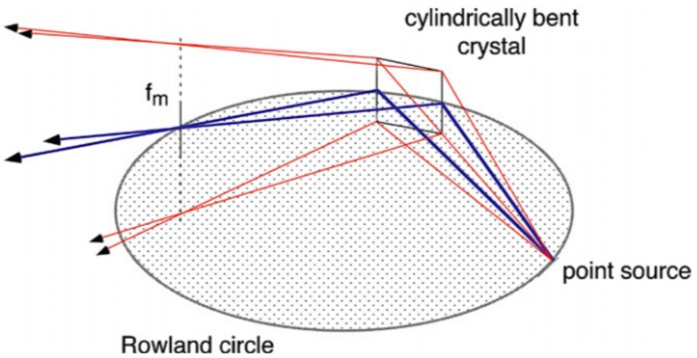


Figure 6. Focusing properties of a cylindrically bent crystal illustrating the divergence of sagittal rays.

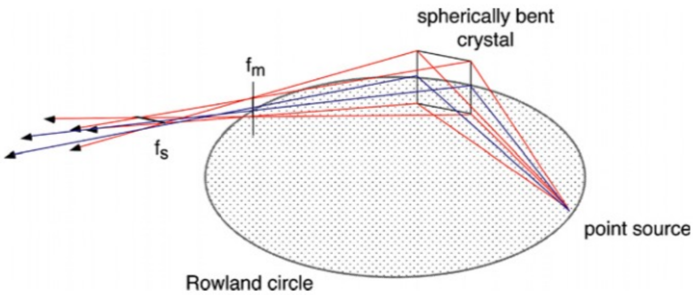
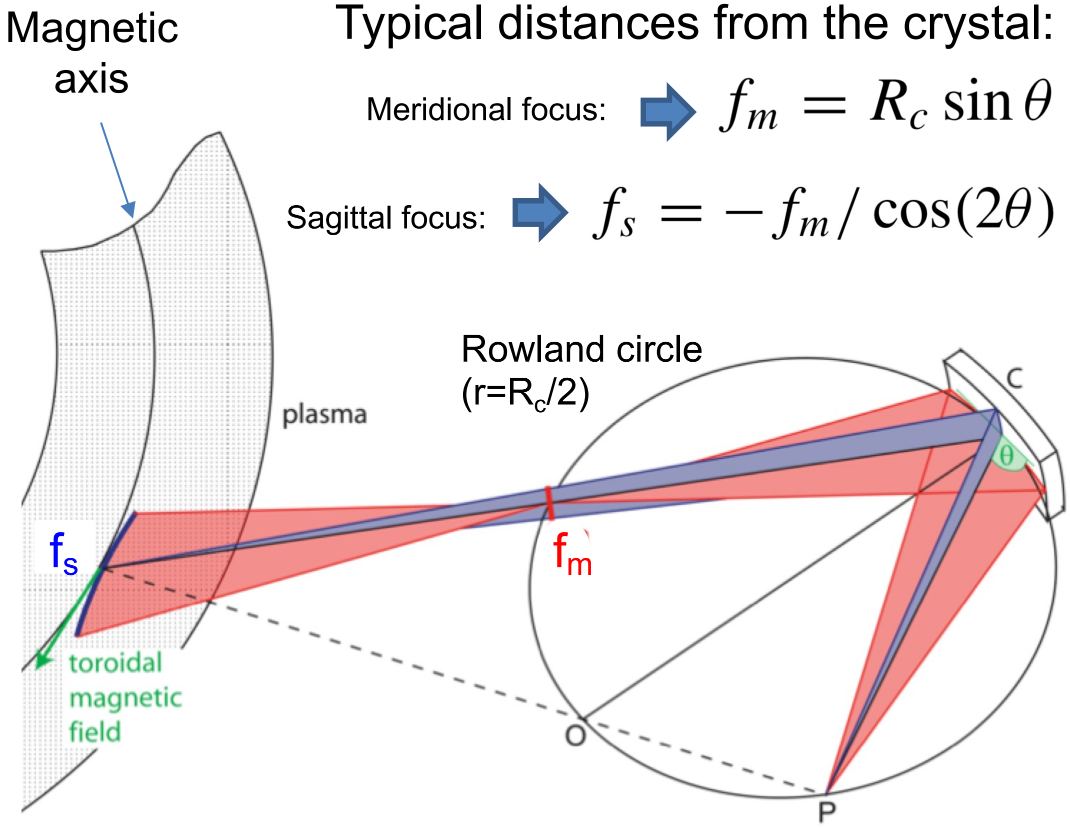


Figure 7. Focusing properties of a spherically bent crystal illustrating the focusing of sagittal rays.

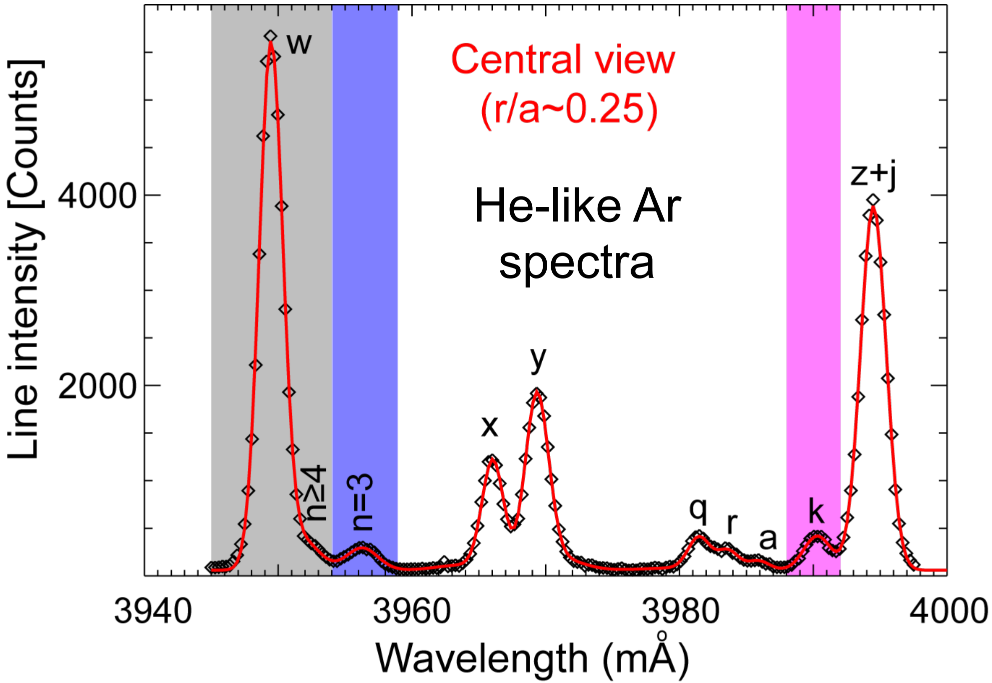
Typical distances from the crystal:

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

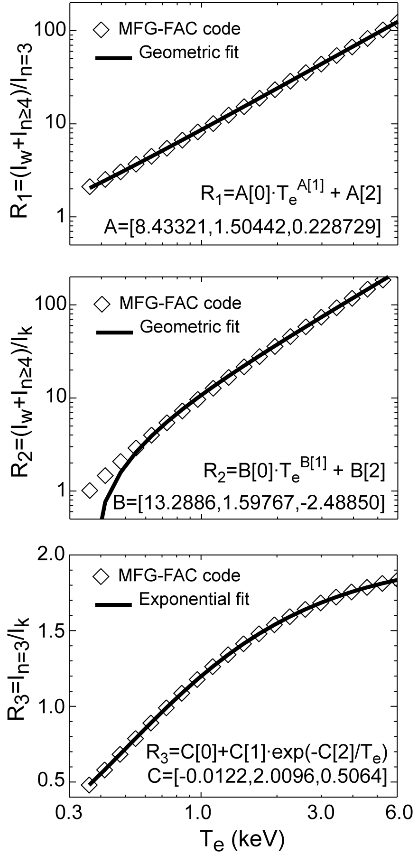
Sagittal focus: $$f_s = -f_m / \cos(2\theta)$$



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



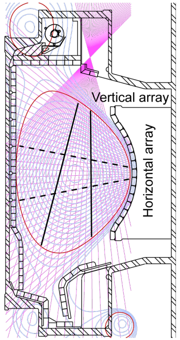
Te-measurements based on the ratio of the resonance line-w and the dielectronic satellites "n=3" and "k"

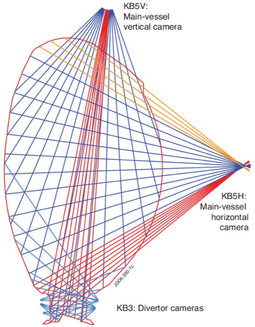


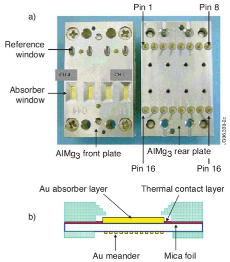
(L. Delgado-Aparicio, un-published)

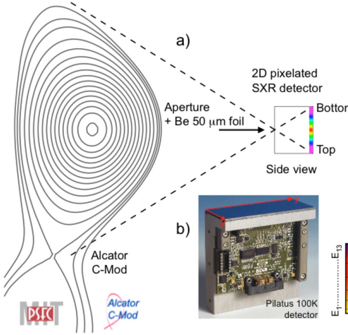
Considered to be a <u>secondary diagnostic technique</u> for the electron temperature (T_e) JT60SA and ITER.

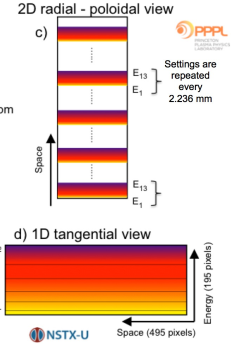
Summary: Modern radiated power diagnostics can help study and resolve P_{rad}, n_Z, $T_{e,i}$, $V_{\phi,\theta}$, Z_{eff} & $n_{e,fast}$ profiles

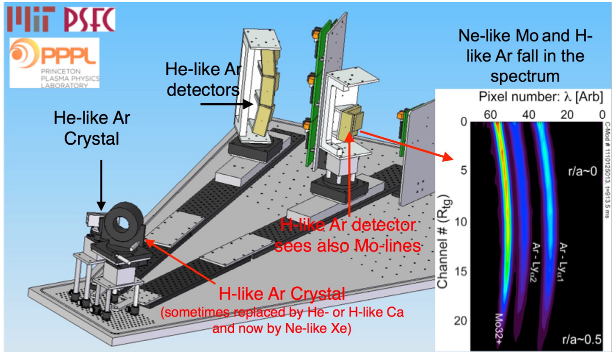












① With the selection of W for the divertor in ITER, understanding the sources, transport and confinement of high-Z impurities is crucial to ITER success.

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%.

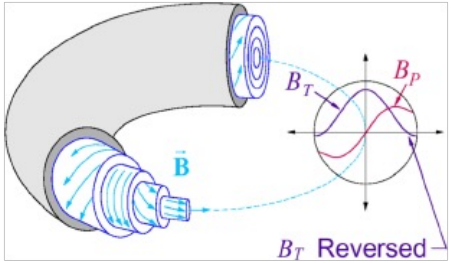
③ Modern diagnostics for overall radiated power and "filtered" spectroscopy allow us to probe P_{rad}, n_Z, $T_{e,i}$, $V_{\phi,\theta}$, Z_{eff} & $n_{e,fast}$ and their profiles!

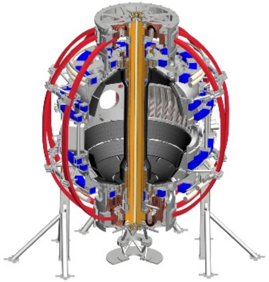
Join us: New core diagnostics (US-lead) will be installed in NSTX-U, MST, WEST, W7X, JT60SA and ITER

WISCONSIN
UNIVERSITY OF WISCONSIN–MADISON

MST

PPPL





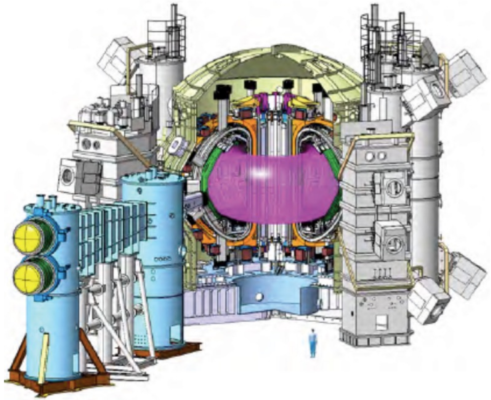
cea

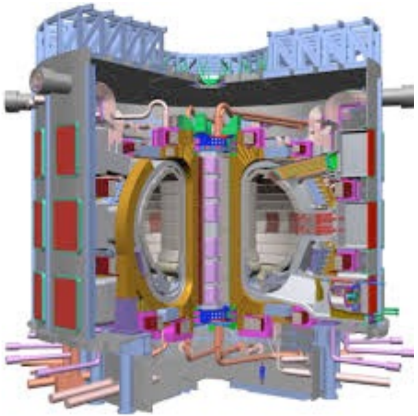
irfm

West

WEST - France

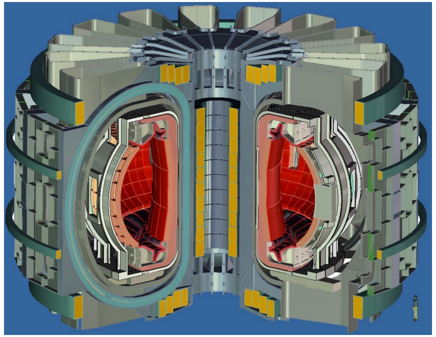
JT60SA





ITER

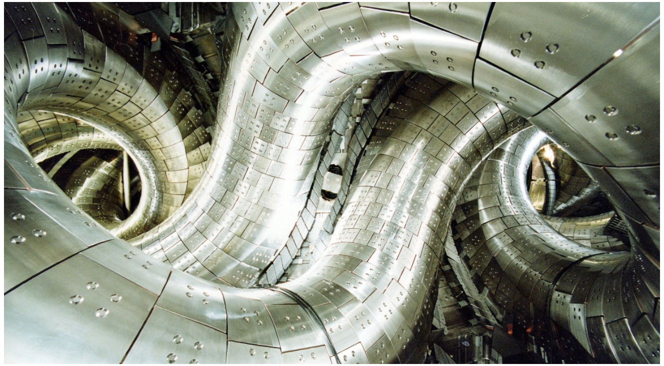
DEMO ?



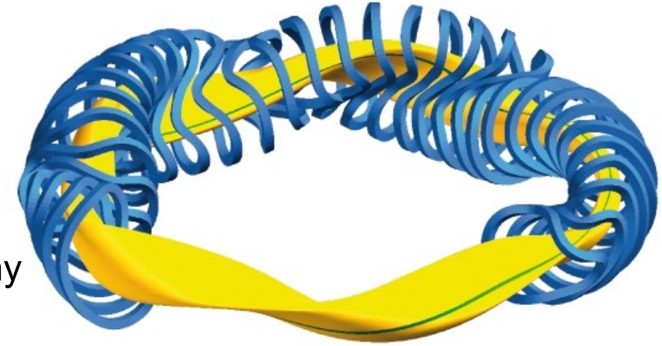
Don't forget about the non-axisymmetric systems and alternative concepts

Stellarators (I_p~0)

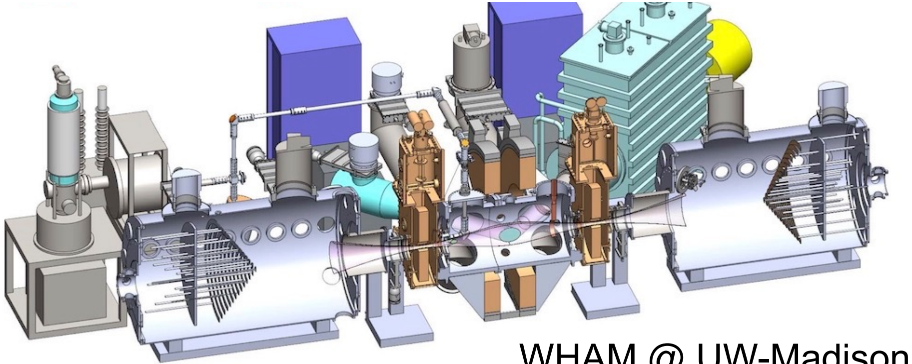
LHD
@NIFS
in Japan



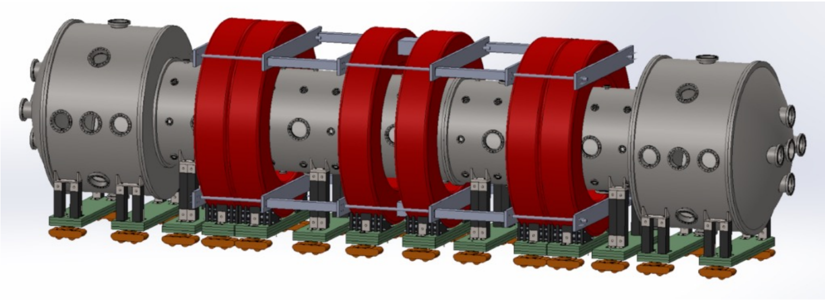
W7X
@MPIPP
in Germany



Magnetic mirrors



WHAM @ UW-Madison



CMFX @ UMD & UMBC

…And opportunities also in the private sector!

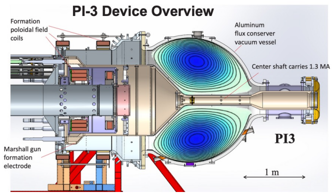
Notable investments in 2021-22

$1.8bn
Commonwealth Fusion Systems

$500m
Helion Energy

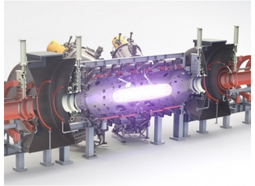
Extraordinary opportunities for public-private-partnerships (PPPs)

GF



Zap

TAE



CFS

TE