Burning-plasma diagnostics: need for radiation-hardened detectors & electronics

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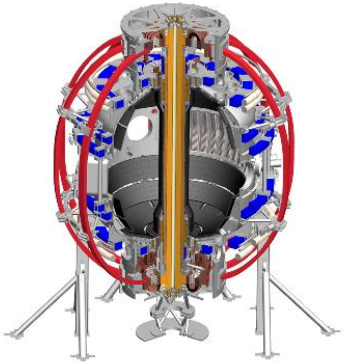
Princeton Plasma Physics Laboratory (PPPL)

31st RD50 Workshop on Radiation hard semiconductor
devices for very high luminosity colliders
CERN, November, 20-22, 2017, Geneva, Switzerland



Outline

① PPPL and fusion basics

② ITER and diagnostics

③ Neutron and gamma-induced noise

④ The x-ray case (x3)

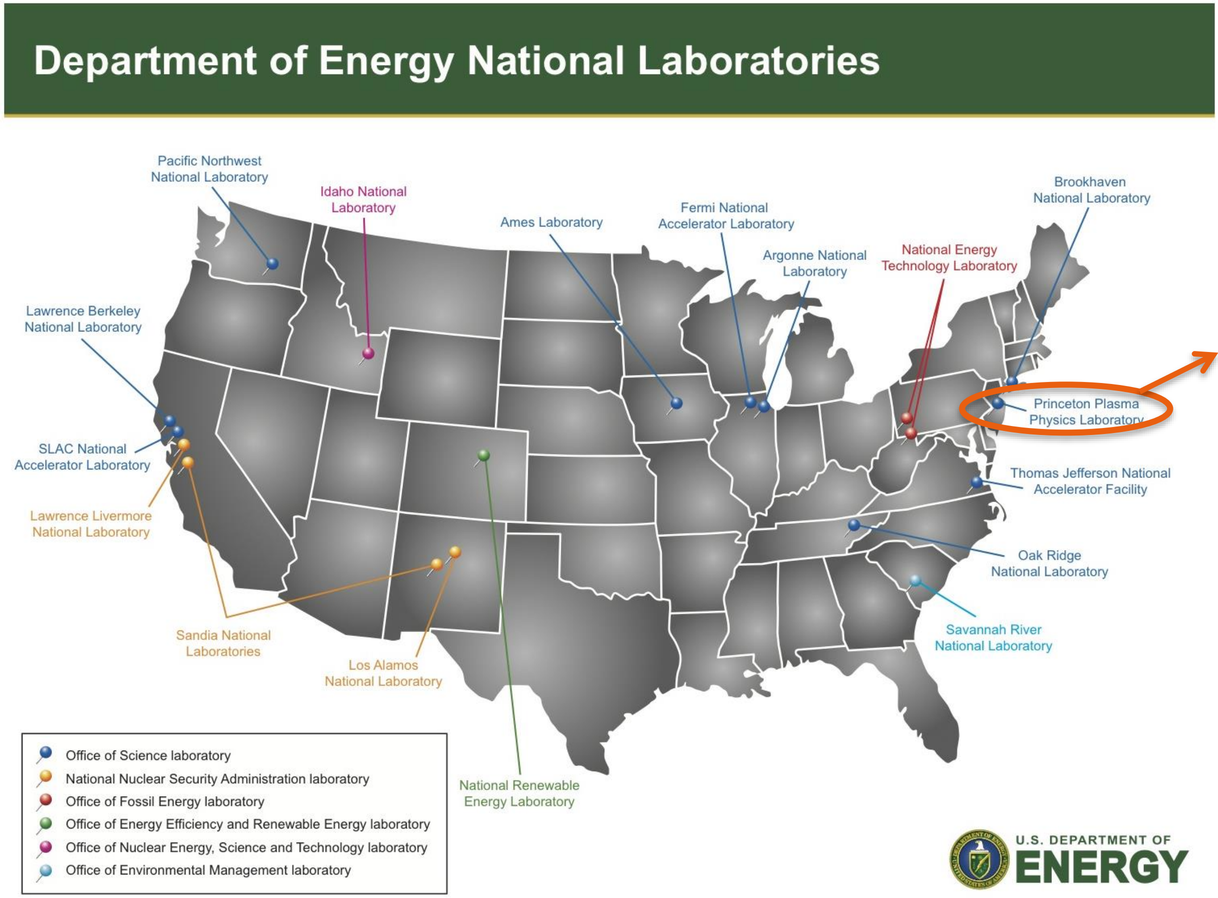
⑤ Synergies between FES and with HEP
(e.g. CERN’s RD50)

⑥ TESTS at the appropriate neutron energies

⑦ Summary

PPPL: Princeton Plasma Physics Lab

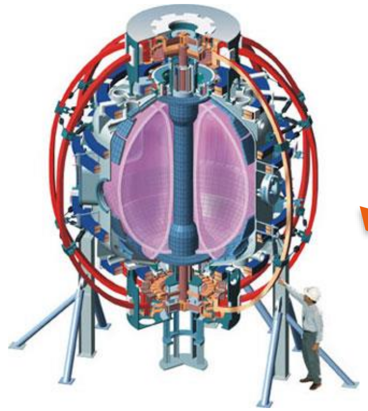
- PPPL is one of 17 DoE national laboratories.
- We are managed by PU but have a government mandate that focuses on fusion energy research and basic plasma science.



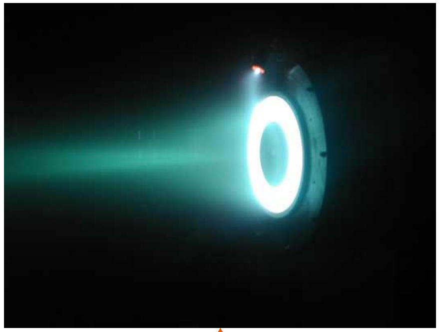
PPPL
PRINCETON
PLASMA PHYSICS
LABORATORY

At PPPL, we try to understand many aspects of plasma physics

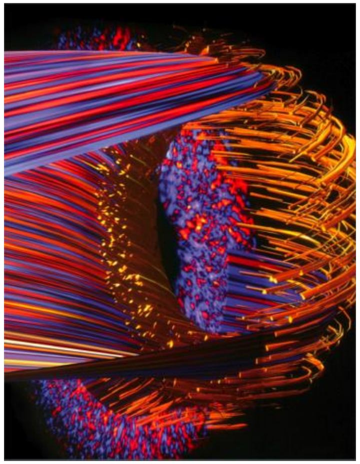
Fusion Research



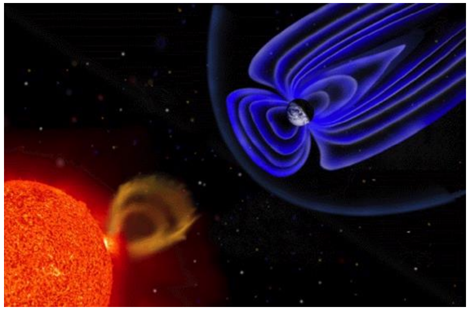
Basic plasma physics



Plasma theory and simulation



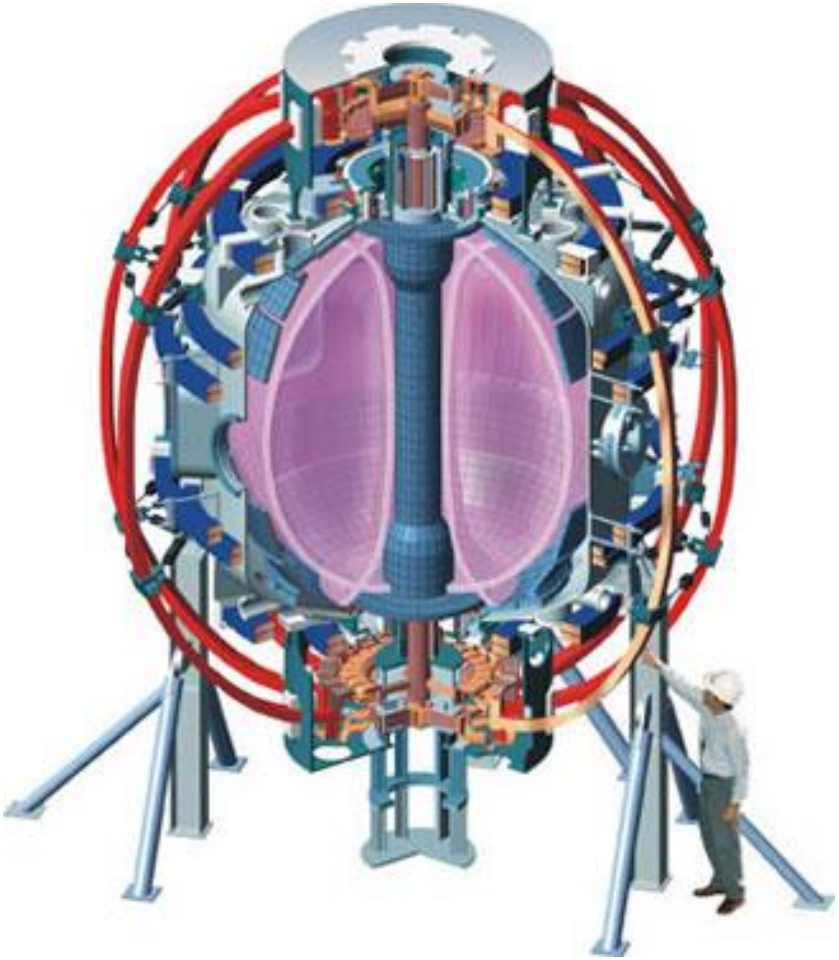
Astrophysical plasmas



PPPL PRINCETON PLASMA PHYSICS LABORATORY

Plasma in other fields (e.g. medicine/nano-materials)

Why is fusion research our main mission? It is simple: an abundant energy source !



① Energy is central to achieving sustainable development for the human race.

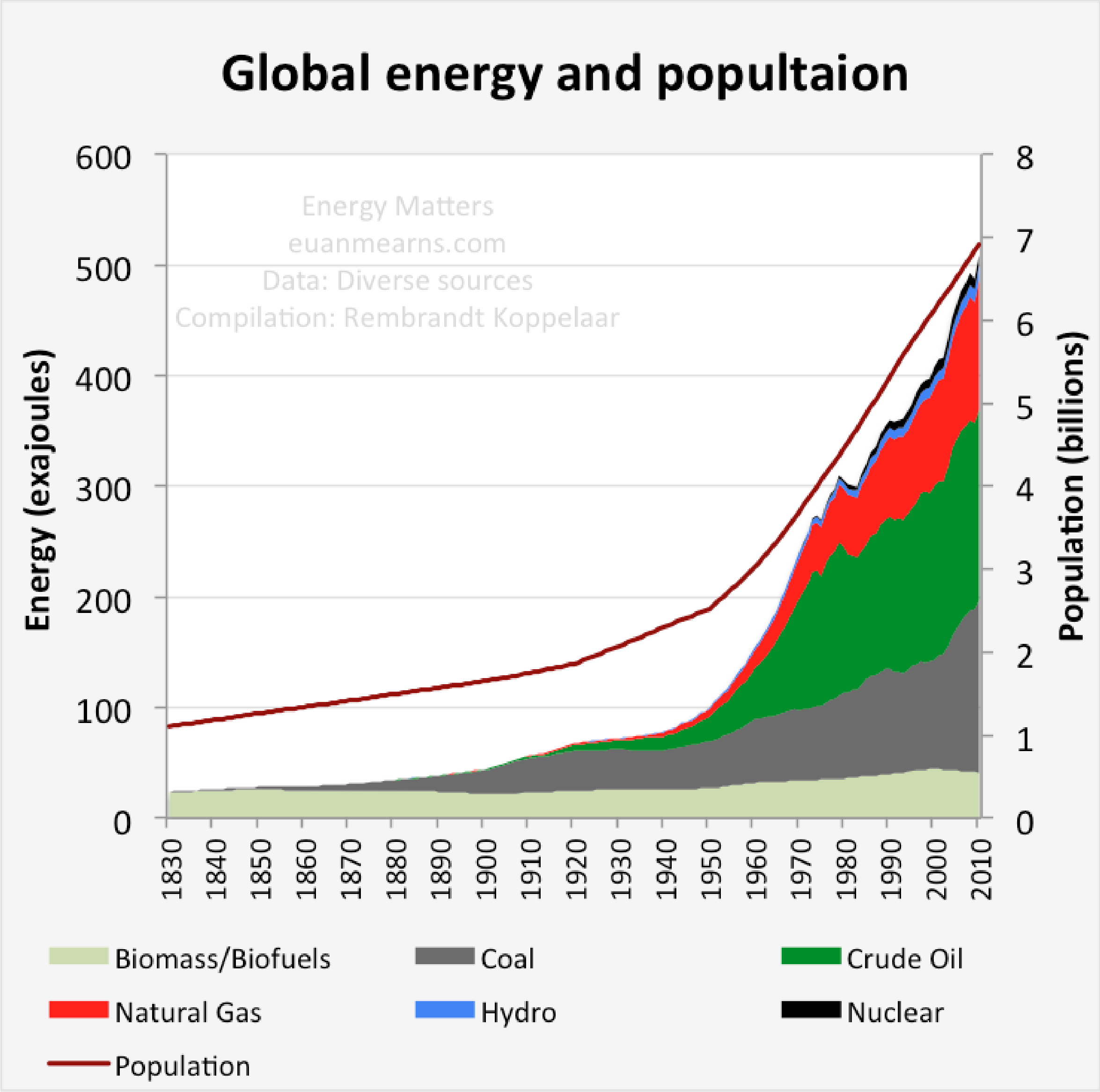
② The **standard of living is directly proportional to our energy consumption**.

③ The world will demand an energy usage of at least double the present energy consumption by 2050!

④ **How bad is the energy problem?**

⑤ At the present rates, the conventional coal, oil and natural gas resources will only last for the next ~300, ~40 and ~50 years, respectively.

World population and energy consumption are related and are increasing dramatically !!!

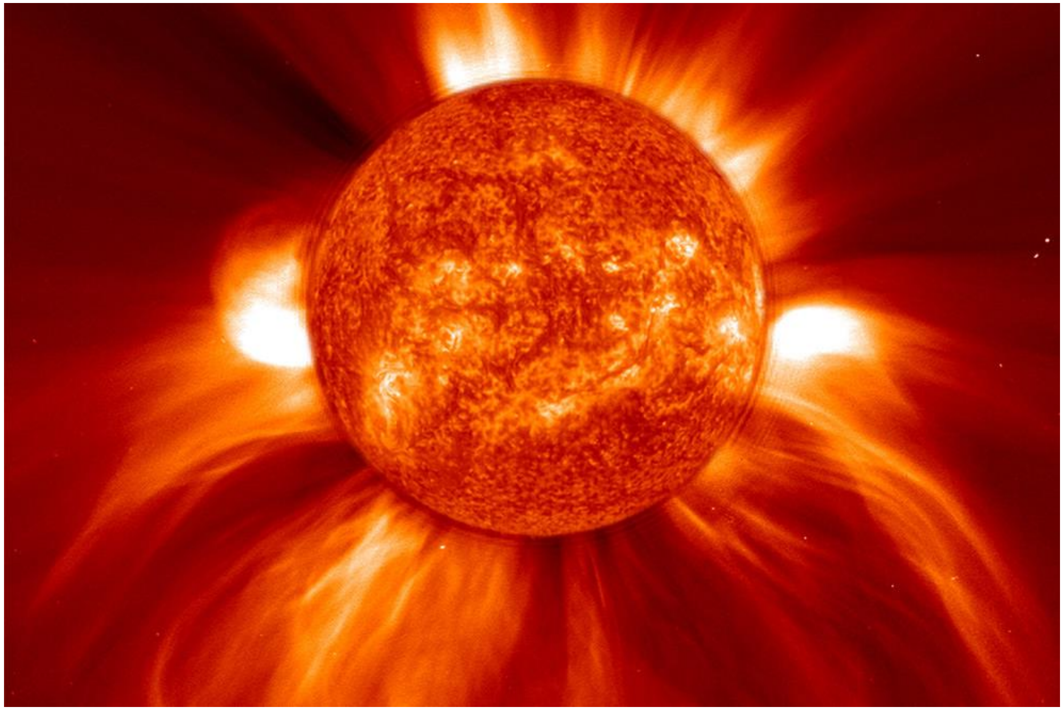


How do we go green?

Fusion is an ideal alternative – the sun's energy comes from FUSION

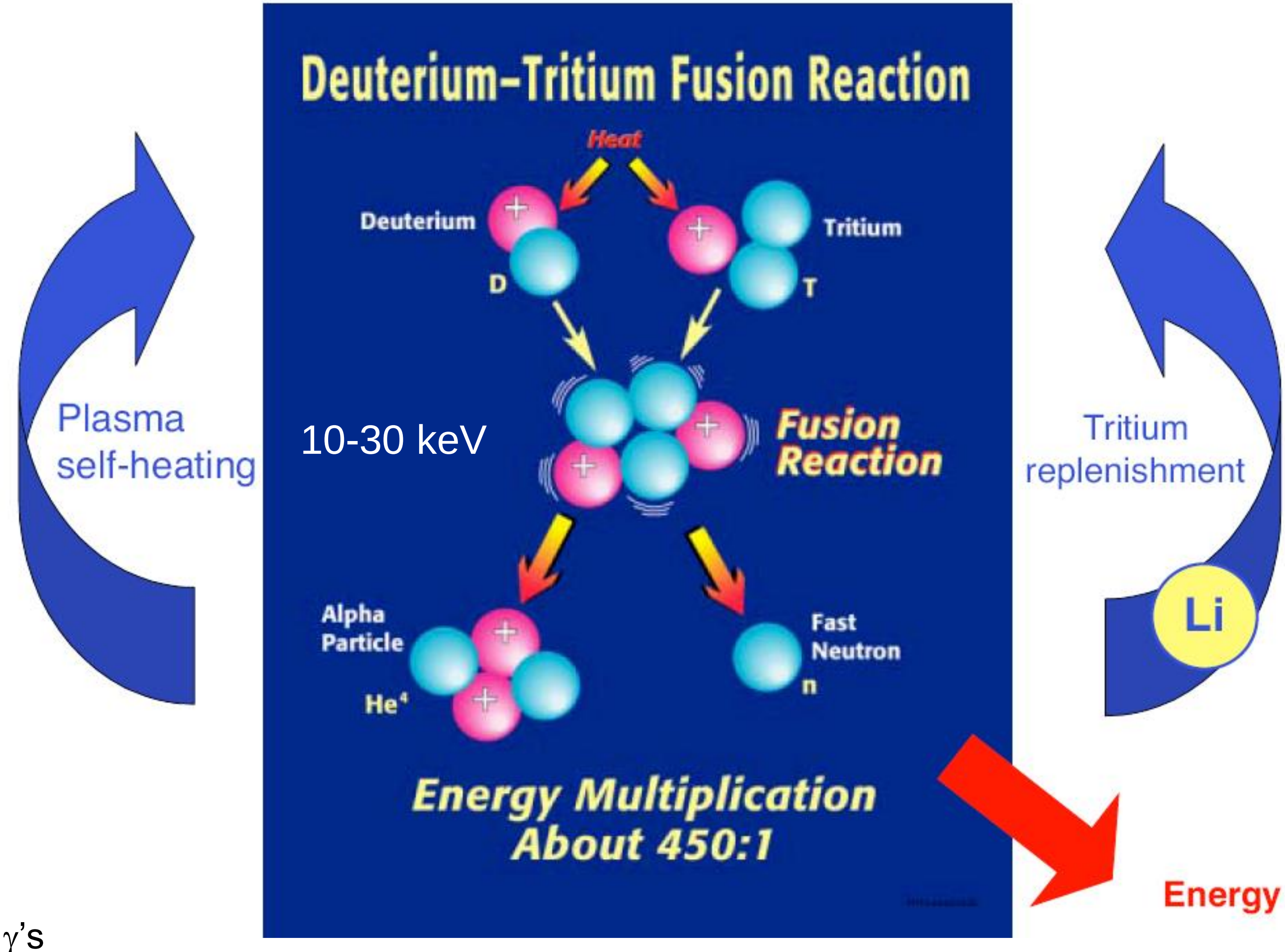
Fusion energy is:

- Clean
- Safe
- Nearly inexhaustible
- Efficient
- Independent of geographical location
- In the future, available 24/7



When small hot atoms (usually hydrogen) combine…. there is a lot of ENERGY produced!

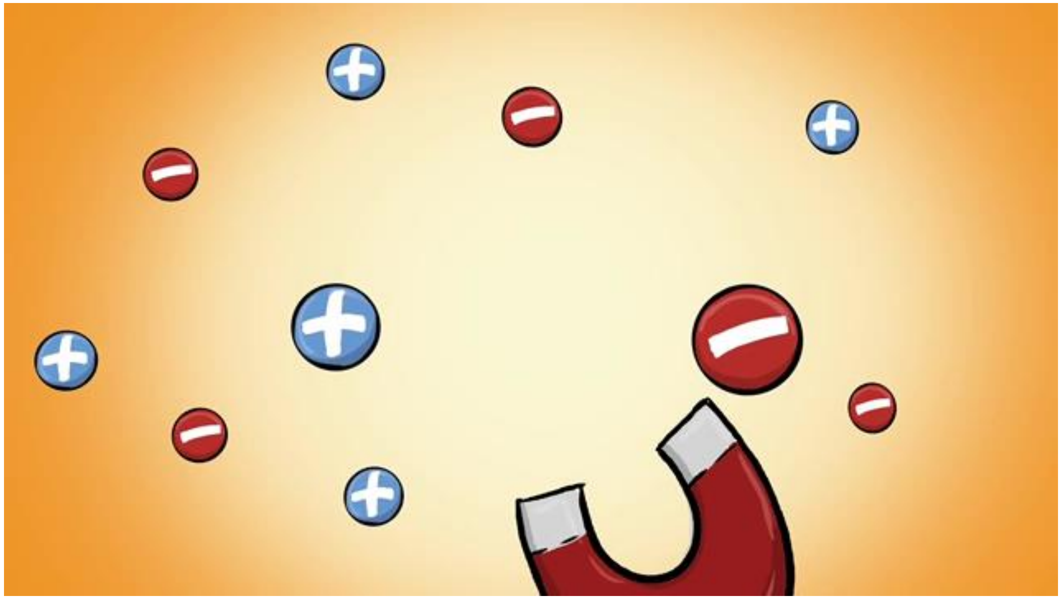
Current nuclear fusion reaction under consideration

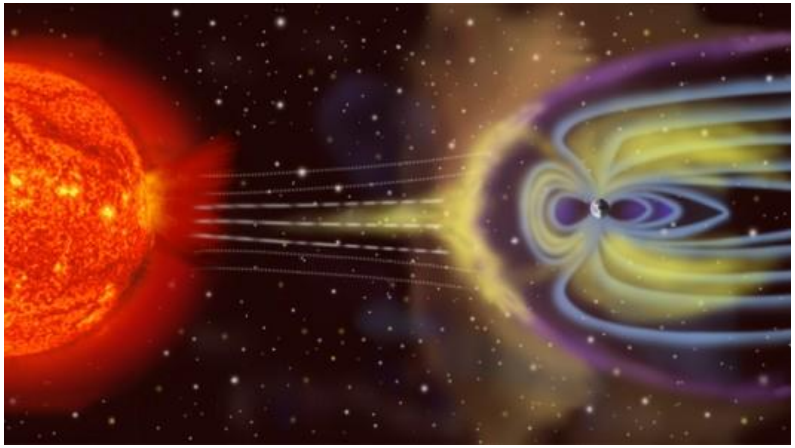


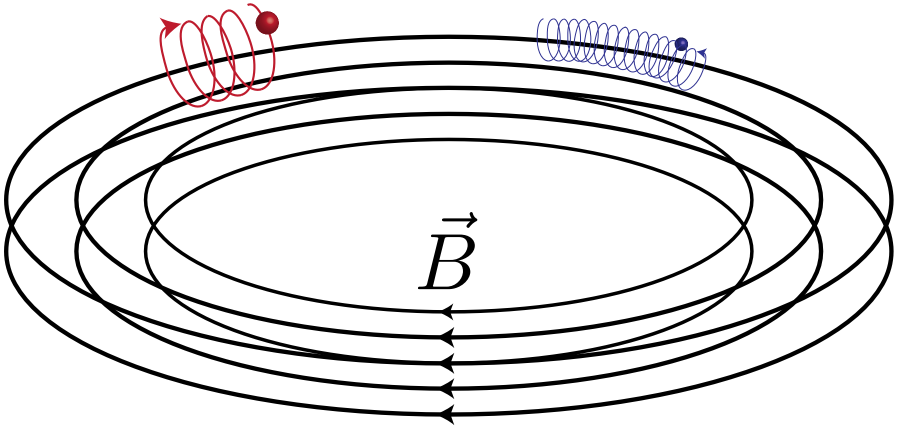
Note: No γ's

At PPPL we use magnetic fields to contain the thermonuclear hot plasma

Plasma can be contained at millions of degrees by trapping them with magnetic field.

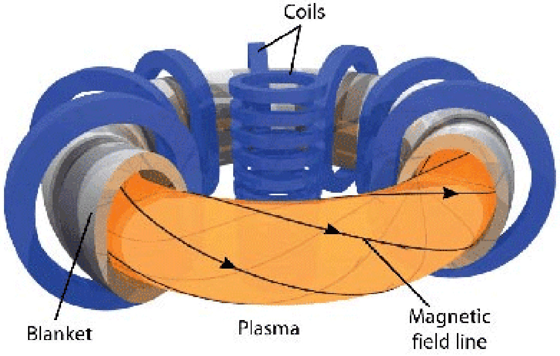




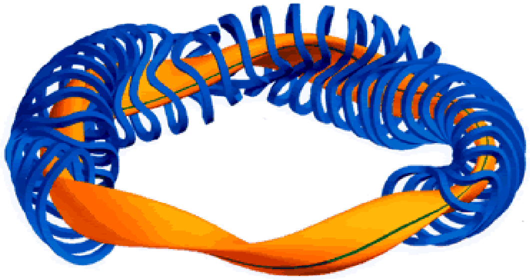


Main magnetic confinement schemes are the tokamak and stellarator

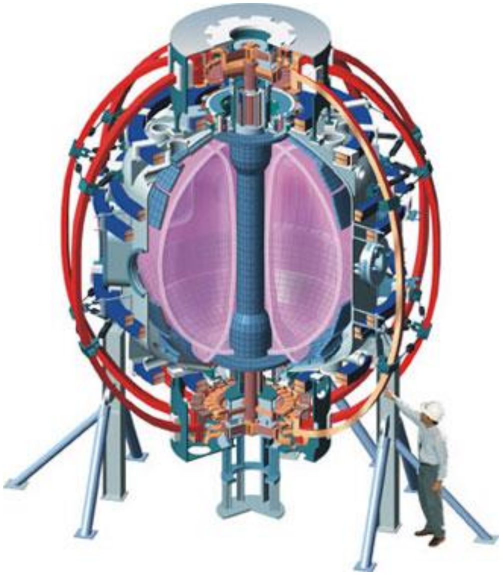
Tokamak



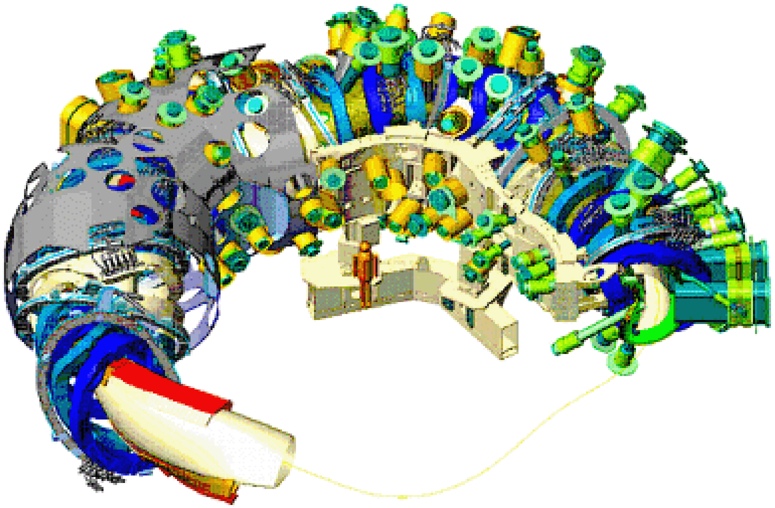
Stellarator



Spherical tokamak (NSTXU @ PPPL)



W7X @ Max-Planck / Germany



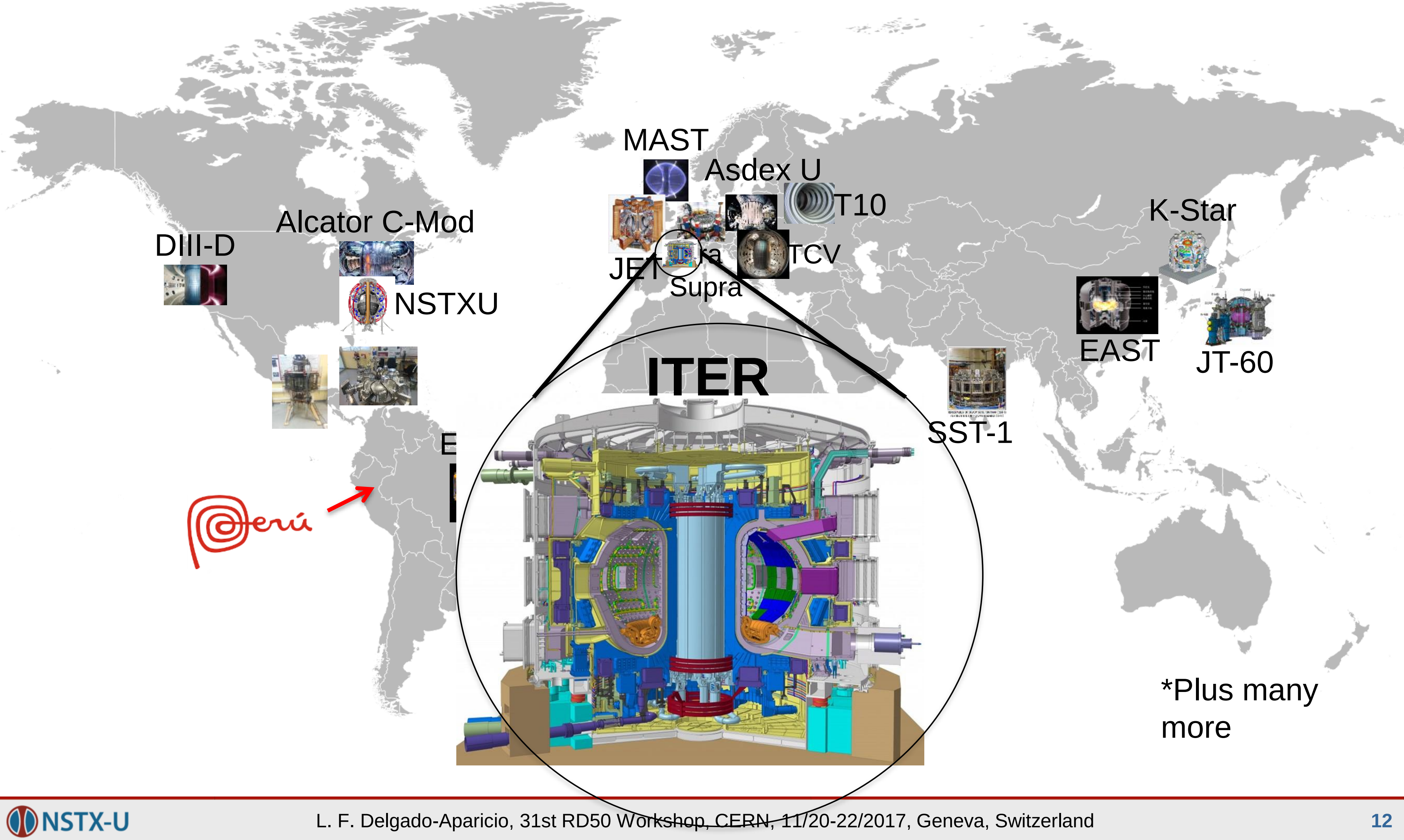
Main systems in the US are in CA, MA and NJ

DIII-D in General Atomics,
San Diego, CA

Alcator C-Mod @ PSFC, MIT
Cambridge, MA

NSTX-U @ PPPL, Princeton University
Princeton, NJ

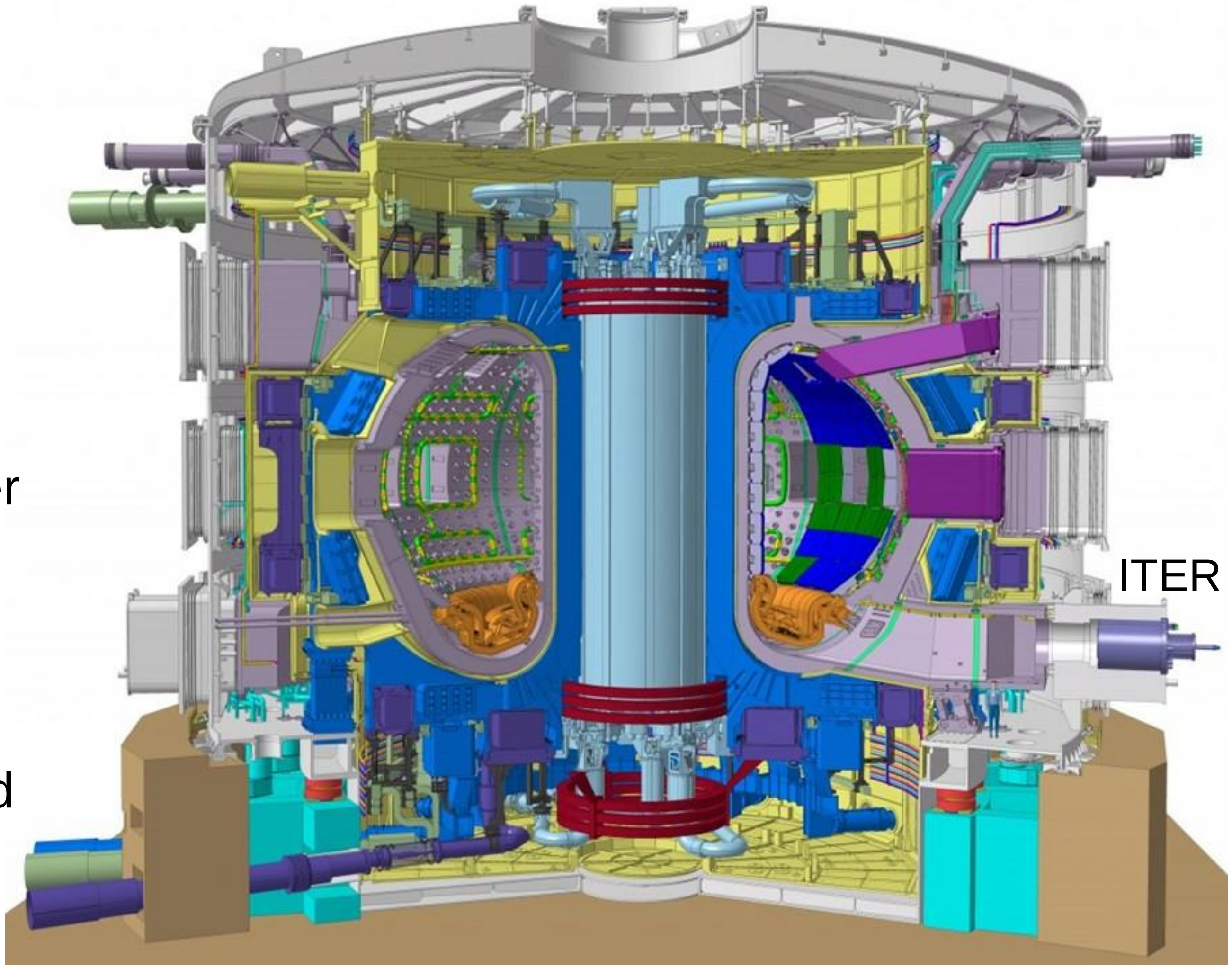
Tokamaks around the world study different plasma parameters and shapes

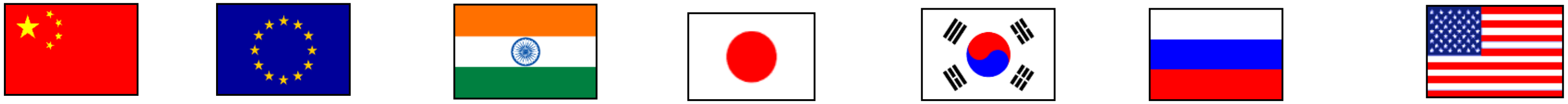


*Plus many more

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

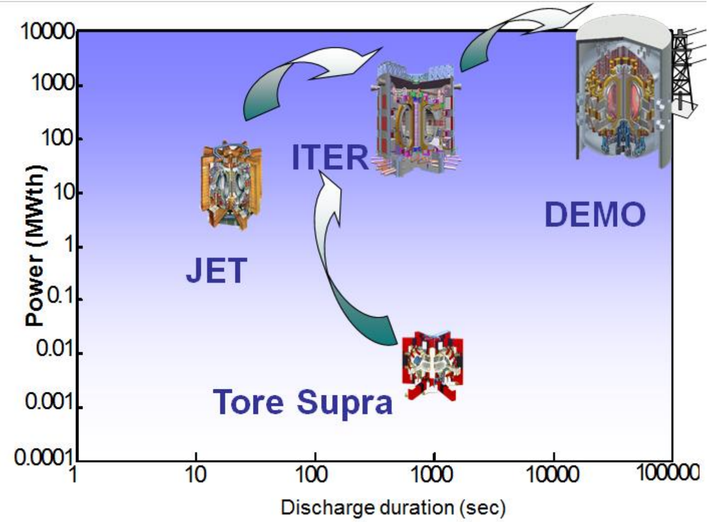
- International Thermonuclear Experimental Reactor
- ~ 30 B$
- Expected to produce 500MW of fusion power
- The 1st time in history where **P_{out}>P_{in}**
- First plasmas expected by ~ 2025

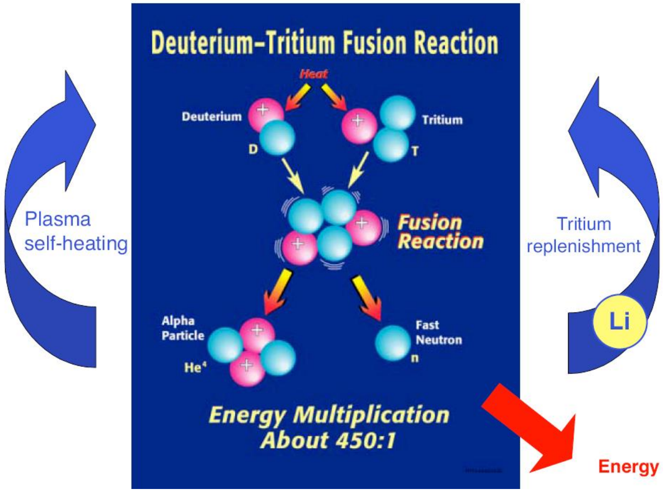




ITER – in latin ‘the way’: the mile-stone to commercial fusion power

- Objective:
  - Scientific and technological basis for reactors that can demonstrate commercial viability of fusion.
  - Cornerstone for DEMO
- Principles:
  - Magnetic confinement of high temperature plasma
  - Superconducting coils, tokamak principle
  - Small fraction of external heating
  - Dominant self-heating through alpha-particles
- Characteristics:
  - Q=10: 500 MW fusion power with only 50 MW external heating
  - Single discharge duration: 500s; accumulated total burn 0.6 years~10^7 s

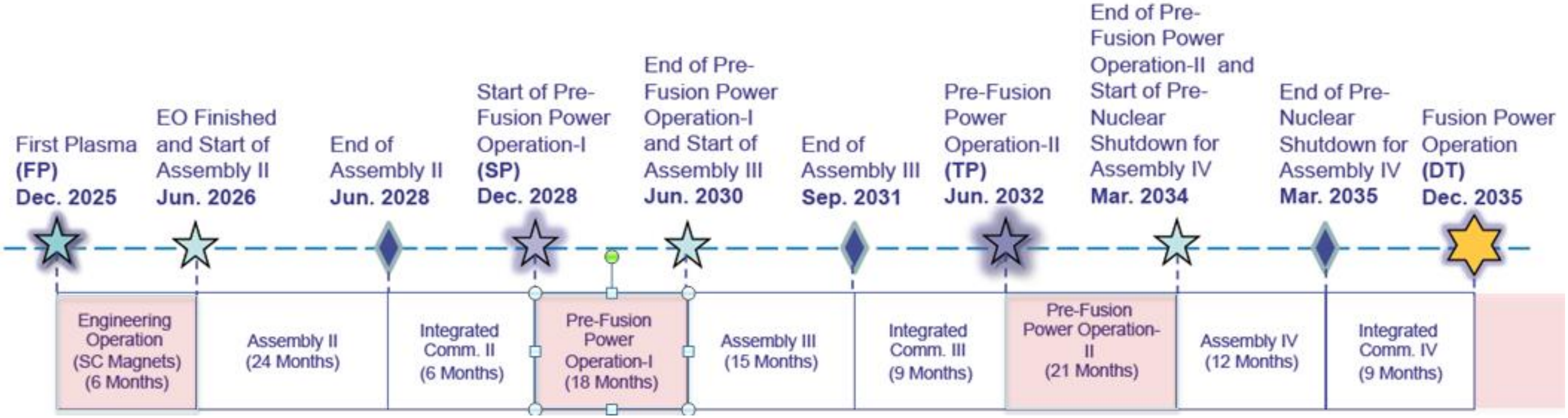




ITER schedule – staged approach

- 2007 Official starting point of ITER Organization
- 2017 Building is in full swing
- First plasma is planned for end of 2025

Tokamak Complex: Resting on 493 seismic pads, the reinforced concrete basement slab bears the 400 000-ton



First Plasma **(FP)** **Dec. 2025**

EO Finished and Start of Assembly II **Jun. 2026**

End of Assembly II **Jun. 2028**

Start of Pre-Fusion Power Operation-I **(SP)** **Dec. 2028**

End of Pre-Fusion Power Operation-I and Start of Assembly III **Jun. 2030**

End of Assembly III **Sep. 2031**

Pre-Fusion Power Operation-II **(TP)** **Jun. 2032**

End of Pre-Fusion Power Operation-II and Start of Pre-Nuclear Shutdown for Assembly IV **Mar. 2034**

End of Pre-Nuclear Shutdown for Assembly IV **Mar. 2035**

Fusion Power Operation **(DT)** **Dec. 2035**

Engineering Operation (SC Magnets) (6 Months)

Assembly II (24 Months)

Integrated Comm. II (6 Months)

Pre-Fusion Power Operation-I (18 Months)

Assembly III (15 Months)

Integrated Comm. III (9 Months)

Pre-Fusion Power Operation-II (21 Months)

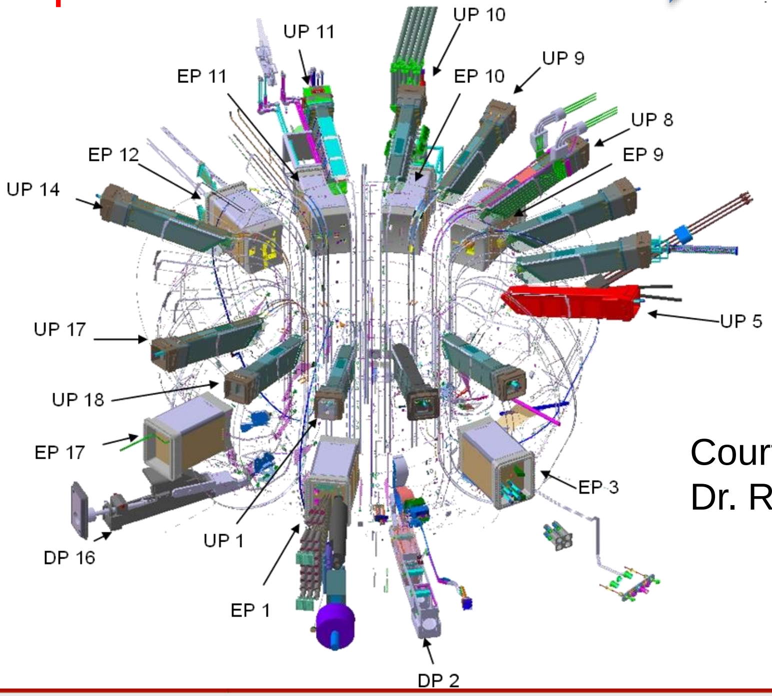
Assembly IV (12 Months)

Integrated Comm. IV (9 Months)

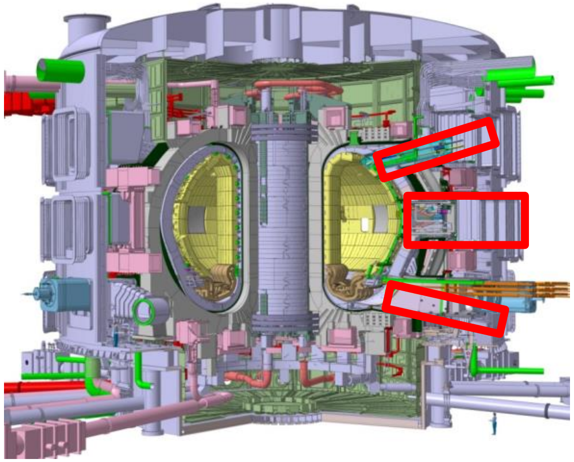
Courtesy of Dr. R. Reichle (ITER)

ITER diagnostics – roles and scope

- Provision of physics measurements for:
  - Safe operation
  - Investment protection
  - Control of plasma & first wall
  - Physics evaluation of phenomena



- Scope of measurements:
  - Magnetics
  - Fusion products (e.g. n_{He}, n)
  - Plasma density and temperature (e.g. $n_{e,D,T,Z}$, $T_{e,D,T,Z}$)
  - Heat radiation
  - Fuel and impurity spectroscopy
  - Plasma fluctuations
  - Plasma-wall interactions



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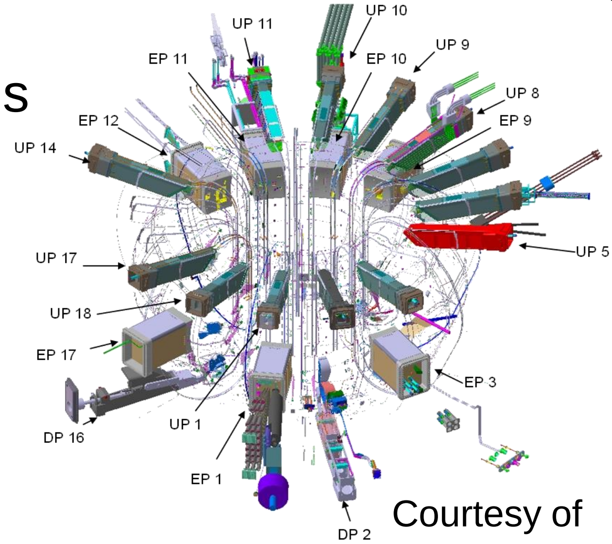
Issues constraining or eliminating conventional diagnostic measurements in burning plasmas



Courtesy of
Dr. R. Reichle (ITER)

① Compact design due to lack of port access (due to space required for blankets, energy conversion systems as well as shielding from heat & neutrons)

② High neutron fluxes and γ-induced-noise

③ Long-pulse operations ≥400 s

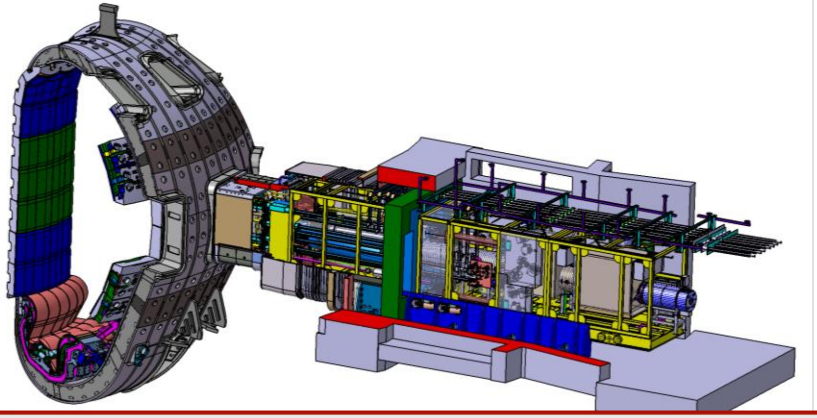
④ The presence of high-magnetic fields.

⑤ High wall temperatures (cooling required)

⑥ Vacuum

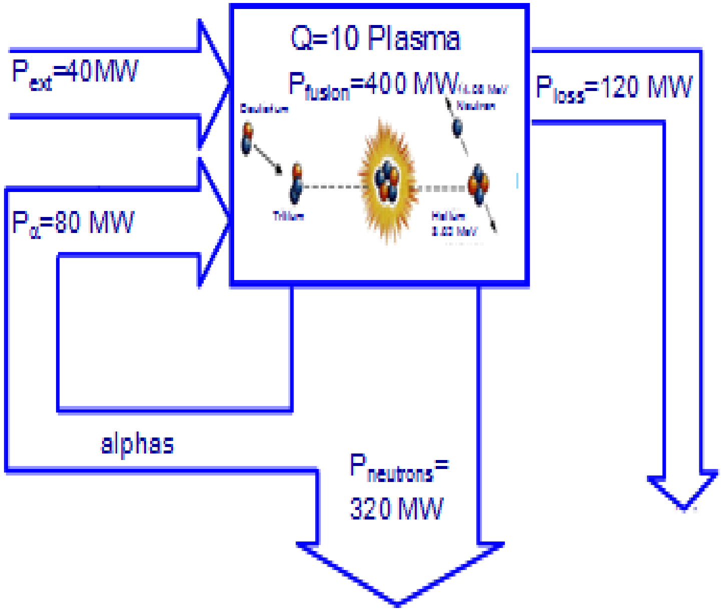
FUTURE CHALLENGE for DEMO/FNSF:

a) The stored energy will be at least 5× larger than in ITER plasmas
b) Longer-pulse operations!

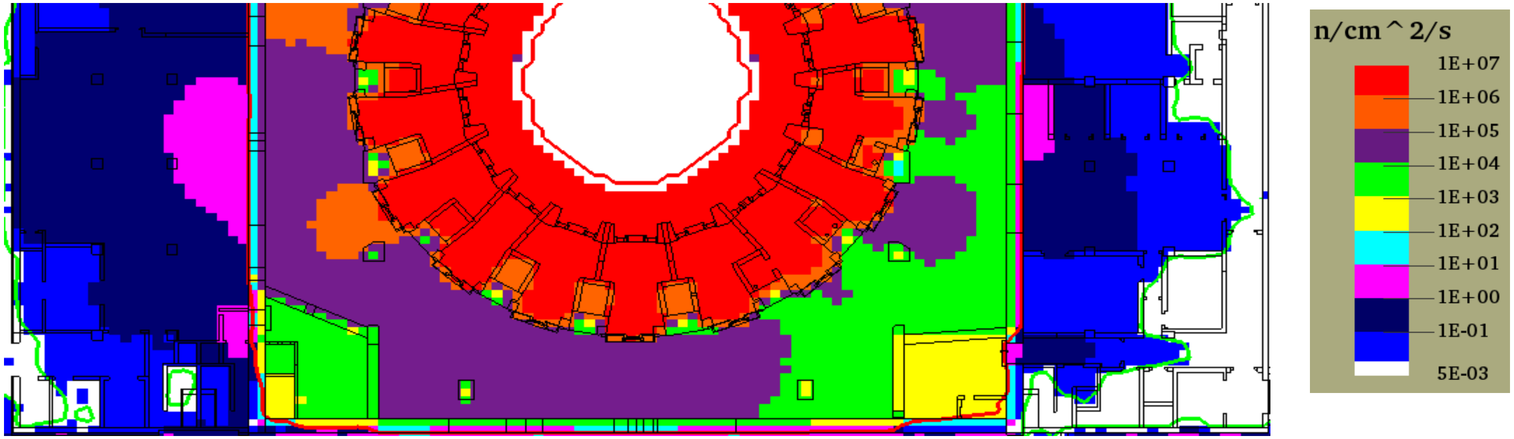


Neutron radiation environment: the new challenge!

- New challenges:
  - New French nuclear regulation: ITER=INB 174
  - Organization with 8 stakeholders
  - Bigger and more power-full;
  - Achieving shut-down dose rates;
  - Low maintenance, limited access;
  - Limited space;
  - New measurements and ranges;
  - New roles related to nuclear safety;



Total Neutron Flux at Equatorial Level



Courtesy of
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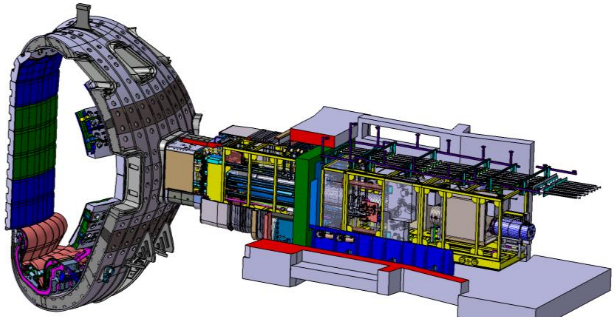
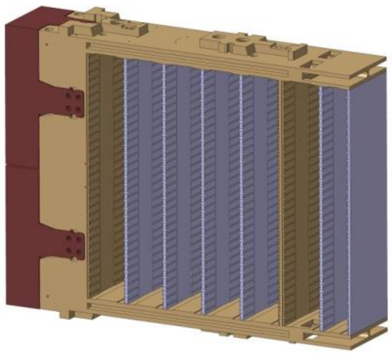
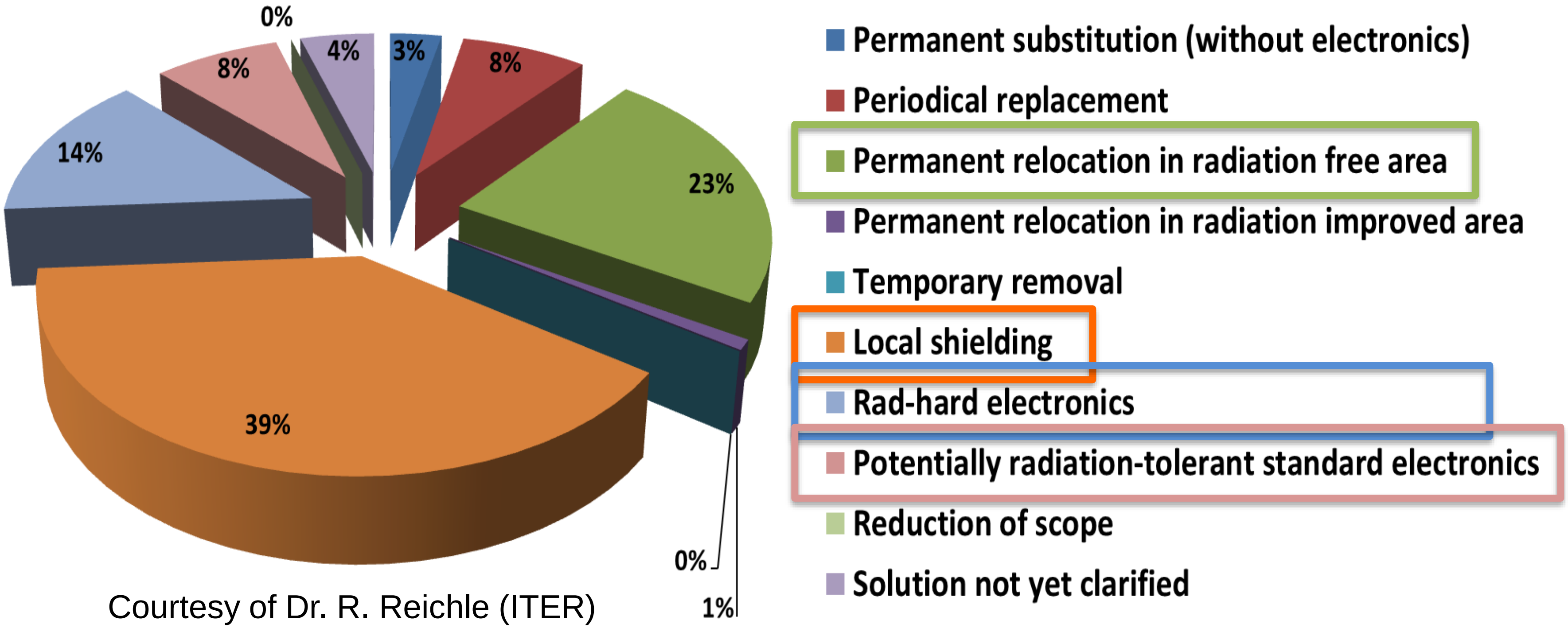
Strategies to mitigate radiation. Balance shifts providing radiation hard detectors + electronics



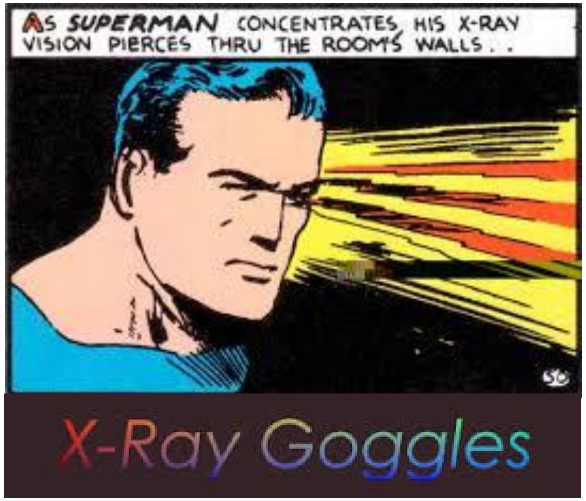
- Shield module driven by engineering criteria:
  - Good shielding and low shut down dose rate (ALARA)
  - Weight limit vs maintenance
  - Design flexibility for payload

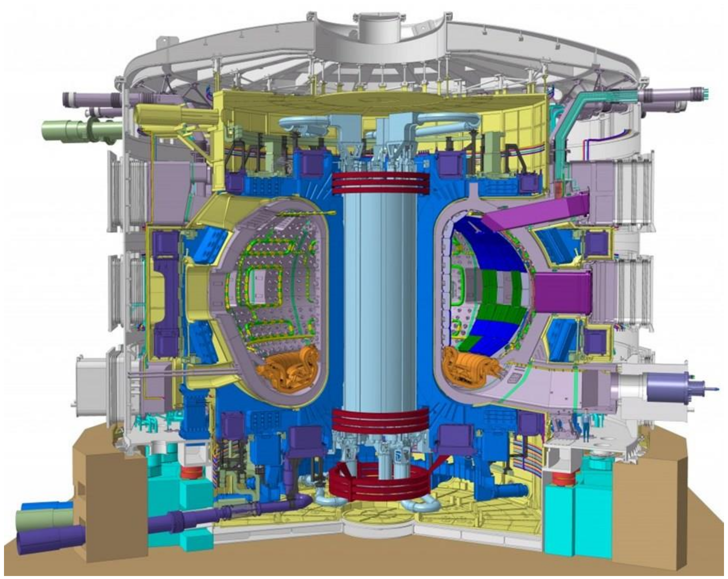




Courtesy of Dr. R. Reichle (ITER)

THE X-RAY CASE: So…how to diagnose these thermonuclear plasmas at ~300 million ^{o}C ?

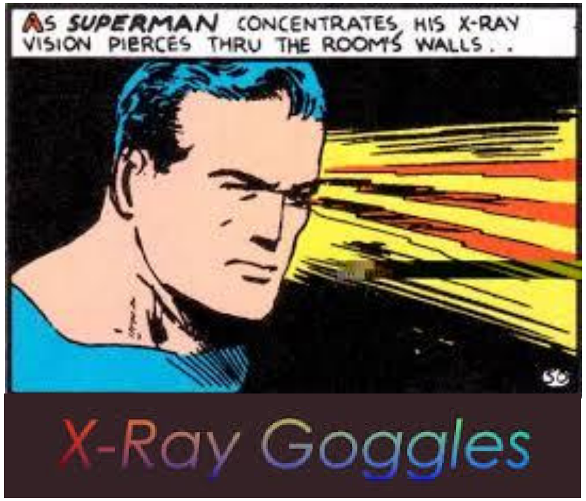




Nearly 90% of the radiated power in ITER will be in the x-ray range:

SXR: 1<E<20 keV
HXR: 20<E<400 keV

THE X-RAY CASE: So…how to diagnose these thermonuclear plasmas at ~300 million ^{o}C ?

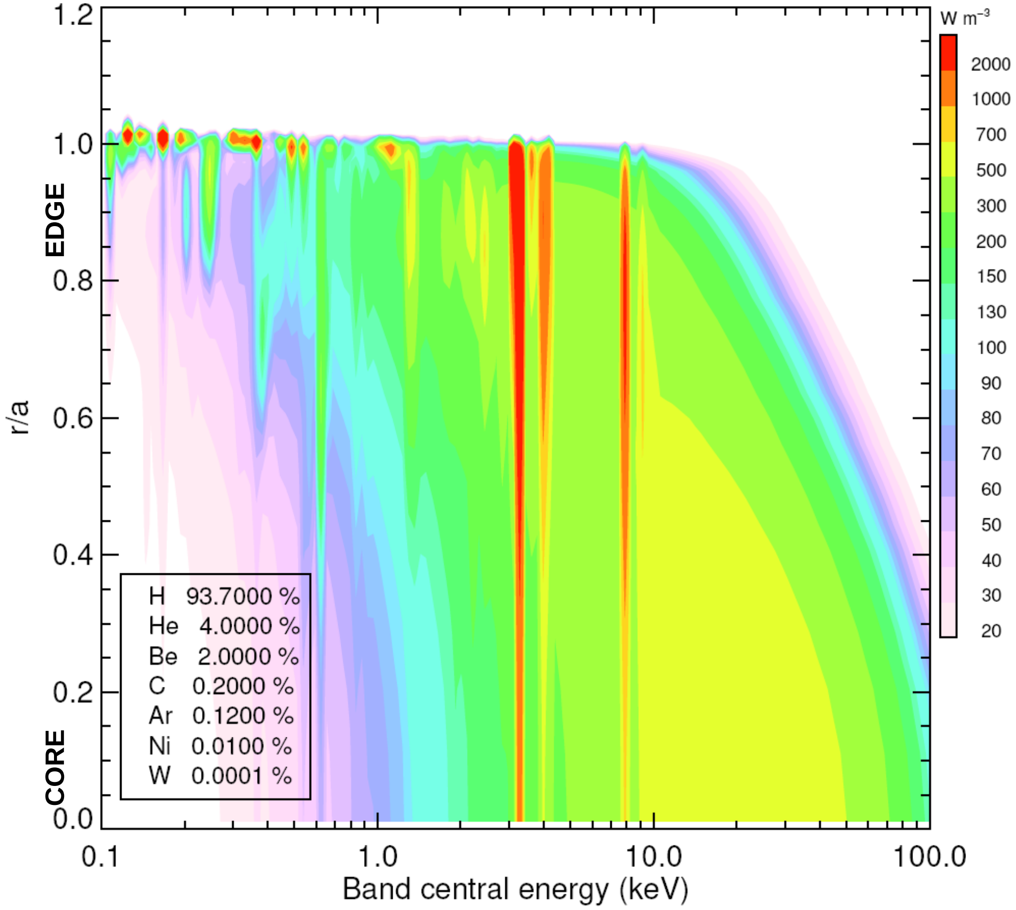


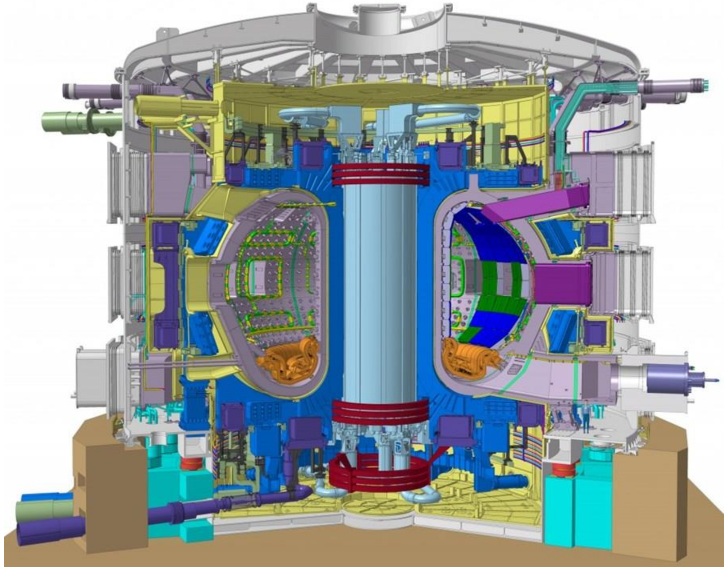
IDEAL: Line & continuum in 5% energy bands, but radially resolved

E < 10 keV: mainly n_Z information

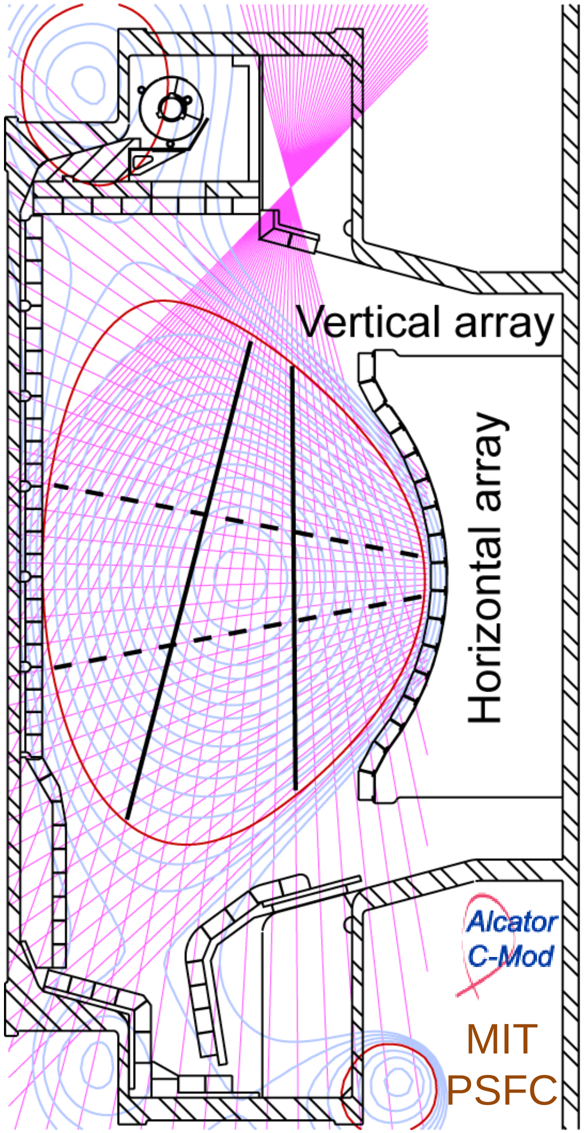
E > 10 keV: mainly T_e , Z_{eff} information

Modern detectors will be able measure this…



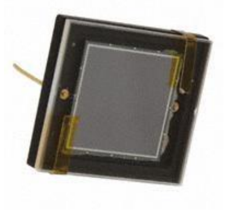


Conventional SXR tomography integrates in photon-energy using metal filter & diode arrays

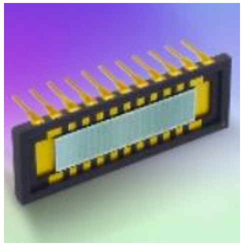


DIRECT EXAMPLES (e.g. Si)

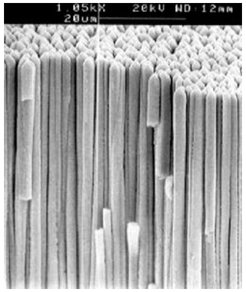
AXUV-100



AXUV-20



INDIRECT EXAMPLE (e.g. CsITl)



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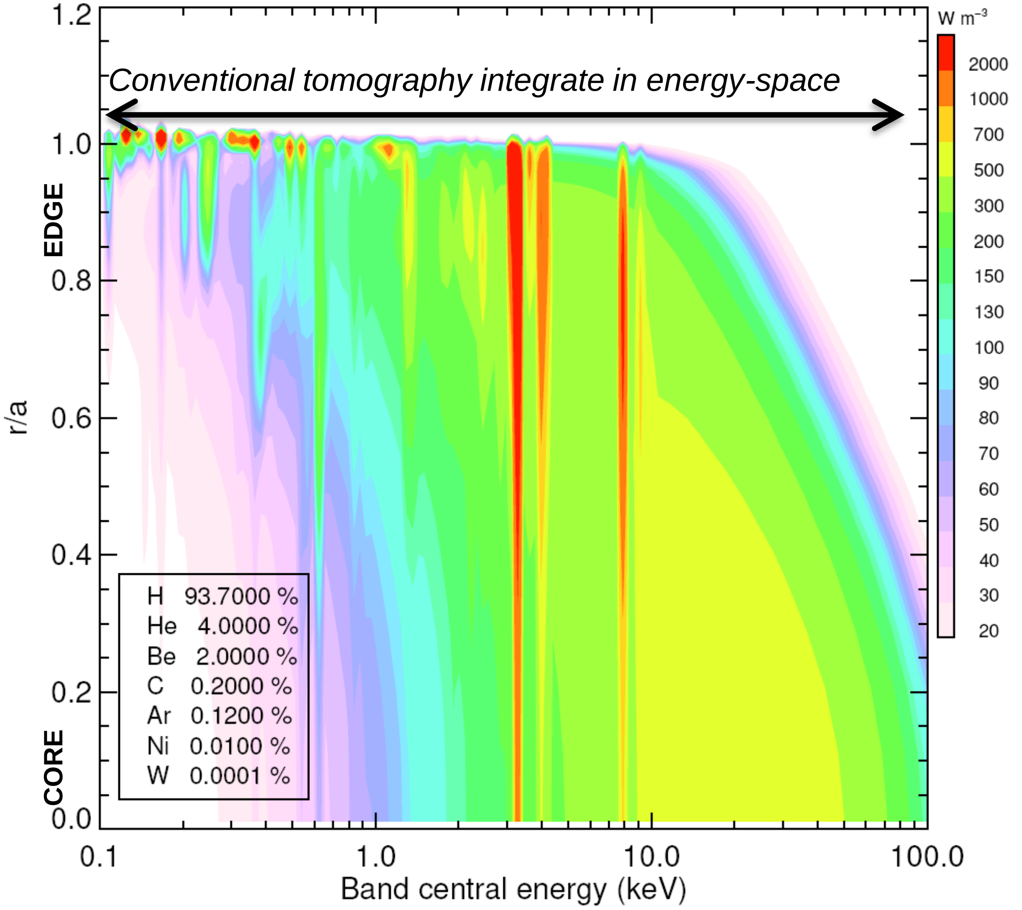
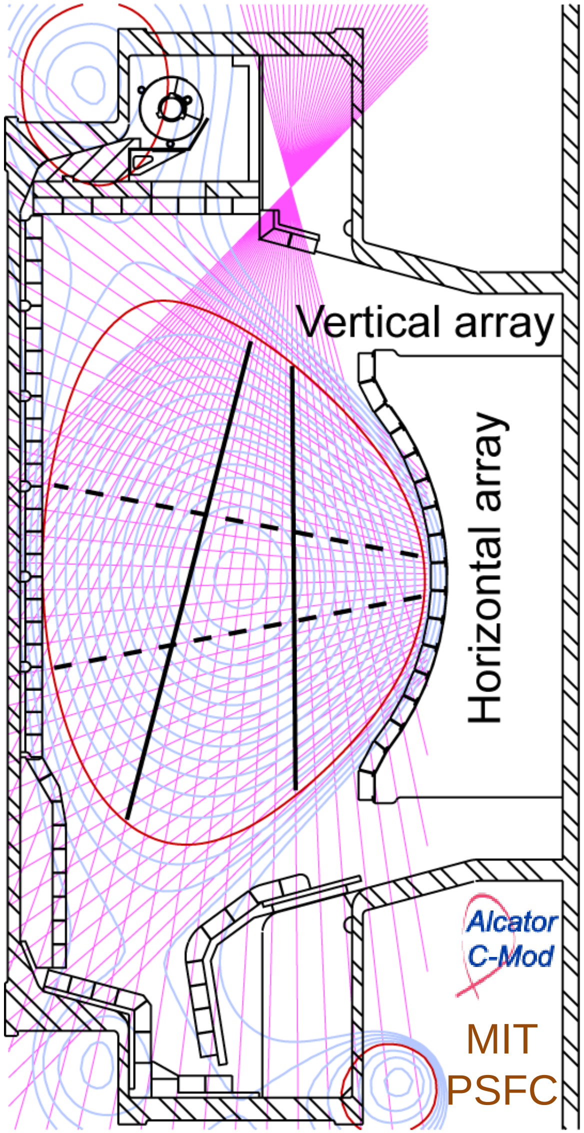
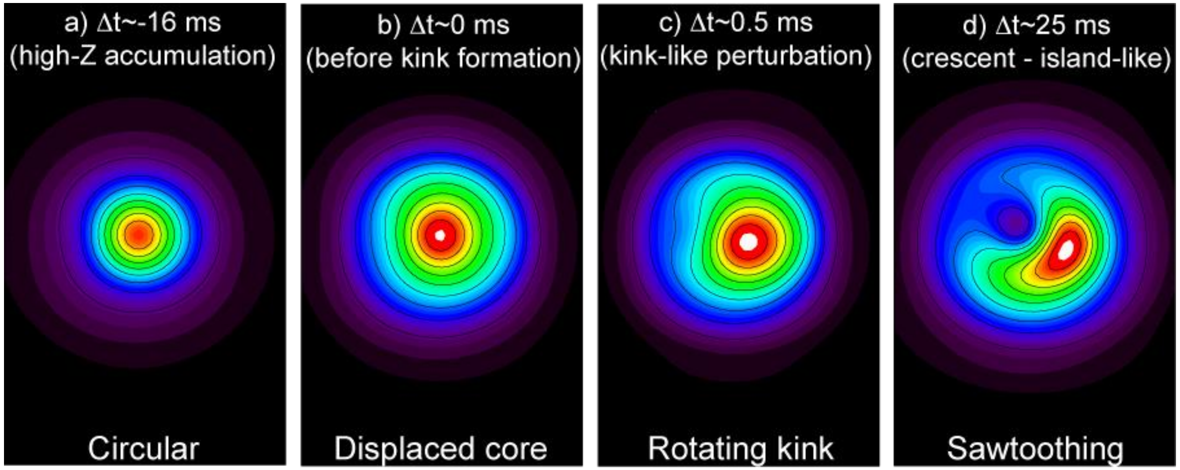


Conventional SXR tomography is used for stability, MHD and transport studies

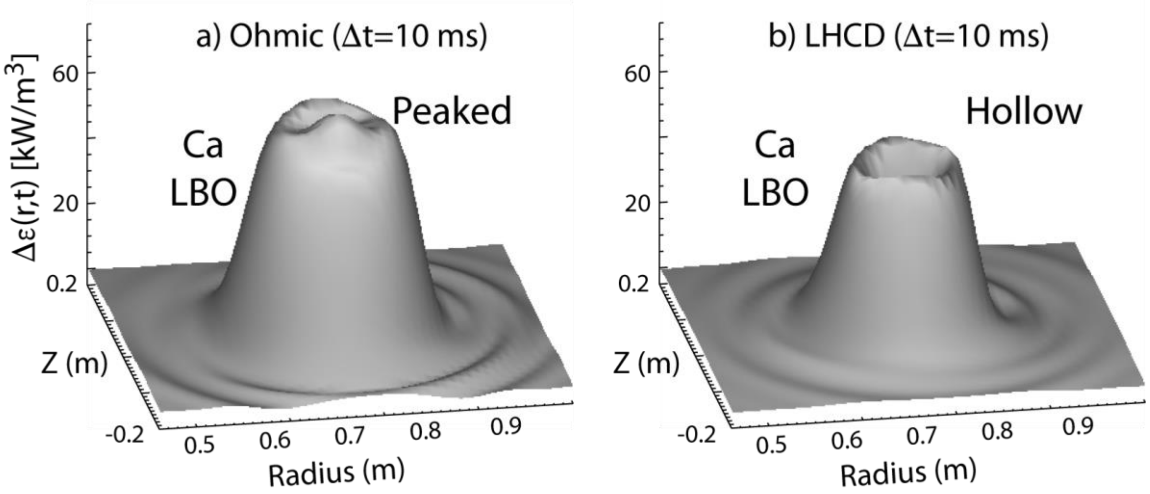


a) Stability and MHD [e.g. (m,n) modes and sawteeth]



L. Delgado-Aparicio, et. al., PRL,’12, NF’13

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



How do we extract information from narrow and/or wider energy bands ?

Narrow bands

- High-resolution spectrometers
  - Doppler spectroscopy
- Probes mainly the ion-channel
  - T_i, $V_{\phi,\theta}$, n_Z
  - $E/\Delta E$~10000-20000

Wider bands

- Low-resolution spectrometers
  - Multi-energy spectroscopy
- Probes electron and ion channels
  - T_e, n_Z, ΔZeff, Z_{eff}, $n_{e,fast}$
  - $E/\Delta E$~10

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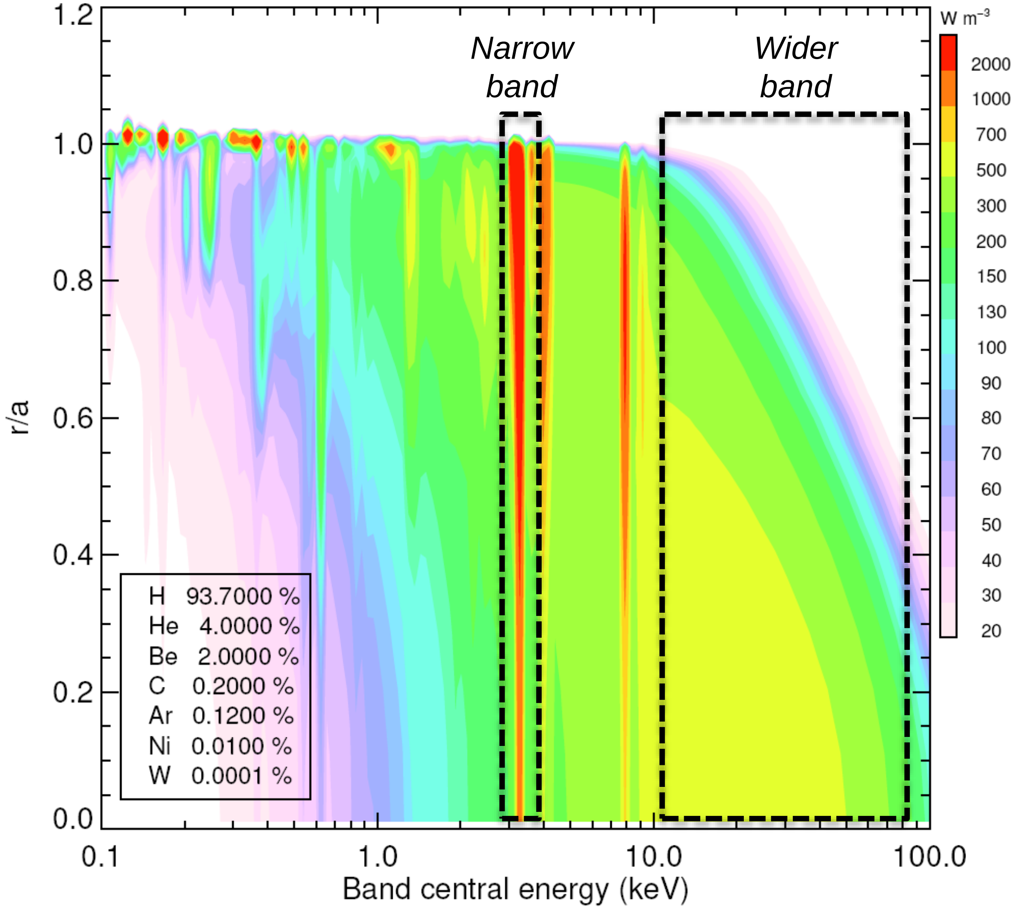
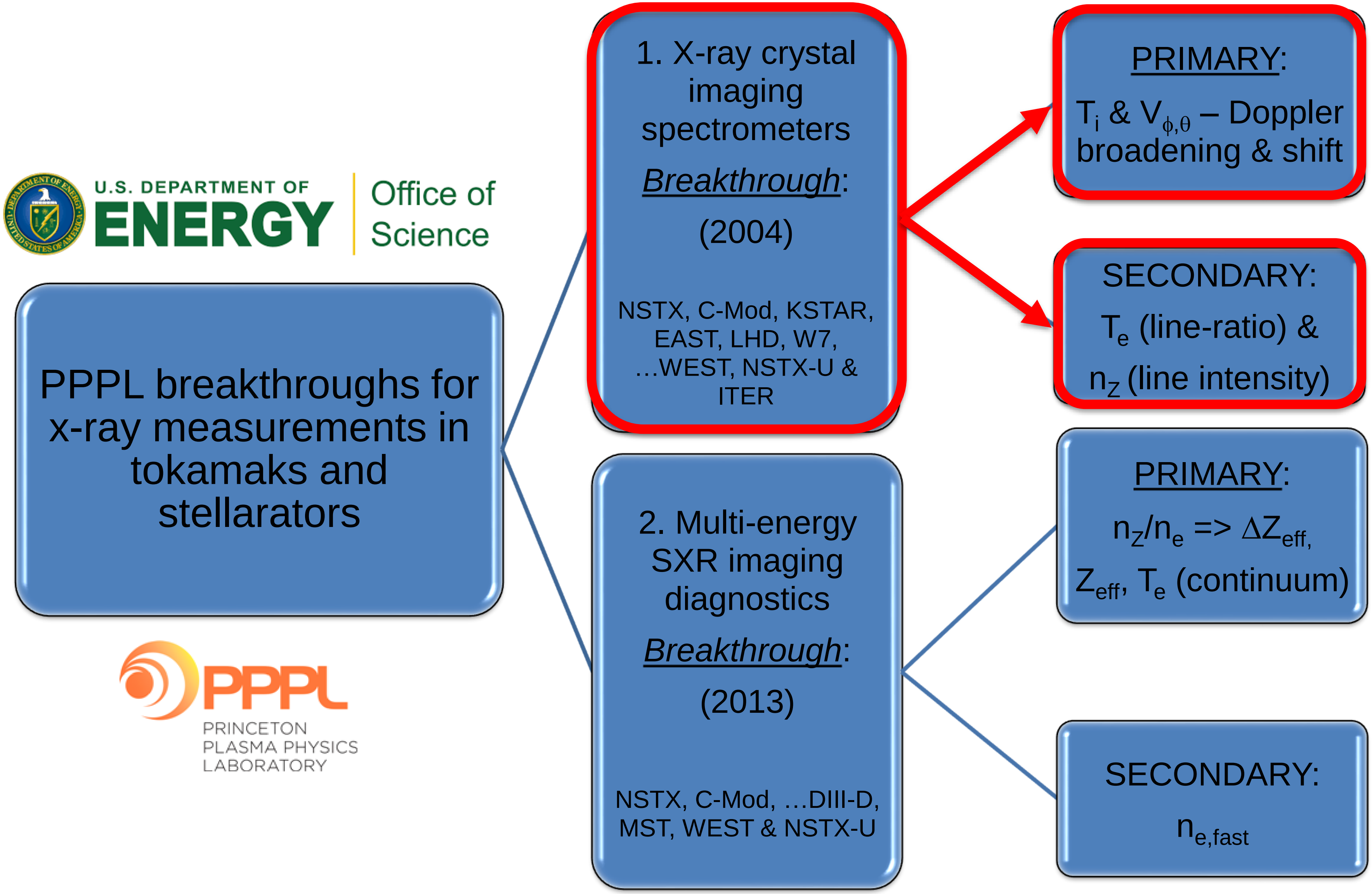
Modern detectors will be able measure this…



X-ray group at PPPL developed new concepts for MCF plasmas (extrapolate to ITER & beyond)

U.S. DEPARTMENT OF ENERGY | Office of Science



PPPL breakthroughs for x-ray measurements in tokamaks and stellarators

1. X-ray crystal imaging spectrometers

Breakthrough:

(2004)

NSTX, C-Mod, KSTAR, EAST, LHD, W7, …WEST, NSTX-U & ITER

PRIMARY:

T_i & $V_{\phi,\theta}$ – Doppler broadening & shift

SECONDARY:

T_e (line-ratio) &

n_Z (line intensity)

2. Multi-energy SXR imaging diagnostics

Breakthrough:

(2013)

NSTX, C-Mod, …DIII-D, MST, WEST & NSTX-U

PRIMARY:

$n_Z/n_e \Rightarrow \Delta Z_{eff}$,

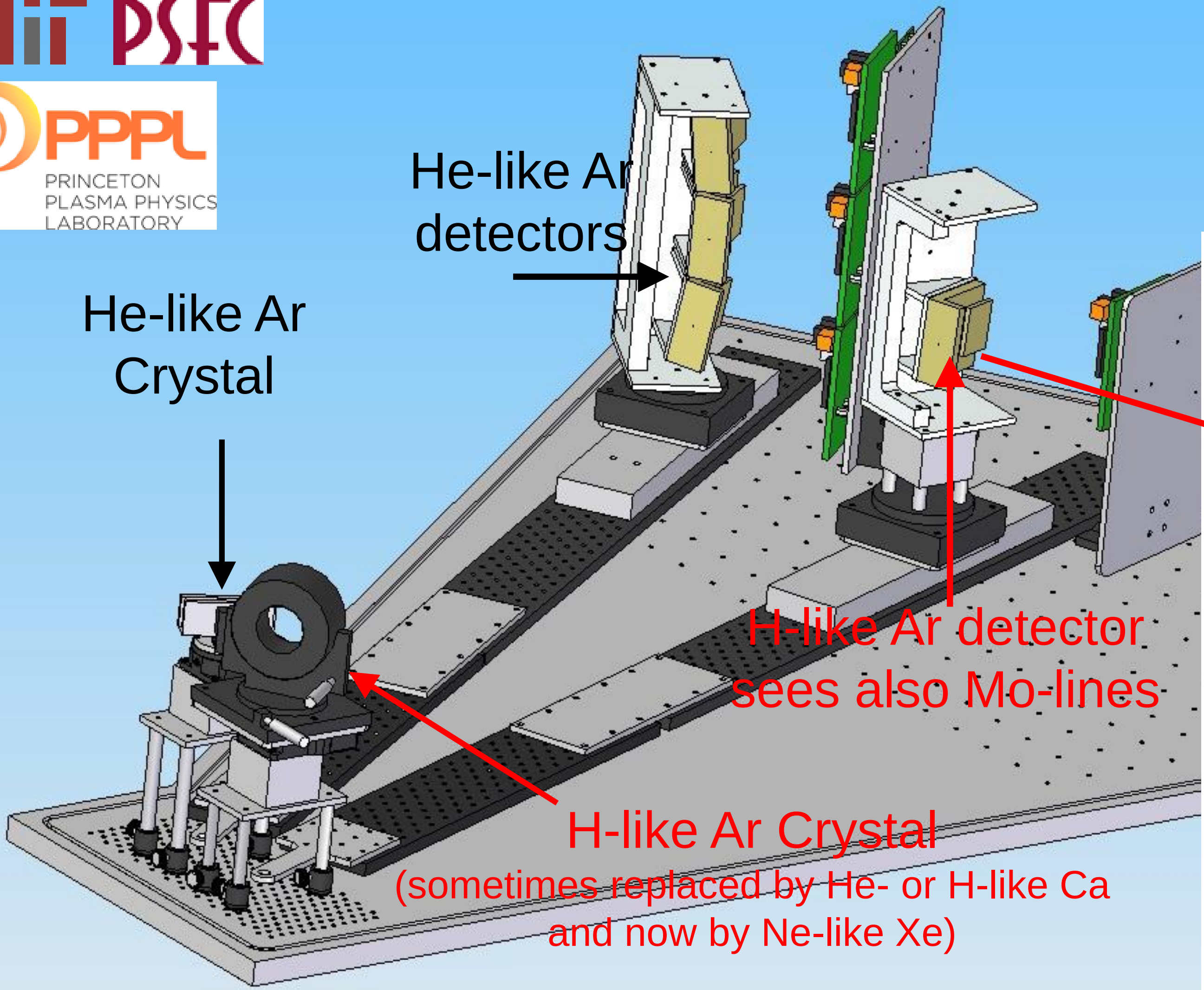
Z_{eff}, T_e (continuum)

SECONDARY:

$n_{e,fast}$

PPPL PRINCETON PLASMA PHYSICS LABORATORY

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



He-like Ar detectors

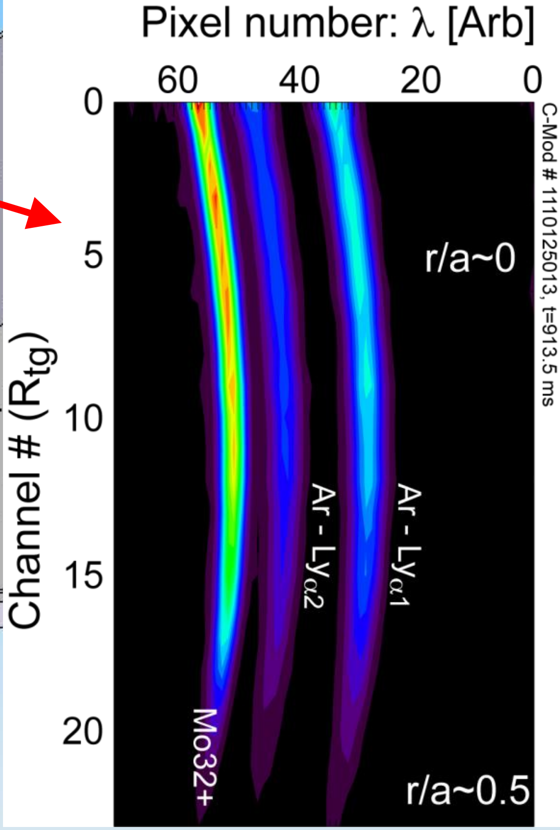
He-like Ar Crystal

H-like Ar detector sees also Mo-lines

H-like Ar Crystal

(sometimes replaced by He- or H-like Ca and now by Ne-like Xe)

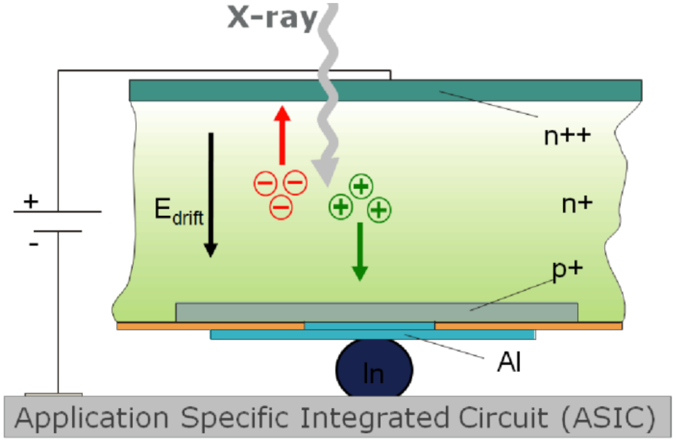
Ne-like Mo and H-like Ar fall in the spectrum



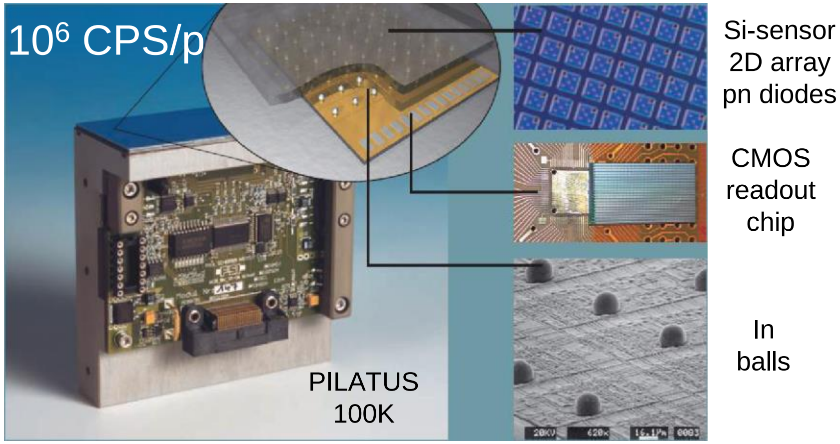
Similar systems have been installed in NSTX, KSTAR, EAST, LHD, W7 and in the future, NSTX-U, WEST & ITER

Pilatus detectors enable breakthrough of 100k pixels (min.) at single/multiple energy ranges

Operates in single photon counting mode



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



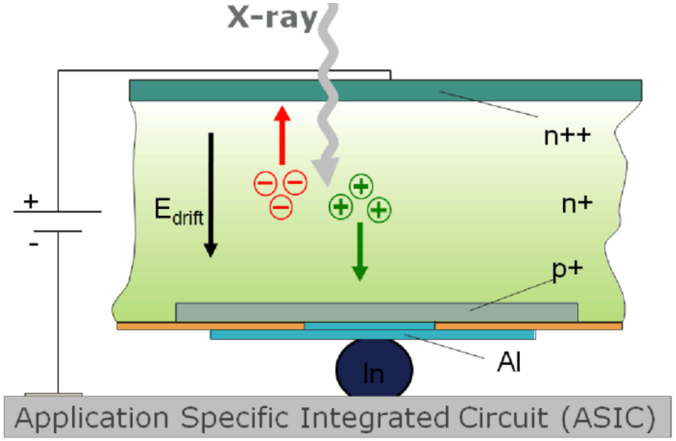
Thanks to important advances in the x-ray detector technology it is now possible to simultaneously record high resolution images of x-ray photons at single OR multiple energy ranges through direct x-ray detection.

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

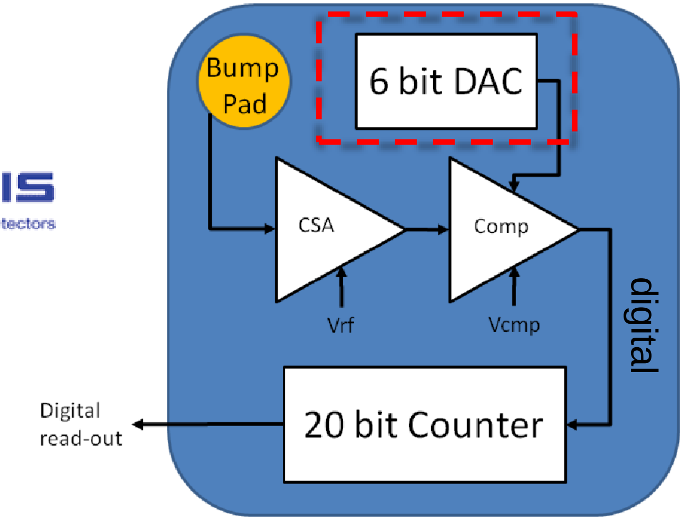
PILATUS3 900K-IPP in-vacuum detector for x-ray plasma spectroscopy

Pilatus detectors enable breakthrough of 100k pixels (min.) at single/multiple energy ranges

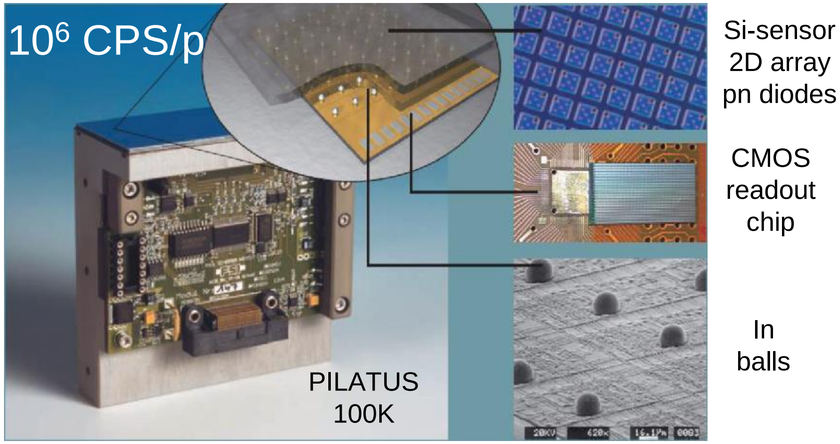
Operates in single photon counting mode



Photon counting circuit in **each pixel**



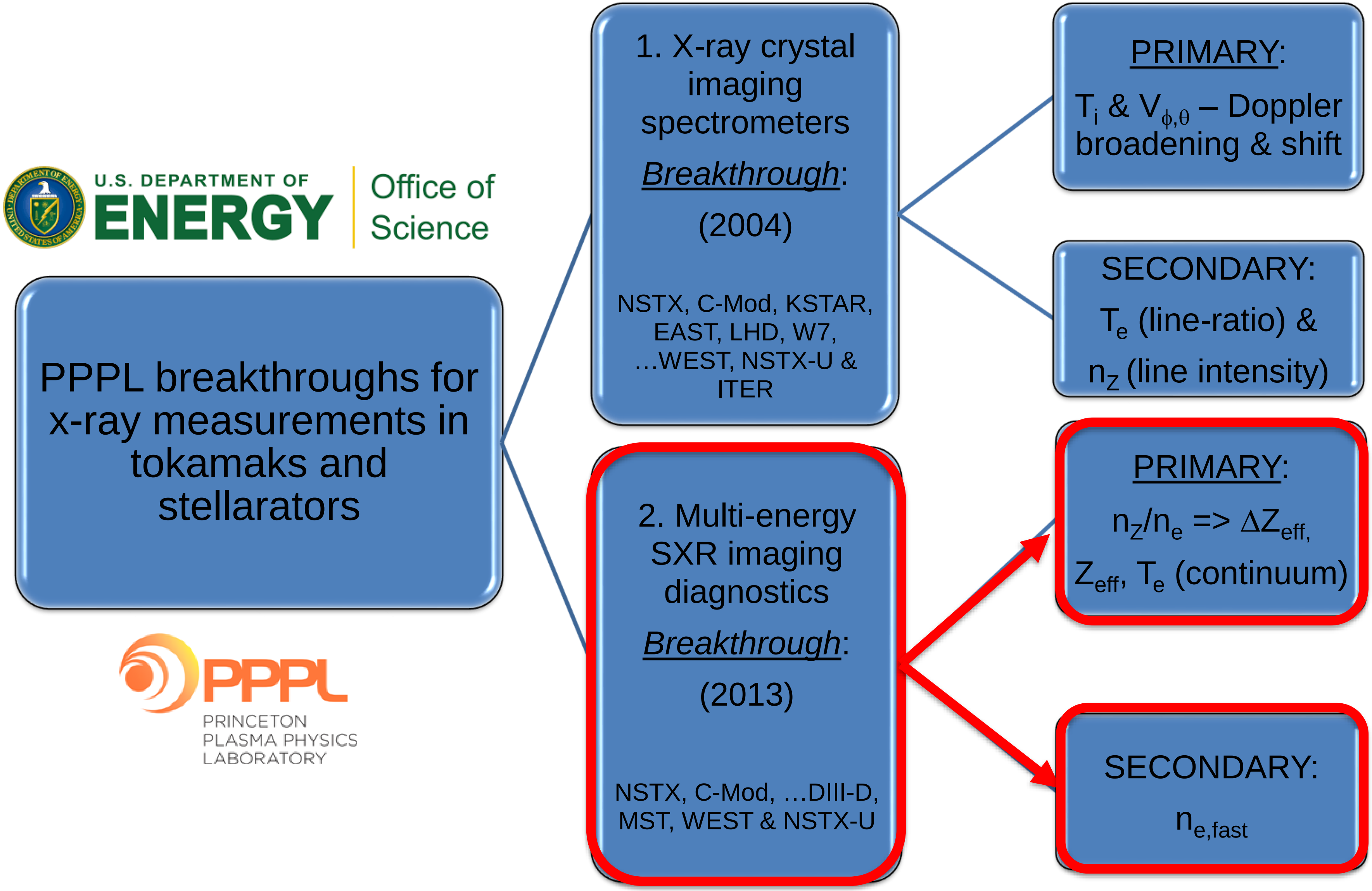
CMOS hybrid pixel technology developed originally for synchrotrons (CERN + PSI + DECTRIS)



- New maximum frame rate of 500 Hz (1ms integration + 1 ms readout).
- New 10^7 CPS/p for PILATUS3
- The comparator voltage of the readout chip (V_{cmp}) controls the *global* threshold energy.
- The threshold energy can be individually *refined/trimmed* using a built-in 6-bits DAC (V_{trim}).

X-ray group at PPPL developed new concepts for MCF plasmas (extrapolate to ITER & beyond)

U.S. DEPARTMENT OF ENERGY
Office of Science



PPPL breakthroughs for x-ray measurements in tokamaks and stellarators

1. X-ray crystal imaging spectrometers

Breakthrough:

(2004)

NSTX, C-Mod, KSTAR, EAST, LHD, W7, …WEST, NSTX-U & ITER

PRIMARY:

T_i & $V_{\phi,\theta}$ – Doppler broadening & shift

SECONDARY:

T_e (line-ratio) &

n_Z (line intensity)

2. Multi-energy SXR imaging diagnostics

Breakthrough:

(2013)

NSTX, C-Mod, …DIII-D, MST, WEST & NSTX-U

PRIMARY:

$n_Z/n_e \Rightarrow \Delta Z_{eff}$,

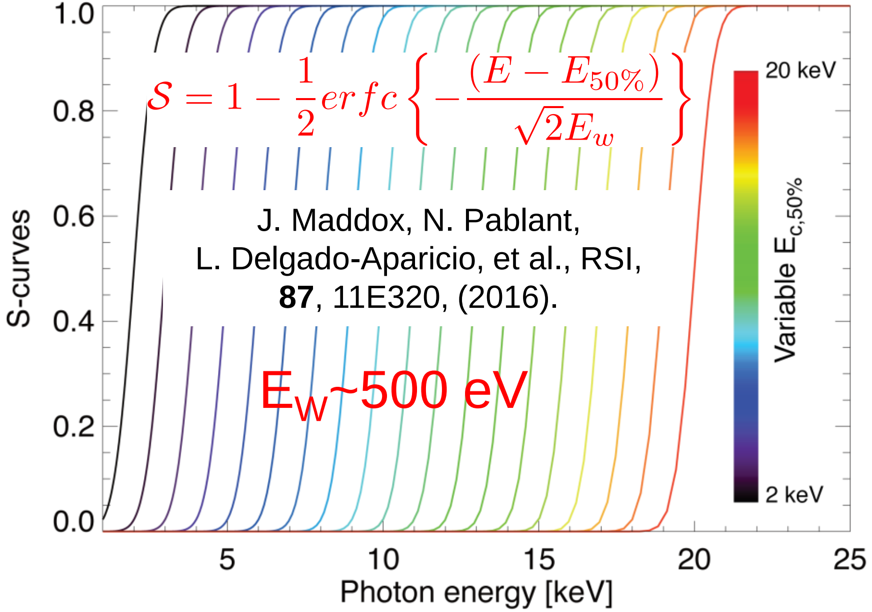
Z_{eff}, T_e (continuum)

SECONDARY:

$n_{e,fast}$

PPPL
PRINCETON
PLASMA PHYSICS
LABORATORY

V_{comp} and V_{trim} allows individual coarse & fine tuning of energy range (per-pixel): E_{width}~500 eV

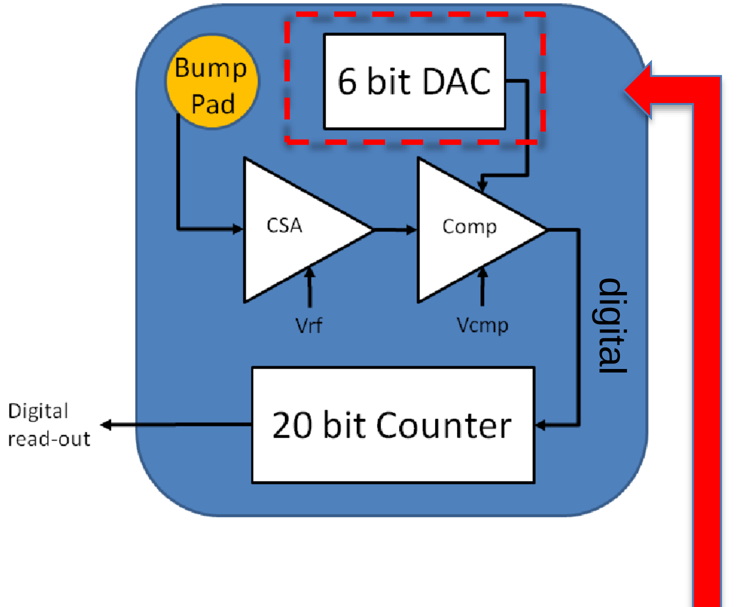


$$S = 1 - \frac{1}{2} erfc\left\{-\frac{(E - E_{50\%})}{\sqrt{2}E_w}\right\}$$

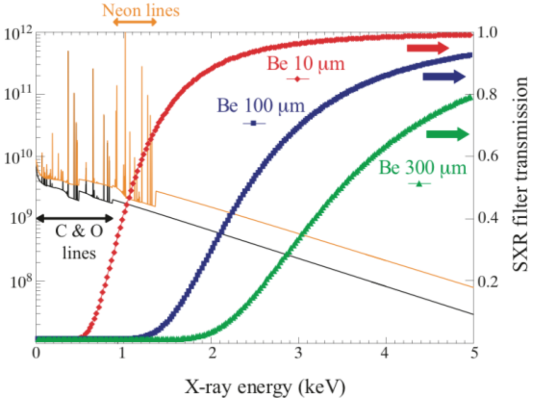
J. Maddox, N. Pablant,
L. Delgado-Aparicio, et al., RSI,
87, 11E320, (2016).

E_W~500 eV

Photon counting circuit in **each pixel**



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

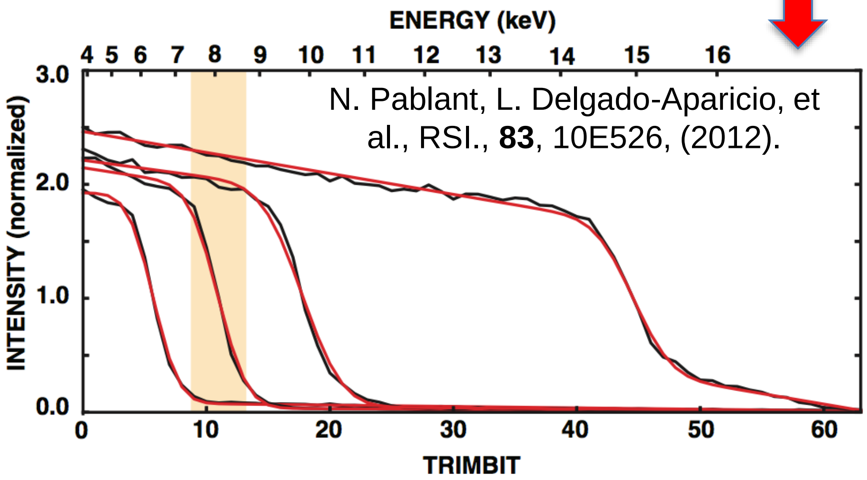


Filters:

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

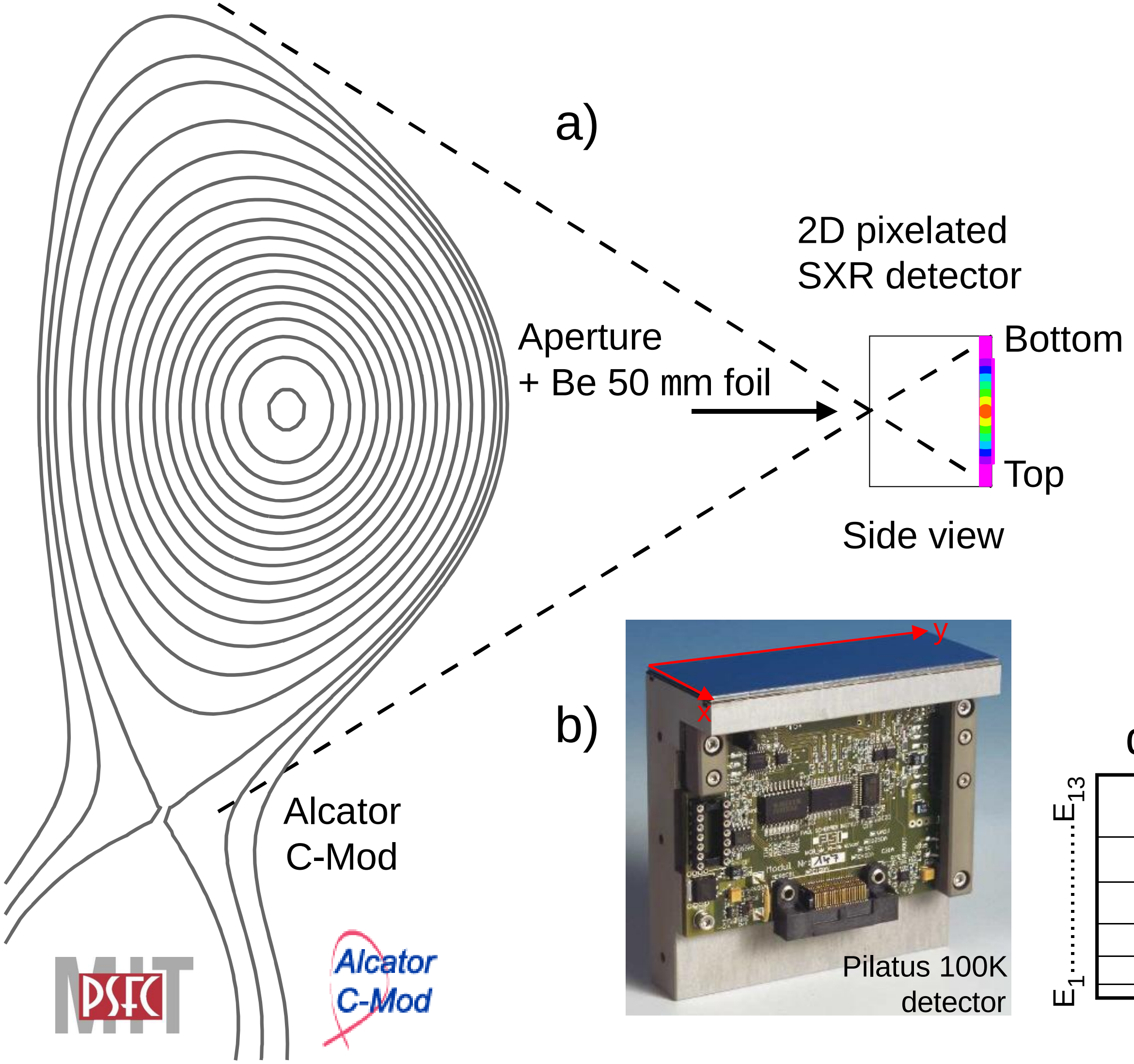
$$\Rightarrow \frac{d\mathcal{T}}{dE}\Big|_{E_0} \sim \frac{1}{E_0}$$

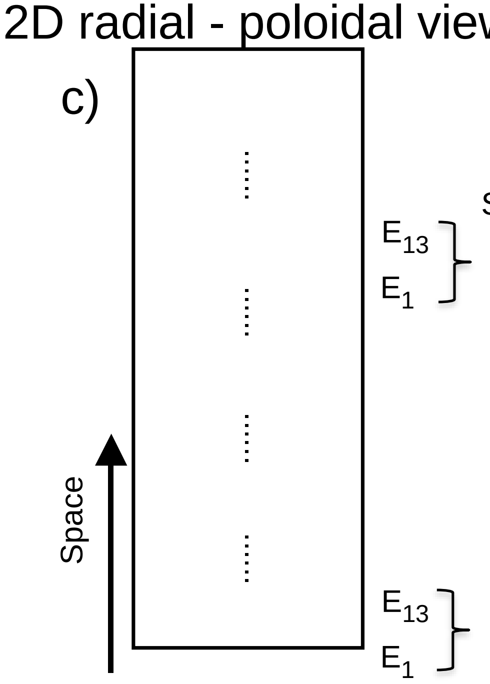
L. Delgado-Aparicio, et. al., RSI,'10, NF'11

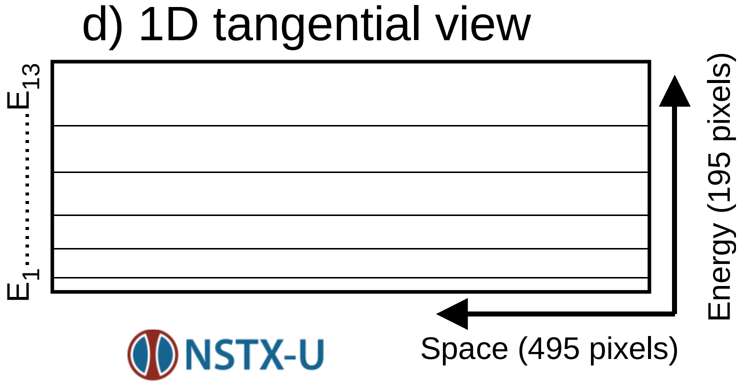


N. Pablant, L. Delgado-Aparicio, et al., RSI., **83**, 10E526, (2012).

New ME-SXR imaging concept combined the best features from PHA & multi-foil methods



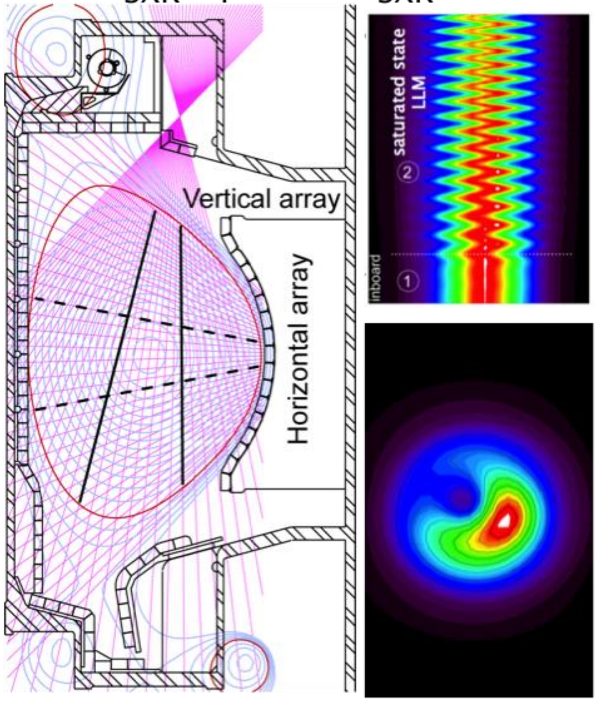




L. Delgado-Aparicio, et al., RSI, **87**, 11E204, (2016).

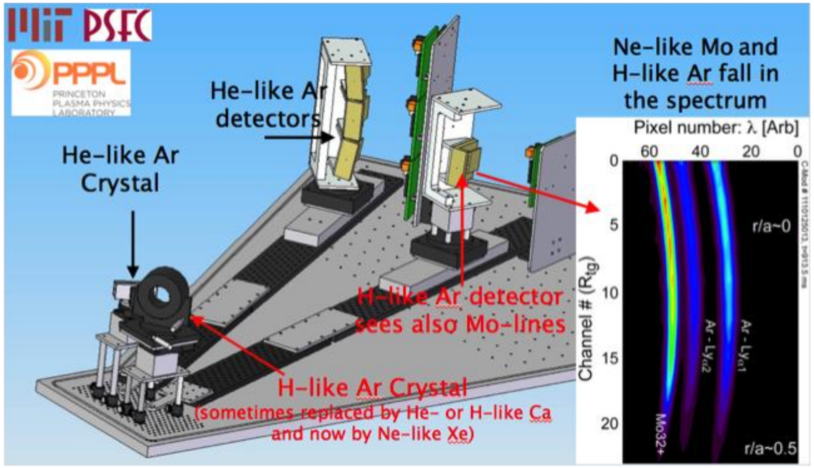
How do we make sure this & other diagnostic suites can also be used in burning plasmas ?

a) X-ray tomography brightness & emissivity: $B_{SXR}(r_T,t) => \varepsilon_{SXR}(R,t)$



- i. Image the plasma
- ii. Plasma position (R_0, Z_0)
- iii. MHD mode ID: (m,n)
- iv. Impurity monitoring: n_Z
- v. If $v\phi,\theta \sim 0 => \varepsilon_{SXR} \sim f(\Psi)$

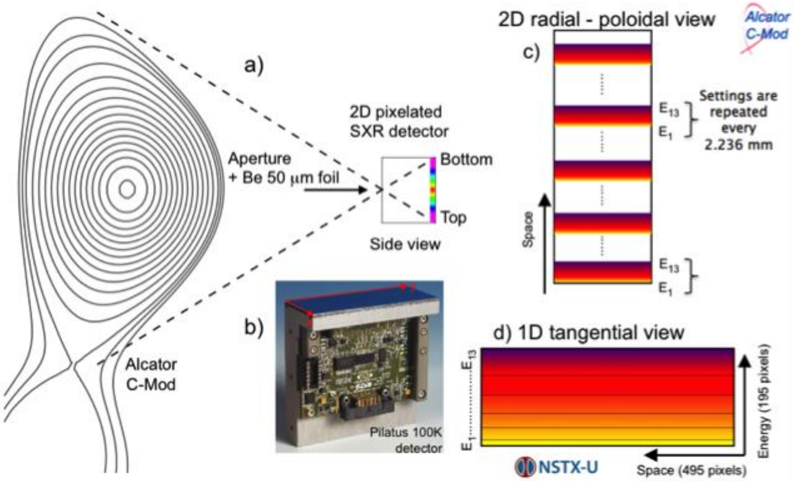
b) High-resolution x-ray spectroscopy: $\varepsilon_{SXR}(R,Z,t,E_X)$



i. Line-intensity: ε_{SXR}

- ii. Z-monitor: n_Z
- iii. T_i
- iv. $v\phi,\theta$

c) Broad-band ME-SXR cameras: $\varepsilon_{SXR}(R,Z,t,\Delta E_x)$



- i. Image plasma
- ii. Position (R_0, Z_0)
- iii. T_e
- iv. Z_{eff}
- v. Z-monitor: n_Z
- vi. δZ_{eff}
- vii. $T_e \sim f(\Psi) => J$, q

Main issues to circumvent are neutron- and gamma- induced noise & LIFETIMES !

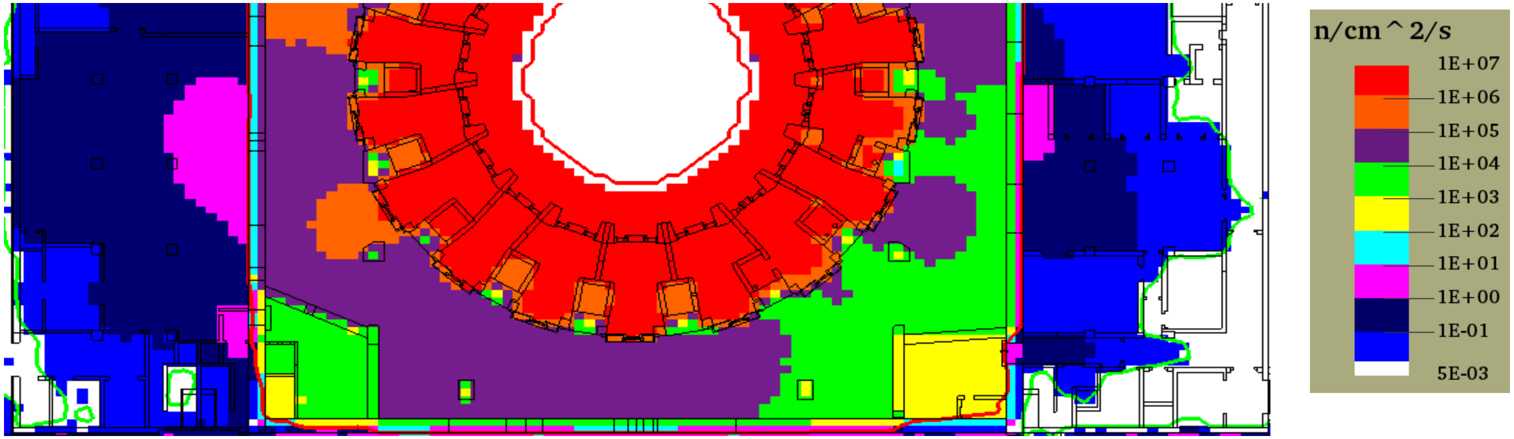
① Conventional Si-detectors are used due to the availability of good quality homogeneous material, and high charge carrier transport properties.

② Unfortunately, conventional Si-detectors can only withstand maximum neutron fluences in the range from 10^{13} up to 10^{14} n_{eq}/cm^2 (max).

③ Lifetimes could be severely shortened by neutron damage since future sensors will have to withstand fluences of 10^{14} up to few 10^{16} n_{eq}/cm^2.

④ Forced to look for new solutions (assessed by RD50) which are compatible with very-high-luminosity experiments (up to 10^{16}-10^{17} n_{eq}/cm^2).

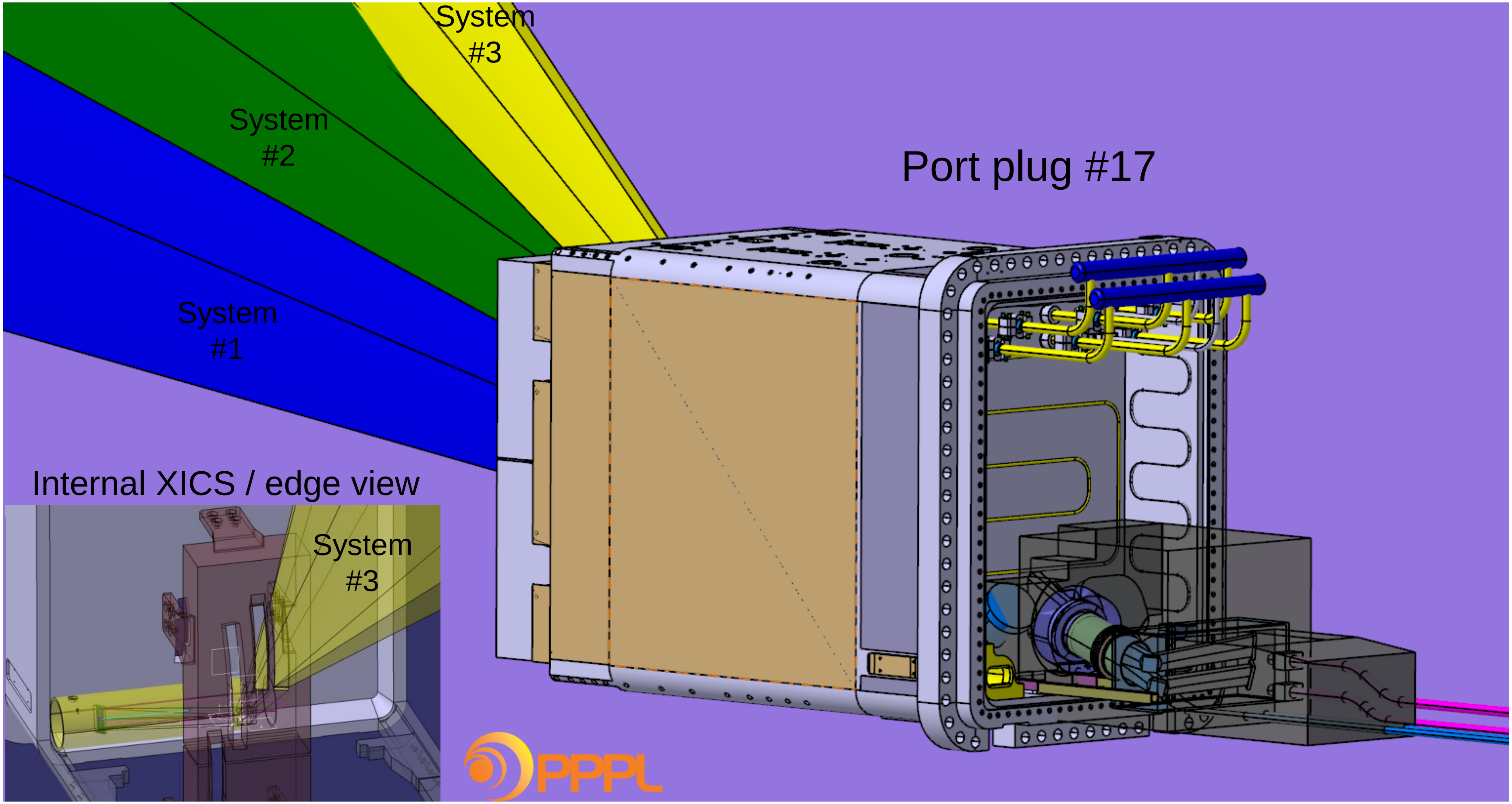
Total Neutron Flux at Equatorial Level



Courtesy of Dr. R. Reichle (ITER)

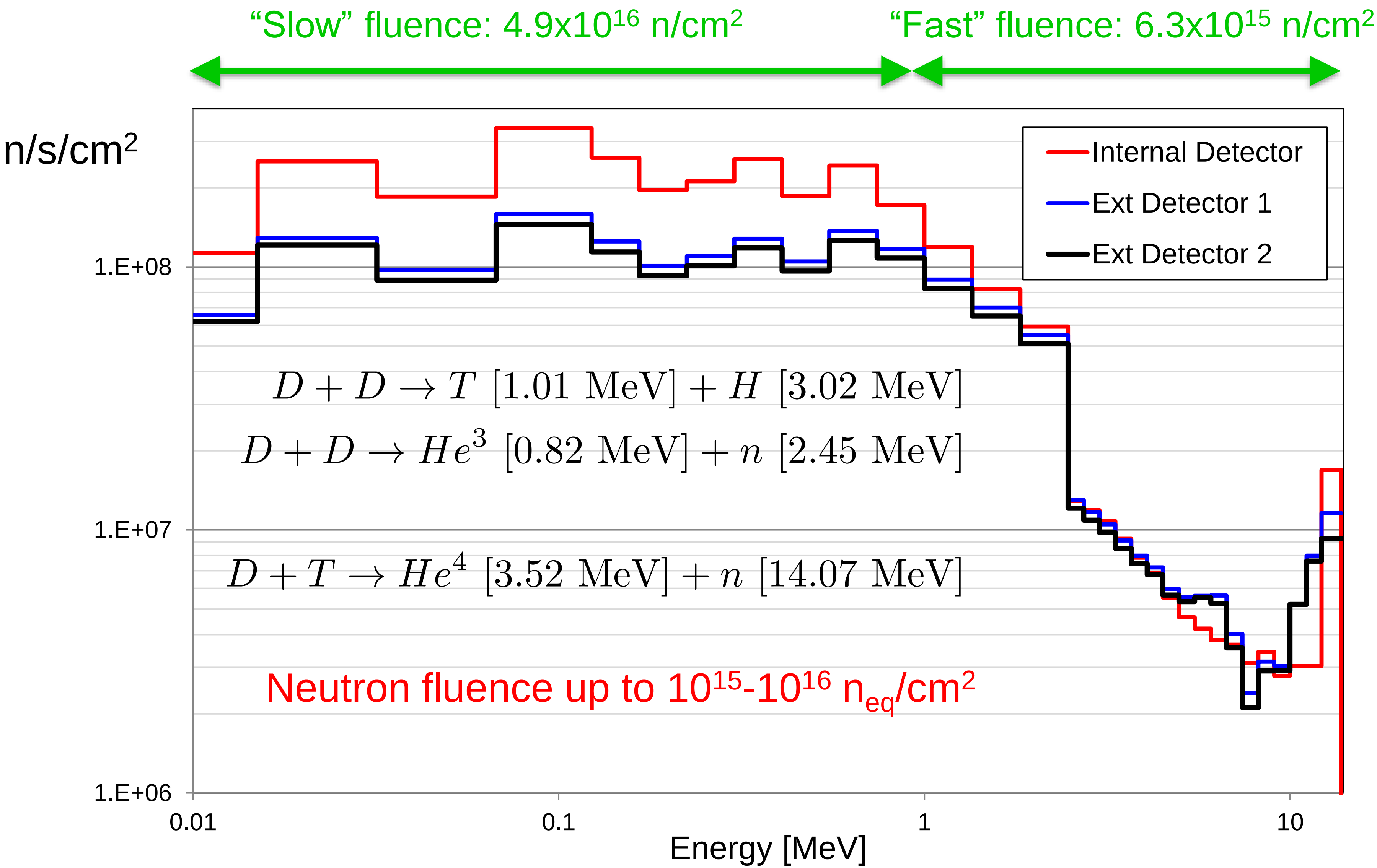
EXAMPLE: Three US core XICS systems will be installed in ITER to measure V_t and T_i profiles

Internal system #3 posses serious challenges
(e.g. effects of neutrons, gammas, B and dB/dt on crystals and detectors)



Detectors for x-ray crystal spectrometer have to survive strong neutrons fluxes @ ITER

(and x10 beyond ITER)



“Slow” fluence: 4.9×10^{16} n/cm^2

“Fast” fluence: 6.3×10^{15} n/cm^2

$$D + D \rightarrow T\ [1.01\ \mathrm{MeV}] + H\ [3.02\ \mathrm{MeV}]$$

$$D + D \rightarrow He^3\ [0.82\ \mathrm{MeV}] + n\ [2.45\ \mathrm{MeV}]$$

$$D + T \rightarrow He^4\ [3.52\ \mathrm{MeV}] + n\ [14.07\ \mathrm{MeV}]$$

Neutron fluence up to 10^{15}-10^{16} n_{eq}/cm^2

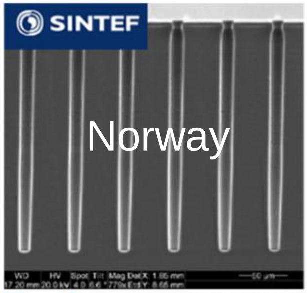
Finding synergies between fusion energy science (FES) and high-energy physics (HEP) communities

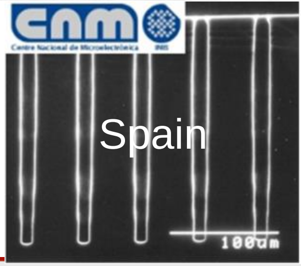
Semiconductor detectors will be exposed to hadron fluences to more than 10^{16} n_{eq}/cm^2 (HL-LHC, 2024-26) and more than $7x10^{17}$ n_{eq}/cm^2 (FCC, >2035)

CERN's RD50 Status Report - May 2016:
G. Casse and M. Moll

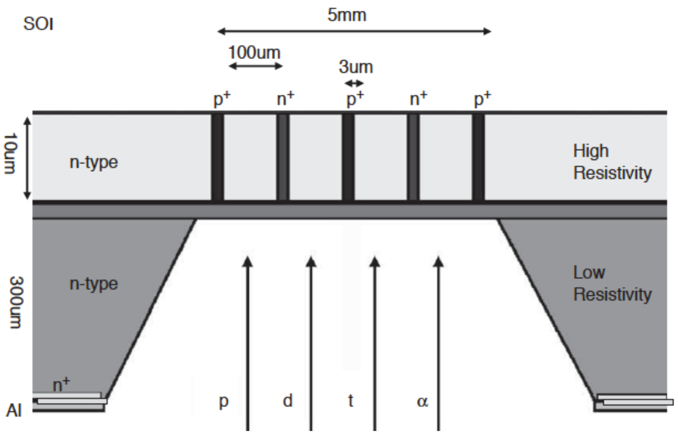
① Test new sensors for fusion applications:

- Aiming at neutron hardness $\gtrsim 10^{16}$ n_{eq}/cm^2
- Compare standard Si detectors with: a) electrode configs. (e.g. 3D), b) enrichment techniques (e.g. H, C, O, N, Ga) or c) other materials (e.g. SiC for high-T)
- Possible fusion applications for ultra-thin 3D silicon detectors





a) Neutral particle analyzers (NPA)
b) Fast-ion loss detectors
c) UV spectroscopy ✓
d) Low-E x-ray spectroscopy



G. Pellegrini, NIMA, **604**, 115, (2009)

BENEFIT: 100% detection efficiency and low sensitivity for the (n,γ) background

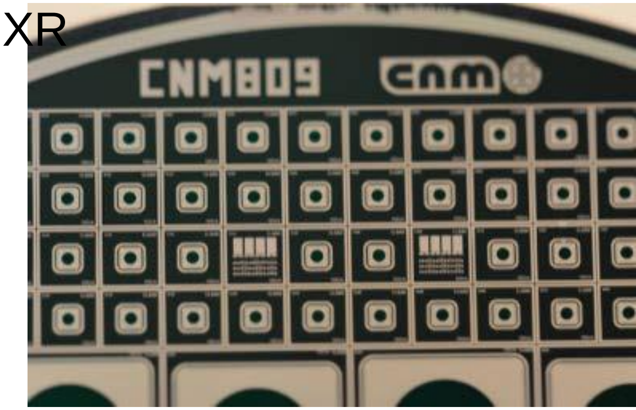
Finding synergies between fusion energy science (FES) and high-energy physics (HEP) communities

Semiconductor detectors will be exposed to hadron fluences to more than 10^{16} n_{eq}/cm^2 (HL-LHC, 2024-26) and more than $7x10^{17}$ n_{eq}/cm^2 (FCC, >2035)

CERN's RD50 Status Report - May 2016:
G. Casse and M. Moll

② Consider testing detectors for SXR spectroscopy (e.g. tomography, x-ray crystal spectrometers and ME-SXR cameras) for ITER-DT and beyond.

- U3DTHIN but with a higher-Z (e.g. GaAs, CdTe)
- Silicon 3D
- Testing new structures:
    a. LGADs
    b. Inverted LGADs (iLGADs)
    c. HVCMOS



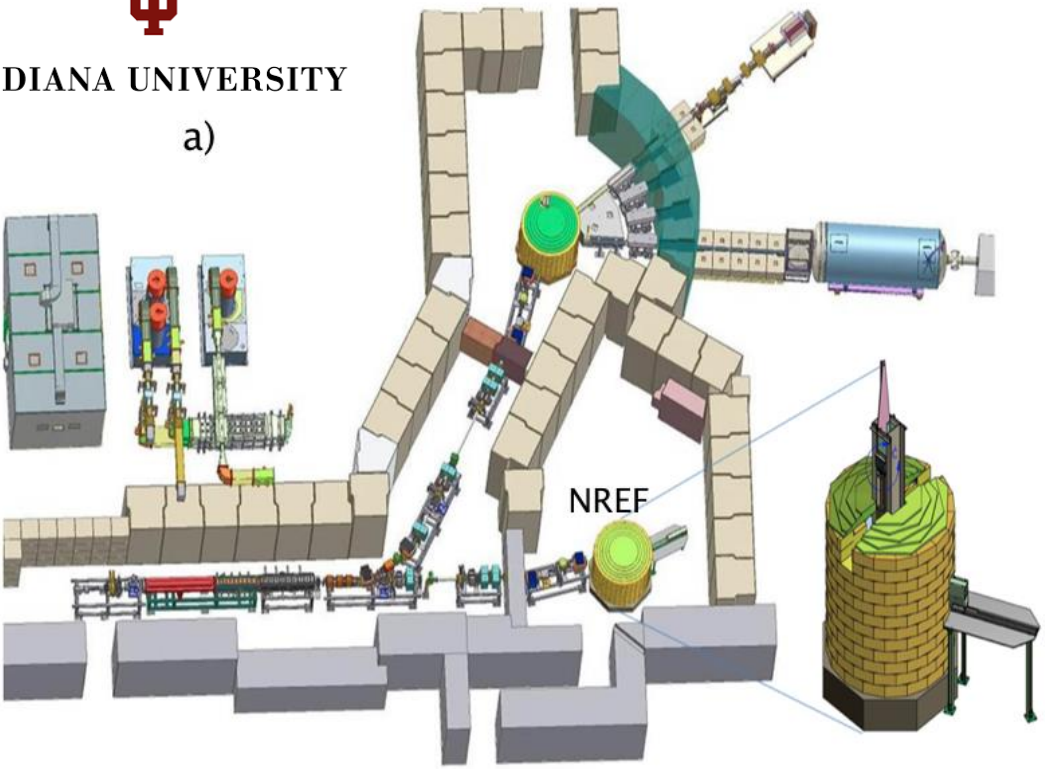
LGAD Ga-doped wafer

③ The hard x-ray (HXR) region of the spectrum (E>20 keV) is also very important (e.g. runaways, W-spectra, RF-driven tails ⇒test/use GaAs, CdTe)

④ Also interested in exploring fluences greater than 10^{16} n_{eq}/cm^{-2} [e.g. expected beyond CERN's HL-LHC (CERN's Future Circular Colider?)]

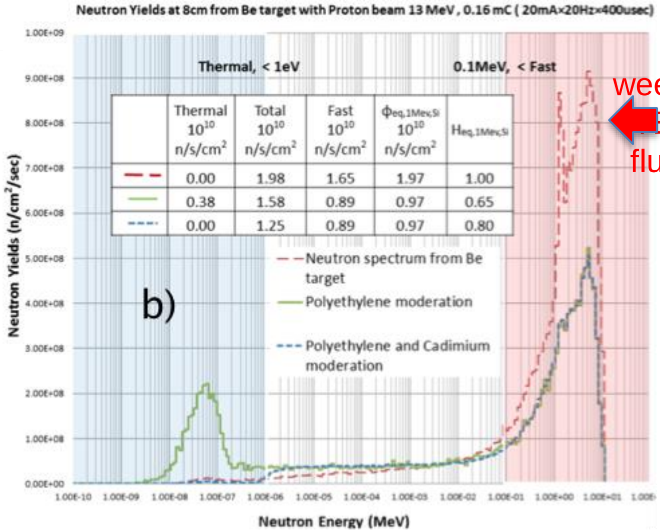
Testing sensors at ITER and DEMO conditions can be done using low-energy neutron sources

INDIANA UNIVERSITY



LENS
The Low Energy Neutron Source

NREF
(Neutron Radiation Effects Facility)



	Thermal 10^{10} n/s/cm²	Total 10^{10} n/s/cm²	Fast 10^{10} n/s/cm²	$\phi_{eq,1MeV,Si}$ 10^{10} n/s/cm²	$H_{eq,1MeV,Si}$
– –	0.00	1.98	1.65	1.97	1.00
—	0.38	1.58	0.89	0.97	0.65
- - -	0.00	1.25	0.89	0.97	0.80

1-2 weeks for ER-DT fluences

The neutron flux at the device under test (DUT) is approximately 2x10^{10} neutrons/cm^2/sec in the range of **2-8 MeV**, produced by a 13 MeV proton beam, and with low gamma contamination

Several fusion experiments (e.g. D3D-USA, WEST-France and JT60SA-Japan) will operate before ITER

E.G.: schedule for JT60SA (Naka, Japan)

← 2.5 MeV DD neutrons →

Courtesy of
Dr. R. Reichle (ITER)

First Plasma **(FP)** **Dec. 2025**

EO Finished and Start of Assembly II **Jun. 2026**

End of Assembly II **Jun. 2028**

Start of Pre-Fusion Power Operation-I **(SP)** **Dec. 2028**

End of Pre-Fusion Power Operation-I and Start of Assembly III **Jun. 2030**

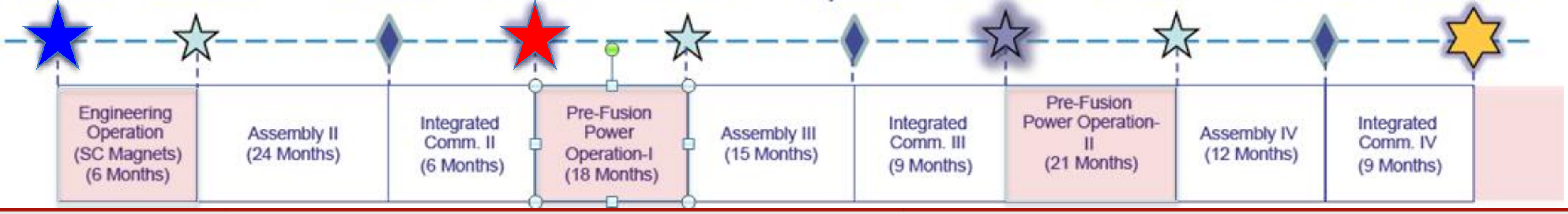
End of Assembly III **Sep. 2031**

Pre-Fusion Power Operation-II **(TP)** **Jun. 2032**

End of Pre-Fusion Power Operation-II and Start of Pre-Nuclear Shutdown for Assembly IV **Mar. 2034**

End of Pre-Nuclear Shutdown for Assembly IV **Mar. 2035**

Fusion Power Operation **(DT)** **Dec. 2035**



Summary

1. Fusion community interested in maintaining diagnostic techniques using semiconductor detectors (e.g. NPA, fast-ion losses, x/γ/n-spectroscopy)

2. SXR/HXR – in particular - provides a unique opportunity of measuring a variety of important plasma properties ($T_{e,i}$, n_Z, ΔZ_{eff}, Z_{eff} and $n_{e,fast}$).

3. ITER-DT imposes challenges to nearly all diagnostics with neutrons fluences of the order of 10^{14} up to few 10^{16} n_{eq}/cm^2.

1. Rad-hard detectors & electronics for fusion diagnostics are needed!!!

2. Fusion community NEEDS: Diodes, linear diode arrays & 2D-sensors with pixels < 100 μm

3. Limitation of Si above 20 keV for study of non-Maxwellian tails (e.g. runaways, RF-LHCD tails) and W-emission. Use higher-Z: GaAs, CdTe.

4. Systems with two-energy-thresholds will eliminate γ-induced noise.

5. Need to find synergies between fusion energy science (FES) and high-energy physics (HEP) communities

6. Test new detectors in 1-10 MeV neutron sources and fusion experiments

Acknowledgments

K. W. Hill[1], M. Bitter[1], B. Stratton[1], M. E. Austin[2,3,4], J. E. Rice[5], D. Stutman[6], R. Granetz[5], D. Den Hartog[7], E. Hollman[8], W. Heidbrink[9], D. Liu[9], R. Boivin[3,10], D. Brower[3,11], R. Reichle[3,12], R. Barnsley[3,12], M. Ullan[13], G. Pellegrini[13], C. Fleta[13], D. Baxter[14], T. C. Rinckel[14], D. Johnson[1], R. Feder[1], N. Pablant[1], J. Klabacha[1], J. Irby[5], K. Tritz[6], L. Reusch[7], M. DeBack[3,12], A. Sirinelli[3,12], M. Ono[1], M. Zarnstorf[1] and P. Efthimion[1]

1 Princeton Plasma Physics Laboratory, Princeton, NJ, 08543
2 US Burning Plasma Organization (BPO), Topical Group on Diagnostics
3 International Tokamak Physics Activity (ITPA) Topical Group on Diagnostics
4 University of Texas – Austin, Austin, TX, 78712
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7 University of Wisconsin-Madison, Madison, WI, 53706
8 University of California, San Diego, CA, 92093
9 University of California, Irvine, CA, 92697
10 General Atomics, San Diego, CA, 92121
11 University of California, Los Angeles, CA, 90095
12 ITER, St Paul Lez Durance Cedex, France
13 National Center of Microelectronics (CNM-IMB-CSIC), Barcelona, Spain
14 Center of Exploration of Energy and Matter, Indiana University, Bloomington, IN 47408

EXTRAS

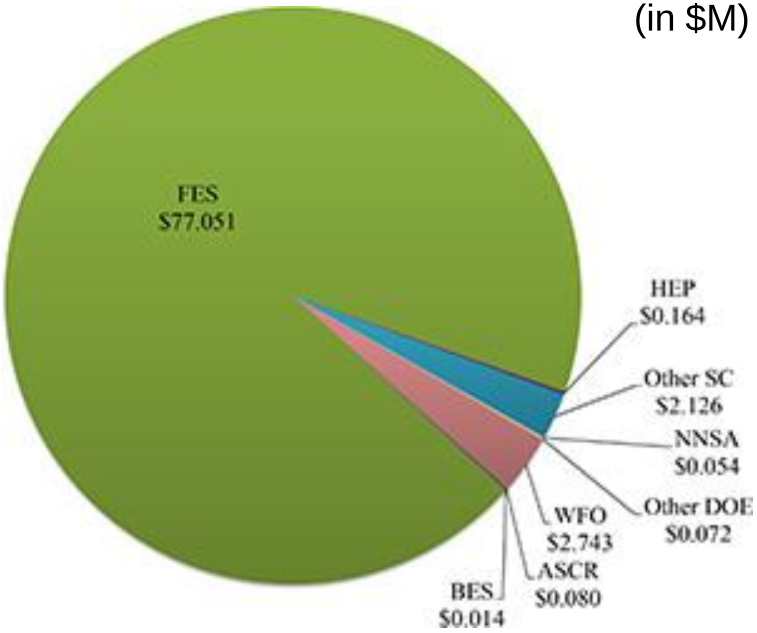
Lab at-a-Glance: Princeton University Plasma Physics Laboratory (PPPL), Princeton, NJ

Quick Facts
- Location: Princeton, New Jersey
- 88.5 acres and 34 buildings
- 414 Full Time Employees
- 40 Students
- 300 Visiting Scientists

Core Capabilities
- Large Scale User Facilities
- Advanced Instrumentation
- Mechanical Design and Engineering
- Plasma and Fusion Energy Science
- Power Systems
- Electrical Engineering
- Systems Engineering and Integration

Office of Science User Facilities
- National Spherical Torus Experiment-Upgrade (NSTX-U)

Recent Annual Funding by Source (in $M)



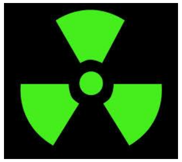
DHS = Department of Homeland Security
EERE = DOE Office of Energy Efficiency and Renewable Energy
EM = DOE Office of Environmental Management
NE = DOE Office of Nuclear Energy
NNSA = National Nuclear Security Administration
WFO = Work for Others

<u>DOE-Office of Science (SC) Programs</u>:
ASCR = Advanced Scientific Research Computing
BES = Basic Energy Sciences
BER = Biological and Environmental Research
FES = Fusion Energy Sciences
HEP = High Energy Physics
NP = Nuclear Physics

Estimated world energy resources calls for a long term “GREENER” solution

DANGEOROUS

Fuel	Proved recoverable reserves (2003)	Years of use at the current rate of consumption
Coal	0.9×10^{12} tons	210
Crude Oil	1.2×10^{12} barrels	30-40
Natural gas	170×10^{12} m^3	60-70
Uranium (Fission reactors)	2.0×10^{6} tons	40-50
Uranium-238 & Thorium-232 (Breeder reactors)	2.0×10^{9} tons	~ 3000
Deuterium and Lithium (DT fusion reactors)	**Energy content (TWyr)**	**Years of supply at current levels**
Deuterium	5×10^{11}	1.5×10^{11}
Lithium (known reserves)	9×10^{3}	3×10^{3}
Lithium (in sea water)	1.7×10^{8}	6×10^{7}



“Green” solution

L. Delgado-Aparicio, Ph. D. thesis.

Renewables have limited potential due to low energy density and fluctuations in time

EXAMPLE: Generating 1000 MW for one year

Solar panels in Europe

Mean solar illumination in Europe is 120 W/m^2

Using a solar cell with an efficiency of 20% (at best).

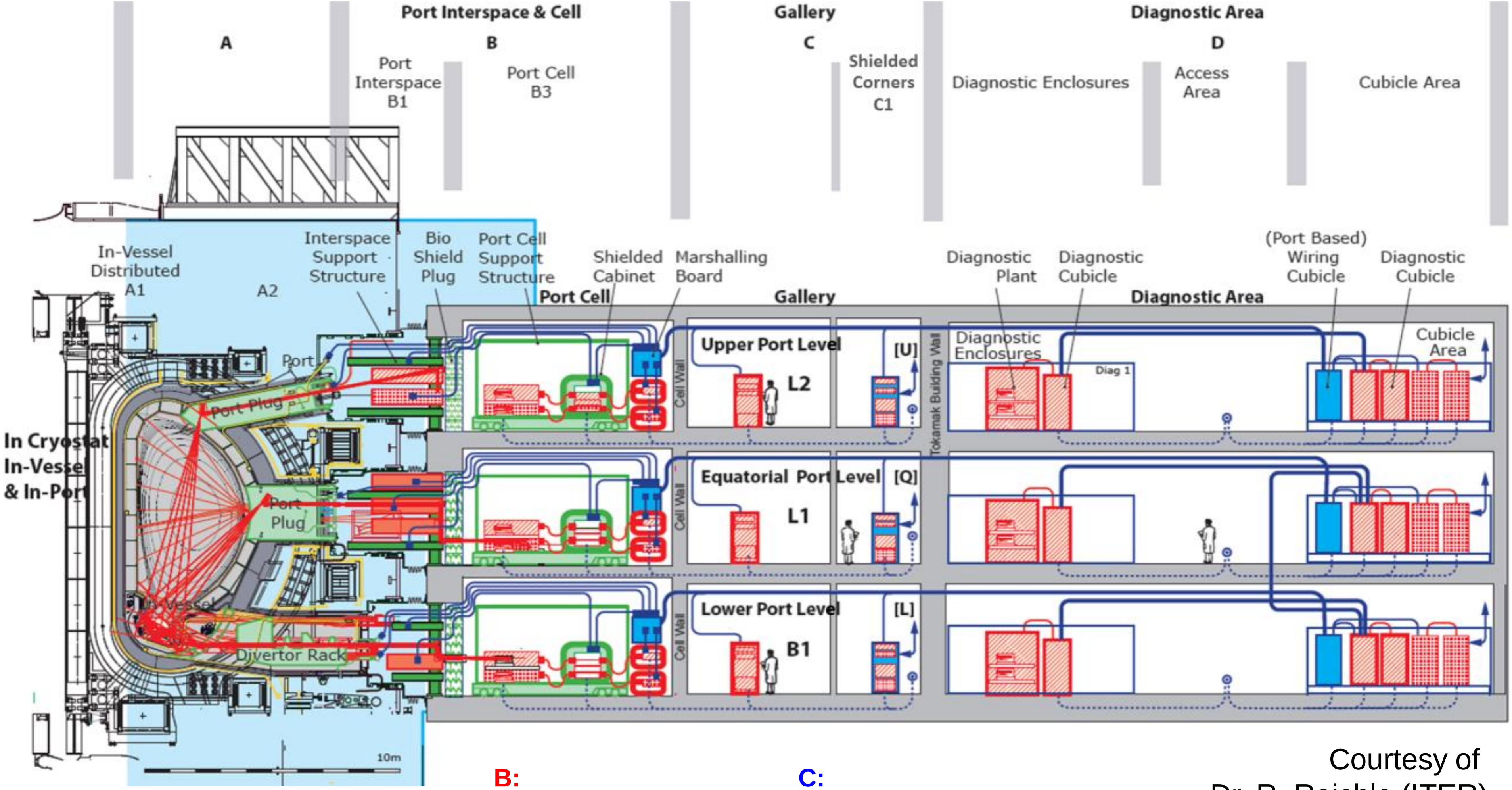
Area=100 km^2

Amount of renewable resources for 1000 MW:

- Wind power: 3300 win turbines (with 55 m blades)
- Bio-gas fuel: 60 million pigs = 80 million chickens.
- Bio-alcohol fuel: 6200 km^2 of sugar beat = 16000 km^2 of corn
- 30000 km^2 of wood


AP / The Nation

ITER ports, cells, galleries and diagnostics areas (shielding modules vs ALARA)



Courtesy of
Dr. R. Reichle (ITER)

A: Radiation hard sensors and cables

B: Preamps, CCDs and IR cameras. Medium-rad hard cables, fibers. Transmission lines

C: Electronics cubicles Low rad hard fibres

D: Electronics cubicles, spectrometers

… and more challenges facing FNSF/DEMO (=>use more x-rays, γ's, microwave, neutrons)

① The consequences due to an insufficient set of diagnostics or particular diagnostic failures could be catastrophic (e.g. disruptions).

② The objectives of measurements in DEMO/FNSF:

a) Quite different from the objectives of the physics measurements on present fusion devices

b) Measurements for plasma control towards optimizing reactor performance will become more important than measurements for physics validation.

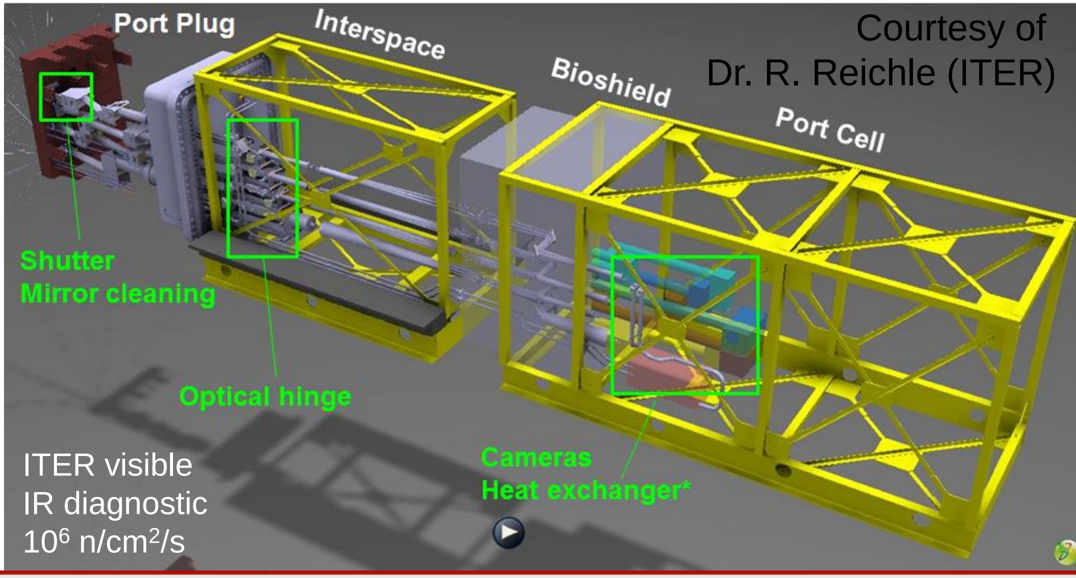
c) Control operations done by a small number of diagnostics !!!

DO NOT RELY on:

- inductive magnetic sensors
- visible optical detection systems
- in-vacuum mirrors/labyrinths.

RELY MORE on:

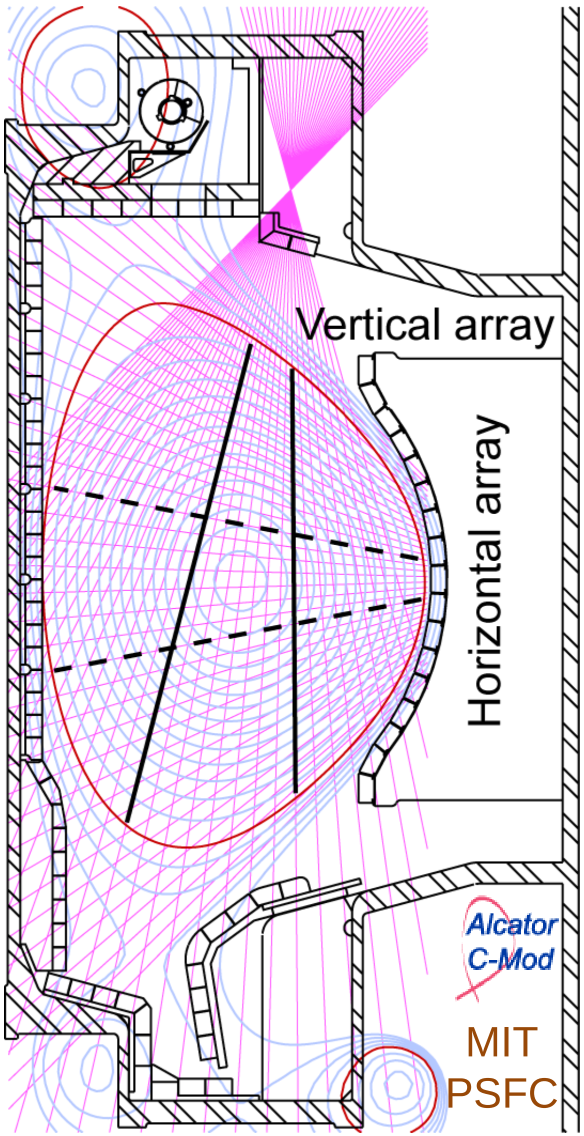
- SXR-, HXR-, γ-spectroscopy
- Neutrons spectroscopy
- Microwave diagnostics



Courtesy of Dr. R. Reichle (ITER)

ITER visible IR diagnostic 10^6 n/cm^2/s

…however, it is very difficult to extract local information from SXR emission



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 $f(E_e/k_BT_e)$

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: $S(E_{ph})$

Novel multi-energy pixel configuration allows users to extract information from emission

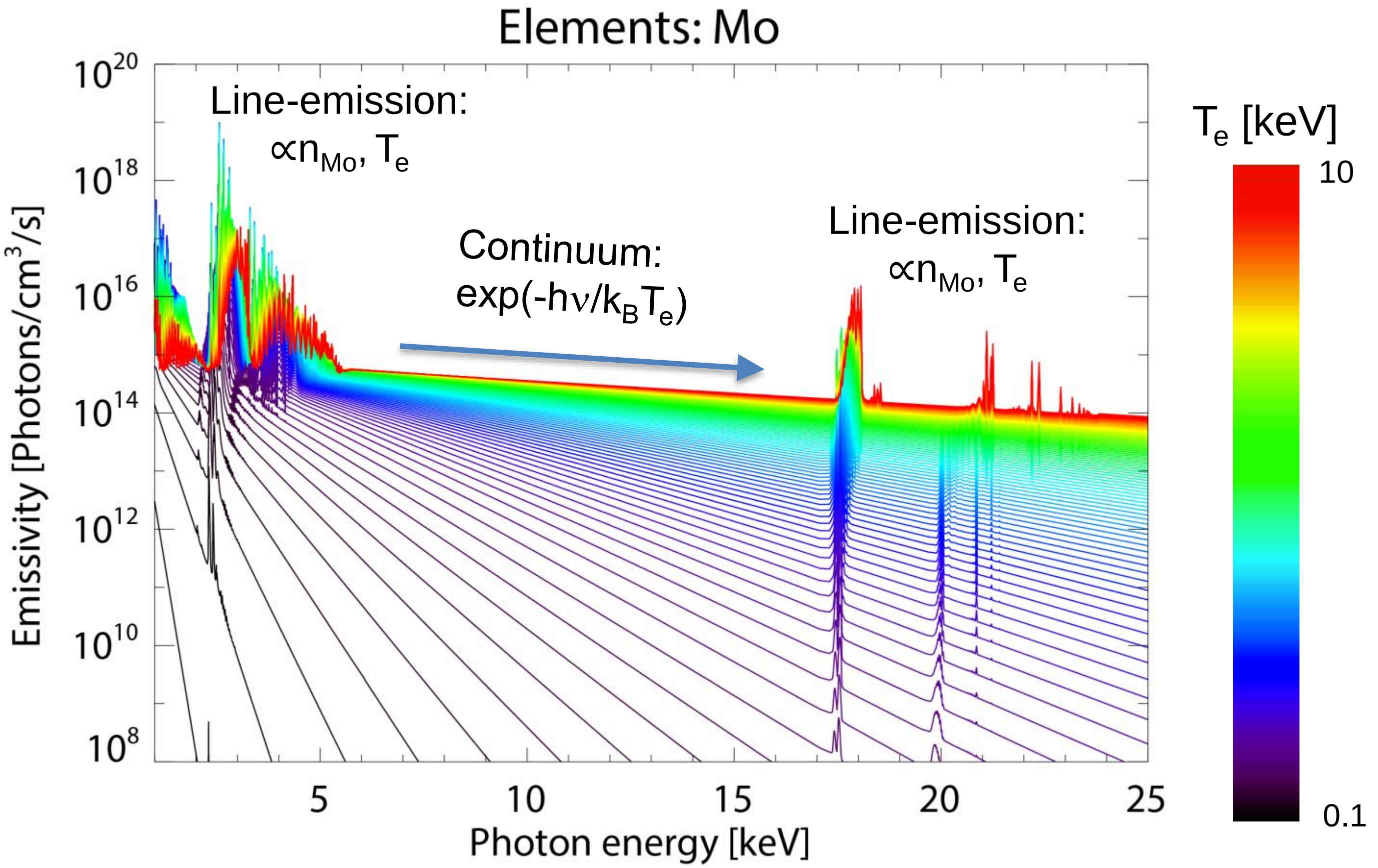
EXAMPLE: MOLYBDENUM

Mo-emission (Ne-, He- & H-like) between 2-5 and 17-22 keV ranges can be radially resolved

GOALS:

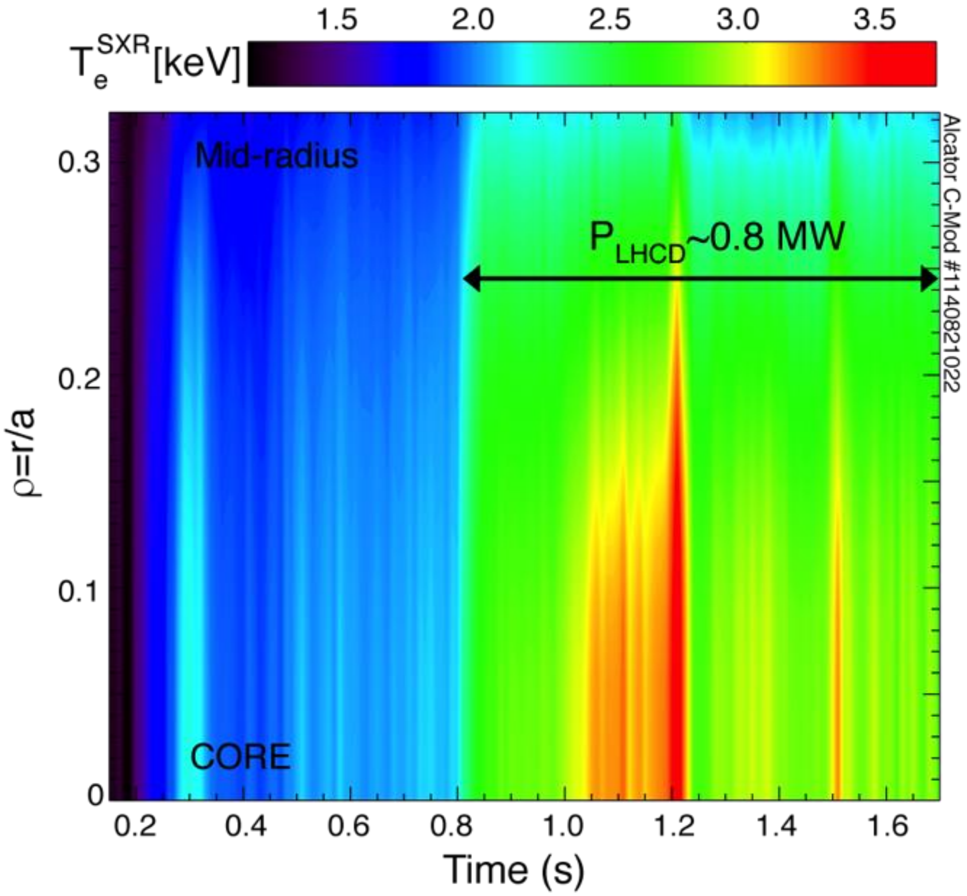
① Obtain n_Z & ΔZ_{eff} by sample or ***bracket*** line-radiation

② Obtain T_e, Z_{eff}, & $n_{e,fast}$ by ***sample*** the continuum-radiation

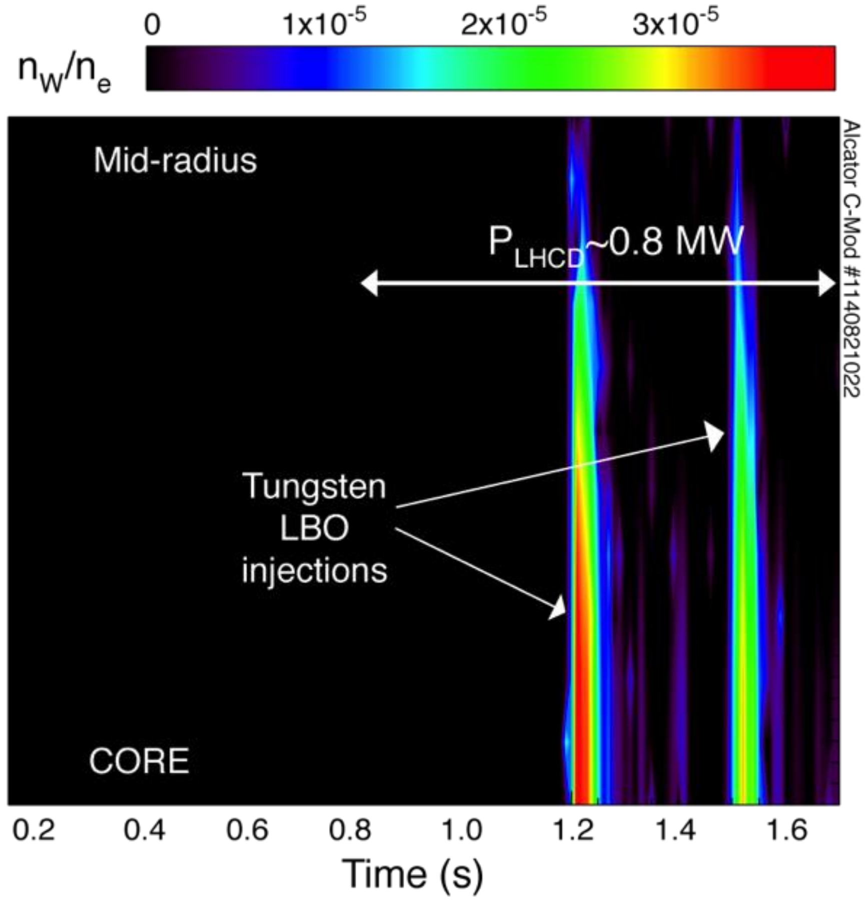


Multi-energy SXR diagnostic can provide, also, simultaneous T_e and n_Z profile measurements

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



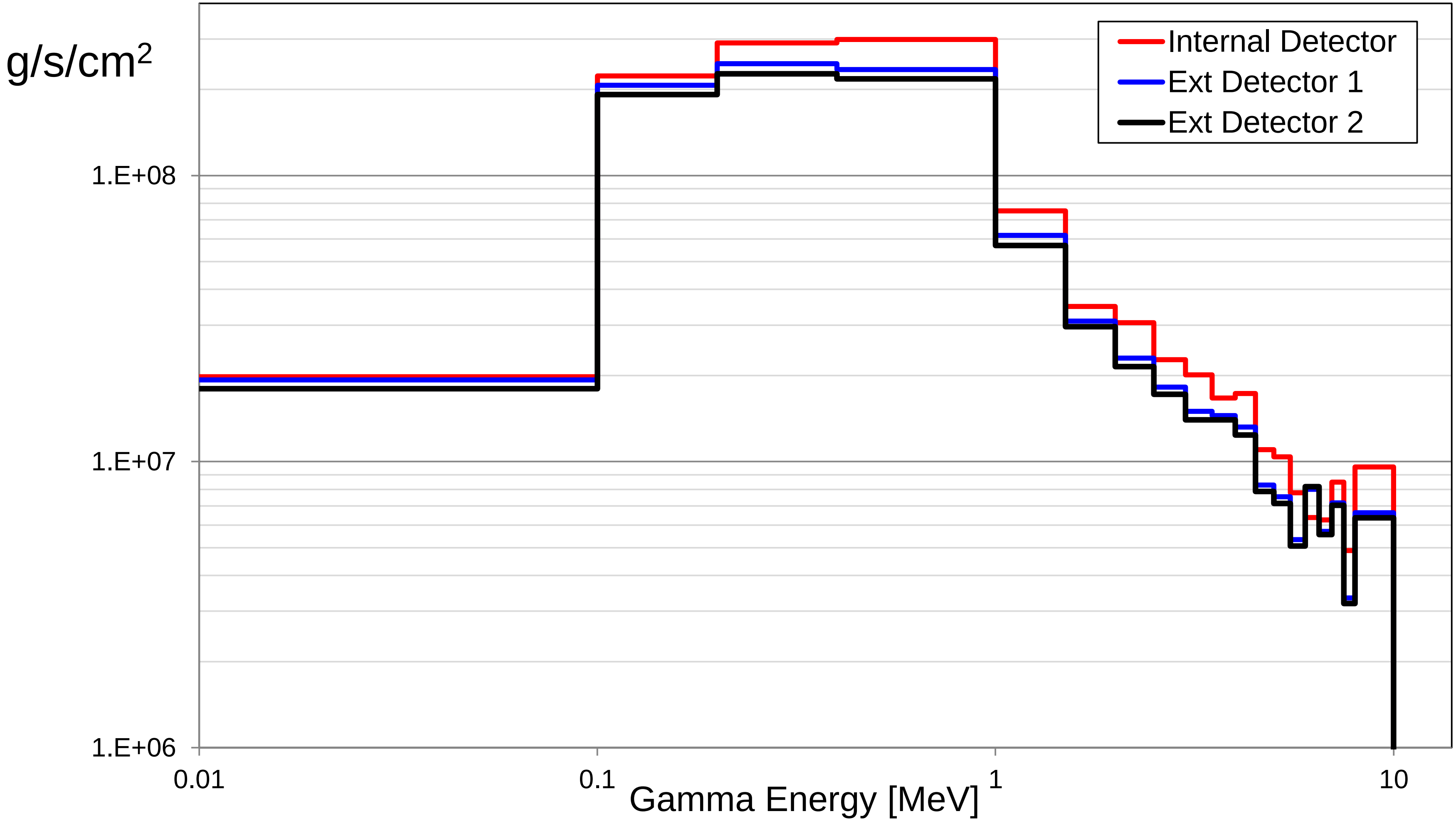
Tungsten density fraction



L. Delgado-Aparicio, et al., RSI, **87**, 11E204, (2016).

Detectors for x-ray crystal spectrometer must have discriminator between x's and γ's

Sea of gammas are produced from the interaction between neutrons, plasma facing components, vacuum vessel, and supporting structure



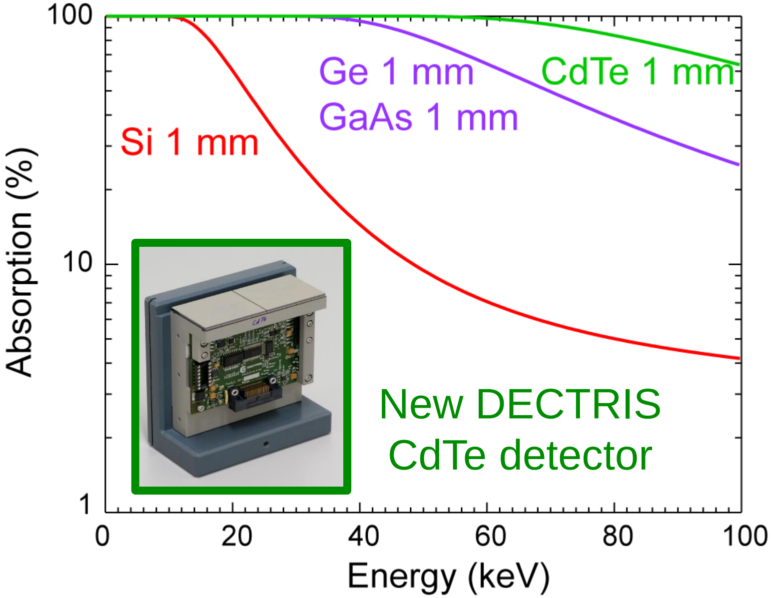
Multi-energy HXR measurements can be done also on the high-energy tails **(ITER & beyond)**

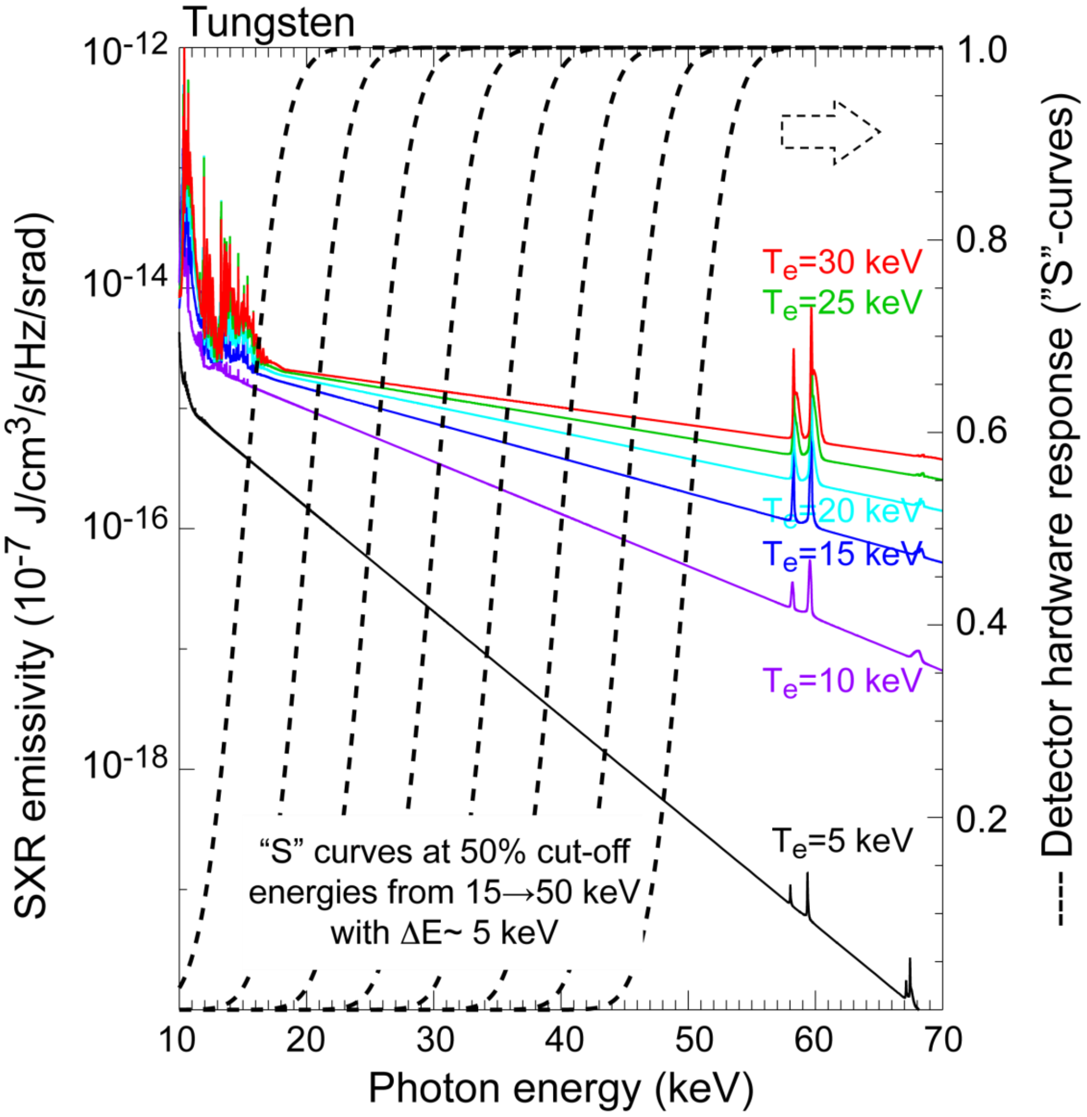
① Using W continuum + line-emission: PPPL-reports 4477 (L. Delgado-Aparicio, *et al.*)

② Runaways + RF-driven tails

③ New detectors with 100k pixels developed using 1mm CdTe

① Test in tokamaks with W-PFCs (WEST, ASDEX, EAST, JET).

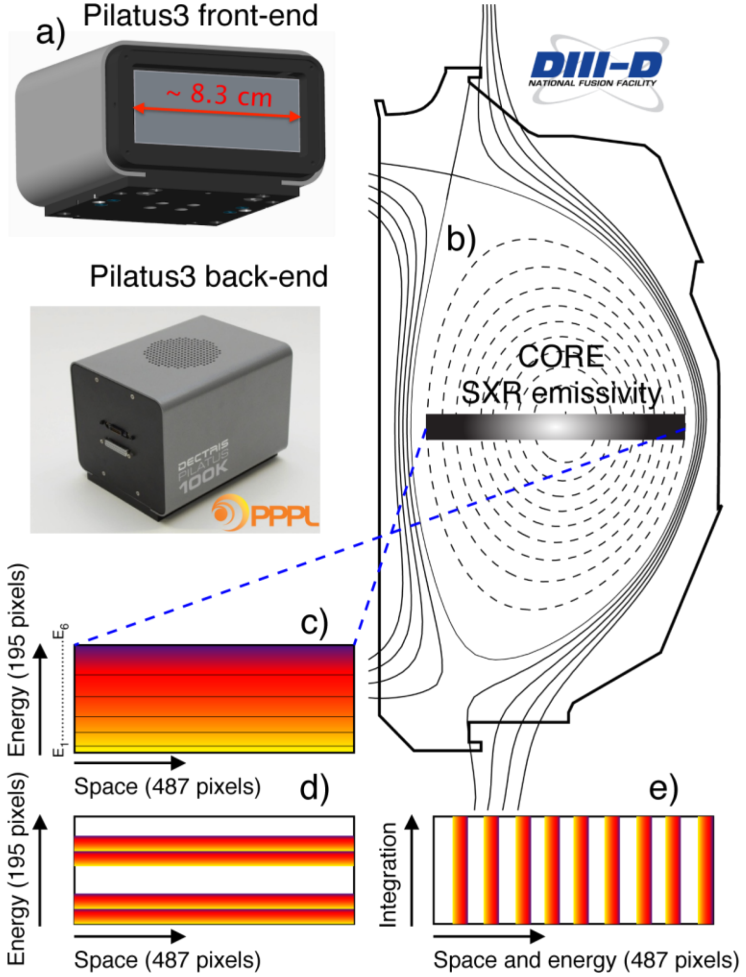




New multi-energy SXR diagnostic will be exported to several machines around the world

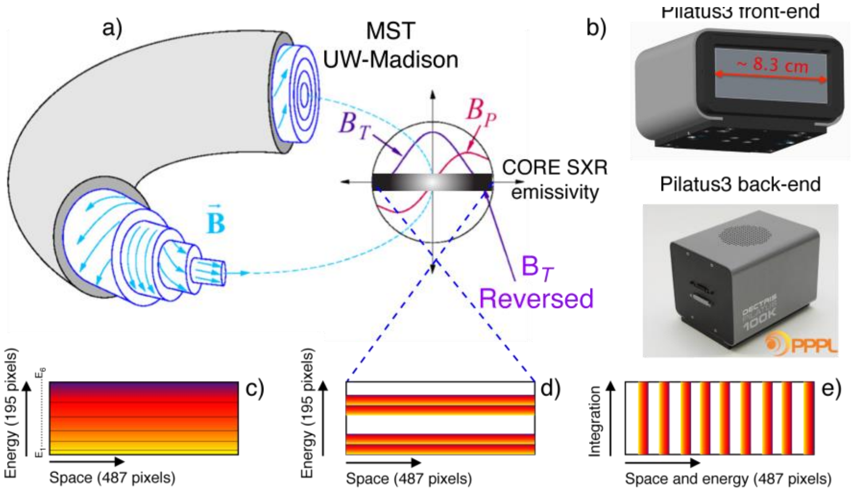
DIII-D (2017-2020)

L. Delgado-Aparicio, et al., PPPL-report, 5364, (2017).



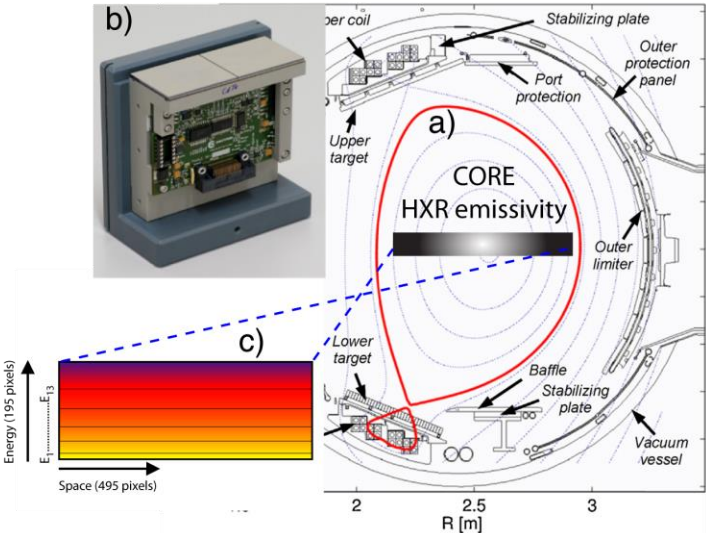
MST (2017-2018)

L. Delgado-Aparicio, et al., PPPL-report, 5367, (2017).

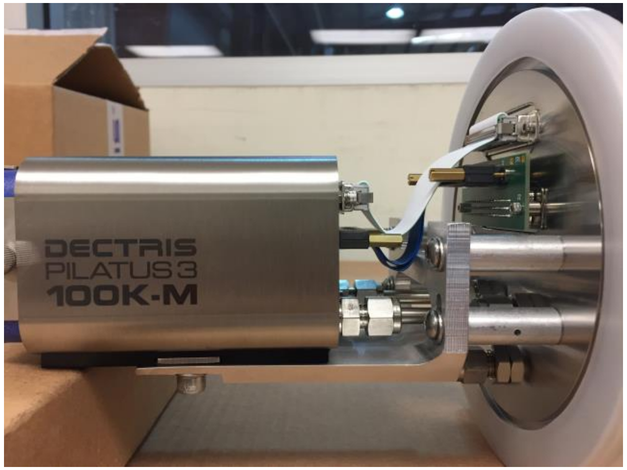


WEST (2018-2021)

K. Hill and L. Delgado-Aparicio, *Novel x-ray diagnostics for profile measurements in tokamak plasmas, (2016).*



New progress in detector technology will further advance plasma diagnostics in the next decade



① New Pilatus3X Silicon detector technology

- Thermal plasmas
- FR=500 Hz
- 172X172 μm^2
- 1.6<E<30keV
- 1-energy range per pix
- To be installed in:

a. MST at U.W.-Madison
b. DIII-D at GA
c. NSTX-U at PPPL
d. QUEST at Kyushu U.

② New Pilatus3X CdTe detector technology

- Non-thermal + W
- Fr=500 Hz
- 172X172 μm^2
- 10<E<100 keV
- 1-energy range/pix
- To be installed in:

a. WEST in France
b. …

③ New EIGER Si detector technology

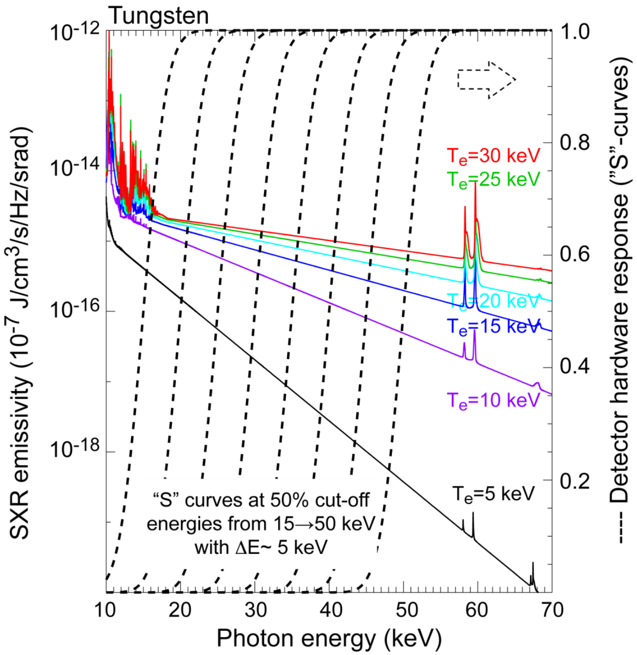
- Thermal plasma
- FR=40 Hz -10 kHz
- 75X75 μm^2
- 2<E<30 keV
- 2-energy range/pix

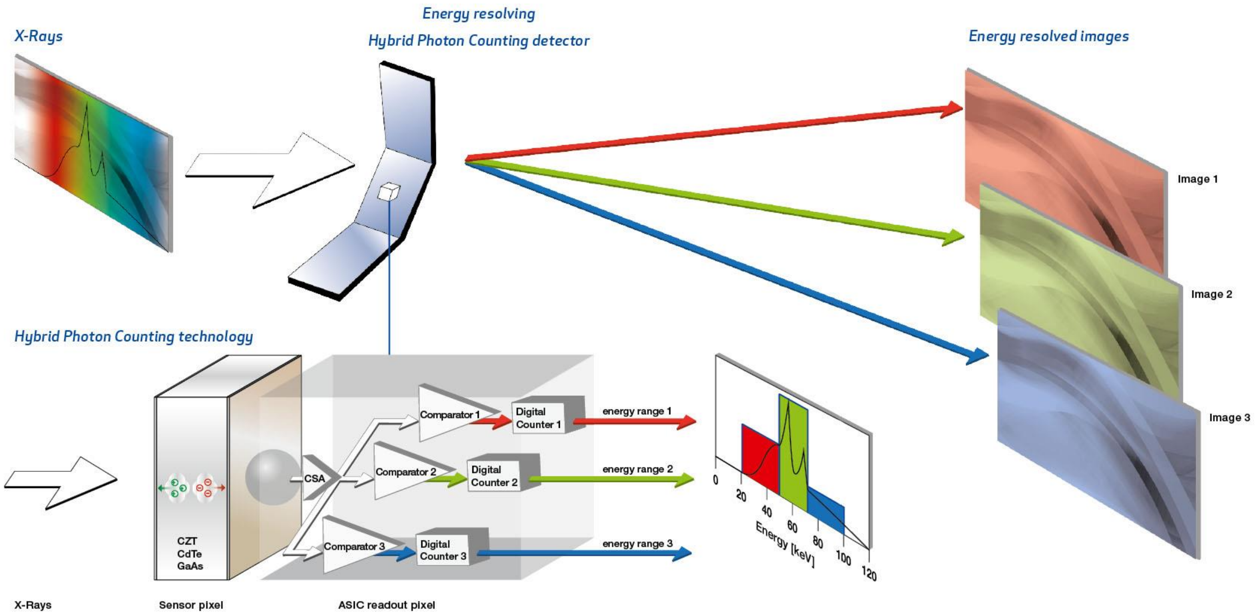
④ New SANTIS detector technology

- Non-thermal + W
- FR=40 Hz
- 75X75 μm^2
- 10<E<100 keV
- 2- or 4-energy range/"pix"

⑤ Hybrid Si/CdTe option for simultaneous thermal + non-thermal studies

New multi-energy HXR technology with several comparators could sample photon distribution

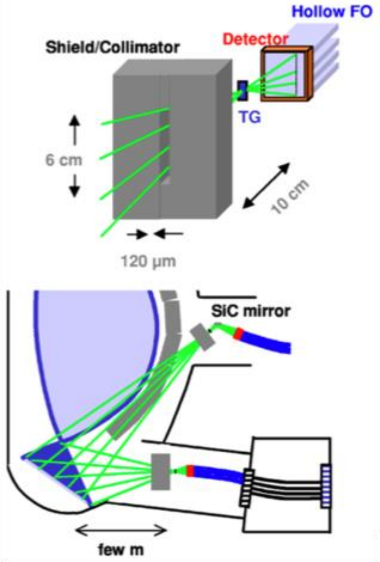




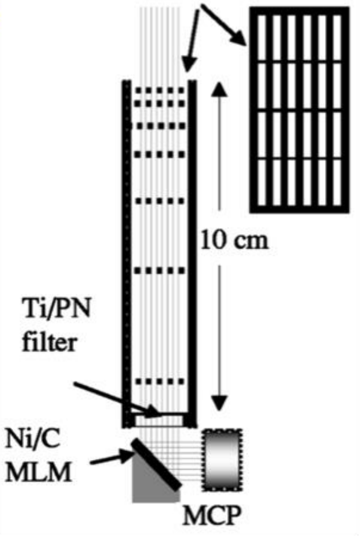
ME-HXR provides a unique opportunity of measuring a variety of important plasma properties

a) Thermal plasma (e.g. T_e and Z_{eff})
b) Non-thermal plasma
  - Electron runaways (e.g. $n_{e,fast}$)
  - RF-induced non Maxwellian population (e.g. LHCD tails - $n_{e,fast}$)
c) Tungsten high-energy –emission
d) Also useful for new atomic physics studies (e.g. He- and H-like Uranium)

The development and demonstration of light-extractor technologies is equally important

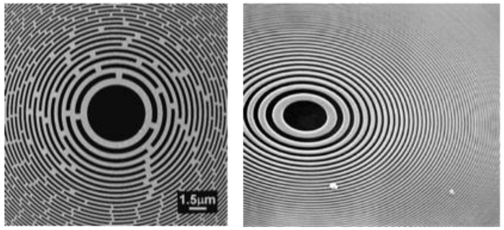


D. Stutman, et al, RSI, **76**, 023505, (2005).



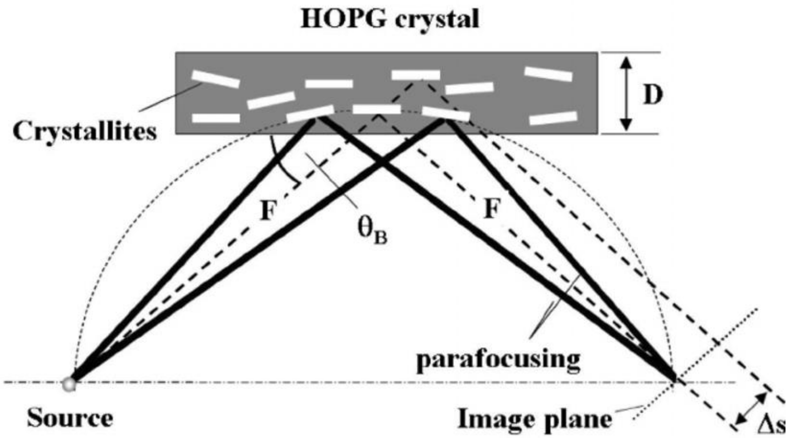
D. Stutman, et al, RSI, **76**, 013508, (2005).

Metallic zone plates for SXR & HXR are now available

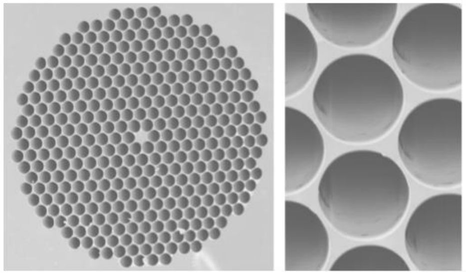


① UV and x-ray light-extractors using metallic transmission gratings, multi-layer mirrors and (Fresnel) zone plates.

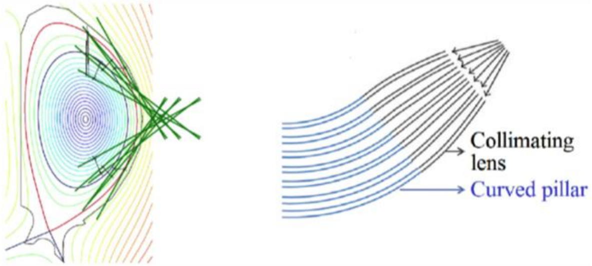
② HOPG/HAPG x-ray pre-reflectors can work both BOTH the XICS and ME-SXR concepts



③ Hollow fiber optics (with efficient scintillators) or x-ray policapillary lenses should be used as efficient x-ray light extractors



J. D. Joannopoulos, et al, Nature, **386**, 143, (1997).



D. Mazon, et al, RSI, **87**, 11E302, (2016).

Irradiation and tests of hardened detectors & electronics can take place also in existing fusion facilities

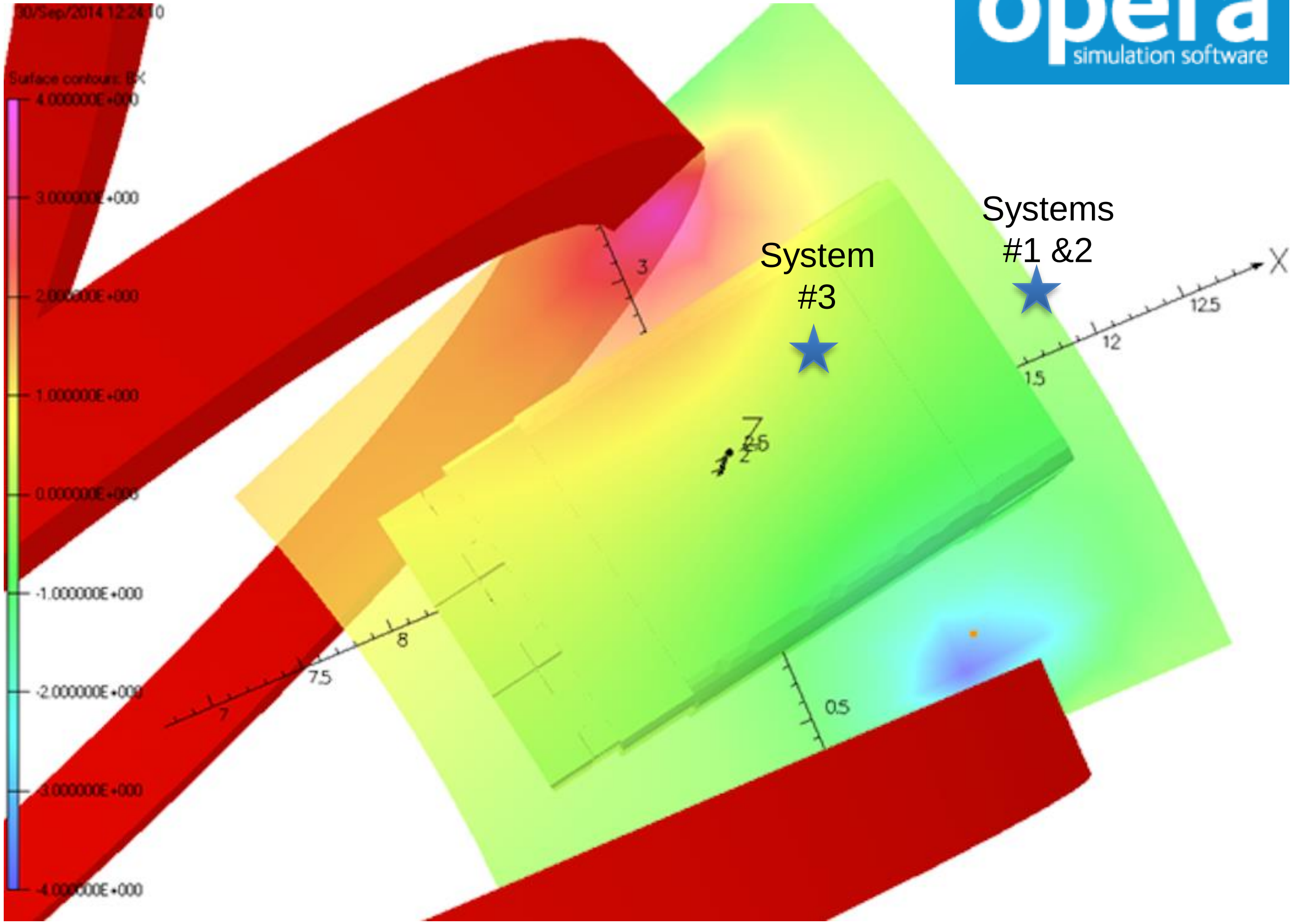
DIII-D in General Atomics,
San Diego, CA

Alcator C-Mod @ PSFC, MIT
Cambridge, MA

NSTX-U @ PPPL, Princeton University
Princeton, NJ

Three XICS detector systems will be installed in between toroidal field coils

ITER – OPERA simulation



- The magnetic fields were extracted from a plasma disruption scenarios MDDWEXP16.

- 15 MA plasma current decay exponentially to zero in 16 ms.

- The field at plasma center is 5.3 T @ 6.2 m.

- **System#3 tests**
  a. **1.7/2.4 T DC**
  b. **3.5 T/s**

B-tests up to 3.3T & 3T/s were possible due to valuable partnership between PPPL & industry

① Detectors not designed to be near strong B's.

② Partnerships between national laboratories and industry should be explored in full!

③ Other detectors + electronics can also be tested in a similar fashion

Results