The Way to Fusion Energy

Imaging applications on ITER

Robin Barnsley, with ITER and EFDA/JET contributors

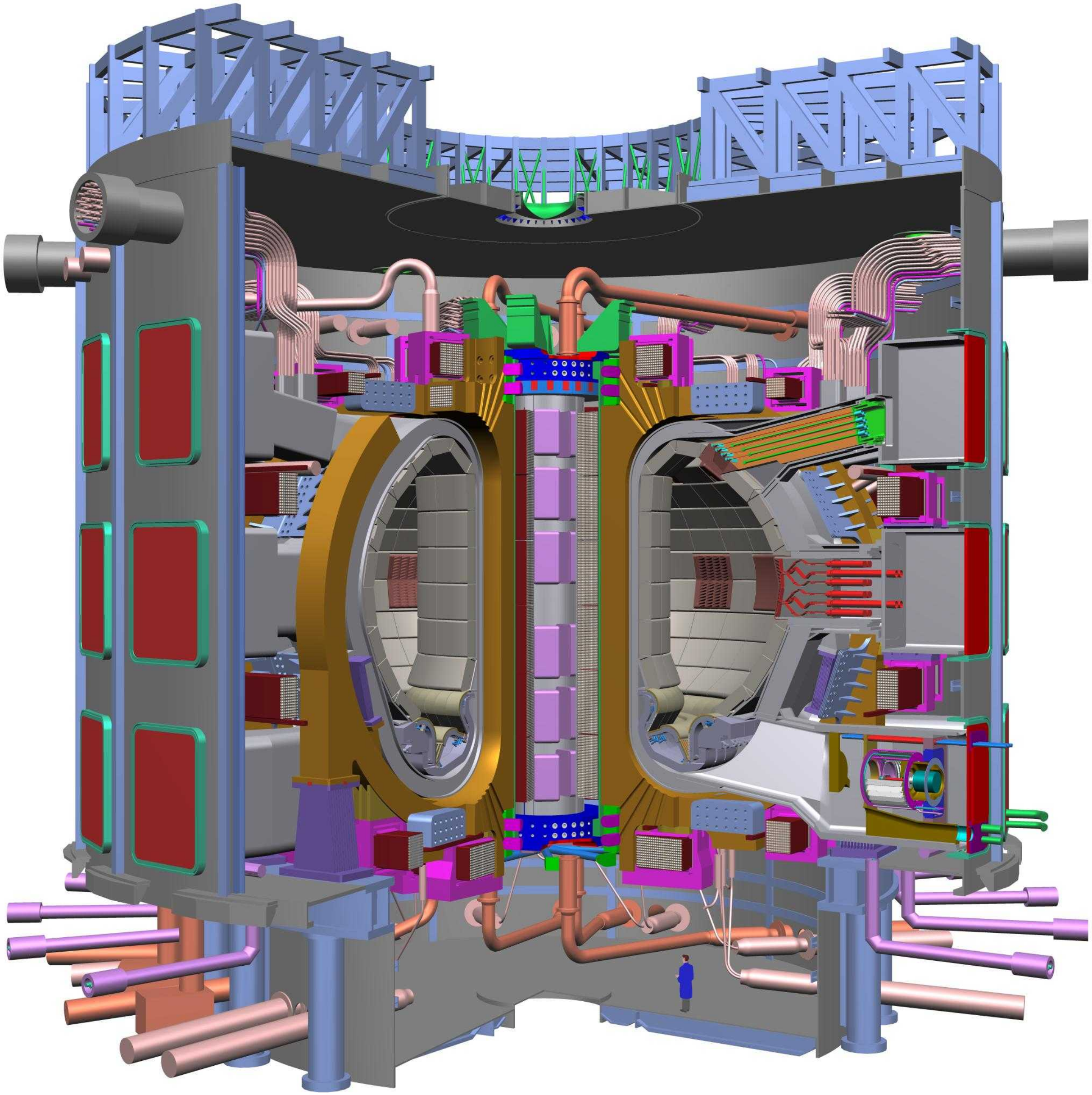
Queen's University Belfast and EFDA/JET

Visiting researcher, ITER International Team, Cadarache, France

A Costley, L Bertalot, K Itami, T Sugie, G Vayakis, C Walker

ITER Diagnostics Group

- ITER diagnostics
- Bolometry — Radiated power IR –> hard x-ray.
- IR-Visible-UV — Imaging for spectroscopy protection and control.
- VUV — Characteristic of cooler edge plasma.
- X-ray — Hot core plasma. Direct imaging and crystal spectroscopy.
- Gamma-ray — Spectroscopy of nuclear reactions.



ITER (www.iter.org)

- Superconducting Tokamak
- Single-null divertor
- Elongated, triangular plasma
- Additional heating from negative-ion neutral-beams, ECH and ICH

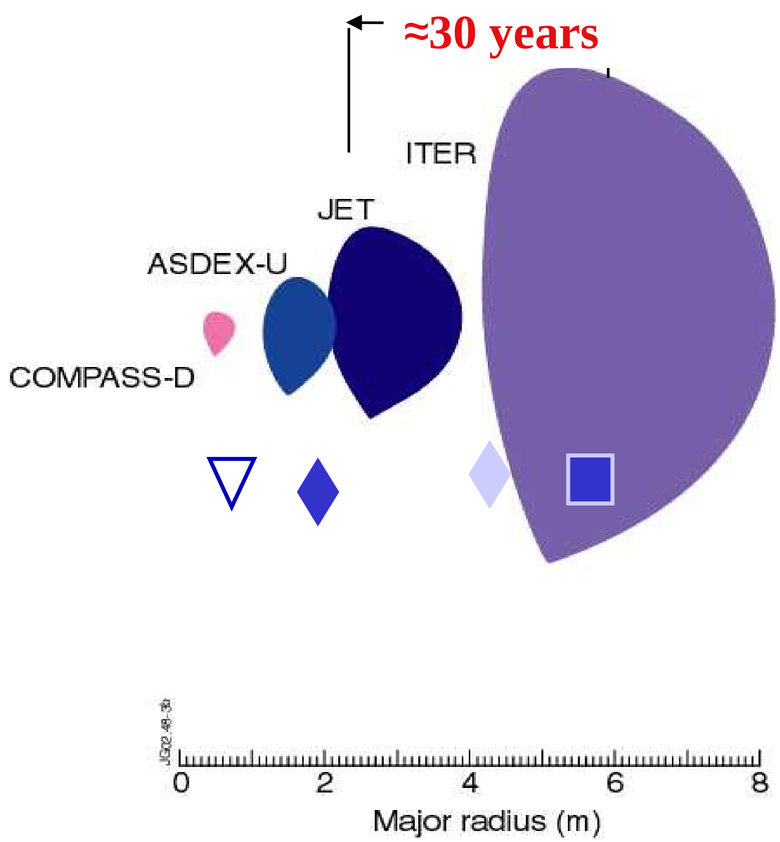
R (m)	6.2
a (m)	2
V_P (m^3)	850
I_P (MA)	15(17)
B_t (T)	5.3
δ,κ	1.85, 0.5
P_{aux} (MW)	40-90
P_α (MW)	80+
Q (P_{fus}/P_{in})	10
Prad (MW)	48

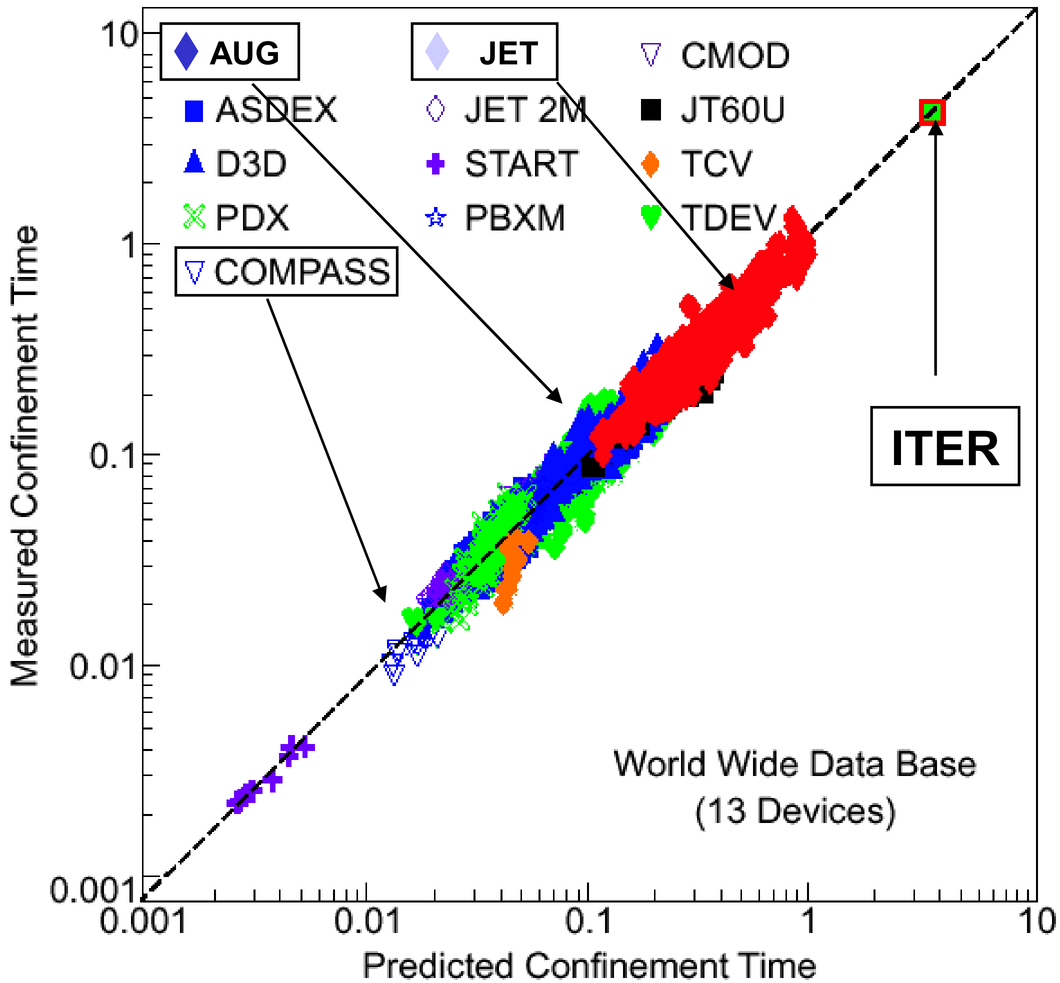
Scaling to ITER from previous experiments

Physics performance can be extrapolated better than factor 2.

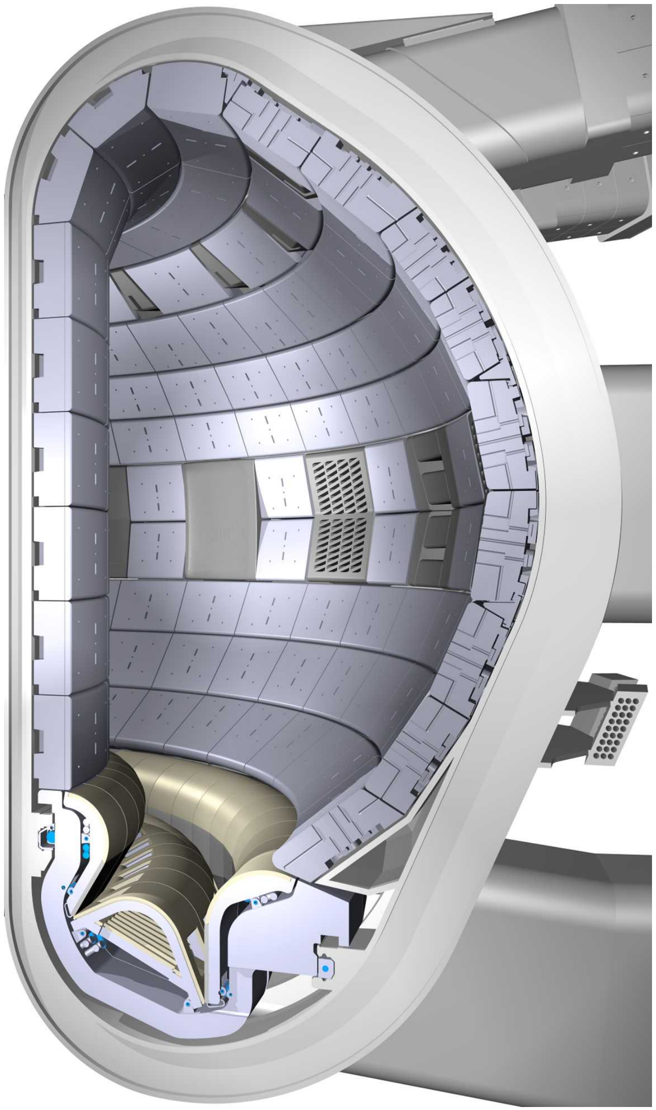
Technological developments ongoing for:

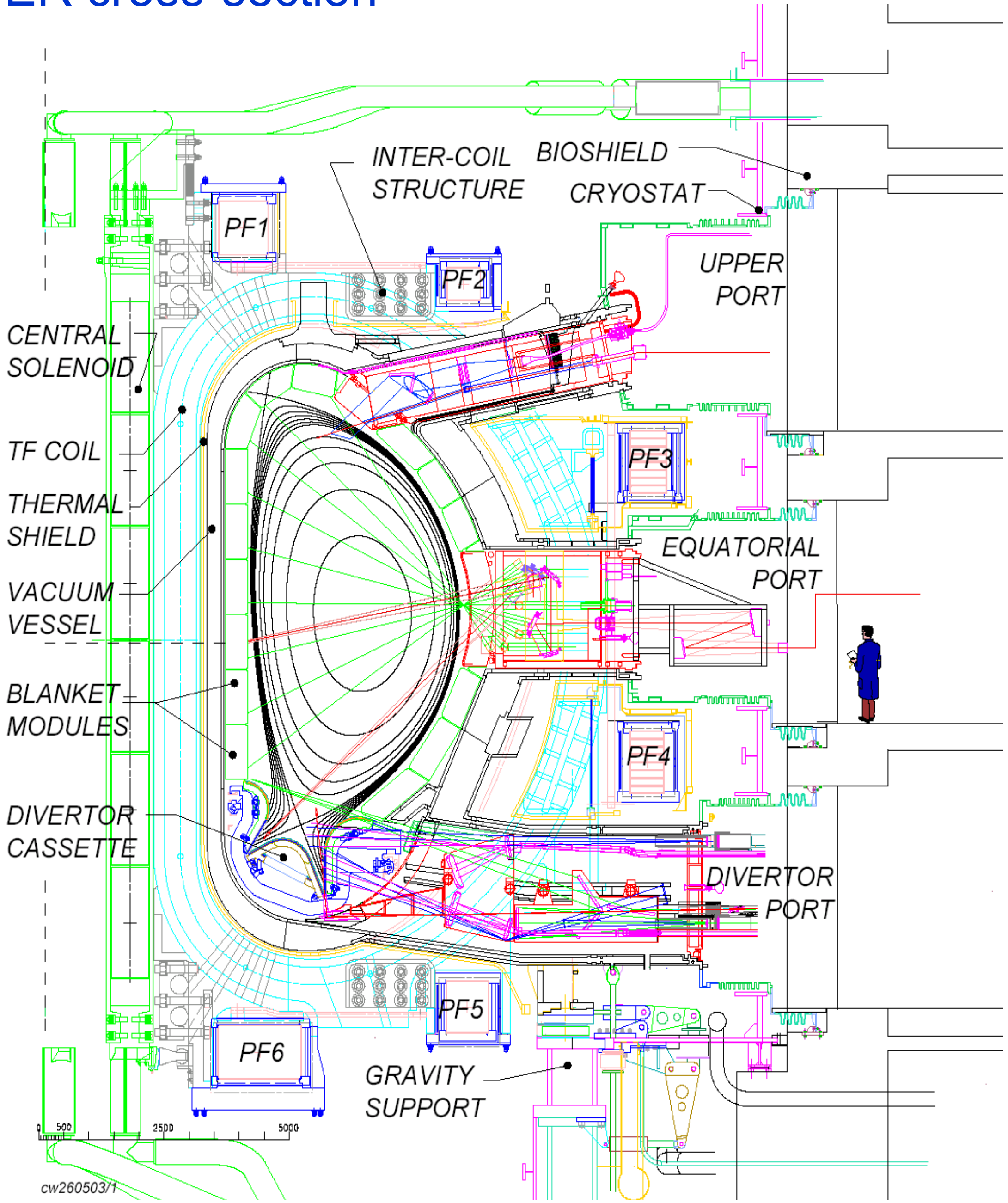
- First wall: blanket and divertor modules, diagnostic mirrors.
- Material properties under heavy neutron irradiation.





ITER cross-section





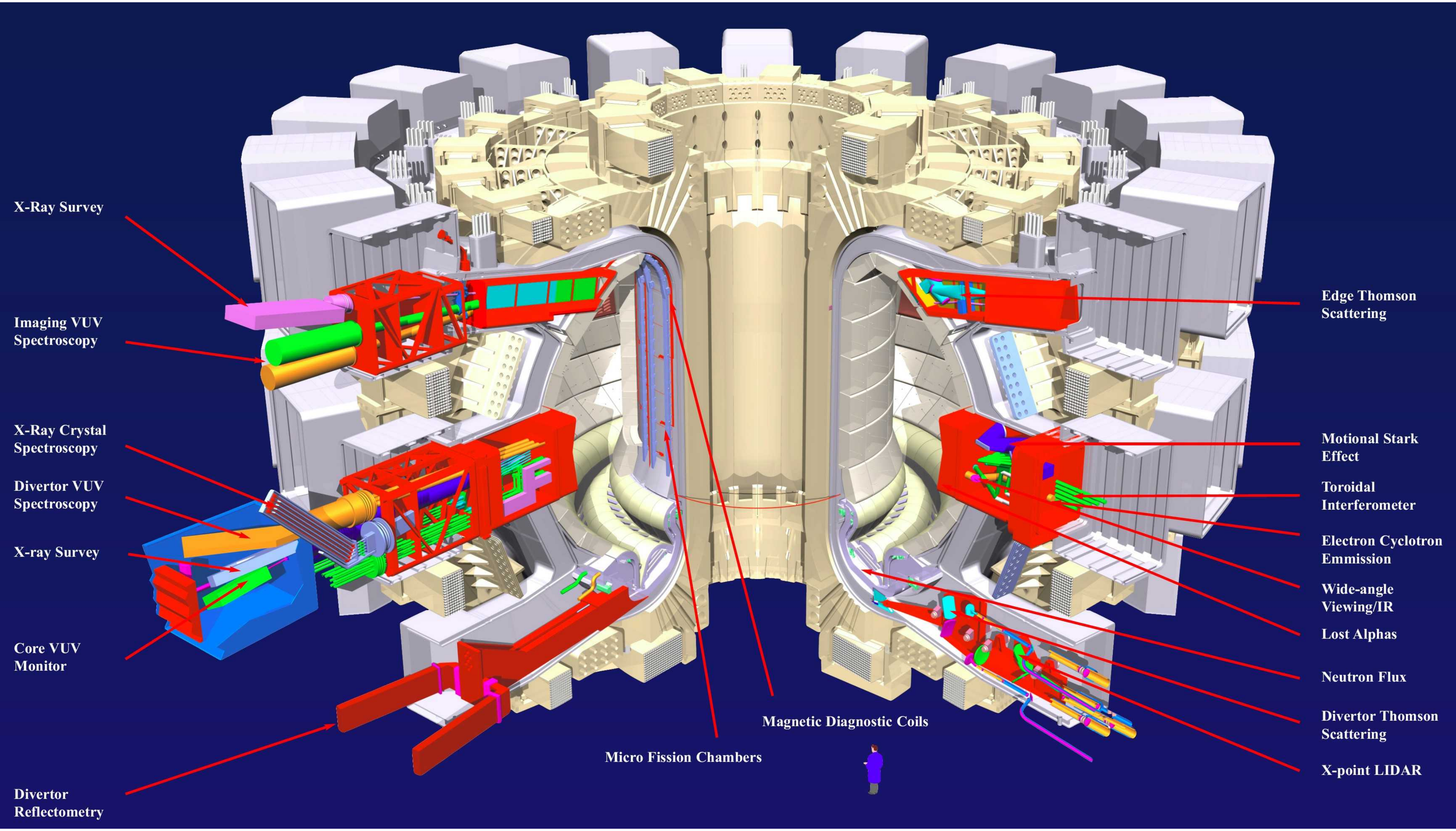
ITER Diagnostic System

Magnetic Diagnostics	**Spectroscopic and NPA Systems**
Vessel Magnetics	CXRS Active Spectr. (based on DNB)
In-Vessel Magnetics	H Alpha Spectroscopy
Divertor Coils	VUV Impurity Monitoring (Main Plasma)
Continuous Rogowski Coils	Visible & UV Impurity Monitoring (Div)
Diamagnetic Loop	X-Ray Crystal Spectrometers
Halo Current Sensors	Visible Continuum Array
Neutron Diagnostics	Soft X-Ray Array
Radial Neutron Camera	Neutral Particle Analysers
Vertical Neutron Camera	Laser Induced Fluorescence (N/C)
Microfission Chambers (In-Vessel) (N/C)	MSE based on heating beam
Neutron Flux Monitors (Ex-Vessel)	**Microwave Diagnostics**
Gamma-Ray Spectrometers	ECE Diagnostics for Main Plasma
Neutron Activation System	Reflectometers for Main Plasma
Lost Alpha Detectors (N/C)	Reflectometers for Plasma Position
Knock-on Tail Neutron Spectrom. (N/C)	Reflectometers for Divertor Plasma
Optical/IR Systems	Fast Wave Reflectometry (N/C)
Thomson Scattering (Core)	**Plasma-Facing Components and Operational Diagnostics**
Thomson Scattering (Edge)	IR Cameras, visible/IR TV
Thomson Scattering (X-Point)	Thermocouples
Thomson Scattering (Divertor)	Pressure Gauges
Toroidal Interferom./Polarimetric System	Residual Gas Analyzers
Polarimetric System (Pol. Field Meas)	IR Thermography Divertor
Collective Scattering System	Langmuir Probes
Bolometric System	**Diagnostic Neutral Beam**
Bolometric Array For Main Plasma	
Bolometric Array For Divertor	

- **Measurements for**:
- Machine protection
- Plasma control
- Physics studies
- ~45 parameters in total

ITER diagnostics are port-based where possible

Each diagnostic port-plug contains an integrated instrumentation package



Ports contain several diagnostics

Common features:

High fluxes onto plasma-facing mirrors

- Nuclear radiation - 0.5 MW / m^2
- Heat, peaking in x-rays
- Escaping neutrals and ions

Mirror/waveguide labyrinths for shielding

- Require extensive neutronics analysis
- Performance compromised
- No fibres, lenses or windows in port

Some systems cannot use labyrinths

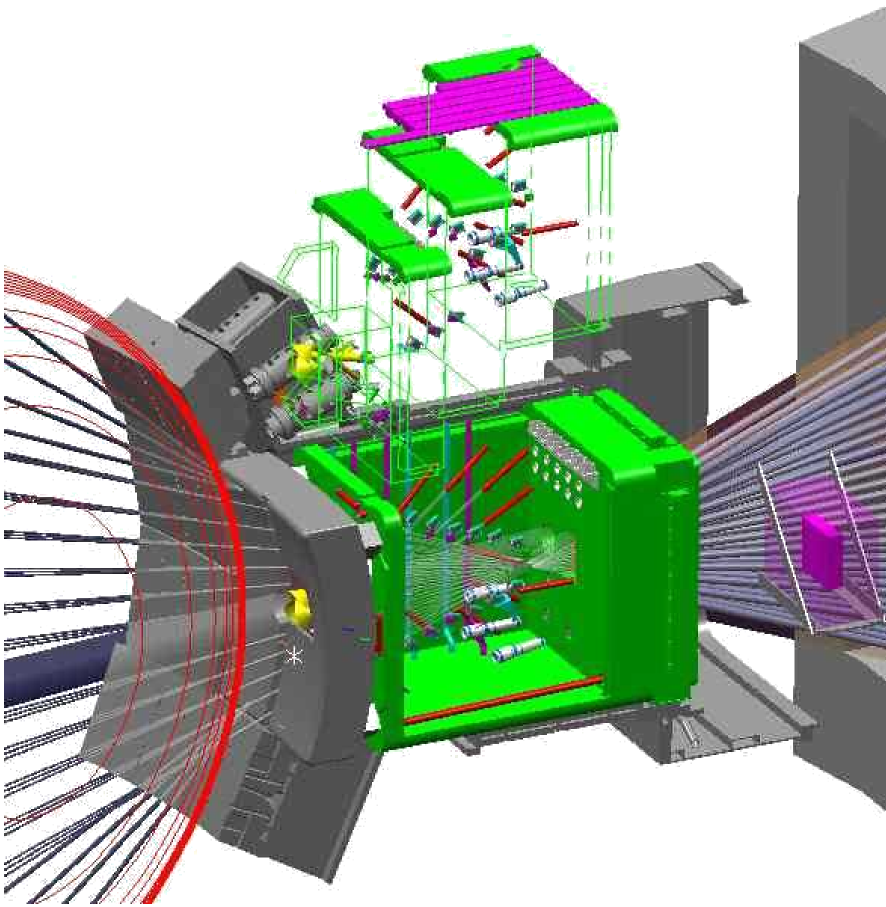
- X-ray camera, spectroscopy
- Neutron and gamma cameras

Some systems require vacuum extensions

- VUV spectroscopy
- Neutral particle analyser

High electromagnetic loads

- Plasma current of 15MA can disrupt in 40ms



2. Bolometry

- Radiated power ranges from IR to hard x-ray
- Total radiated power measurement required for
  - Machine protection
  - Power balance

ITER-relevant development

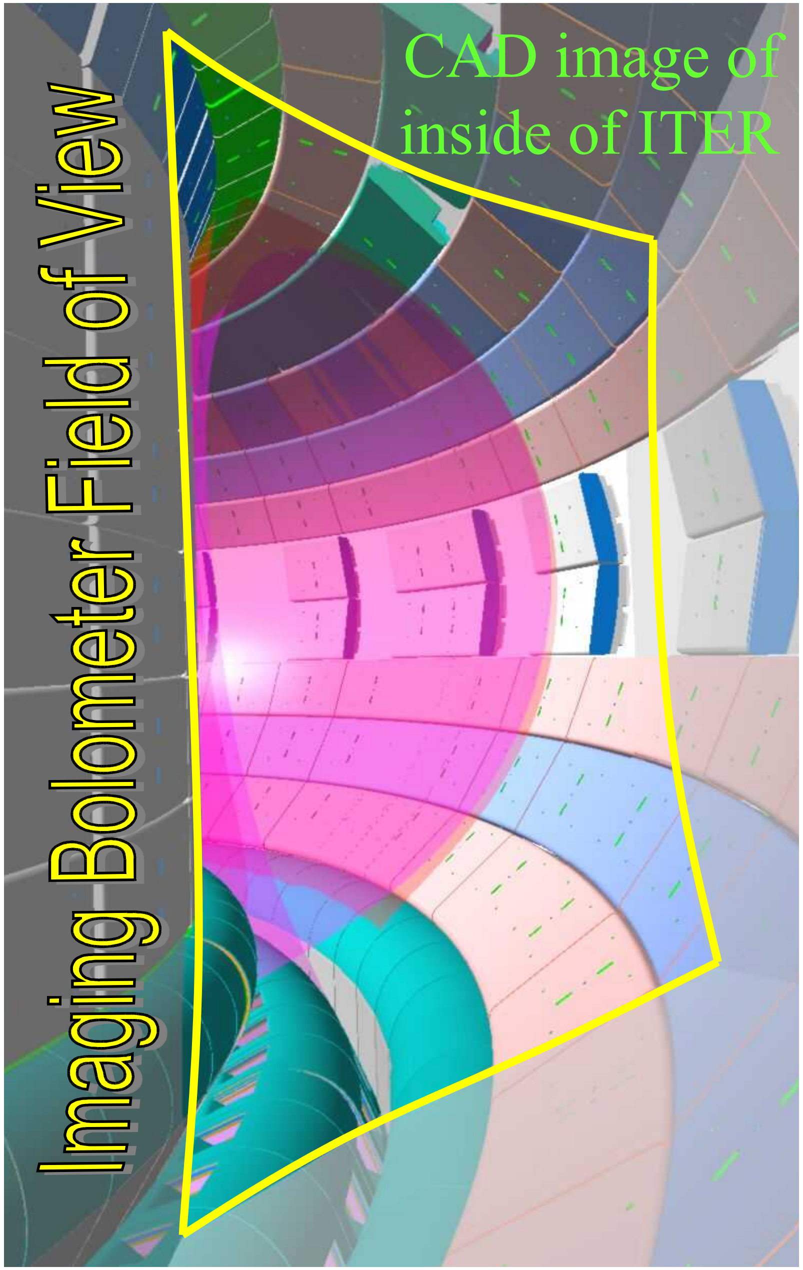
- JET
- JT-60

B.J. Peterson. This meeting Friday 8th. Paper 09-4

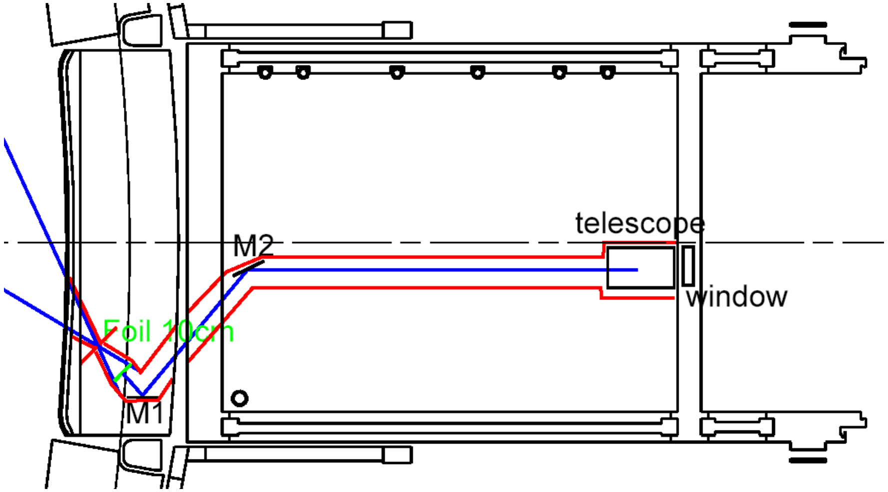
Imaging applications on ITER

- In-vessel main plasma
- Divertor bolometer

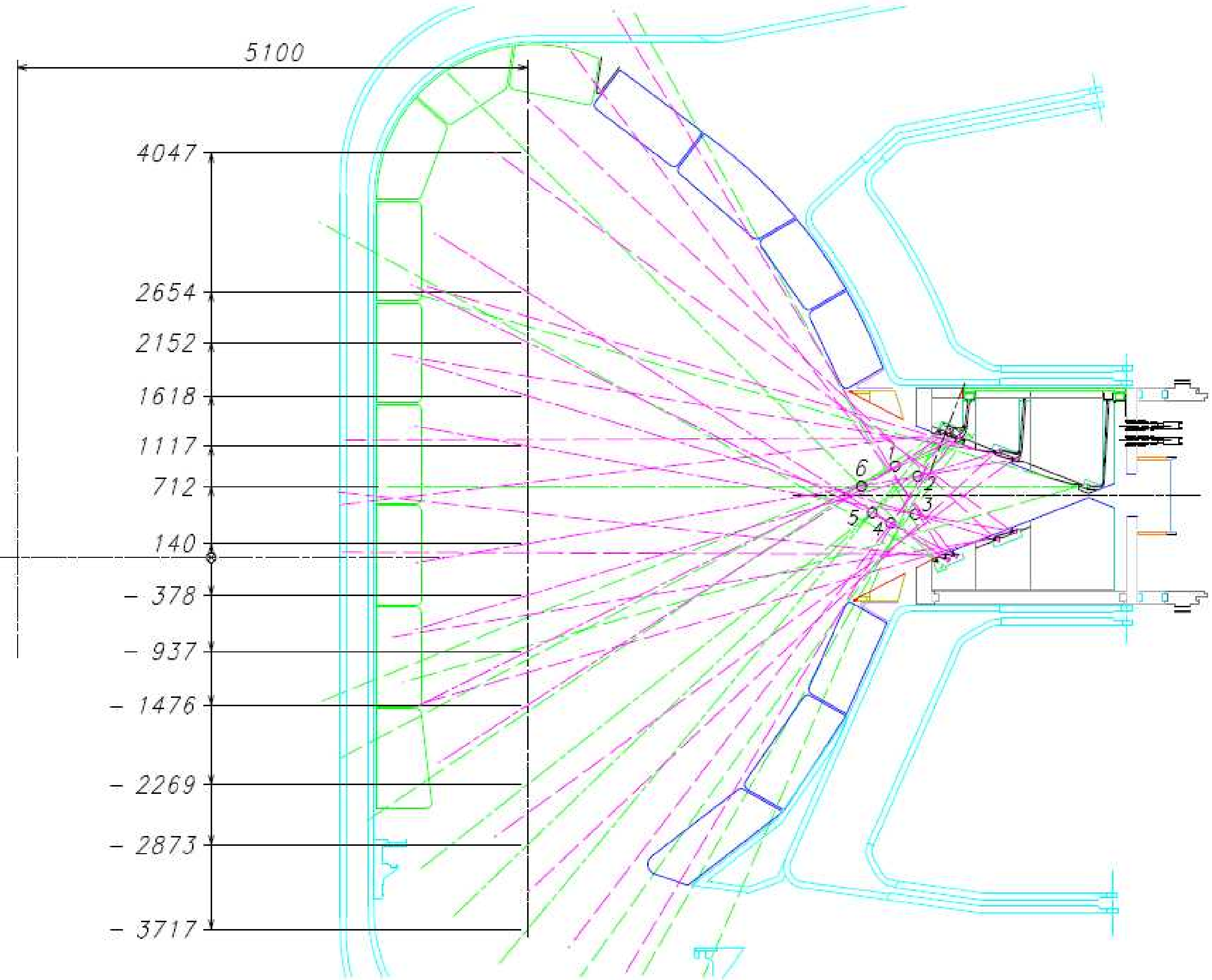
Imaging Bolometer for ITER: IRVB Specifications



- **IR camera: FLIR/Indigo/Phoenix**
  - **temperature resolution: <25 mK**
  - **frame rate: 100 Hz**
  - **pixels: 640 x 512 pixels, 14 bit**
- **Foil: W (other options:Ta, Pt)**
  - **size: 0.01 x 70 x 90 mm,**
  - **photon energy range: E_{ph} < 21 keV**
- **Bolometer:**
  - **time resolution: 10 ms**
  - **channels: 12 (h) x 17 (v) = 204**
  - **sensitivity: NEPD = 190 μW/cm², S/N <100**



Views for bolometers in ITER port-plug



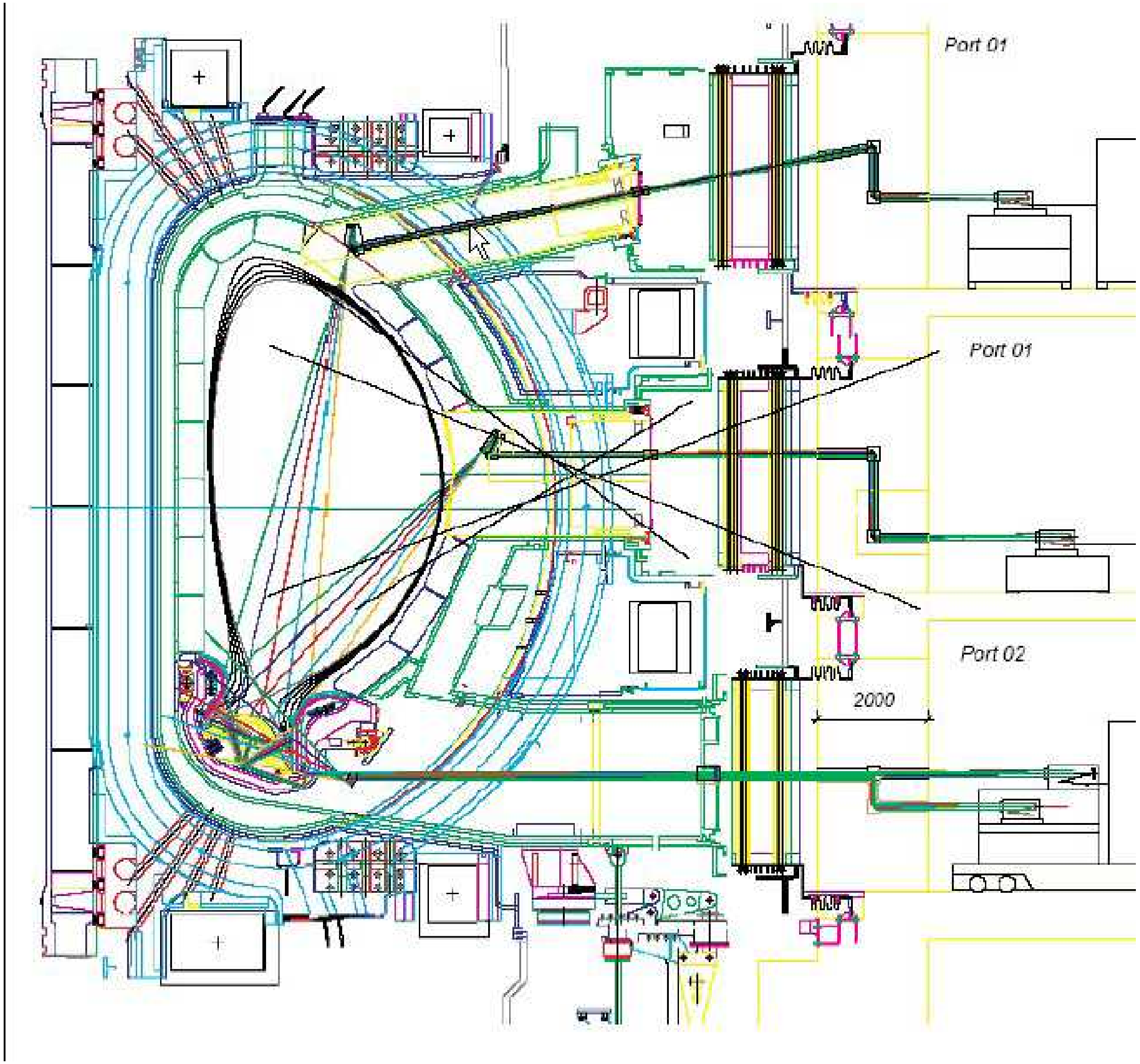
- Bolometers share viewing-slot with Radial Neutron Camera
- Fewer views than with the in-vessel bolometers
- Can be replaced

3. IR, Visible & near-UV

- Wide-angle cameras for wall monitoring and inspection
- Spectroscopy of neutral and weakly ionized impurities, mainly edge influxes
- Charge-exchange recombination spectroscopy
- Laser Thomson scattering off hot electrons

- **Imaging implementations on ITER**
  - IR Thermography for target temperatures
  - 6 views for H-alpha and visible spectroscopy
  - Visible continuum array for Z_{eff} profile
  - Visible-IR viewing system with near-complete view of first-wall
    - 6 systems in upper ports
    - 4 systems in equatorial ports

ITER divertor visible-UV viewing optics



This conference

Ogawa et al P6-13

Divertor spectroscopy

Kato et al P13-01/ P8-02

Upper port engineering

4. Vacuum ultraviolet

- Highly ionized ions in divertor and outer plasma
- Real-time impurity monitoring for machine protection
- Windows not possible – require vacuum extension
- Grazing incidence spectrometers and optics
- Micro-channel-plate detectors

- **ITER-relevant development**
  - JET: D-T compatible, radiation-shielded, RT data feedback.
  - TEXTOR: 4-channel VUV spectrometer.

- **Imaging implementations on ITER**
  - Core plasma imaging VUV spectrometer
  - Divertor plasma imaging VUV spectrometer

Spectroscopy of Tungsten is important for ITER core and divertor plasmas

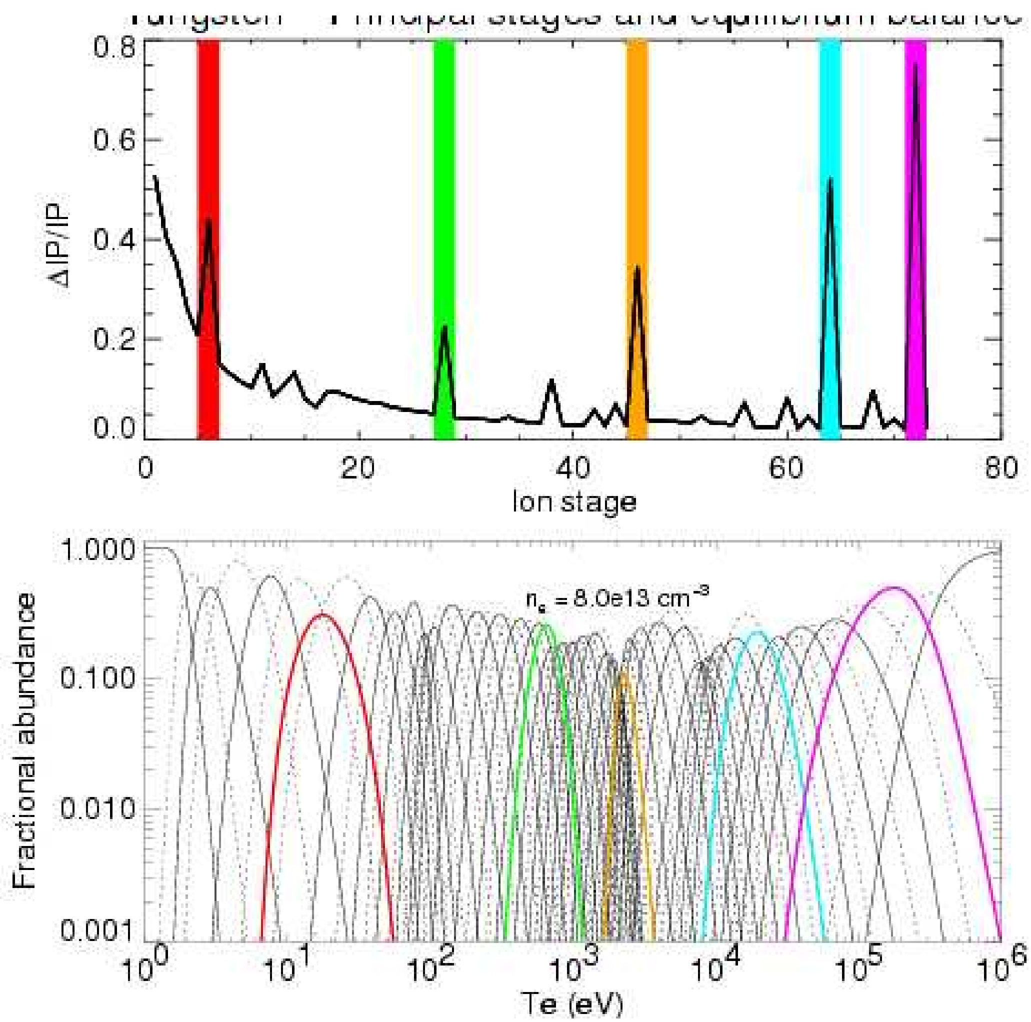
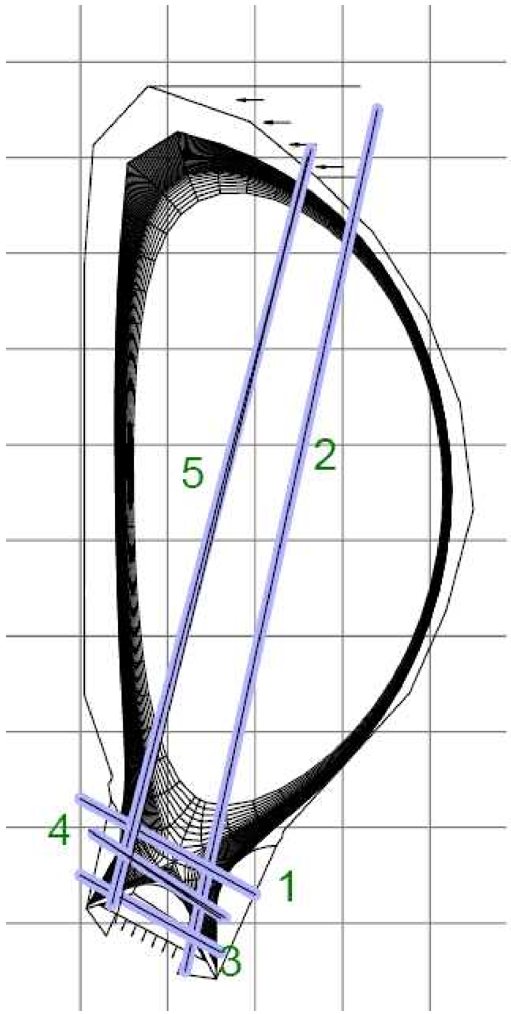
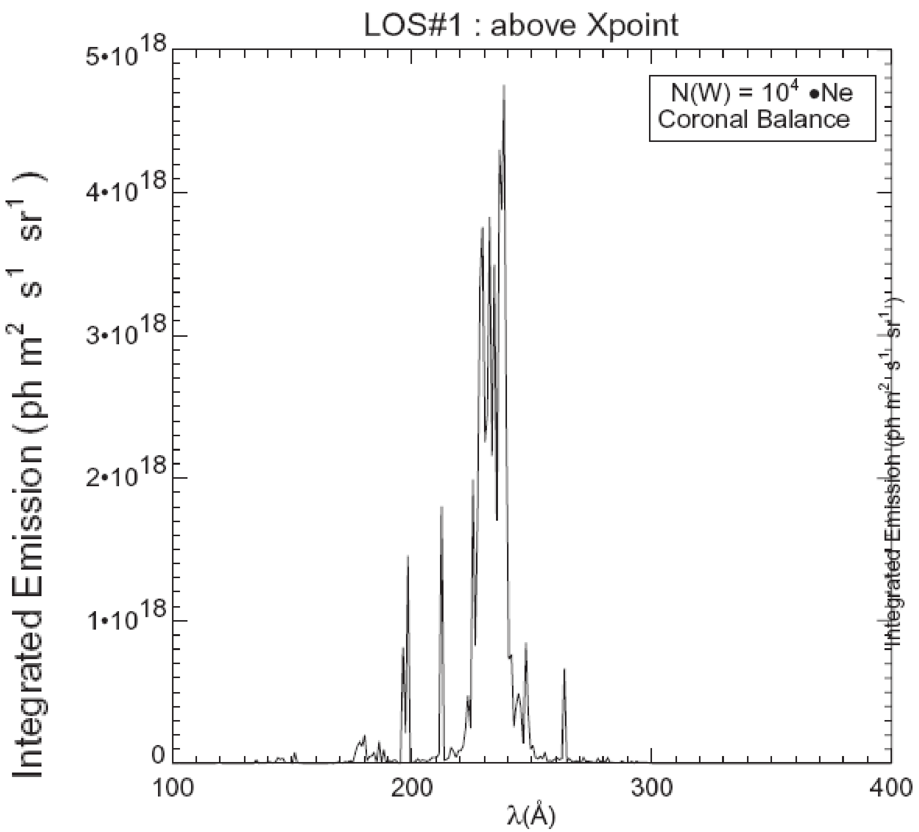


Fig.9. Coronal fractional abundance of W ions (below), with (above) a guide to the shells with greatest ionization potential ranges Δ IP/IP.

VUV spectroscopic imaging is important for the edge and divertor plasmas

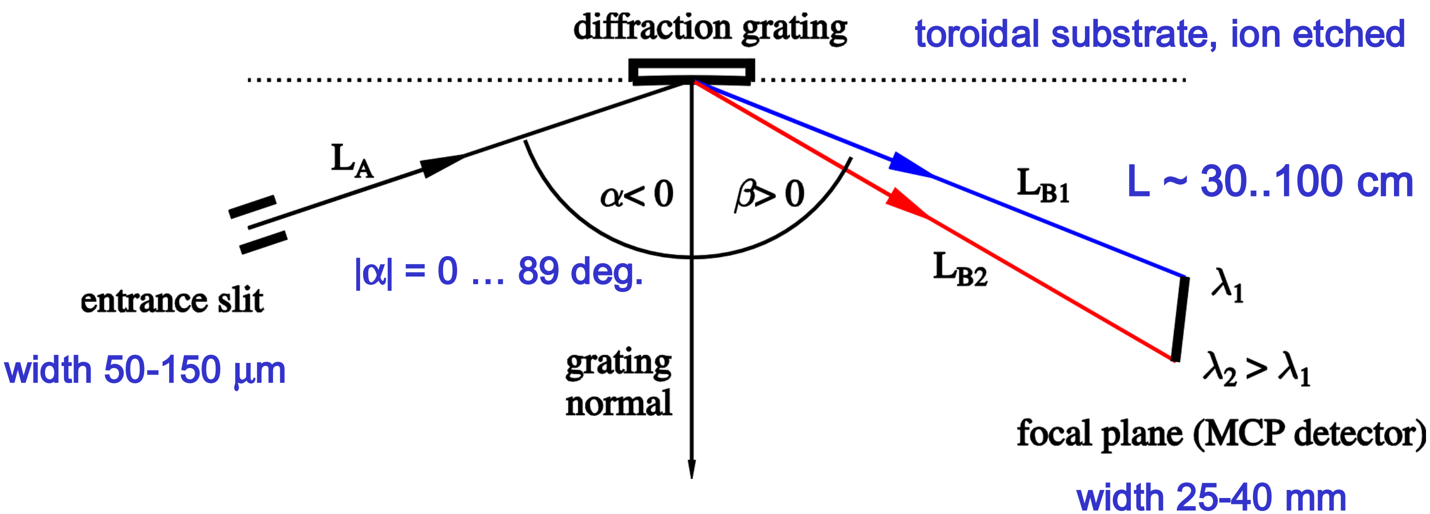
- Monitor impurity influxes in real time
- Impurity transport studies





Modelled tungsten spectrum integrated along one line-of-sight in the ITER divertor plasma

General layout of VUV spectrometers



Fonck R J et al, Appl. Opt. **21** 2215 (1982)
Biel W et al., Rev. Sci. Instrum. **75** 3268 (2004)

Spectrometer design issues:

- incidence angle (reflectivity, diffraction efficiency)
- large etendue (but good wavelength resolution)
- The grating is optimized match the detector resolution

Imaging VUV spectrometer for ITER

Grating is designed to match a given detector

This design is for a conservative 100um: MCP -> phosphor –> CCD

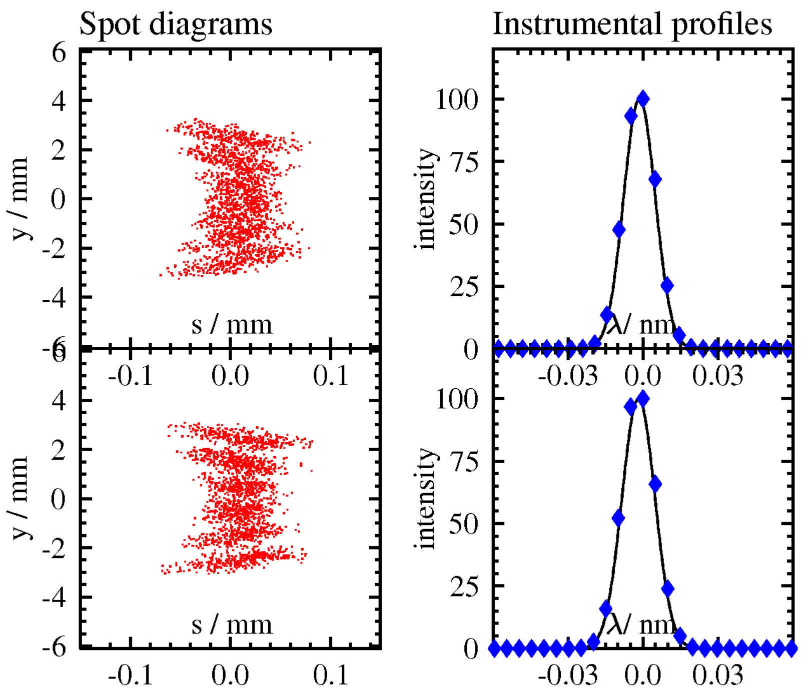
Ray-Tracing calculations for toroidal grating ITER Imaging Dr. W. Biel, IPP, FZ Juelich

(All dimensions given are in mm, angles in degrees, origin located in the grating centre)

G = 2292.00 / mm, α= -60.000, L_A = 1300.00, rs0 = 1300.00. MCP angle = 54.00

β_1 = 54.875, β_2 = 53.750, L_{B1} = 1293.03, L_{B2} = 1292.89

Slit height 6.0, width 0.06. Grating height 16.0, width 36, aperture 50.00, Light source extended



λ= 21.00 nm :
Imaging line width = 0.0117 nm
Bandpass line width = 0.0134 nm
Detected line width = 0.0149 nm
Etendue = 6.0649E-005 mm^2 sr
Transmission = 0.17549
TH = 0.99366
Dispersion = 0.19412 nm/mm

λ= 26.00 nm :
Imaging line width = 0.0123 nm
Bandpass line width = 0.0139 nm
Detected line width = 0.0155 nm
Etendue = 6.1153E-005 mm^2 sr
Transmission = 0.17695
TH = 0.99980
Dispersion = 0.19955 nm/mm

Average line width: from imaging = 0.0120 nm, mean camera output width = 0.0152 nm
Mean Resolution = 1550, mean Etendue = 6.1156E-005 mm^2 sr

Relatively high resolution
$\lambda/\lambda\delta$ ~ 1500

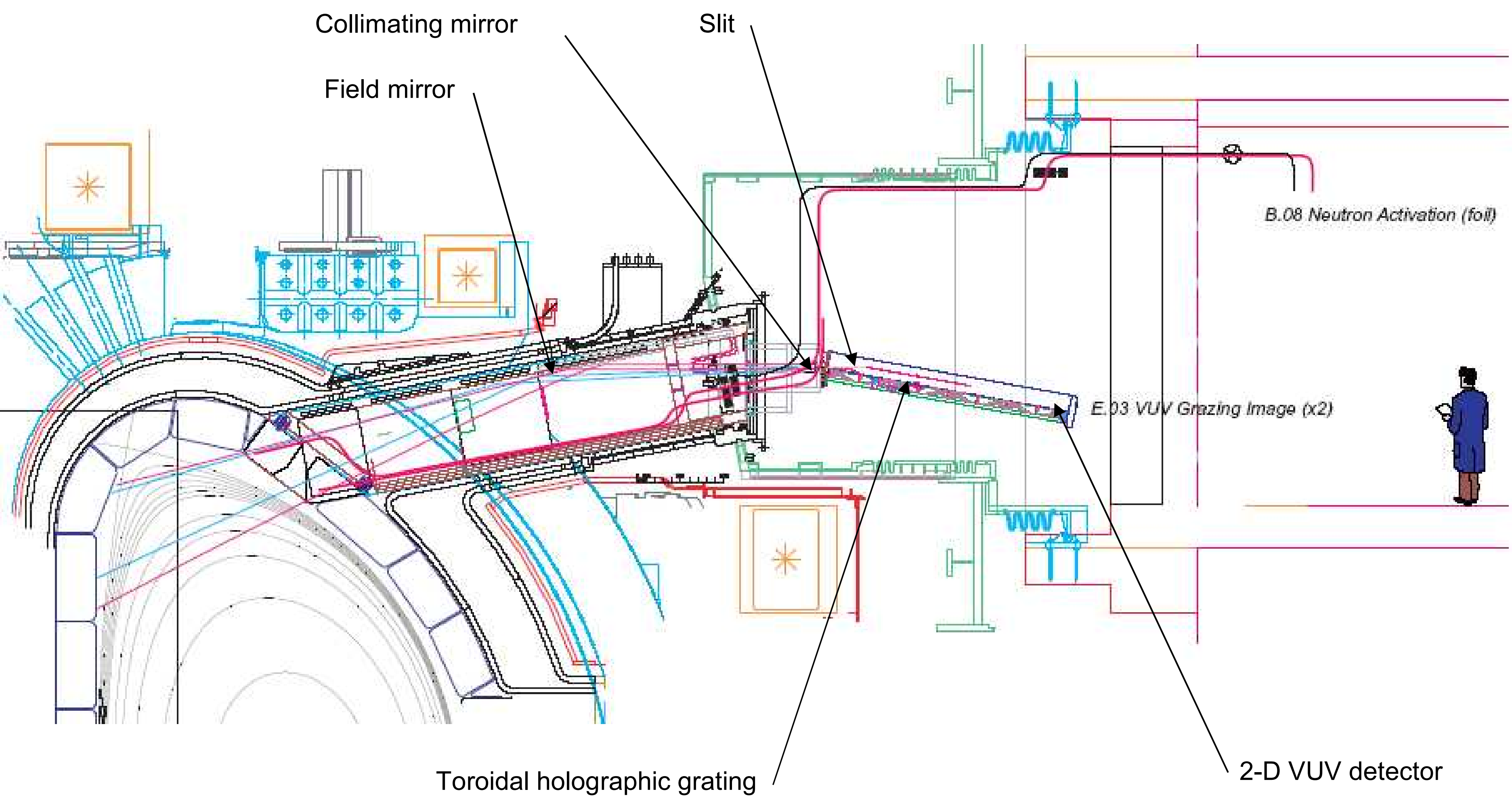
Relatively narrow
Wavelength range
21 nm – 26 nm

Angle of incidence:
α = 60 degrees

Relevant spectral lines:

He II	25.632 nm
Be IV	25.627 nm
C V	22.279 nm
O V	21.515 nm
Kr XXVI	22.00 nm
Ar XV	22.115 nm
Cr XXII	22.290 nm
Fe XXIV	25.509 nm
Ni XXVI	23.420 nm
Ni XVII	24.918 nm
Cu XVIII	23.424 nm

ITER Imaging VUV spectrometer in Upper Port #06
(Similar system for divertor)



5. X-rays

- Peak of the radiated power (P_{rad} ~ 40 MW)
- Broadband imaging of core plasma, ~1-100 keV
- High resolution spectroscopy of highly-ionized core ions ~ 0.1 – 0.5 nm
- Crystal optics
- Energy-resolving photon-counting detectors

- **ITER-relevant development**
  - TEXTOR: Imaging crystal spectrometer
  - K.W. Hill, Poster P6-33
  - S G Lee Poster P6-36

- **Imaging implementations on ITER**

  - In vessel x-ray camera. Vacuum photo-diodes – very radiation hard.
  - Ex-vessel x-ray camera. Fast energy-resolving detectors
  - High-resolution crystal spectrometers

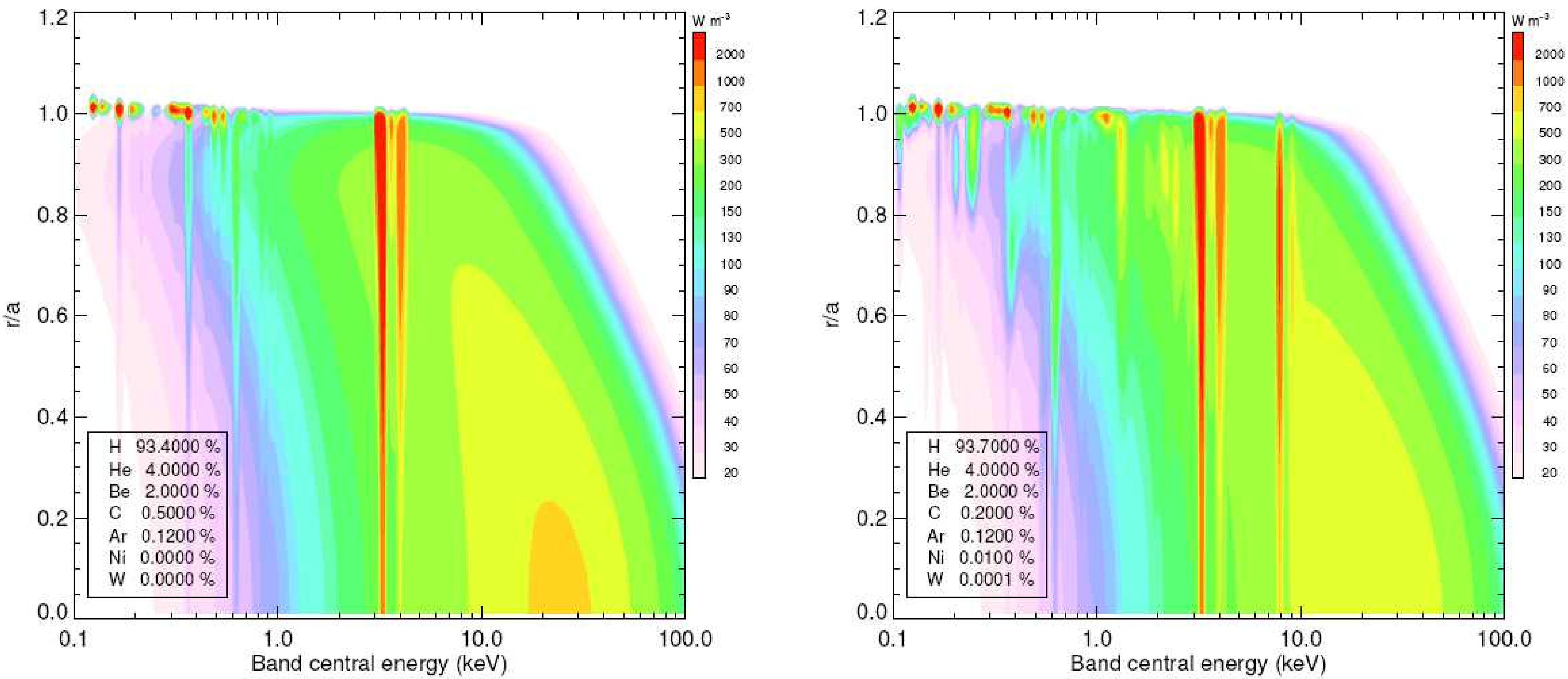
ADAS-SANCO modelled ITER broadband x-ray spectra

Line and continuum in 5% energy bands, radially resolved

< 10 keV: mainly impurity information

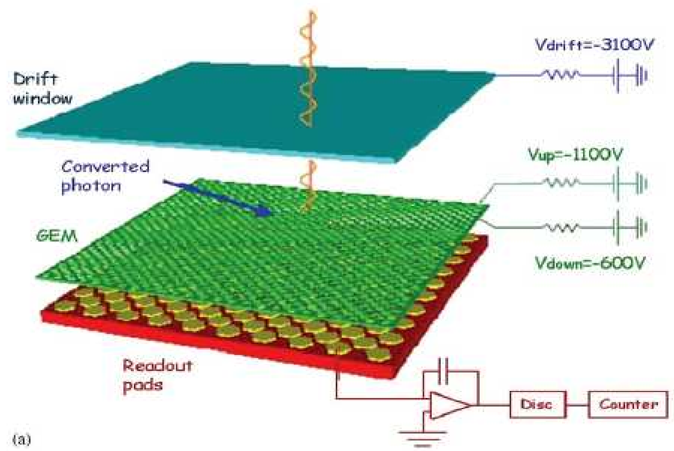
> 10 keV: mainly Te information

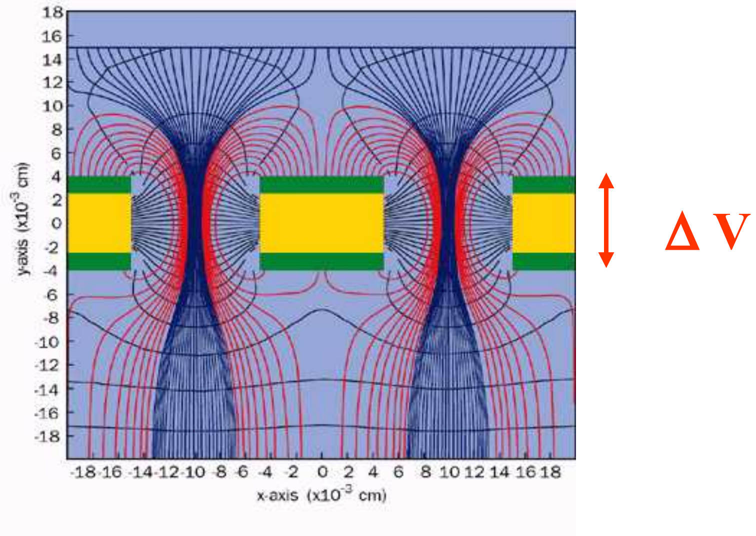
Modern detectors will be able measure this…



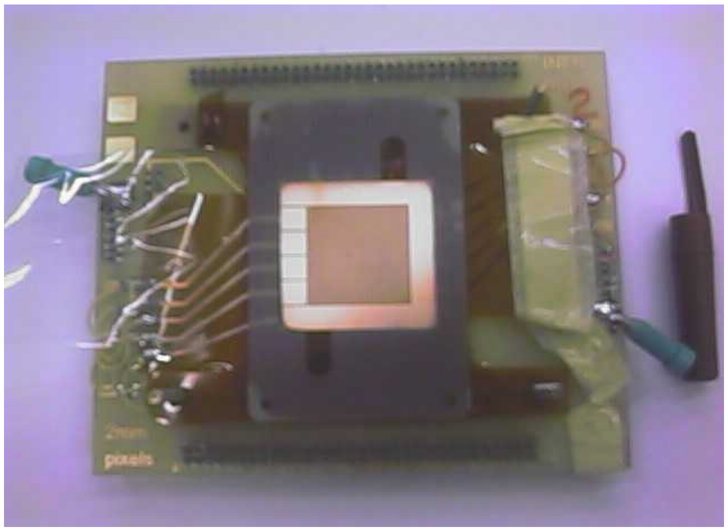
ENERGY-RESOLVED FAST 2-D X-RAY IMAGING

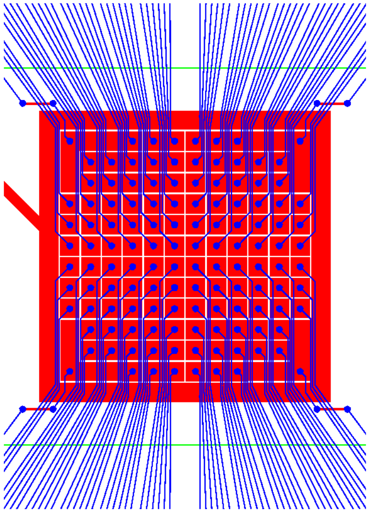
D Pacella ENEA – Frascati , Italy. APS – HTPD , 19-22 April 2004 , San Diego, CA, USA

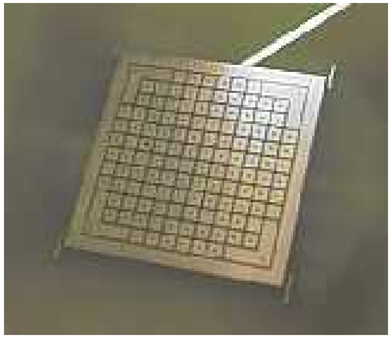




Prototype GEM detector. PIXCS-128 128 pixels







Energy resolution on each pixel in a wide energy range
Independent window analyzer on each pixel, capable of > 10^6 count/s

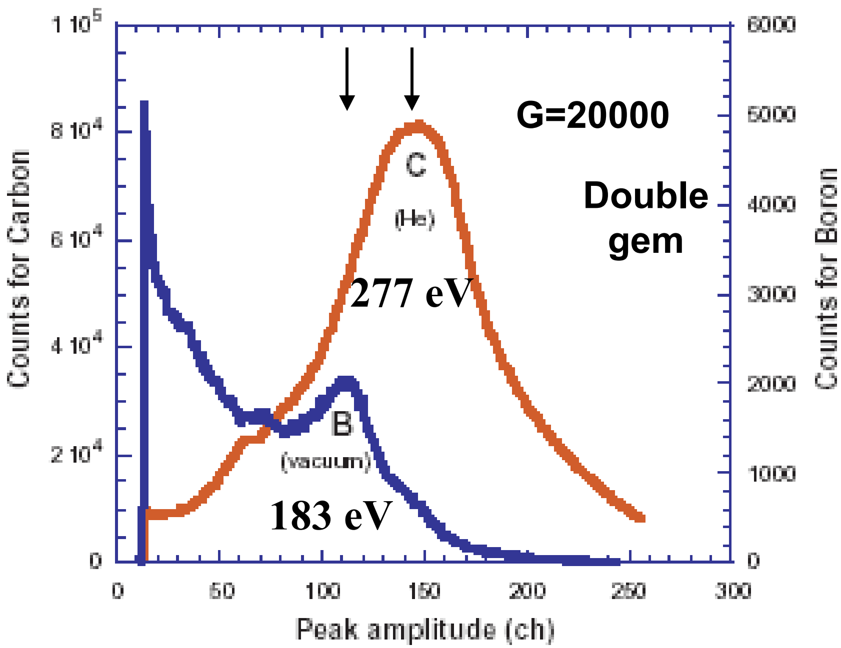


Fig. 4. Spectrum of carbon (277 eV, right axis) with double GEM and He between source and detector. Spectrum of boron (183 eV, left axis), with double GEM and vacuum between source and detector.

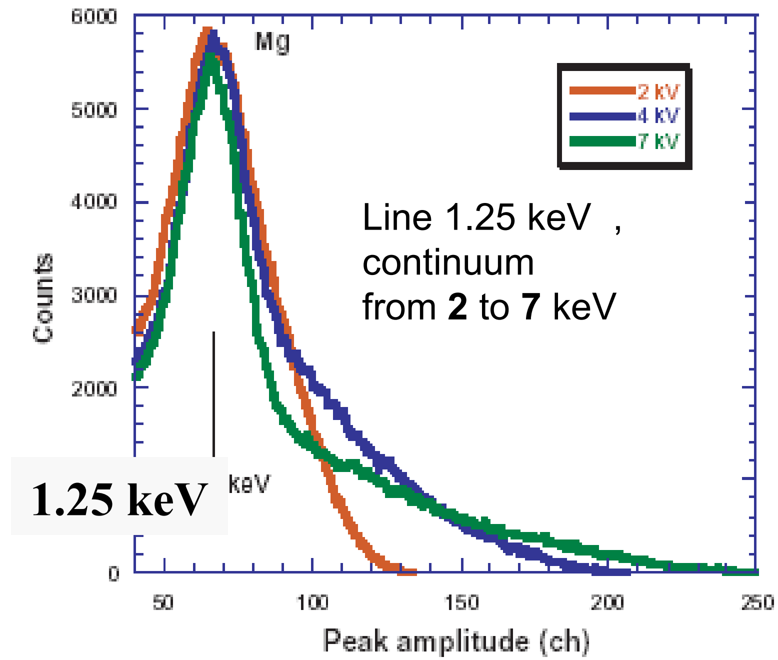
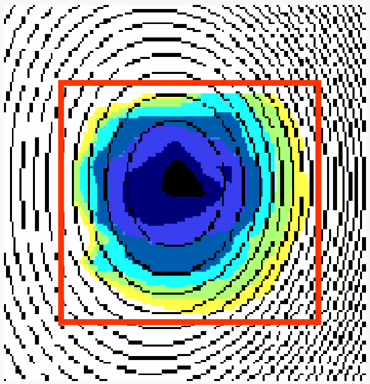
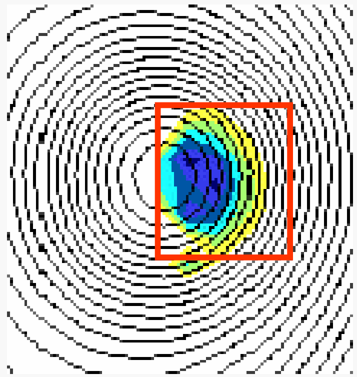


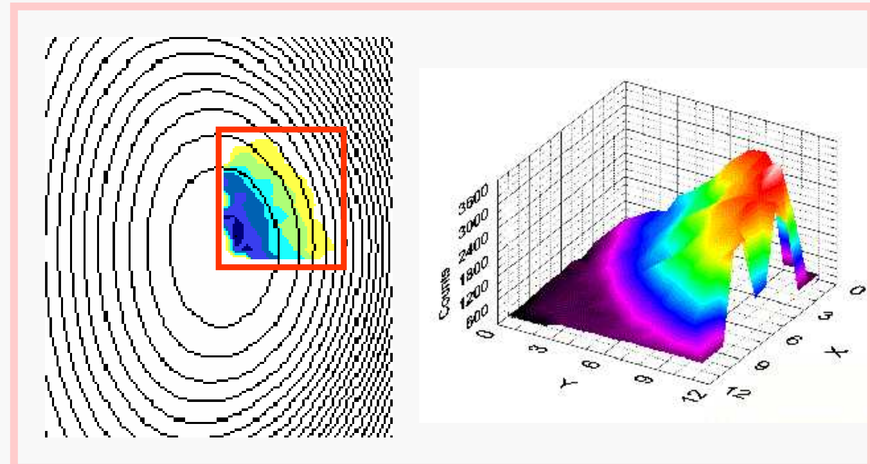
Fig. 5. Spectra of Mg (1.25 keV) with different Voltages for the anode of the X-ray source: 2.5 kV (red), 4 kV (blue), 7 kV (green). Spectra are normalized to the peak emission of the K feature.

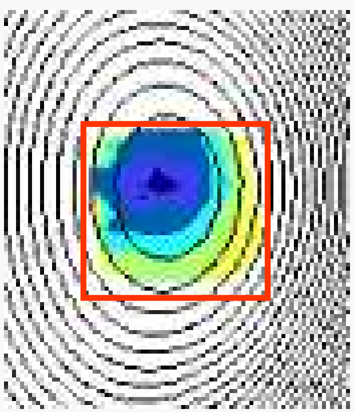
Steerable, "zoomable" x-ray pin-hole camera with tangential view
Fast spectroscopic imaging is valuable to study cross-field transport

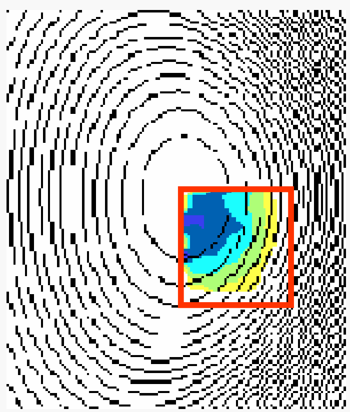
Tangential views of NSTX plasma (Madison, Wisconsin)

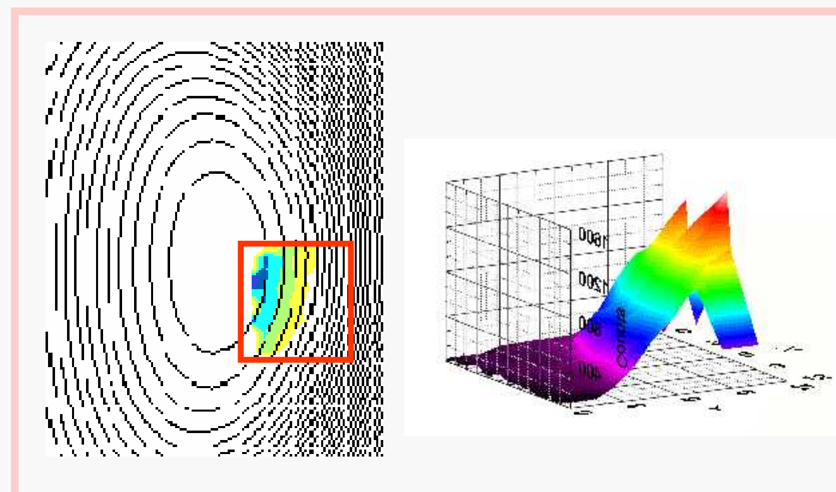




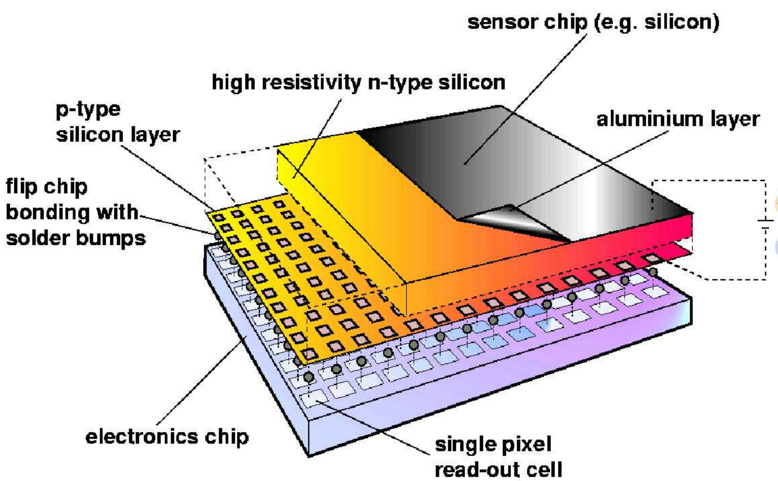








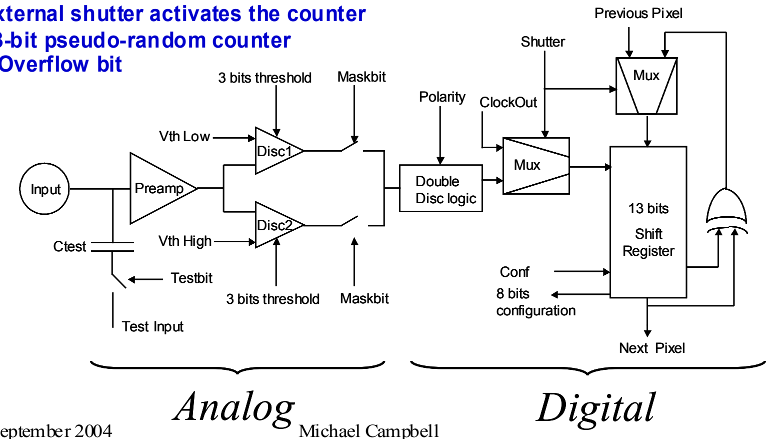
MEDIPIX2 Hybrid Pixel Detector



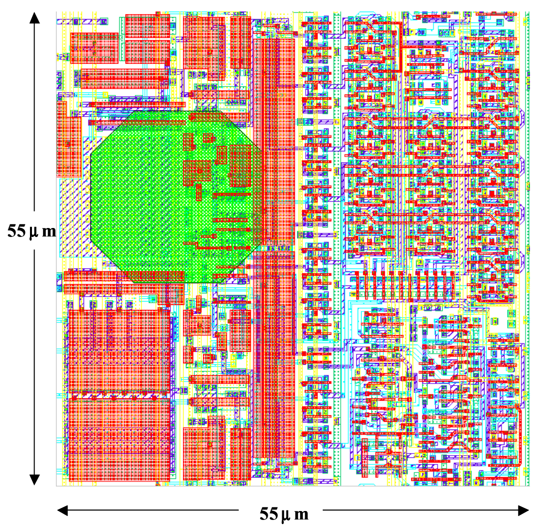
Detector and electronics readout are optimized separately

Medipix2 Cell Schematic

- Charge sensitive preamplifier with individual leakage current compensation
- 2 discriminators with globally adjustable threshold
- 3-bit local fine tuning of the threshold per discriminator
- 1 test and1 mask bit
- External shutter activates the counter
- 13-bit pseudo-random counter
- 1 Overflow bit

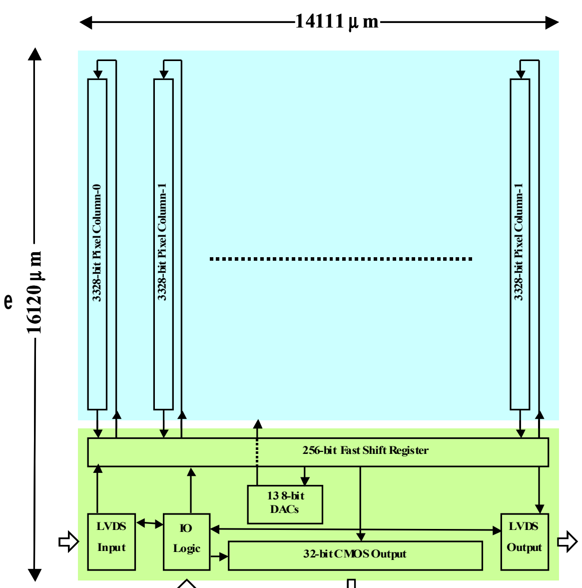


Medipix2 Cell Layout



Medipix2 Chip Architecture

256 x 256 pixels
3ms readout time

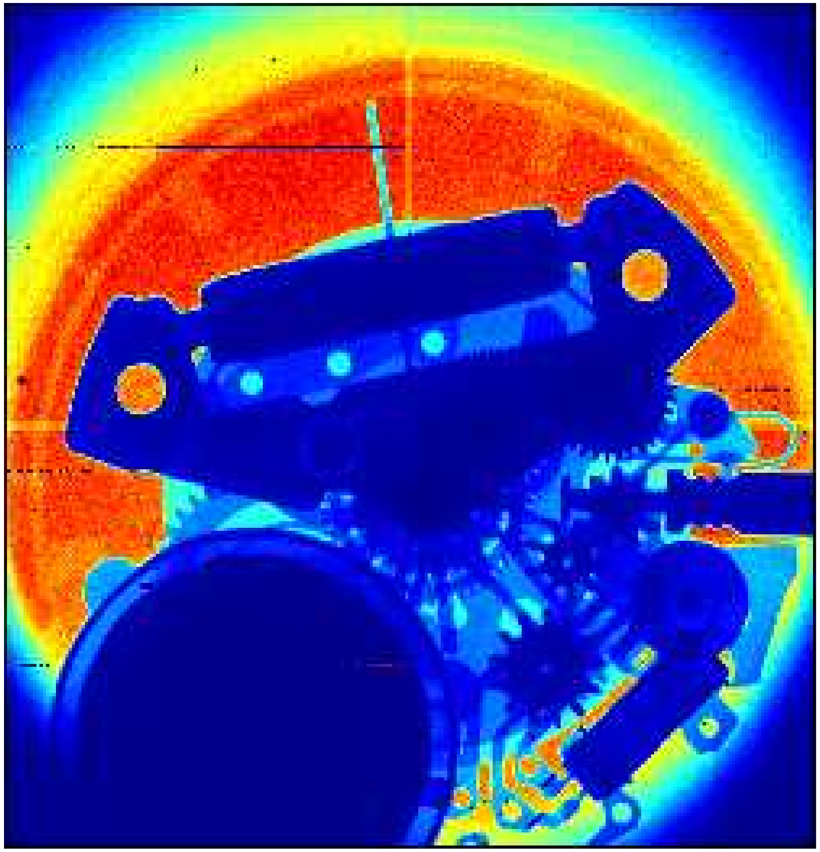


The revolution in x-ray/particle detectors

CERN Medipix II active pixel detector

Applications:

- X-ray imaging PHA
- Imaging X-ray crystal spectrometer
- Counting heavy ion beam probe
- Compact (imaging?) NPA

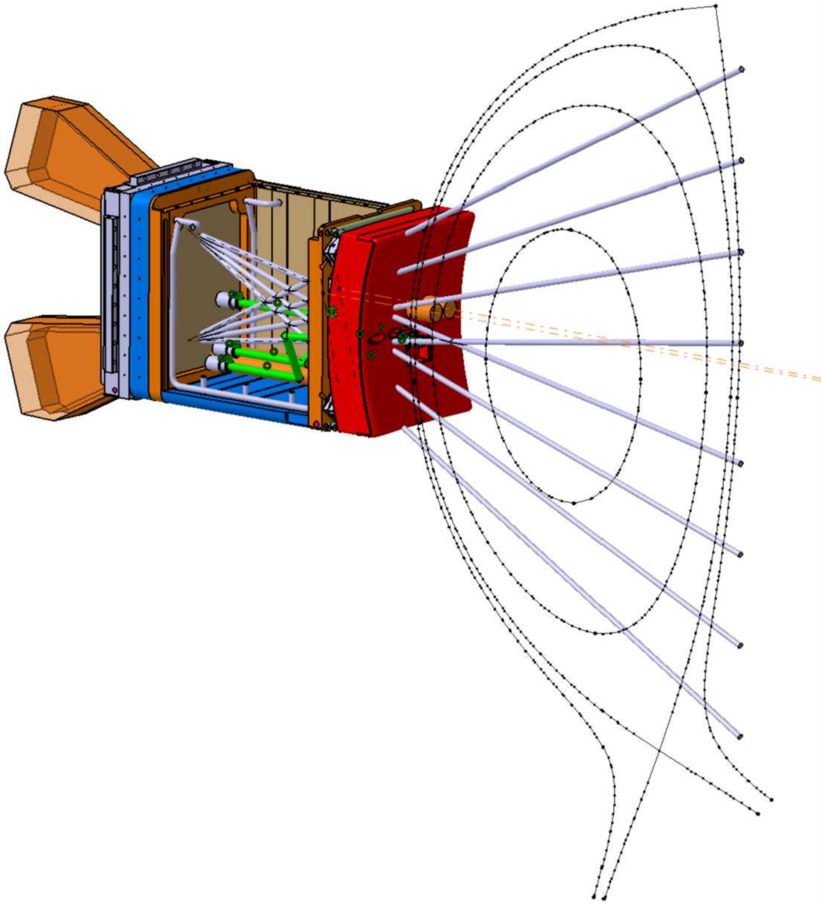


Medipix II in 2 x 2 array

Photon-counting ~ 5% energy-window at ~20 keV

Medipix II with USB interface

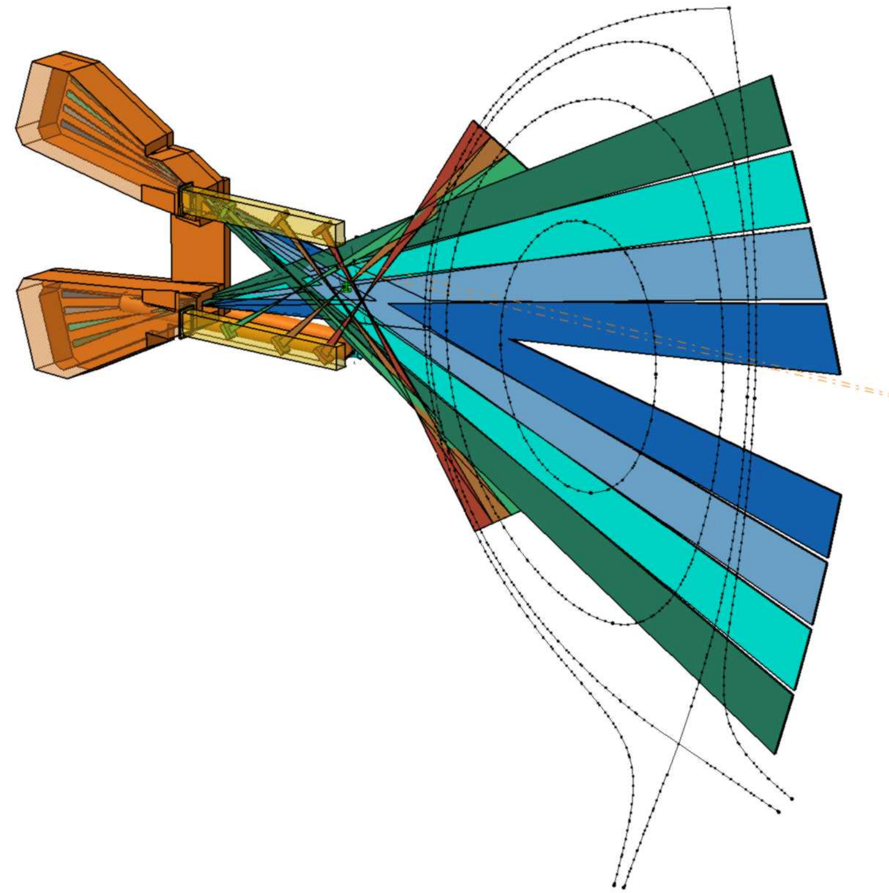
Update of ITER x-ray camera



Reference design

Based on JET D-T x-ray camera “KJ5”

Discrete chords

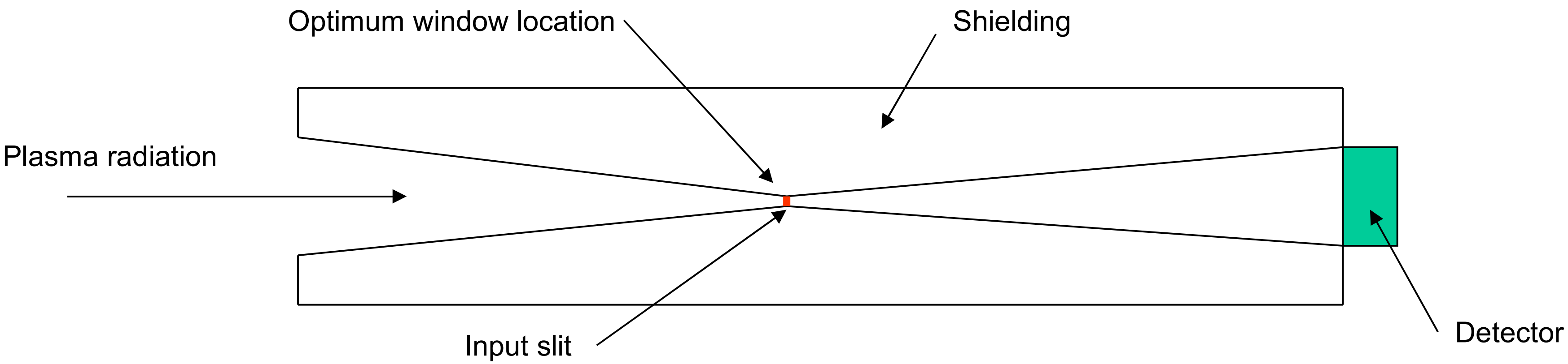


Continuous poloidal resolution

Outer plasma viewed by in-port detectors in removable cassettes

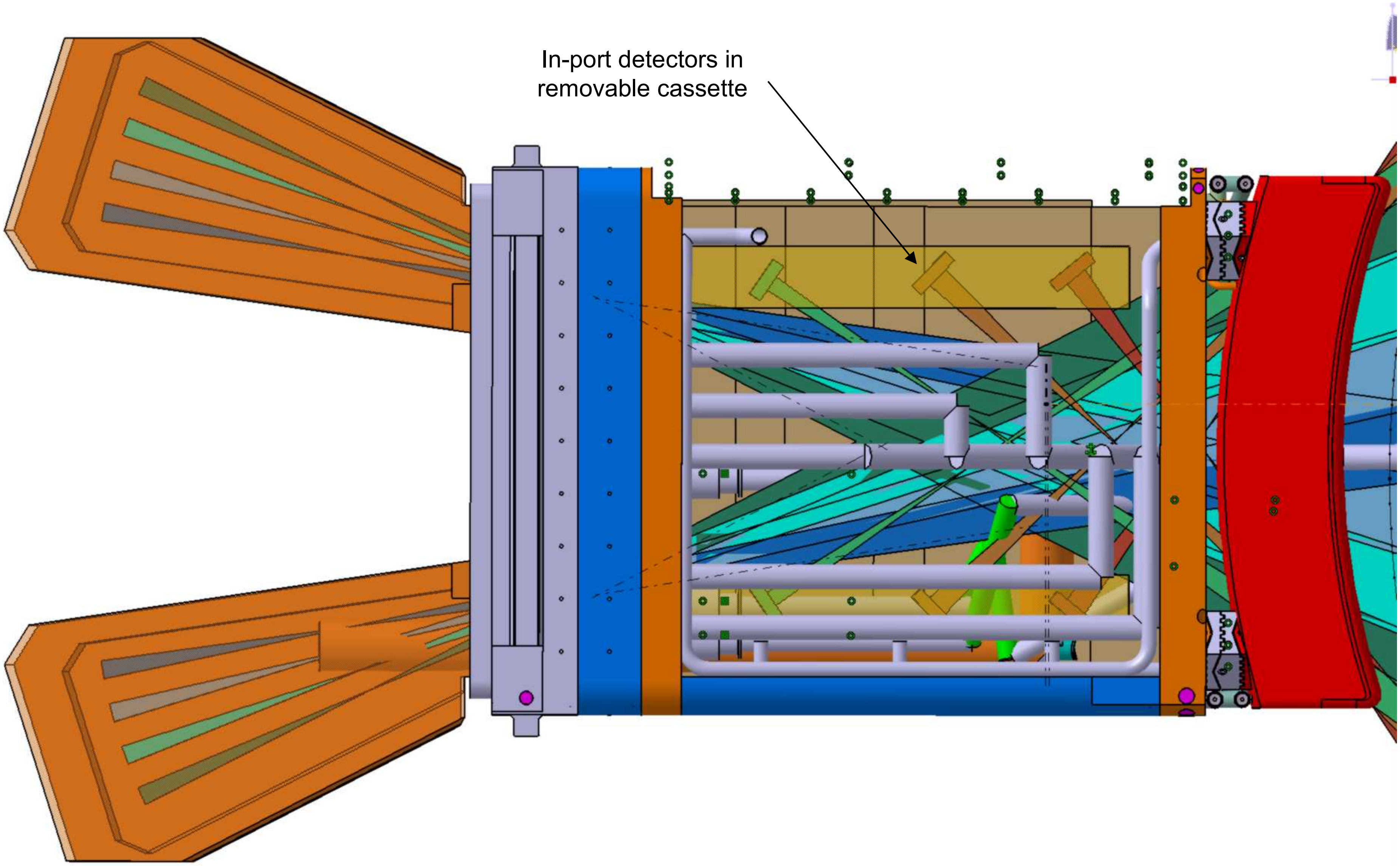
Outline parameters of ex-vessel x-ray camera module

- Narrow angle of view to maximize neutron shielding
- Window can be substantial eg 1-5 mm Be or **1-2 mm diamond**
- Detector: Fast, radiation-hard, photon-counting, energy-resolving position-sensitive detector
    - eg CERN-Medipix, PSI-Pilatus, ENEA-Pacella

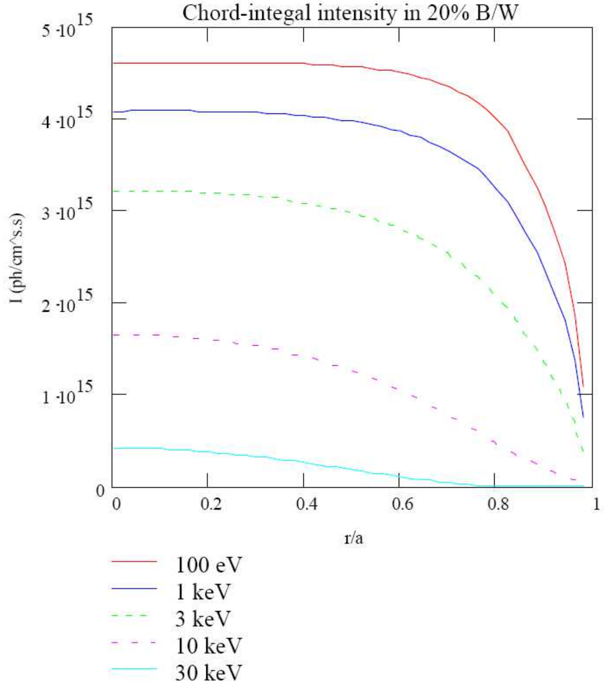


Outline dimensions		Detector performance	
- Entrance slit to detector:	~ 1 m	- 1d spatial resolution:	<~ 250 um
- Entrance slit to plasma:	~ 5 m	- Energy range:	1 – 100 keV
- Slit width x height:	1 x 5 mm^2	- Multi-channel energy resolution:	5 -15%
- Angle of view:	5 deg.	- Peak count-rate:	1.5 . 10^9 /cm^2.s
- Poloidal resolution for 1mm slit:	5 mm	- Max direct neutron flux:	6 . 10^6 /cm^2.s
- Blanket slot width:	< ~20 mm	- Time for n-fluence of 10^14 /cm^2:	~ 10^7 s

Ex-vessel x-ray camera in Eq 09



Signals, and emission reconstruction

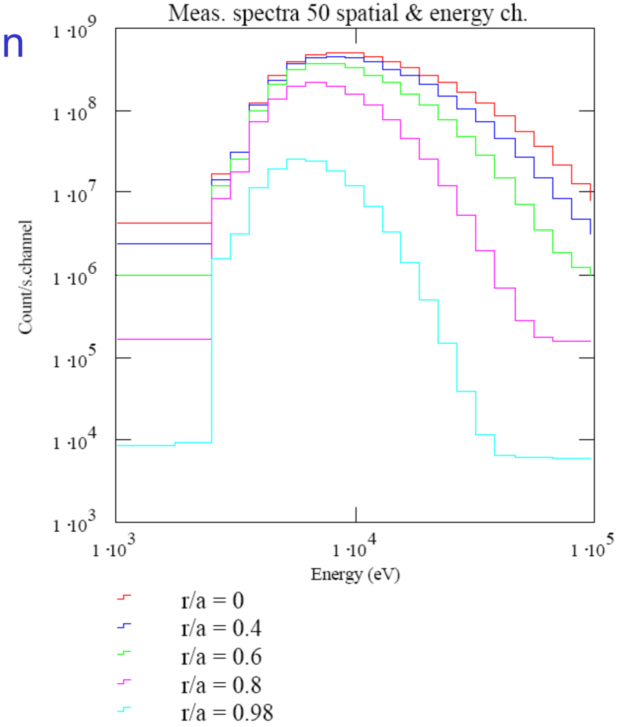


+ Instrument geometry
+ 1 mm Be window
+ Detector QDE

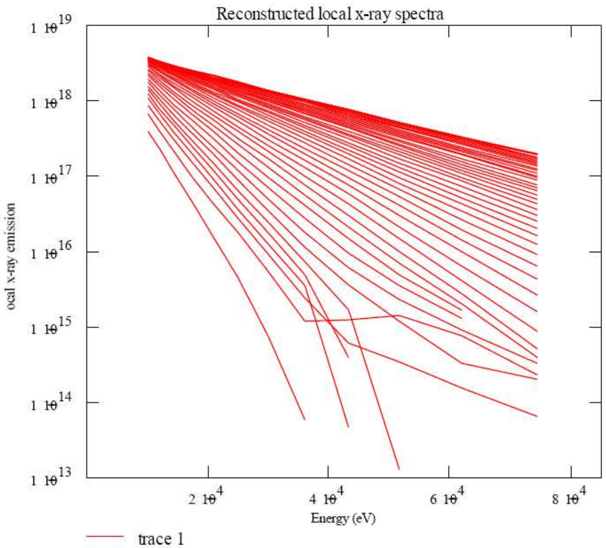
  (x-ray 0.5, and neutron 1.0)

+ Poisson counting noise
+ Neutron background

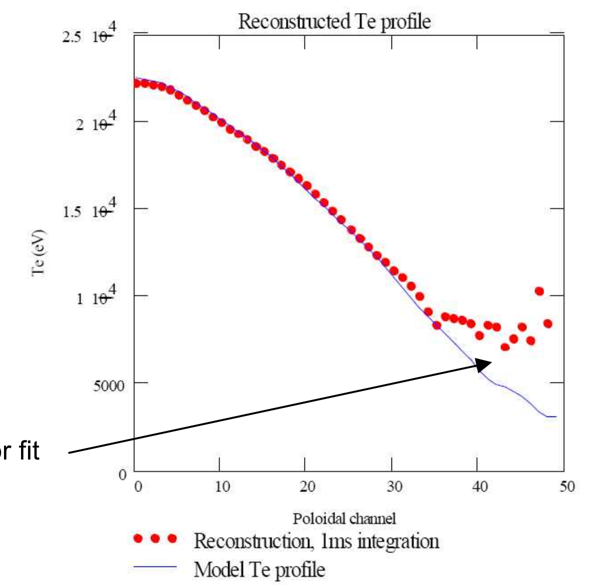
  (only direct so far)



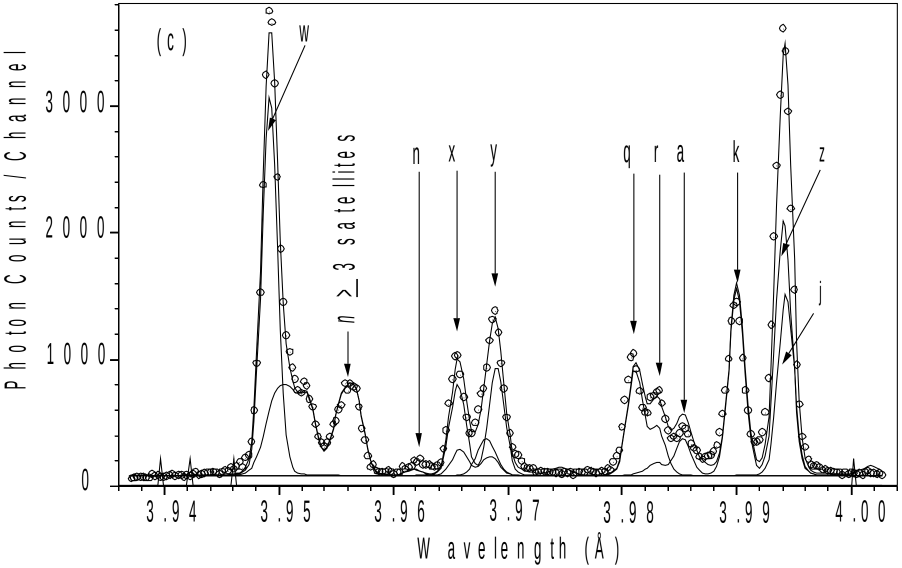
Analytic Abel inversion



Fit 1/e gradient for local Te at each chord

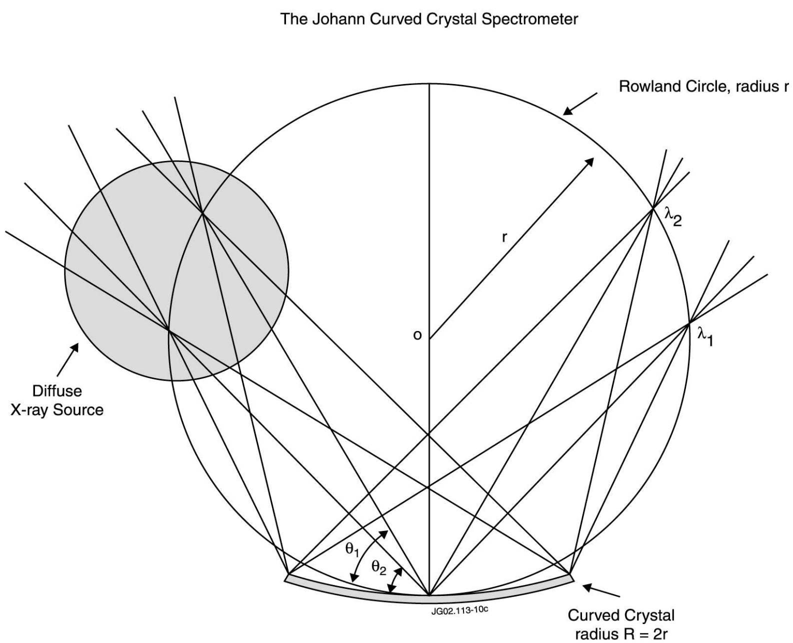


Artefact due to fixed energy range for fit at each chord. Can be improved



Te = 0.58 keV from <u>all</u> diel. satellites & line **w**; Ti = 0.45 keV

ArXVII spectrum from NSTX - Manfred Bitter



High-resolution x-ray spectroscopy

Extensively, but not exclusively, He-like ions.

~Te/Z: 250eV: Ne, 500eV,:Ar, 2keV: Fe-Ni, 10keV:Kr

Requires $\lambda/\delta\lambda$ >~ 5000, hence λ < 1.3 nm for crystals

T_i:	Doppler broadening
$V_{tor/pol}$:	Doppler shift
T_e	Dielectronic satellite ratio
n_e	Forbidden line ratio z/(x+y) (sometimes)
Z_{eff}	Continuum τ_{imp} Impurity injection
n_{imp}	Absolute calibration

Simple and reliable - bent crystal & pos. sens. detector.

Crystals are cheap dispersive elements, eg Si < 1kEur

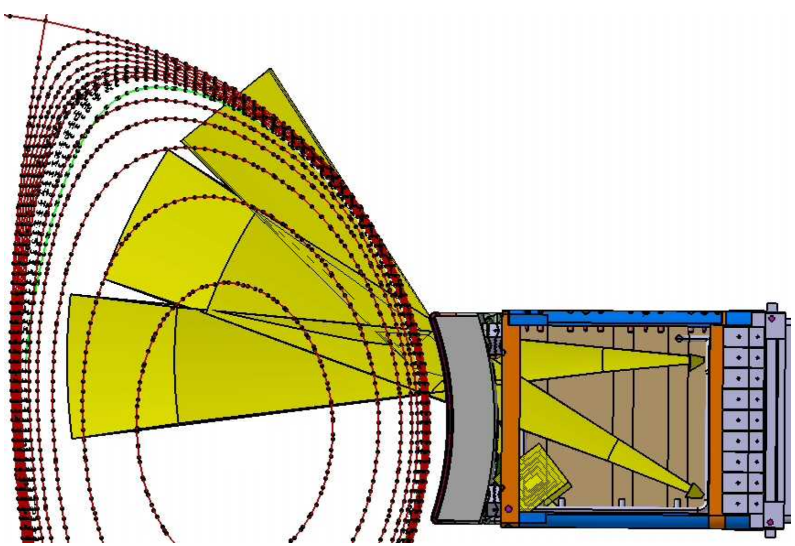
Energy resolving detector makes it doubly dispersive, with excellent signal-to-noise ratio.

All crystal-window-detector processes are volume effects, leading to calculable and stable calibration. (1 mm Carbon ~ transparent at 10 keV).

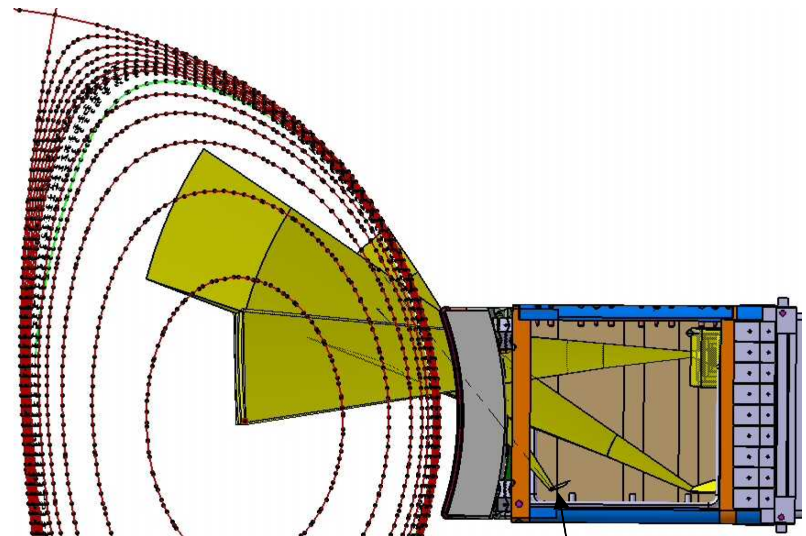
Detector developments have been the key to progress:

1st gen.	Photographic film
2nd gen.	Multiwire prop. counter, ~ 3 - 25 m radiius
3rd gen.	Solid state eg CCD, 0.5 - 2 m radius
4th gen.	Imaging with fast 2-d detector

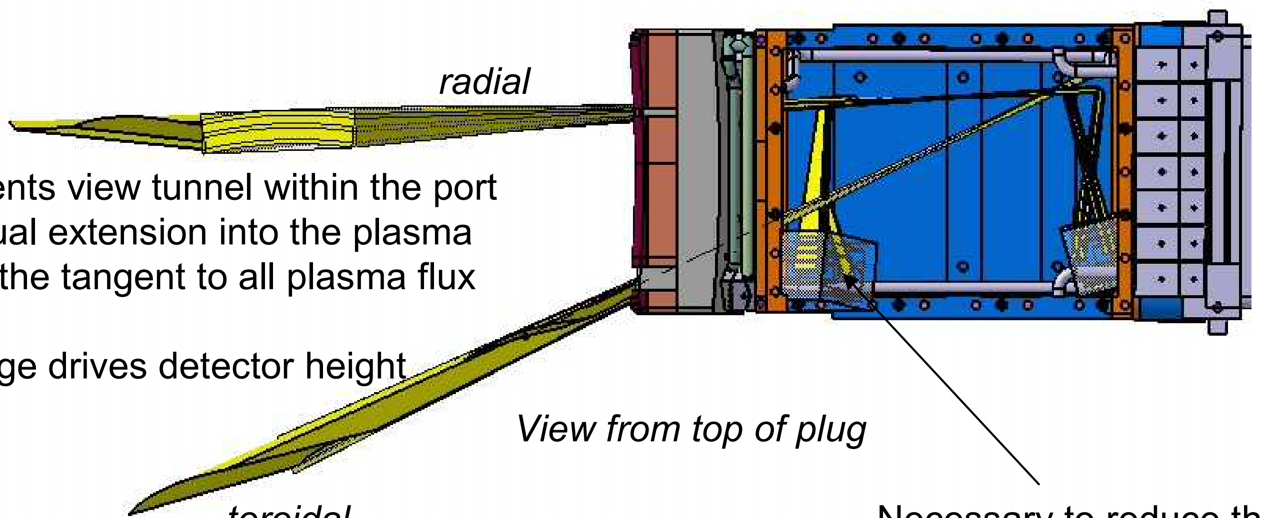
High resolution imaging crystal spectrometer for ITER



Plasma coverage by radial views



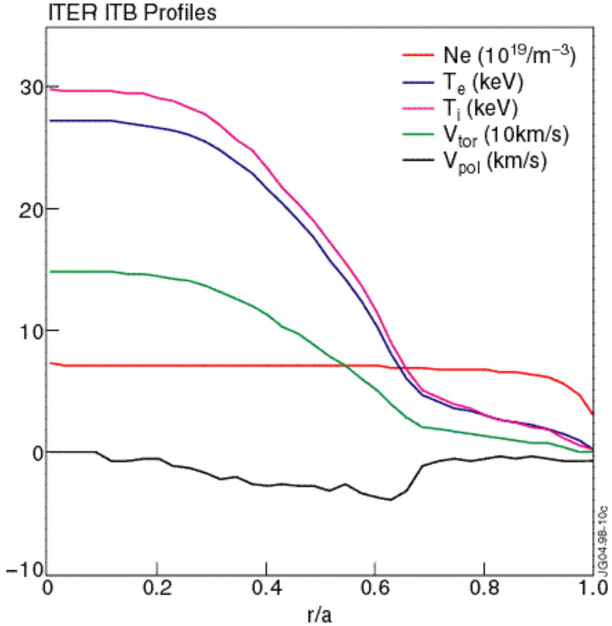
Plasma coverage by toroidal views

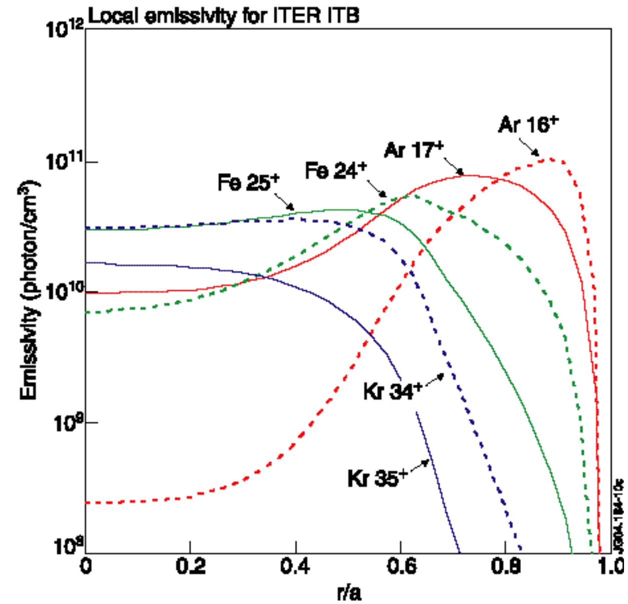


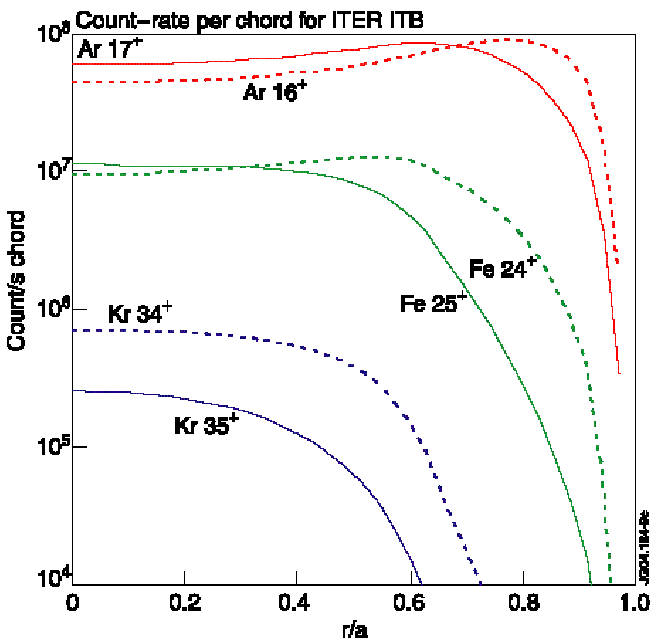
- Yellow represents view tunnel within the port plug and its virtual extension into the plasma
- Aim is to view the tangent to all plasma flux surfaces
- Spatial coverage drives detector height

Necessary to reduce the crystal-detector distance for the furthest-forward toroidal view spectrometer

ITER impurity line emission and x-ray spectrometer signals







Top left Modelled ITER radial profiles

Top right Local emissivity of impurity spectral lines

Bottom Simulated signals for imaging x-ray crystal spectrometer

Incremental radiated powers for added impurity concentrations of $10^{-5}.n_e$ are:

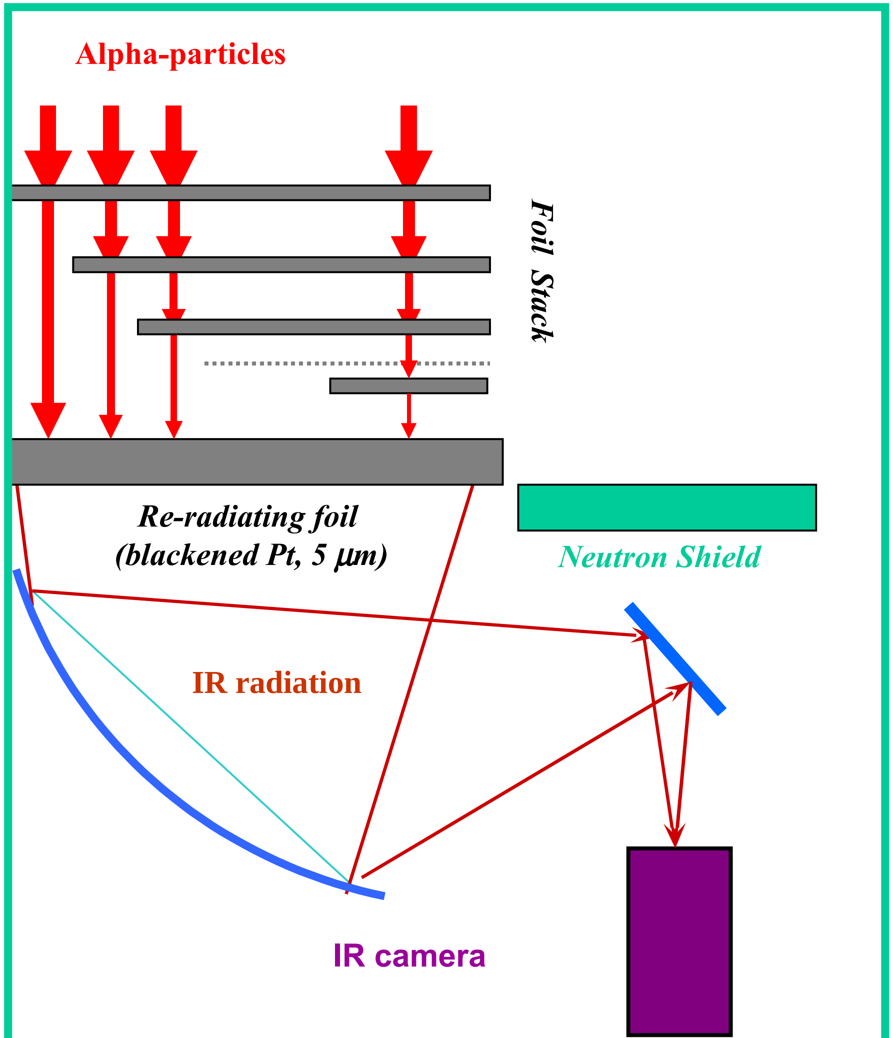
Ar: 0.25 MW Fe: 0.8 MW Kr: 1.4 MW

6. Gamma-rays and neutrons

- Nuclear reactions among fuel and light impurity nuclei
- Optics large rather than complex – slits, slots and shielding
- Neutron measurements for total power and reaction profile
- Gammas for high energy particles – alphas, non-thermal ions

- **Imaging implementations on ITER**
  - Radial neutron camera
  - Vertical neutron camera
  - Gamma-ray camera

Lost Alpha Energy Discriminator using Multi-foil Thermal Detector and Infrared Imaging Bolometer



- 2-D diagnostic uses IR camera to measure change in foil temperature (IR imaging bolometer) due to absorption of alpha particle energy
- Foil stack is used as energy discriminator in one dimension and the other dimension can be used for spatial or pitch angle resolution
- Optics are used to bring IR signal around neutron shield to IR camera
- Energy resolution is determined by number, thickness and material of foils in stack
- Immune to secondary electron emission, radiation-induced electromotive force and induced currents

B. J. Peterson, NIFS, Japan; A. G. Alekseev, TRINITI, Russia

Gamma-ray spectroscopy of nuclear reactions

γ -ray spectrometry provides information on distribution function of charged fast particles

γ -ray emission is produced by

- fusion products: p(3 MeV, 15MeV), T (1 MeV), ^{3}He(0.8 MeV), α (3.5 MeV)
- ICRF-driven ions: H, D, T, ^{3}He, ^{4}He

due to nuclear reactions with fuel and with the main impurities, Be and C

α-particle diagnosis at JET is based on the nuclear reaction ^{9}Be(α,nγ)^{12}C

Nuclear reactions observed in JET involving fast ...

deuterons

^{9}Be(d,pγ)^{10}Be
^{9}Be(d,nγ)^{10}B
^{12}C(d,pγ)^{13}C

protons

D(p,γ)^{3}He
T(p,γ)^{4}He
^{9}Be(p,γ)^{10}B
^{9}Be(p,p'γ)^{9}Be
^{9}Be(p,α γ)^{6}Li
^{12}C(p,p'γ)^{12}C

tritons

T(d,γ)^{5}He
^{9}Be(t,nγ)^{11}B
^{12}C(t,γ)^{15}N
^{12}C(t,nγ)^{14}N
^{12}C(t,$\alpha\gamma$)^{11}B

^{3}He

D(^{3}He,γ)^{5}Li
^{9}Be(^{3}He,pγ)^{11}B
^{9}Be(^{3}He,nγ)^{11}C
^{9}Be(^{3}He,dγ)^{10}B
^{12}C(^{3}He,pγ)^{14}N

^{4}He and α's

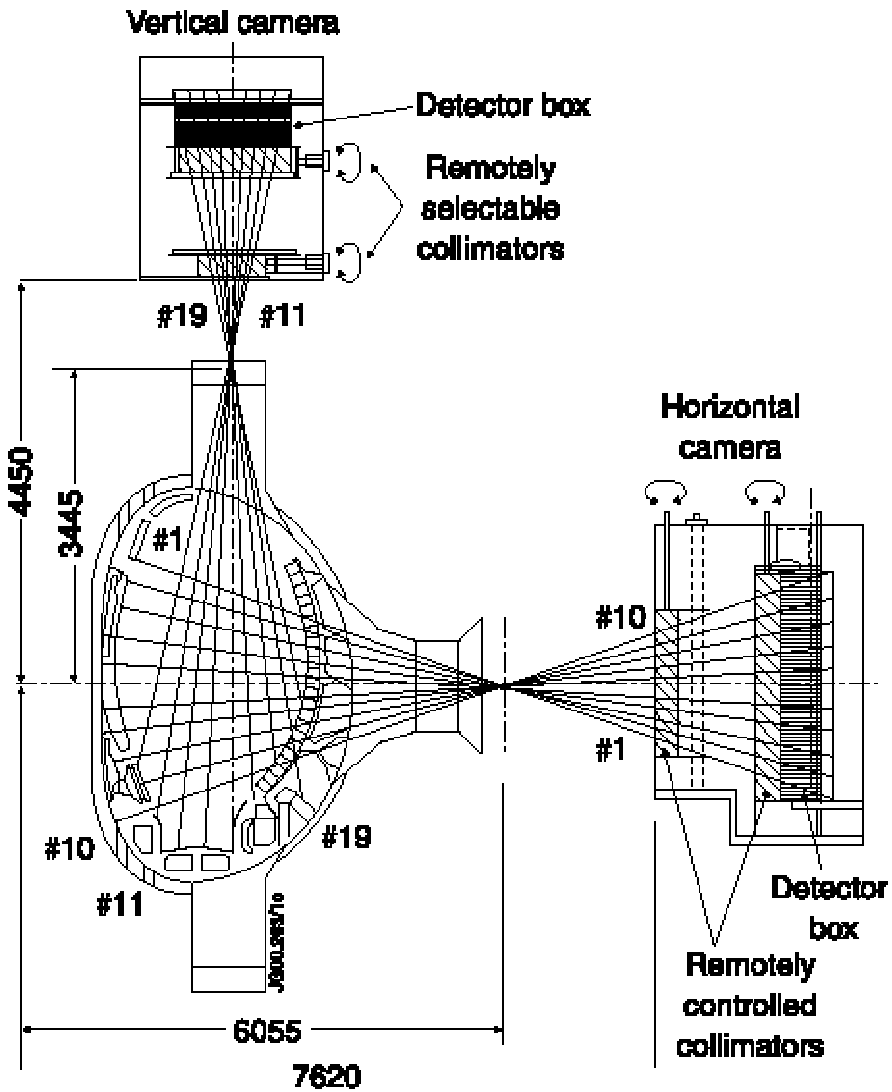
^{9}Be(α,nγ)^{12}C

Spectroscopic γ-ray imaging of fast ions

V Kiptily, 31th EPS Meeting, London, 2004

UKAEA Fusion Working in Europe

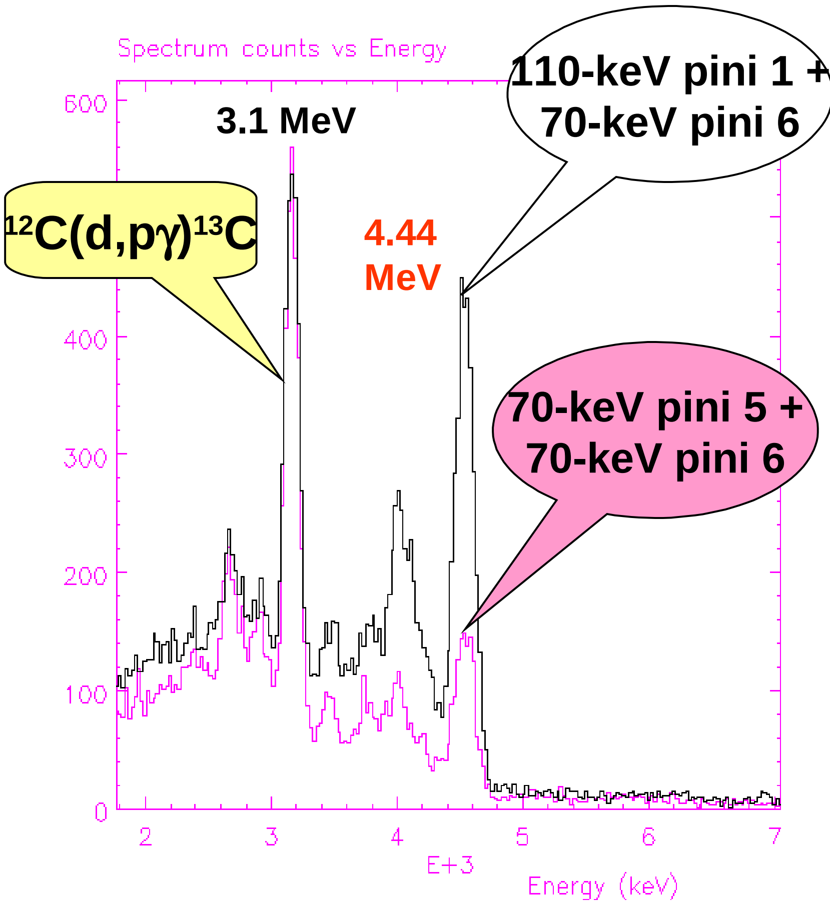
Gamma-ray camera - shared with neutron camera



On **JET** γ -ray emission profile measurements provide information about spatial distribution of fast alphas

- **vertical camera - 9 lines-of-sight**
- **horizontal camera - 10 lines-of-sight**
- **Collimators: Ø10 and 21 mm**
- **Space resolution: 10 cm in centre**
- **γ-Detectors: 10x10x15 mm CsI-diodes**

Acceleration of ^{4}He and D-ions in 3rd harmonic Ion Cyclotron RF heating experiments



Nuclear reactions:

$^{9}Be(\alpha,n\gamma)^{12}C$ and $^{12}C(d,p\gamma)^{13}C$

γ-ray spectra are used for the ^{4}He-and D-ion tail temperature and slowing-down time assessments.

Kiptily V , Nucl. Fusion 42, 999 (2002)

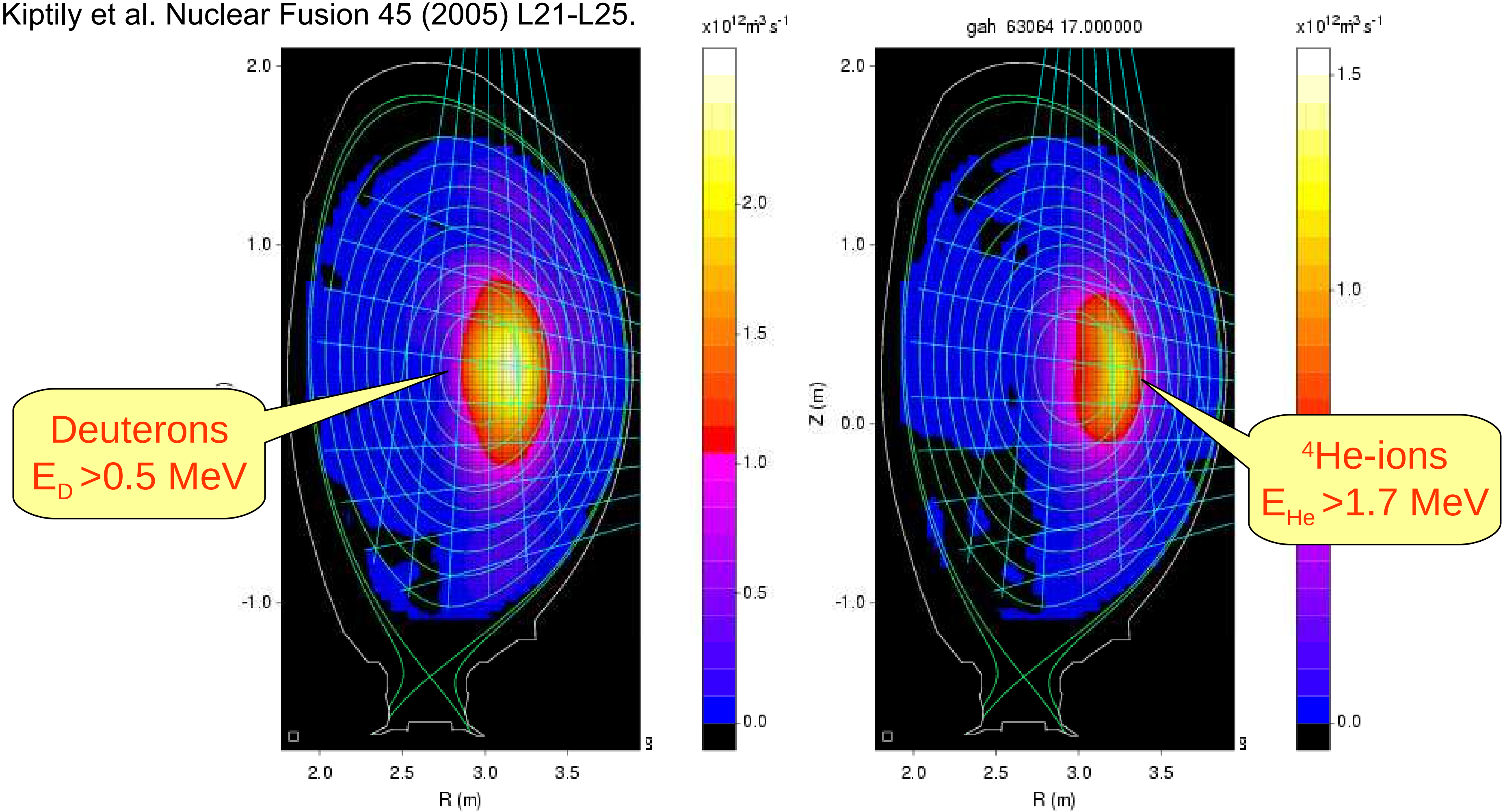
The tail-like ^{4}He energy-distribution function is similar to the fusion α distribution in the TTE.

Typical tail-temperature in these experiments: $\langle T\rangle_{He}$ ~ 300 - 700 keV

Simultaneous spectroscopic γ-ray imaging of ^{4}He and D-ions

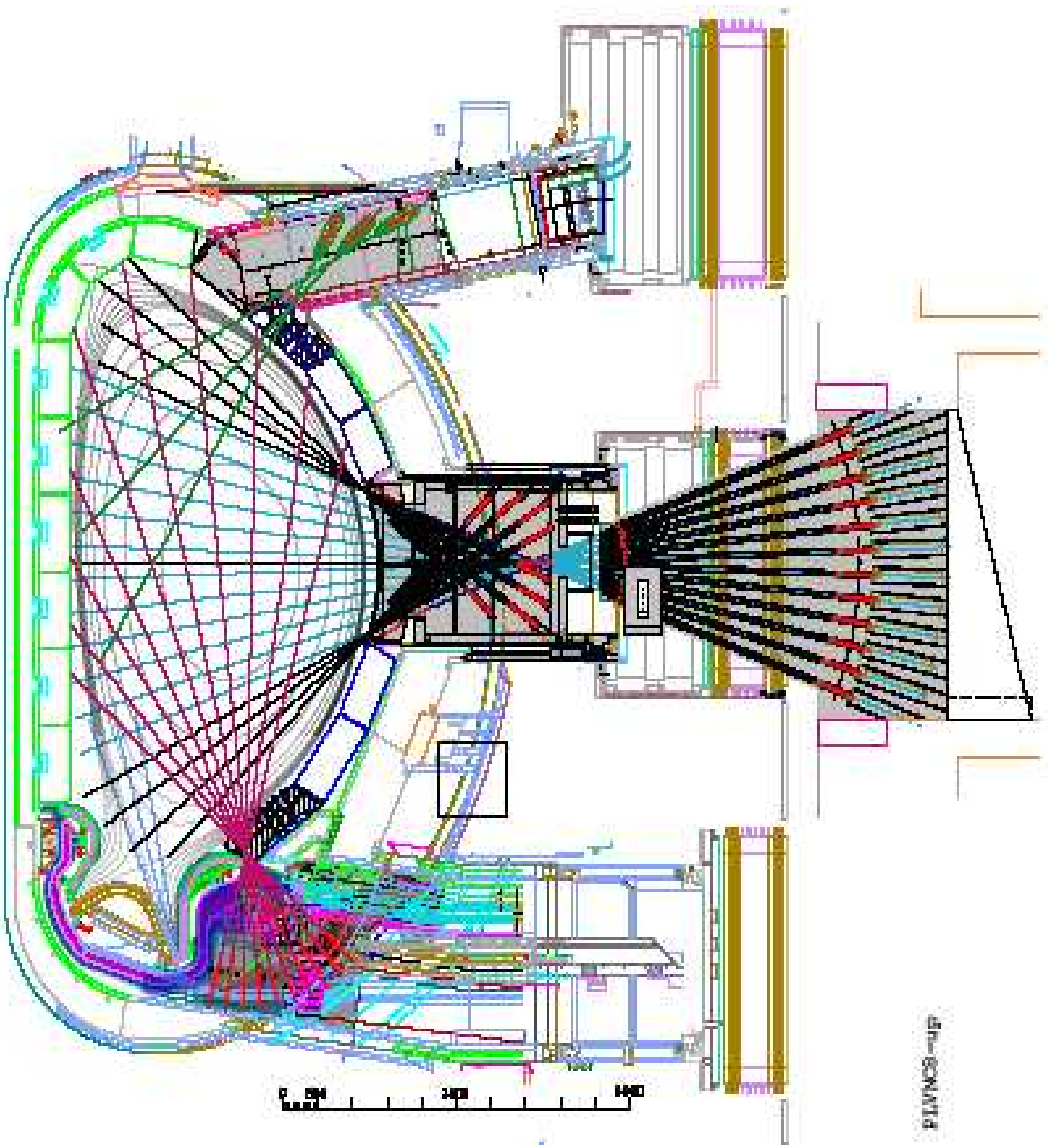
$^{12}C(d,p\gamma)^{13}C$, 3.1 MeV and $^9Be(\alpha,n\gamma)^{12}C$, 4.44 MeV

Kiptily et al. Nuclear Fusion 45 (2005) L21-L25.



7.8 MW ICRH with co-current wave launch, 2 MW NBI, monotonic q-profile

Neutron and γ-cameras for ITER



Radial camera

- 20 Views total
- 12 ex-vessel
- 8 in-vessel – dictated by narrow port

Vertical camera

- Required to detect in-out asymmetry
- Difficult to integrate
- Divertor location favoured

Instrumentation

- Counters and spectrometers
- Fission chambers for neutrons
- Scintillators for gammas and neutrons
- Natural and CVD diamonds

Summary

Fusion research in general

- There is a move from discrete views towards imaging instruments and detectors.

  New developments in micro-wave

  Already in IR, Visible, x-ray

  Required for VUV

  Potential for gamma-ray

ITER diagnostics

- We need fast, 2d, radiation-hard, photon-counting detectors with background rejection.
- Reference diagnostic designs are based on current technology – often conservative.
- Improved radiation hardness and background rejection would improve performance:

  More open apertures

  Reduced labyrinths

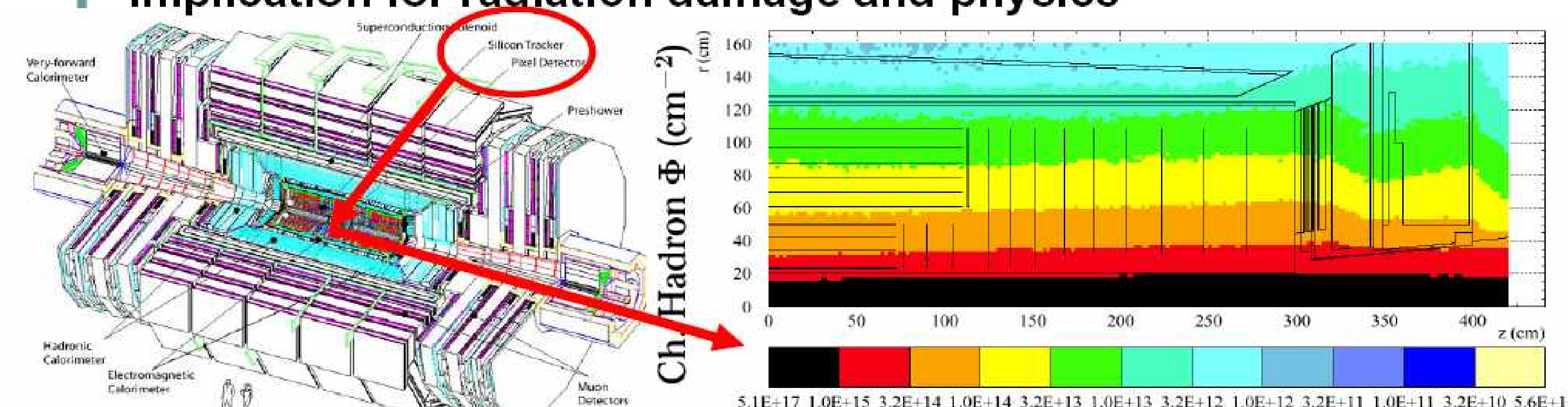
  Detector closer to plasma

SLHC and tracking

	LHC (2007)	SLHC (2015)
Proton Energy:	7 TeV	12.5 TeV
Collision rate:	40 MHz	80 MHz
Peak luminosity:	10^{34} $cm^{-2} \times s^{-1}$	10^{35} $cm^{-2} \times s^{-1}$
Int. luminosity:	500 fb^{-1}	2500 fb^{-1}

~ 100 pile-up events per bunch crossing for 12.5 ns bunch spacing compared to ~20 at 10^{34} cm^{-2} s^{-1} and 25 ns

- **If same granularity and integration time as now, the tracker occupancy and radiation dose increases by a factor of 10 ⇒ implication for radiation damage and physics**

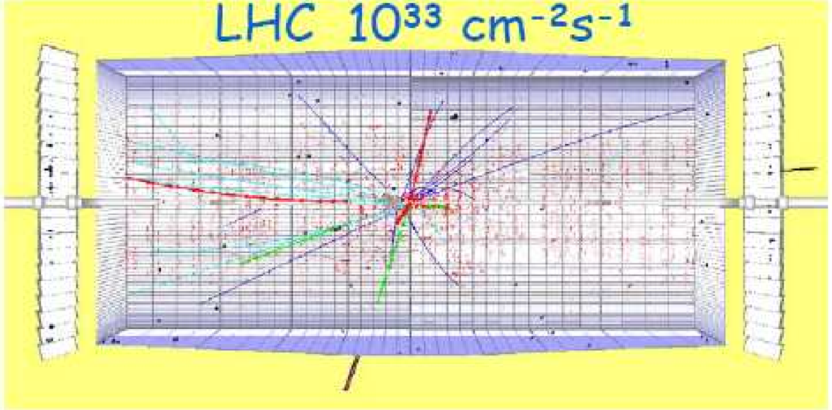


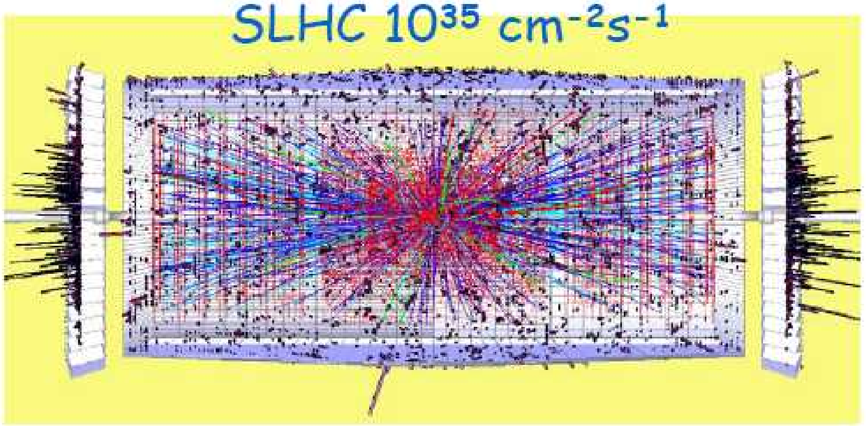
M. Hutinen: "Radiation issues for Super-LHC", SLHC Electronics Workshop, 26/2/04, CERN

SLHC and tracking

- $dn^{cha}/d\eta$/crossing ≈600 and ≈3000 tracks in tracker ⇒more granularity if we aim at same performance we expect from the LHC trackers

H→ZZ→eeμμ m(higgs)=300 GeV all tracks with p_T<1 GeV removed





- **Integrated Luminosity** (radiation damage) dictates the detector **technology**
- **Instantaneous rate** (particle flux) dictates the detector **granularity**

R (cm)	Φ (p/cm^{2})	Technology
>50	10^{14}	Present p-in-n (or n-in-p)
20-50	10^{15}	Present n-in-n (or n-in-p)
<20	10^{16}	RD needed

Daniela Bortoletto Vertex 2005 Nikko Japan 7