Lecture for the ITER International Summer School,

Aix-en-Provence, France, June 22-26, 2009

Plasma Boundary Diagnostics in ITER

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ITER Diagnostic Division

Diagnostics are key part of tokamak research

They provide the reality-check for our physics understanding

In this lecture:

Introduction to ITER Diagnostics

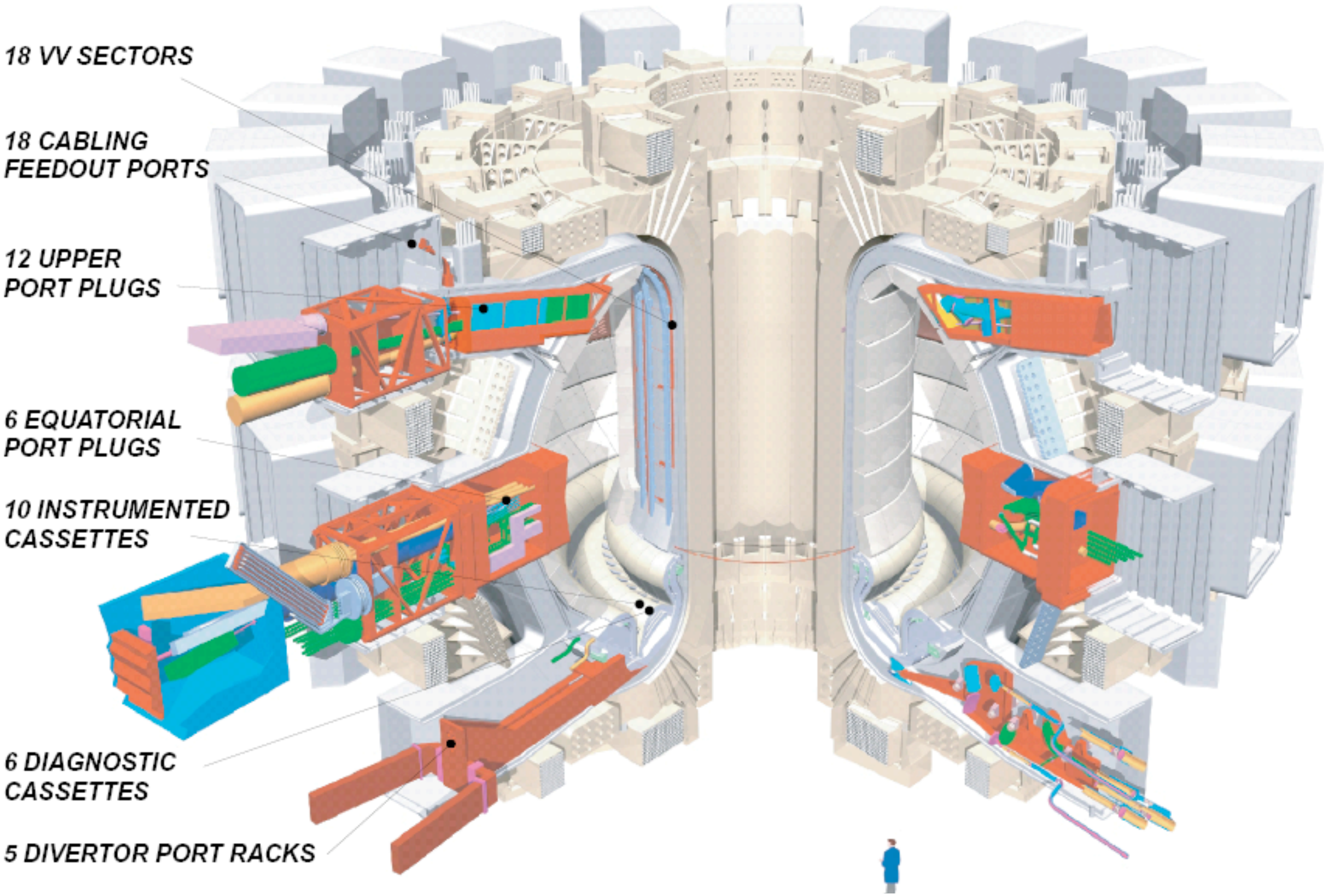
From the boundary physics and first-wall point of view, what measurements are required?

Why are these important?

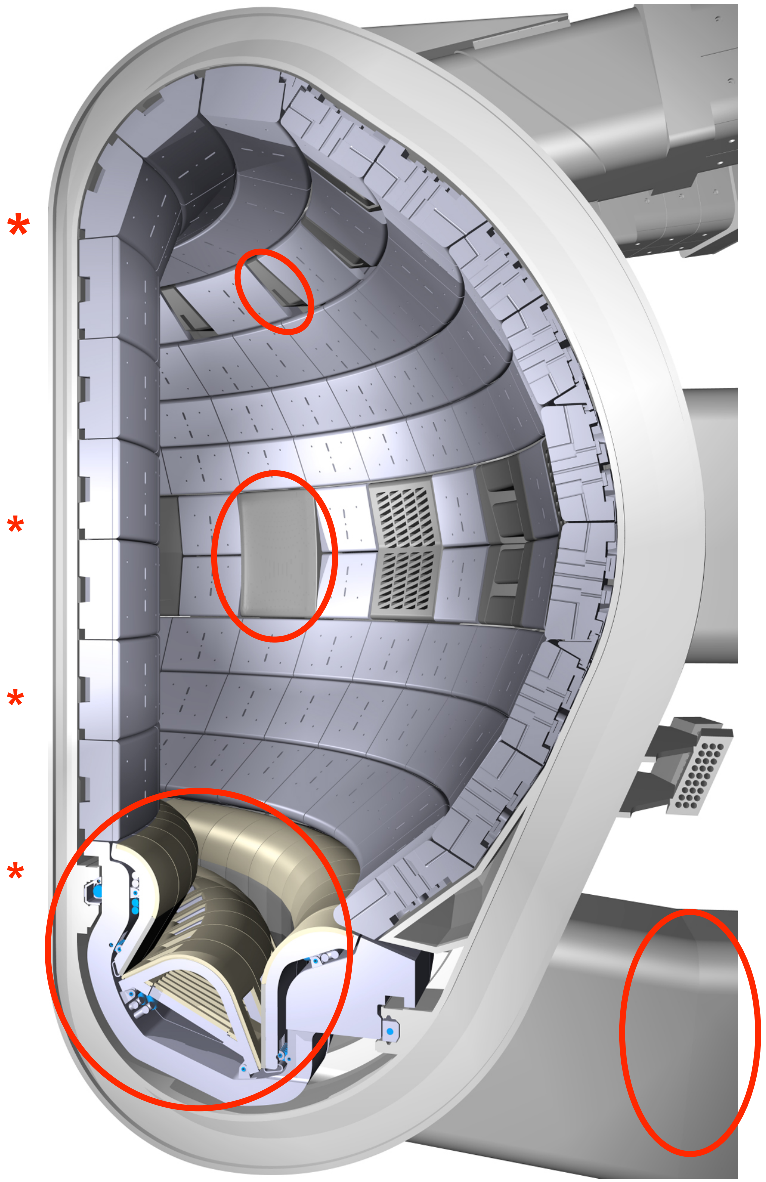
How are these measurements made?

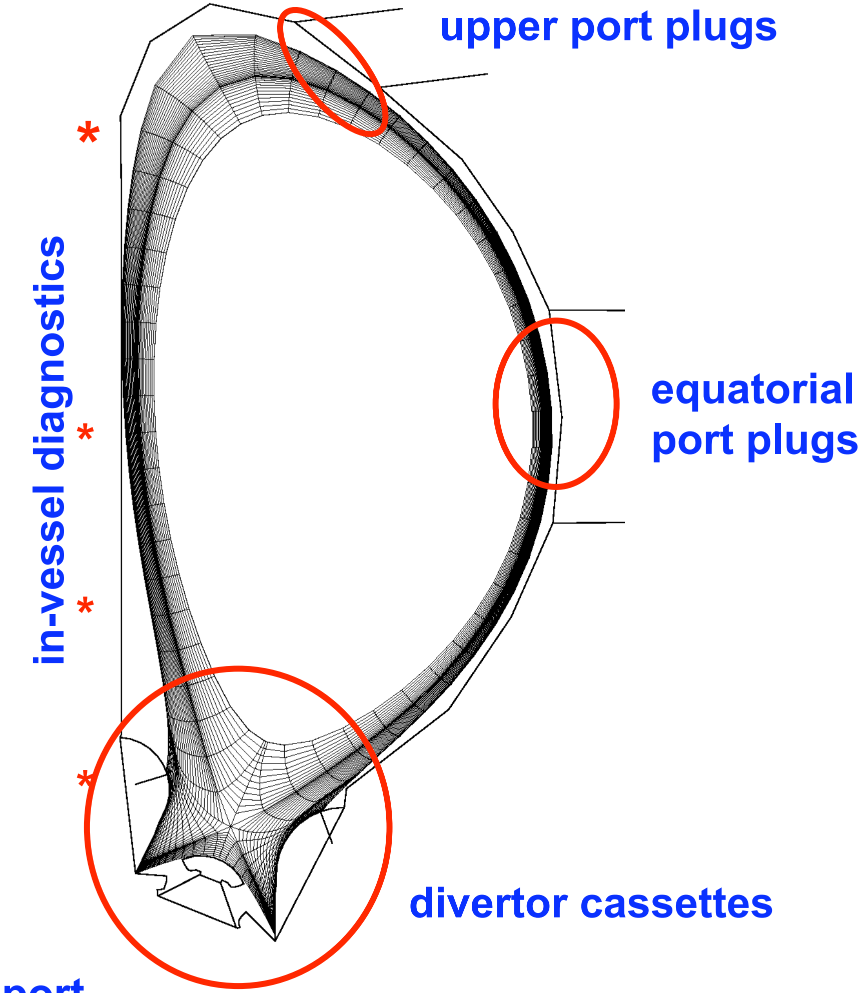
What are the unique problems faced in ITER in comparison to previous tokamaks?

3 levels of diagnostic ports



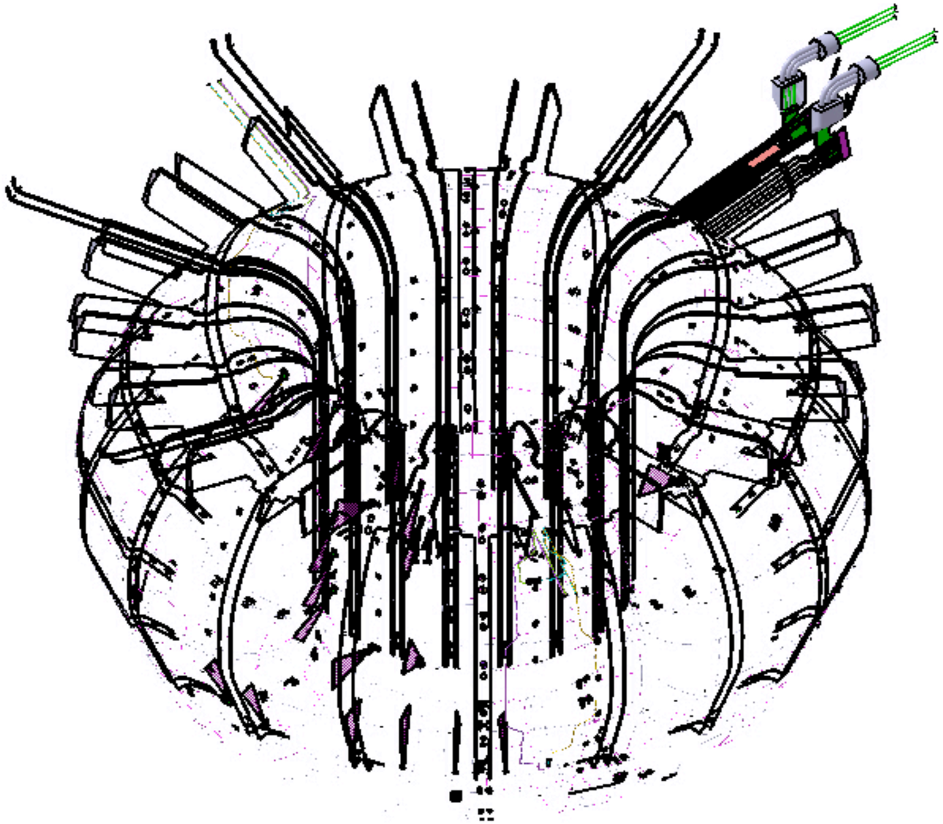
Diagnostic Locations





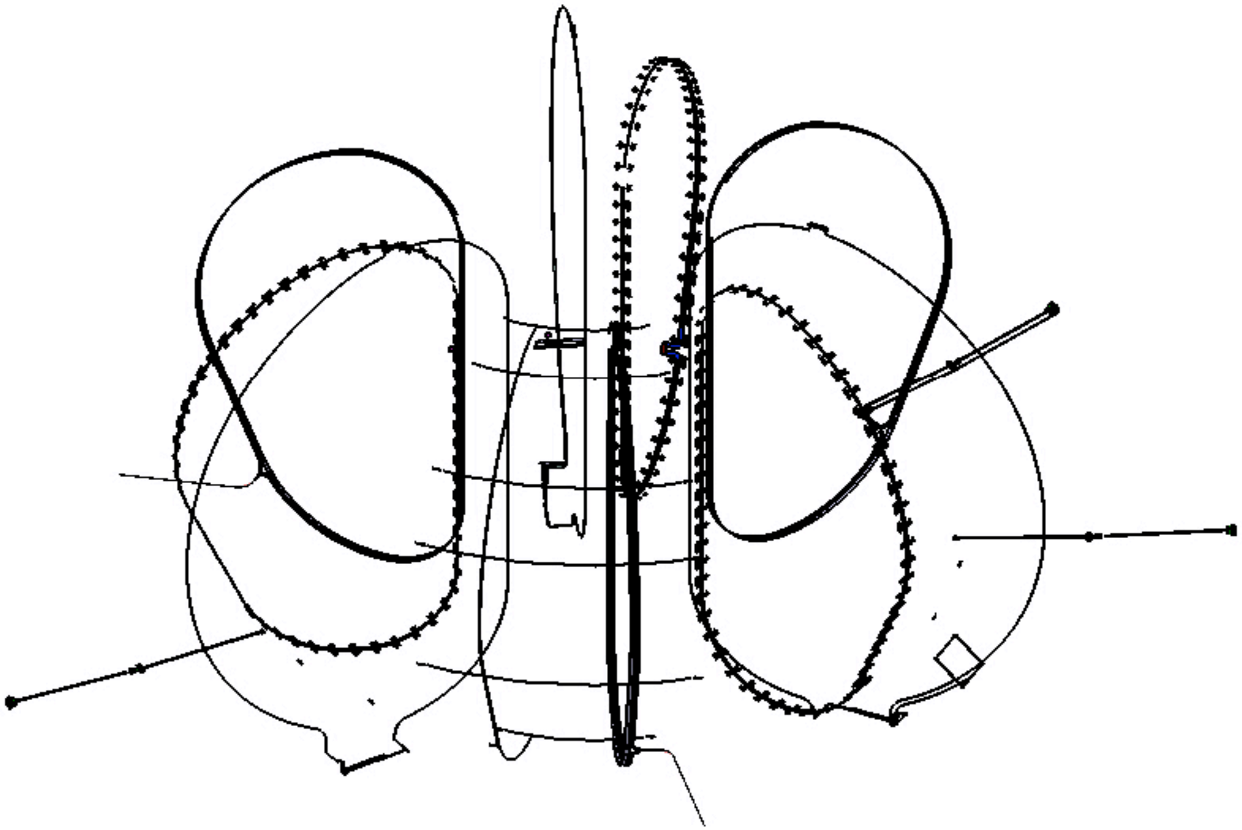
In-Vessel

Distributed Diagnostics

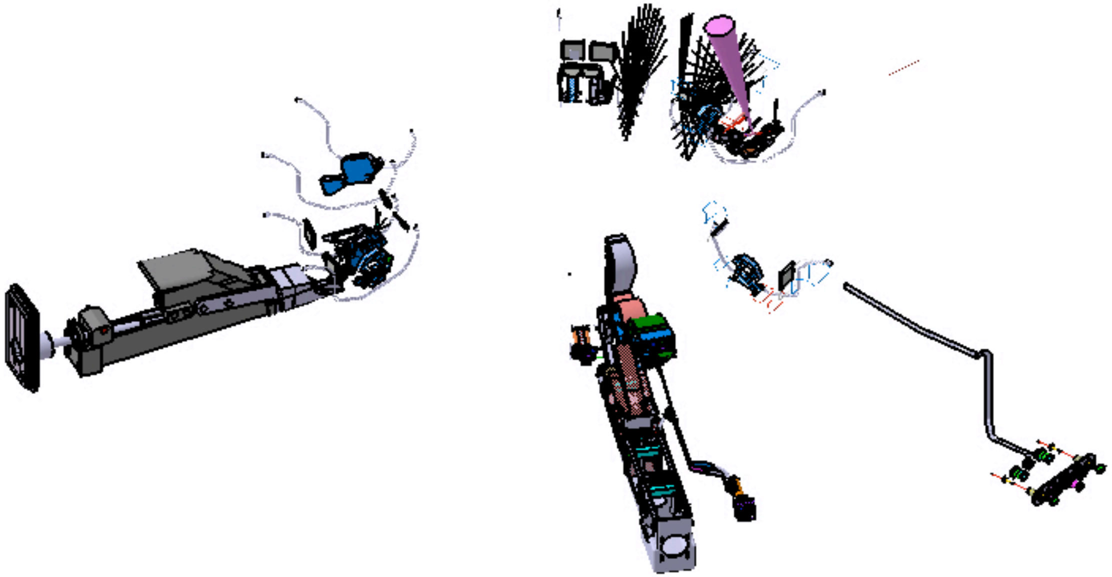


Ex-Vessel

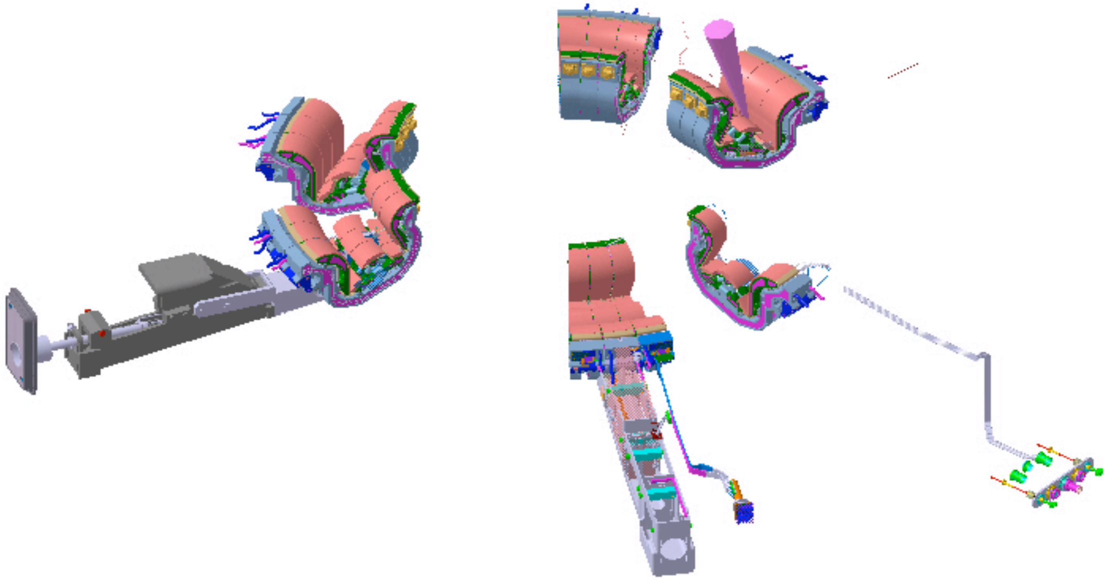
Distributed Diagnostics



Divertor Diagnostics (electrical)

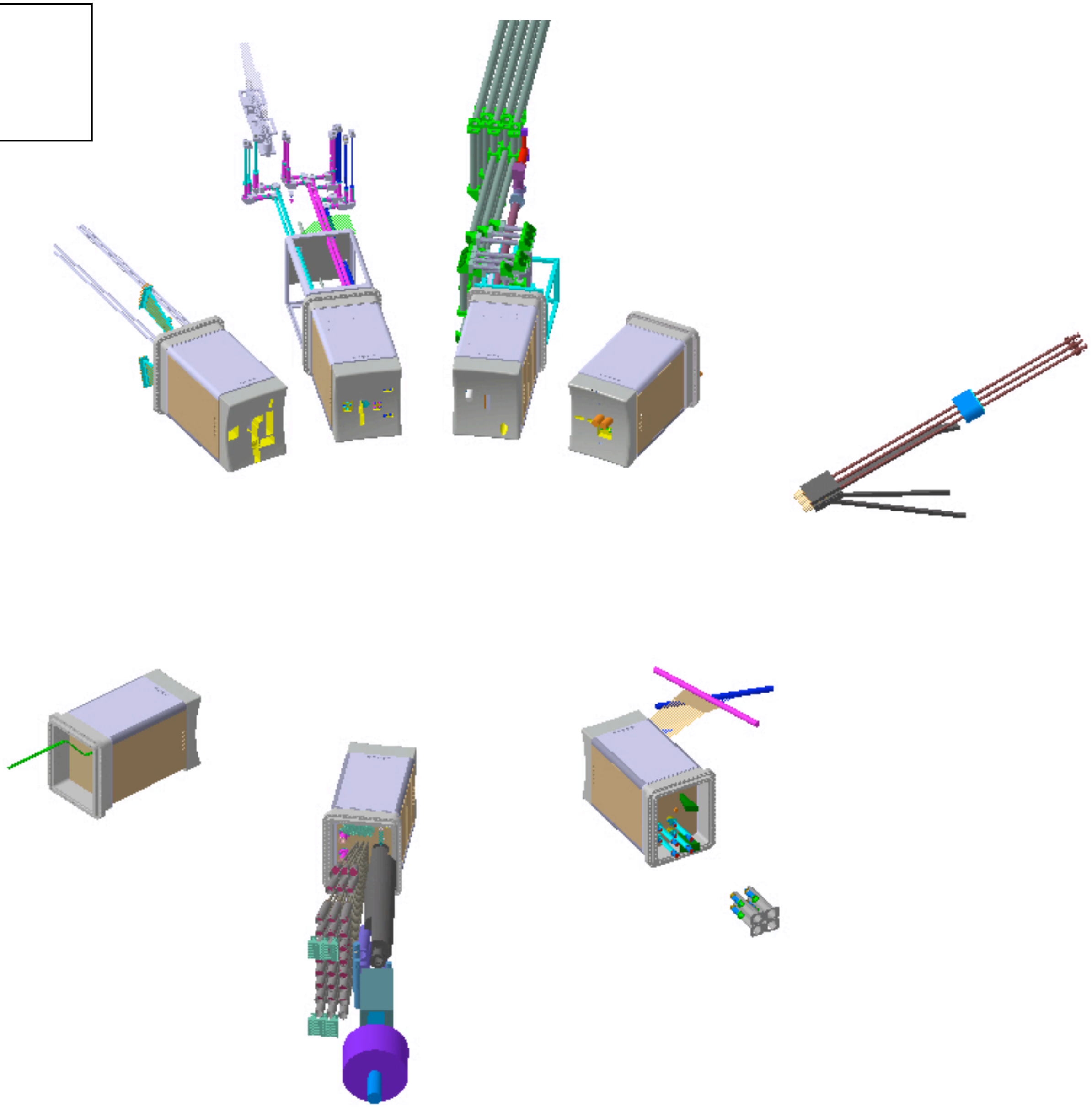


Divertor Diagnostics (optical)

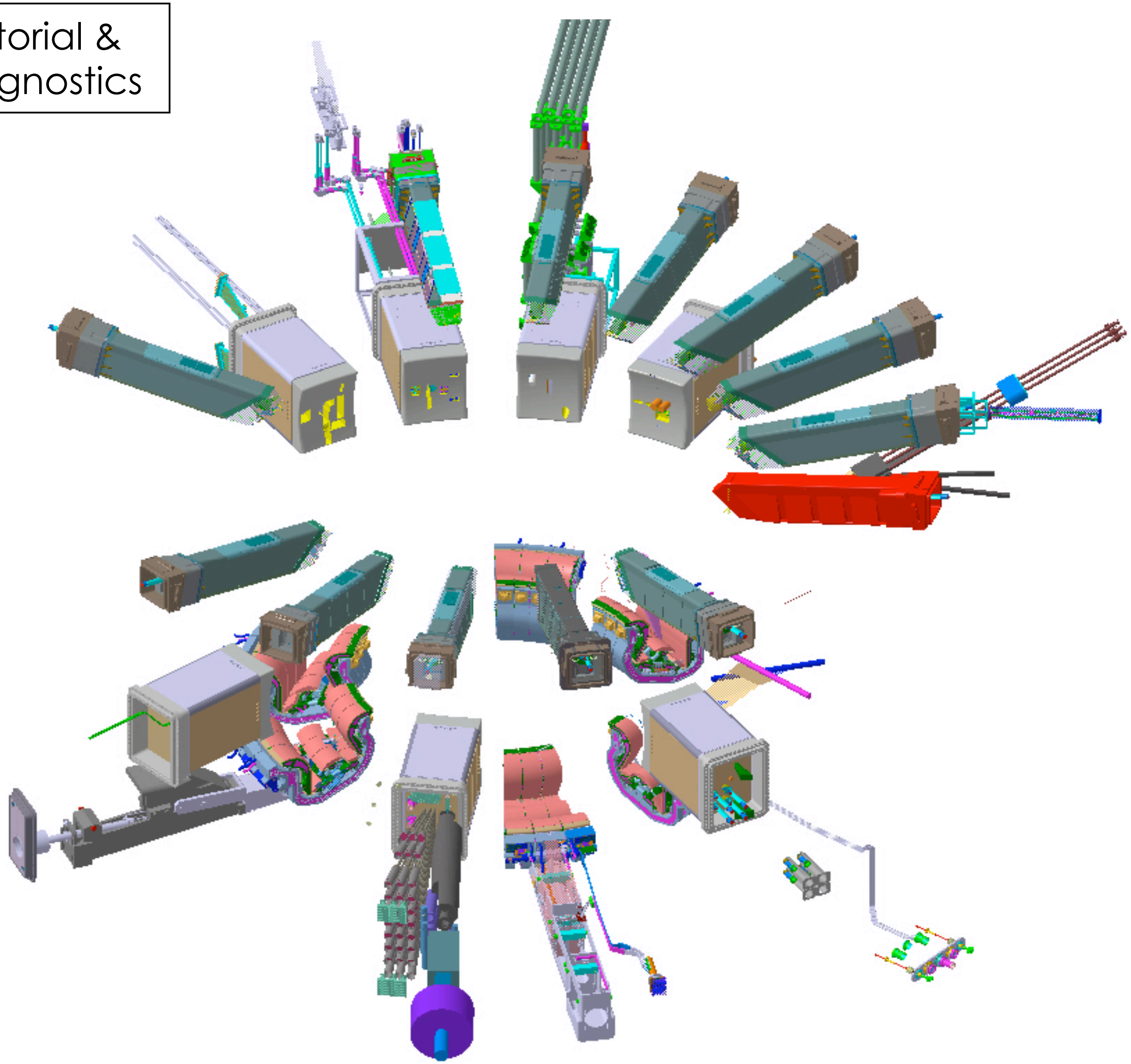


Equatorial Port

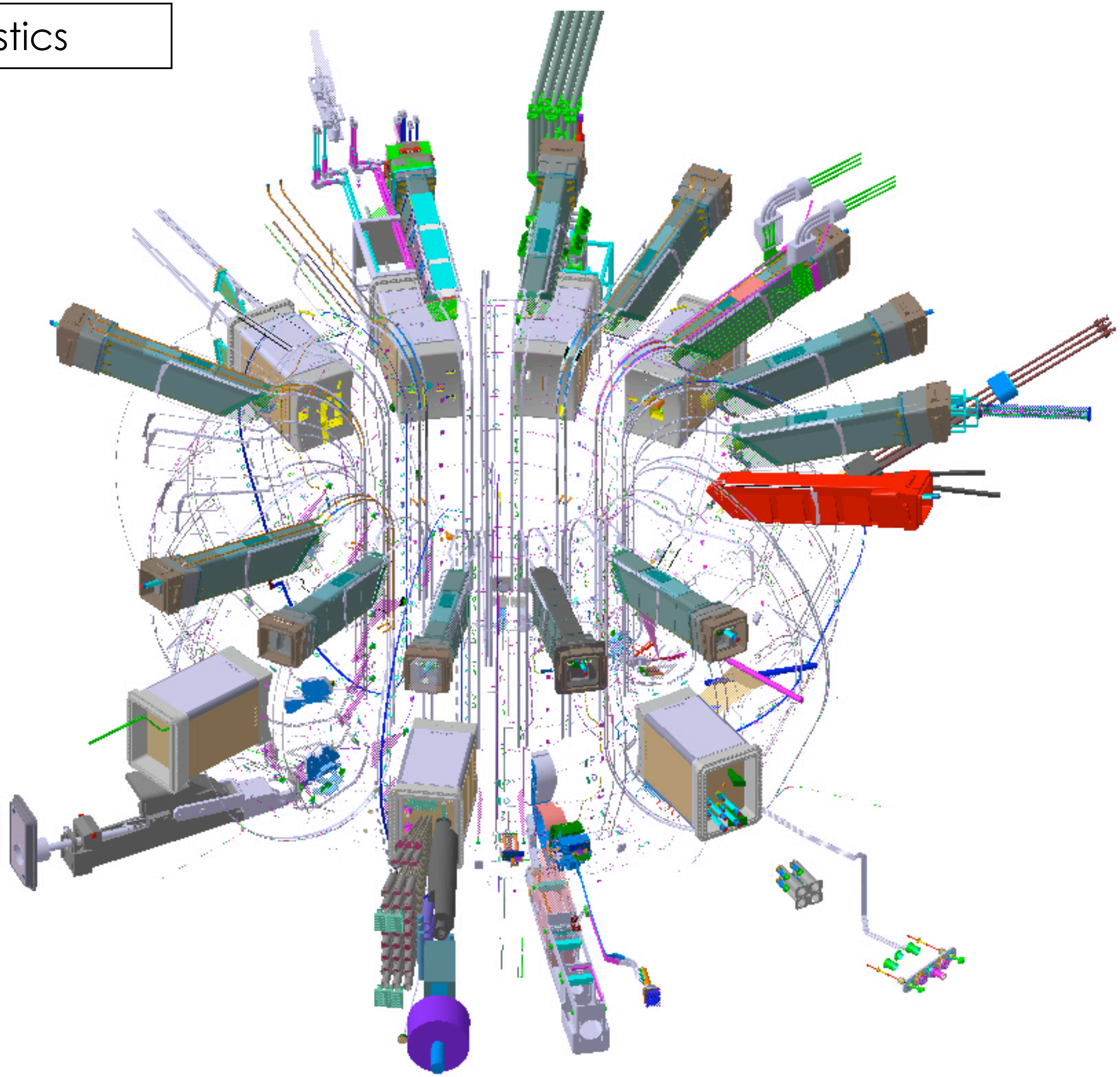
Diagnostics

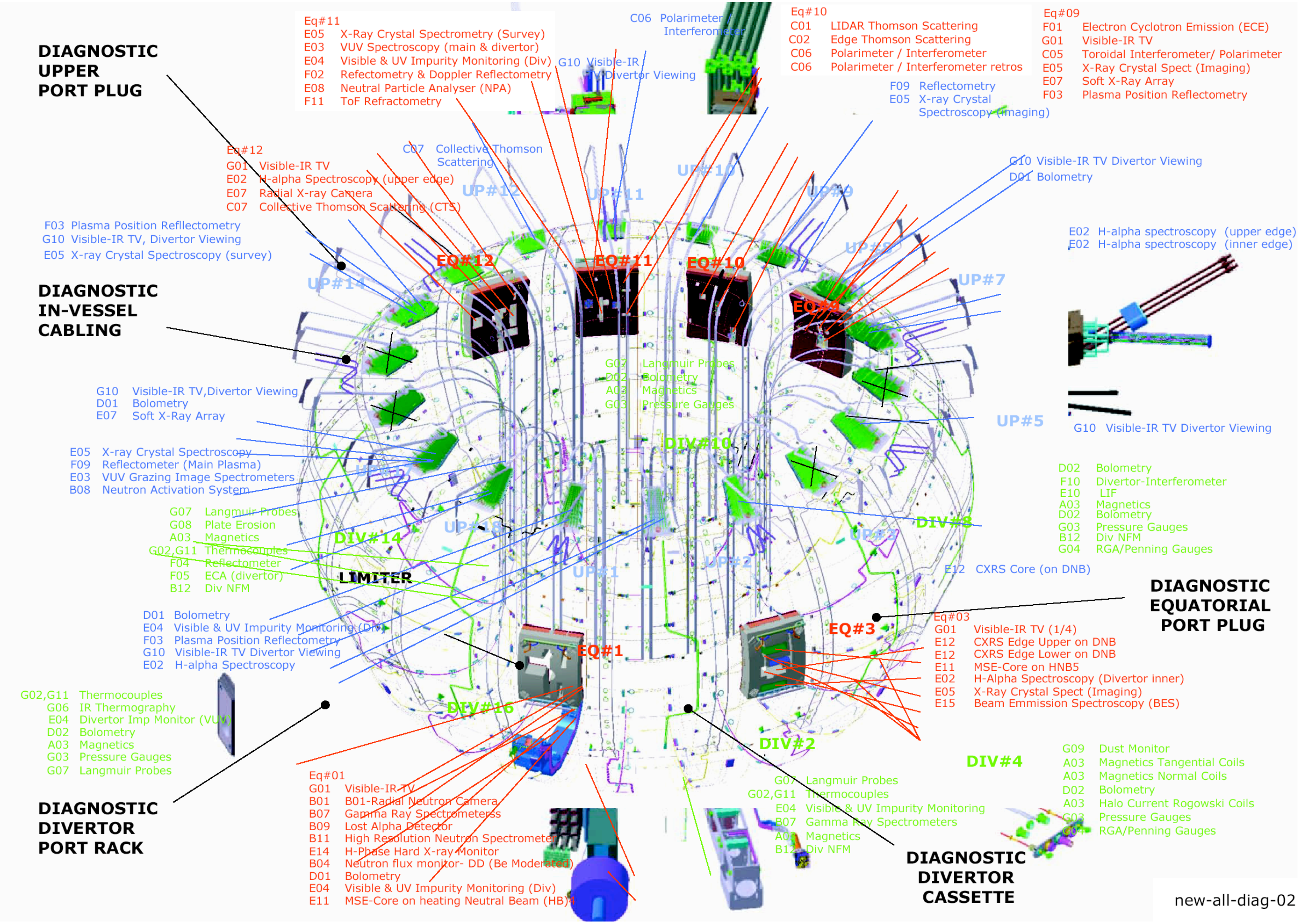


Divertor, Equatorial & Upper Port Diagnostics



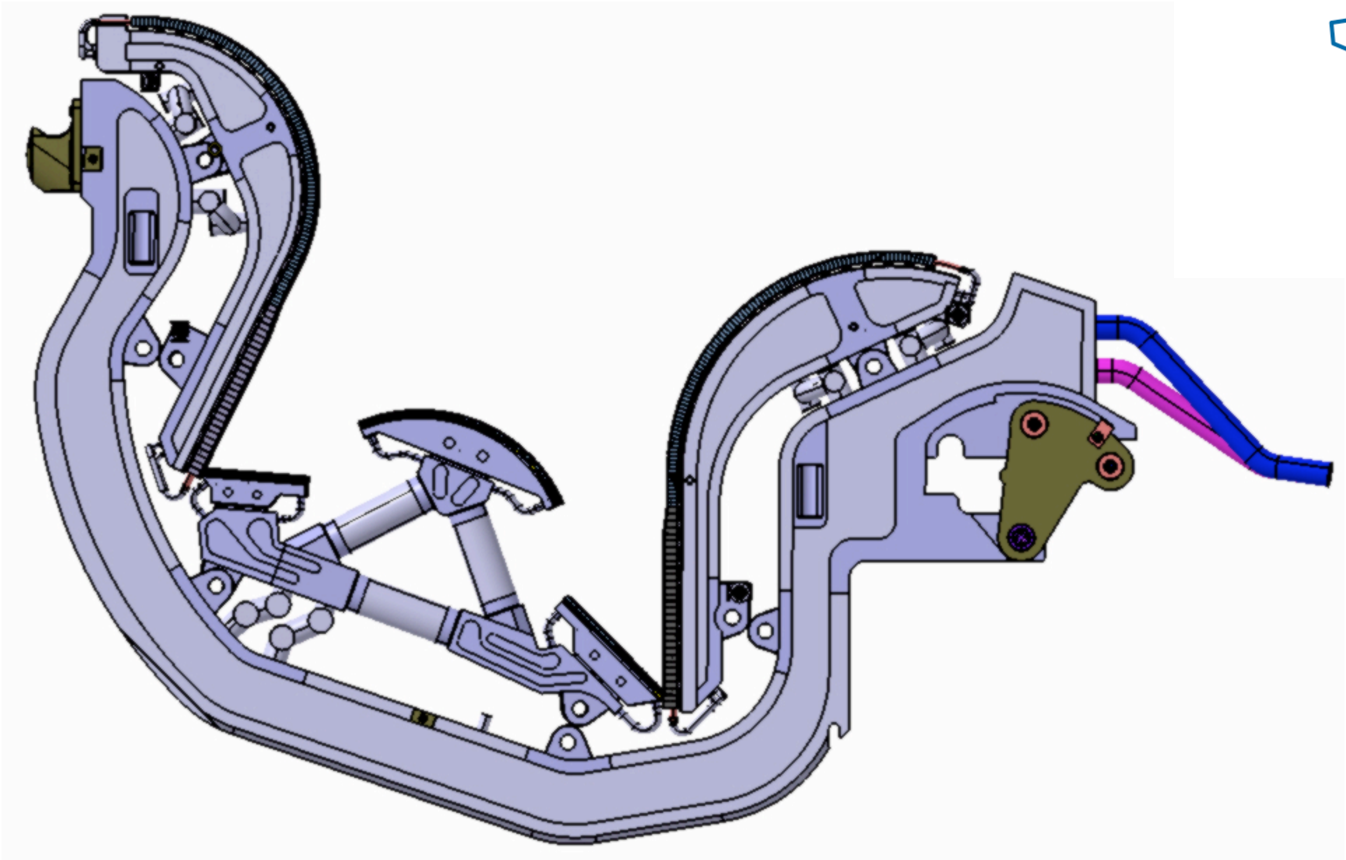
All Diagnostics

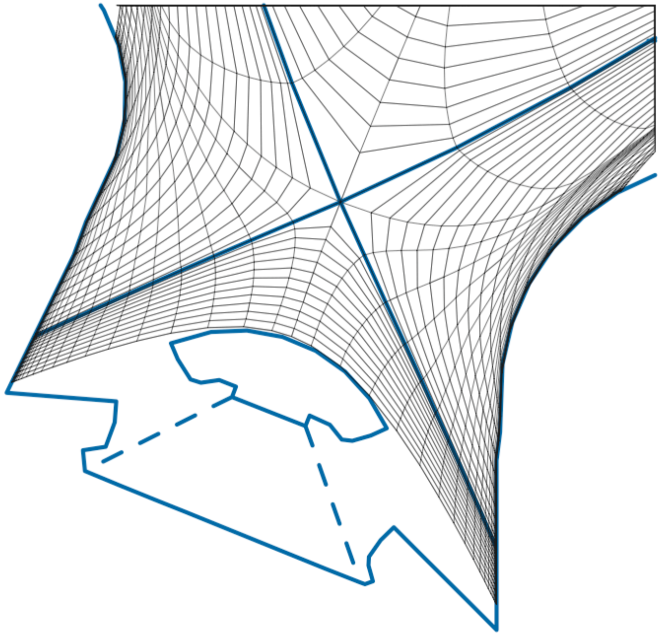




new-all-diag-02

Diagnostic Locations: Divertor Cassettes





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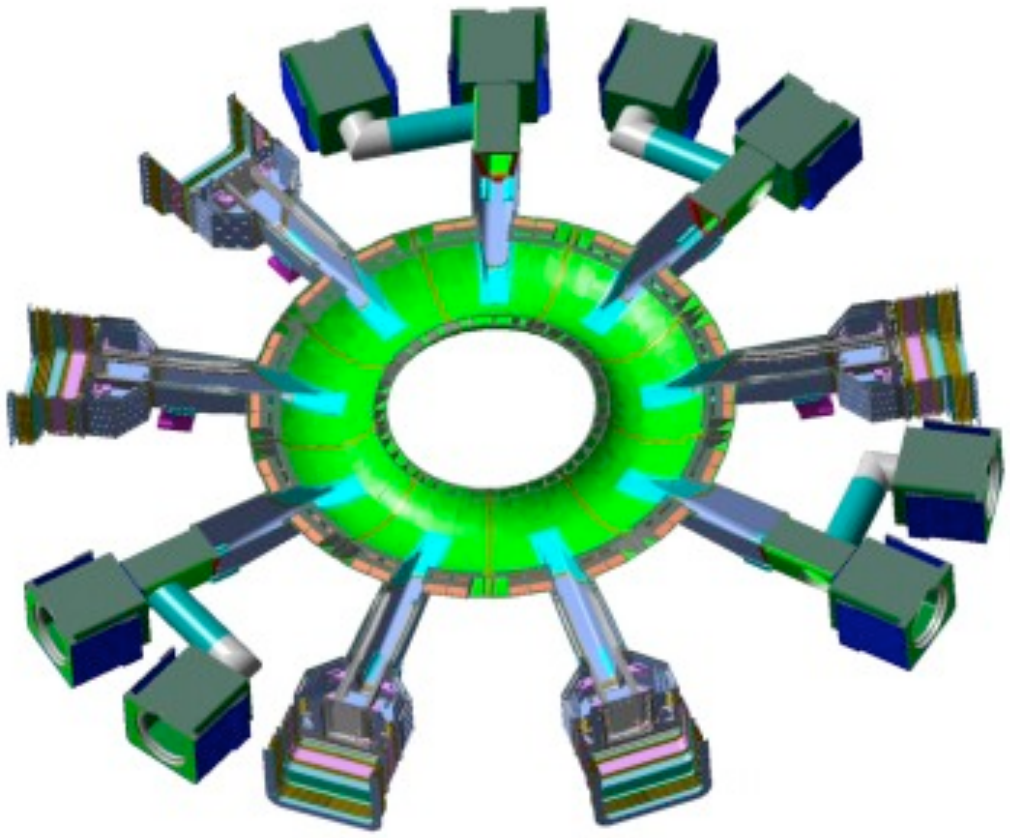
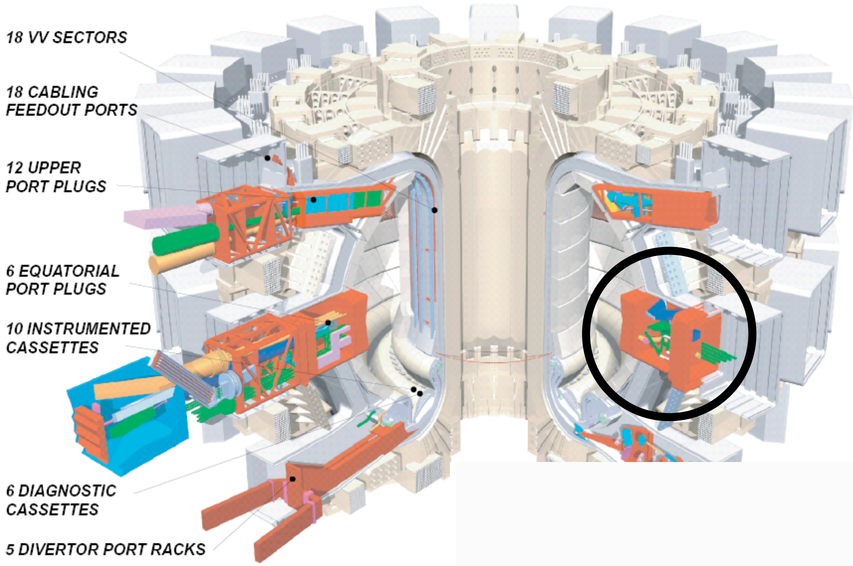
Diagnostic Locations: Lower Ports



Diagnostic Locations: Equatorial Port Plugs



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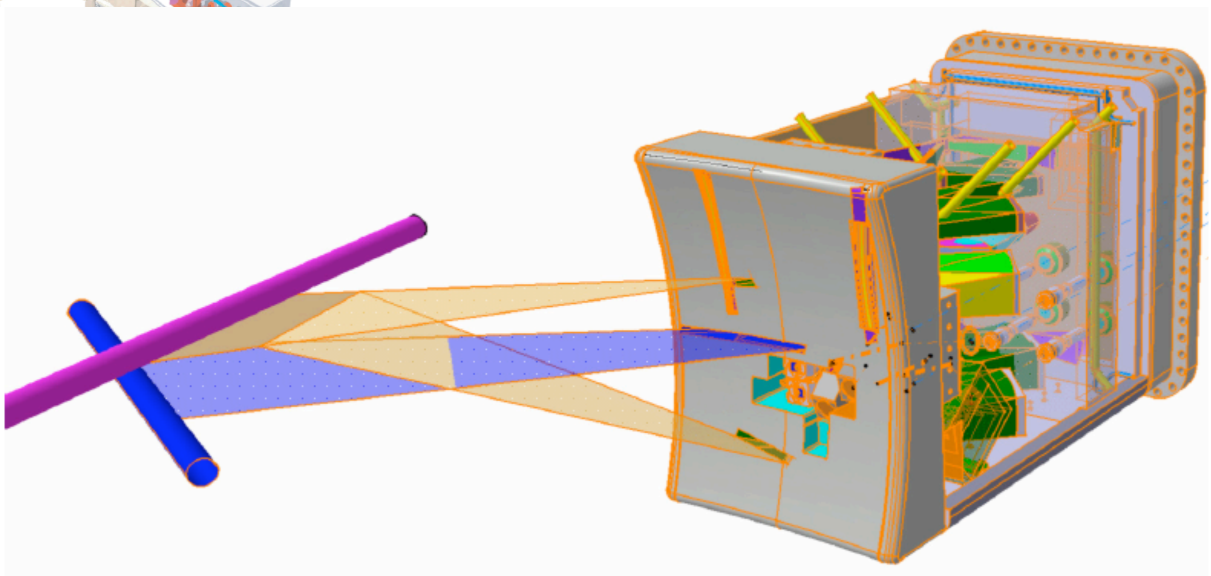
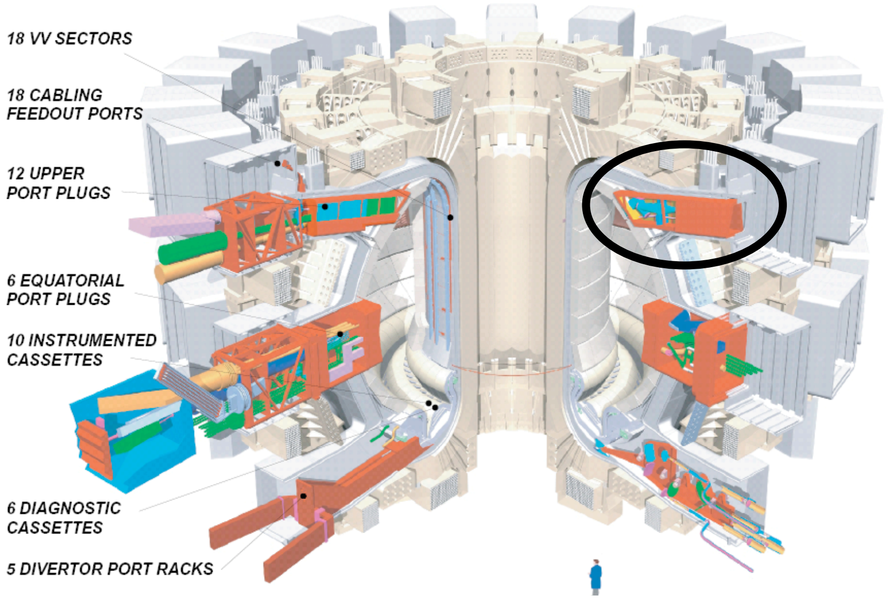
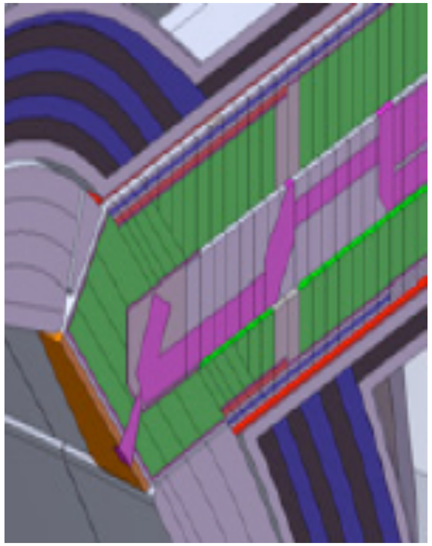
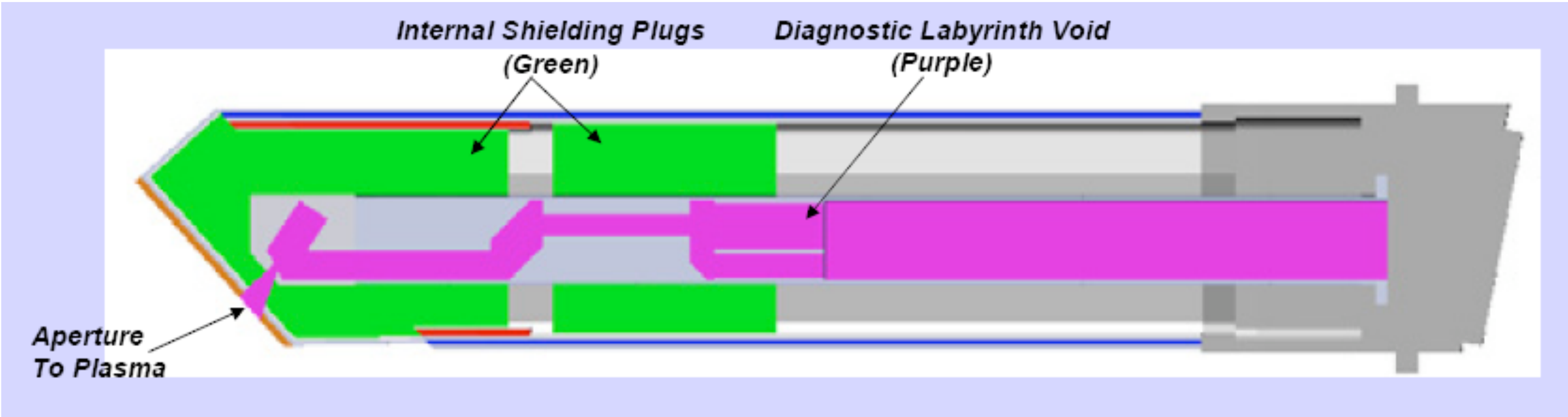


Diagnostic Locations: Upper Port Plugs





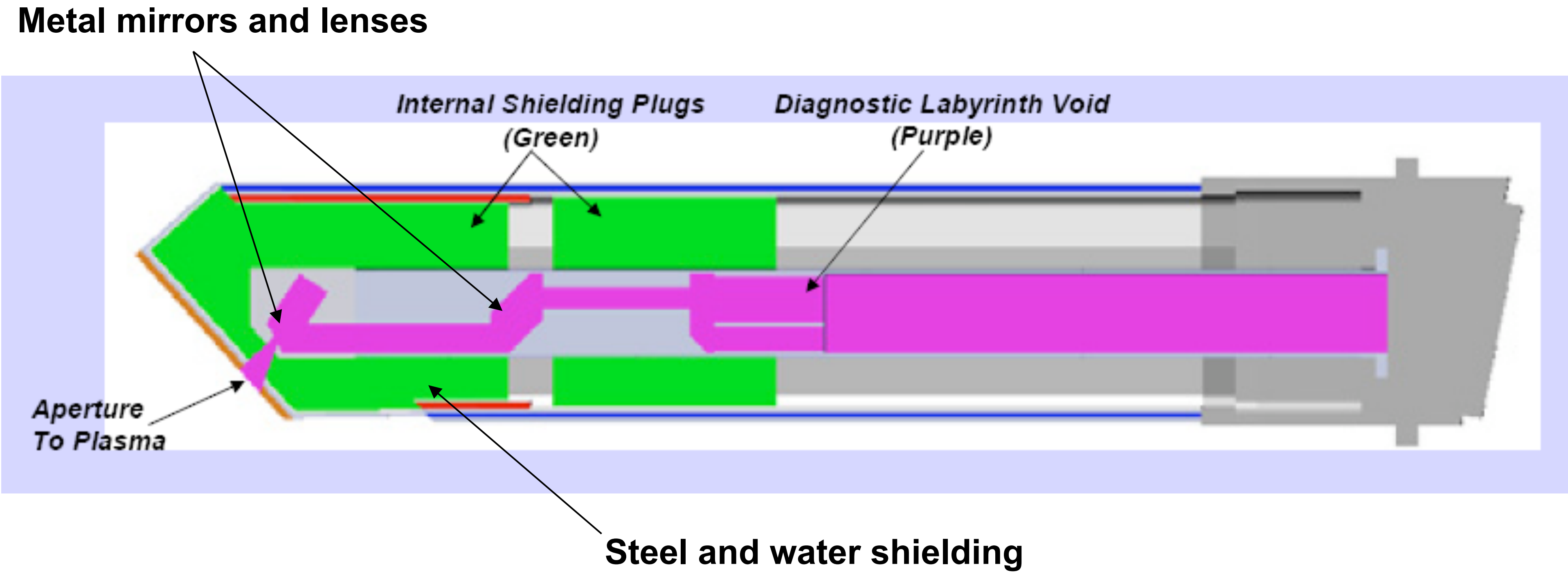


ITER is different from previous devices - Issues

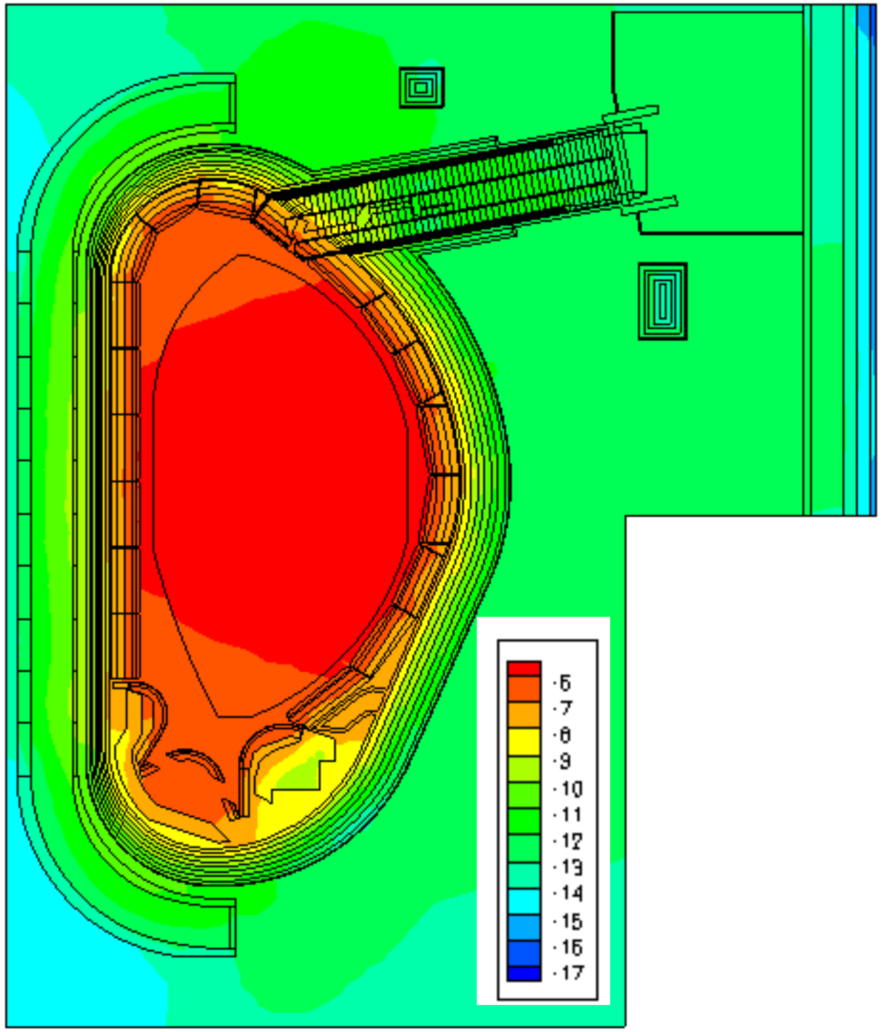
Issue	*Solution*
Diagnostic penetrations must not allow the "leakage" of radiation (neutrons, gammas).	*Provide ~0.5 m of stainless steel and water shielding* *Provide optical labyrinth paths*
Diagnostics must endure steady-state surface (plasma radiation) and volumetric (neutrons, gammas) heat loads.	*Provide sufficient water cooling*
Optical diagnostics must forgo the use of transmission lenses and fibres close to the plasma because of darkening.	*Use metal mirrors and lenses*
Large amounts of erosion/redeposition will rapidly coat and degrade forward mirrors.	*Use fast shutters, hot mirrors, in situ mirror cleaning and replacement*

Radiation Shielding and Optical Labyrinth

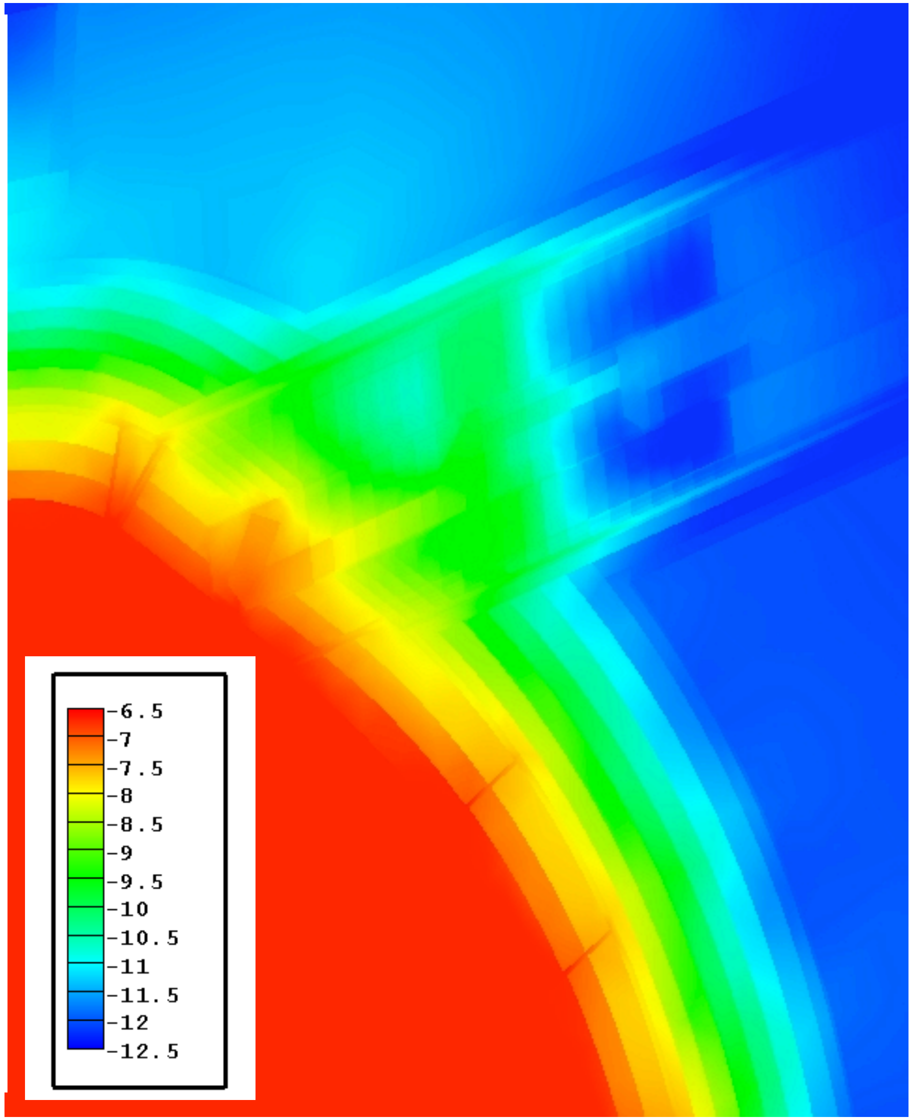
Upper Port Plug



Neutron Flux Contours



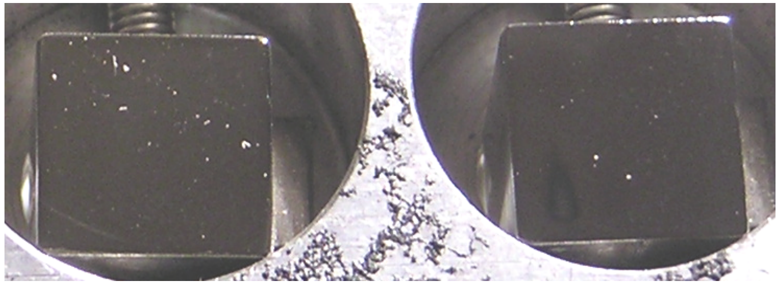
Vis/IR Camera Model

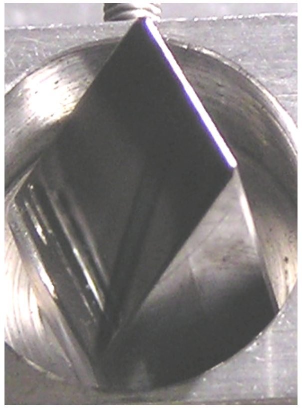


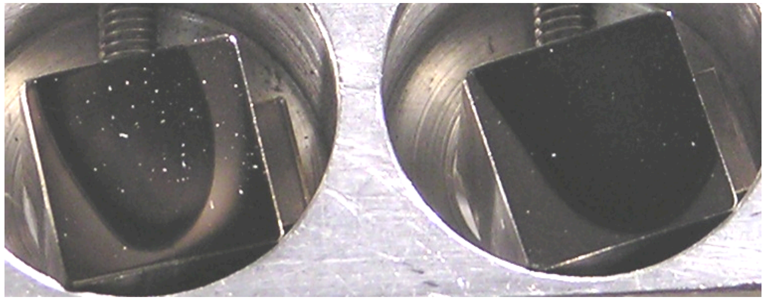
Flux = 1.7753E20*10^x

Test Mirrors Exposed in JET – equivalent to 8 ITER pulses

Outer Wall Molybdenum Mirrors



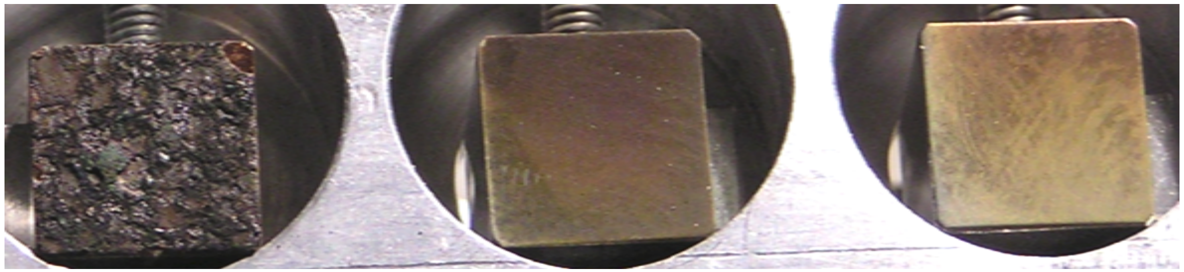


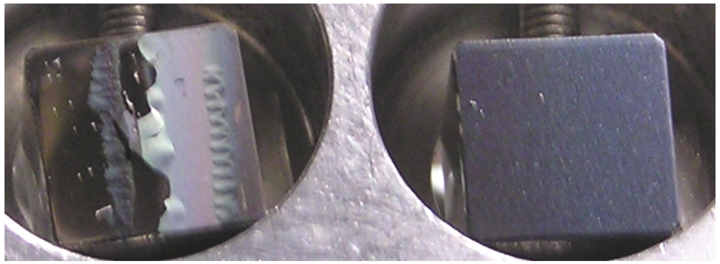


0 cm 1.5 cm 1.5 cm 3 cm 4.5 cm

Inner Divertor, Stainless Steel Mirrors

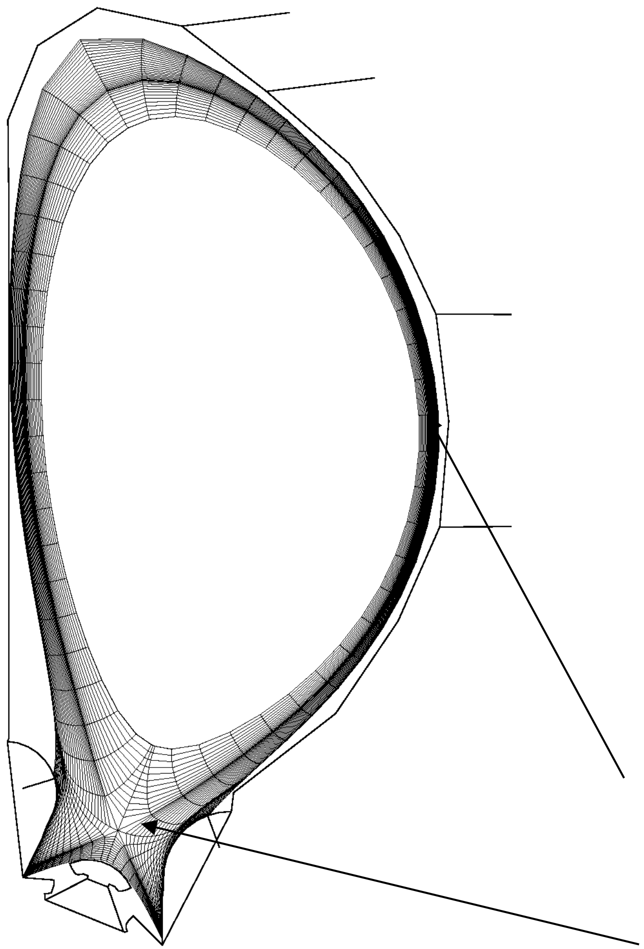
Base Outer





0 cm 1.5 cm 3 cm 0 cm 0 cm

What measurements are required?



To protect the machine and to increase our understanding we need to measure:

- •Heat fluxes
- •Plasma conditions (ne, Te)
- •Neutral fuel and ash densities
- •Radiatied Power
- •Fuel and Impurity Fluxes
- •Impurity densities and temperatures

- •Spatially-resolved profiles
- •Fast Time-Resolved

Measurements focus on,

•the SOL/boundary plasma in the main chamber (1D)

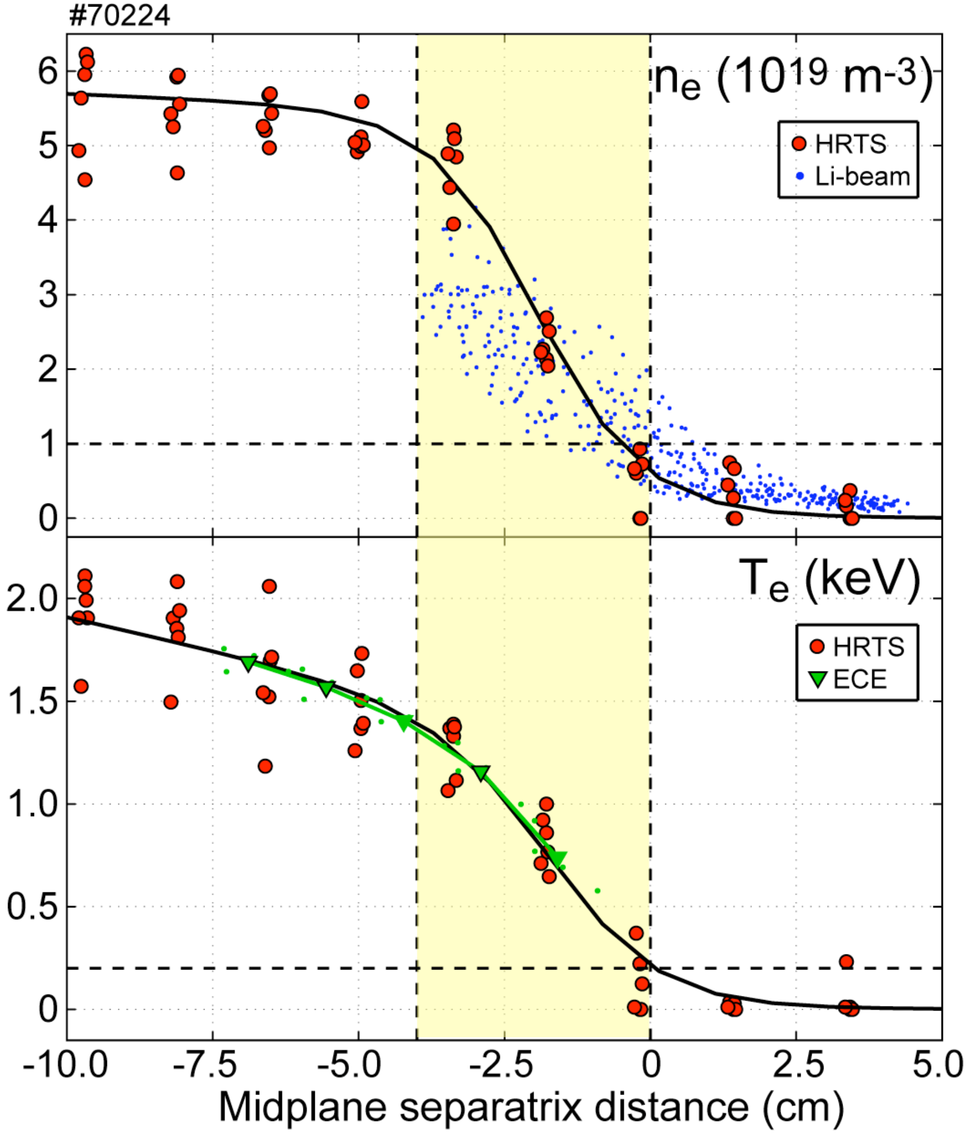
•the divertor plasma (2D)

+ first-wall measurements (heat flux)

SOL –1D

M. Beurskens-JET

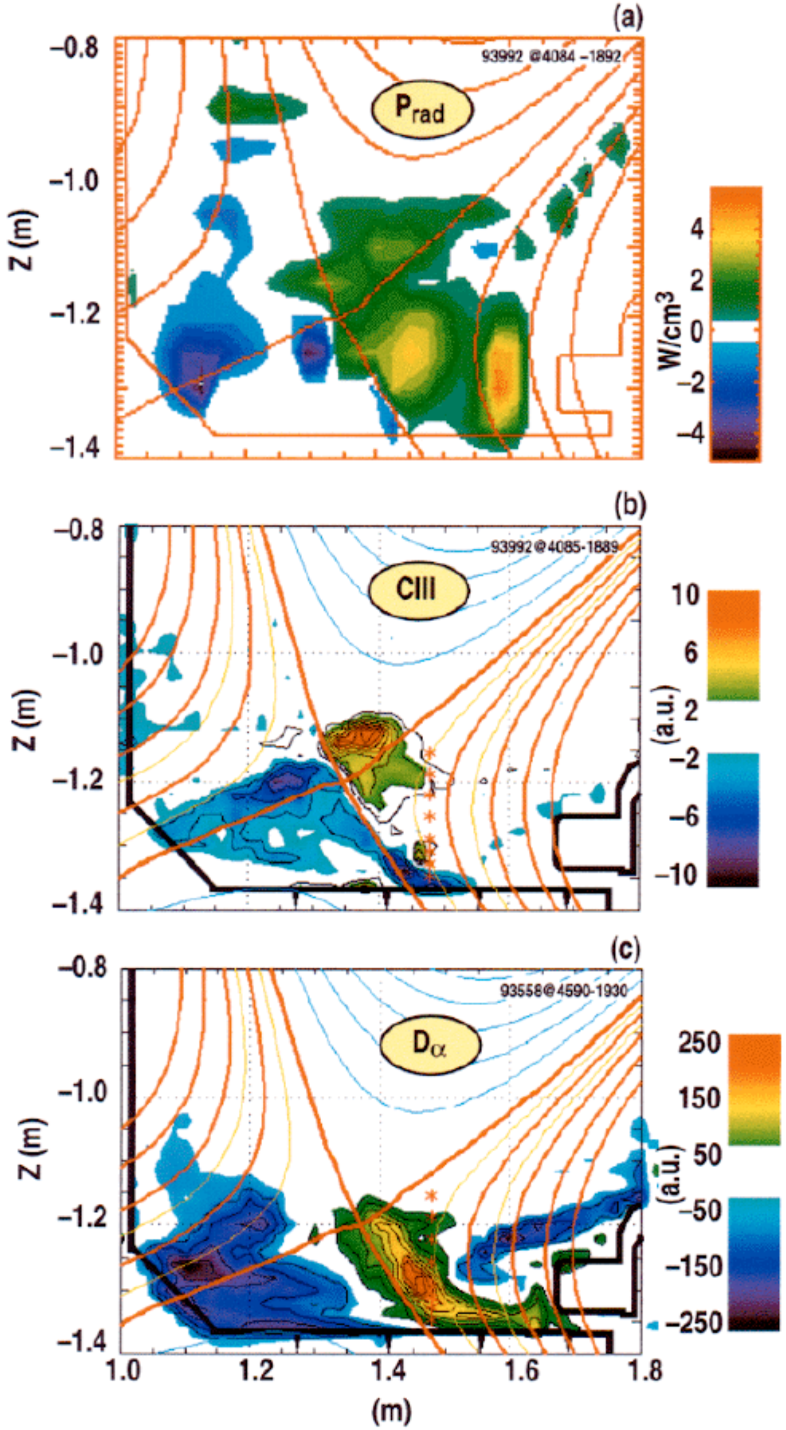
Type I ELMy H-mode



Divertor –2D

Fenstermacher - DIII-D

Partially detached conditions



Remainder of this lecture we will cover,

Langmuir Probes
Thomson Scattering
Bolometers
Spectroscopy
Interferometry
Reflectometry
IR Thermography
Ionization Gauges
Residual Gas Analyzers
Thermocouples

Focussing on their use in diagnosing the plasma boundary and first-wall

Langmuir Probes

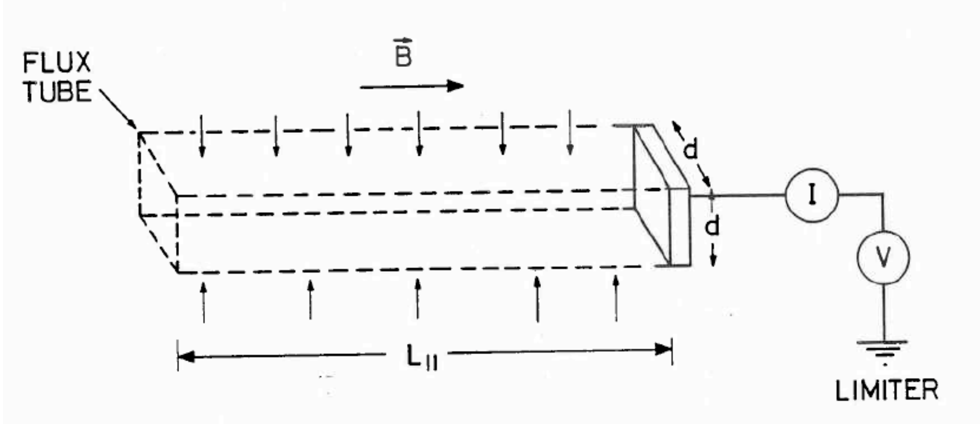
The first diagnostic in plasma physics (1920's)

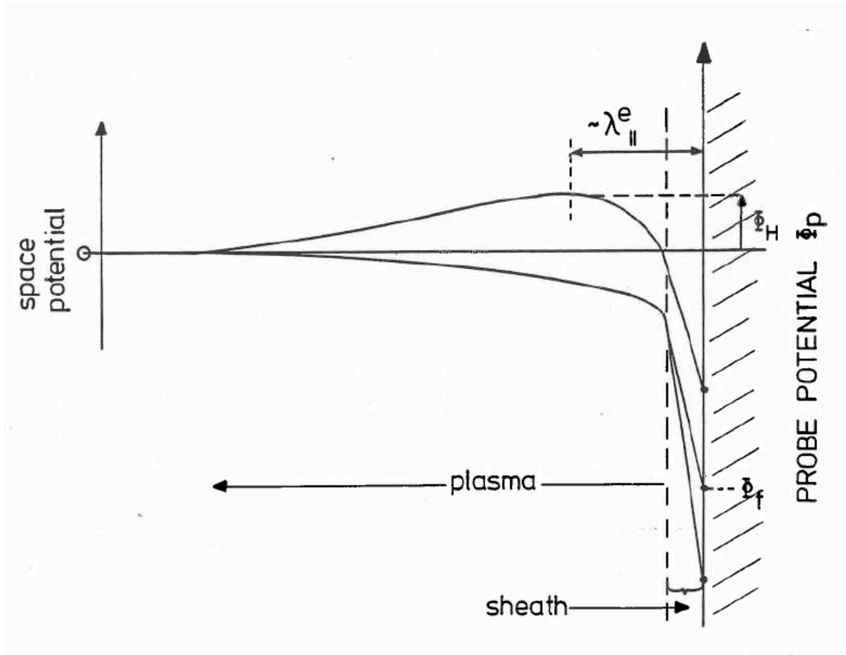
The simplest….simply a wire inserted in the plasma!

Interpretation in unmagnetized plasma is straightforward

In magnetized plasma interpretation is sometimes not so simple.

See Stangeby's book.



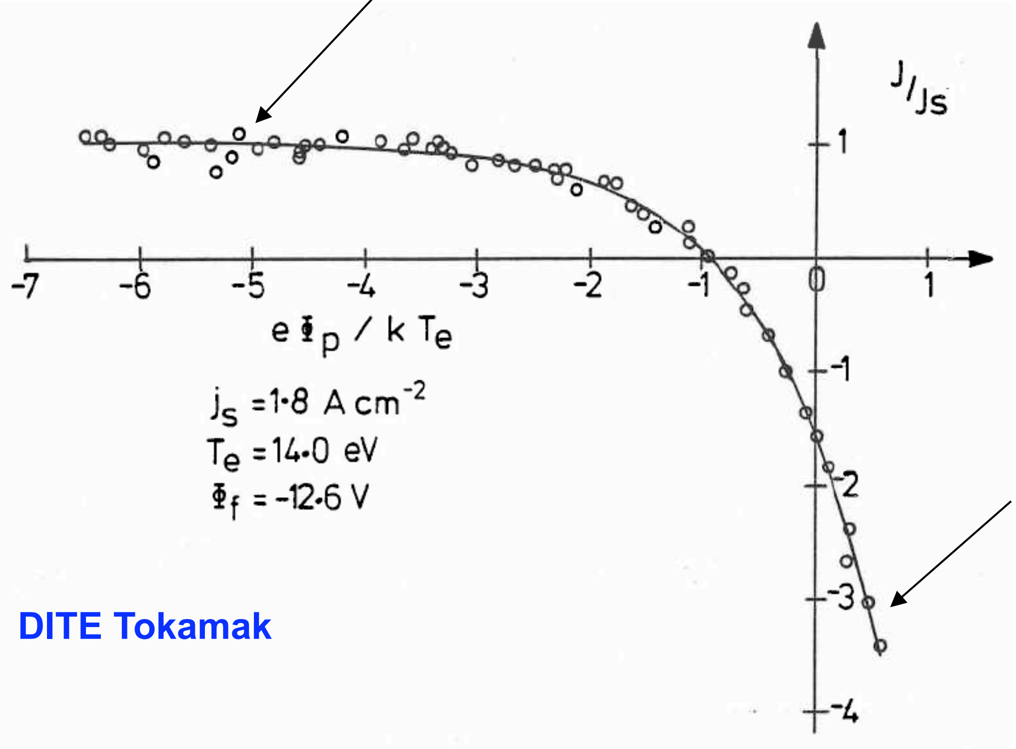


Pitcher 1987

Langmuir Probes

Current density = $j = j_s \left[1 - \exp\left(\frac{e(\Phi_p - \Phi_f)}{kT_e}\right)\right]$

Ion saturation current density



Electron collection

Pitcher 1987

ITER Divertor Plate Langmuir Probes

- **Measurement of plasma parameters at divertor target**

  Ion flux 10^{20}-10^{24} $m^{-2}s^{-1}$

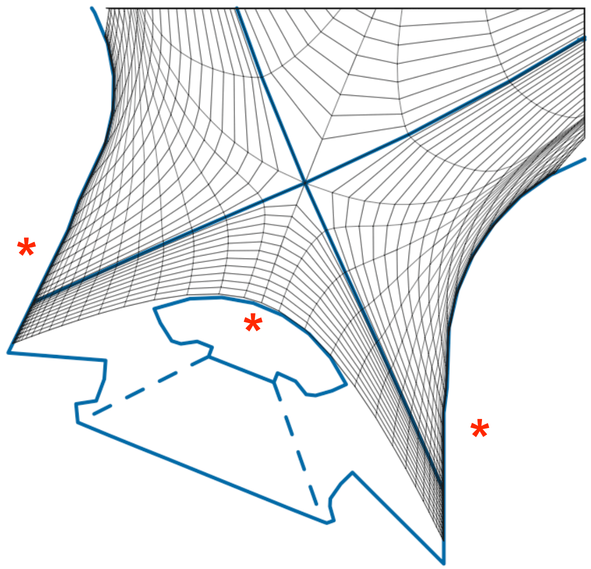
  T_e at target 1-300eV

  n_e at target 10^{18}-10^{21} m^{-3}

  Response time: 1 ms

- **Indicate plasma state (eg. detachment)**

- **Measure of strike point position**



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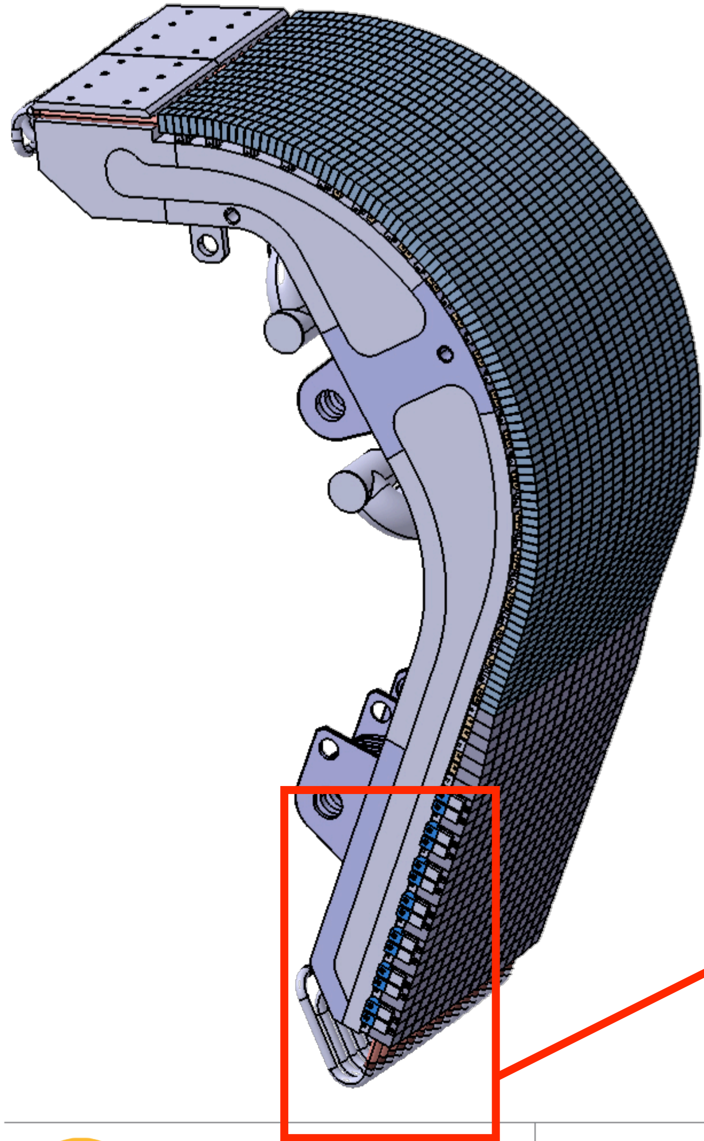
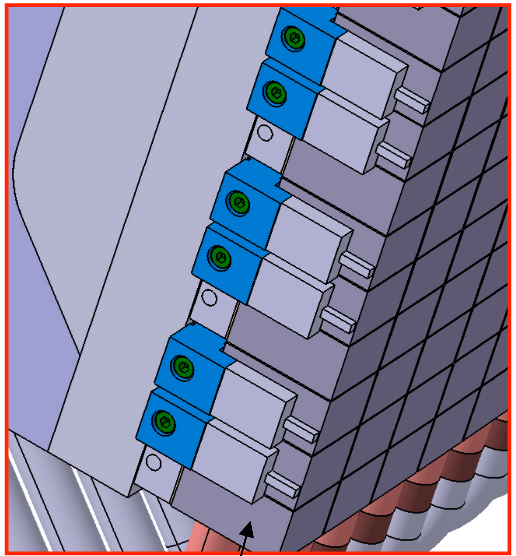
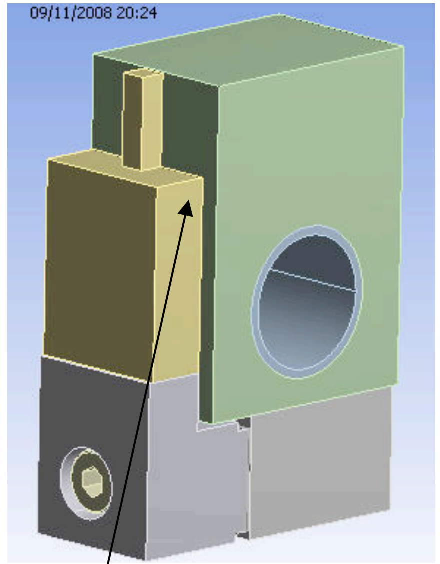
ITER Divertor Langmuir Probes

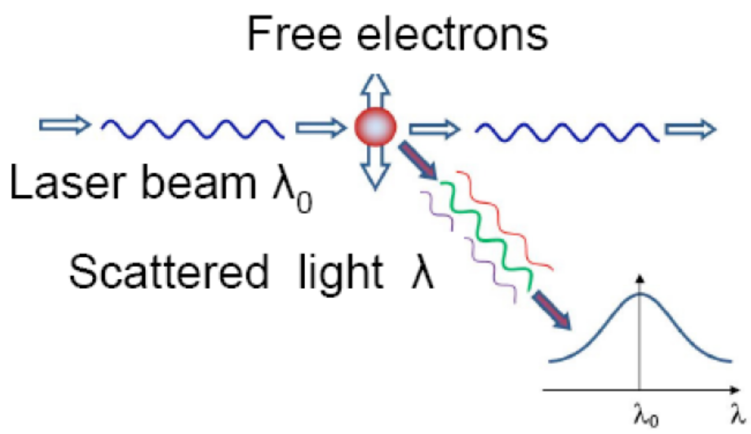






Susceptible to erosion/redeposition

Thomson Scattering



Re-radiation (scattering) of intense light by free electrons

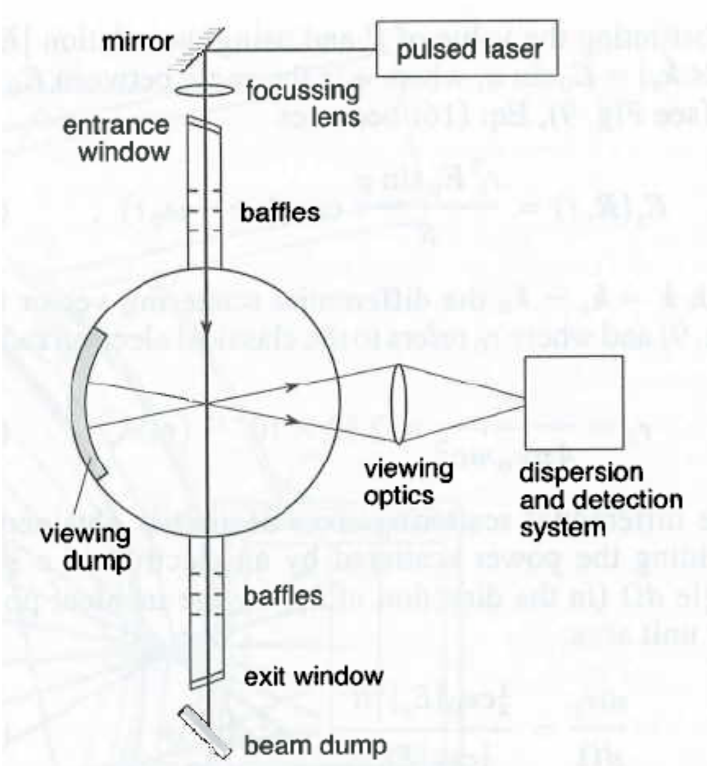
The wavelength of the scattered light is shifted because the electron is moving, i.e. the scattered ligh is Doppler shifted

The scattered light has a wavelength distribution which depends on the velocity distribution of the free electrons…..can be related to Te, the amount of scattered light is proportional to ne

The efficiency of scattering is VERY low, requiring very intense lasers, i.e. Ps/P0 ~10-15

Because the wavelength of the scattered light is close to the laser wavelength extremely good rejection of incident laser beam and stray light is required.

Good light baffles, beam dumps, interference filters, spectrometers



$$P_s = P_0 \frac{d\sigma_T}{d\Omega} \sin^2(\varphi) n_e \Delta L\, \Omega\, S(k,\omega) \,,$$

Assuming a Maxwellian (non-relativistic),

$$S(\lambda_s) = \frac{1}{\Delta\lambda_e \sqrt{\pi}} \exp\left[-\left(\frac{\lambda_s - \lambda_0}{\Delta\lambda_e} \right)^2 \right] ,$$

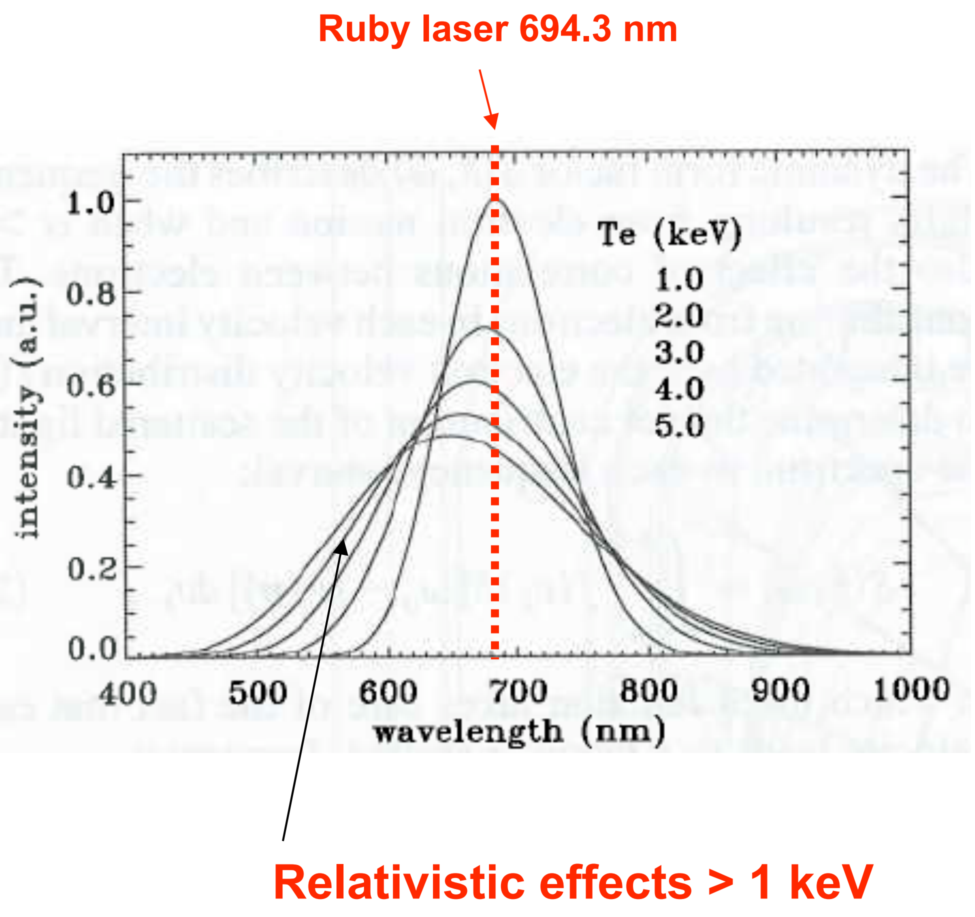
where

k_B = Boltzmann constant

λ_0 = wavelength of the incident radiation

λ_s = wavelength of the scattered radiation.

$$\Delta\lambda_e \text{ (nm)} = 1.94\sqrt{T_e \text{ (eV)}}$$



Main chamber boundary: T_e = 1 keV $\Delta\lambda$ = 61 nm

Divertor: T_e = 10 eV $\Delta\lambda$ = 6.1 nm

Thomson Scattering:
Divertor & x-point

- **Measurement along outer divertor leg**

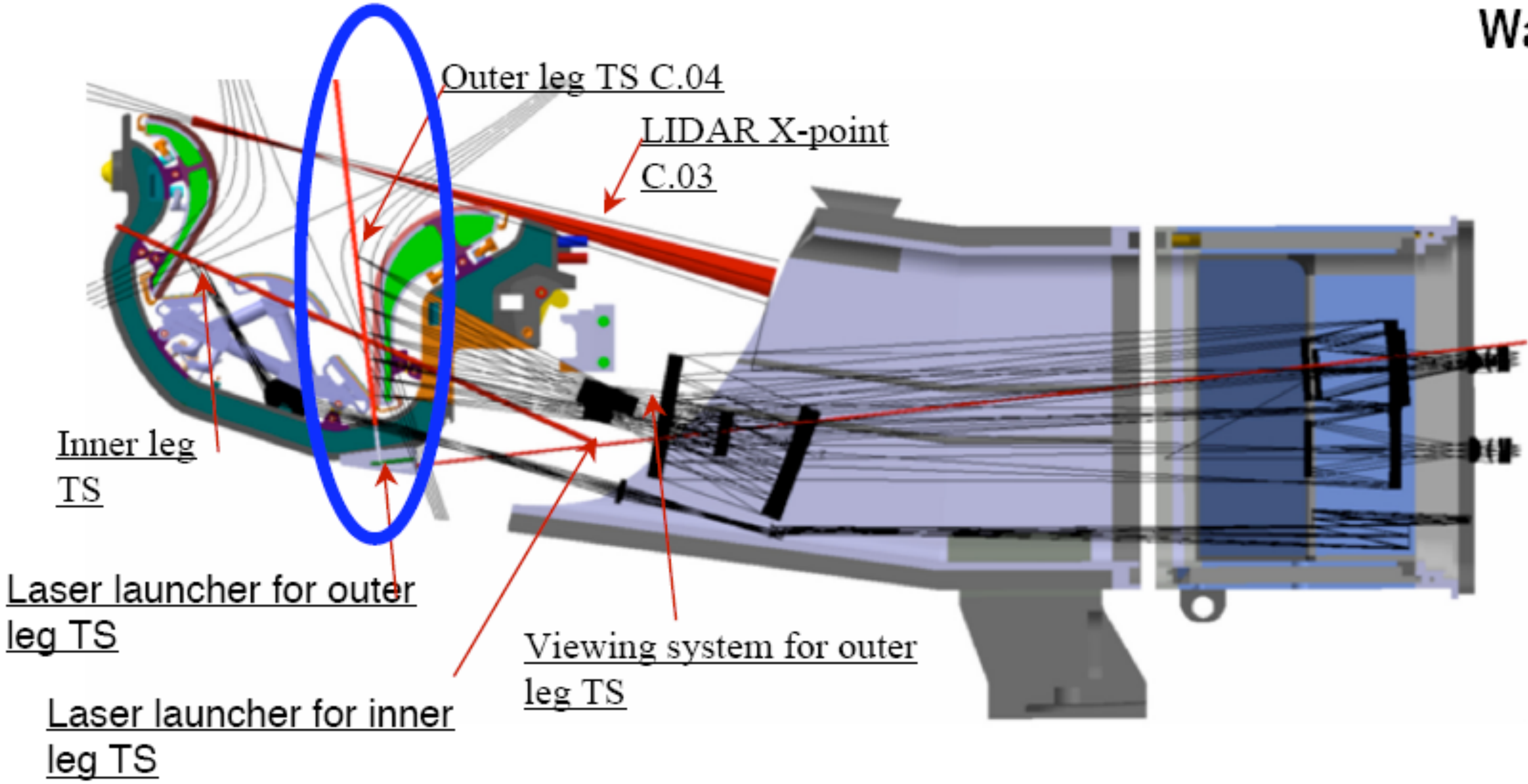
  T_e at target 1-200eV

  n_e at target 10^{19}-10^{22} m^{-3}

- **Measurement through x-point**

  n_e profile near x-point $5x10^{18}$-$3x10^{20}$ m^{-3}

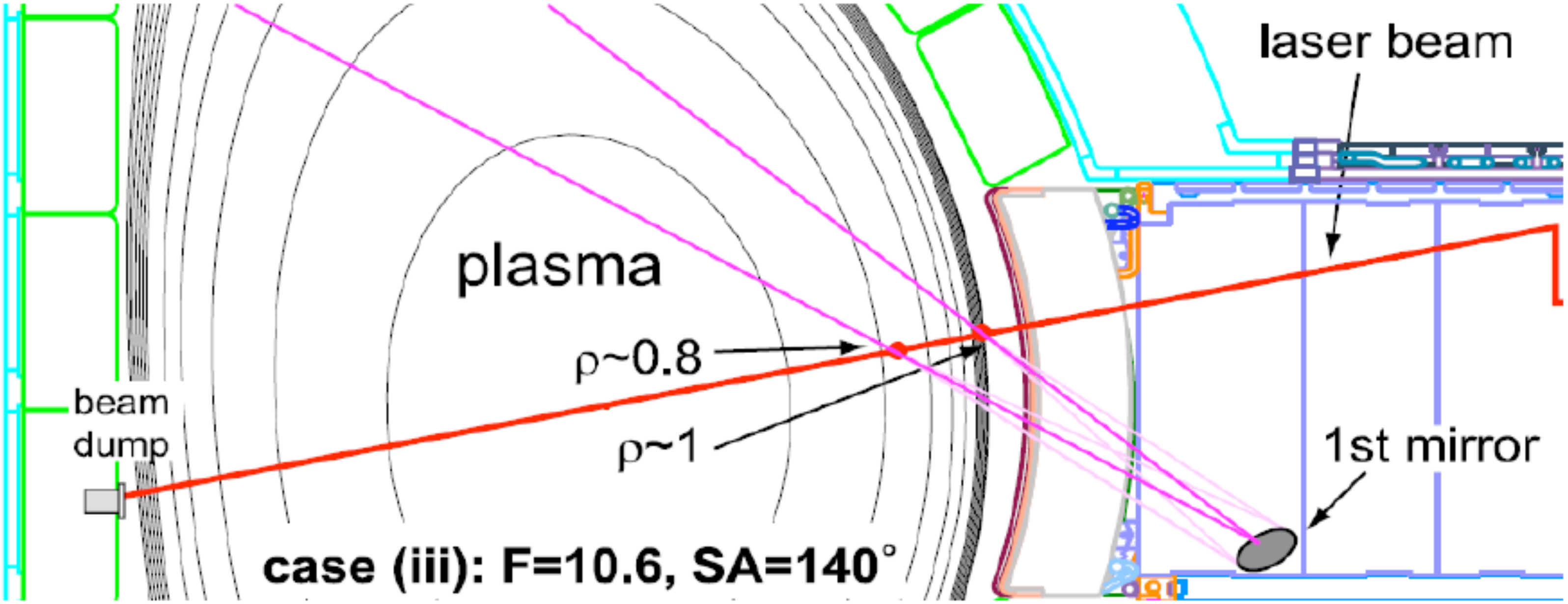
  T_e profile near x-point 10ev-3keV



- Multipoint Thomson
- Uses gap between divertor cassettes
- Laser path stearable for minor path adjustment

- LIDAR Thomson
- Requires a cutout in blanket module above divertor

JA-Edge TS - Midplane Outline View



Walsh

Bolometers

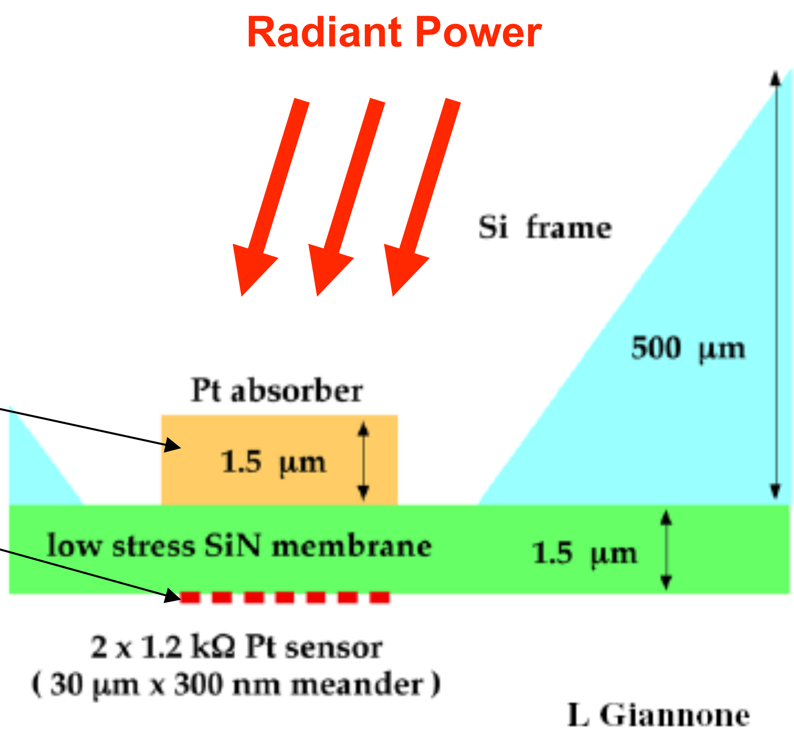
To measure radiated power

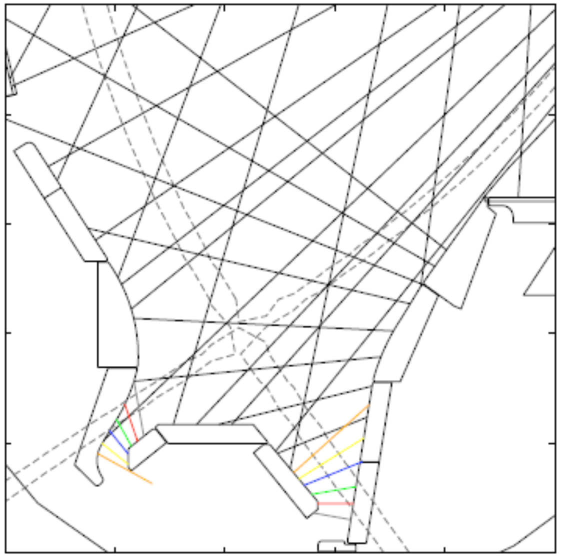
One might argue that bolometers were the first fusion plasma diagnostic as they were used to measure radiated power from the sun by Langley in 1878!

Basically consists of:

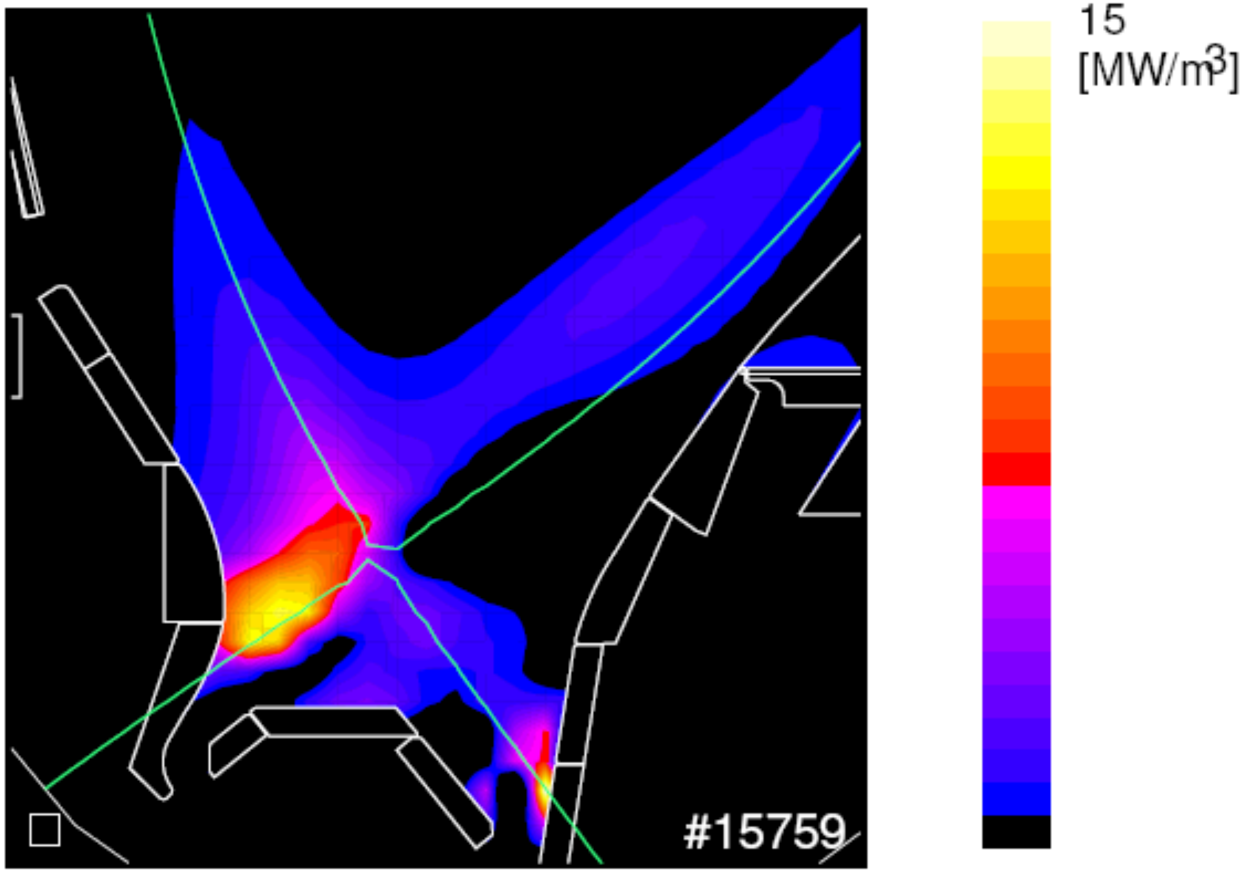
1. Absorber

2. Thermometer





ASDEX-Upgrade



Deconvolving complicated radiation patterns with arrays of bolometers

J.C. Fuchs

Complications

Toroidal asymmetries

High level of radiated power in the divertor

Electrical noise

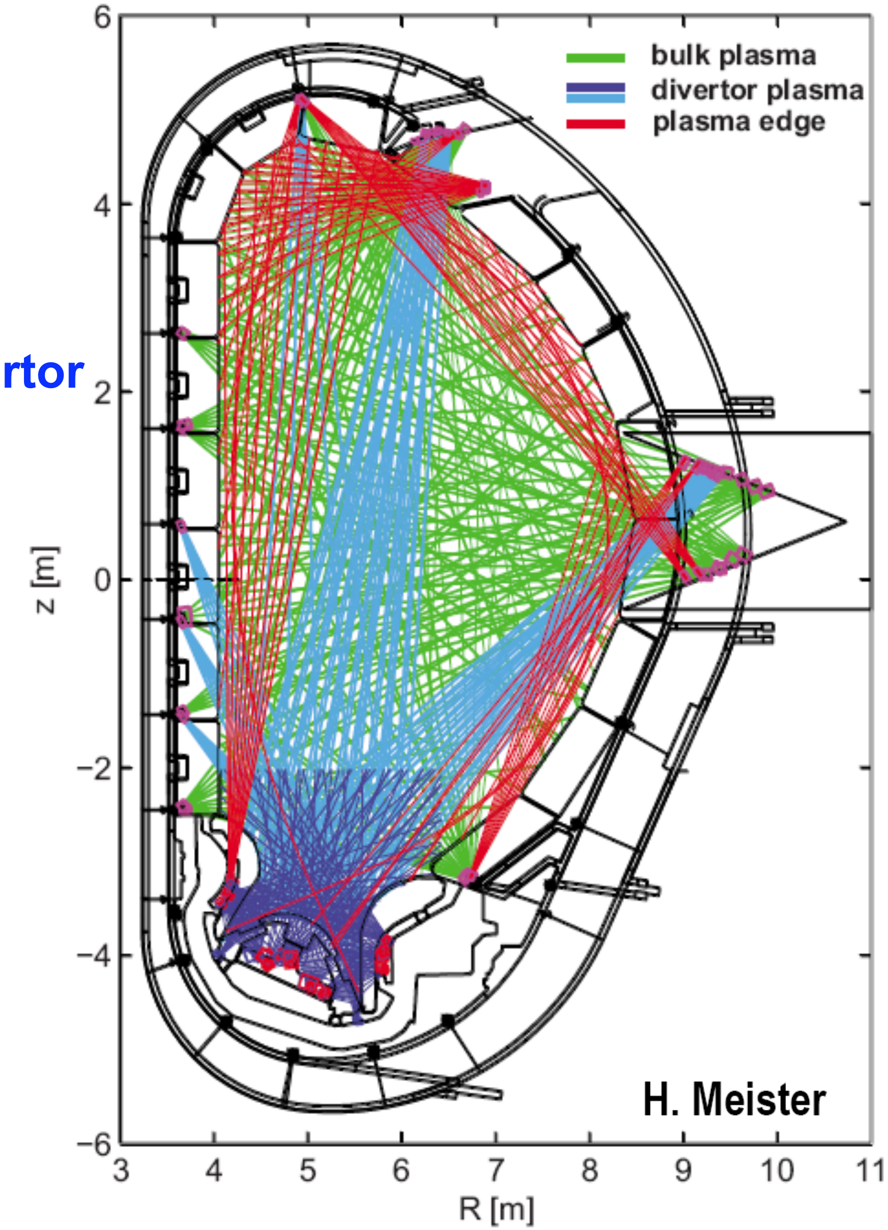
Sparse data

Neutral particles

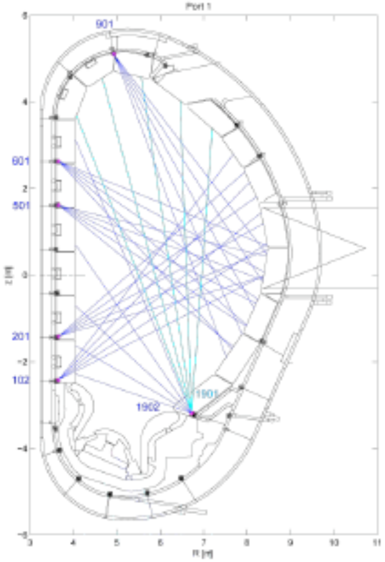
Gas in the bolometers

Deposition/dust inside the bolometer

Radiation (n, gamma) effects

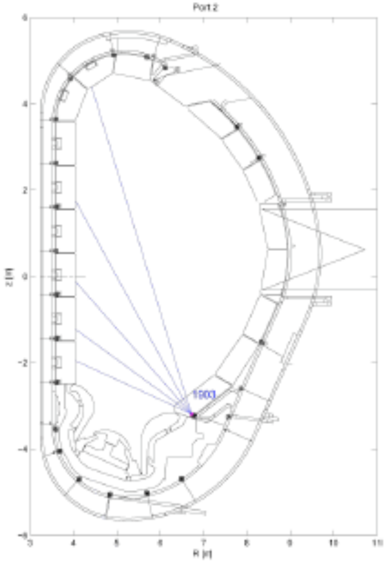


Port 1



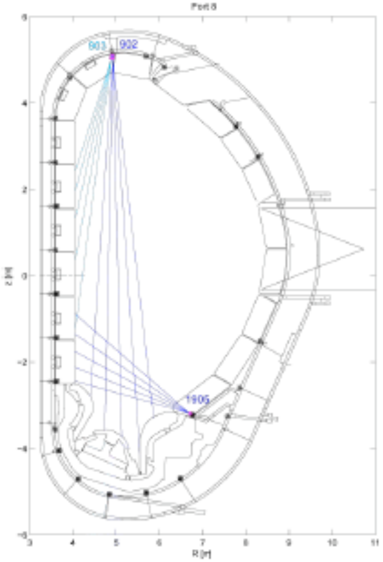
- 5 mini-cameras on HFS
- 2 mini-cameras behind BM18

Port 2



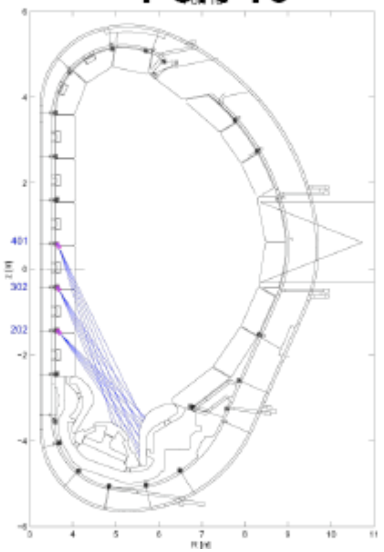
- 1 mini-camera behind BM18

Port 8



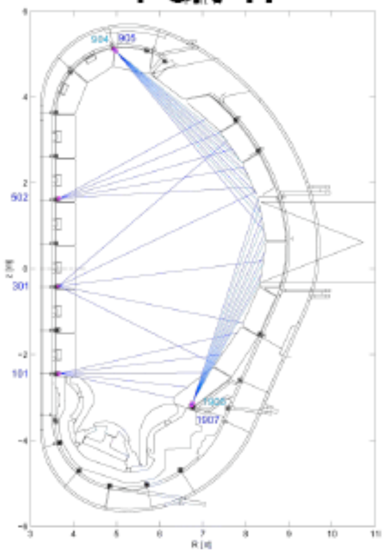
- 2 mini-cameras on HFS
- 1 mini-camera behind BM18

Port 16



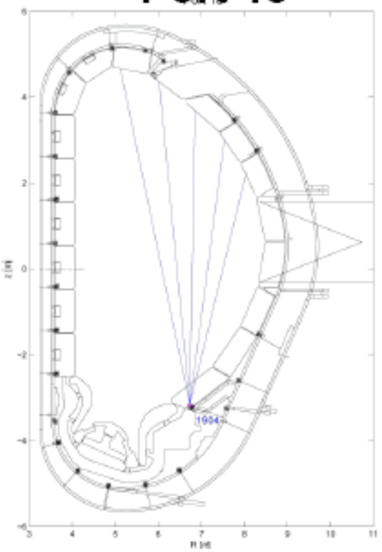
- 3 mini-cameras on HFS

Port 17



- 5 mini-cameras on HFS
- 2 mini-cameras behind BM18

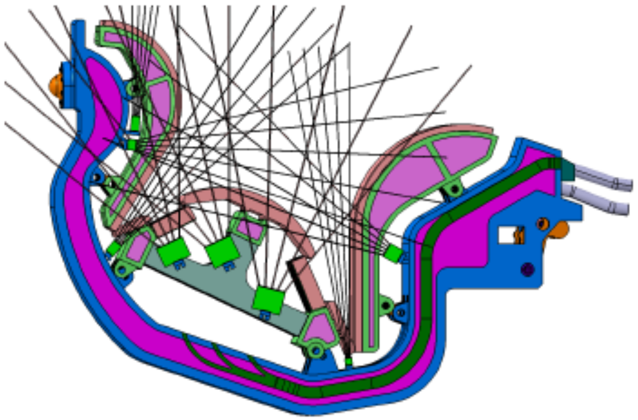
Port 18

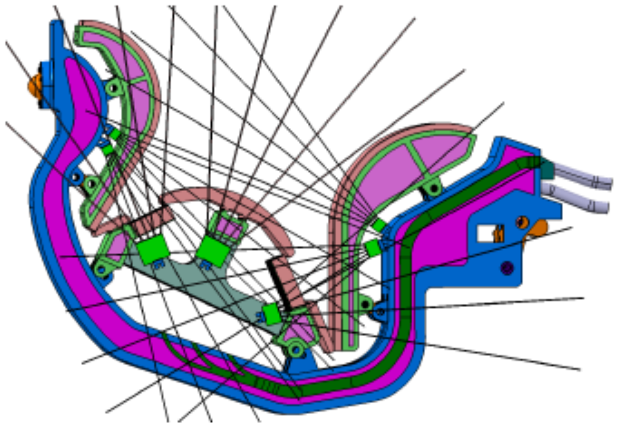


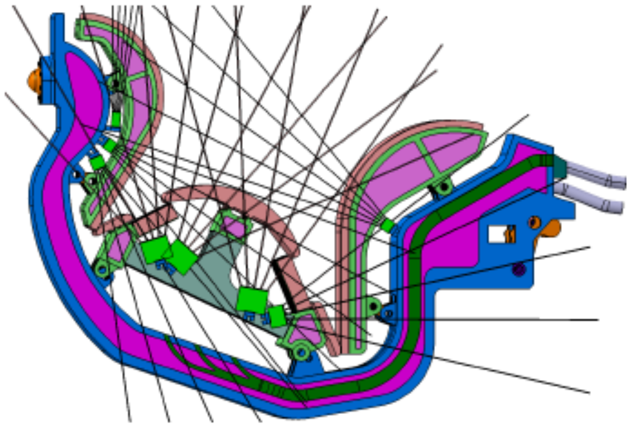
- 1 mini-camera behind BM18

H. Meister

Port 8	Port 10	Port 16



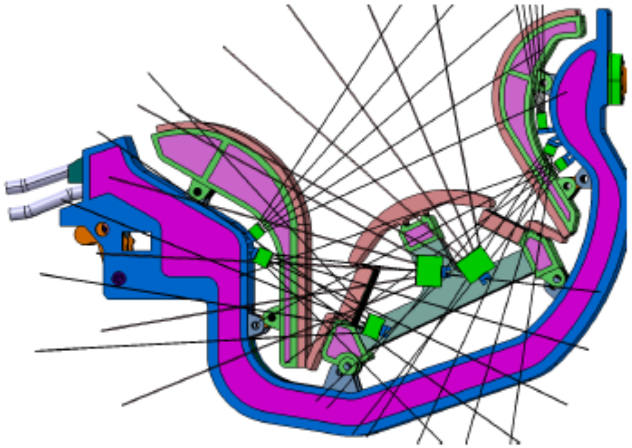


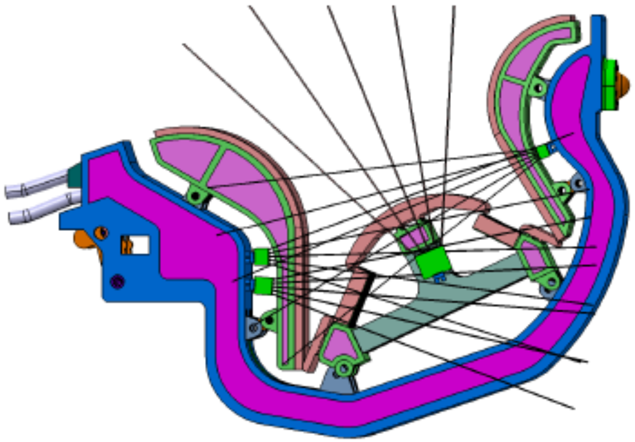


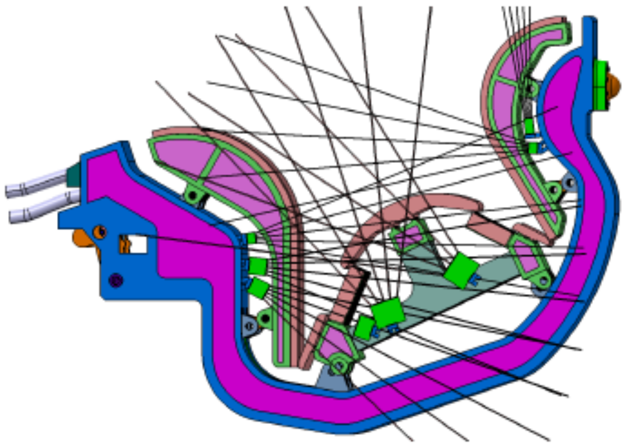
- 8 mini-cameras in **DC21**
- 8 mini-cameras in **DC23**

- 7 mini-cameras in **DC27**
- 4 mini-cameras in **DC29**

- 8 mini-cameras in **DC45**
- 8 mini-cameras in **DC47**







H. Meister

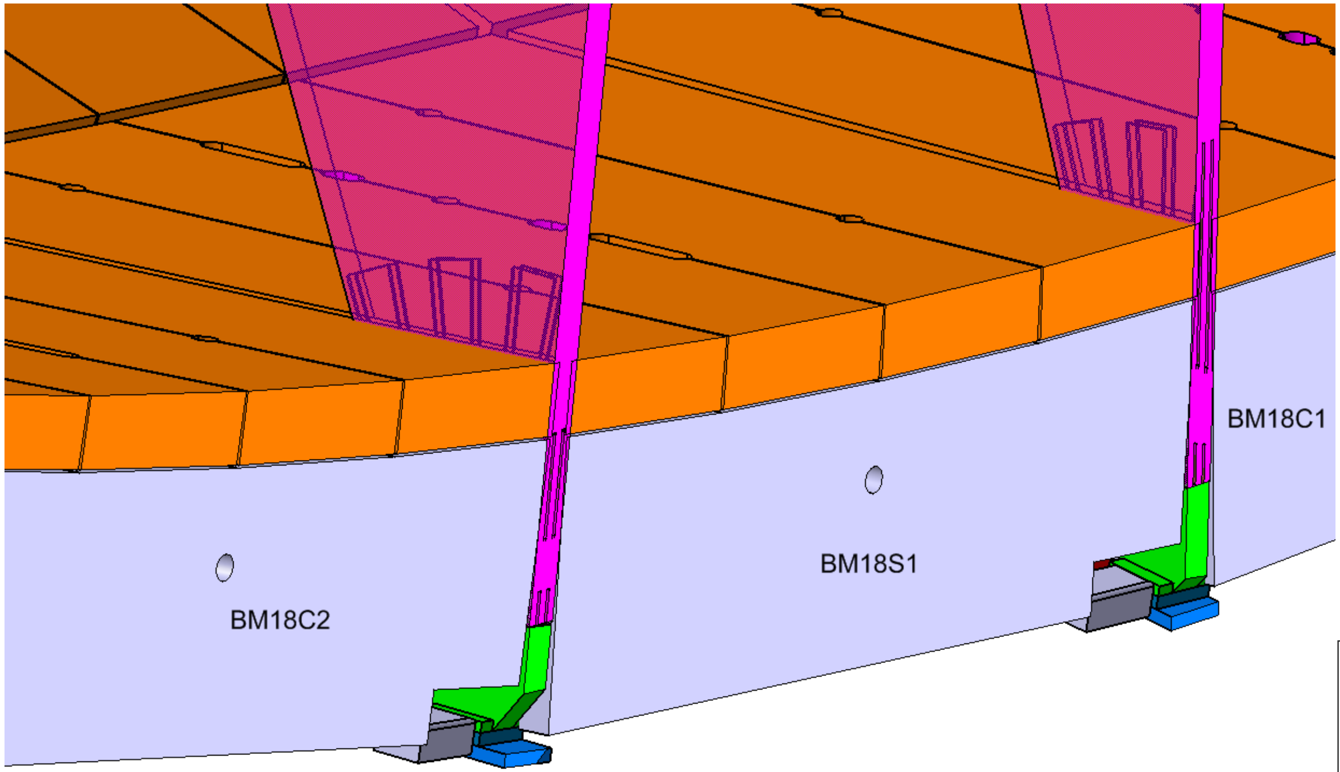
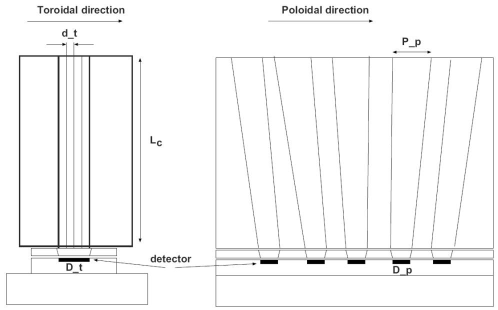
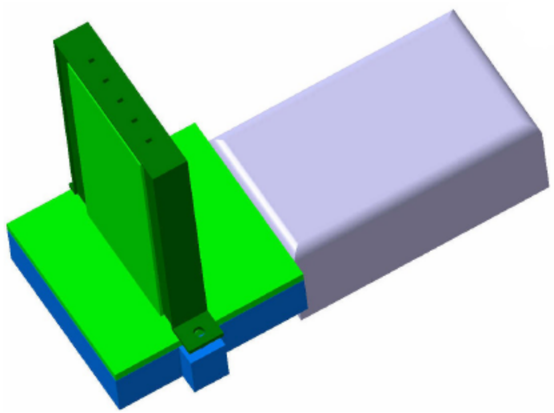


Figure 4 shows the cut out required for Sector 1, Port 1S & Port 2C, BM 18 viewed from the plasma on the Divertor side

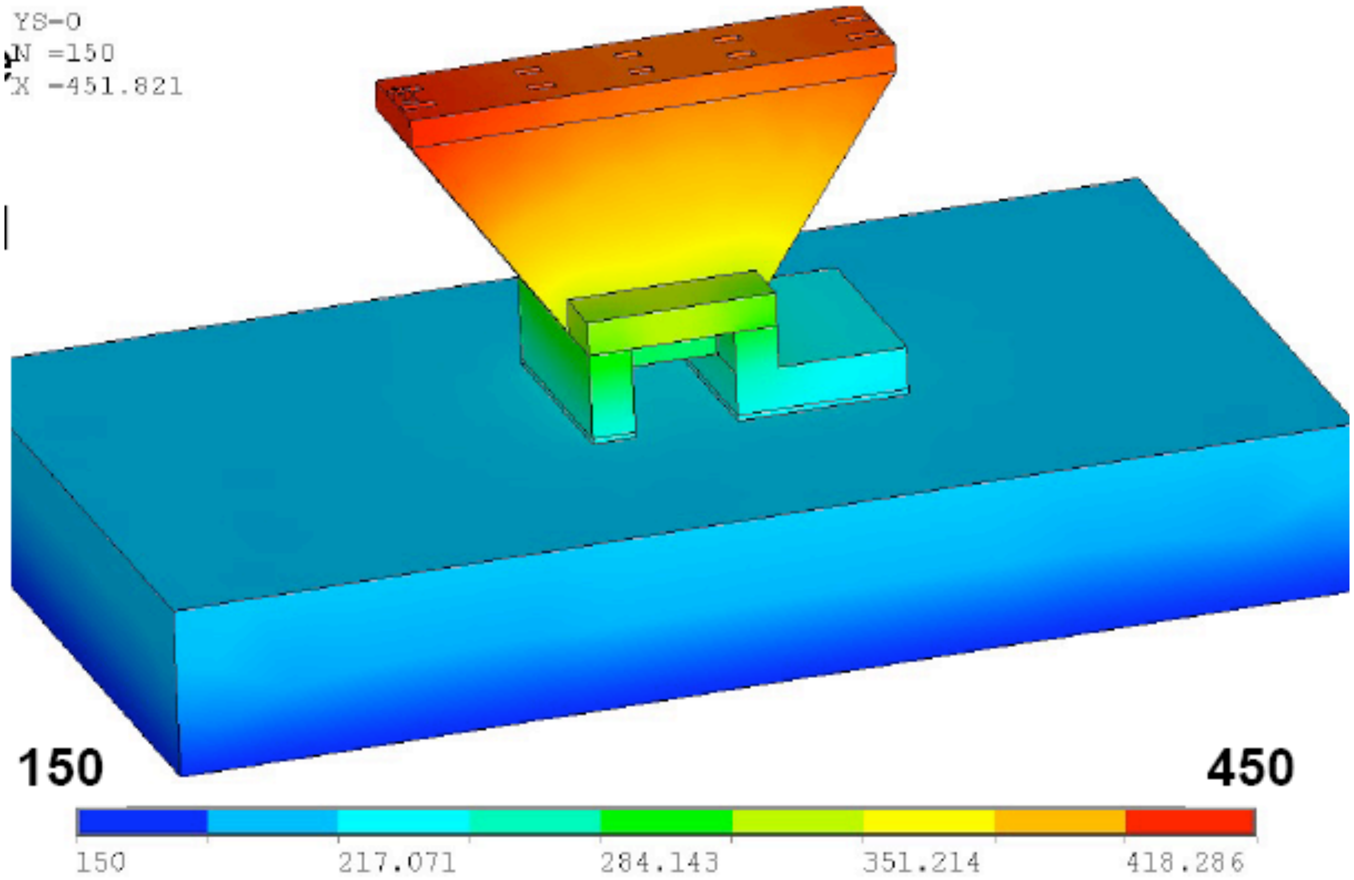


- **Bolometer mini-camera** (5 LOS)
  - Detector-housing: 80mm x 90mm, 45mm high
  - Collimator: length <130mm
  - Extension for cabling?



H. Meister

Head loading due to neutrons and gammas



H. Meister

UV and Visible Spectroscopy

Wavelength range: 200 nm to 1000 nm

Spectrometers (1D distributions) – good spectral resolution

Cameras + Interference Filters (2D distributions) – poor spectral resolution

Neutral and low ionization states >>> essentially influx measurements, not density measurements

----

2D images are essential for machine protection, i.e. points of intense plasma-wall interaction are easily identified

Low Ionization Stages

Spectroscopic Notation/Ion stage

BeI BII BIII BeIV fully- stripped

$$\mathrm{Be} \longrightarrow \mathrm{Be}^{+} \longrightarrow \mathrm{Be}^{+2} \longrightarrow \mathrm{Be}^{+3} \longrightarrow \mathrm{Be}^{+4}$$

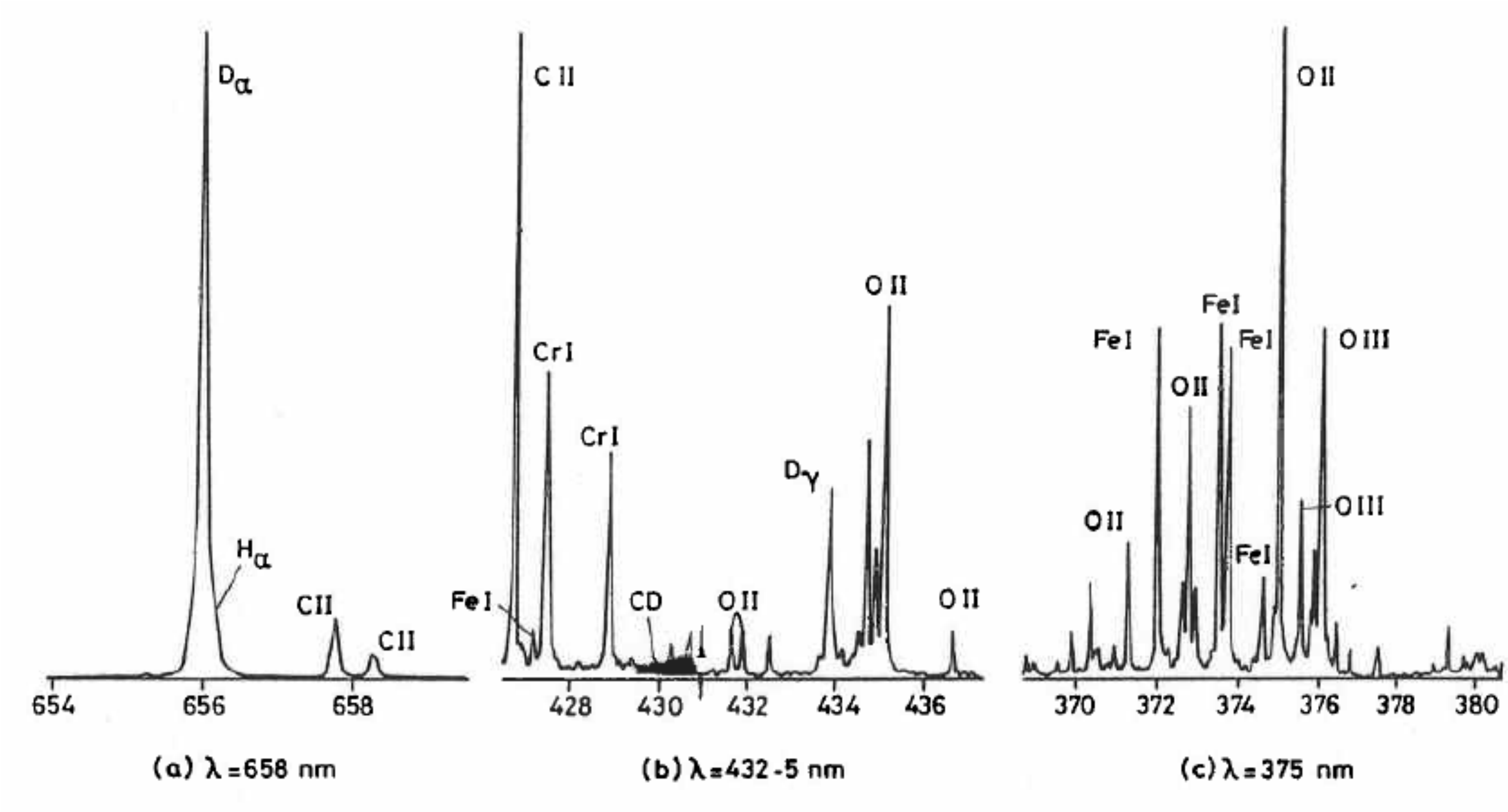
Are not in equilibrium with the plasma, i.e. electron ionization is not balanced by recombination

Recombination partly in the volume but mostly on surfaces.

Measured species and why they are important

D, T	Recycling and fuelling location, ionization source in the boundary
He	Fusion ash fluxes, in comparison with D,T is related to gas compression in the divertor
Be, C, W	primary plasma-facing components, dominant source of radiated power, transport influences erosion/ redeposition, dust and tritium retention
O	indicative of recent air/water leaks
N, Ne, Ar	may be added on purpose as a radiator
Fe, Ni, Cr, Cu	may indicate a failure of a PFC
Molecular bands (e.g. CD, CT)	evidence of chemical erosion of graphite

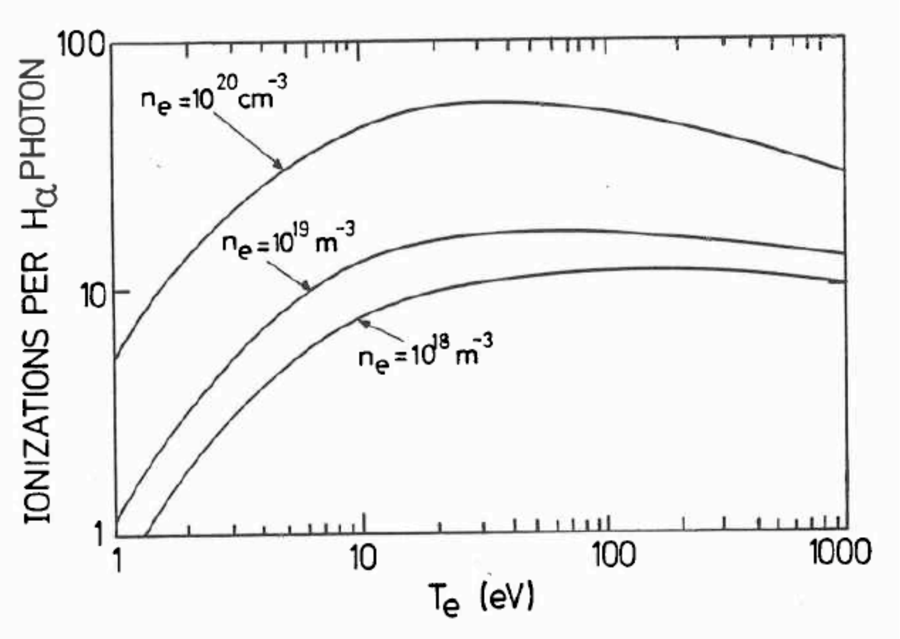
Typical visible spectra



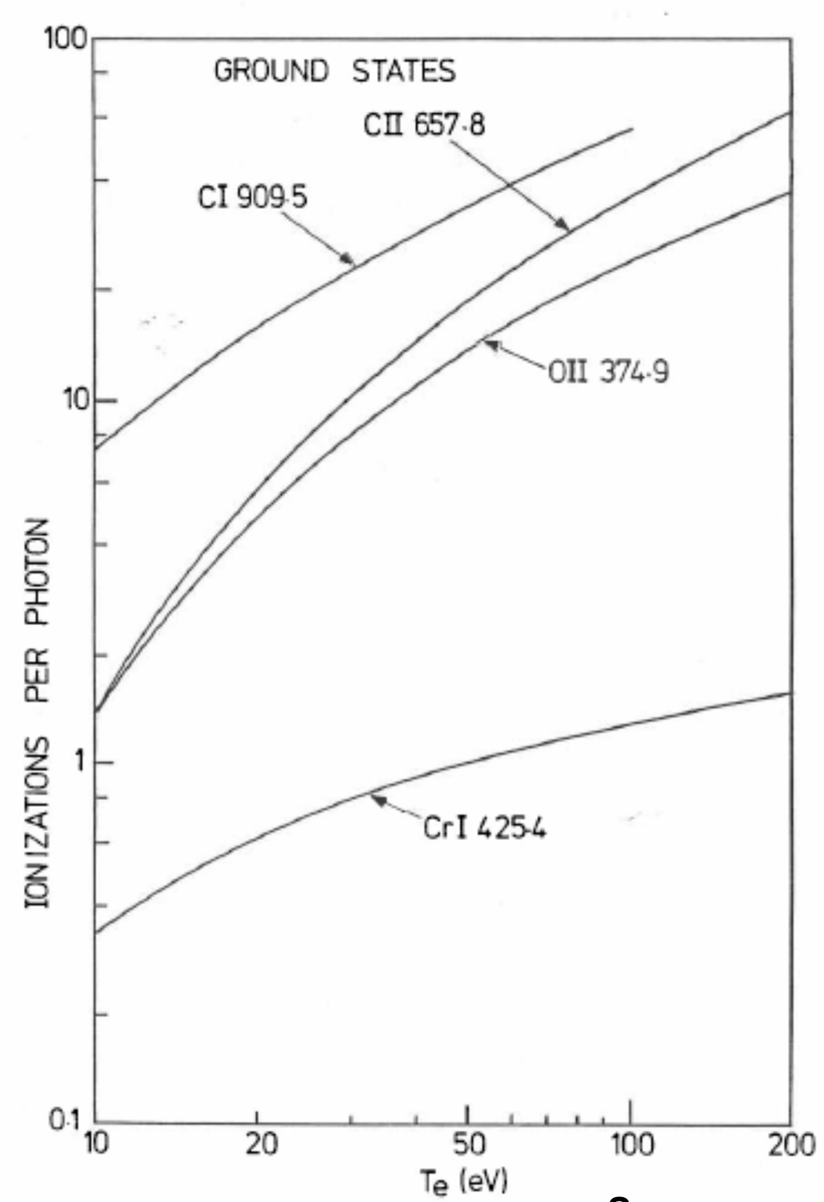
Pitcher DITE 1985

Photon Efficiency

Particle influx ~ photon flux



Johnson and Hinnov



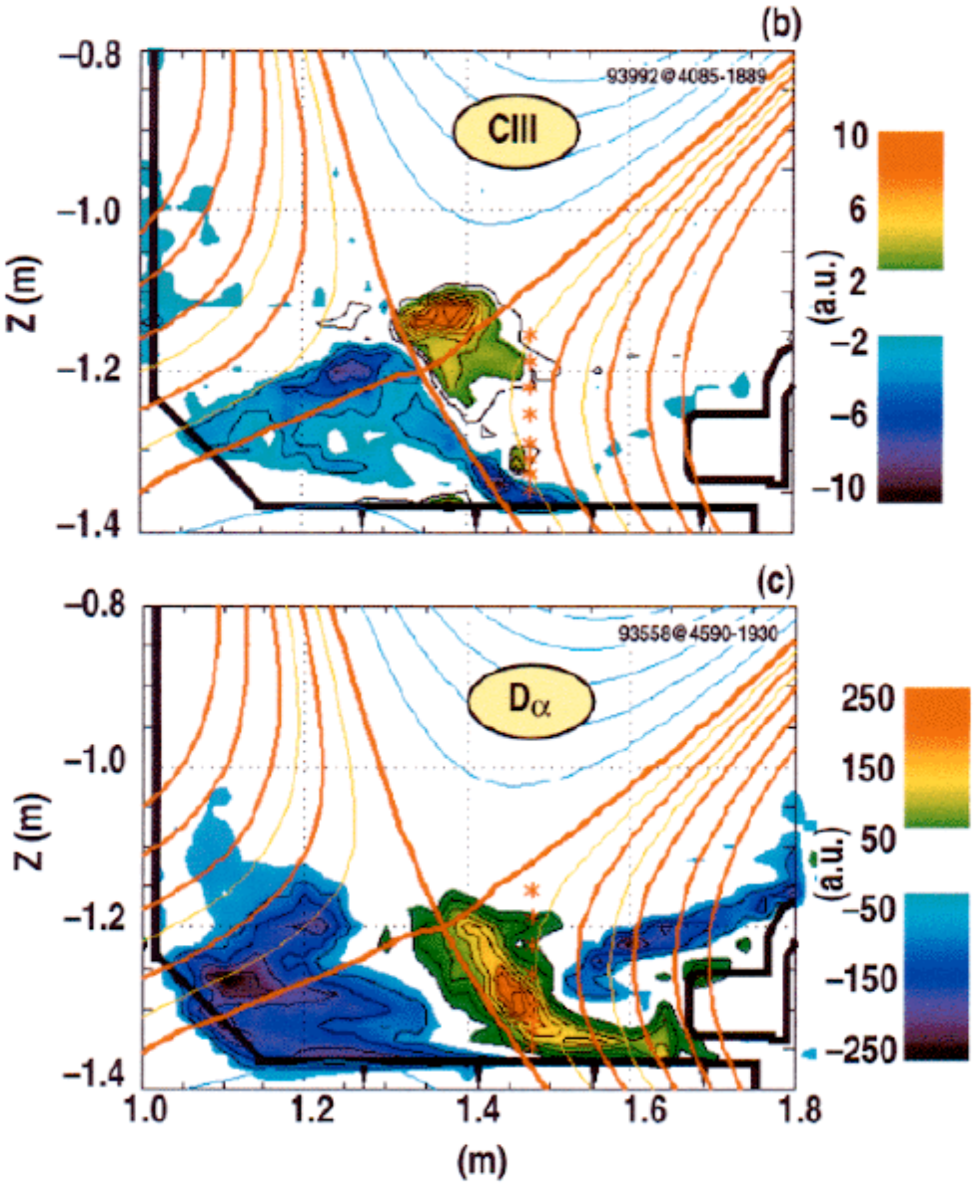
Summers

At low temperatures (< 1 eV) volume recombination becomes important, e.g. in cold divertors.

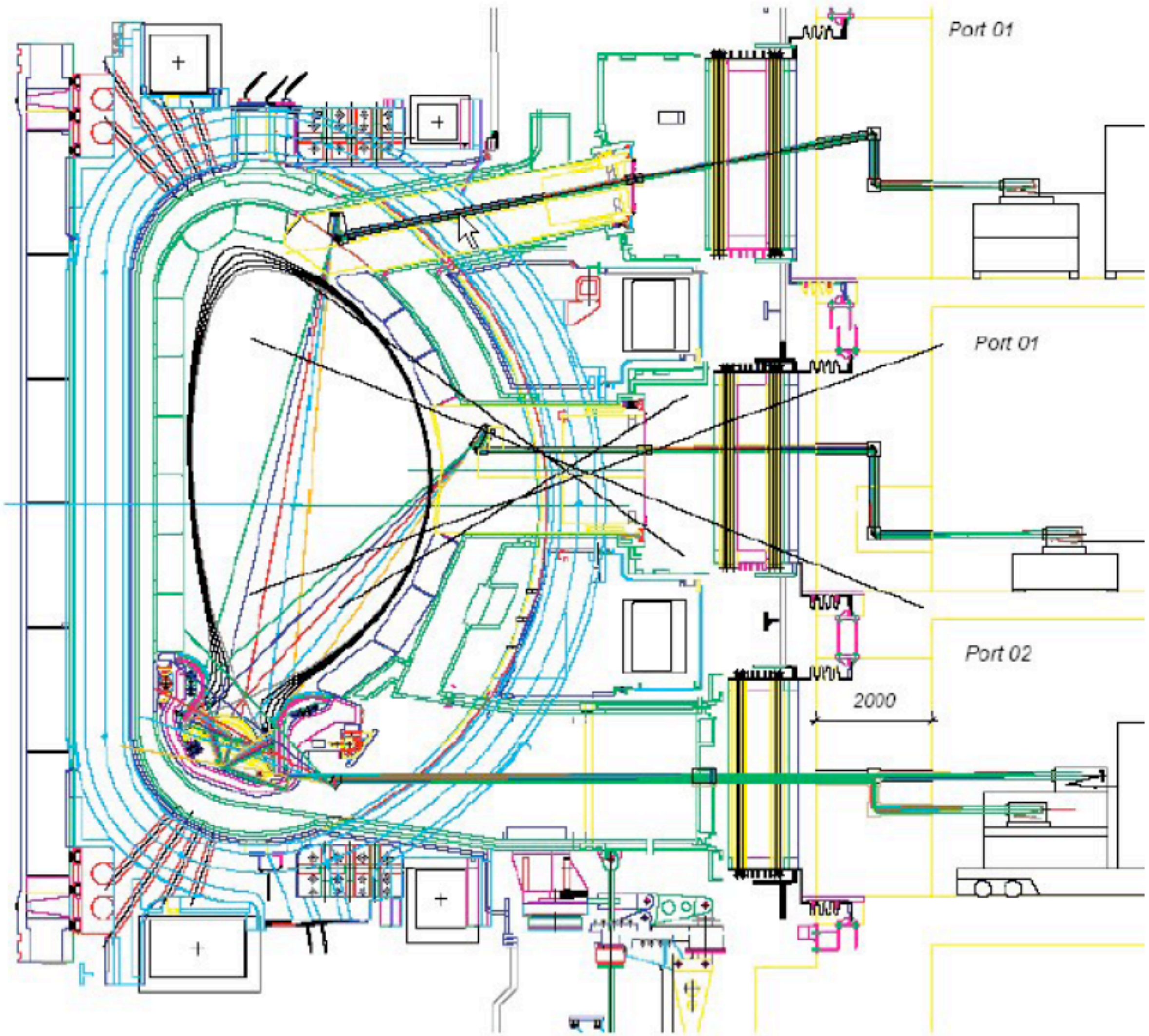
In this case simple interpretation using photon efficiencies is not possible.

A high value of Hχ compared with Hα is indicative of recombination

Partially detached conditions in DIII-D



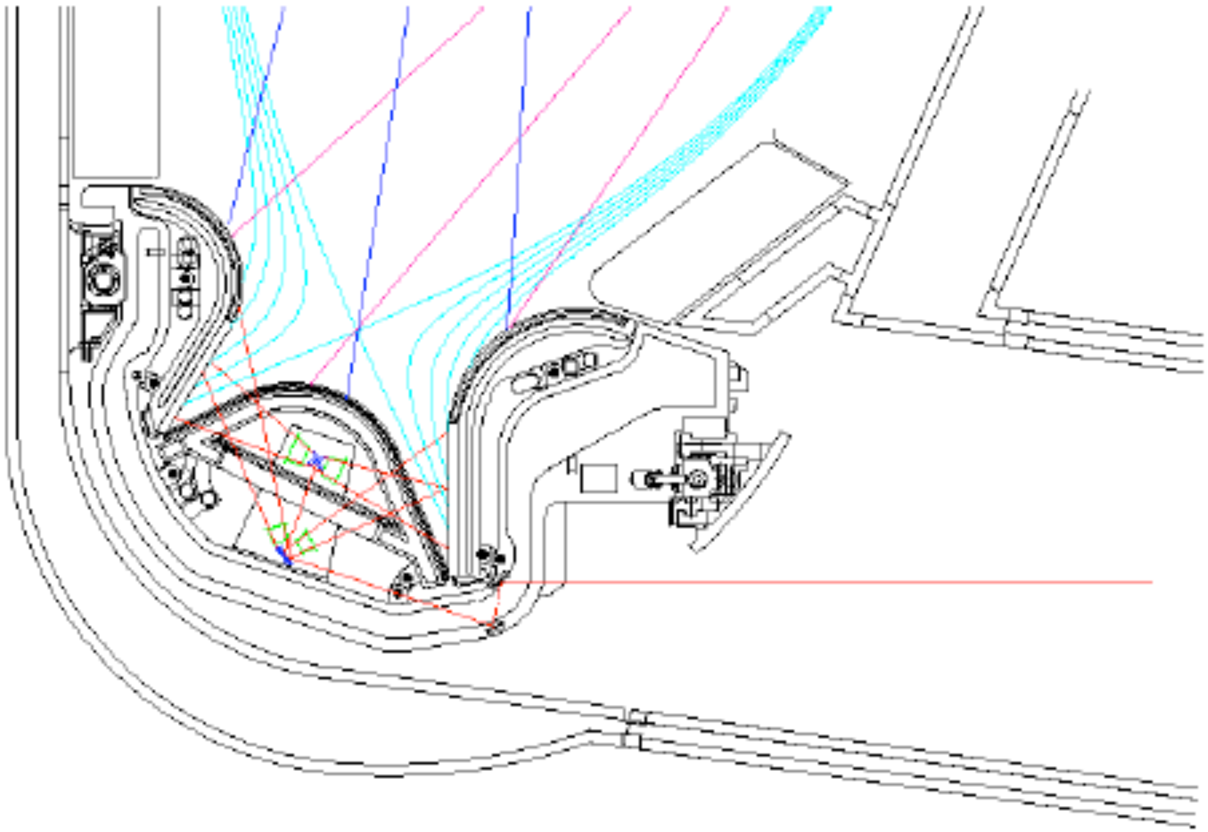
Divertor Impurity Monitor



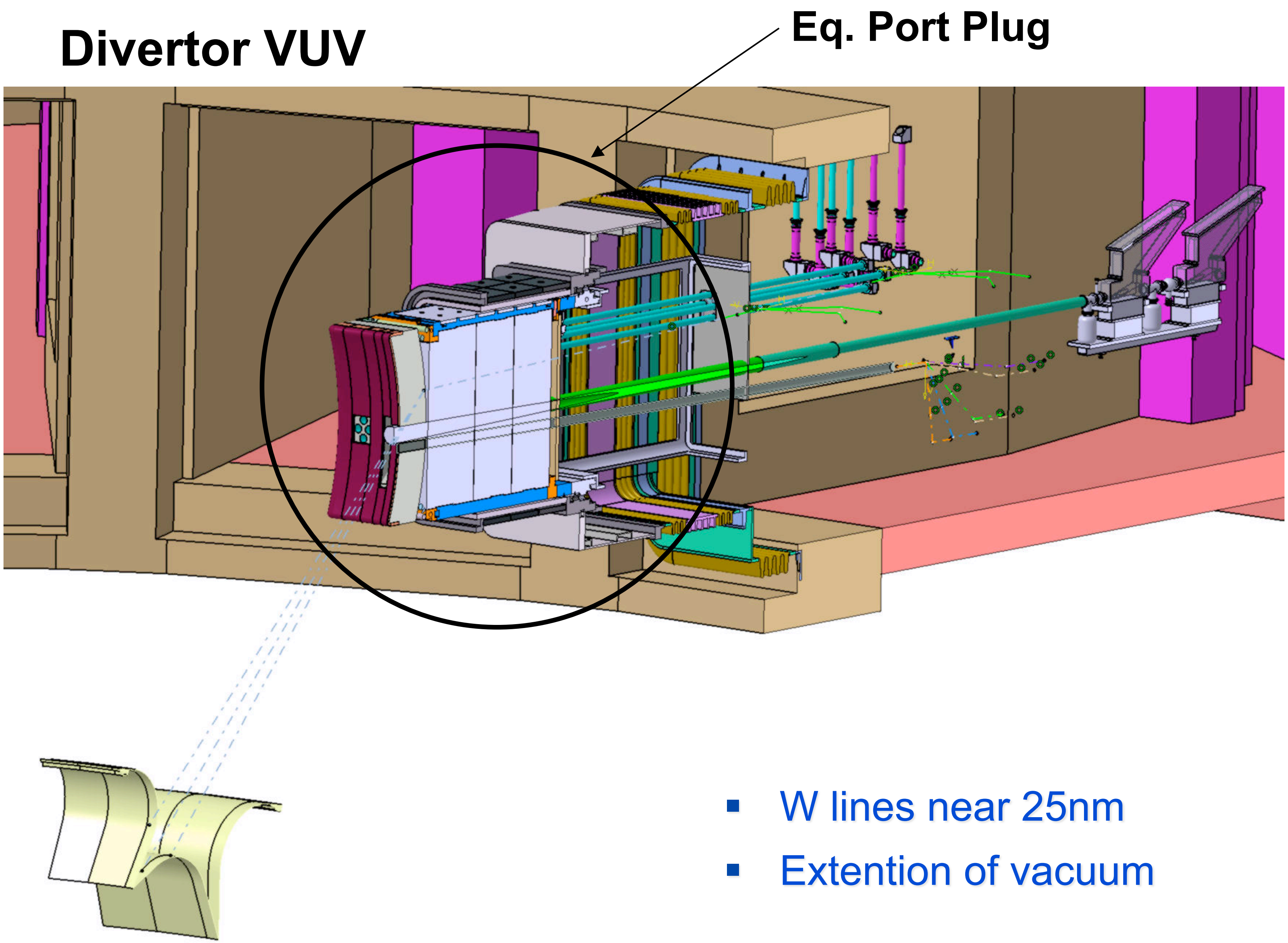
- Visible & UV light
- Divertor in flux of D &T, and D/T ratio
- Influx of impurities into divertor: Be, C, Cu impurities

Divertor Impurity Monitor

- Includes viewing from divertor dome, as well as from equatorial and upper ports



Divertor VUV



- W lines near 25nm
- Extention of vacuum

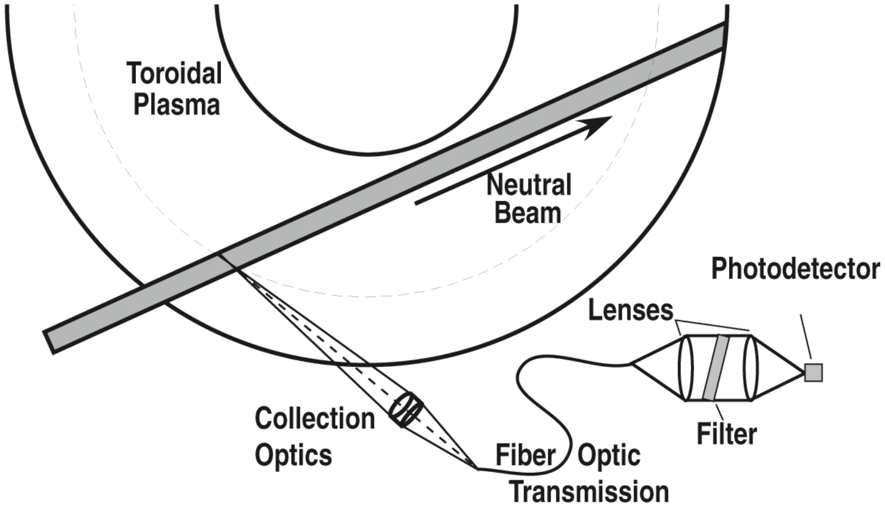
Charge-Exchange Recombination Spectroscopy

Once fully stripped low-Z impurities are nearly invisible

CXRS makes them visible by passing an electron to the ion

Allows both n_{imp} and T_i measurements

$$\boxed{H^0 + A^Z \longrightarrow H^+ + A^{Z-1*}}$$

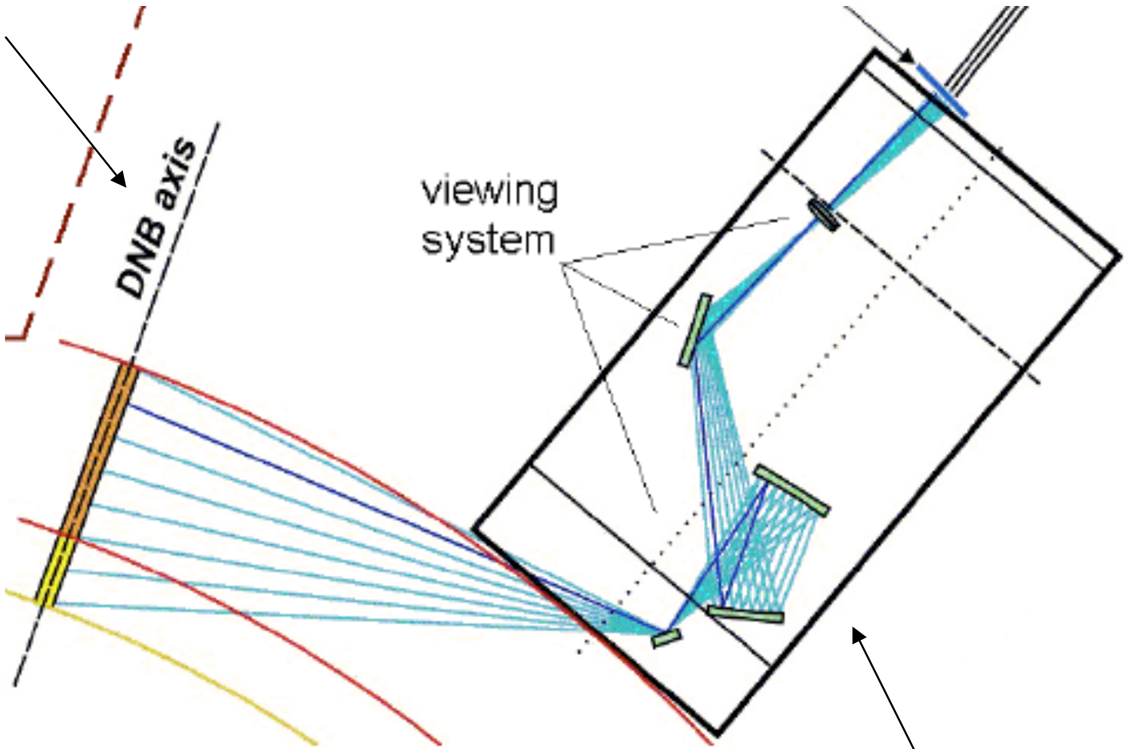


- Advantages:
  - Provides localized measurements via ‘crossed beams’ geometry.
  - Improves background rejection using beam modulation, detector gating.

DM. Thomas et al., *Fusion Science and Technology*, vol 53, 487 (2008)

ITER Edge CXRS

Diagnostic Neutral Beam



Top View

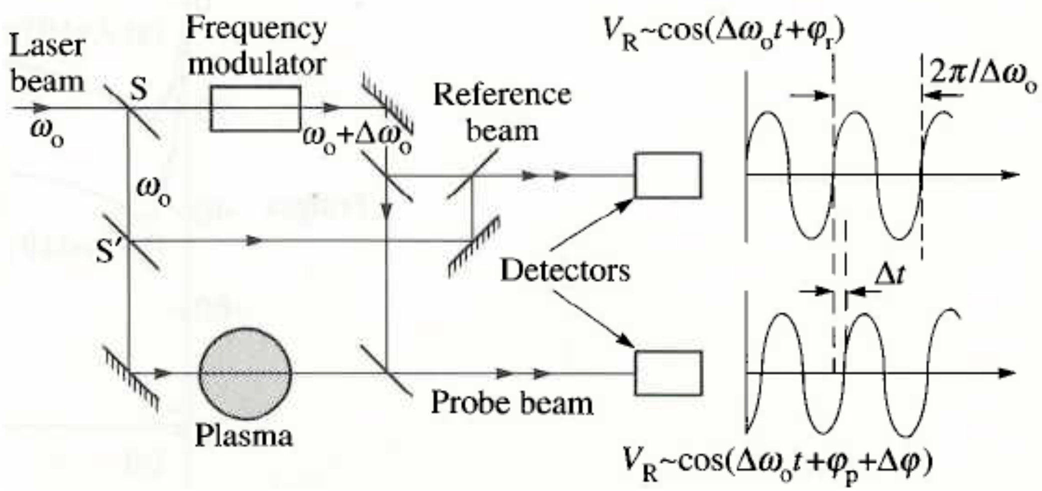
Equatorial Port Plug

Tugarinov, et al, ITPA15

Divertor Inteferometry

Change in phase of laser beam passing through a plasma,

$$\Delta\phi = [\lambda e^2/(4\pi\varepsilon_0 m_e c^2)] \int n_e \, dl$$

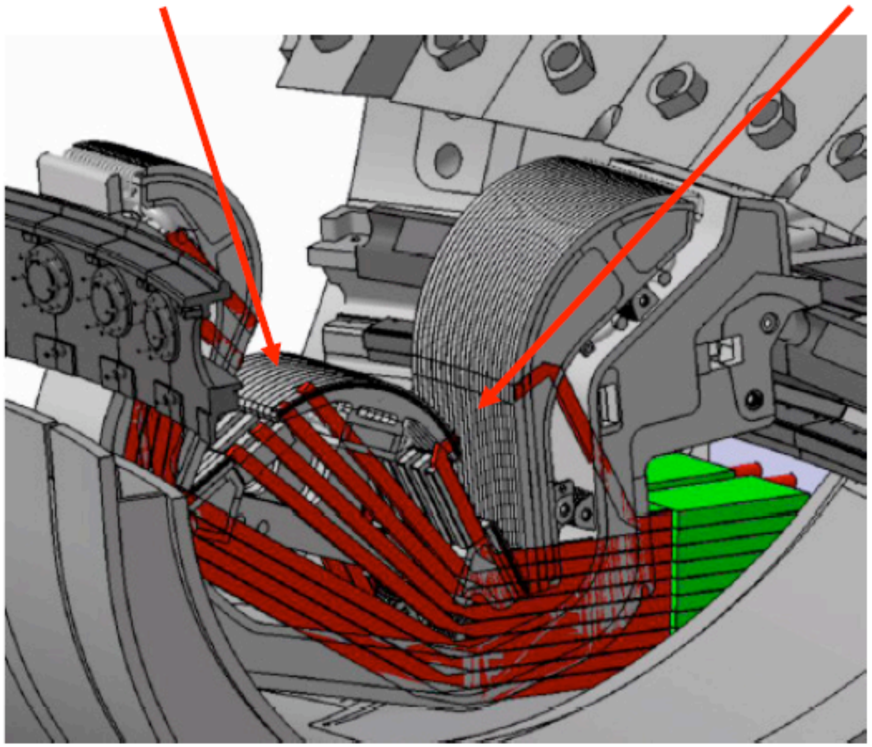


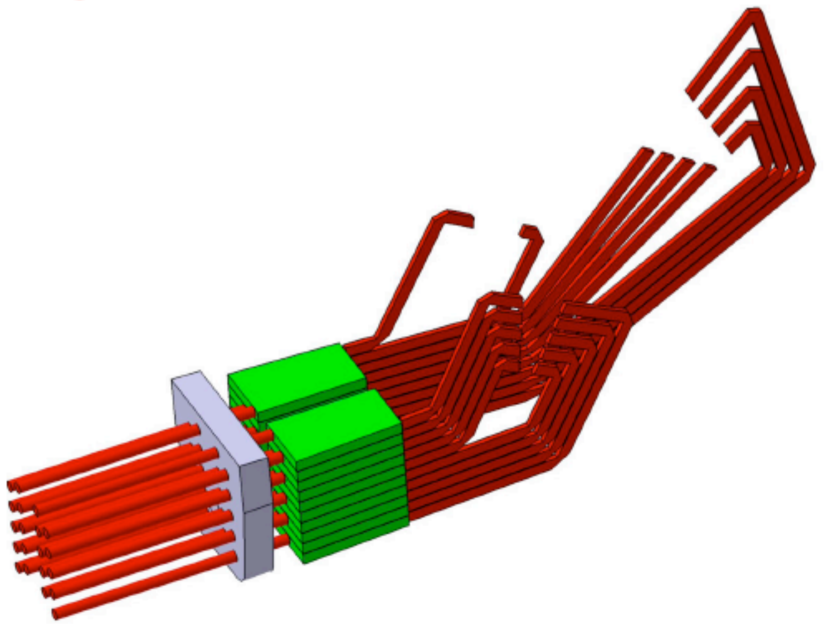
Typically, λ is 10 μm to 1 mm.

<u>Two-Colour System</u>: To deal with vibrations and thermal expansion two coincident lasers are used at different wavelengths, e.g. 9.3 μm and 10.6 μm, or 48 μm and 57 μm. Phase shift due to plasma is proportional to λ, while that due to vibrations is proportional to 1/λ. This allows shift due to plasma and mechanical shift to be separated.

Divertor Interferometer

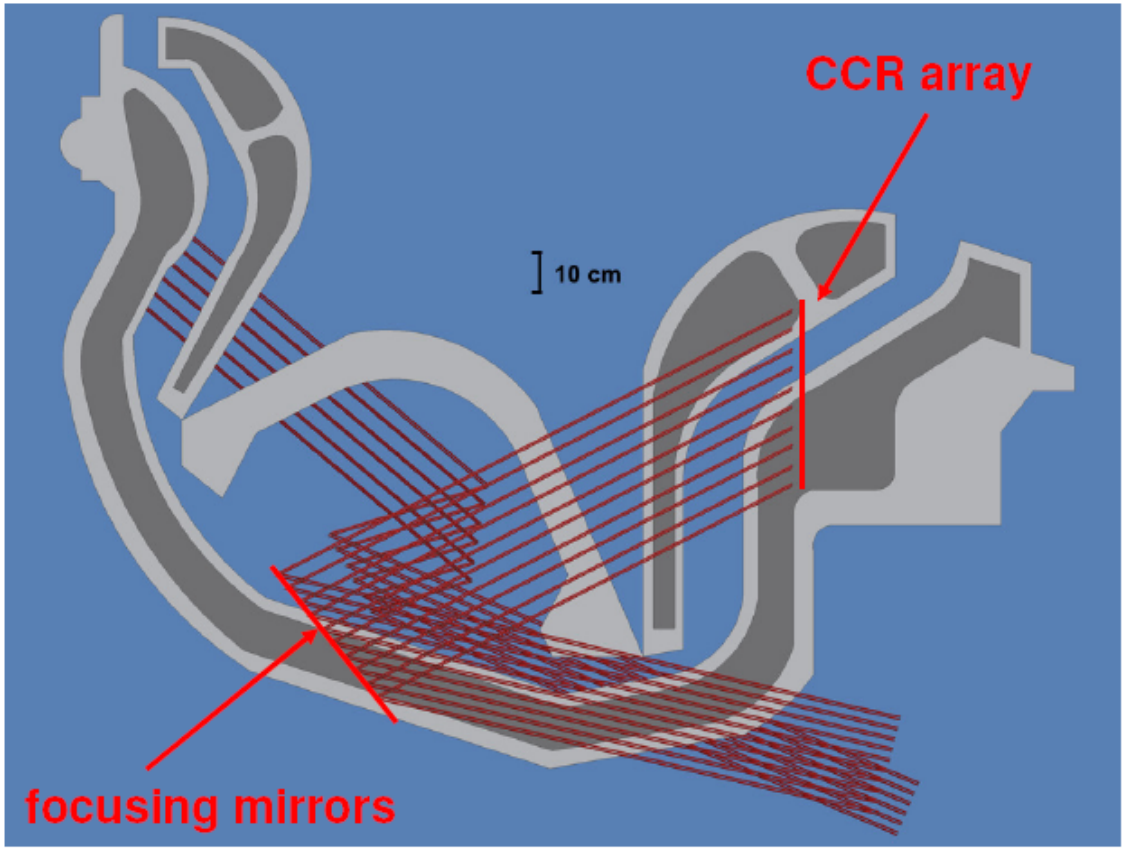
- **Measures divertor line integrated density along several chords**
- **Requirement 10^{19}-10^{22} m^{-3}, 1ms, 5cm spatial resolution along leg**
- **Determine position of ionization front**





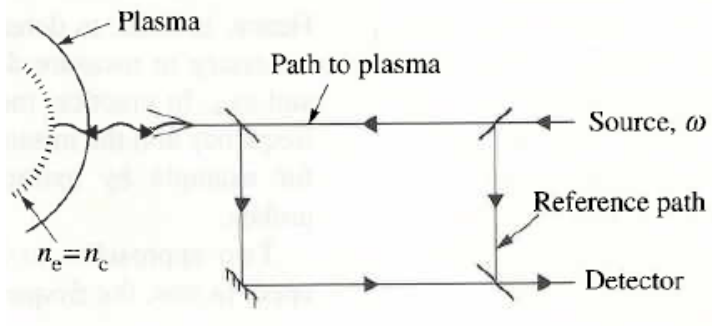
Inner leg: 4 chords
Outer leg: 6 chords

Divertor Interferometer



- Wave guide scheme vs. free propagation
- Work in 20mm gap between adjacent divertor cassettes
- Cube Corner Retroreflector
- Thermal expansion, machine movement, alignment system with feedback
- Optimum wavelength 10.6um (beam size)

Reflectometry



An alternative to interferometry is reflectometry.

Microwave radiation is launched up the density gradient and reflected at the critical frequency ω_c

Waves can propagate by two modes: ordinary mode (E parallel to B) and extraordinary mode (E field perpendicular to B)

In the case of the ordinary mode total reflection occurs when:

$$\omega = \omega_{pe}$$

Plasma frequency >> $$\omega_{pe} = \left(\frac{n_c e^2}{\varepsilon_0 m_e}\right)^{1/2}$$

Total phase delay of an ordinary mode wave during propagation in the plasma and reflection at the cut-off layer is ➔

$$\phi = 2\frac{\omega}{c}\int_{R_c}^{R_{ant}} \mu(R)\,\mathrm{d}R - \frac{\pi}{2}$$

where the integral is along the major radius, R, and

$$\mu(R) = \left(1 - \frac{\omega_{pe}^2(R)}{\omega^2}\right)^{1/2}$$

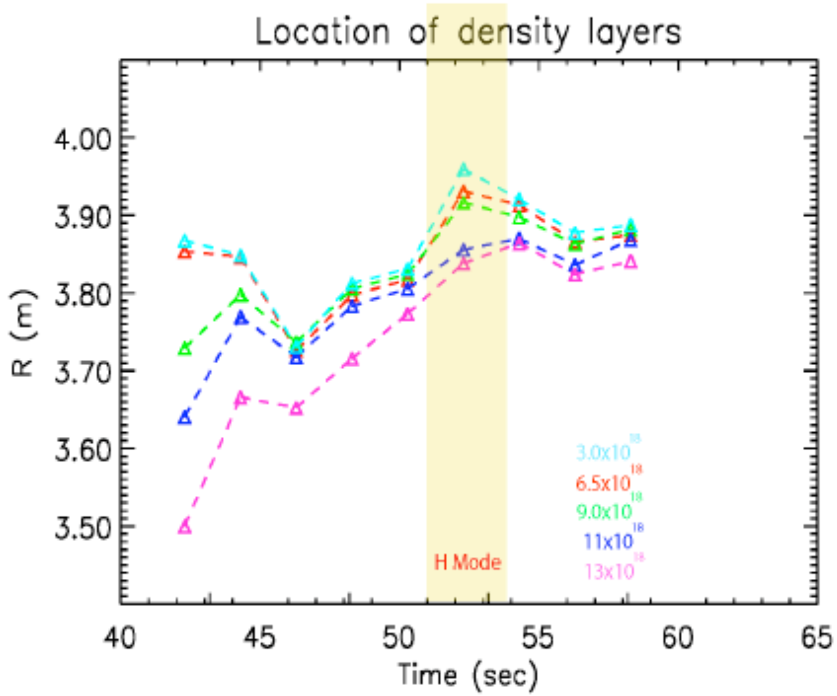
where,

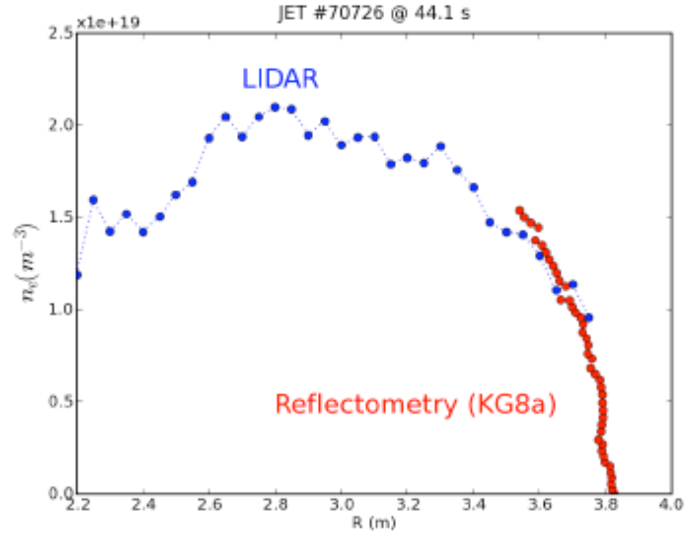
R_{ant}	the antenna radius
R_c	is the reflecting radius
$\mu(R)$	the refractive index for O-mode

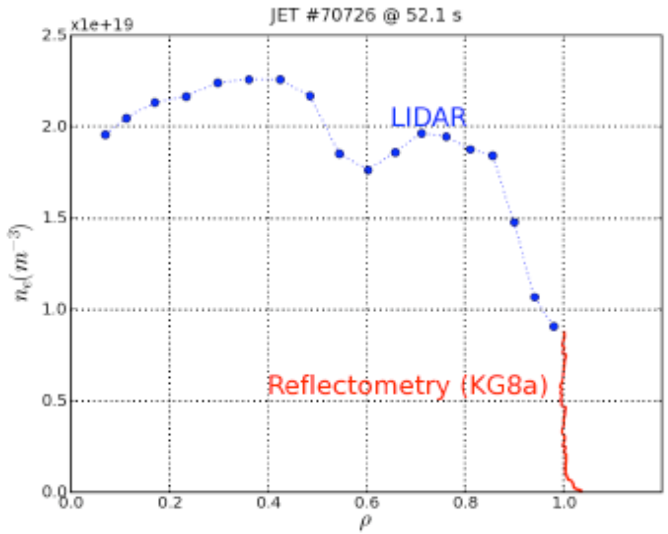
Development of profile reflectometer on JET

A.Sirinelli

- KG8a system: installed Feb. 2007 by IST & JOC
- 1 swept frequency band (50-70 GHz)
- Promising results, but limited access (B_T = 2.4T)
- Data acquisition also limited (Δt = 2s)
- Some hardware improvements still to be implemented





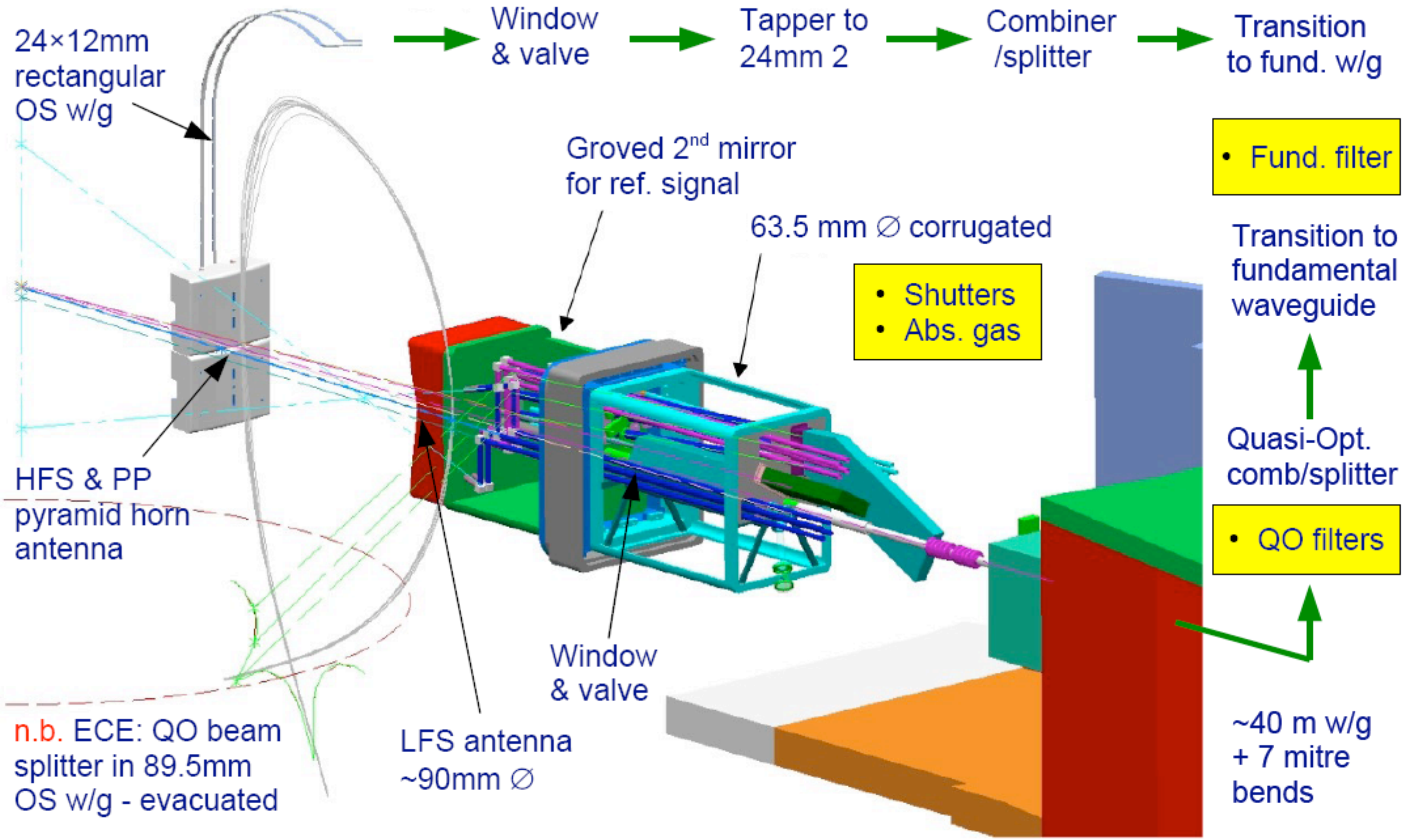


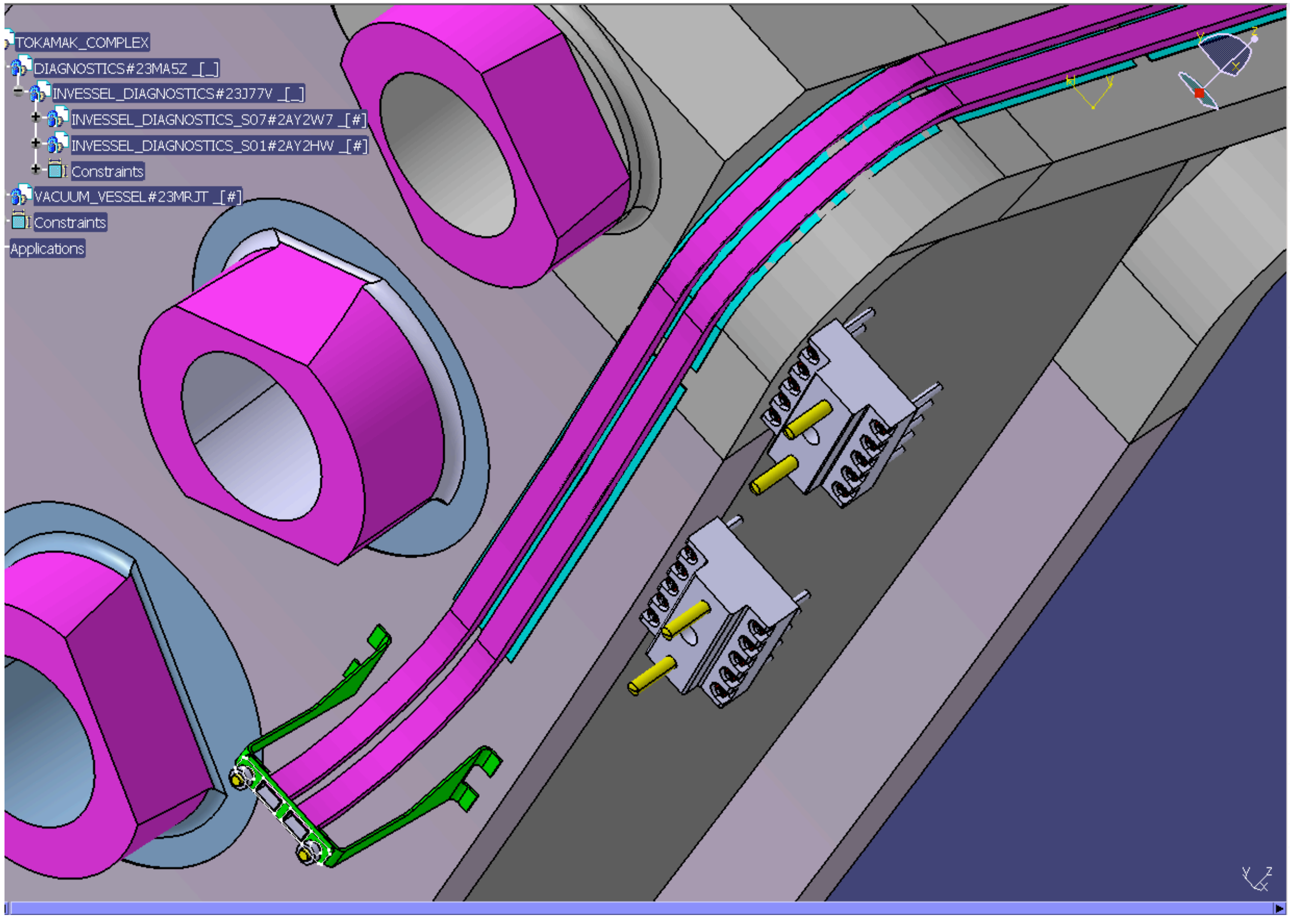
Edge Reflectometry in ITER

O-mode, 3 bands, 15 – 60 GHz

O-mode plasma position	15 – 60 GHz	3 bands: K, Ka, U
LFS O-mode profile	15 – 60 GHz+	3 bands as above
LFS O-mode profile	40 – 160 GHz	4 bands: U, E, F or W, D
LFS Xu-mode profile	76 – 180GHz	2(or 3) bands: W, D, (G)
HFS Xl-mode profile	8 – 78 GHz	3-5 bands: (X), K, Ka, U, (V/E)
HFS O-mode profile	15 – 127 GHz	5-6 bands: K, Ka, U, E, F

ITER reflectometer waveguide overview




TOKAMAK_COMPLEX
DIAGNOSTICS#23MA5Z _[_]
INVESSEL_DIAGNOSTICS#23J77V _[_]
INVESSEL_DIAGNOSTICS_S07#2AY2W7 _[#]
INVESSEL_DIAGNOSTICS_S01#2AY2HW _[#]
Constraints
VACUUM_VESSEL#23MRJT _[#]
Constraints
Applications

Infra-Red Thermography

Has both a machine protection function and physics function

Heat flux related to incident plasma conditions

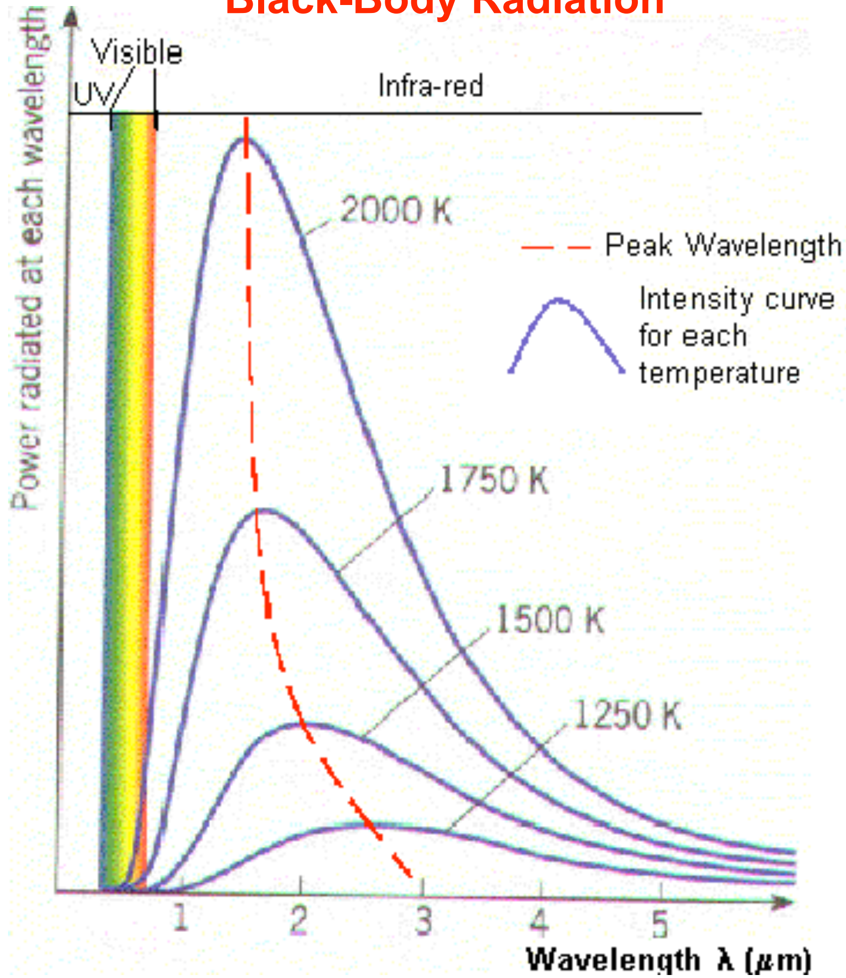
Fast cameras can follow ELMs

Need to cover large fraction of inside of the vessel, 80% appears feasible

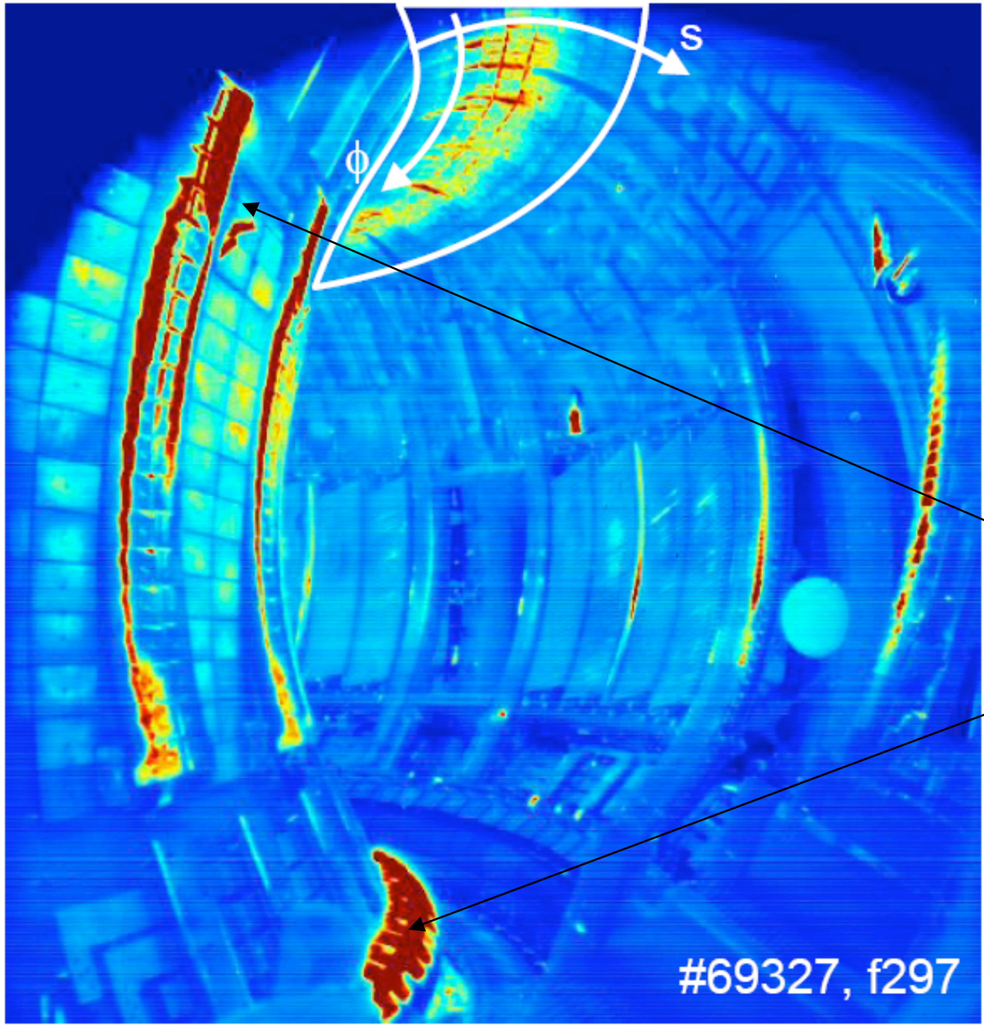
Measures black-body radiation, 3 um to 12 um, depending on detector

< 3 um can be influenced by molecular band emission

Black-Body Radiation



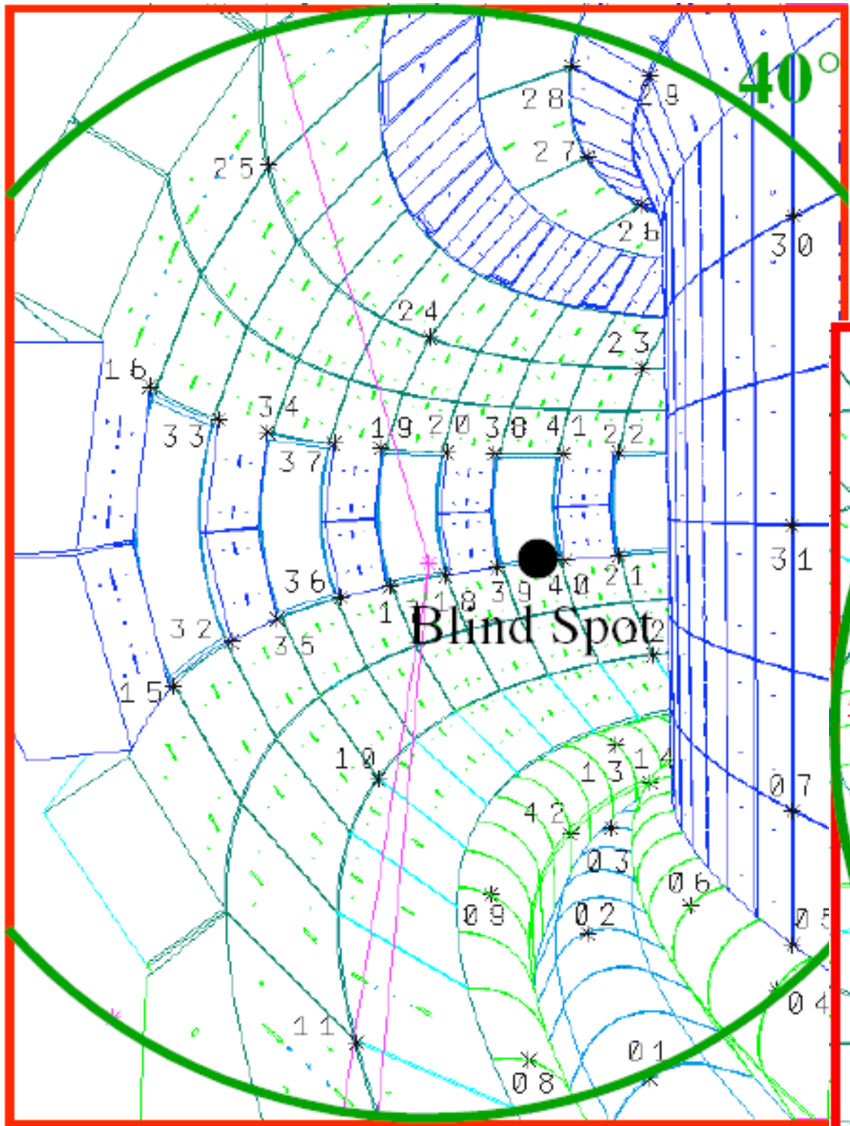
Fast Camera on JET

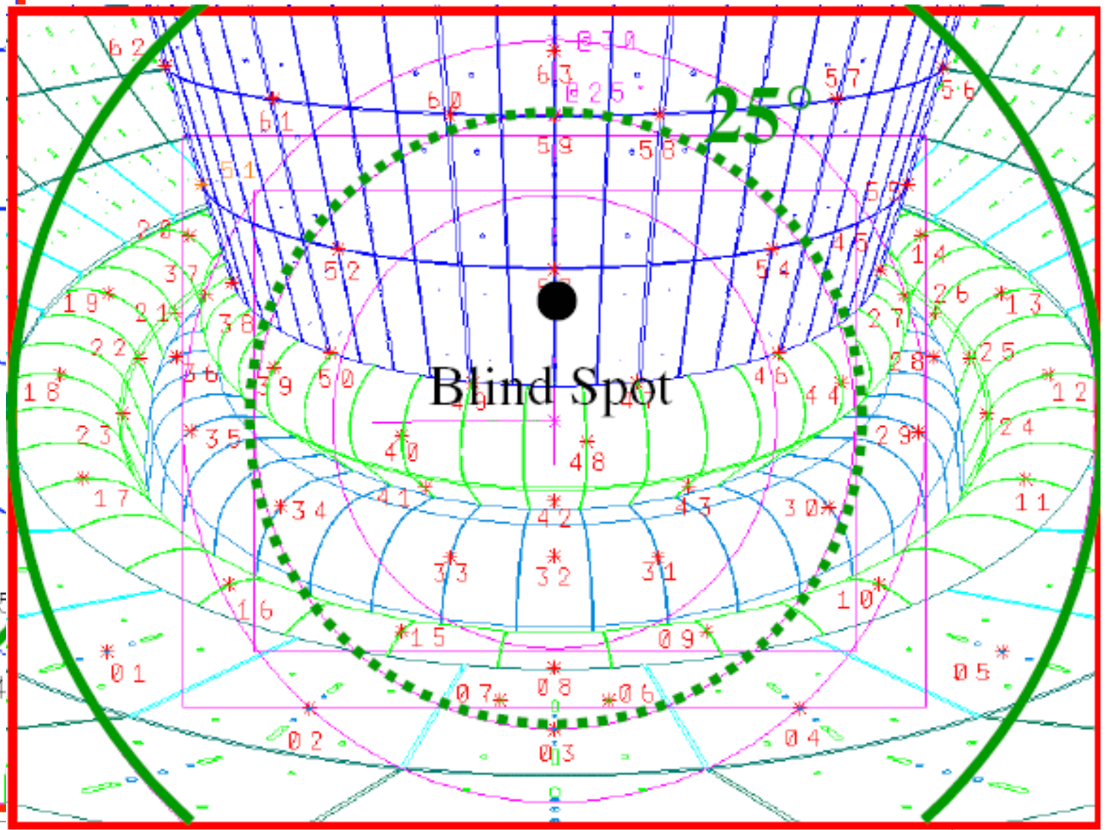


Density limit disruption (DLD)

Hot spots

ITER Main Chamber IR Thermography
view from equatorial ports

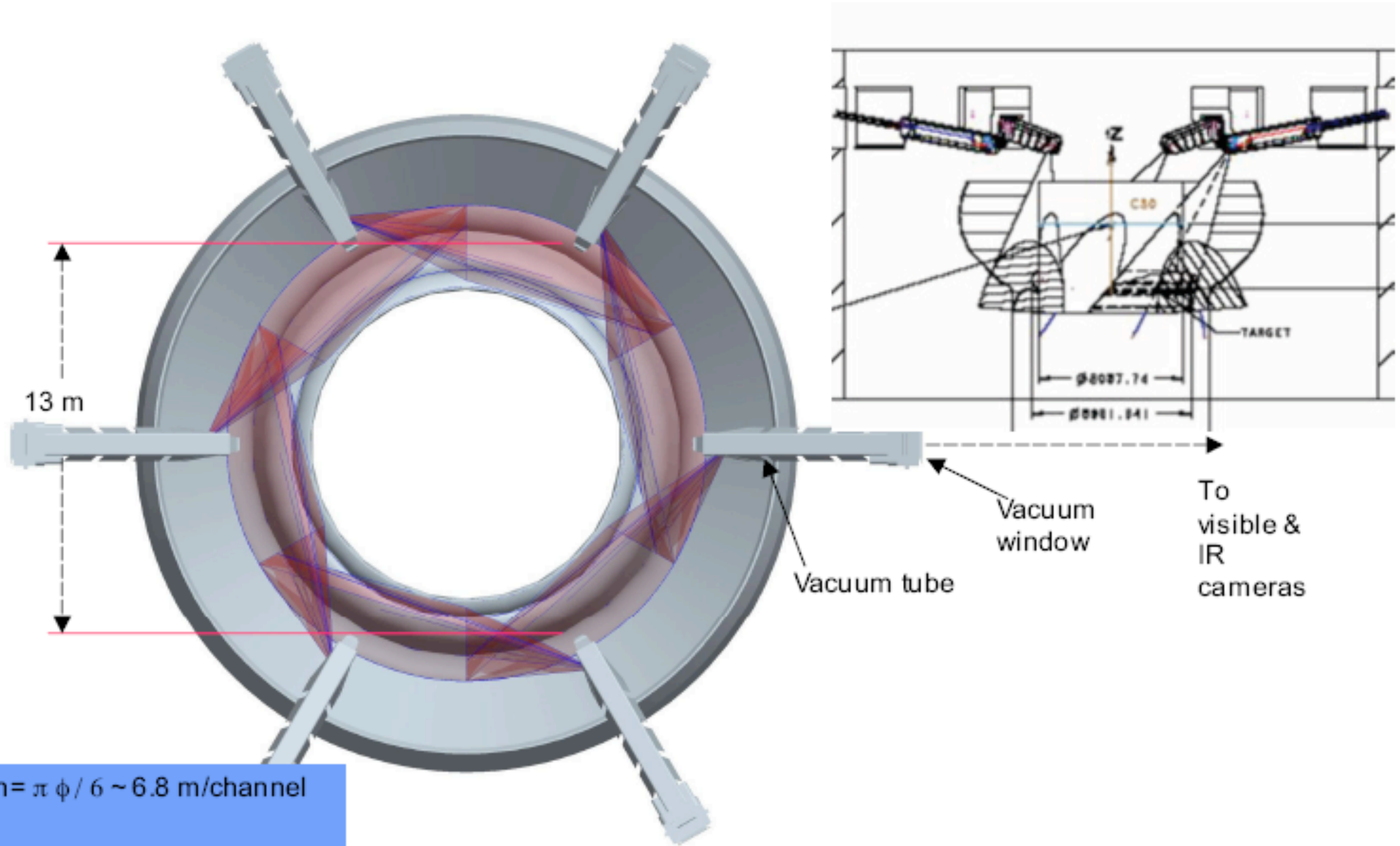




Main Chamber IR Thermography view from upper ports

IRTV system uses 6 locations to provide 360 degrees coverage on ITER divertor

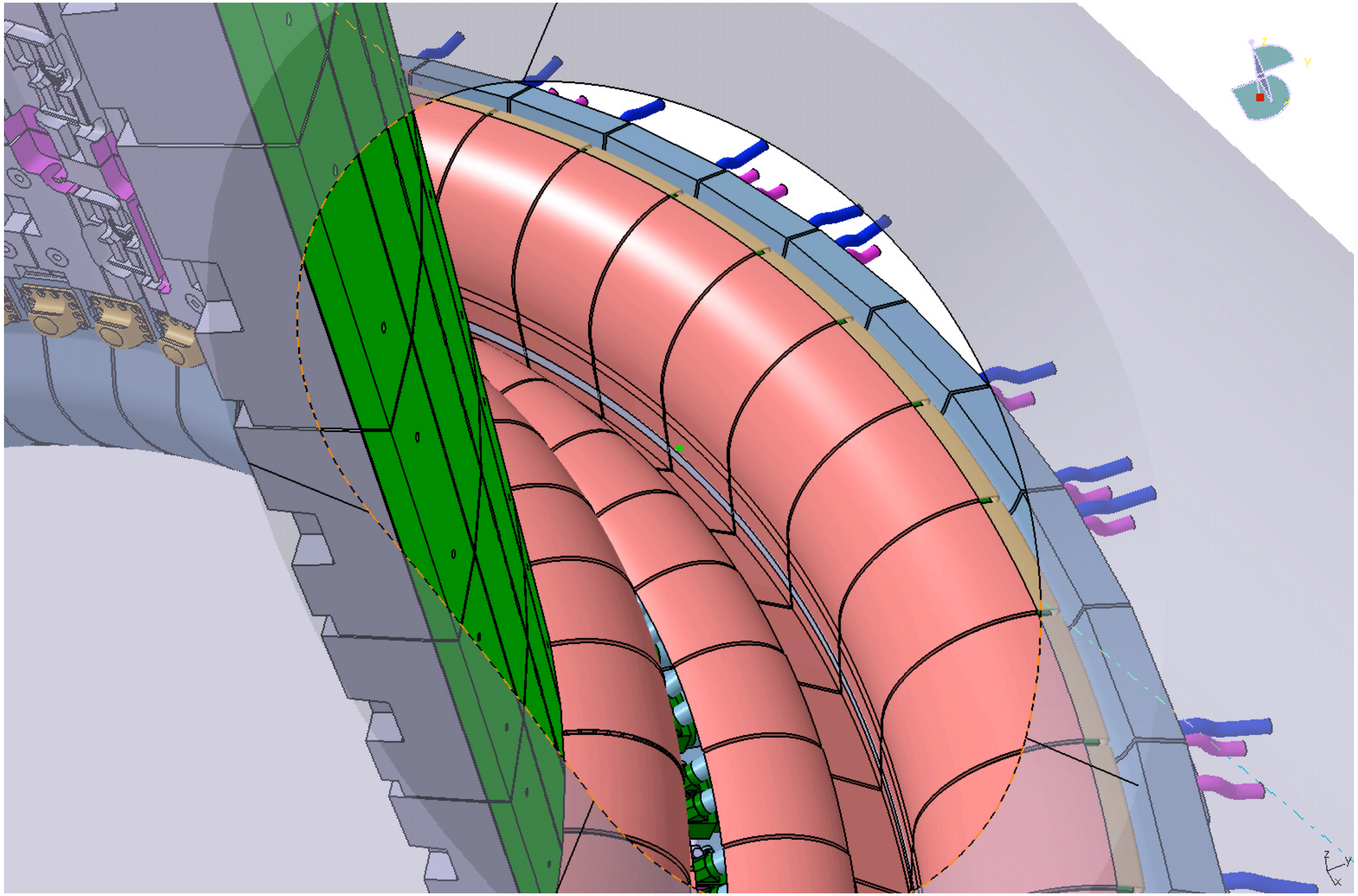
Top View



Object length = $\pi\ \phi / 6$ ~ 6.8 m/channel

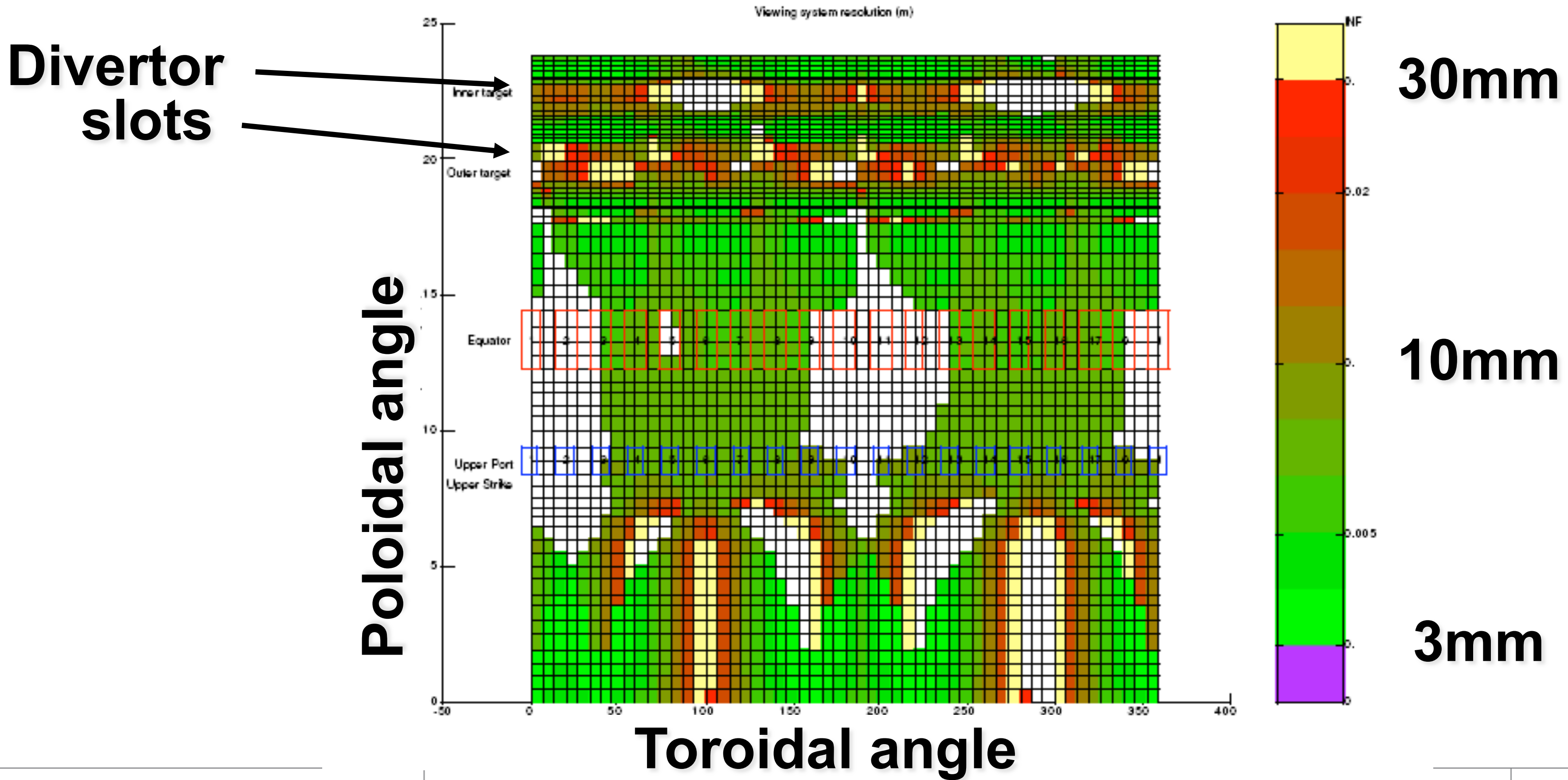
System is side-looking to allow view of divertor trough

Upper Vis/IR Views – downward and toroidal

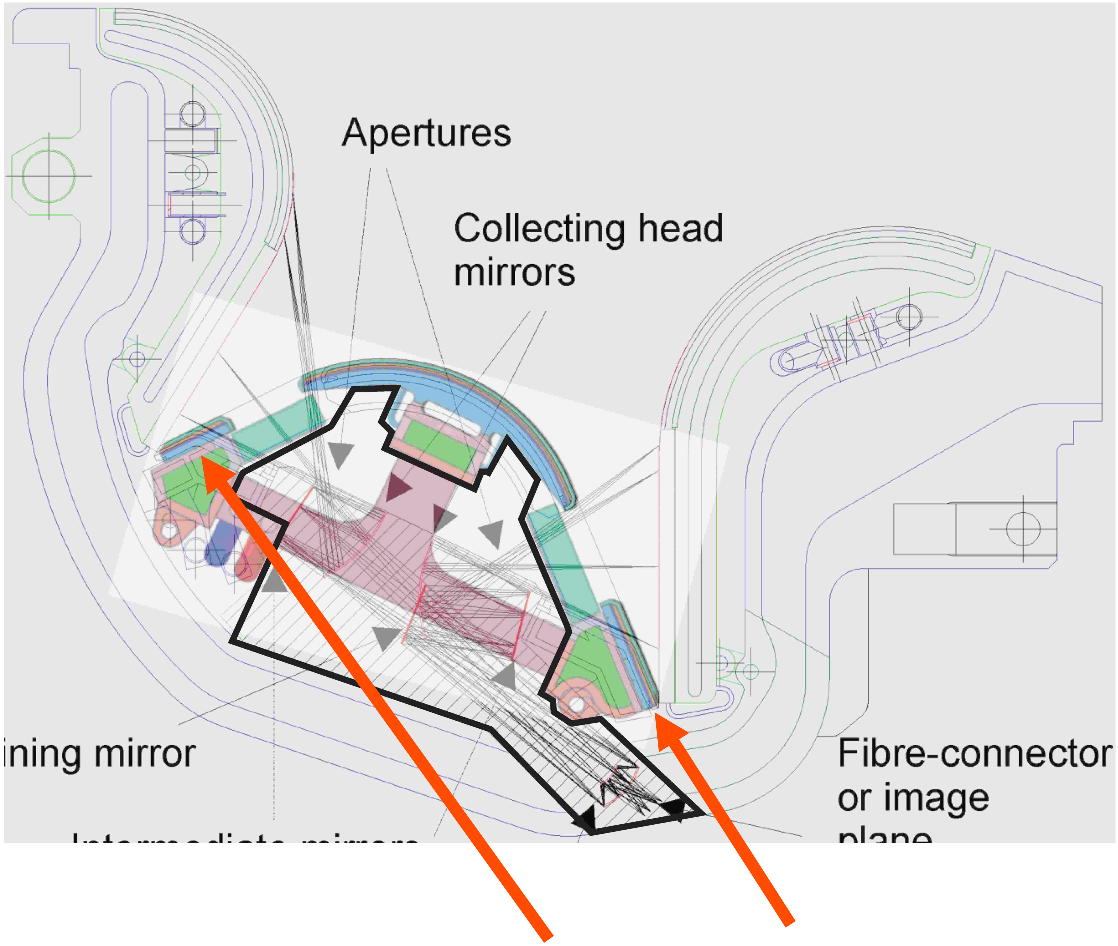


Main Chamber IR Thermography

- ITER requirements: ~ full coverage, 3mm resolution at divertor
- Main chamber systems offer ~ 35 mm spatial resolution of divertor

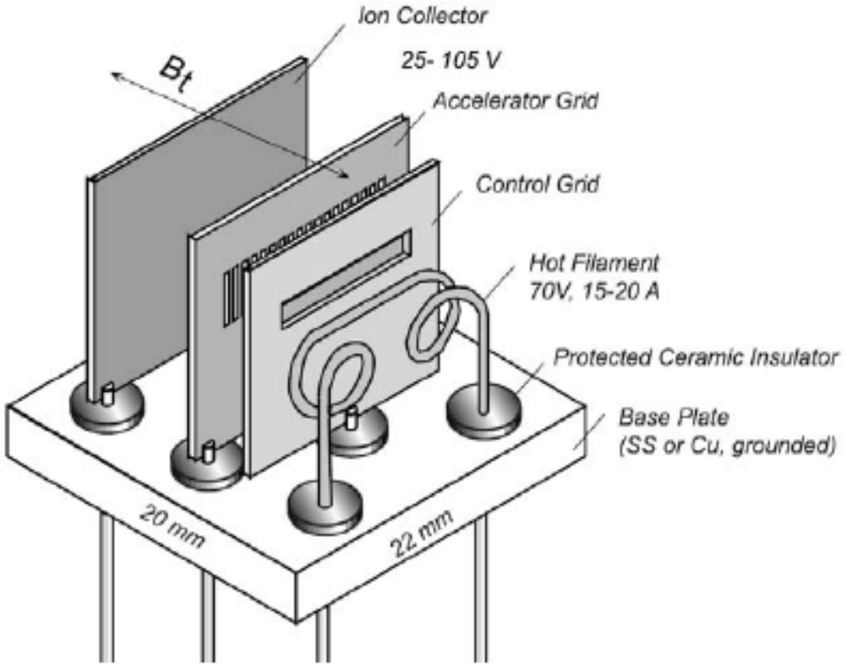


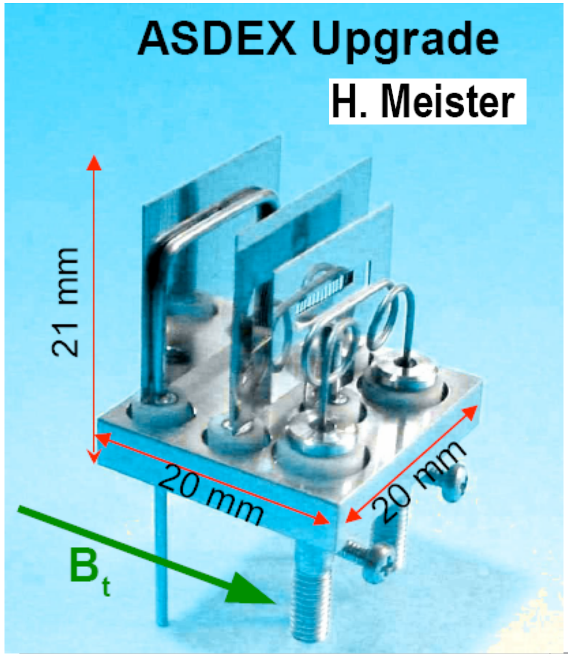
Divertor IR Thermography



- Light from different points on target relayed to spectrometer
- Fiber optics or mirrors being considered for relaying light in vessel out from the cassette
- Implemented in central part of cassette

Toroidal gaps in dome PFC allow view of strike point





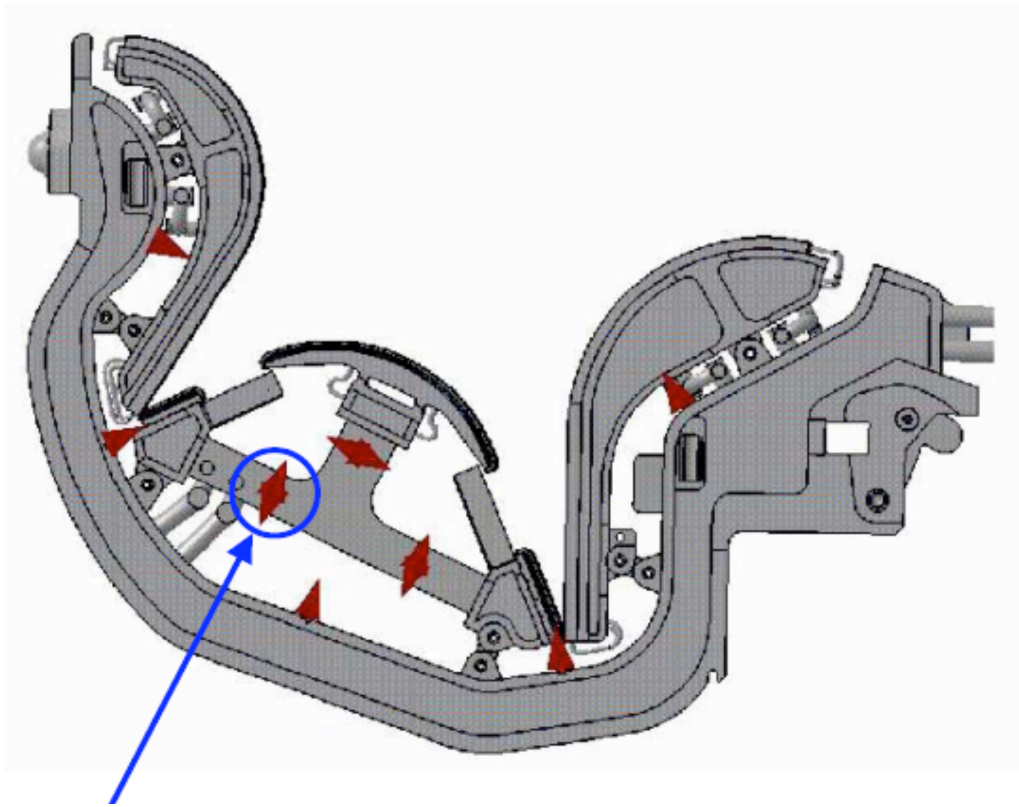
Ionization Gauges

- Upper limit of ASDEX gauge pressure range 10 Pa, could be extended to 15Pa with some effort
- Gauges developed to extend range to 20 Pa.
- Uses thermionic emission from a hot filament: lifetime issue
- Also envisaged/considered for main chamber pressure measurement

Pressure Gauges

- Measure neutral pressure in the divertor
- Range: 10^{-4} -20 Pa
- Response time: 50 ms

- Locate gauges in volume between PFC & cassette body
- Electrical connection made through remote handled plugs & sockets
- Aperture in gauge housing samples incident flux



Ionization gauge

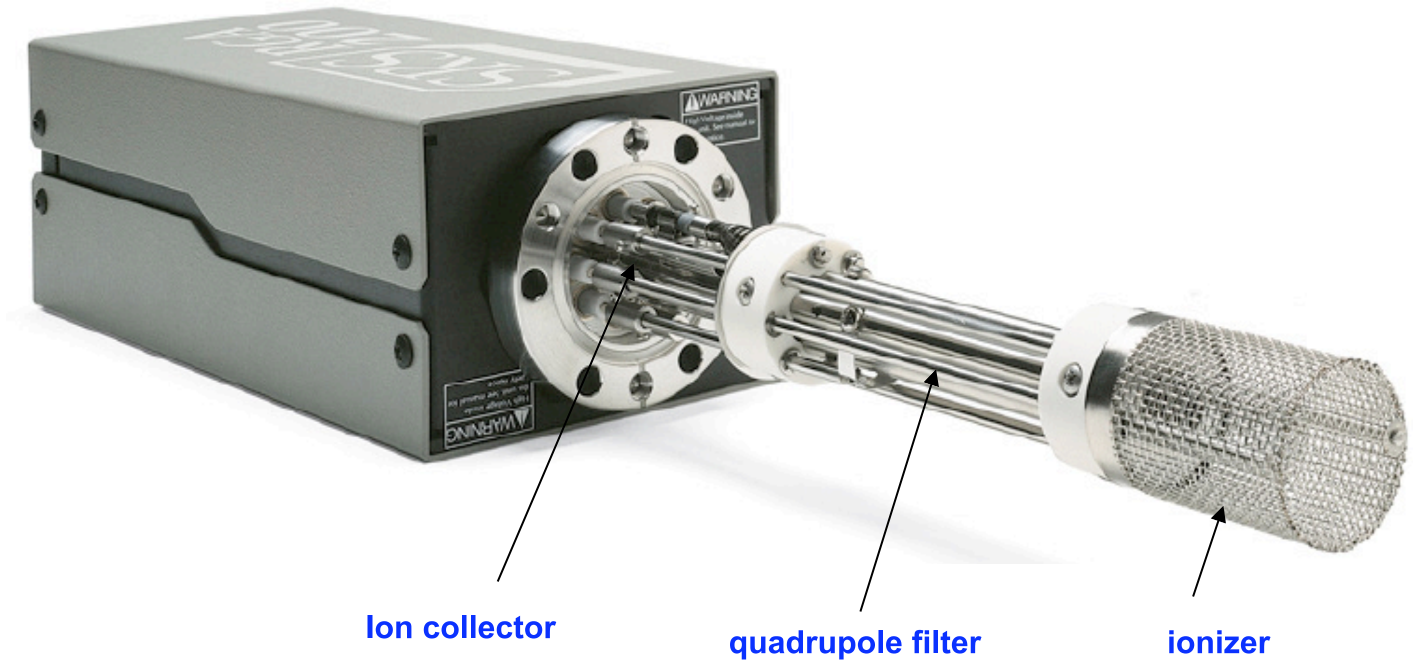
Residual Gas Analyzers

RGAs are used during plasma operation to analyze the composition of the divertor gases, e.g. H, D, T, He, Ne, Ar, H2O, hydrocarbons, etc

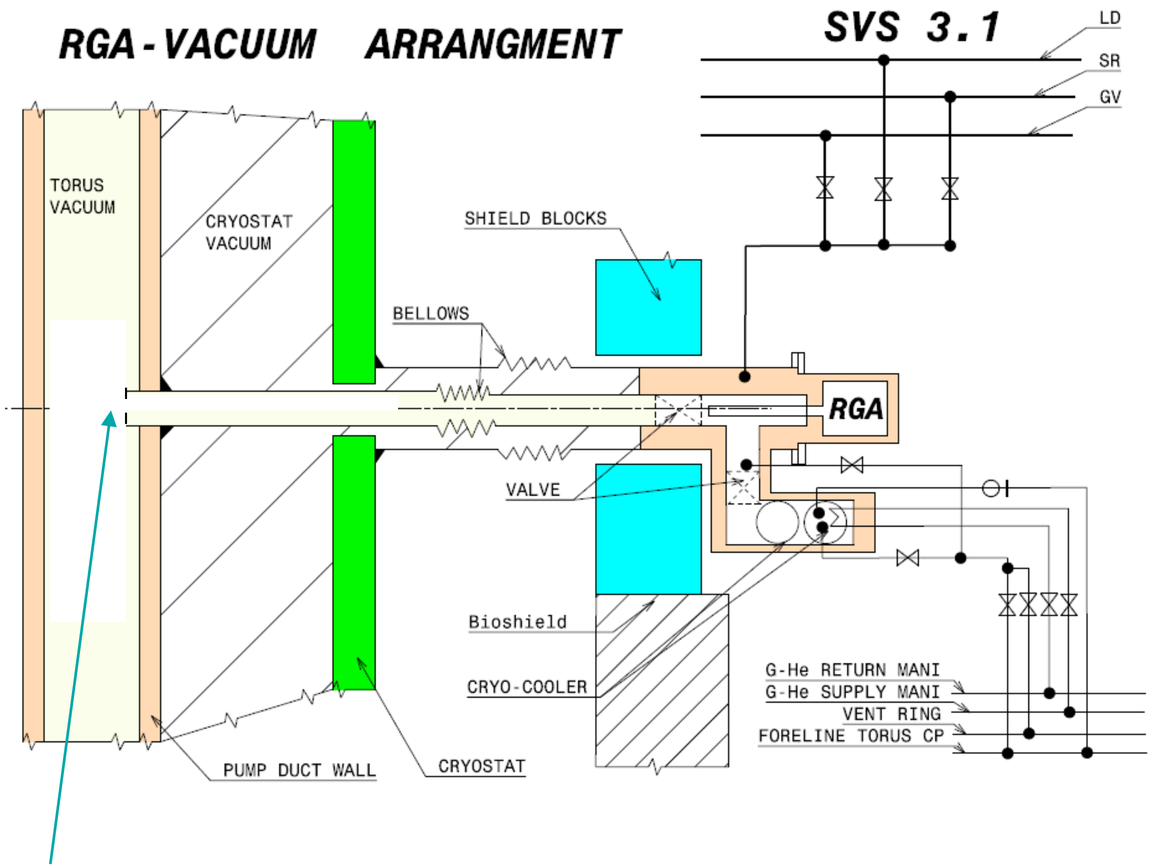
Like an ionization gauge, but with charge to mass resolution

Most common instrument is a quadrupole analyzer, commercially available

Often problems with coincident masses, e.g. D2 and He, mass 4



Residual Gas Analyser



Limiting orifice

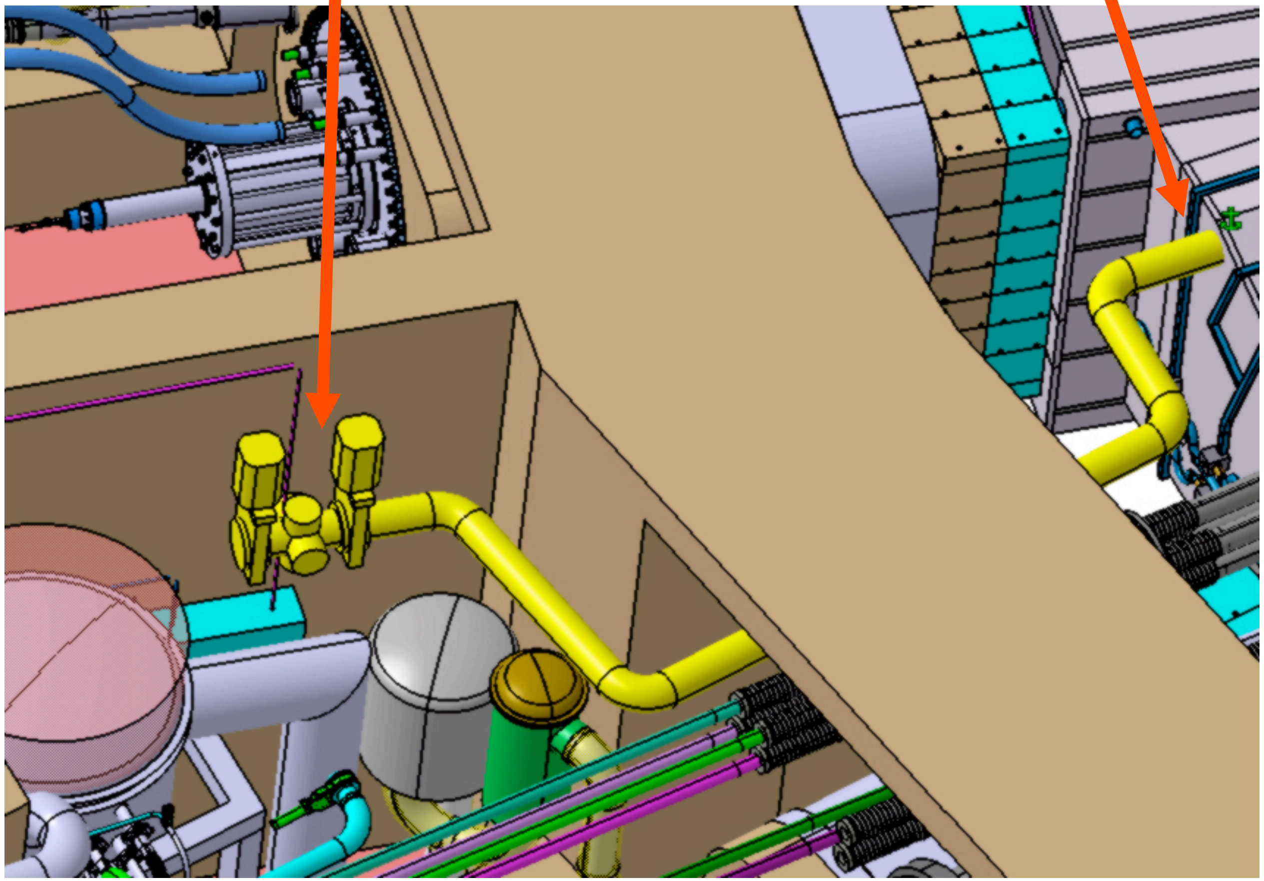
- Sample gas through limiting orifice
- QMS gives charge to mass discrimination
- Penning discharge spectroscopy proposed for He/D discrimination
- ~1 sec time response due to length of sample pipe
- Similar system sampling main chamber envisaged

- **Measure composition of exhaust gas**
  - **gaseous erosion products**
  - **helium exhaust rate**
  - **D/T ratio**
- **Divertor Neutral gas pressure ~1-20 Pa**

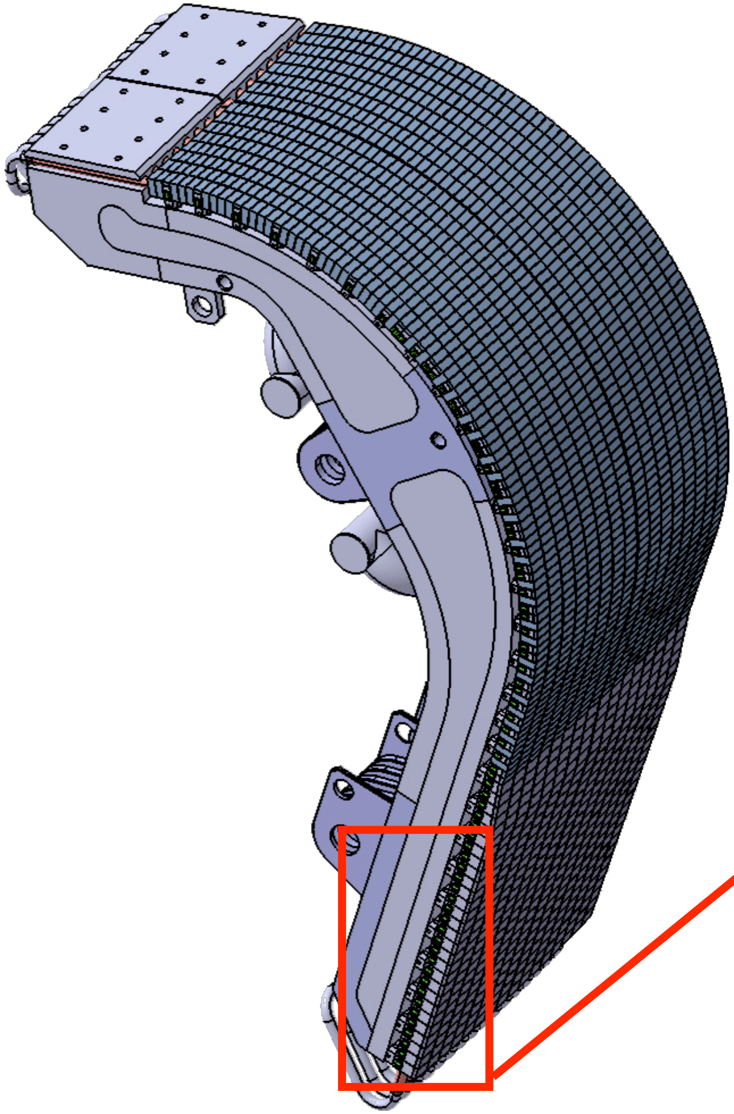
Residual Gas Analyser

Residual gas analysis station

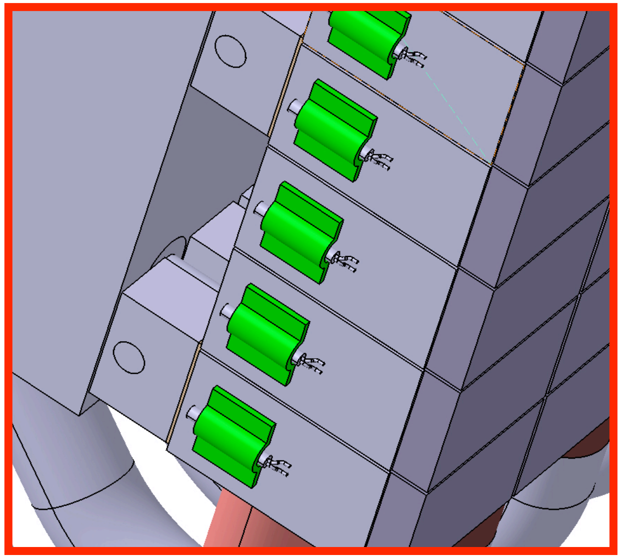
Gas sampling point



Divertor Thermocouples



Can be used to derive heat fluxes.



Specially modified target to incorporate metallic coating on the side of the CFC & W monoblocks to spot weld surface thermocouples

Summary

- ITER is a challenging machine to diagnose
  - Neutron and gamma radiation implications on shielding, cooling and optics
  - Erosion/redeposition >> mirror problem
- 1D distributions in the SOL, 2D in the divertor
- Several diagnostics are still at the pre-conceptual level. Significant R&D and design still required!
- A large amount of detailed design still ahead of us.
- We are starting now to be ready for first plasma in 2018, with probably 20 years of plasma operation to follow
- Close to 30 years of interesting diagnostic engineering and tokamak physics ahead of us!!

Important References

- John Wesson, "Tokamaks"
- Nuclear Fusion 47 (6) 2007, "Progress in the ITER Physics Basis"
- A. E. Costley and D. W. Johnson, Eds, Fusion Science and Technology 53 (2) 2008, "Plasma Diagnostics for Magnetic Fusion Research"
- P. C. Stangeby, "The Plasma Boundary of Magnetic Fusion Devices"
- C. S. Pitcher and P. C. Stangeby, "Experimental Divertor Physics", Plasma Physics Controlled Fusion 39 (1997) 779-930
- G. Federici et al, "Plasma-Material Interactions in Current Tokamaks and Their Implications for Next-Step Fusion Reactors", Nuclear Fusion 41 (2001) 1967