Overview of ITER Diagnostics Procurements and ongoing R&D in EU

- **Context**
- **Review of EU diagnostic contribution**
- **Procurement and contract opportunities summary**

On-behalf of the F4E Diagnostic Project Team and many contributors from European Fusion Laboratories and ITER Organization

Seminario Científico-Industrial, Barcelona, 18/Nov/2014, Benoit Brichard

Why Plasma Diagnostic are needed ?

FUSION FOR ENERGY

- **The ITER machine is still an experimental device dedicated to understand thermonuclear plasma behaviour and demonstrate that energy gain can be 'achieved' (safely …)**
- **Three main diagnostic functions: Machine Protection, Advanced Control and Physics**

GROUP 1a Measurements For Machine Protection and Basic Control	GROUP 1b Measurements for Advanced Control	GROUP 2 Additional Measurements for Performance Eval. and Physics
Plasma shape and position, separatrix- wall gaps, gap between separatrixes	Neutron and α-source profile	Confined α-particles
Plasma current, q(a), q(95%)	Helium density profile (core)	TAE Modes, fishbones
Loop voltage	Plasma rot. (tor and pol)	T_e profile (edge)
Fusion power	Current density profile (q-profile)	n_e, T_e profiles (X-point)
$\beta_N = \beta_{tor}(aB/I)$	Electron temperature profile (core)	T_i in divertor
Line-averaged electron density	Electron den profile (core and edge)	Plasma flow (divertor)
Impurity and D,T influx (divertor, & main plasma)	Ion temperature profile (core)	$n_T/n_D/n_H$ (edge)
Surface temp. (div. & upper plates)	Radiation power profile (core, X-point & divertor)	$n_T/n_D/n_H$ (divertor)
Surface temperature (first wall)	Z_{eff} profile	T_e fluctuations
Runaway electrons	Helium density (divertor)	n_e fluctuations
'Halo' currents	Heat deposition profile (divertor)	Radial electric field and field fluctuations
Radiated power (main pla, X-pt & div).	Ionization front position in divertor	Edge turbulence
Divertor detachment indicator (J_{sat}, n_e, T_e at divertor plate)	Impurity density profiles	MHD activity in plasma core
Disruption precursors (locked modes,m=2)	Neutral density between plasma and first wall	
H/L mode indicator	n_e of divertor plasma	
Z_{eff} (line-averaged)	T_e of divertor plasma	
n_T/n_D in plasma core	Alpha-particle loss	
ELMs	Low m/n MHD activity	
Gas pressure (divertor & duct)	Sawteeth	
Gas composition (divertor & duct)	Net erosion (divertor plate)	
Dust	Neutron fluence	

See: A.J.H. Donné *et al.*, "Chapter 7: Diagnostics," in "Progress in the **ITER Physics Basis**," Nucl. Fusion **47** (2007), S337–S384

The ITER project defines the Plasma Parameter specifications

- **The ITER project defines the specifications for each Plasma Parameter to be measured (or derived). However these specifications focus on the Diagnostic Set and not on individually diagnostic**

Example of Plasma Parameter specifications

--- [55s1174]

Table MP014: Measurement Parameter 014. Neutron-and-Alpha-source Profile shall be delivered with the following specifications [55s1175]

Condition	Range	Time Res.	Spatial Res.	Accuracy
-	$10^{14} - 6\times10^{18}$ n.m^{-3}.s^{-1}	1 ms	a/10	10 %

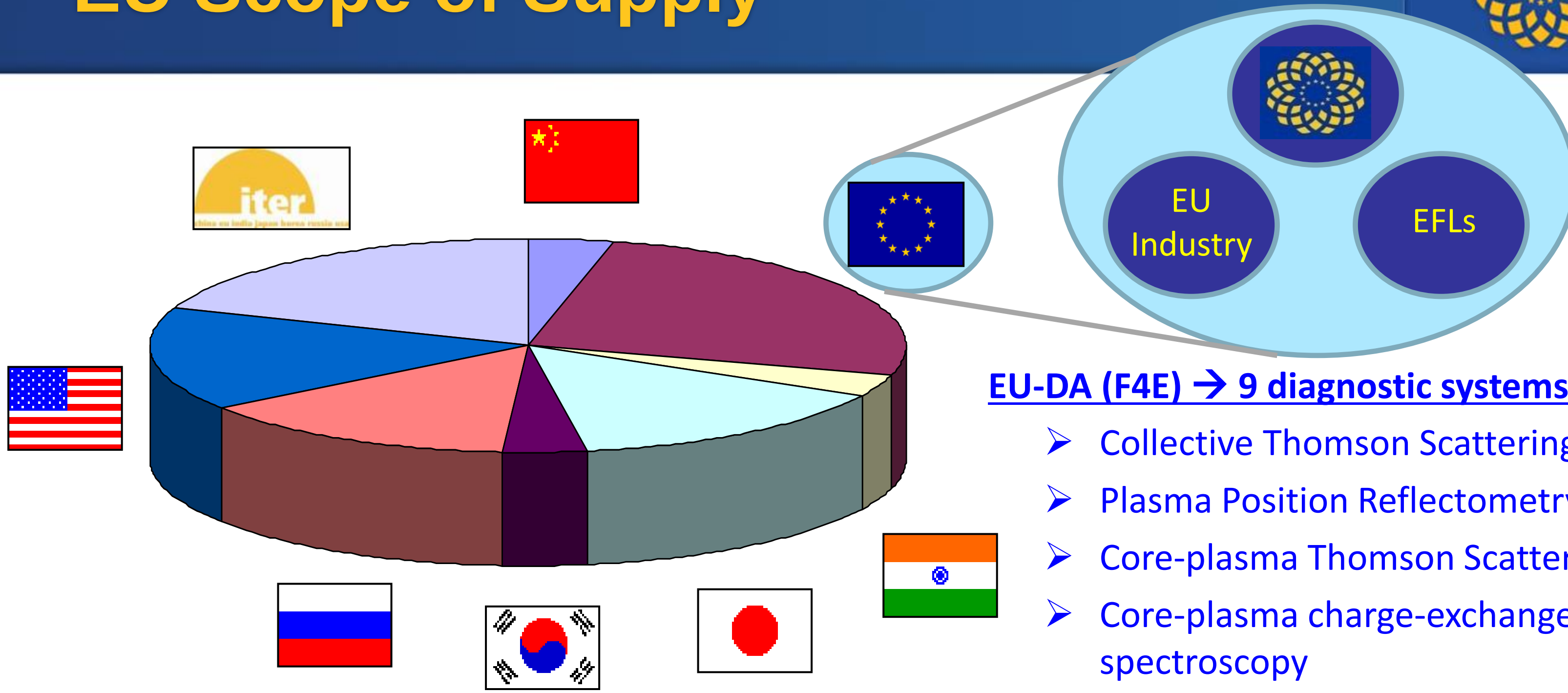
The following diagnostic system(s) shall be provided to contribute to meeting this requirement:

- 55.B1 Radial Neutron Camera - Primary
- 55.B2 Vertical Neutron Camera - Primary
- 55.B7 Radial Gamma Ray Spectrometers - Back-up
- 55.BD Vertical Gamma Ray Spectrometers - Back-up
- 55.B4 Neutron Flux Monitors - Supplementary
- 55.B8 Activation System - Supplementary
- 55.BC Divertor Neutron Flux Monitors - Supplementary

Need to flow down the specifications to individual diagnostic

ITER Document: - System Requirement Document - SRD-55 (Diagnostics) from DOORS

EU Scope of Supply



EU-DA (F4E) → 9 diagnostic systems to be procured

- Collective Thomson Scattering
- Plasma Position Reflectometry
- Core-plasma Thomson Scattering
- Core-plasma charge-exchange recombination spectroscopy
- Radial Neutron Camera
- Wide Angle Viewing System
- Magnetics diagnostics
- Bolometers
- Pressure Gauges

EU-DA (F4E) only concept (no procurement)

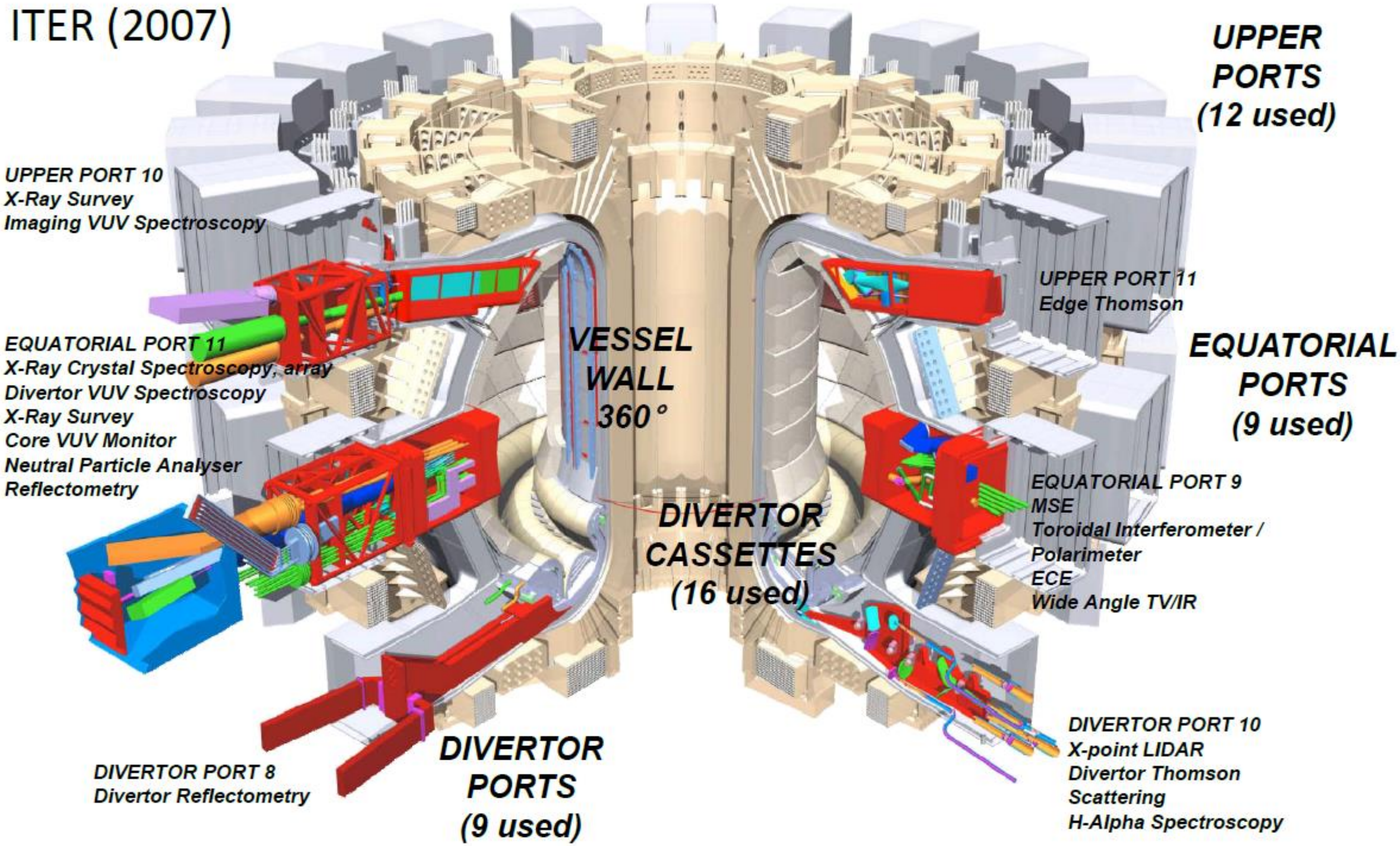
- Gamma spectrometer
- High resolution neutron spectrometer

About 40 diagnostic are considered necessary to meet the Plasma Parameter Specifications

EU-DA (F4E) → also in the Diagnostics scope:

- In-vessel Services (cables, conduits , connectors etc.)
- 3 upper port plugs, 2 equatorial port plugs
- Port structures (shielding modules, support structures)
- Diagnostic integration

Diagnostics into Tokamaks – ITER



The ITER environment is challenging

Environment	Compared with JET
Nuclear: neutron and gamma radiation → heating and damage (detailed values → next slide)	
Typical **neutron fluxes** in relevant locations vary between 10^{13}–10^{17} n/m²s, of which a significant fraction is 14MeV neutrons	~ 10×
Fluence of between 10^{20}–10^{24} n/m² over the lifetime of ITER.	~ 10^6×
The **gamma dose rate** varies between 10^{-2}–10^{2} Gy/s in the relevant locations during plasma operation, and up to 1Gy/s continuously	~ 10×
Nuclear heating up to 1 MW/m³	~ 0
Non-nuclear heat loads: plasma radiation and particle fluxes	~ 5×
Long pulse lengths (> 400 s)	~ 100×
Vacuum, including tritium/safety compatibility, beryllium handling, feedthroughs and windows	
Restrictions on materials: vacuum compatible **and** neutron compatible (e.g. low outgassing, transmutation to harmless substances, re-weldable after activation)	
Magnetic field >5 T in vessel, appreciable elsewhere (e.g. 0.05 T where some electronics).	
Loads during disruptions: Accelerations up to 15*g* (for of the order ms) and EM loads (halo and Eddy currents)	
Very **noisy** environment	
Inaccessible → reliability over ITER lifetime → **severe engineering challenge**	

- Context
- **Review of EU diagnostic contribution**
- Procurement summary and contract opportunities

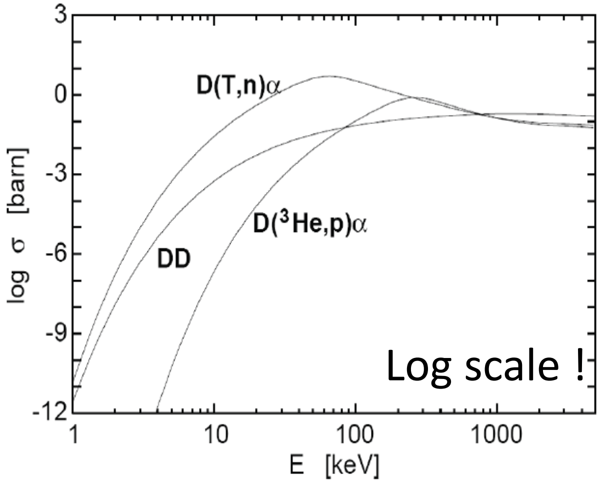
Radial Neutron Camera (RNC)

Function: Measures the profile of the neutron emissivity

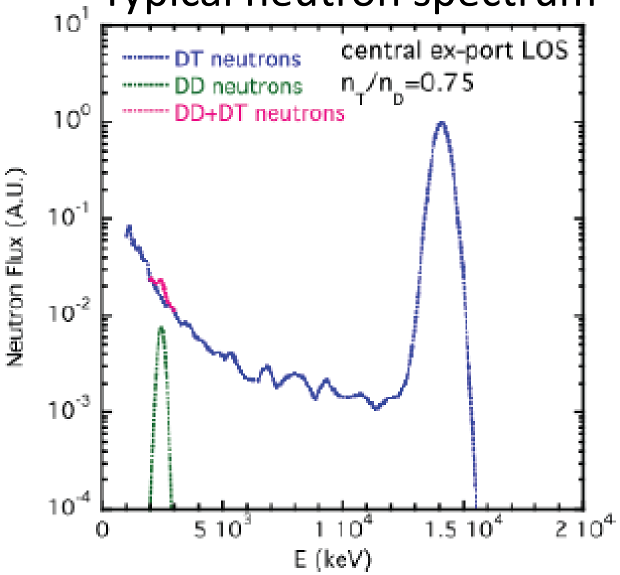
Principles

${}^{2}_{1}D + {}^{3}_{1}T \rightarrow {}^{4}_{2}He$ (3.5 MeV)	$+ n^0$ (14.1 MeV)		
${}^{2}_{1}D + {}^{2}_{1}D \rightarrow {}^{3}_{1}T$ (1.01 MeV)	$+ p^+$ (3.02 MeV)	50%	
$\rightarrow {}^{3}_{2}He$ (0.82 MeV)	$+ n^0$ (2.45 MeV)	50%	
${}^{2}_{1}D + {}^{3}_{2}He \rightarrow {}^{4}_{2}He$ (3.6 MeV)	$+ p^+$ (14.7 MeV)		

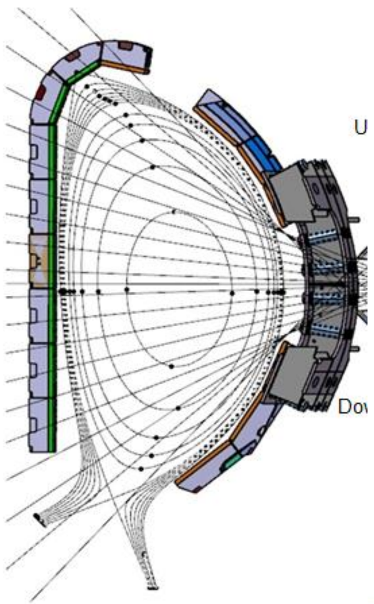
Reaction Cross-Section

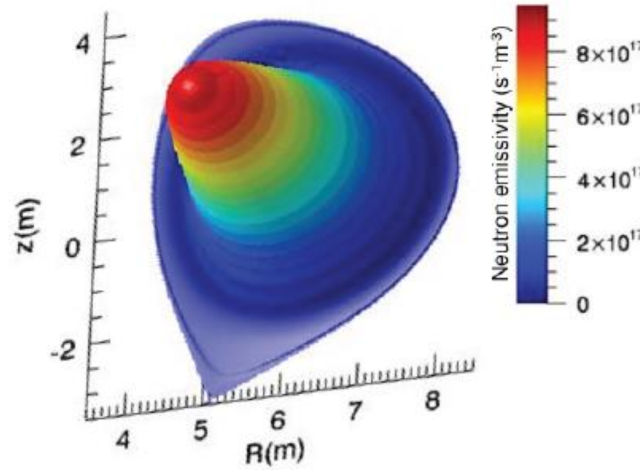


Typical neutron spectrum



Line of sight from plasma





Example neutron emissivity 2D map for the ITER scenario 2

Radial Neutron Camera (RNC)

Components:

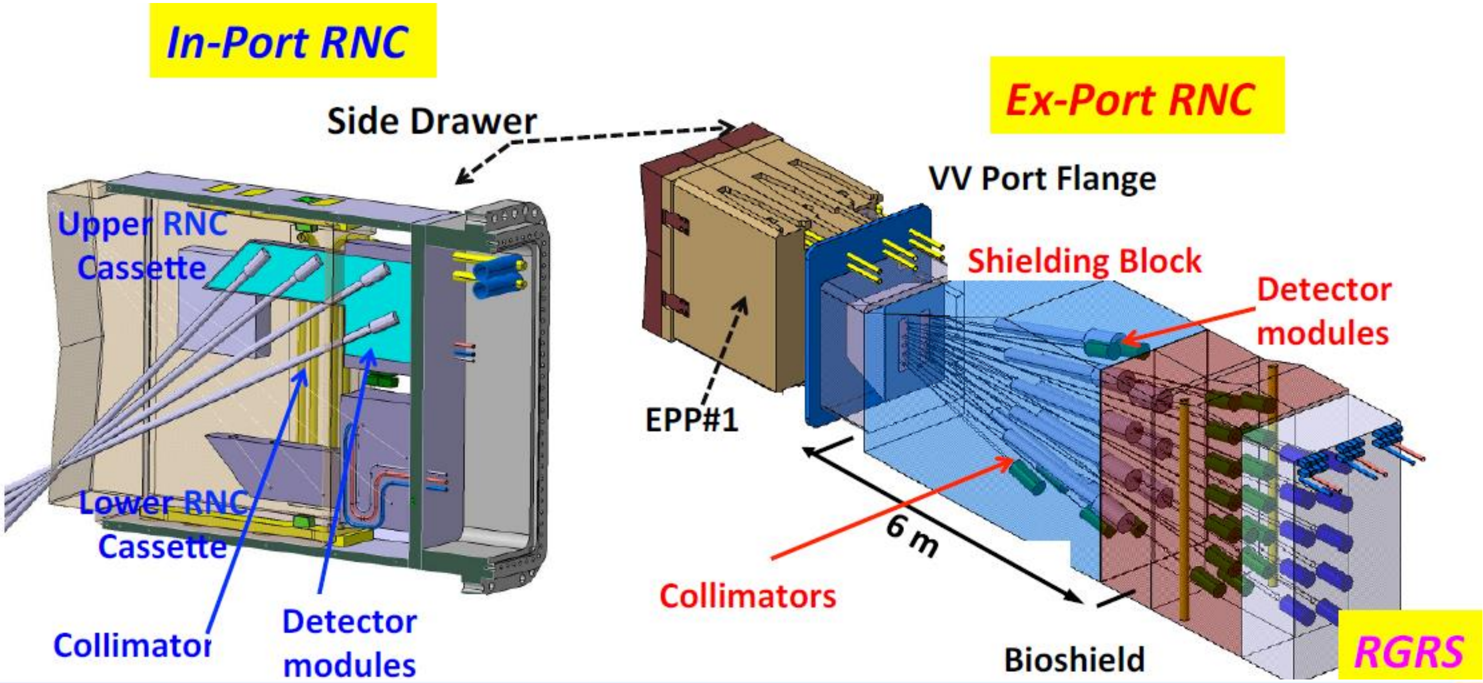
- Long and short collimators
- Neutron detector modules & electronic readout
- Radioactive calibration source
- Neutron beam dump
- Auxiliary shielding blocks
- Vacuum window

Location in ITER

Integrated in Equatorial Port Plug #01

R&D and prototyping

- Testing scintillator & CVD Diamond
- PMTs & Preamplifiers
- Emissivity Reconstruction Algorithm assessment

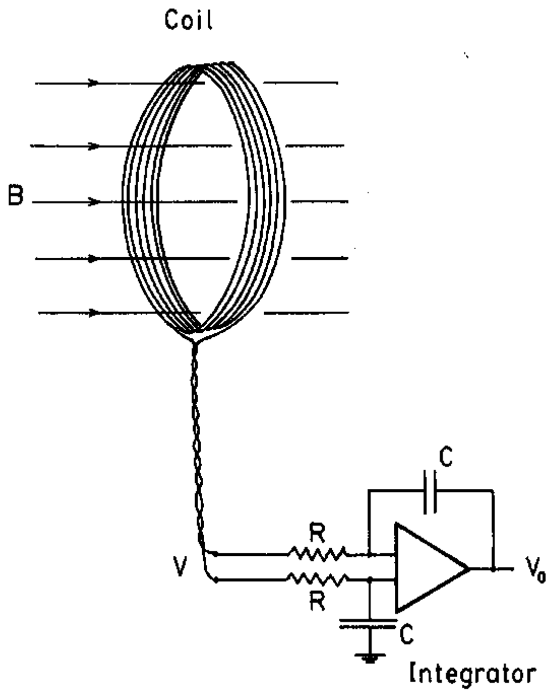


Magnetic Sensors (main systems)

Function: Measures plasma current, halo current, shape, movement, energy

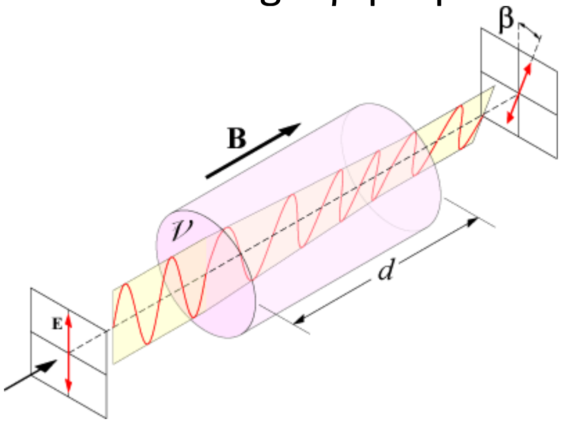
Principles: either using electrical or light signal

Lenz Law (induction): voltage is created in coils embracing a time varying magnetic field



V=*N A* d*B*/dt

Faraday effect: In presence of a **B**, a linearly polarized light experiences a non reciprocal rotation of an angle β proportional to **B**.



Considering a closed (N) loop of fiber, according to the Gauss theorem, this angle is simply proportional to the electrical current flowing through the sensing coil.

$$\theta = V\ N \oint \mathbf{H} \cdot \mathbf{dl} = VNI$$

V is the Verdet constant, about 10^{-6} µrad/A @ 1550 nm

Magnetic Sensors (main systems)

<u>Components</u>:

- Winding & Pick-up coils
- Fibre-optic sensor
- Attachments and clips
- Feedthrough
- Back-end electronics and control and data-analysis SW

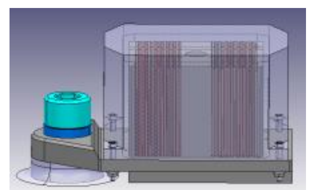
<u>Location in ITER</u>

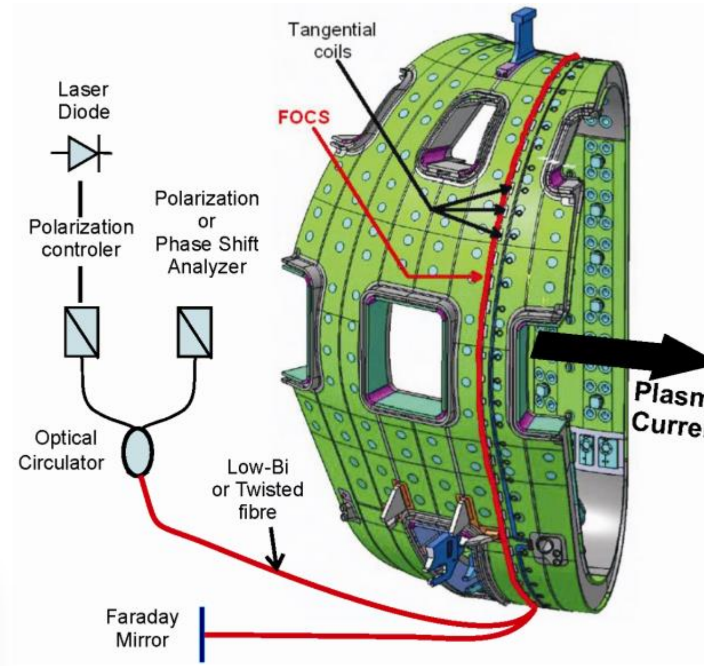
- Integrated all around the Vacuum Vessel

<u>R&D and prototyping</u>

- Final design FOCs completed
- Irradiation test of 2nd generation IVC (2016)
- Design & manufacture in-vessel HF sensor (2016)
- Electronics

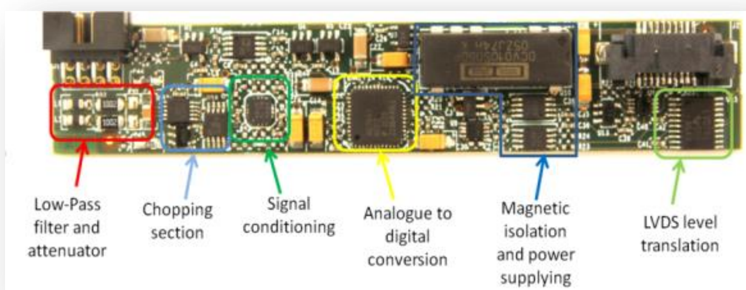
HF sensor head





Inner Vessel Coil

Long-Pulse Integrator



Plant controller candidate technologies identified

Prototype Outer Vessel Coil
(~400 units foreseen)

Collective Thomson Scattering (CTS)

FUSION FOR ENERGY

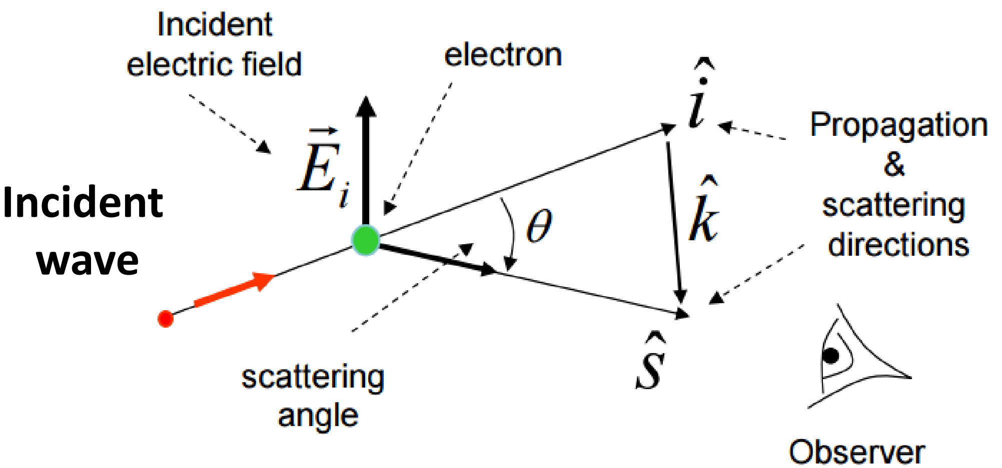
<u>Function</u>: Measures ion-distribution function, the fuel-ion ratio and ion rotation velocities

<u>Principle:</u> Scattering Theory: the **E** and **B** components of the incident wave accelerate the particle, which in turn emits radiation in all directions.

Thomson Scattering (TS) is a limit case of Compton Scattering, $\hbar\omega_i << m_e c^2$ =511 keV

Frequency shift of scattered wave

$\omega_s = \omega_i + \mathbf{k.v_e}$; $\mathbf{k=k_s-k_i}$



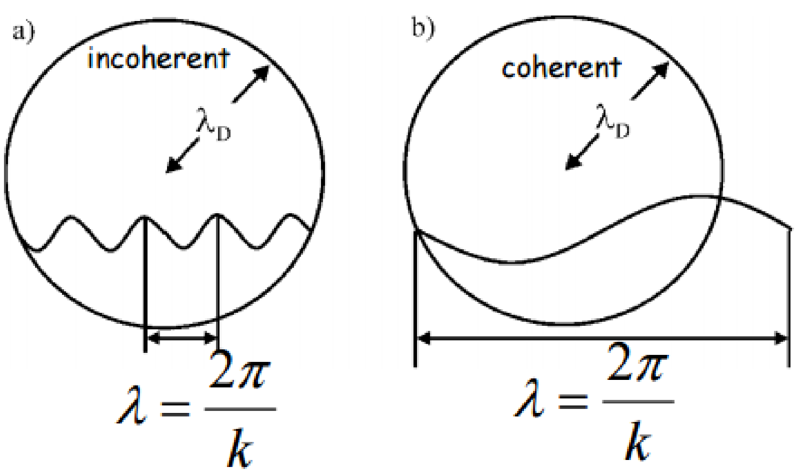
In case of single electron (incoherent)

Scattered power <P> = $\sigma_{TS} \sin^2\theta \langle I_o \rangle$

Max power $\theta=\pi/2$ and σ_{TS} =6.64x10^{-29} m^2

In case of plasma, coherent scattering effect can take place :

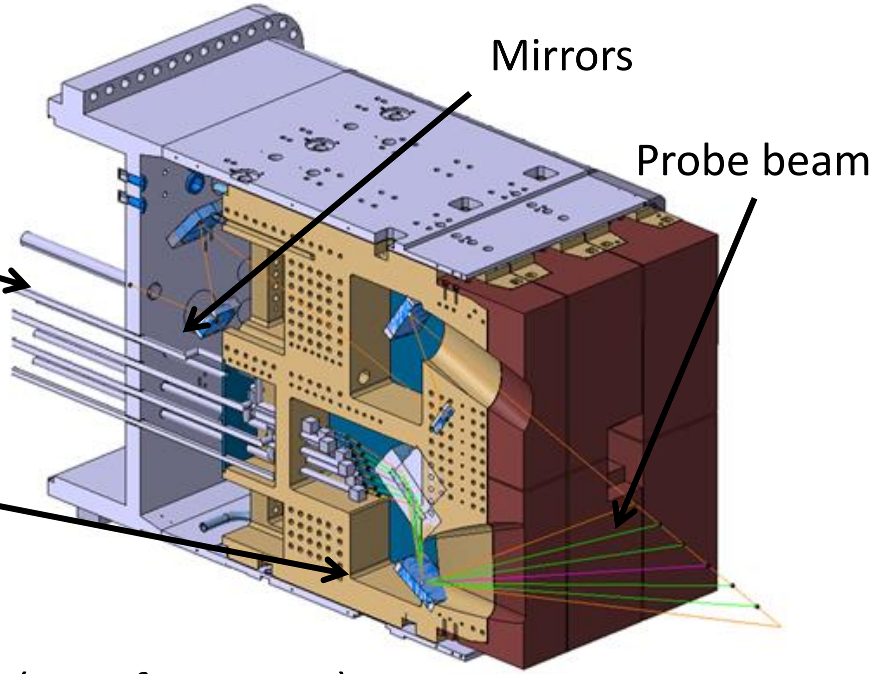
- incident wavelength: λ_ι
- Debye length $\lambda_D = \sqrt{\frac{\varepsilon_o K_B T_e}{e\, ne}}$=7.4 10^5 $\sqrt{\frac{T_{e(eV)}}{n_e(m3}}$
- Condition for collective scattering $\lambda_D << \lambda_\iota$

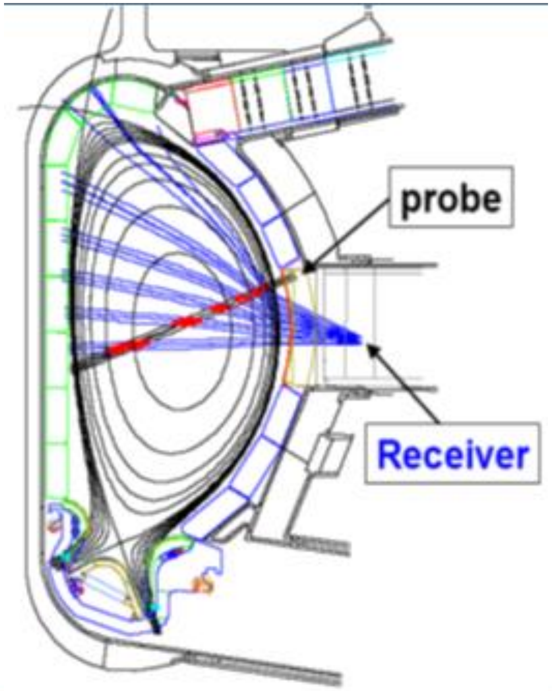


Collective Thomson Scattering (CTS)

<u>Components</u> (in-port-plug):

- Launcher antenna and mirrors
- Horn antenna array
- Corrugated waveguide components
- In situ calibration and maintenance tools
- Supporting structures
- Receiver mirrors and horns





<u>Components (out of EU scope):</u>

- High power gyrotron (1MW at 60 GHz)
- Back-end electronics, control & DA SW

<u>Location in ITER:</u>

- Integrated in Equatorial Port Plug #12

<u>R&D and prototyping</u>

- Movable launcher mirror
- Antenna receiver

Core-Plasma Thomson Scattering (CPTS)

FUSION FOR ENERGY

Function: Measures e- density and temperature (from Doppler broadening)

Principle:

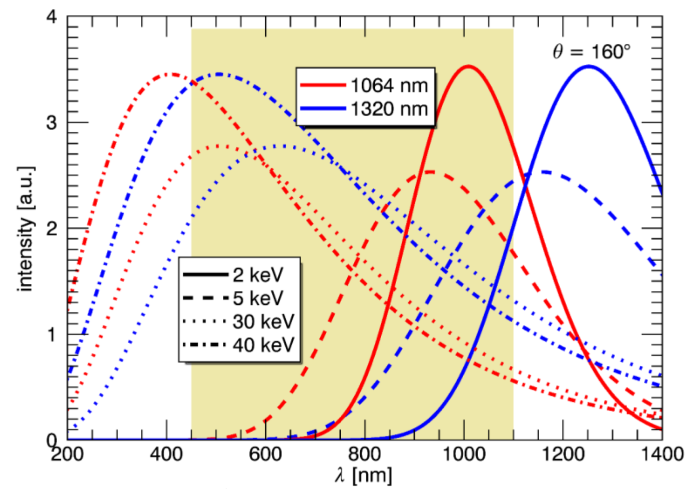
Thomson Scattering: a photon interact with an electron and is scattered (randomly) without losing energy (elastic scattering). Thomson cross section is weak and, so require power full laser source.

The amount of scattered light tells about the electron density.

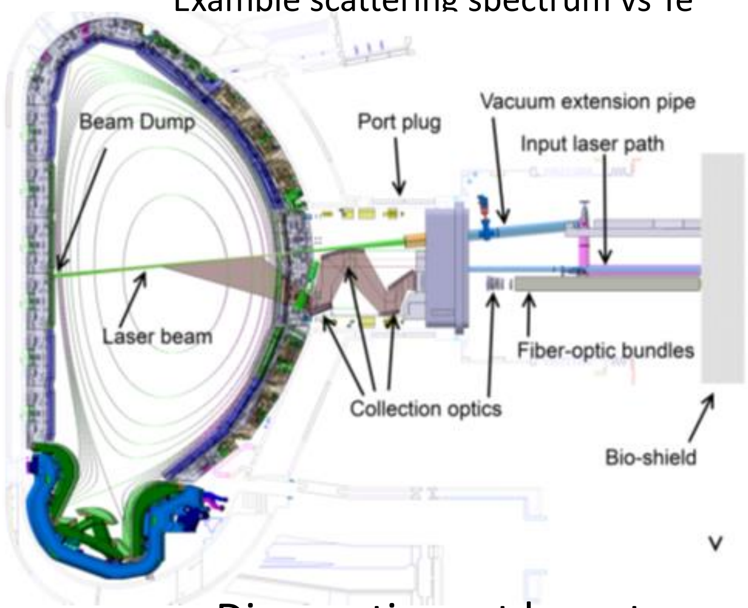
Doppler shift: If the electron moves (with respect to the observer), the scattered light will be either red or blue shifted at longer (red, e away from the source) or shorter (blue) wavelengths (λ).

The $\Delta\lambda$ tells about the electron velocity (or Temperature).

Imaging Thomson Scattering: Optics focus on each measurement point along the beam path. JADA and RFDA are working on synonymous systems for the Edge and the Divertor regions.



Example scattering spectrum vs Te



Diagnostic port layout

Core-Plasma Thomson Scattering (CPTS)

Components:

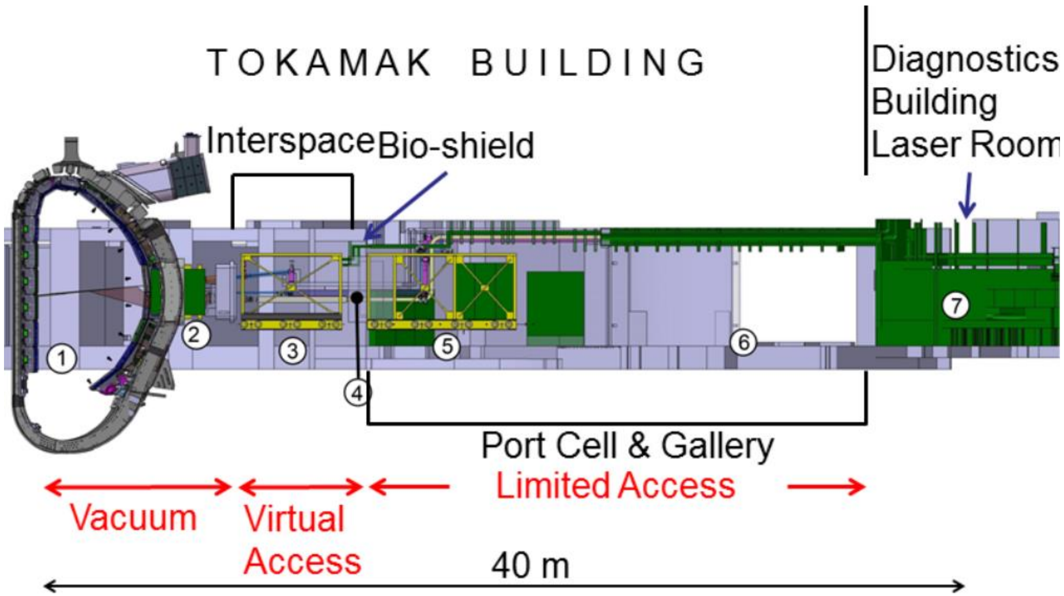
- Short-pulse high-energy LASER
- Fast, sensitive VIS-NIR detectors
- Optical components: mirrors, lenses and fibre-optic transmission lines
- Mechanical support structures / Beam dump
- Back-end electronics
- Control and data-analysis SW

Location in ITER

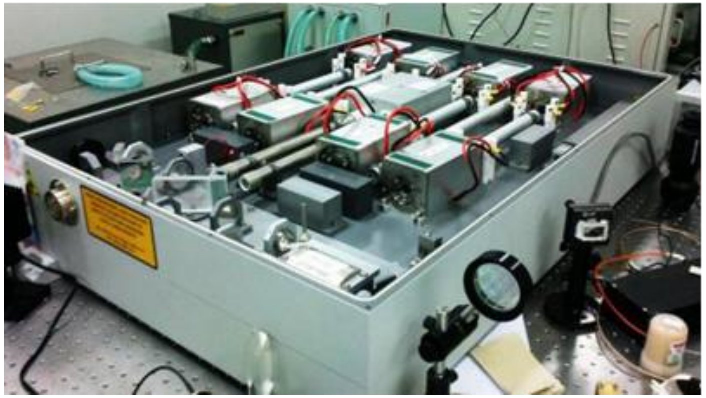
- Integrated in Equatorial Port Plug #10

R&D and prototyping

- Mirror cleaning and lifetime
- Collection optics and alignment
- High-power fast laser (5J-4ns; 100 Hz)
- Radiation-hard Fibre bundle



Laser prototype

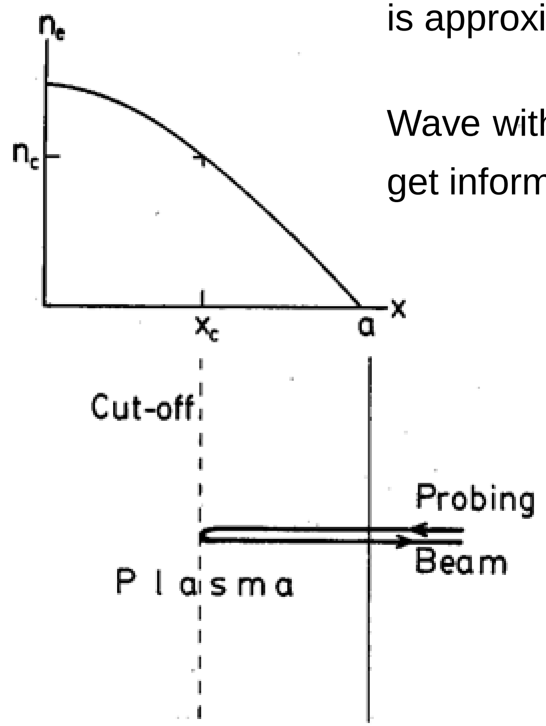


Plasma Position Reflectometry (PPR)

Function: Measures the plasma-edge position (gaps)

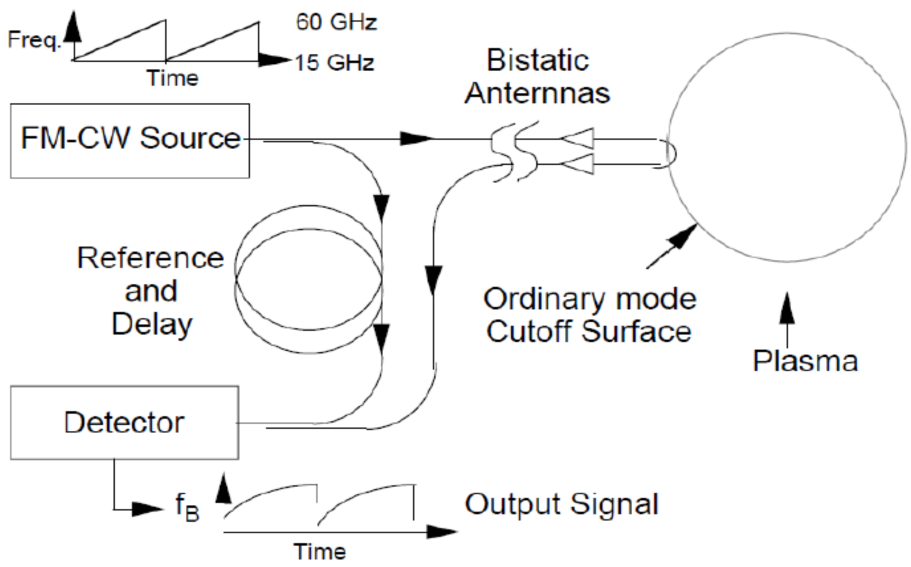
Principles

In some circumstances and for some wave modes, the plasma **refractive index** is approximately $N^2=1-\omega_p^2/\omega^2$, with plasma frequency $\omega_p^2=(n_e e^2/\varepsilon_0 m_e)$.



Wave with $\omega<\omega_p^2$ can be reflected. By swiping of a range of frequencies , we can get information on the density profile by measuring the phase of the reflected

Phase-delay measurement



Plasma Position Reflectometry (PPR)

<u>Function</u>: Measures the plasma-edge position (gaps)

<u>Components</u>:

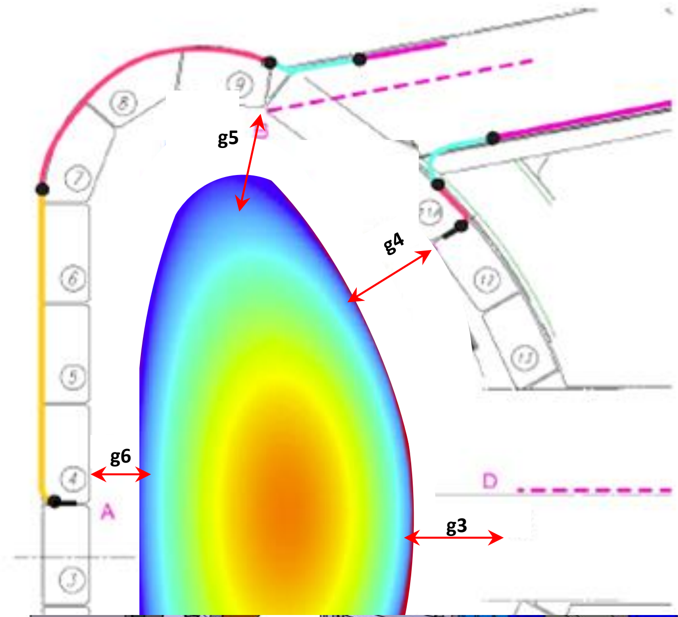
- Low power generators
- Frequency sweeping (range 15-75 GHz)
- Antennas
- Waveguides and waveguides-joints
- mm-wave components (e.g.: detectors, shutters)
- Back-end electronics
- Control and data-analysis SW

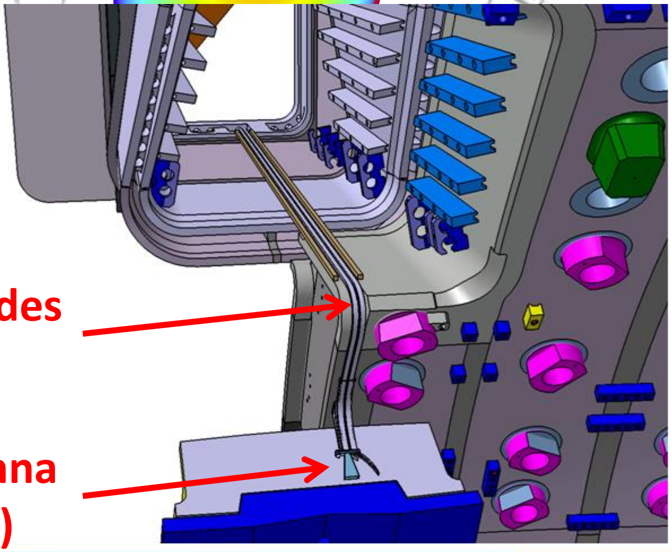
<u>Location in ITER</u> (4 reflectometers):

- In-vessel (locations known as g4 and g6)
- Integrated in Equatorial Port Plug #10 (g3)
- Integrated in Upper Port Plug #01 (g5)

<u>R&D and prototyping</u>

- In-vessel antenna
- 120^0 rectangular waveguide bend
- Combiner/decombiner 15-70 GHz





Core-plasma Charge-exchange recombination spectroscopy (CXRS)

FUSION FOR ENERGY

<u>Function</u>: Measures charge exchange reactions between hydrogen and impurity (fast) ions in the plasma

<u>Principles</u>:

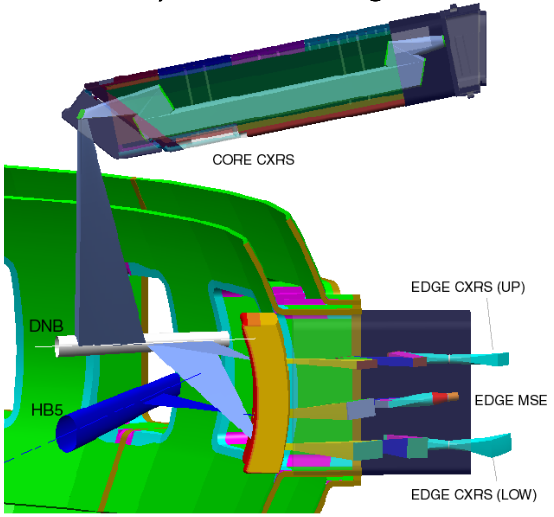
Neutrals are injected through a Neutral Beam Injector (NBI) and interact with (light) impurities by exchanging

Neutral beam → plasma	$A^{q+} + D^0 \rightarrow A^{(q-1)+}\{nl\} + D^+$
Decay from excited level	$A^{(q-1)+}\{nl\} \rightarrow A^{(q-1)+}\{n'l'\} + h\nu$

The stripped ion relaxes by making a well-known light transition. Such optical transitions mainly occur in VIS.

- The intensity of the line tells about the impurity abundance
- The doppler-broadening of the emission line tells about the energy.

Layout of core (EU) and edge (RF) CXRS systems viewing the DNB



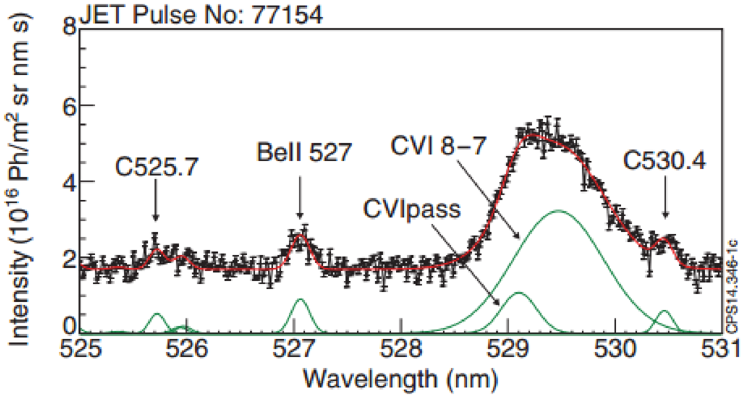
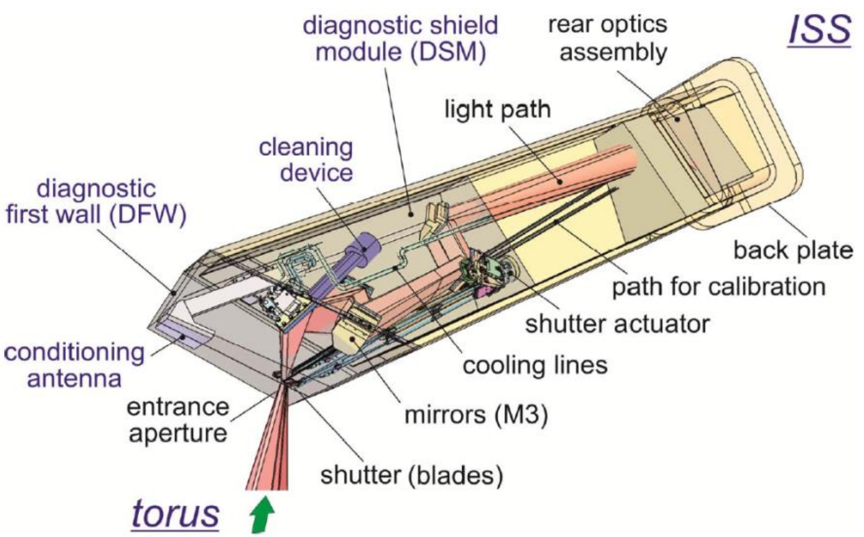


FIG. 1. (JET pulse #77154, 2 T, 1.7 MA, 21 MW of NBI) Spectrum from a JET-C central track with total fit (red) and individual lines (green).

S. Menmuir & al. Rev. Sci. Instrum. 85, 11E412 (2014)

Core-plasma Charge-exchange recombination spectroscopy (CXRS)

Collection optics in Upper-port



<u>Components</u>:

- Reflective and refractive optical components
- Supporting and aligning structures
- Shutter mechanisms for protection
- Fibre optics to transmit light to back-end
- Supporting structures for optical fibres
- Spectrometers and detectors/cameras
- Back-end electronics, control & DA SW

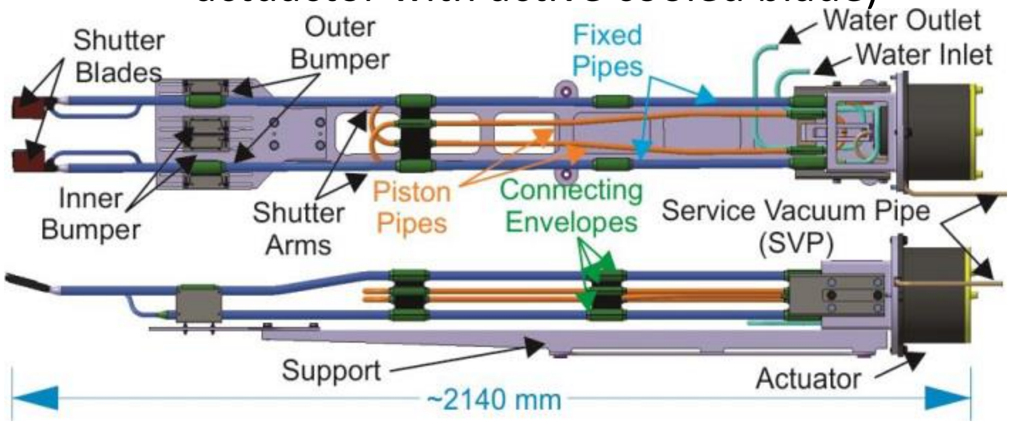
<u>Location in ITER</u>

- Integrated in Upper Port Plug #03

<u>R&D and prototypes test</u>

- Mirror cleaning and shutter
- Collection optics and alignment
- Radiation-Hard fibre bundle

Example of shutter concept (He actuactor with active cooled blade)

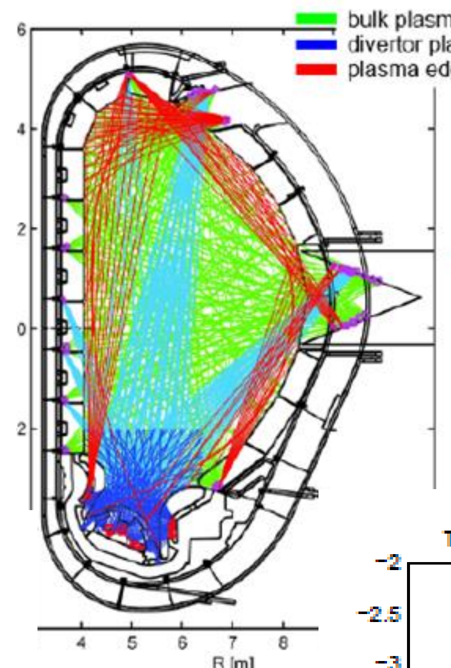


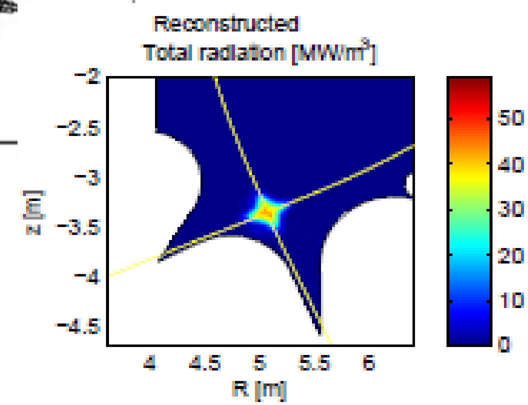
Bolometers

<u>Function</u>: Measure total radiated power in the range of x-rays-IR

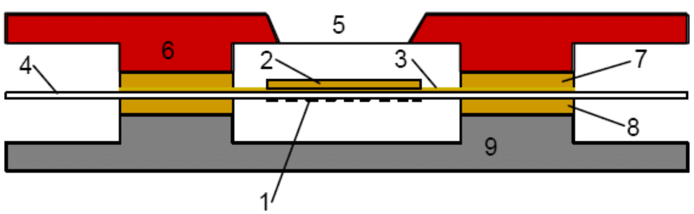
<u>Principles</u> Energy from Radiation is absorbed by a metal absorber which heats up and affects the electrical resistance of the meander. Measurement of the electrical resistance change tells about the radiated power.

Multiple lines of sight enabling 2D tomography reconstruction of the radiated power





Typical Bolometer configuration



1. gold-meander resistor
2. gold-absorber layer (4microns thick)
3. gold heat resistor layer (~0.1 micron thick)
4. mica or kapton carrier foil (~7 microns)
5 viewing window

6. CuCrZr front cooling plate (3mm thick)
7. golden thermal contact layer
8. conduction path
9.Shapal-M back cooling plate (3mm thick)

S. Kálvin, EFDA 06-1447

Bolometers

<u>Components</u>:

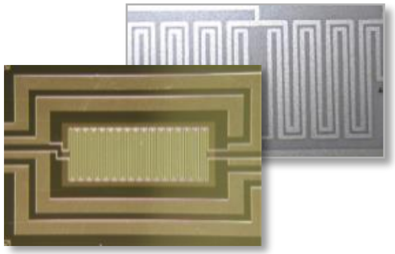
- Foil resistive bolometer (i.e., thin film technology)
- Camera housings
- Cable assembly with connector in bracket
- Back-end electronics
- Control and data-analysis SW

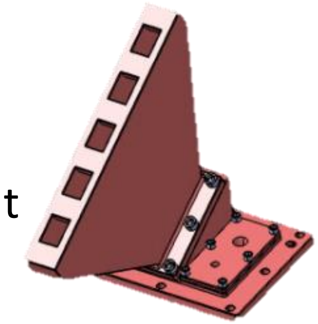
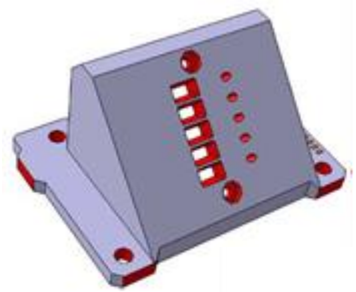
<u>Location in ITER</u>

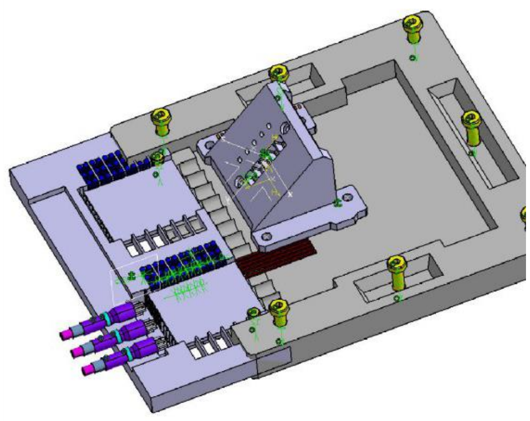
- Integrated in Upper Port Plugs #01 & 17
- Integrated in Equatorial Port Plug #01
- Integrated in lower divertor cassettes
- Integrated directly in the Vacuum Vessel

<u>R&D and prototyping</u>

- Mica and SiN substrates
- Wire bonding of pads (Cu, Pt, Au) to cables
- 3D printed circuit board envisaged to bridge connection from external signal cables to bonded connection on sensor


Pt Resistor Meanders



Camera layout


3D PCB layout

Wide Angle Viewing System (WAVS)

Function: Measures infra-red (IR) and visible light

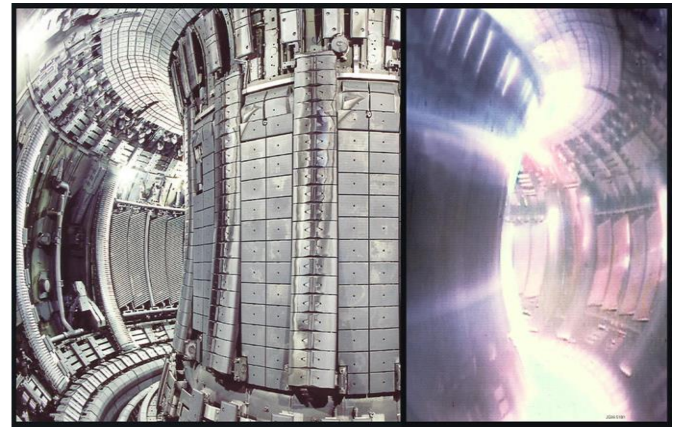
Principles: collect optical IR radiation emitted from hot surfaces for machine protection function and optical VIS radiation for plasma/tokamak view

Components:

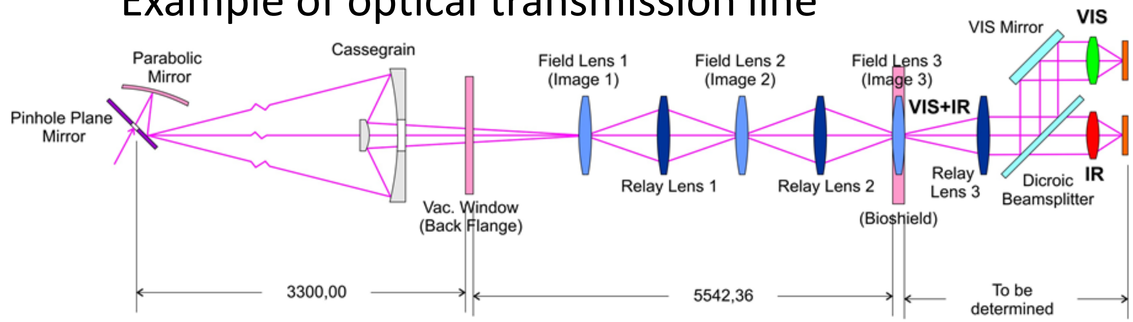
- VIS & IR cameras
- Optical comp (mirrors & lenses)
- Optical transmission lines
- Mechanical support structures
- Back-end electronics
- Control and data-analysis SW

Location in ITER (4 cameras):

- Integrated in Equatorial Port Plug #03
- Integrated in Equatorial Port Plug #09
- Integrated in Equatorial Port Plug #12
- Integrated in Equatorial Port Plug #17



Example of optical transmission line



R&D and prototyping

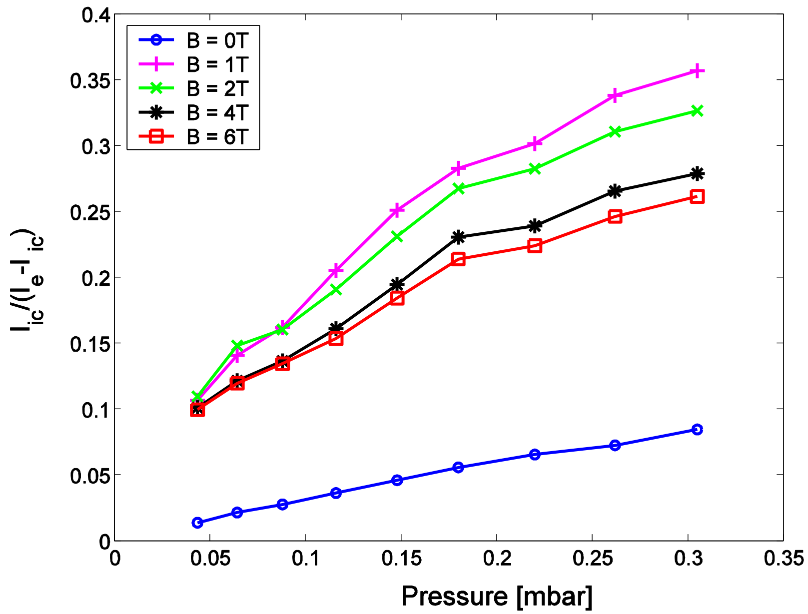
- Irradiation Testing VIS/IR transmission/reflective optics (lenses, coatings, etc…)
- Mirror cleaning and lifetime

Glasses and optical coatings

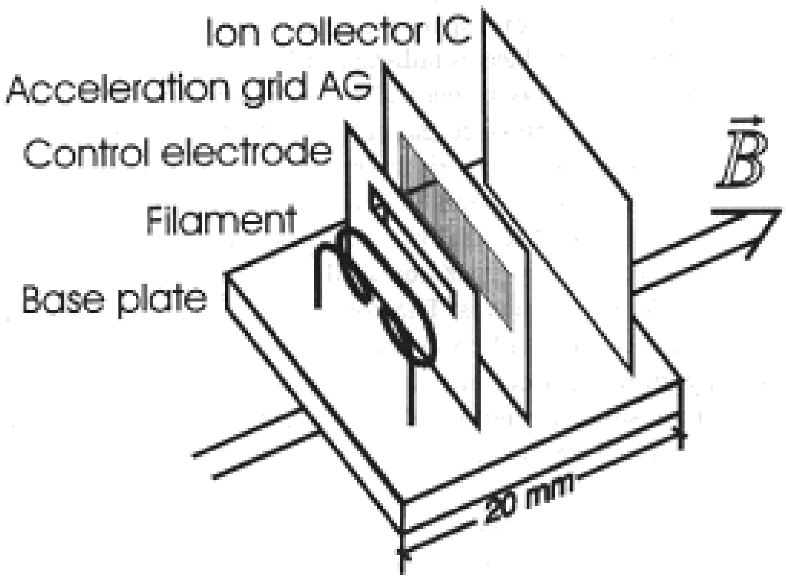
Pressure Gauges (PG) (main systems)

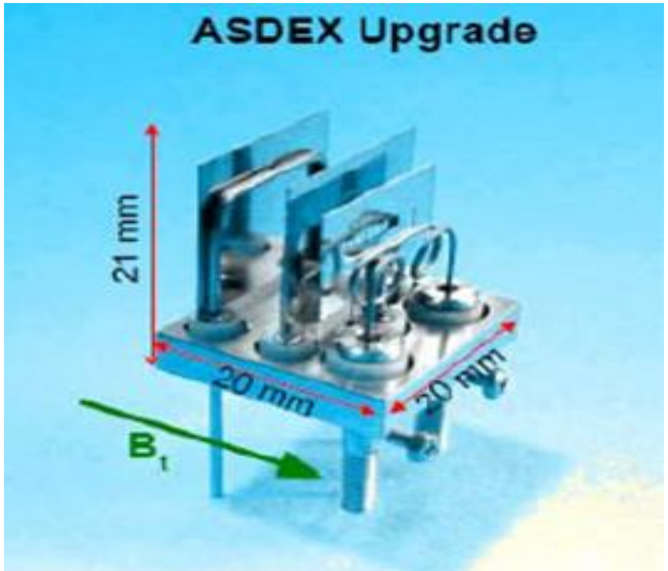
Function: Measure the neutral gas pressure at various locations

Principles: A hot filament emits electrons which are accelerated through a high voltage grid. The accelerated electrons ionizes the “gas”. The collection of the charges produces a current from which the gas pressure can be derived (in calibrated circumstances).



Sensor response of modified ASDEX-type gauges





Pressure Gauges (PG) (main systems)

Components:

- Sensor head assembly (gauge head, mounting platform, encapsulating box and connector)
- Back-end electronics
- Control and data-analysis SW

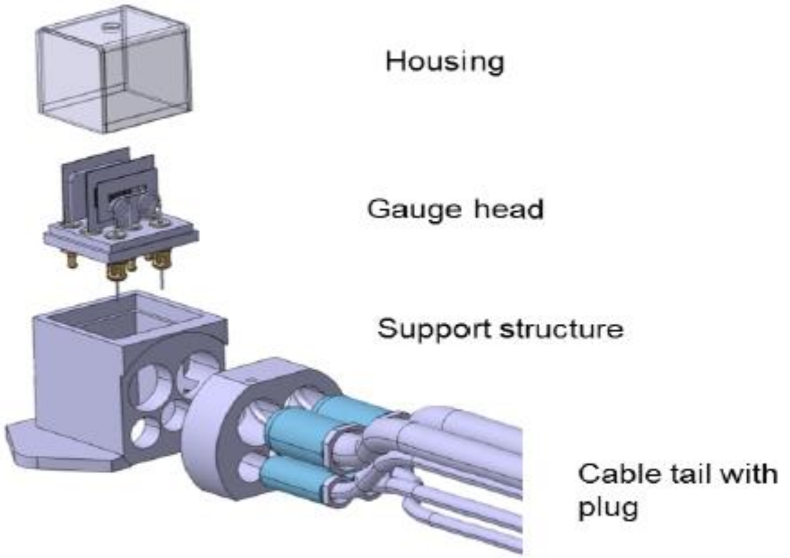
Location in ITER (about 52 gauges)

- Integrated in Equatorial Port Plugs #01 & 10
- Integrated in 4 divertor cassettes
- Integrated directly in the Vacuum Vessel

R&D and prototyping

- Effect on electronics regarding use of long cable
- Filament lifetime (DC current)
- Short and Long term reproducibility test

Schematic of pressure gauge assembly



In-Vessel Services

Function: Feed diagnostic sensors located in all parts of ITER vacuum vessel

Components:

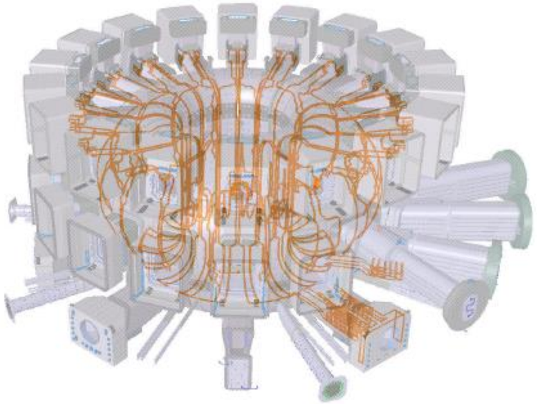
- Electrical service transmission lines for both diagnostic and control signals, including supporting structures and cabling
- Electrical feedthroughs (> 80 units)
- Cable tails (>900 units)
- Connectors

Location in ITER

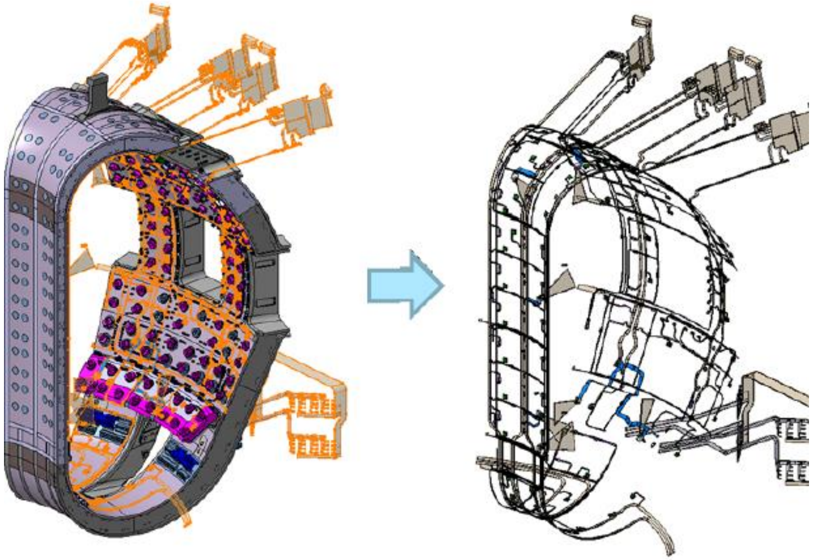
- All around the Vacuum Vessel

Prototype and testing

- Development of remote handling connector
- Irradiation testing of MI cable termination



Cabling path and wiring



Port-Integration

Function: to accommodate diagnostic and services in upper, equatorial & divertor ports

Design currently on-going for upper-port EP10, UP01, EP01, UP03 and UP17

Components:

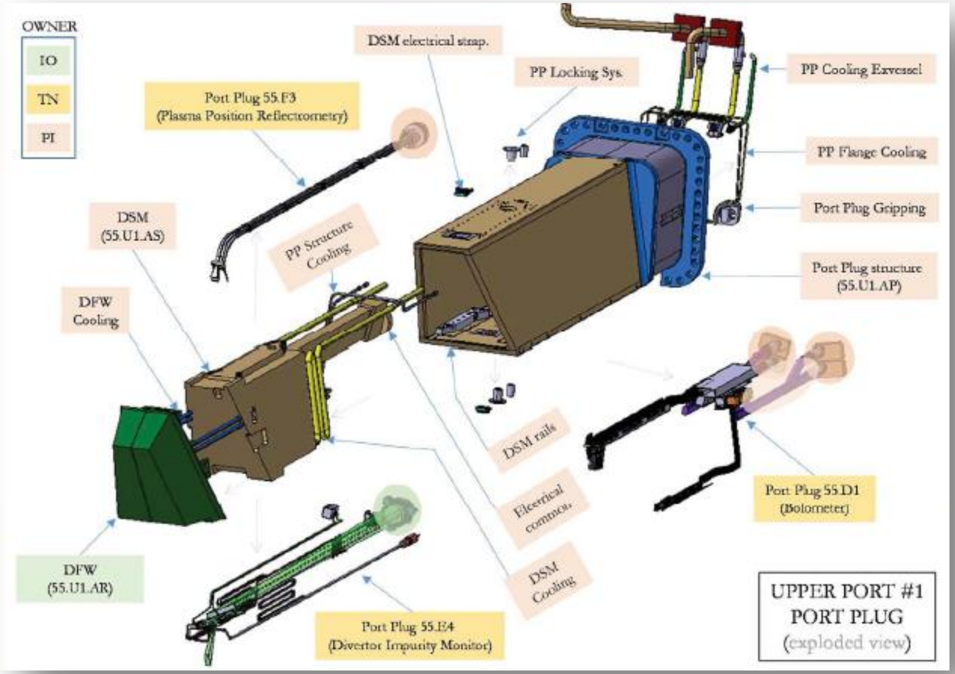
- Structure and support
- Pipes, heat exchanger, cables
- Vaccuum-guard
- Electrical feedthroughs, connector
- …

Location in ITER

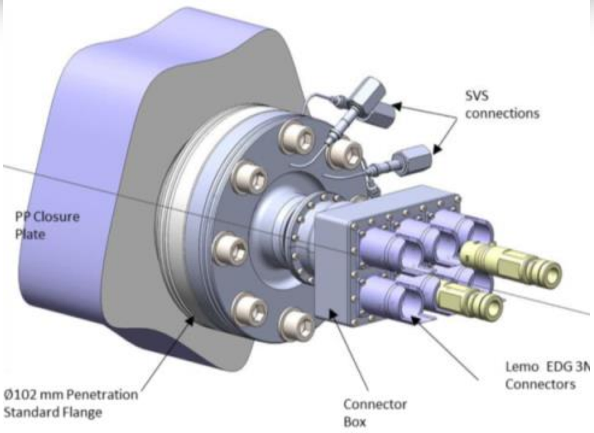
- In-port based systems

R&D and prototypes

- Port plug will be tested in port-Plug facility (>2020)



Example of feedthrough design

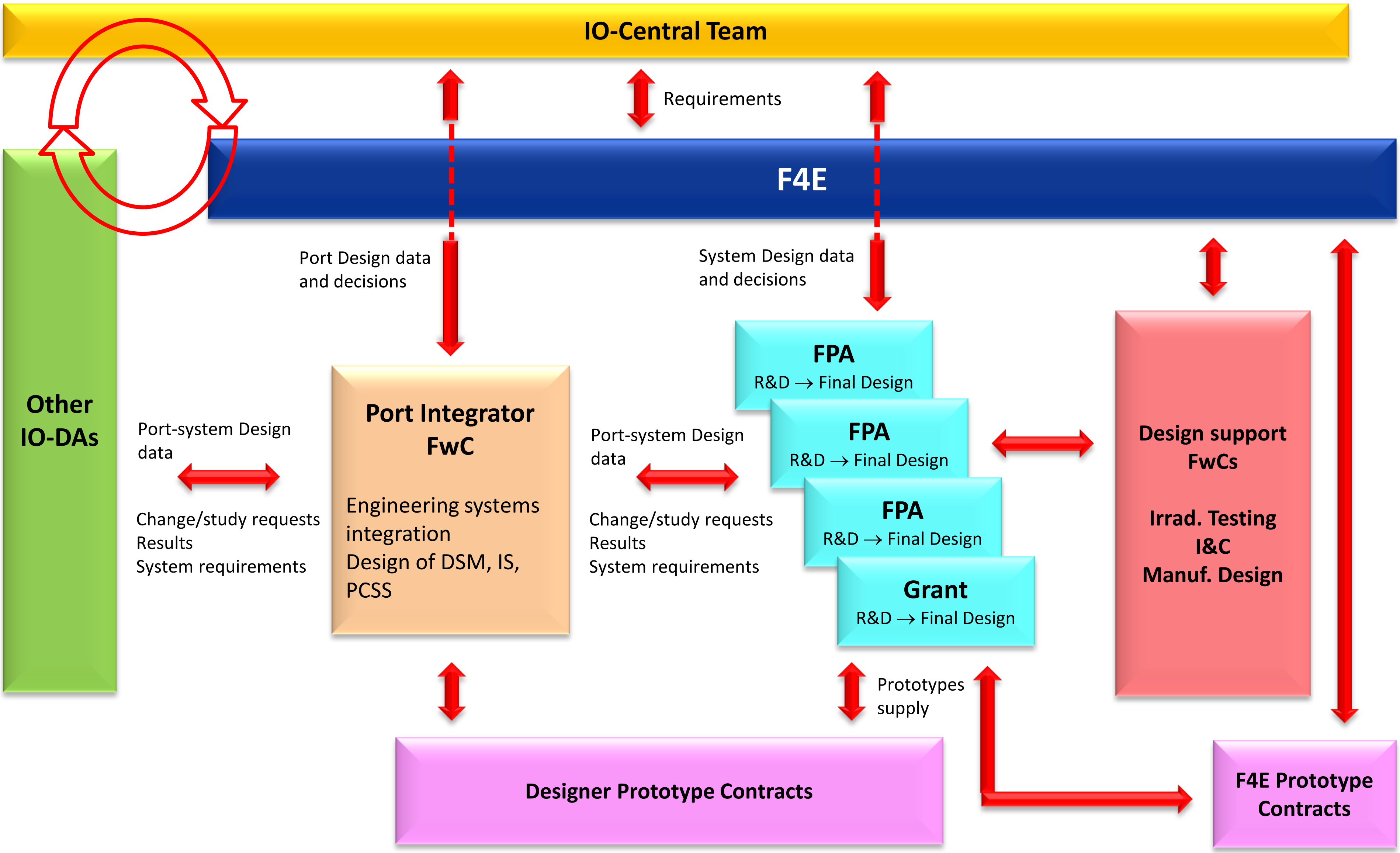


- Context
- Review of EU diagnostic contribution
- **Procurement summary and contract opportunities**

Design Effort is currently raising 120 Full-time Equivalents

- All but 1 of the main design contracts in place
- More than 28 Laboratories and Industry in 12 EU Countries
- By March 2015: Design team ~ 300 professionals contributing

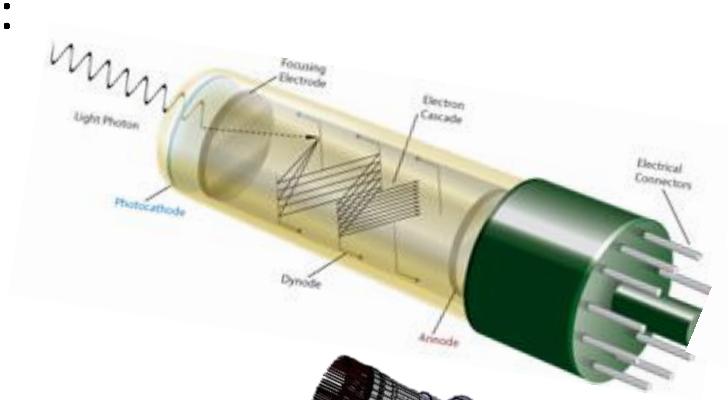
How it all fits together

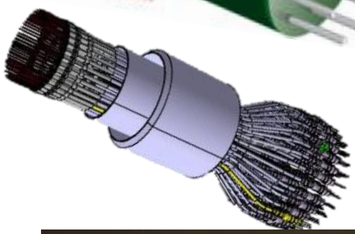


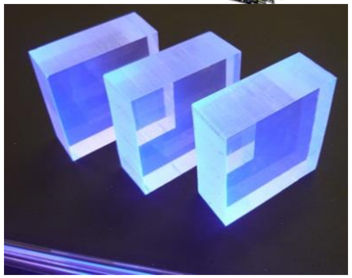
Prototypes and Procurement opportunities for SMEs

Each EU diagnostic system contains many 100’s or 1000’s of component parts in many supply categories:

- Mechanical
- Lasers
- mm-wave
- Cabling and connectors
- Optical
- Spectrometers
- scintillator, CVD Diamonds, fission chamber
- Control & instrumentation electronics
- Calibration sources
- Vacuum equipment







Perhaps 90% of the components are:

- ✓ small-to-medium scale
- ✓ low-order quantity
- ✓ custom-built or at least ‘tailored’

Feedthroughs (basic ones): electrical, mechanical, hydraulic and gas…

⇒ **More and many opportunities for SME involvement**

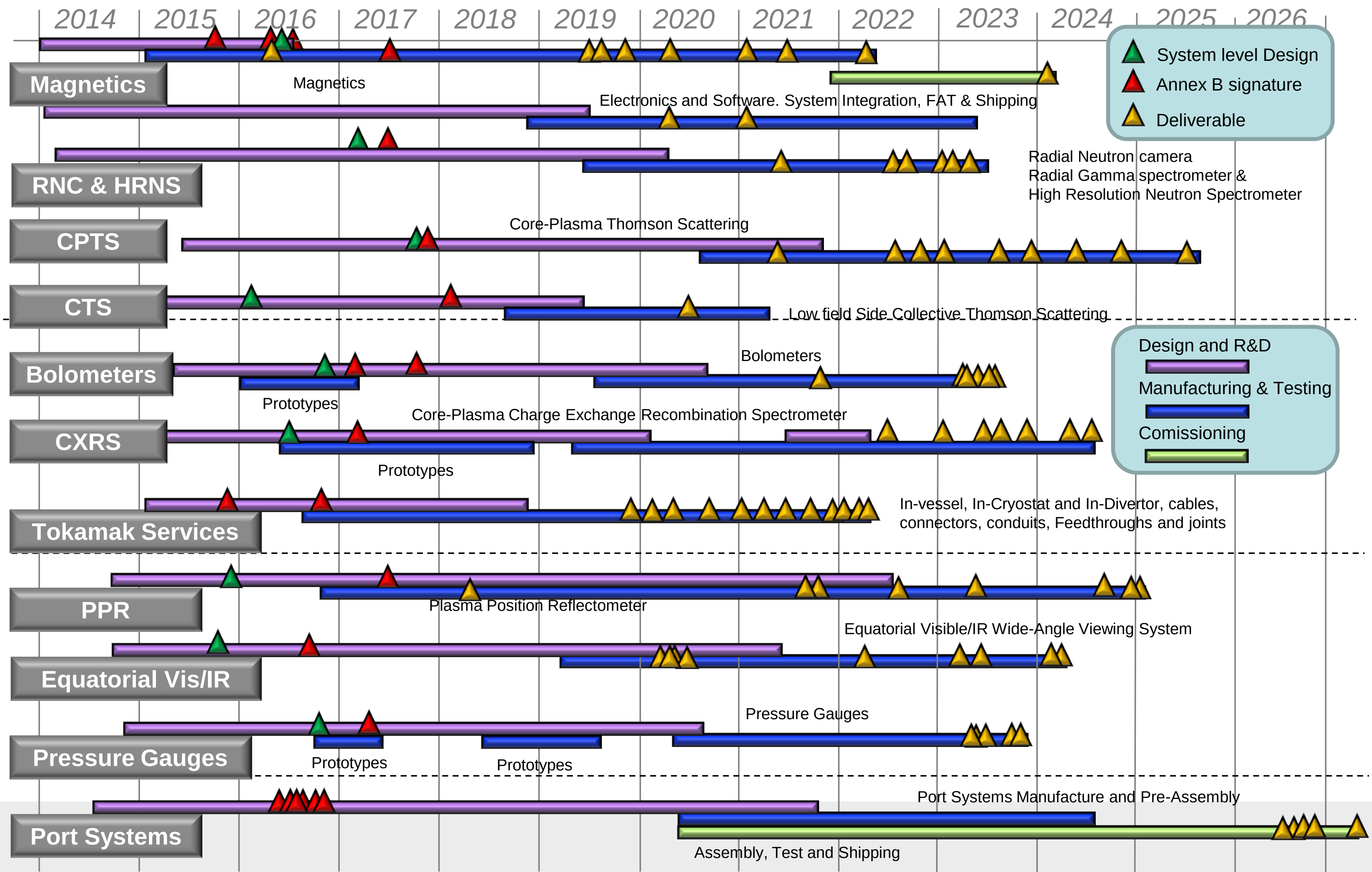
Overview of Main tenders 2015-16

	Key Contracts (total < 40 M€)	Final CfT	Contract Signature
1	Framework Contract for Manufacturing Design Support (preparation of BTP Drawings & Manufacturing Specifications)	2015 Q2	2016 Q1
2	System Level Design Core-Plasma Thomson Scattering	2015 Q2	2016 Q3
3	Bolometer Sensor Prototype	2015 Q4	2016 Q2
4	Design and Manufacture of In-vessel and In-cryostat Electrical Feedthroughs	2016 Q2	2017 Q1
5	Manufacture of Outer-Vessel Pick-up Coils (wound coils)	2016 Q2	2017 Q1
6	Design and Prototyping of Bespoke Instrumentation Hardware	2016 Q2	2016 Q4
7	Design and Manufacture of In-vessel Electrical Cables, Clips and Connectors	2016 Q3	2017 Q2
8	Manufacture of Inner-Vessel Coils	2016 Q3	2017 Q2
9	Manufacture of Platforms for Inner-Vessel High-frequency sensors (wound coils)	2016 Q4	2017 Q3
10	Plasma Position Reflectometry Captive Transmission Components (ex-vessel)	2016 Q4	2017 Q2

Overview of Main tenders AFTER 2016

	Key contracts (total < 70 M€)	Final CfT	Contract Signature
1	Core-plasma Thomson Scattering (detailed design & manufacture)	2018 Q1	2019 Q2
2	Visible/IR Wide-Angle Viewing System (port plug components)	2018 Q2	2019 Q1
3	Front-End components for Low Field Side Collective Thomson Scattering	2018 Q4	2019 Q3
4	Core-plasma Charge Exchange Recombination Spectrometer (port plug components)	2019 Q2	2020 Q3
5	Visible/IR Wide-Angle Viewing System (optical components – ex-port)	2019 Q4	2021 Q1
6	Bolometer Cameras	2020 Q3	2021 Q3
7	Core-plasma Thomson Scattering (lasers)	2021 Q1	2022 Q1
8	Neutron Detectors and Calibration Sources	2021 Q2	2021 Q3
9	Actively Cooled Structures & Support Structures for Port Structures	2021 Q4	2022 Q2
10	Port Assembly	2021 Q4	2022 Q3
11	Core-plasma Charge Exchange Recombination Spectrometers	2022 Q2	2022 Q4

The broad picture



FUSION FOR ENERGY

Thank you for your attention

Follow us on:

www.f4e.europa.eu

www.twitter.com/fusionforenergy

www.youtube.com/fusionforenergy