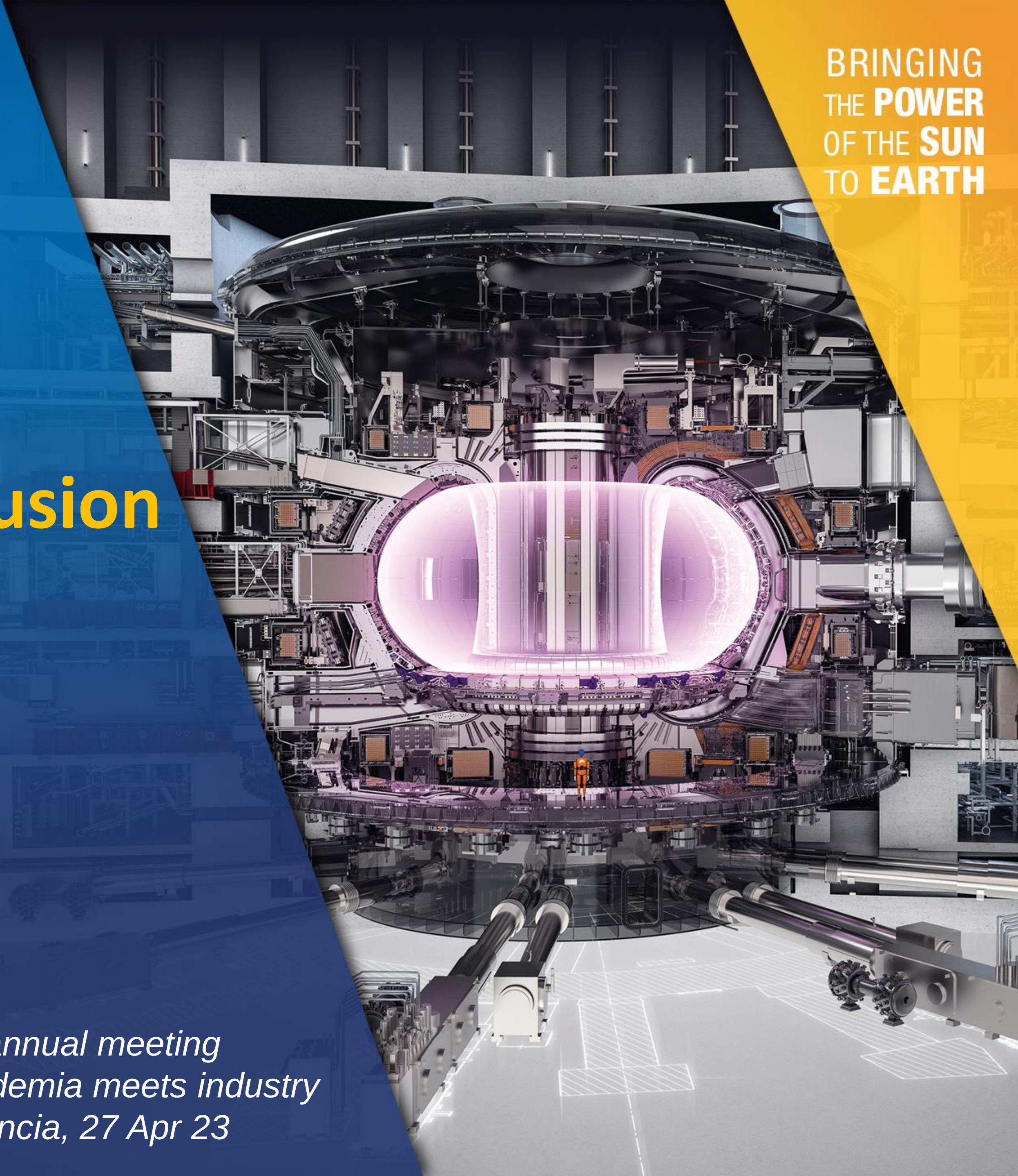
FUSION FOR ENERGY

Overview of EU diagnostics for fusion experiments



on behalf of F4E Diagnostic Team

AIDA innova

2nd annual meeting
Academia meets industry
Valencia, 27 Apr 23

Outline of the talk

- **Introduction. EU Diagnostics to ITER**
- **'Port & Engineering' for Diagnostics integration**
  - Port integration
  - Feedthrough & cables
- **'Non-Optical' Diagnostics**
  - Radial Neutron Camera
  - Pressure Gauges
  - Bolometers
- **'Optical' Diagnostics**
  - Collective Thomson Scattering
  - Core plasma Thomson Scattering
  - Core-plasma Charge Exchange Recombination Spectrometer
  - Wide-Angle Viewing System

Thermonuclear fusion

- At high temperature gases are strongly ionized resulting in the formation of plasma, a mixture of electrons and ion species.

- The most probable reaction for thermonuclear fusion is considered through the use of Deuterium / Tritium gases

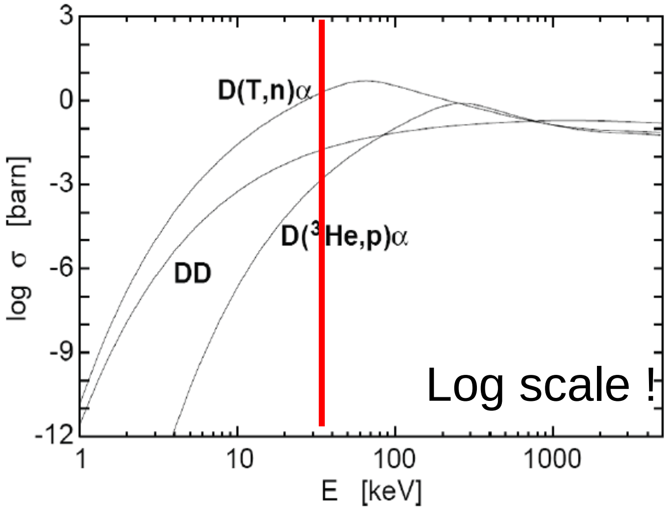
$${}^2_1D + {}^3_1T \rightarrow {}^4_2He \;(3.5\ \text{MeV}) + n^0 \;(14.1\ \text{MeV})$$

$${}^2_1D + {}^2_1D \rightarrow {}^3_1T \;(1.01\ \text{MeV}) + p^+ \;(3.02\ \text{MeV})$$

$$\rightarrow {}^3_2He \;(0.82\ \text{MeV}) + n^0 \;(2.45\ \text{MeV})$$

$${}^2_1D + {}^3_2He \rightarrow {}^4_2He \;(3.6\ \text{MeV}) + p^+ \;(14.7\ \text{MeV})$$

Reaction Cross-Section



- 2 concepts exist: **Magnetic Confinement** & **Inertial Fusion**

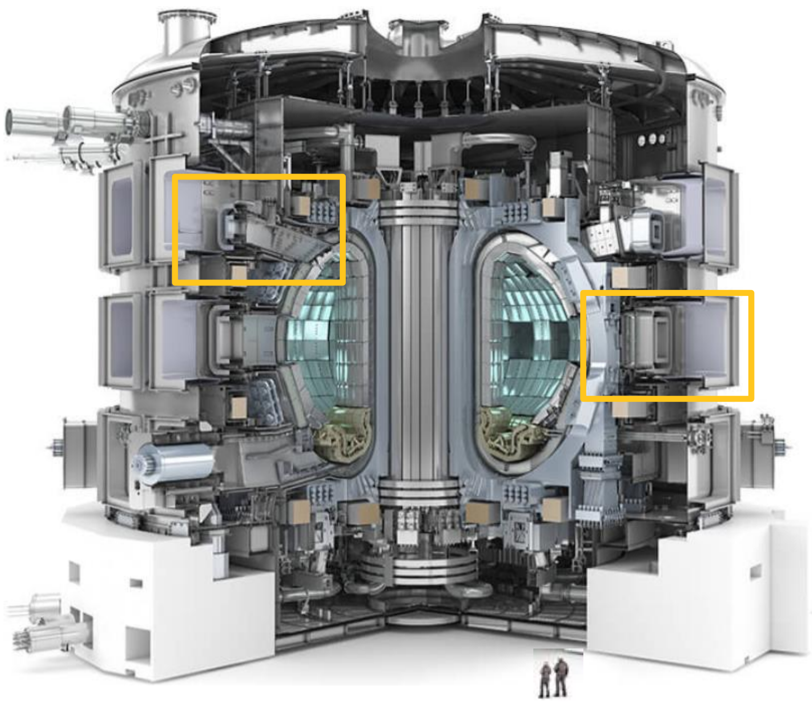
- ITER is a TOKAMAK based on **Magnetic Confinement**

Plasma diagnostics in ITER

The purpose of diagnostics is to **measure plasma and first-wall parameters**. Diagnostics do not measure the parameters directly, but each parameter needs to be derived from the measured quantities (processing/interpretation).

The set of Diagnostics in ITER provides the measurements necessary to **control** fusion reaction, **protect** the machine, evaluate and **optimize** plasma performance and being able to further understand the **plasma physics**.

ITER will rely on approximately **50 different** diagnostic. **Europe** is responsible for roughly **25% of all Diagnostics in ITER**.



- ITER Plasma **diagnostics** face **harsh conditions**
    - Temperature (70-350 C)
    - High magnetic field (100 mT - 5T)
    - Ultra High vacuum
    - Nuclear load (>E17 n/cm^2 ; > MGy)
    - Heavy mechanical load >10 g in disruptions
- ITER Plasma diagnostics are installed in ‘PORT’
- ITER is a **nuclear facility with Tritium** containment **safety** function

Port & Engineering for Diagnostics Integration

European Diagnostics Port Integration

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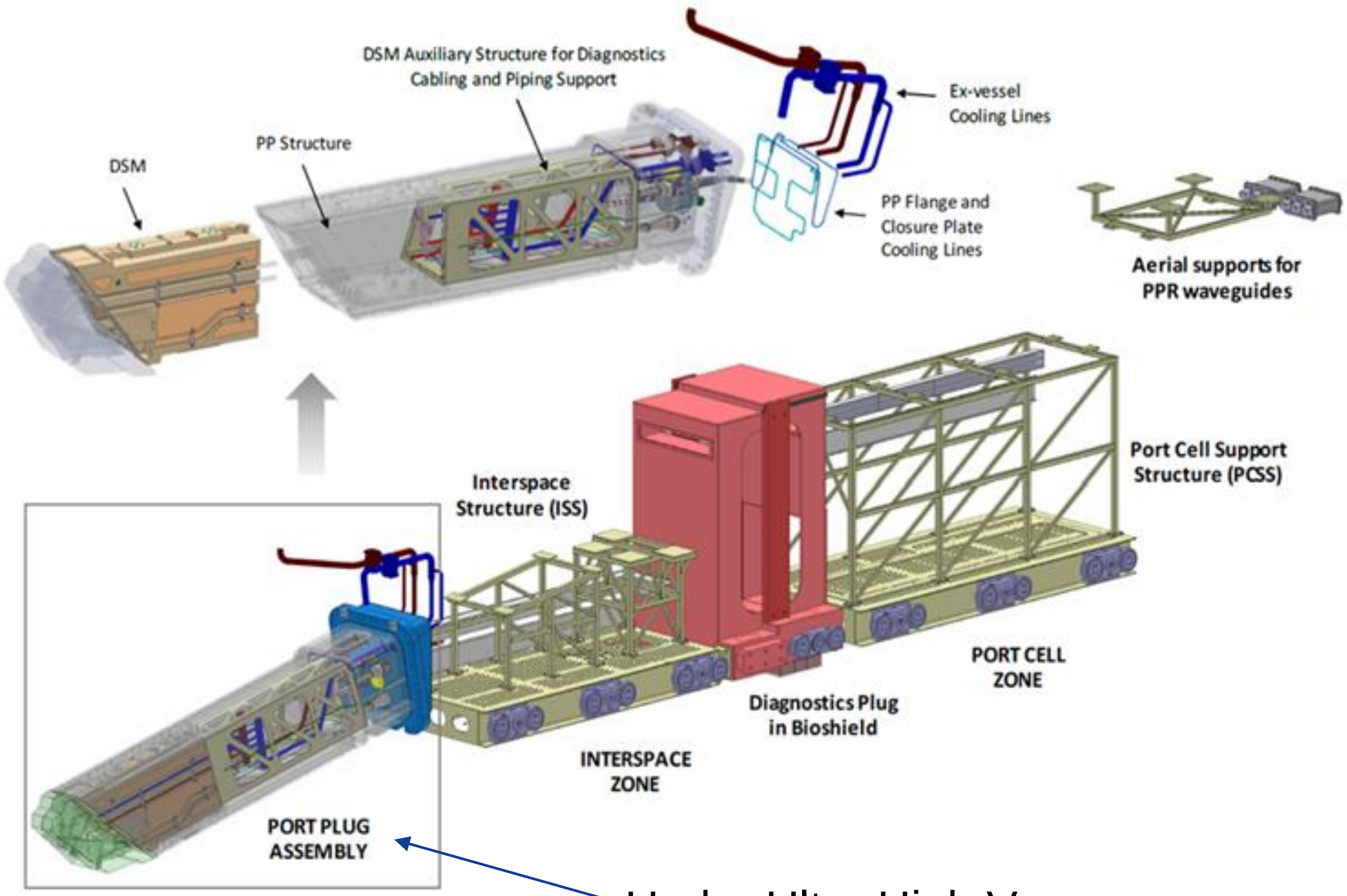
The European Diagnostic Ports Project comprises the integration of six ports:

- Equatorial Ports (**EP01, EP10**)
- Upper Ports (**UP01, UP03, UP10, UP17**)

EU scope
Port plug
Inter-space
Port Cell
Diagnostic integration
Testing in PPTF

EU diagnostic equipment tested & integrated on Port

Current delivery schedule
2024 to 2032



Under Ultra High Vacuum

European Diagnostics Port Integration

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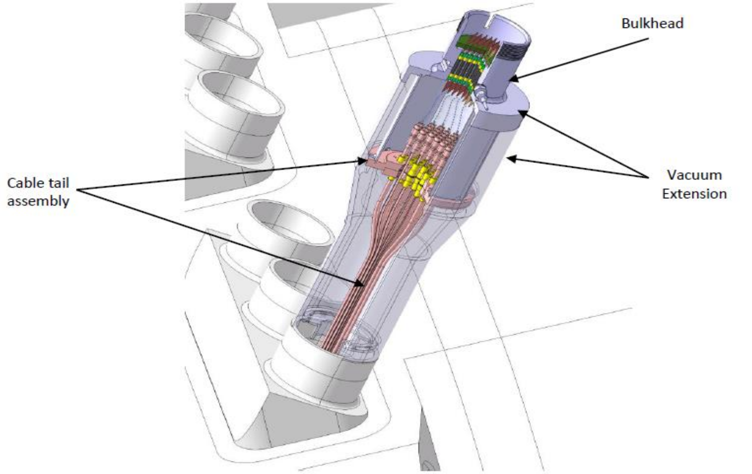
Current status Final design Closed

Successful prototyping of Diagnostic Shielding Module(DSM) manufacturing and joining.



IV-EFT Diagram and Classification

electrical, gas or water feedthroughs.

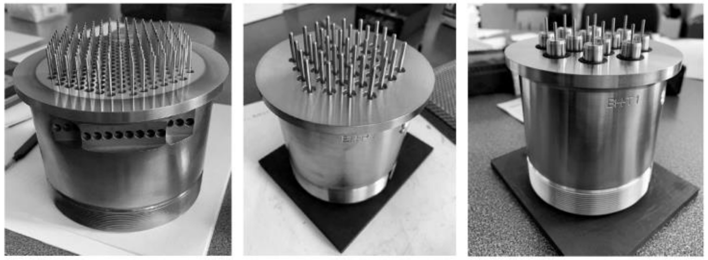
Main manufacturing techniques

- **Forging followed by heavy machining**: for the *DSM* manufacturing,
- **Conventional structures**: configured by standard profiles steel welded together (low cobalt steel structures on ISS/PCSS).
- **B_4C pellets**: hot-pressed or pressureless sintered Boron Carbide.
- **Laser Welding** of individual lids for DSM cavities.
- **Glass to Metal sealing (GTMS)** with double vacuum barrier.

- Procurement Difficulties: **Large amount** of **B4C** and **Low-Cobalt stainless steel**.
- Only one port-plug test facility for all EU Port.

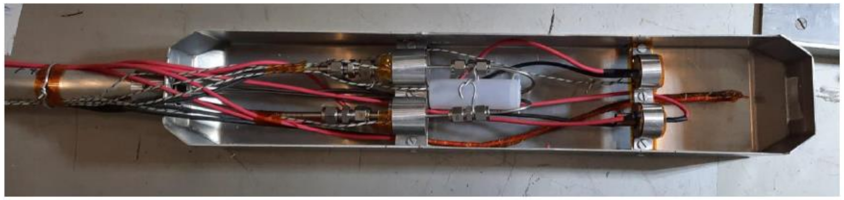
R&D & Testing irradiated GTMS & cables

Manufacture of three Bulkheads samples (double GTMS barrier) with different pin layouts (including coaxial pins)



BULKHEAD TYPE D BULKHEAD TYPE P BULKHEAD TYPE T

- Pin samples irradiated up to 2.24E17 n/cm^2 in fission reactor

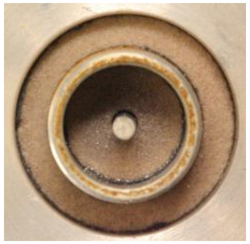


- **Passed Helium Leak Test** <2.69 10^{-10} Pa.m^3/s
- **Passed Electrical Test**: insulation resistance >10 MΩ ; dielectric strength at 1000VAC/50Hz

- Post-irradiation Examination in Hot-Cell does not reveal cracks or damages. Small surface roughness changes

before irradiation

after irradiation



- Range of **mineral insulated cable & thermocouples** (twisted pair, coaxial, quad terminated & compatible for UHV application and able to resist harsh conditions:
- High temperature (200 ºC nominal, 500 ºC peak) and
- Irradiation loads (ITER compatible)
- Excellent air tightness (2,69*10^{-10} Pa*m^3/s)

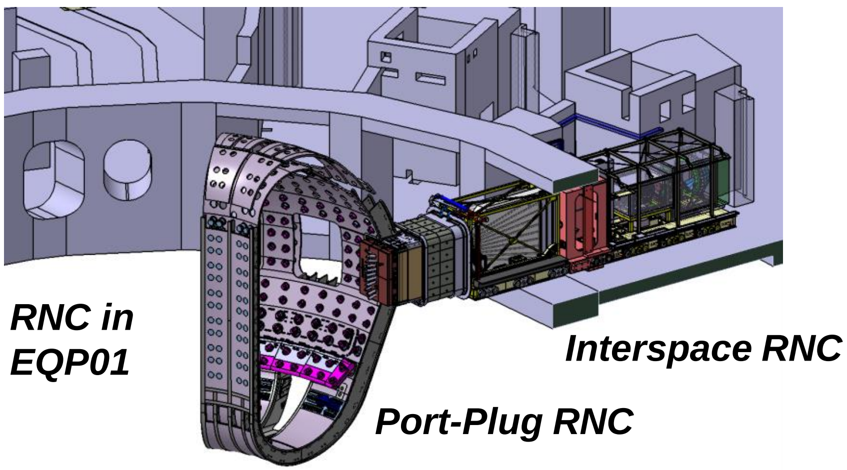
‘Non-Optical’ Diagnostics

Radial Neutron Camera (RNC)

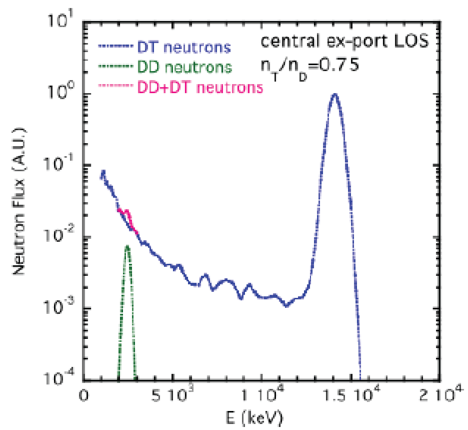
provides real-time measurements of the **neutron emissivity profile** in burning plasma

$$^{2}_{1}D + ^{3}_{1}T \rightarrow ^{4}_{2}He\ (3.5\ MeV) + n^{0}\ (14.1\ MeV)$$

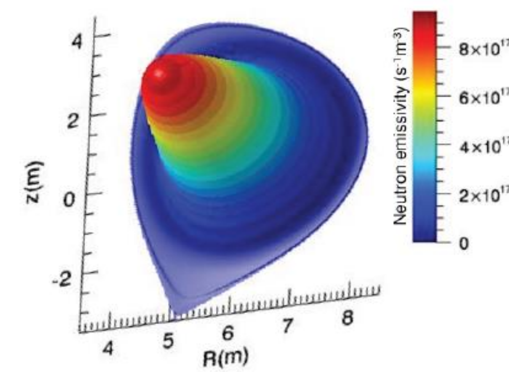
Opening in first wall through line-of-sight → **Collimated neutrons** are counted by fast neutron detectors → Signal sent to DAQ for **profile reconstruction**



Typical neutron spectrum



Tomography / neutron emissivity profile reconstruction



Port-Plug RNC

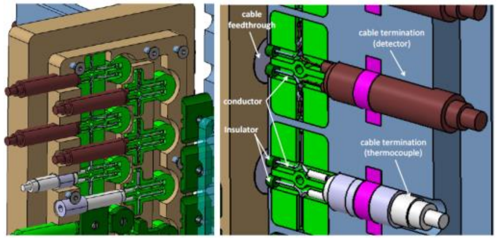
- Cassette with 6 detectors modules
- 6 Collimators
- MI Cables & Electrical feedthrough
- Beam dump & B4C shielding

Port-Interspace/Port-Cell RNC

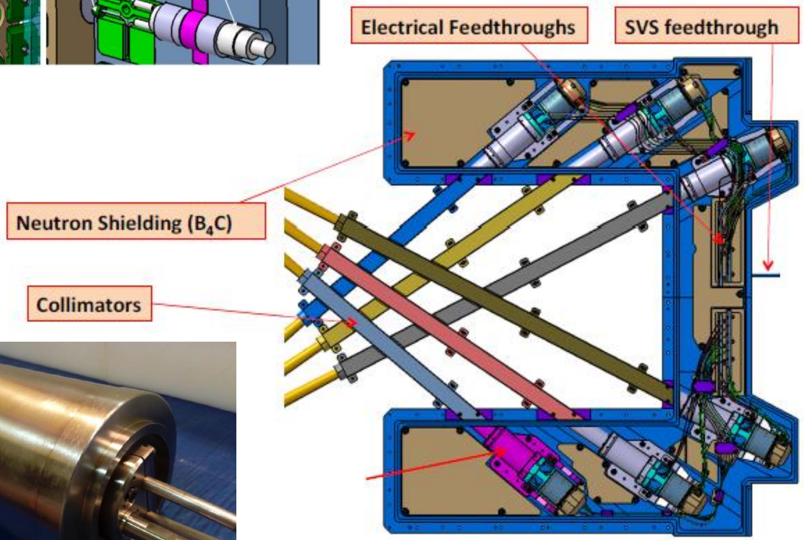
- Shielding with 16 collimators
- 16 Detector modules with cooling loop
- Shielded cabinets for preamplifiers
- I&C cubicles in diagnostic building

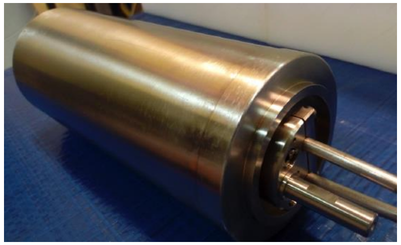
Radial Neutron Camera (RNC)

Port-Plug Subsystem



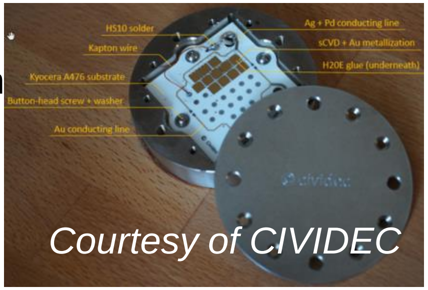
Feedthrough passed leak test
2.16E-9 mbar*l/s after 158
thermal cycling at 200 C





Pure U238 for fast neutron detection
Double wall multistage electrodes
Backup of CVD diamond

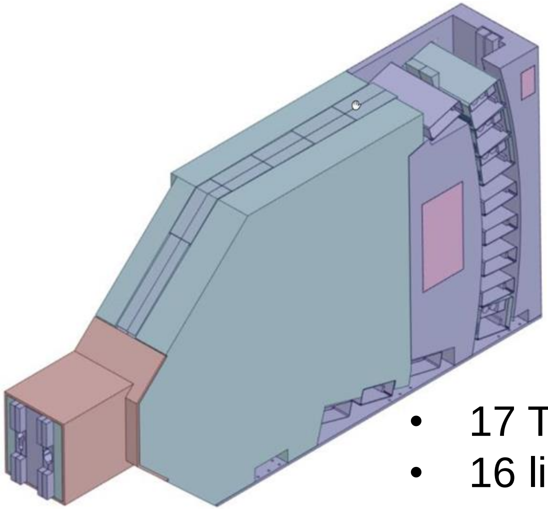
Courtesy of Centronic



Courtesy of CIVIDEC

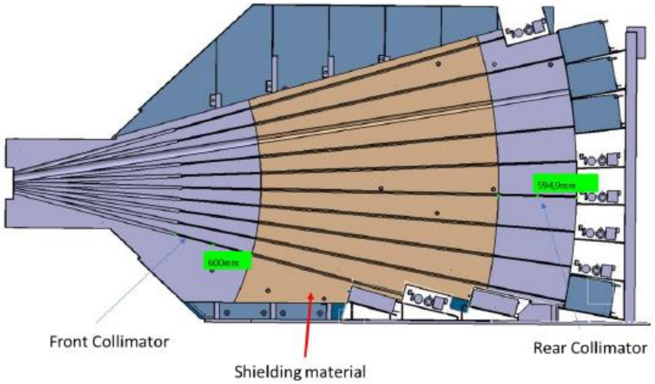
50 micron CVD Diamond matrix
Tested at 200/250 C

Port-Interspace Subsystem



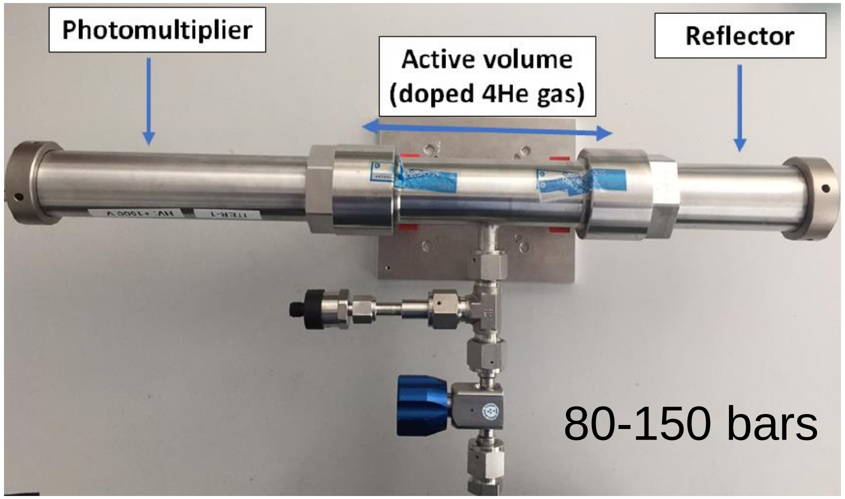
- 17 T shielding block
- 16 lines of sight

- Plastic scintillator
- CVD Diamond Matrix
- He-4 scintillator (new)

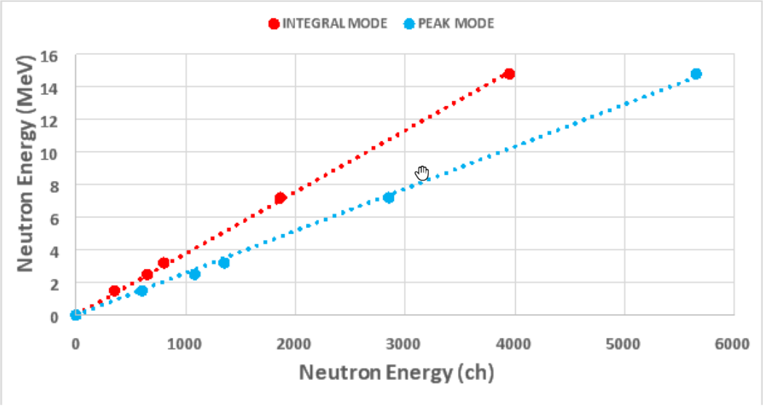


He-4 scintillator: a good robust candidate for fast neutron detection

- Fast neutron produces He recoil atom through high elastic cross-section scattering which ionizes the gas containing dopant that can scintillate
- Gamma-rays mainly interact with the electrons, which ionizes the gas but with less efficiently and with different light pulse characteristic



Good linearity & Gamma-rays rejection !
(but bulky detector)



Courtesy of ENEA & PTB

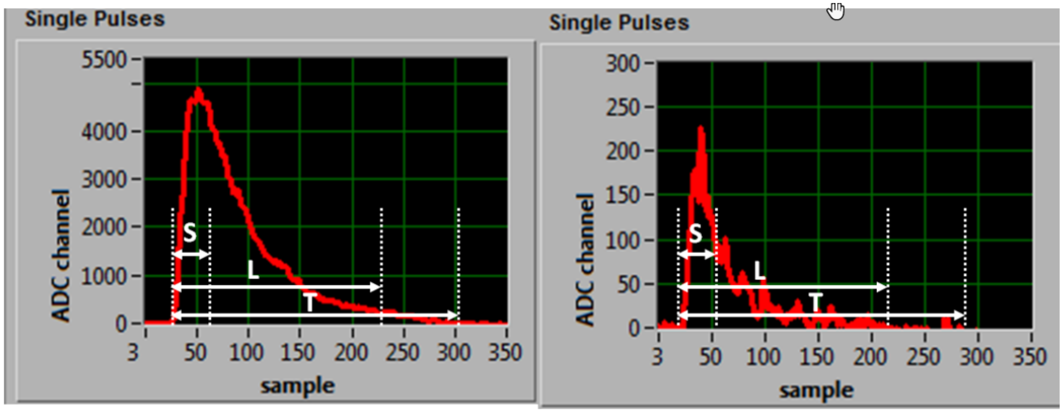
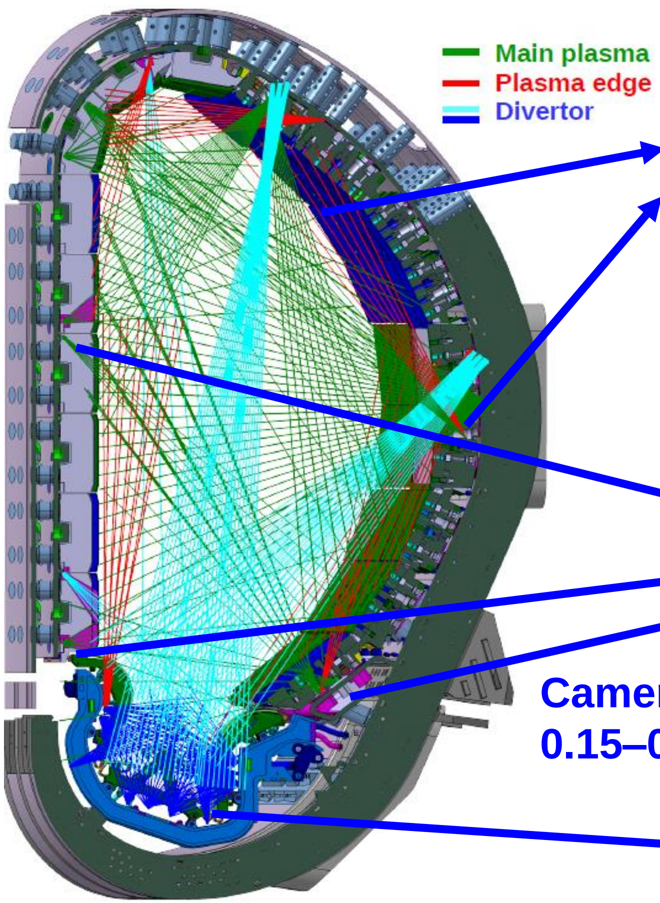
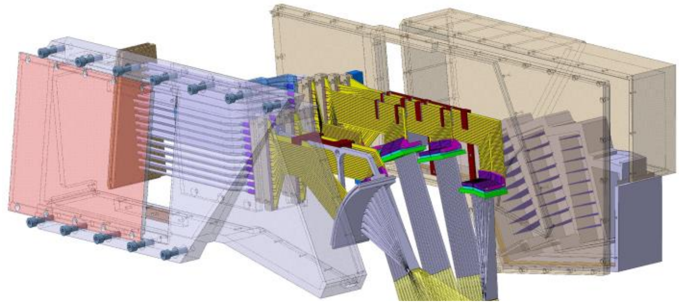


Fig. 13: Short, long and total gates for a typical neutron pulse (left) and gamma pulse (right). 1 sample = 2.5 ns.

Bolometer diagnostic (1/2)

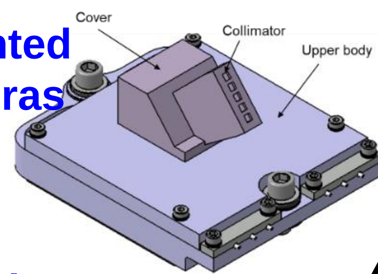
Poloidal distribution



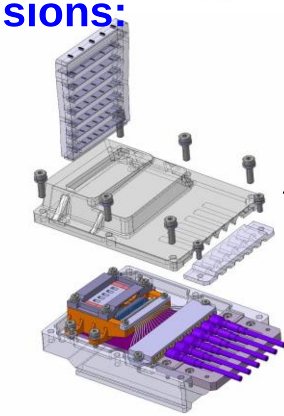


7 port-mounted cameras

22 VV-mounted cameras



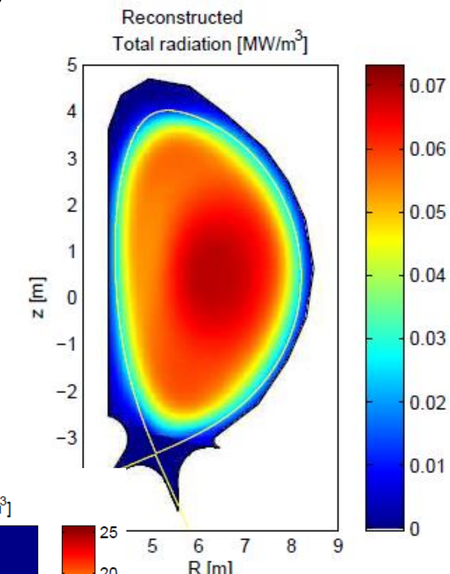
Camera dimensions: 0.15–0.7 m

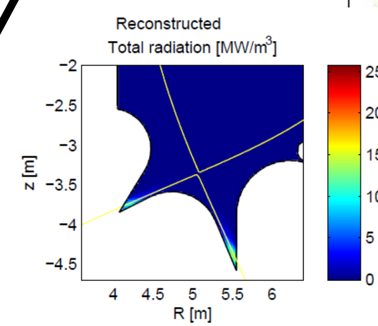


40 divertor-mounted cameras

~500 lines of sight (tomography)

I&C
+
data-analysis software





Purpose: measure profile of total radiated power

x-ray–ir

Bolometer diagnostic (2/2)

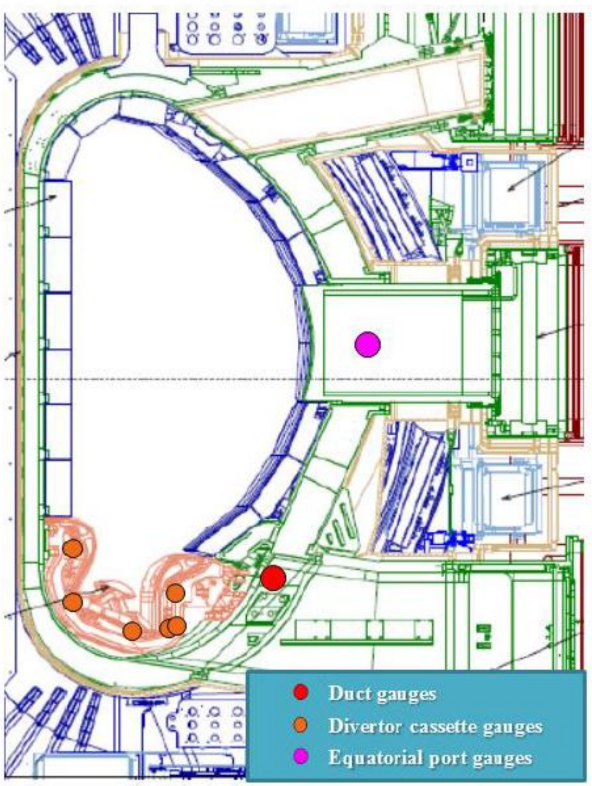
- **Principle:** temperature-sensitive resistors measuring the temperature change resulting from incident radiation (IR / X-rays).
- **Challenges for design of all components:**
  - High electro-magnetic and heating **loads** (<400°C). Nuclear radiation.
  - Precision-machined components in **vacuum** and with space constraints
- **Specialized bolometer sensors** (IR/X-rays) have been prototyped that are suitable for these conditions.
  - Blackened 20-µm thick gold absorber on a thin substrate
  - Developed from typical bolometer sensors used on present-day fusion experiments.

- **Pictures show two unblackened prototypes** (size 5 × 23 mm^2).
- **Testing** for thermal cycling, accidental steam exposure, periodic pressure transients, light bursts and accelerations is in progress.
- **Nuclear irradiation testing** in a research fission reactor is planned.

Diagnostic pressure gauges (DPGs)

DPG is a diagnostic sensor that **measures the pressure** inside the plasma

Indirect measurement of the **ionization current** produced by electrons emitted from a ZrC electrode



DPGs location in the tokamak

The EU scope: 52 Pressure sensors
Electronics and Power Supplies
Data acquisition and I&C

Objectives and requirements

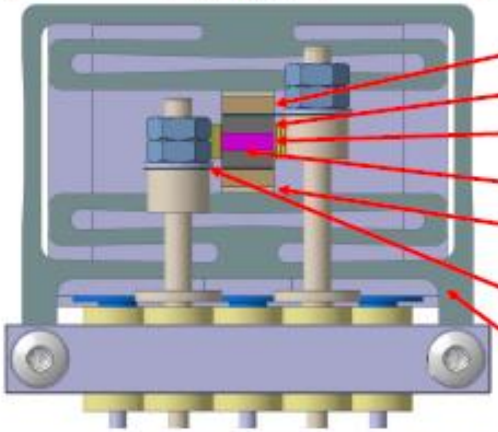
- Measurement of neutral gas pressures at walls
- Basic machine control
- Pressure range during pulse
  - 10^{-4} to 1 Pa in equatorial port (EP)
  - 10^{-2} to 20 Pa in divertor (DC) and lower port (LP)
- Accuracy of 20 % over the pressure range
- Time resolution of 50 ms
- System availability of 99.8 % over ITER lifetime
- No foreseen maintenance

➢ Lifetime expected to be at least 1000 hours

Diagnostic pressure gauges (DPGs)

Indirectly heated zirconium carbide plate is used as an electron emitter

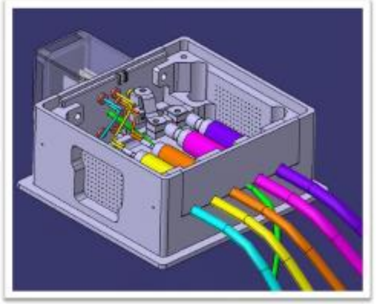
Prototypes were successfully manufactured by two independent suppliers



CAD drawing of gauge head

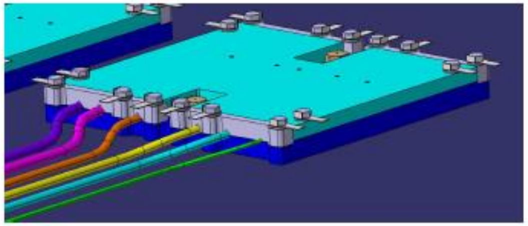

Photo of assembled prototype

Long pulse **tests** in high magnetic fields **up to 6T** completed **successfully**


Gauge head with support structure (lid faded out) and attached MI-cable tail

Endurance at high pressures of hydrogen critical:
Graphite erodes at emitter junction
Ir interlayer slows down the carbon loss rate

Further tests are forecast to double confirm that the design is valid even if with some erosion

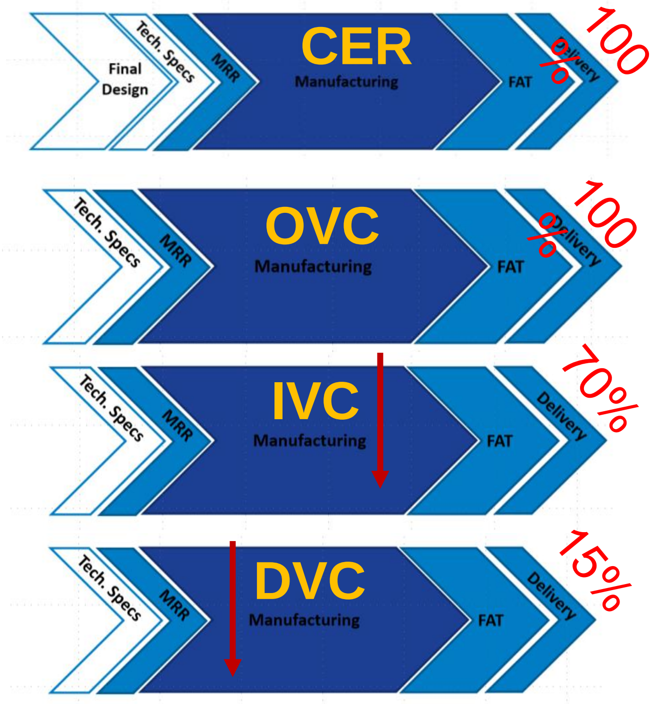
Junction box for connection of mineral insulated (MI) cables in equatorial port


Courtesy of IPP

Magnetic Sensors

The Magnetic Sensors are essential for ITER plasma operation. Their functioning is based on the principle of electromagnetic inductance

STATUS: Delivered/ Manufacturing on-going

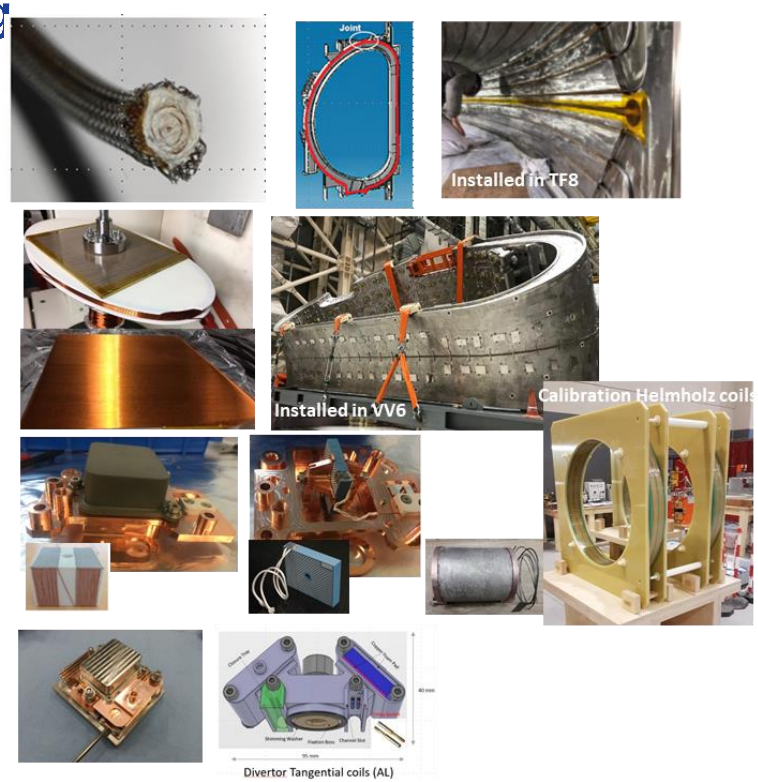


Continuous Rogowsky Coils

Inner Vessel Coils

Outer Vessel Coils

Divertor Coils



Production challenges: High precision machining and assembly of ceramics, manipulation of delicate insulation protections, development of reliable wires weldings, high thickness coating processes.

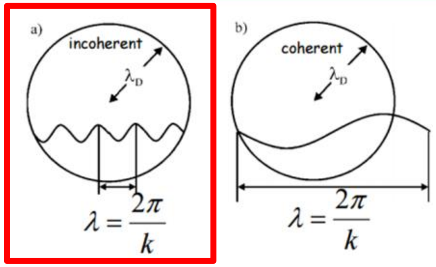
‘Optical’ Diagnostics

Core Plasma Thomson Scattering (CPTS)

Note: if the wavelength of the interrogating beam λ < Debye length

$$\lambda_D = \sqrt{\frac{\varepsilon_o K_B T_e}{e\, ne}}$$

$$= 7.4\ 10^5 \sqrt{\frac{T_e(\mathrm{eV})}{n_e(m3}}$$

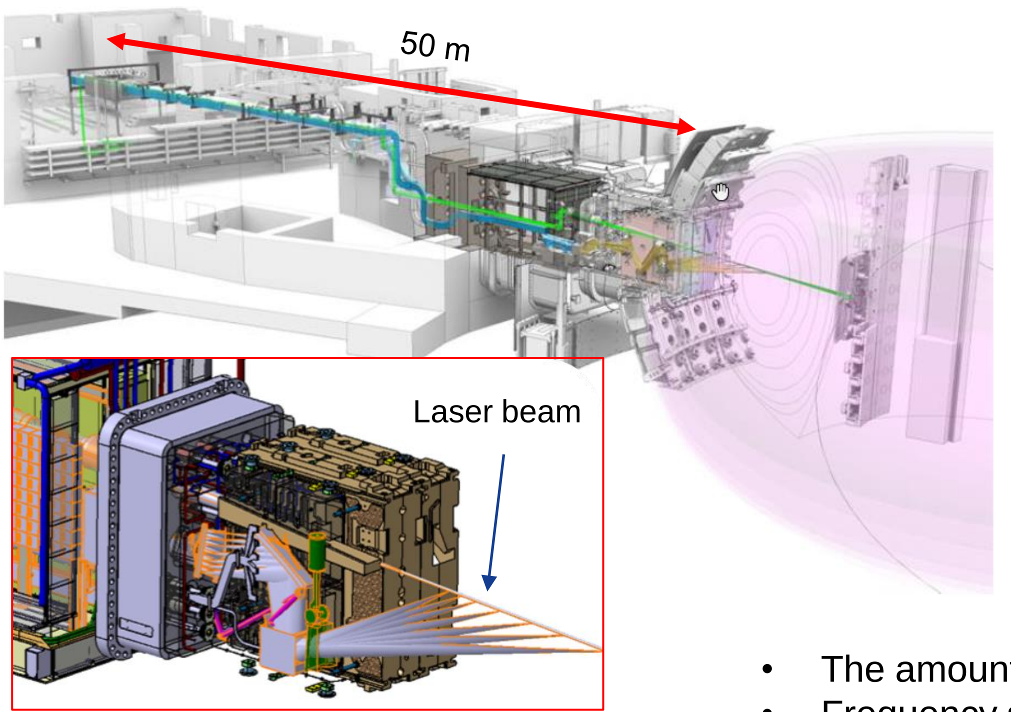


provides real-time measurements of the electron density and temperature from the fusion reaction

Laser light sent into the Plasma

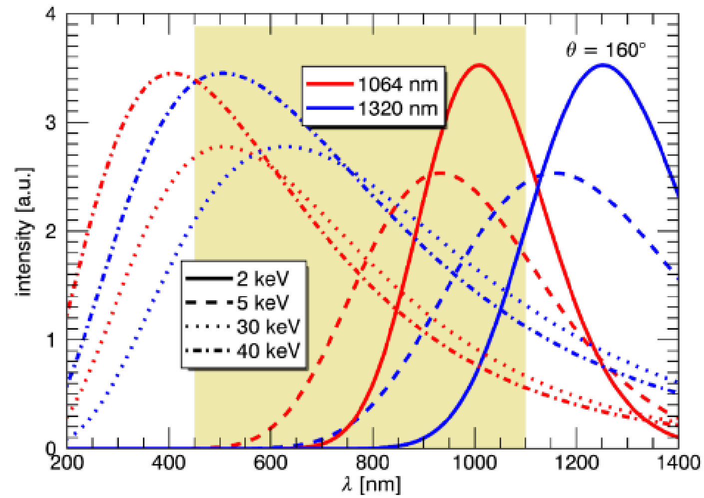
light scattered by the free electrons (Thomson Scattering)

collected & analysed



CPTS in EP10

scattered light - wave shift of laser beam



- The amount of scattered light tells about the electron density.
- Frequency shift tells about electron velocity (Te eV)

Core Plasma Thomson Scattering (CPTS): key components

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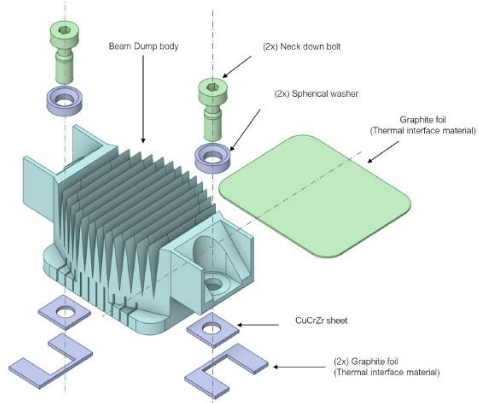
Status: Preliminary design on-going

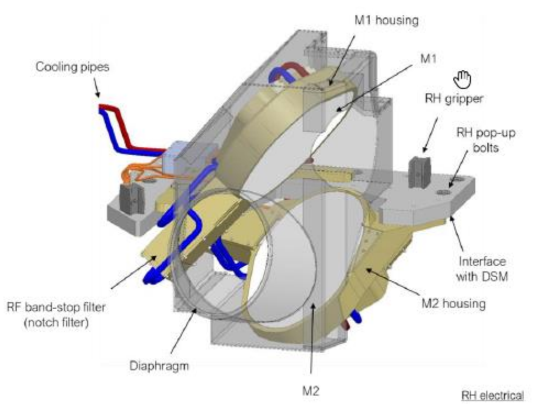
- Beam dump
- High-power laser (Nd-YAG 1064 nm: 5J – 100 Hz – 4 ns)
- First Mirror Unit with Shutter & RF Cleaning
- Collection optics & fibre bundles
- Spectrometers
- Protection Important Components (Confinement barriers)

Beam Dump –
Tantalum Zirconium Molybdenum

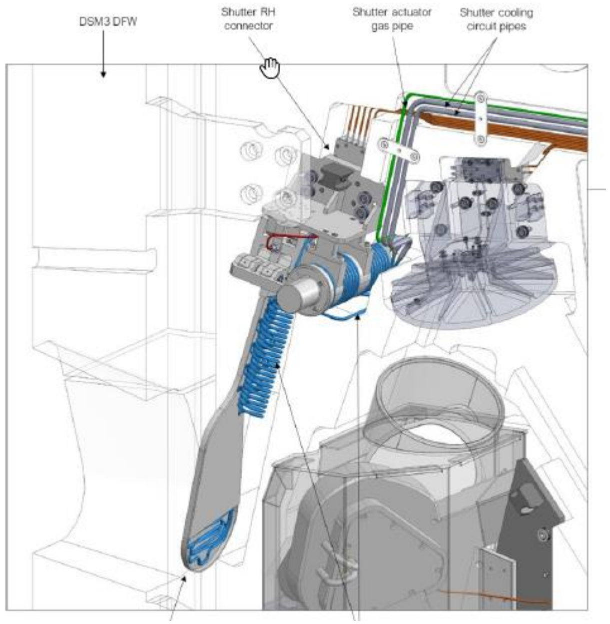


Shutter concept

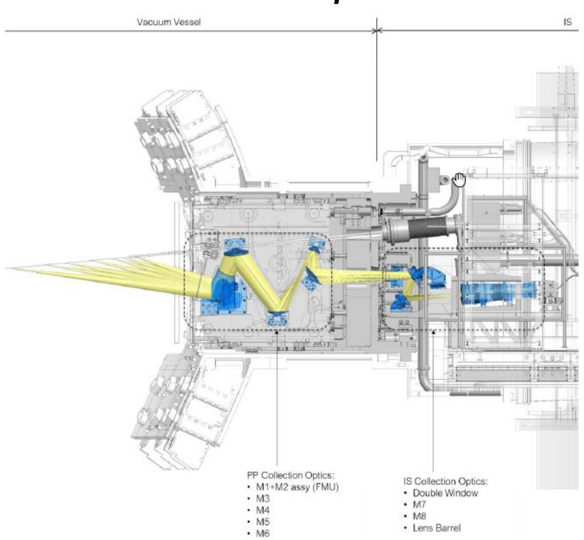
FMU



Integrate cooling & RF cleaning



Collection Optics

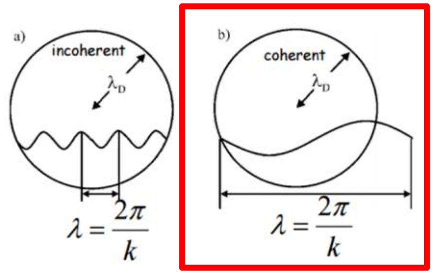


Collective Thomson Scattering (CTS)

Note: if the wavelength of the interrogating beam λ > Debye length

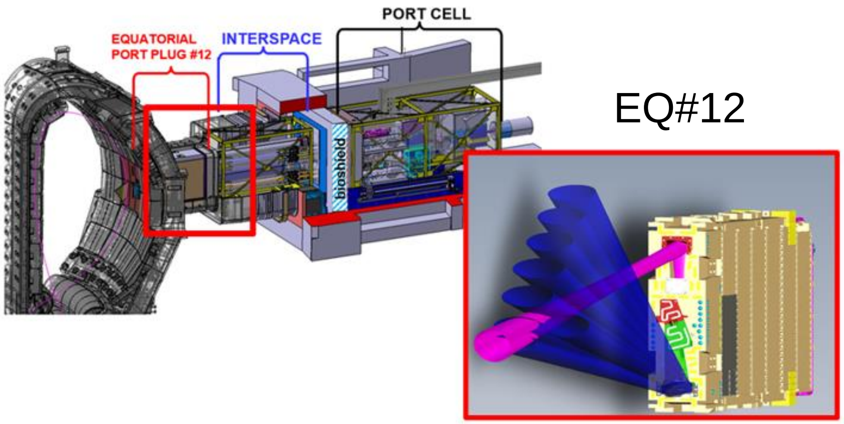
$$\lambda_D = \sqrt{\frac{\varepsilon_o K_B T_e}{e\,ne}}$$

$$=7.4\ 10^5 \sqrt{\frac{T_e(\mathrm{eV})}{n_e(m3}}$$

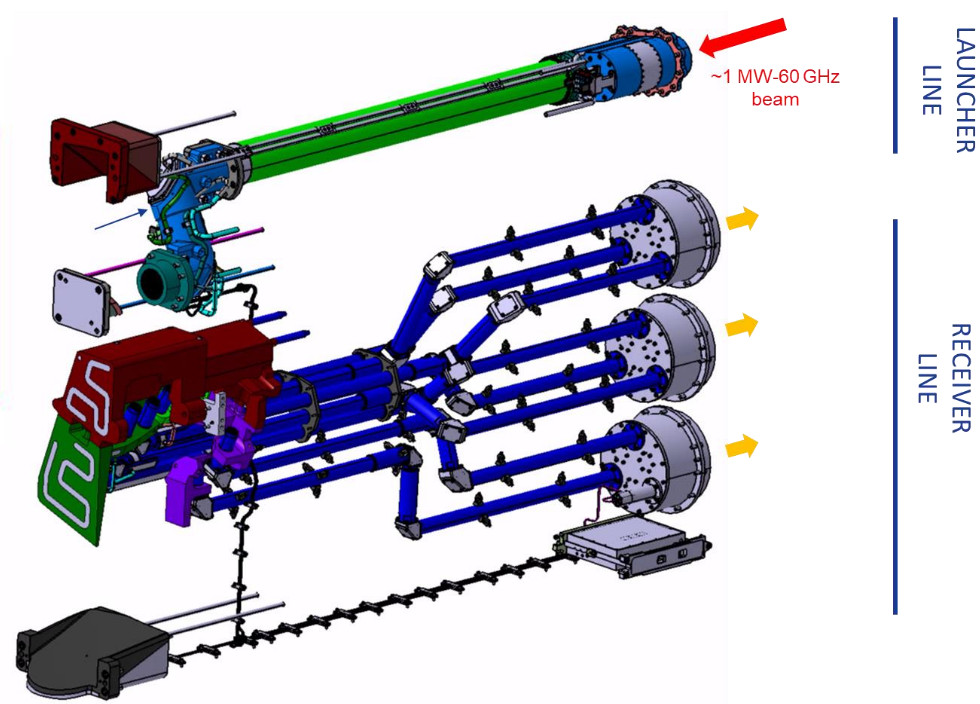


CTS provides real-time measurements of **the fast ions** (products of the fusion reaction)

High power MW beam sent into the Plasma → <u>Collective</u> scattered radiation → Collected & analysed.



CTS in (DSM) #3



RF components → Guide the beam/ Scattered radiation

Mirrors → launch beam /receive signal to/from the plasma

Supporting structures

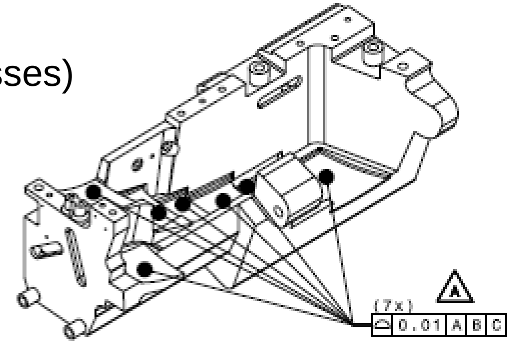
Collective Thomson Scattering (CTS)

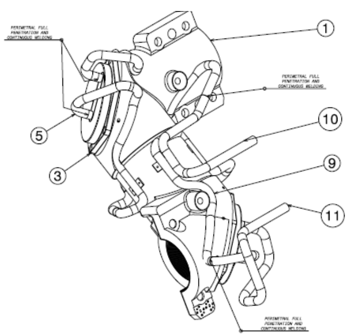
FUSION FOR ENERGY

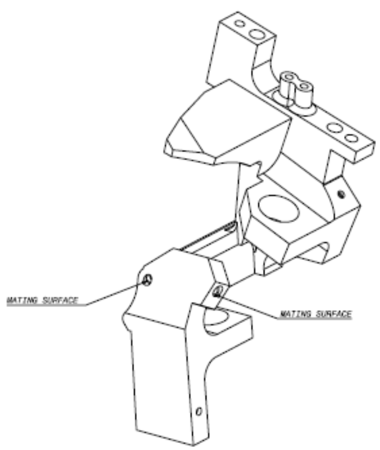
Status: Final design closed

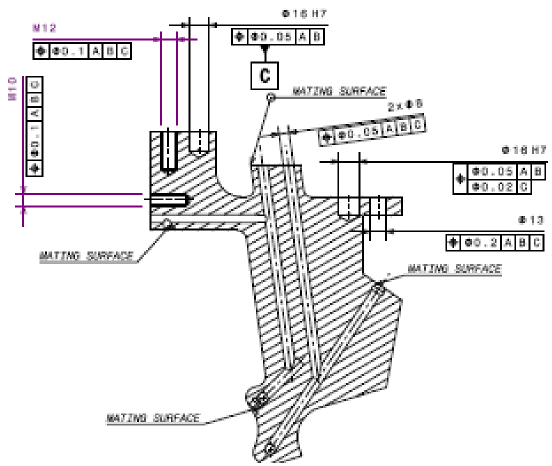
Main manufacturing/testing challenges

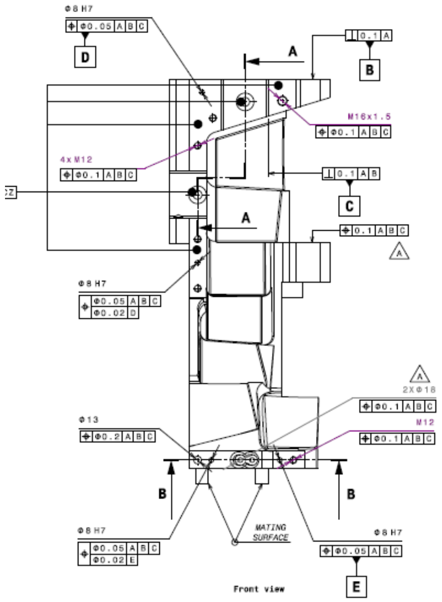
- RF components based on **Circular Corrugated Waveguides** (very low losses)
- **RF Testing** of Full transmission lines
- Joining Techniques (Welding, hipping, brazing) – Next slide
  - Mirrors joint by **Hot Isostatic Pressure**
- **Precision machining** with tight tolerances
  - **Complex shapes** (for machining and bending of cooling pipes)
  - **Gun-drilling** (cooling channels)
  - Mirrors shapes tolerances











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