ipfn
INSTITUTO DE PLASMAS
E FUSÃO NUCLEAR

(some) Nuclear Fusion Challenges and the Portuguese contribution

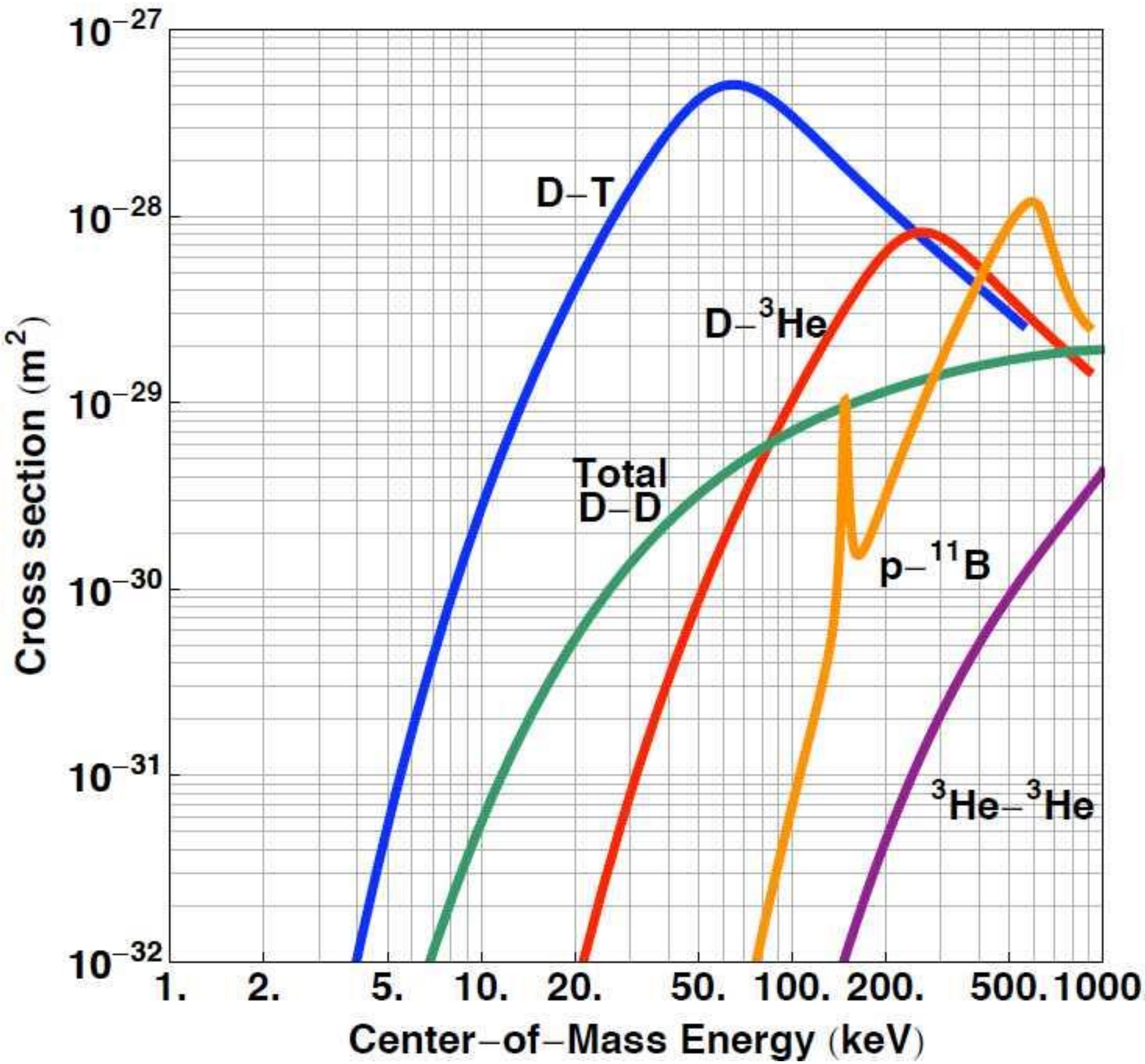
B. Gonçalves
on behalf of IPFN team

I work with Plasmas!

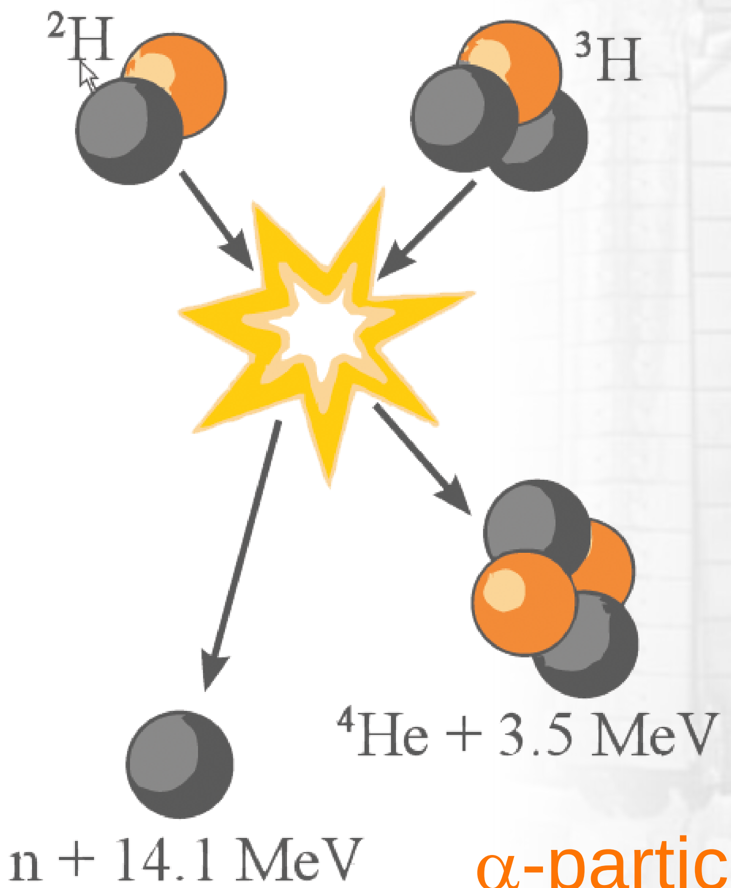
what people usually think about it...

The common knowledge about Nuclear Fusion!

Nuclear fusion 101



Nuclear fusion 101



α-particle heating

Fusion device | JET

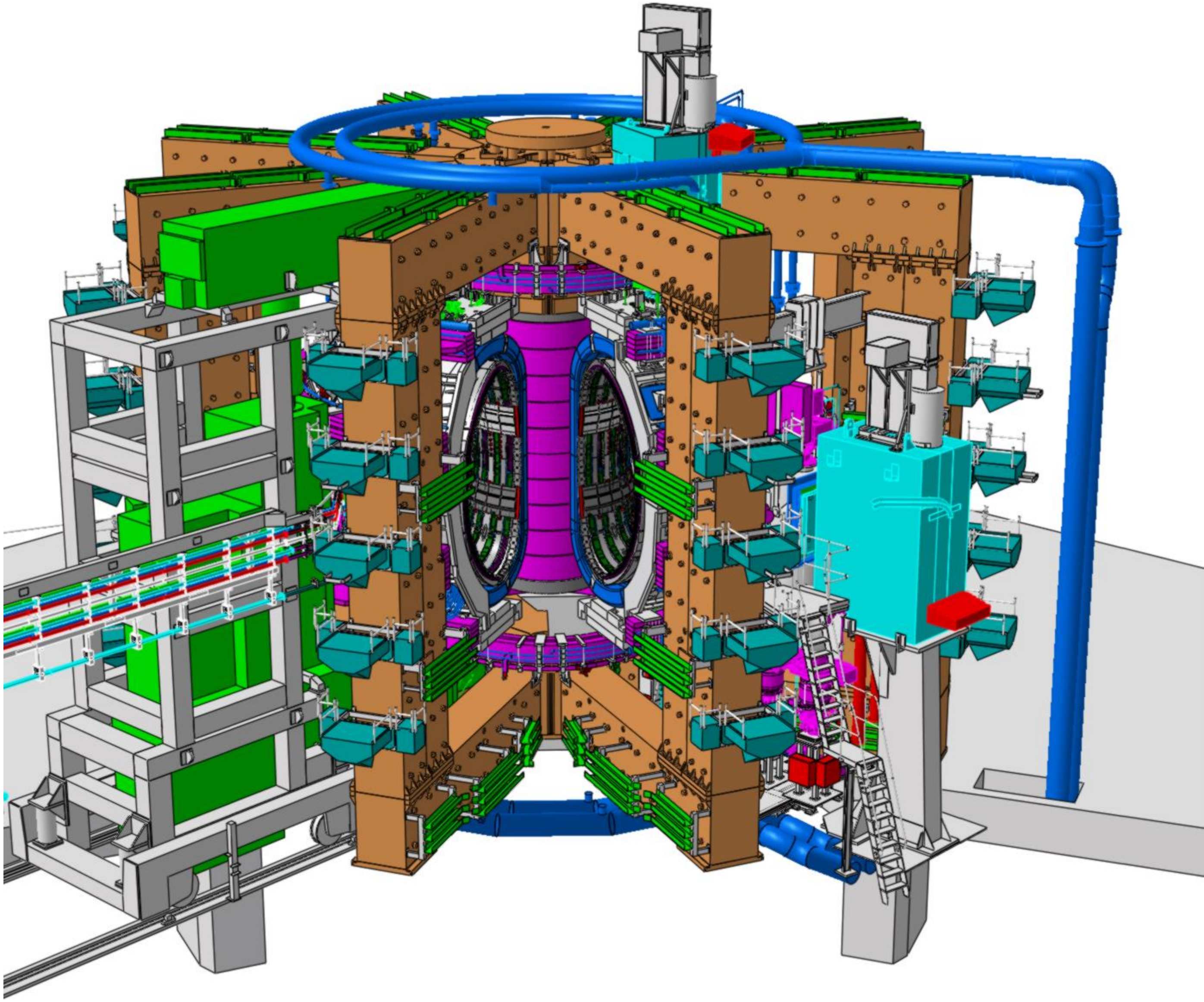
Vacuum vessel

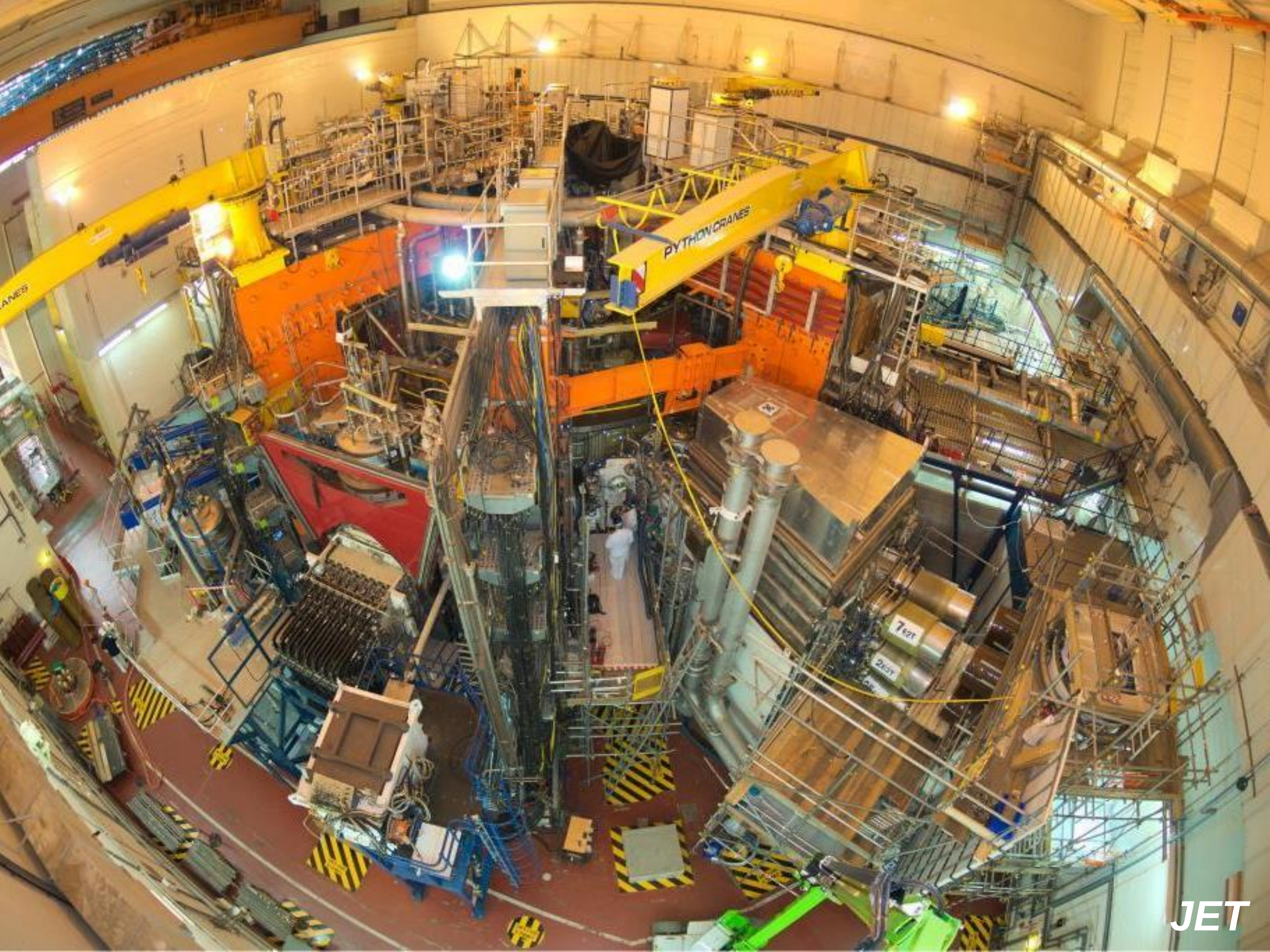
Toroidal filed coils (cooled)

Support structure (2600t)

Poloidal coils

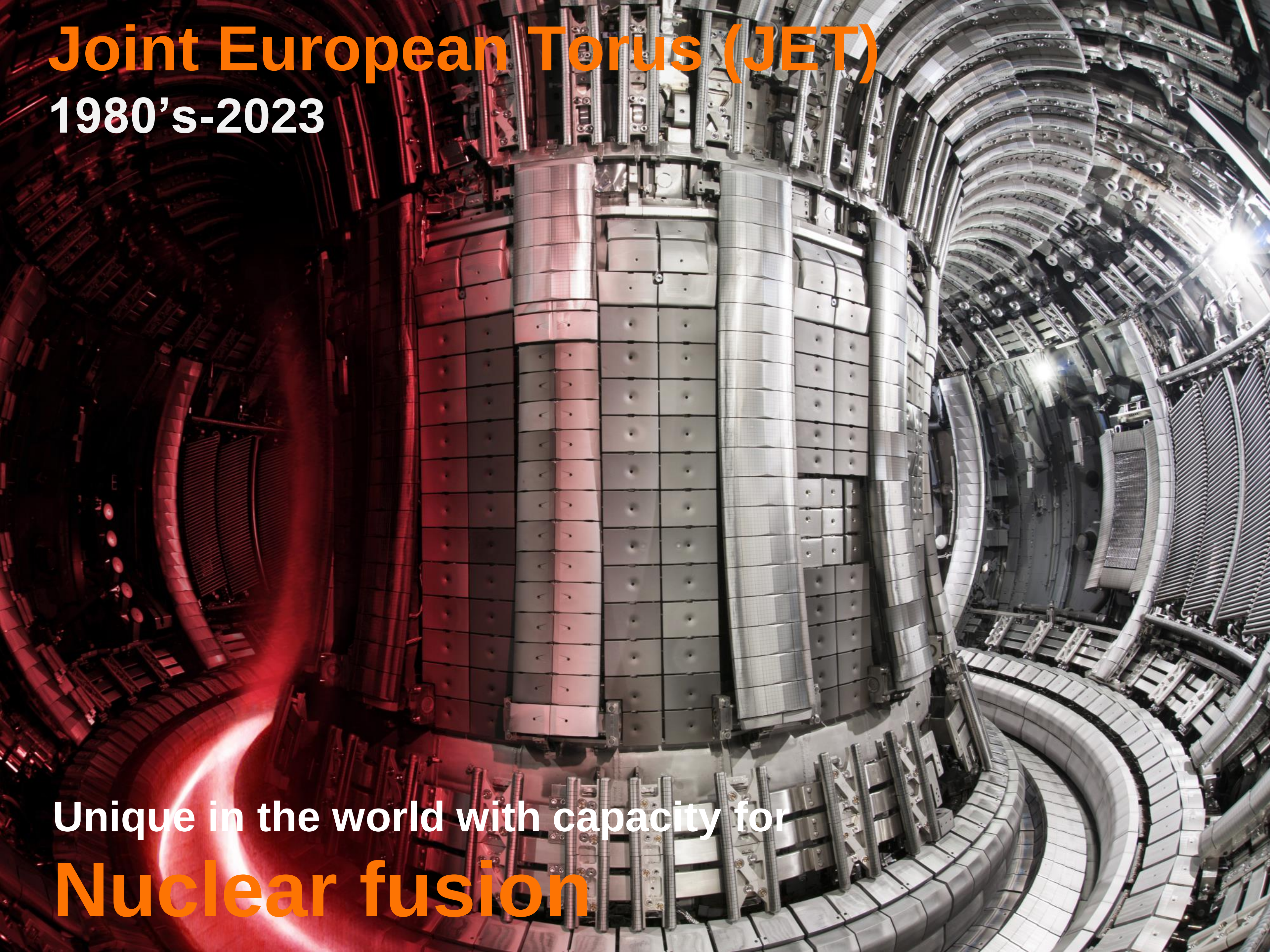
…etc




PYTHON CRANES
JET

Joint European Torus (JET)

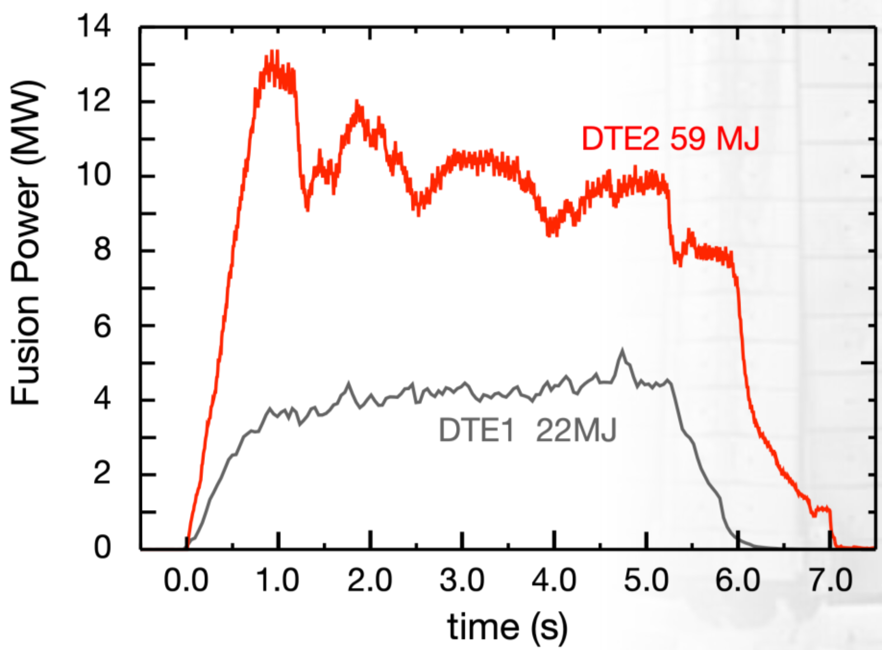
1980’s-2023



Unique in the world with capacity for

Nuclear fusion

Demonstration of fusion energy



Heating

33 MW

5 s, **Q = 0.33**

11 MW

Fusion Energy

Record DT shot 99971

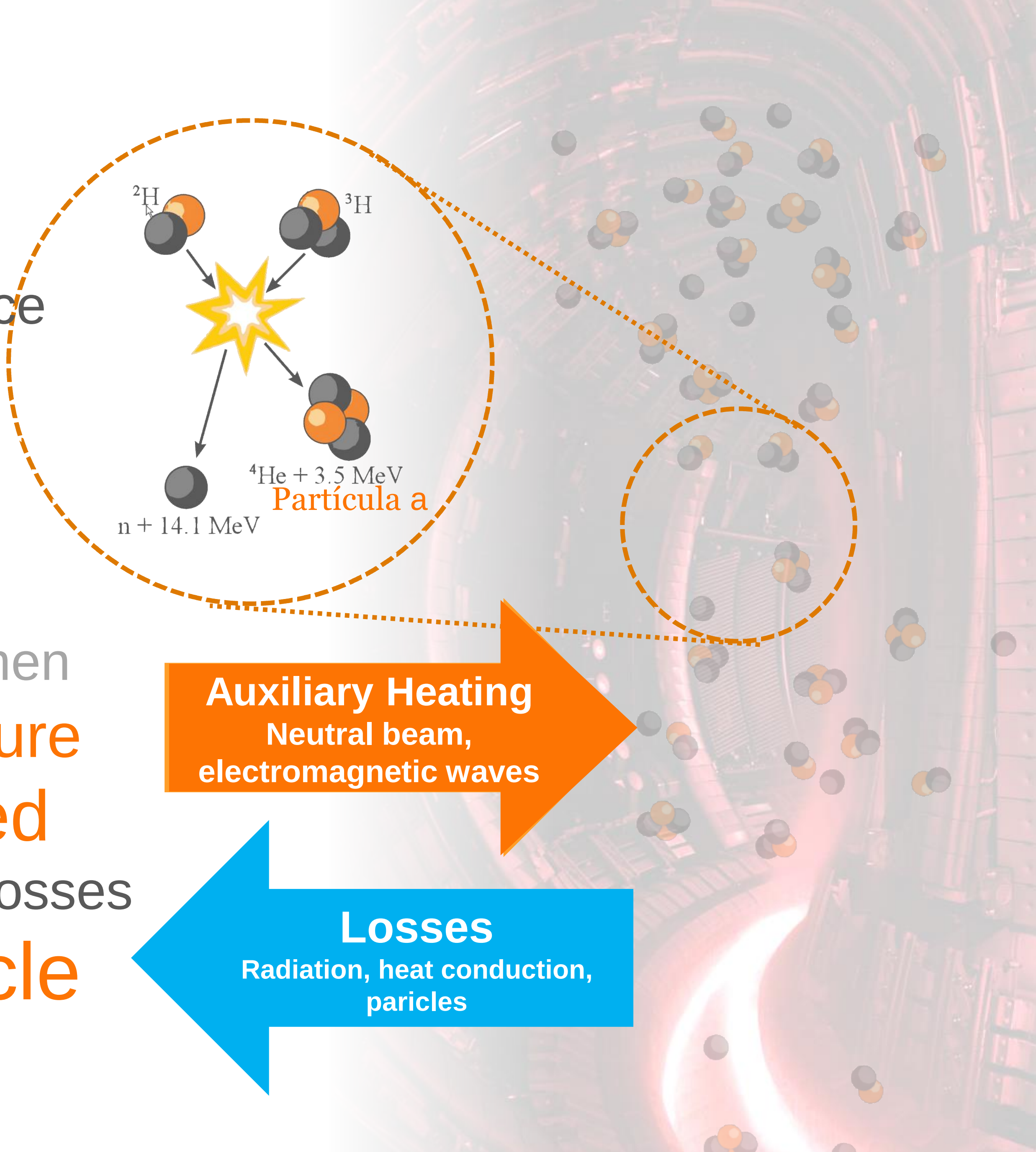
21st December 2021

(Credit: EUROfusion consortium)

Ignition

Overal power balance

$$P_H + P_\alpha = P_L$$



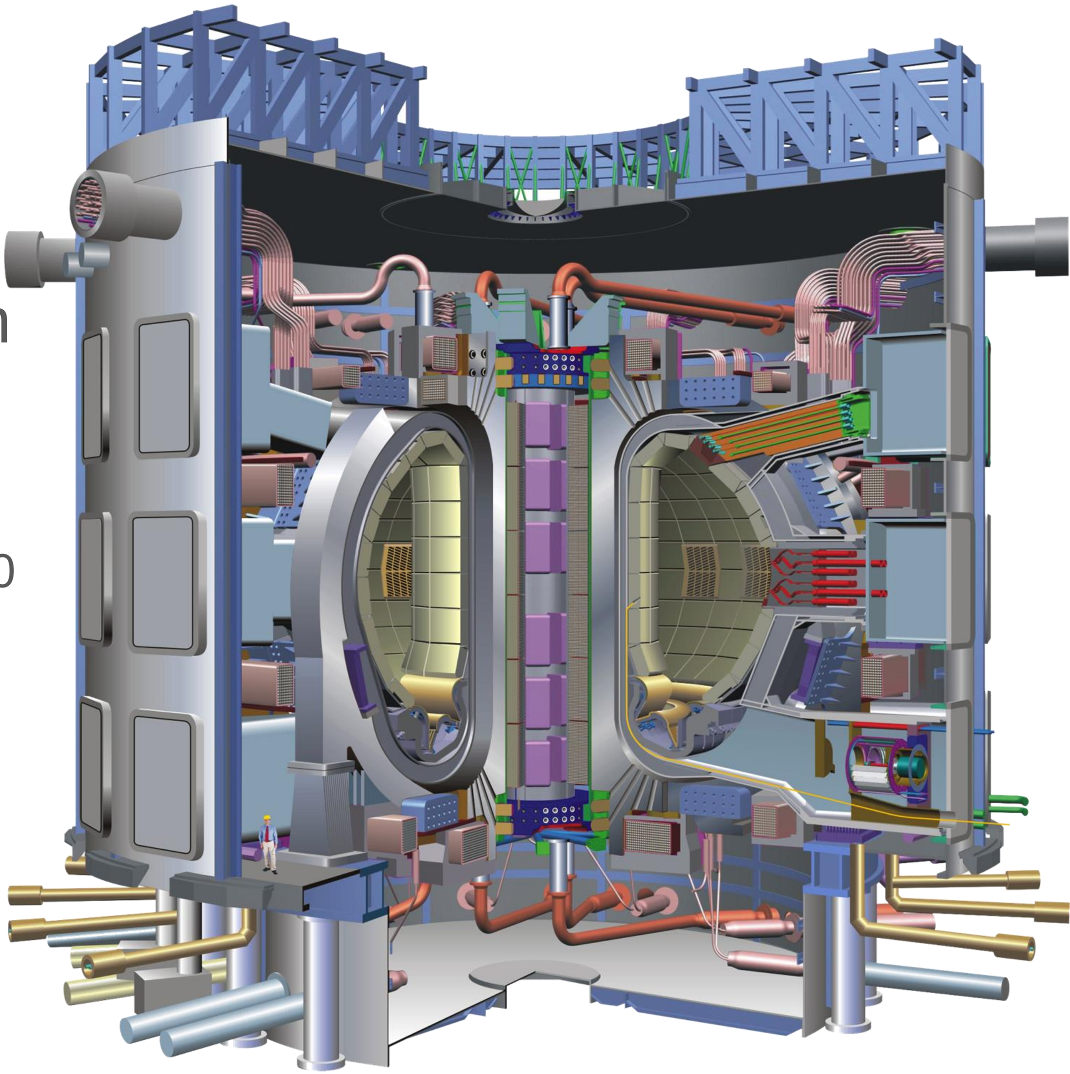
Ignition occurs when plasma temperature can be maintained against the energy losses solely by α-particle heating.

ITER | Mission

To prove scientific and technical viability of fusion

P = 500 MW, **D** = 300 s, **Q** = 10 – 20

To test integration of all technologies required for a fusion power plant



1st sector installation

May 2022

1st sector removal

July 2023

Dimensional non-conformities in the vacuum vessel sector and corrosion-induced cracks in thermal shield piping require repair works.

Fusion plasma parameters

JET as example

Core

T < 20 keV

n ~ 10^{20} m^{-3}

Edge

T < 200 eV

n ~ 10^{19} m^{-3}

Divertor

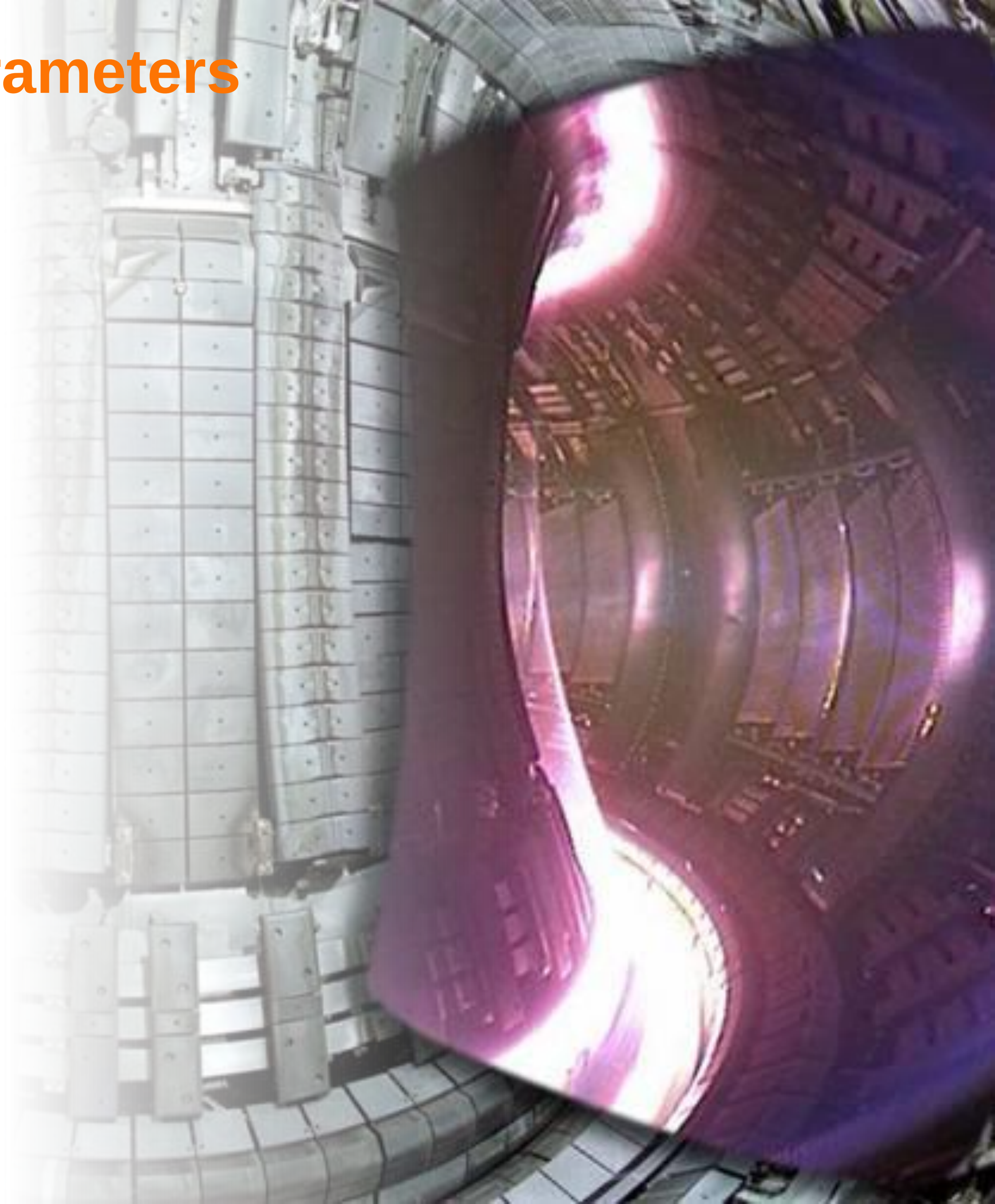
T < 50 eV

n > 10^{19} m^{-3}

q ~ 5 MW/m^2

ITER

q ~ 10 MW/m^2



How hostile is the environment?

High levels of **radiation** and **nuclear heating** near **first wall** and **divertor**,

e.g. ITER

- neutron fluxes ≤ 3×10^{8} n/m^{2}s,
- absorbed dose rate ≤ 2×10^{3} Gy/s,
- plasma radiation ≤ 500 kW/m^{2}
- Neutron heating ~ 1 MW/m^{3}
- pulse length of thousands of seconds

10 x higher than in present machines. (neutron fluxes, absorbed dose rate, plasma radiation)

Compared with 0 (neutron heating)

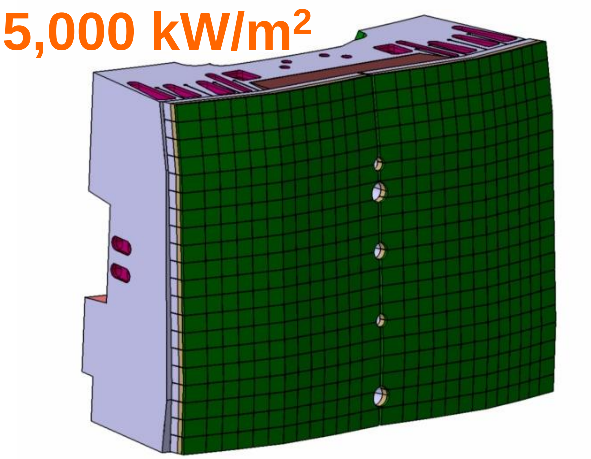
100 x higher than on present day machines (pulse length)

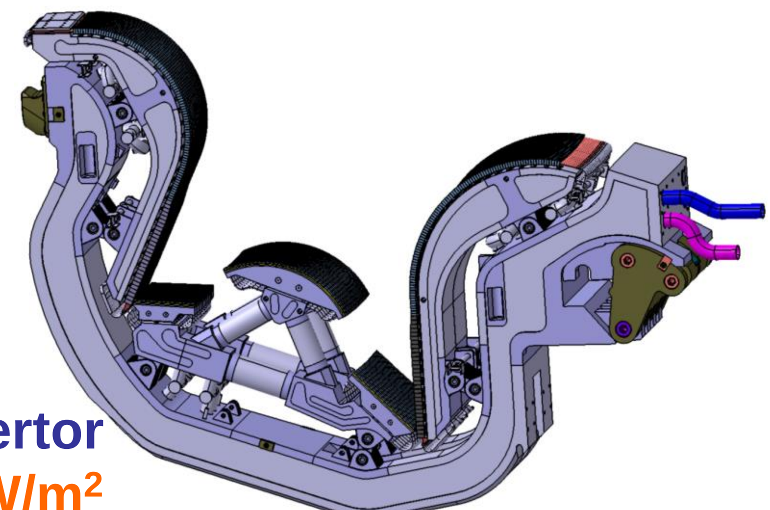
Enormous end-of-life **fluence** levels

ITER: more than **100000x higher** than present machines

Facing the Plasma => High heat fluxes

ITER Blanket
5,000 kW/m²



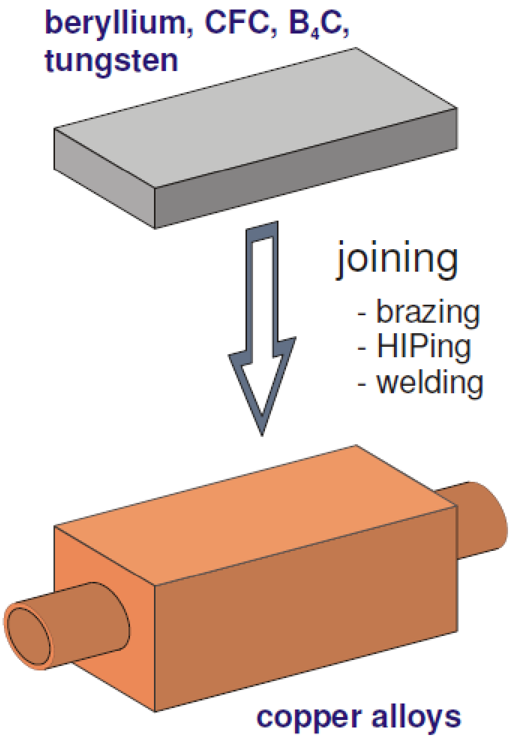


ITER Divertor
10,000 kW/m²

Required properties for wall materials

	CFC	W	Be	Other
High Thermal conductivity	/ Cu alloy	/ Cu alloy		
Good thermo-mechanical properties (response to thermal shocks)	X			
Low neutron activation (neutron flux > 10^{17} $m^2 s^{-1}$)	X		X	V-Ti alloys SiC as strucutral
Resistance to radiation damage (to avoid swelling and embrittlement)	X			
Low chemical affinity to hydrogen (no formation of volatile components)		X	X	
Low accumulation of hydrogen (Tritium inventory must not exceed 0.35 kg		X	X	
Reactivity with oxygen towards the formation of stable non-volatile oxides (gathering of oxygen impurities)			X	

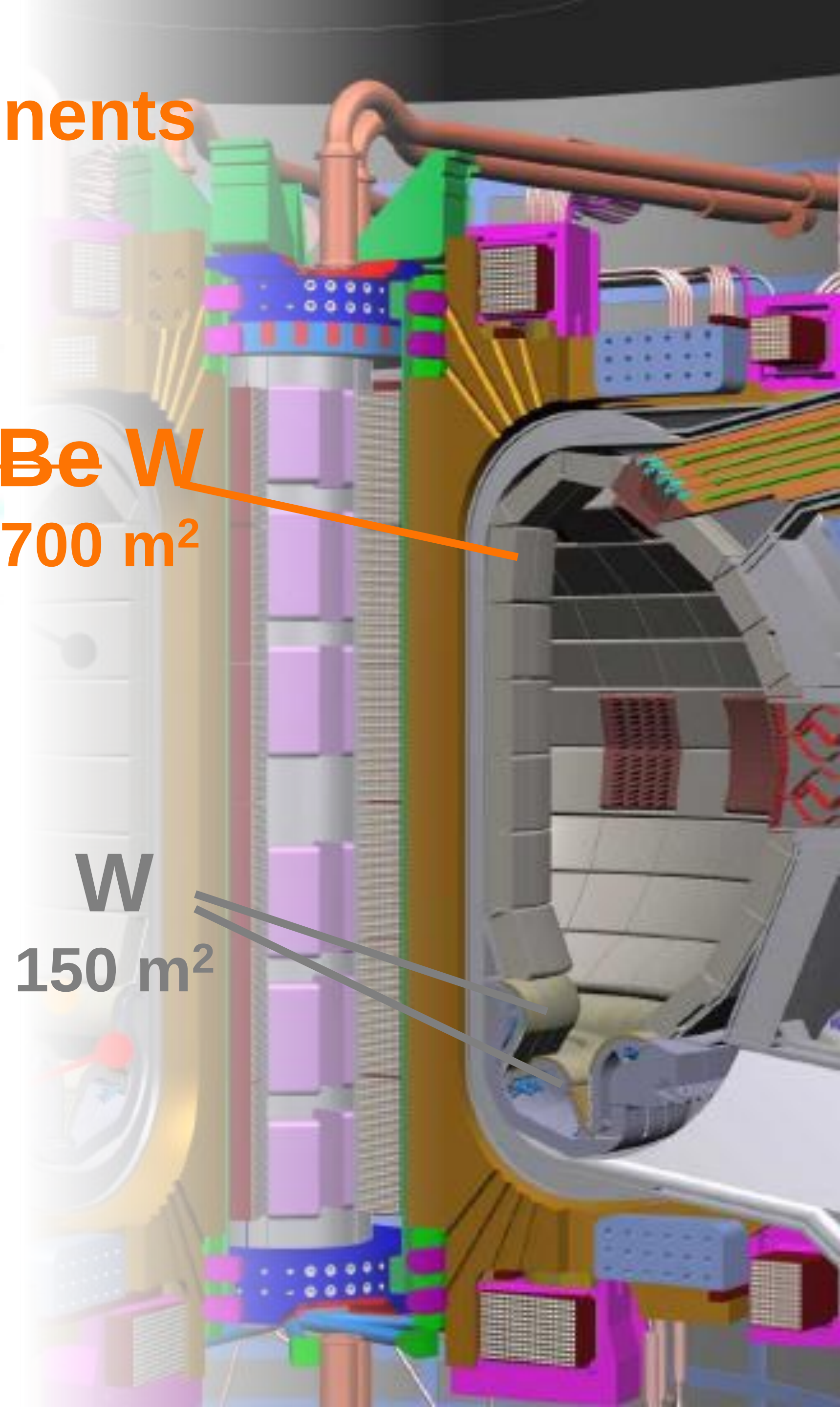
ITER Plasma Facing Components



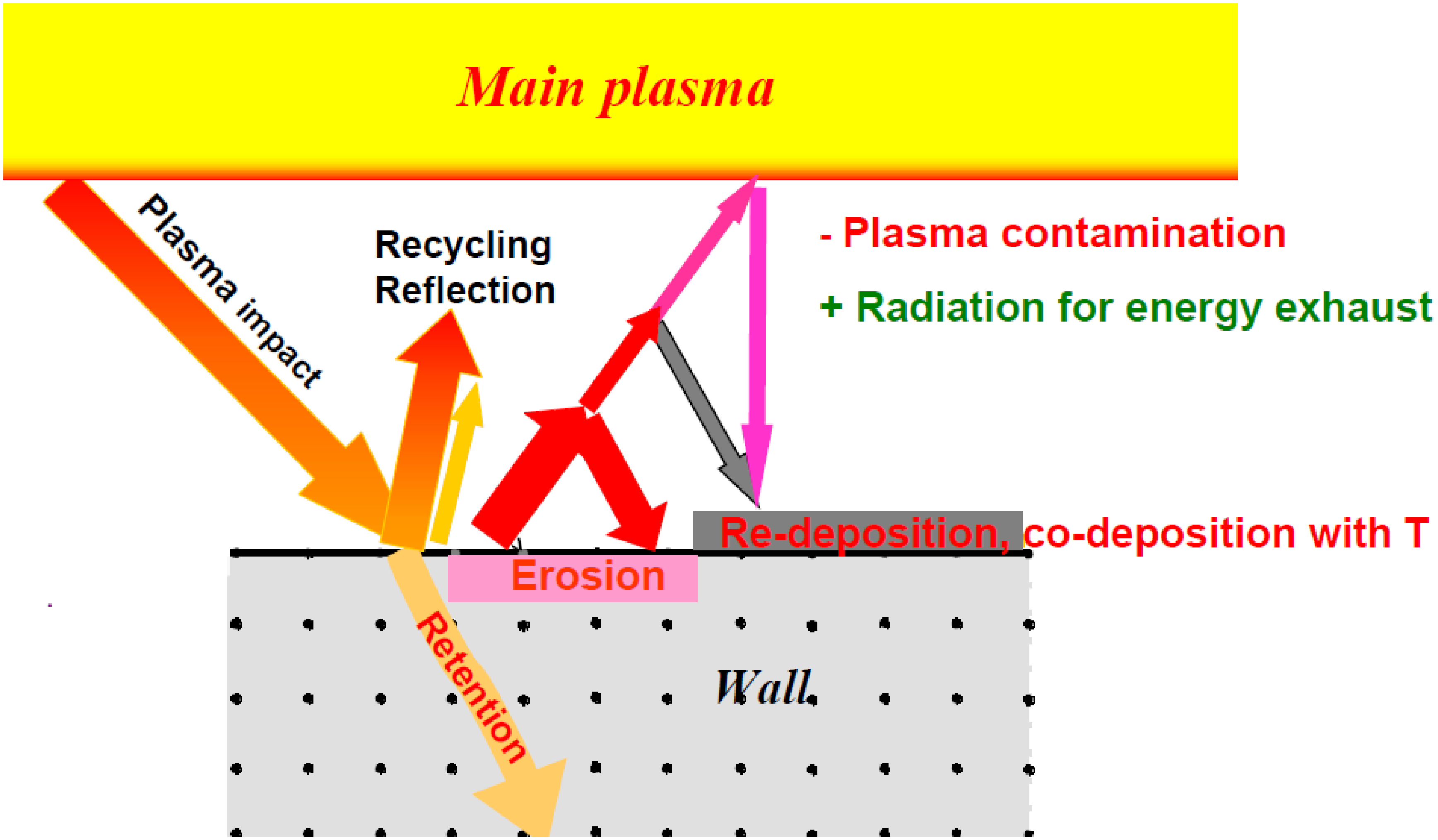
beryllium first wall mock-up

tungsten brush mock-up

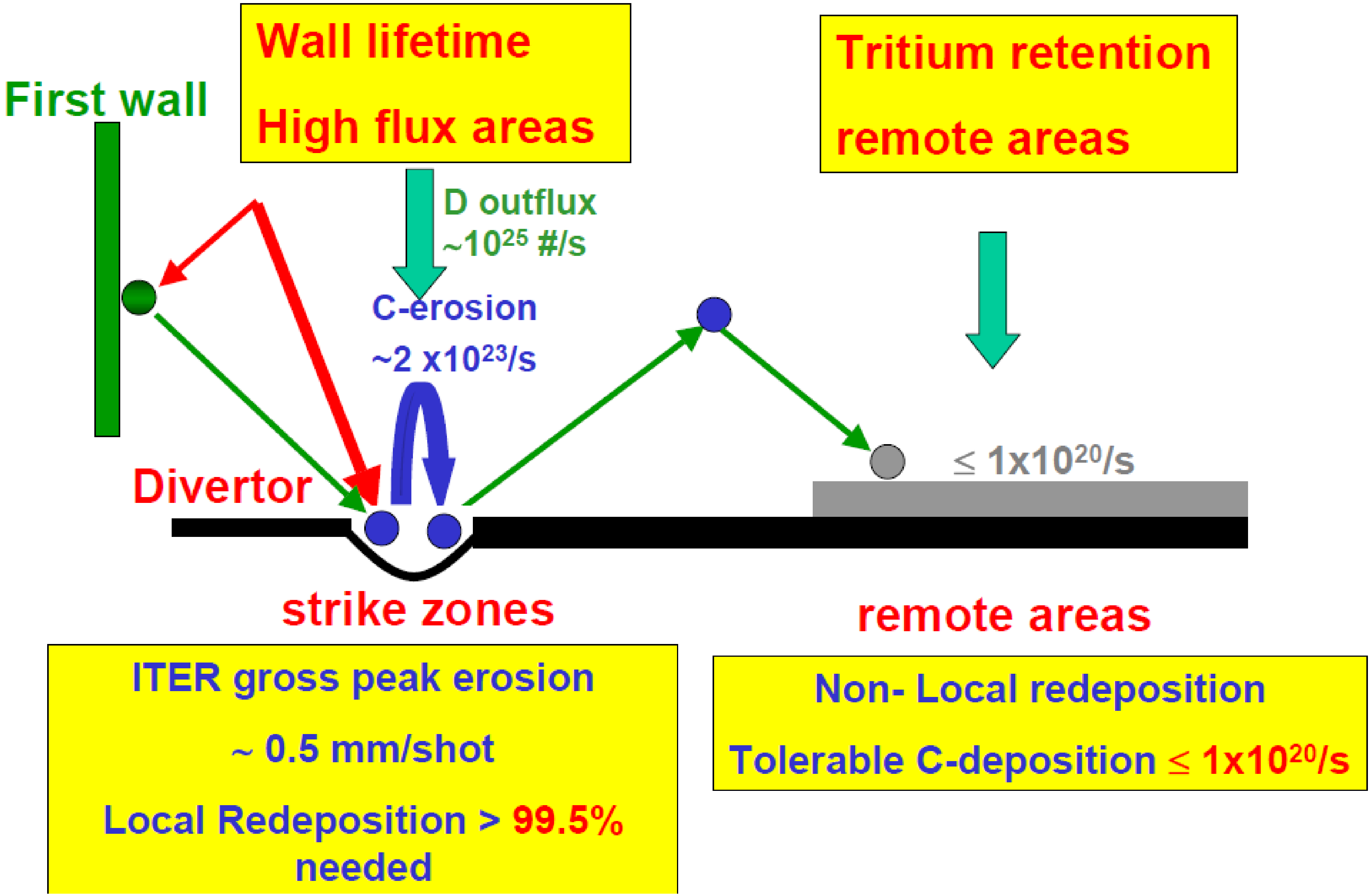
special purpose components



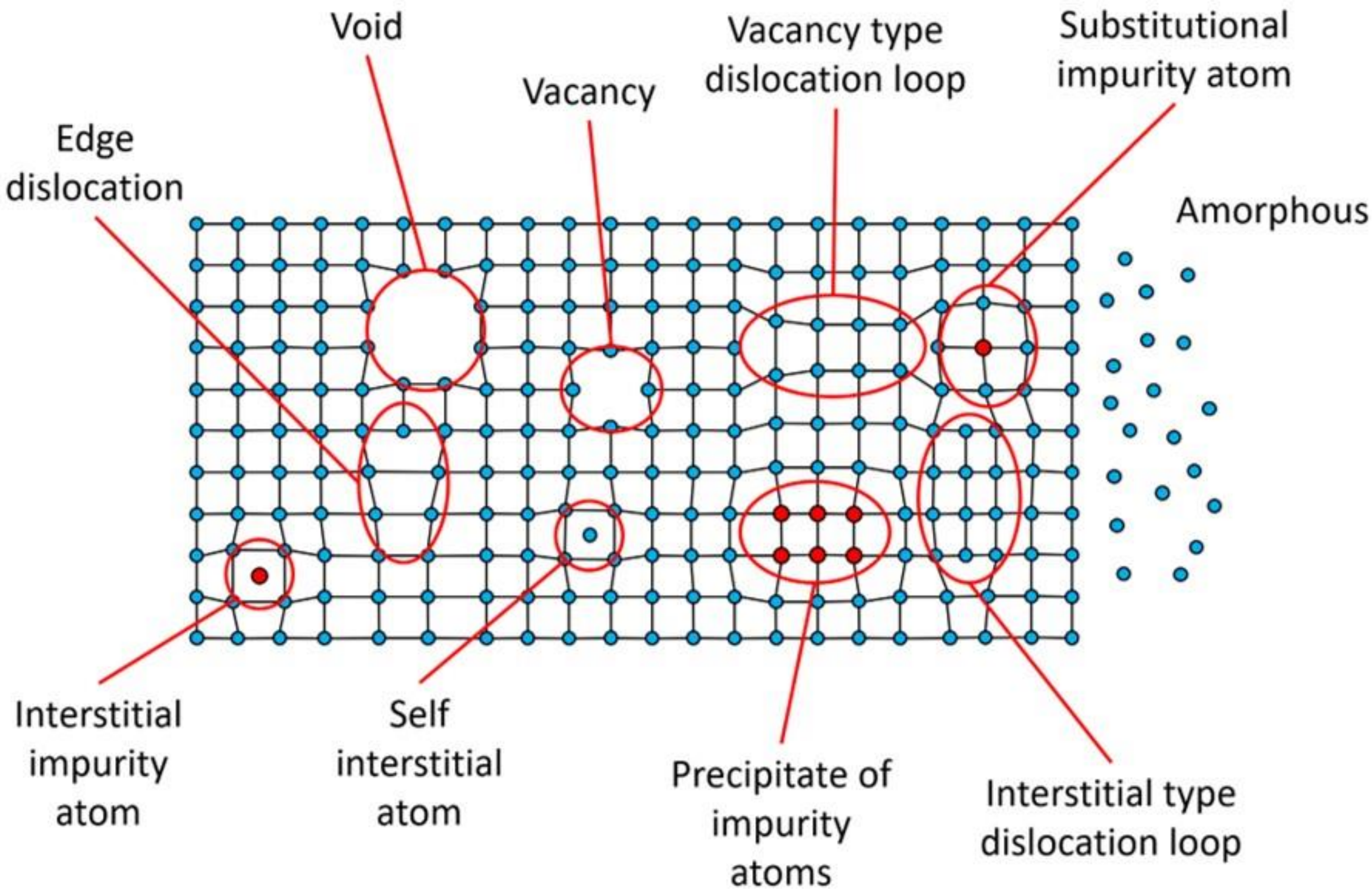
Basic Plasma-Wall Interaction Processes



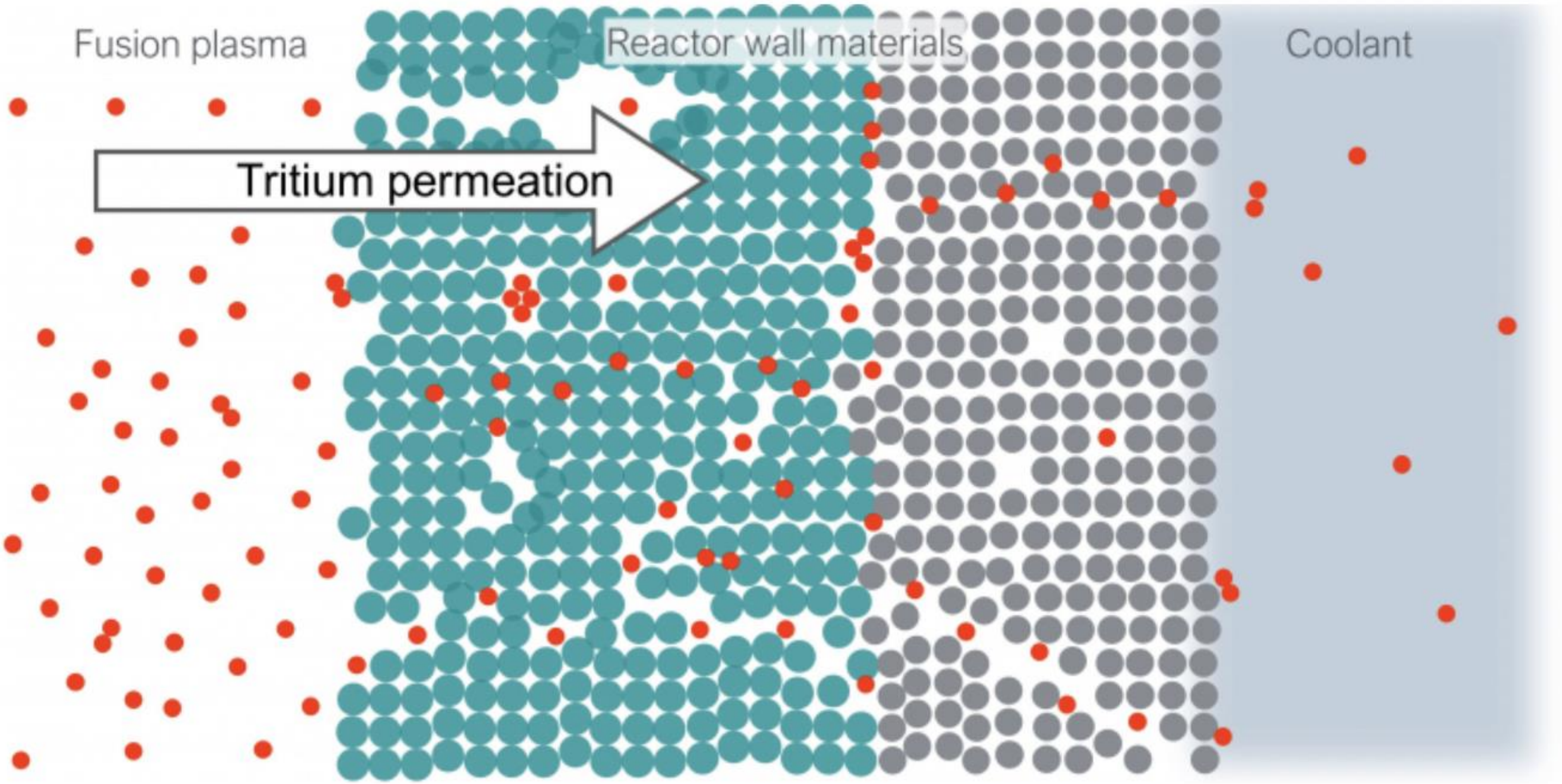
ITER example



Defects on the lattice structure that can change the material properties

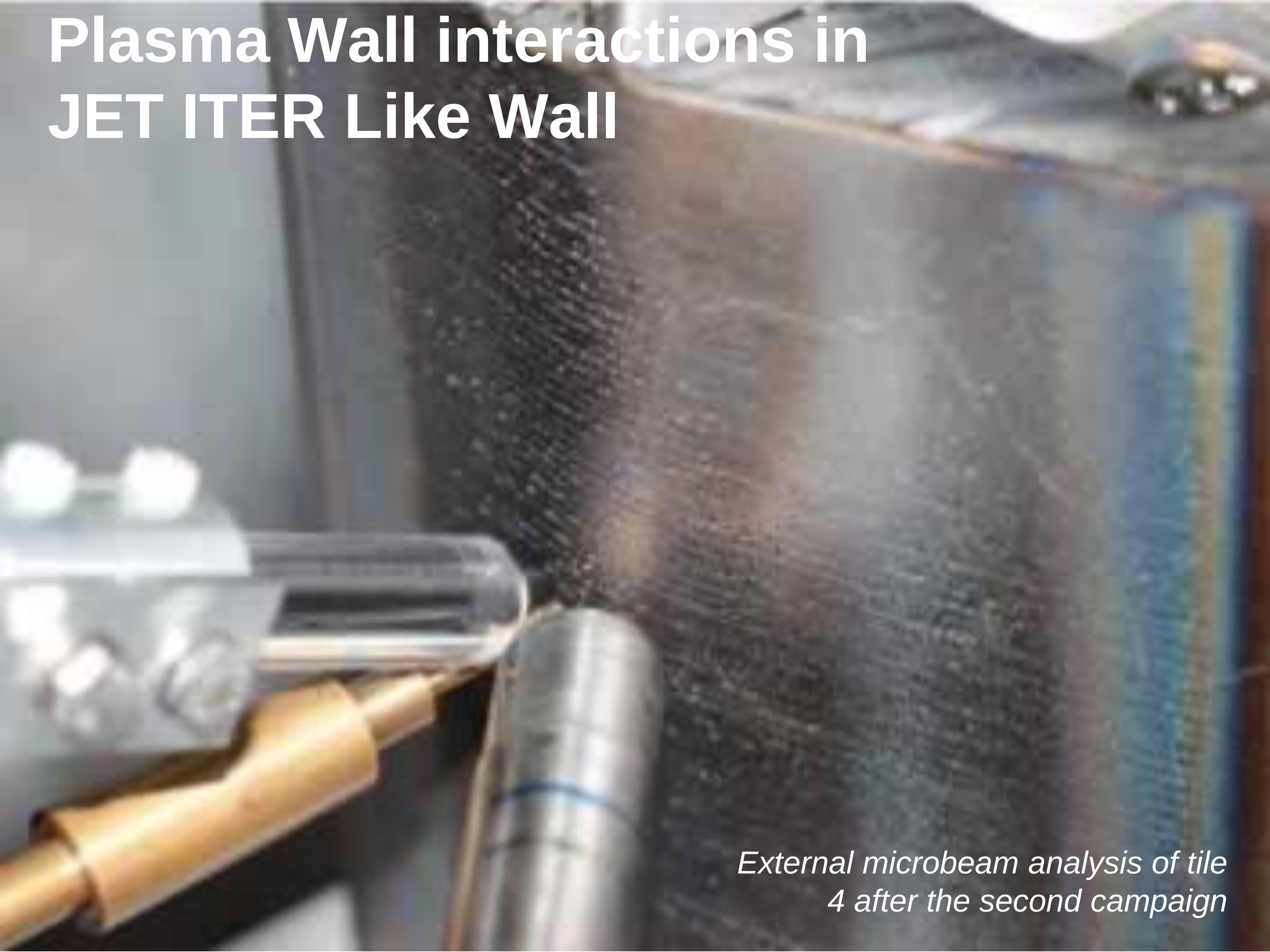


Neutrons produced from fusion reactions create atomic cavities in reactor's wall materials, in which tritium can get trapped or permeate through if not recycled back to the plasma



Credits: K. Heinola /IAEA)

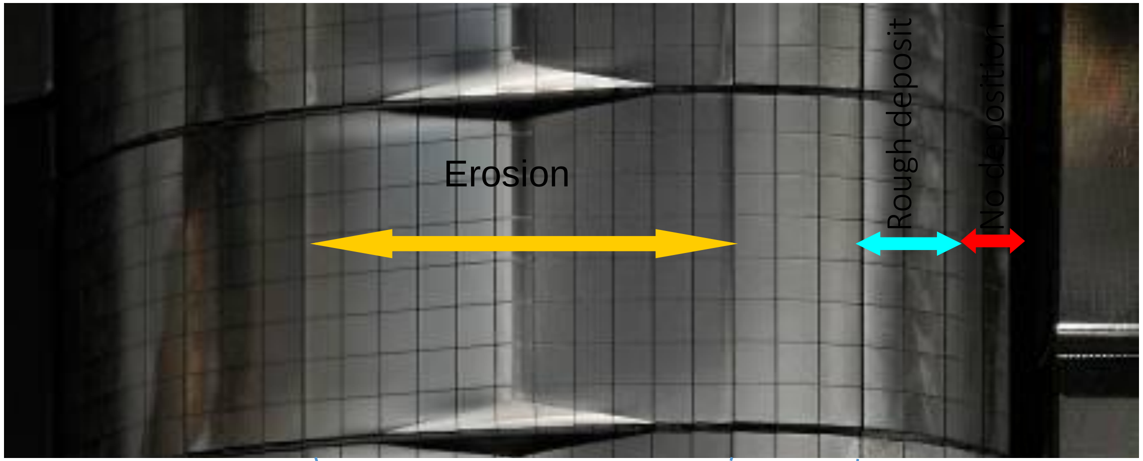
Plasma Wall interactions in JET ITER Like Wall

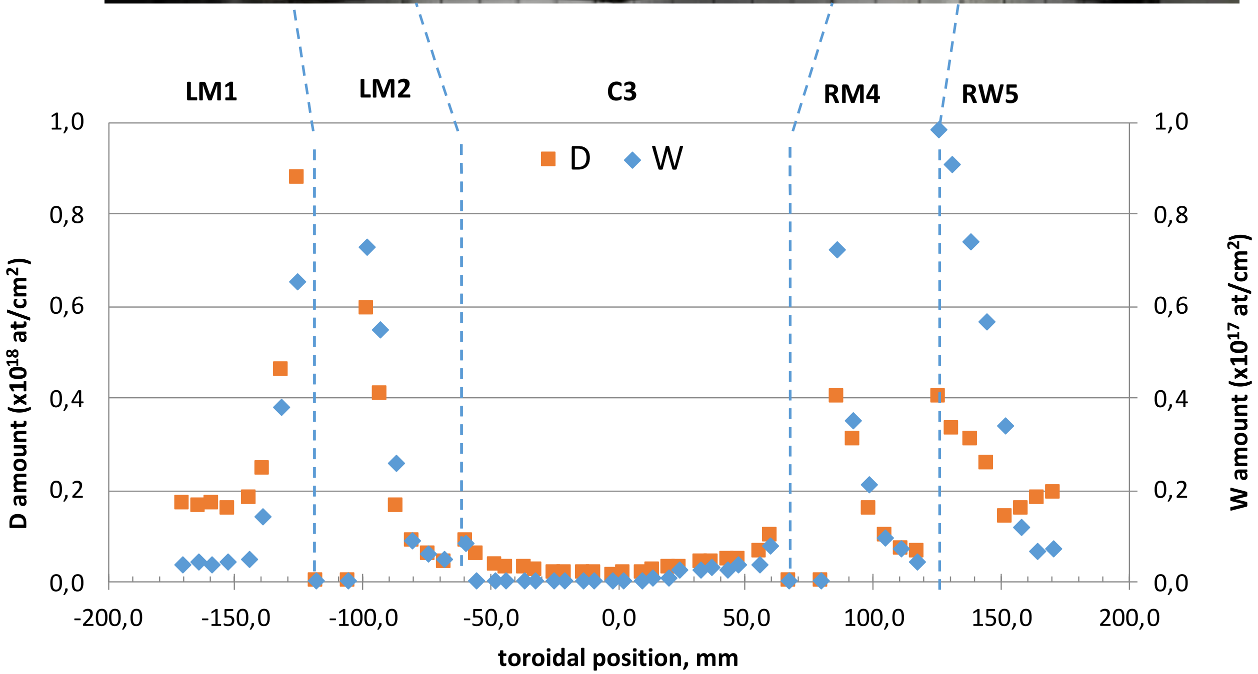


External microbeam analysis of tile 4 after the second campaign

Analysis of Inner Wall Guard Limiter tile

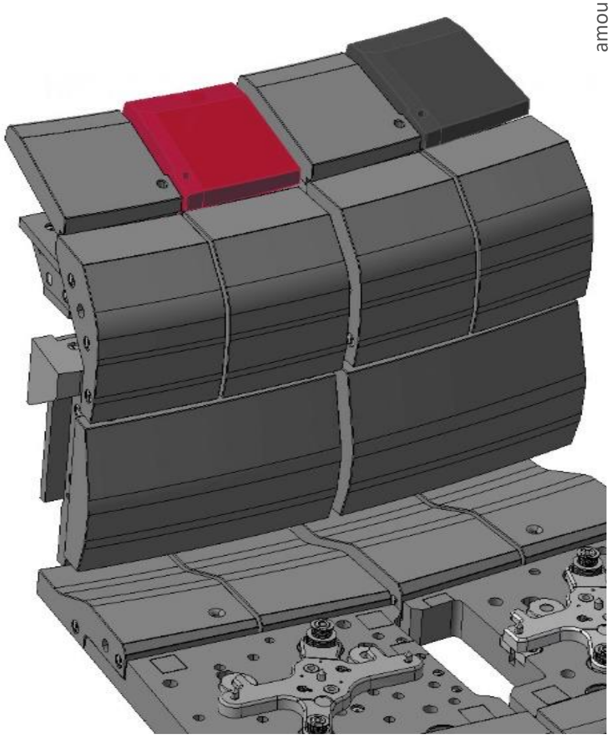
Most 2H trapping occurs on the junction of tile segments

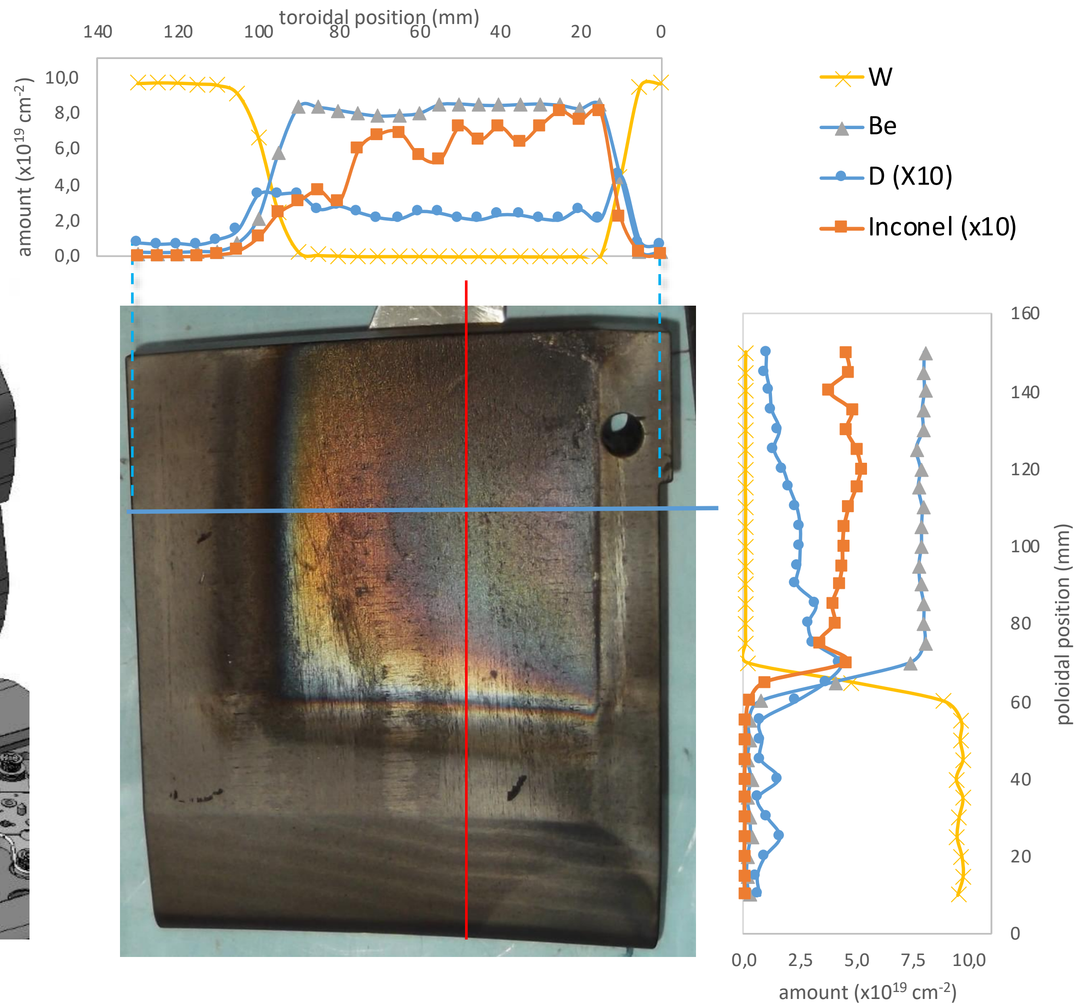




Deposits along toroidal and poloidal directions on JET Divertor tile

2H estimated during first ILW campaign is 18x less than in the carbon wall (2007-09)





A residual amount of dust (flakes) was measured during the campaigns

How to produce a plasma

Central solenoid creates an electric field.

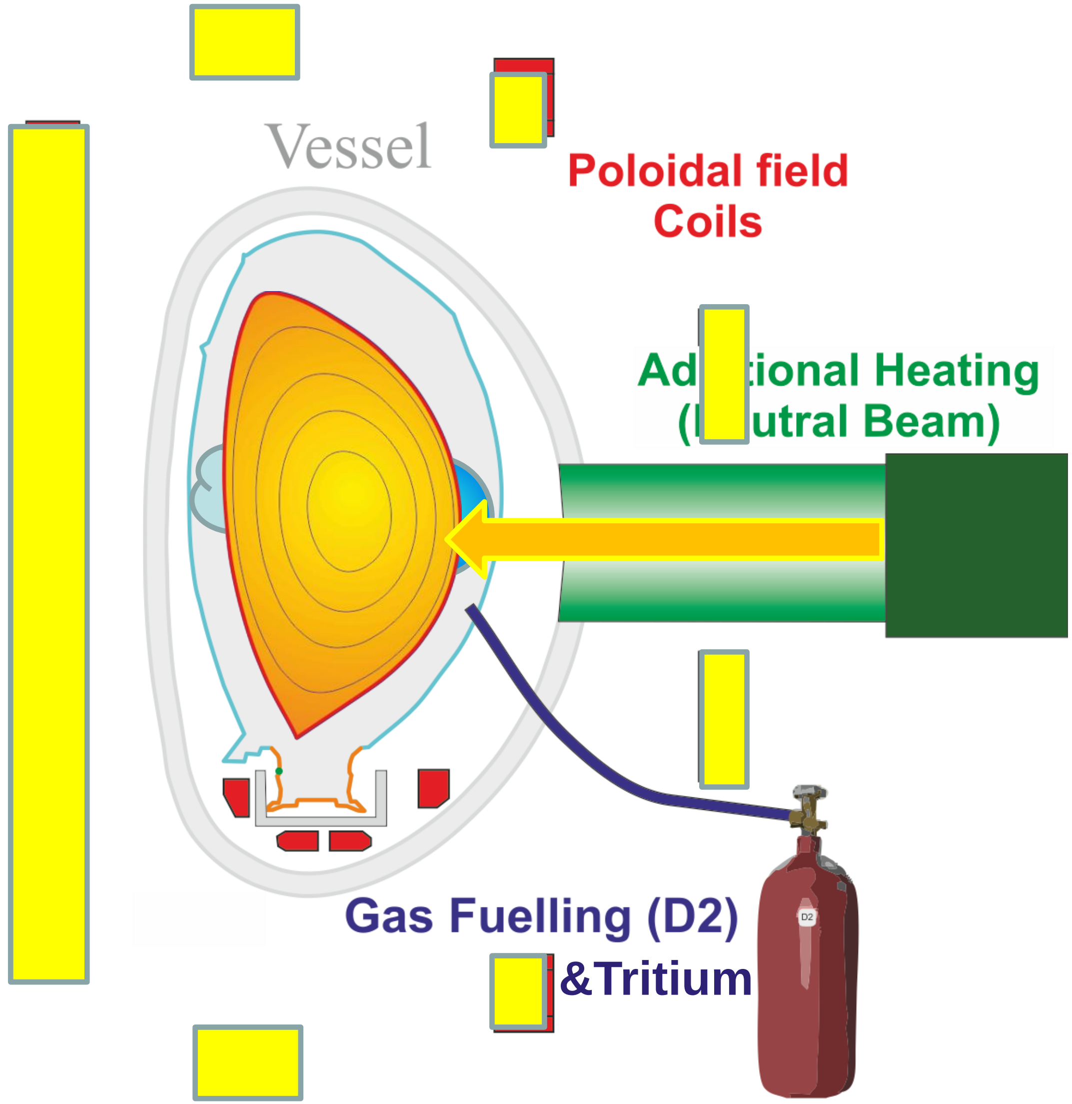
GAS is added and ionised → plasma

During plasma growth PF coils control plasma radial position.

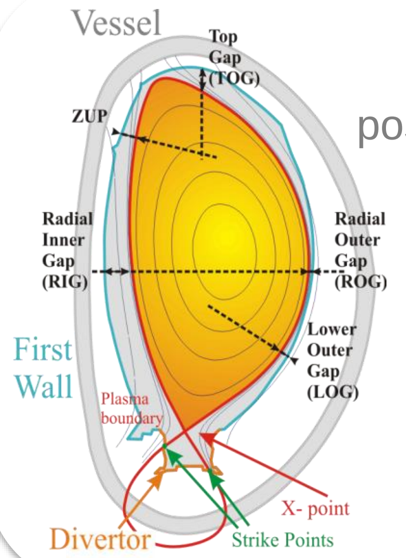
Other PF coils shape plasma into diverted shape

Additional heating heats plasma

Conditions for fusion are reached!



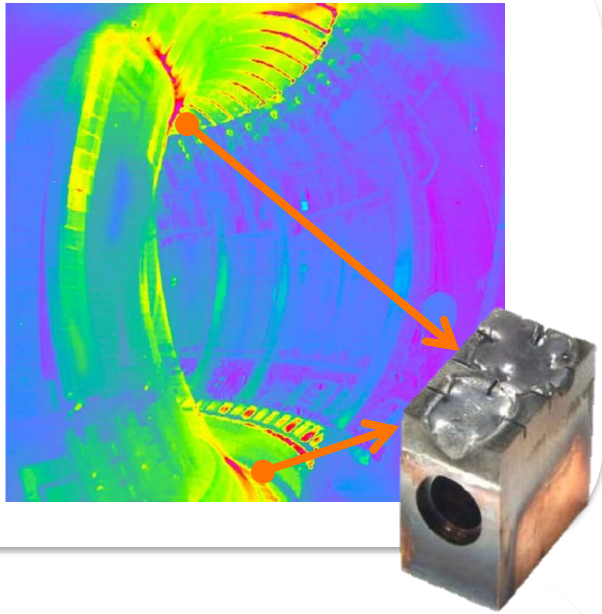
Control in fusion plasmas

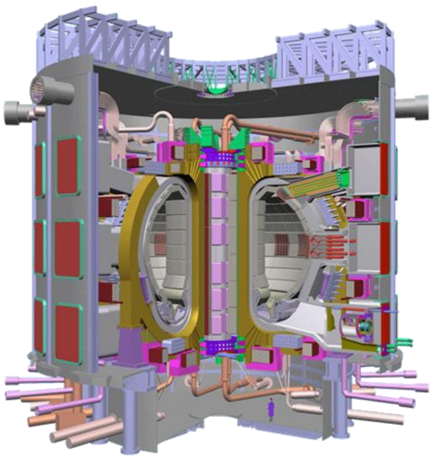


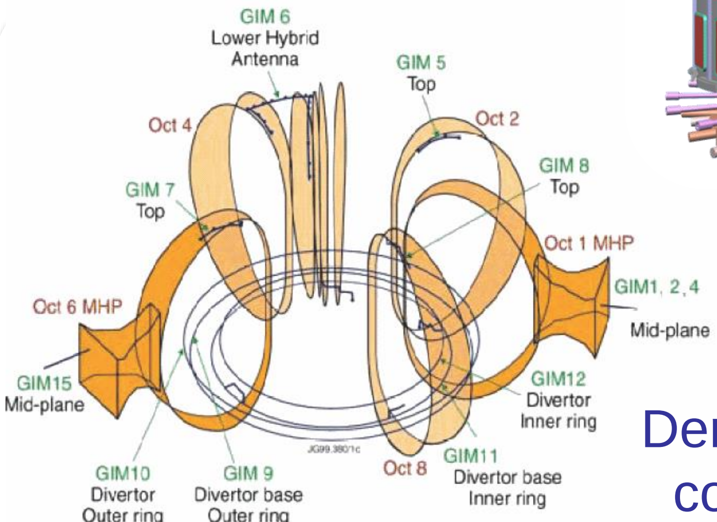
Magnetic control

position, shape & vertical stabilization

Wall protection

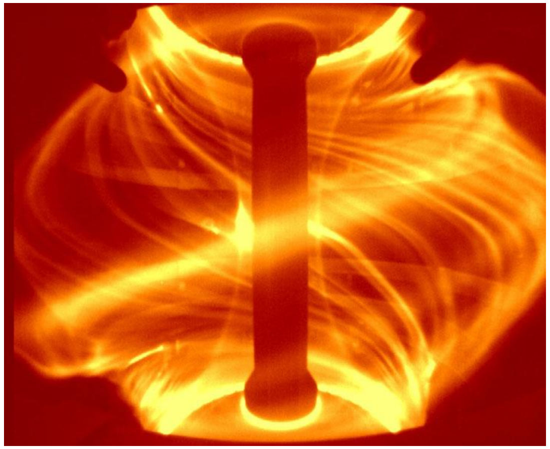




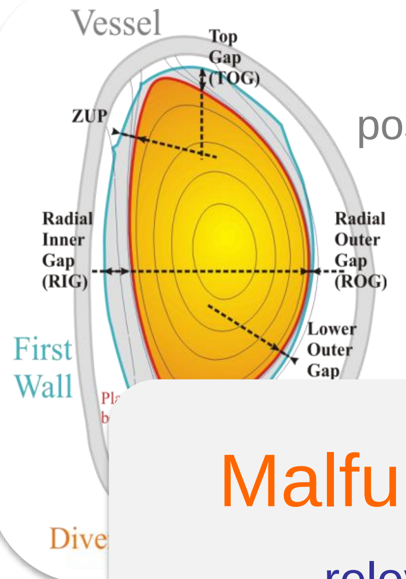


Density control

Instabilities mitigation & control

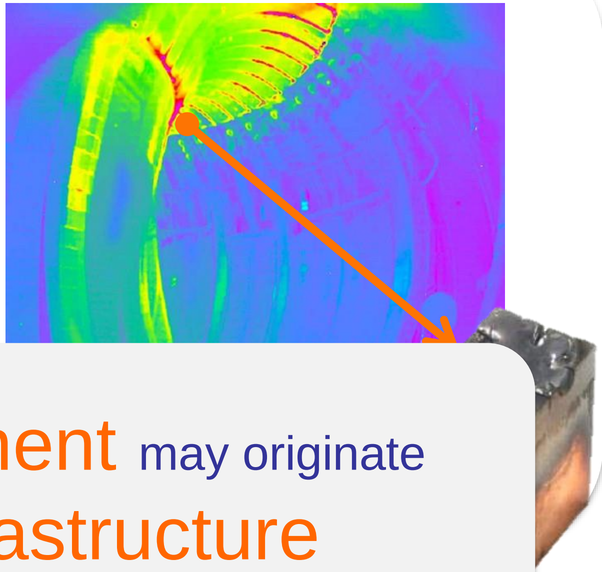


Control in fusion plasmas is critical for safe operation and to achieve high performance

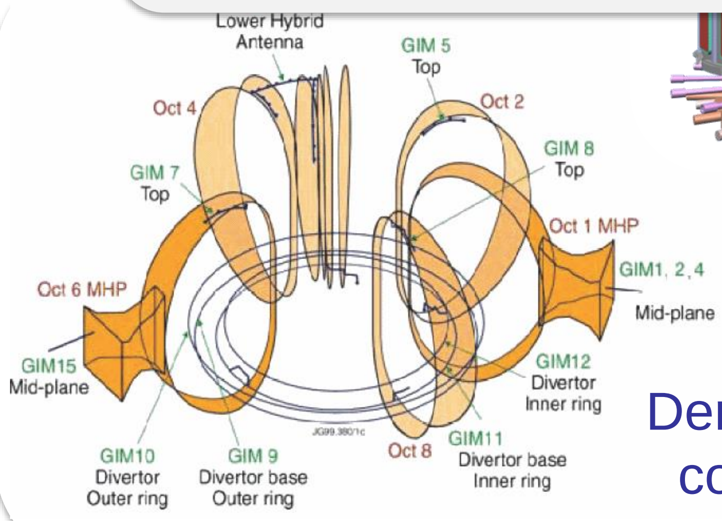


Magnetic control
position, shape & vertical stabilization

Wall protection

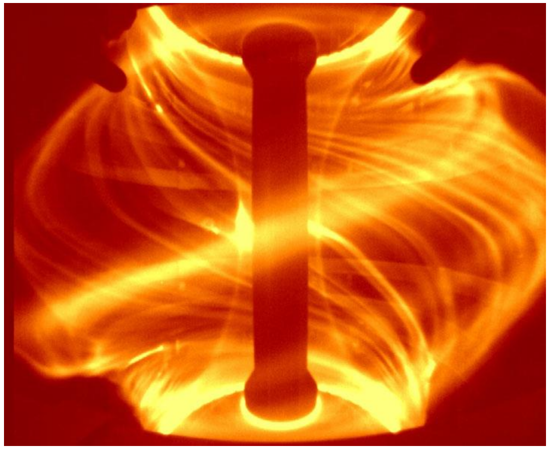


Malfunction of a single component may originate relevant damage to entire infrastructure



Density control

Instabilities mitigation & control



Example | Vertical Stabilisation

Problem
Elongated Plasmas are unstable vertically.
Plasma moves vertically and disrupts in few ms

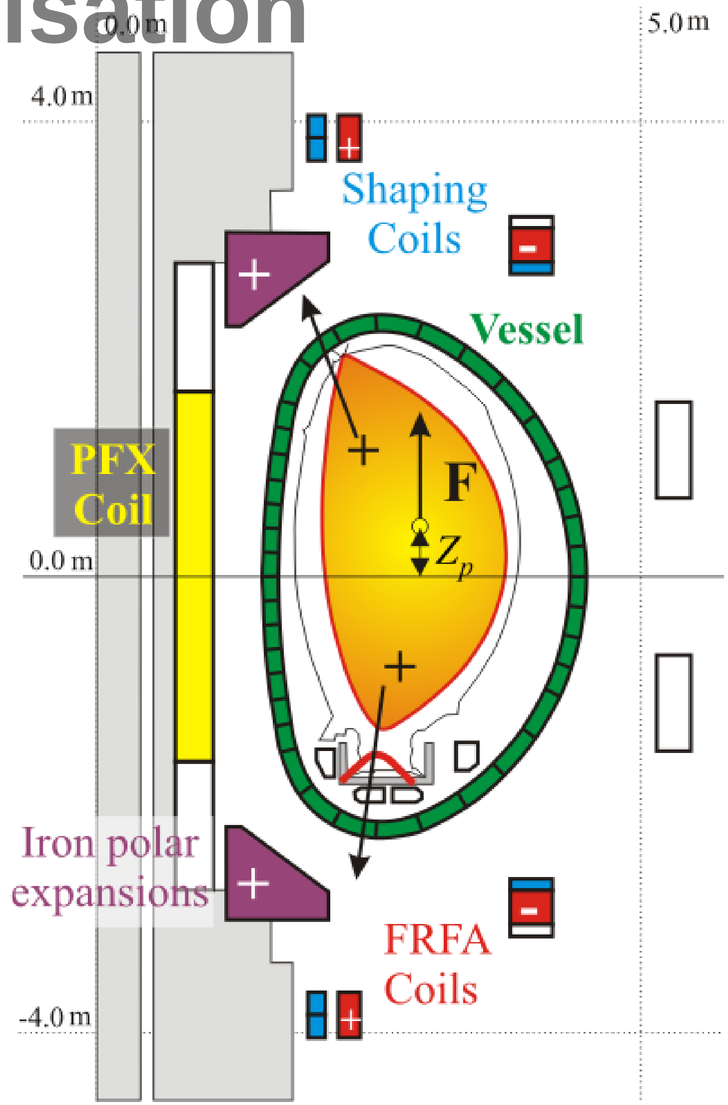
Actuator | **PF Magnets**
Combination of coil currents that pushes plasma vertically

Diagnostic | **Magnetic Diagnostic**
@JET: Combination of 192 magnetic probes

Controller
Fast | Control loop latency of ~300 µs!

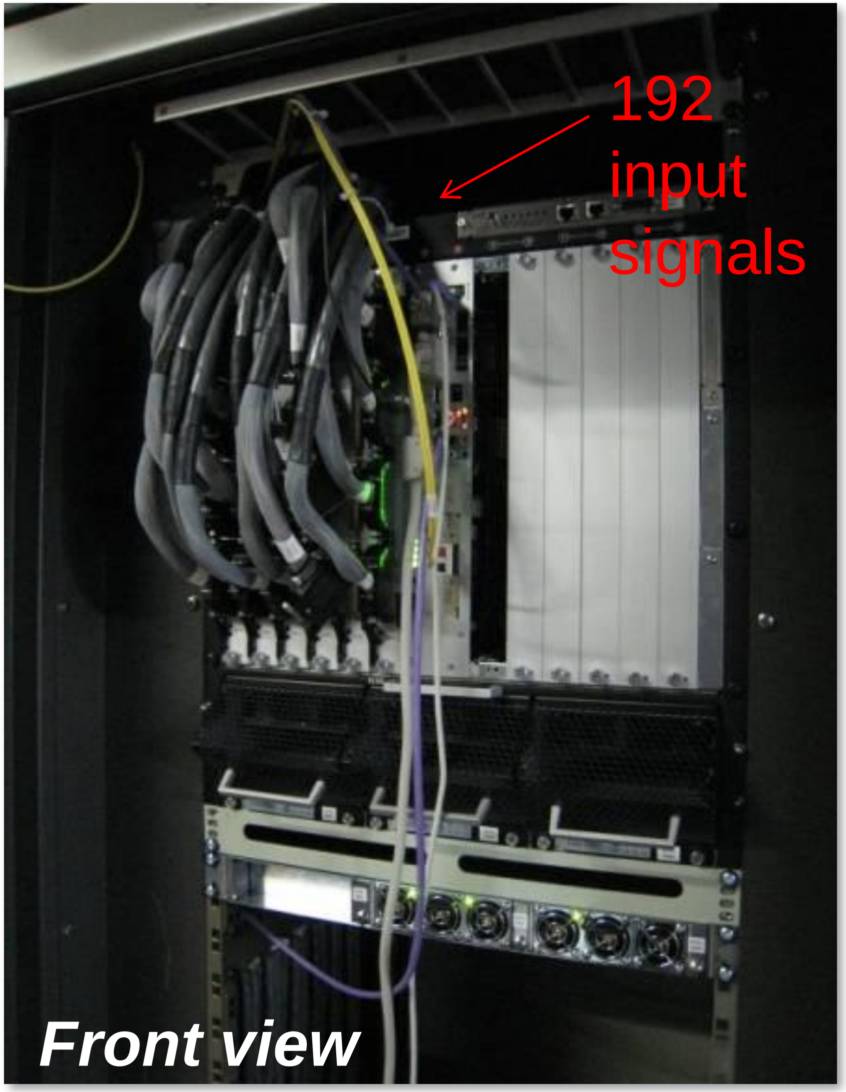
Adaptative | cope with continuously varying instability times

Robust | able to handle large disturbances: ELMs



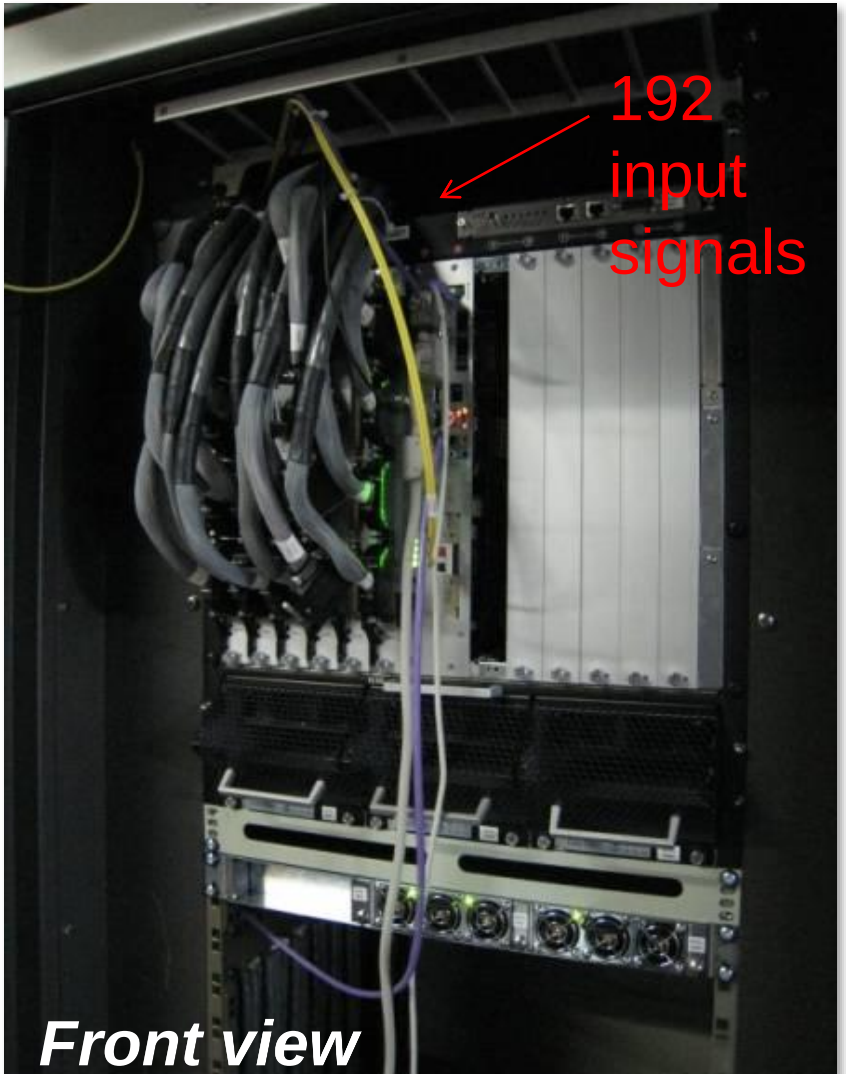
MIMO system designed to make plasma vertically stable while other controllers control plasma position and shape.

JET Vertical Stabilization system



JET Vertical Stabilization system

Example of solution



- 192 signals acquired by ADCs and transferred at each cycle
- 50 μs control loop cycle time with jitter < 1 μs
- Always in real-time (24 hours per day)
    - 1.728 x 10^9 50 μs cycles/day
    - Crucial for ITER very long pulses

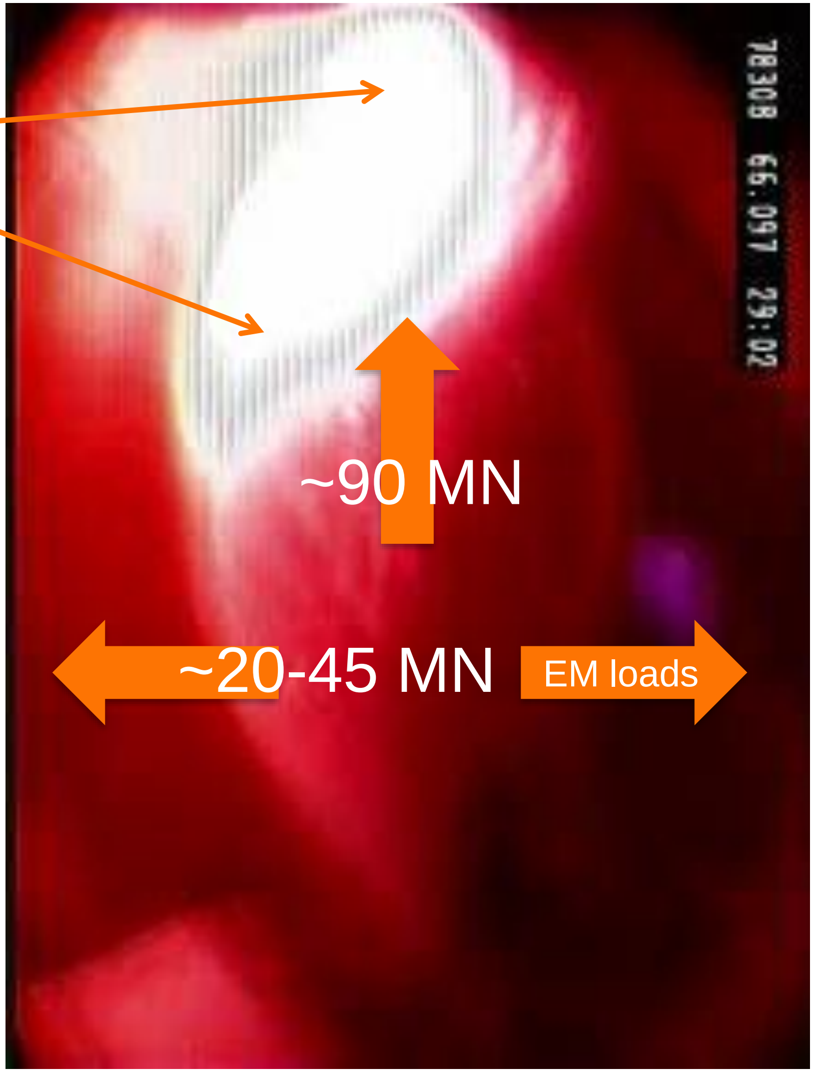
When something fails…

on position control

On ITER similar events will cause huge thermal loads on Plasma Facing Components

30-60 MJ/m^2 for ~0.1s

PFCs cannot be designed to sustain such (repetitive) thermal loads



Will require a far higher level of availability and reliability than previous/existing tokamaks

Steady-state operation calls for High Availability

99.999% up-time (reference for HA), correspond to
~5 minutes of down-time per year

Risk reduction

Resilience to failure

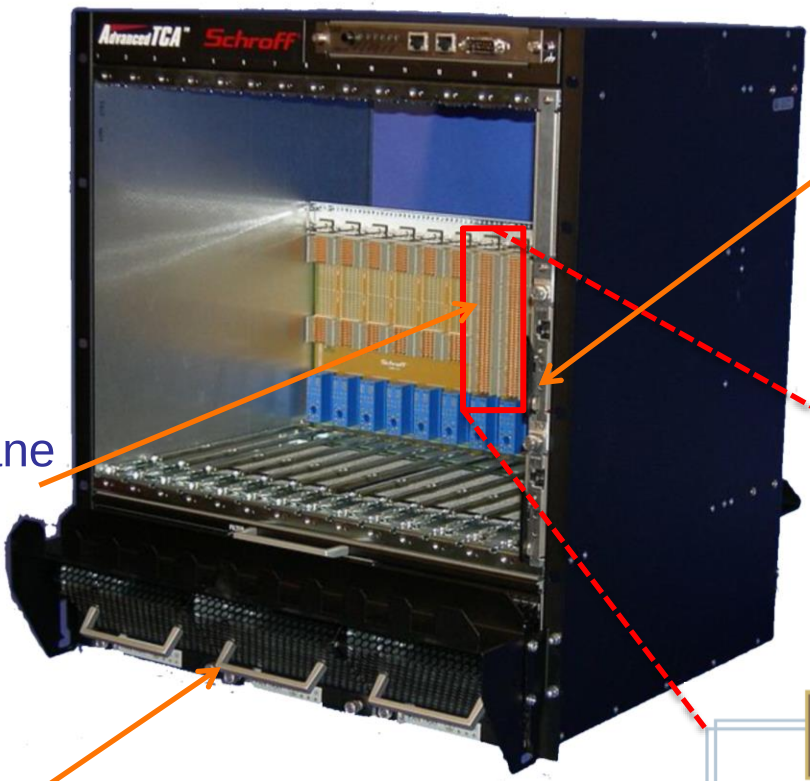
- Sensors - backup set
- Redundant acquisition channels
- Fault detection & mitigation

Requires the use of robust instrumentation standards designed for high availability!

Robustness in the good old days

NASA - Saturn V Apollo Shake Test

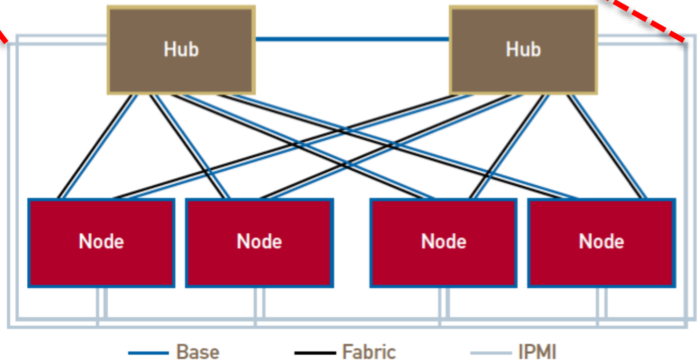
ATCA standard is already designed for high availability & high throughput



Redundant Shelf managers

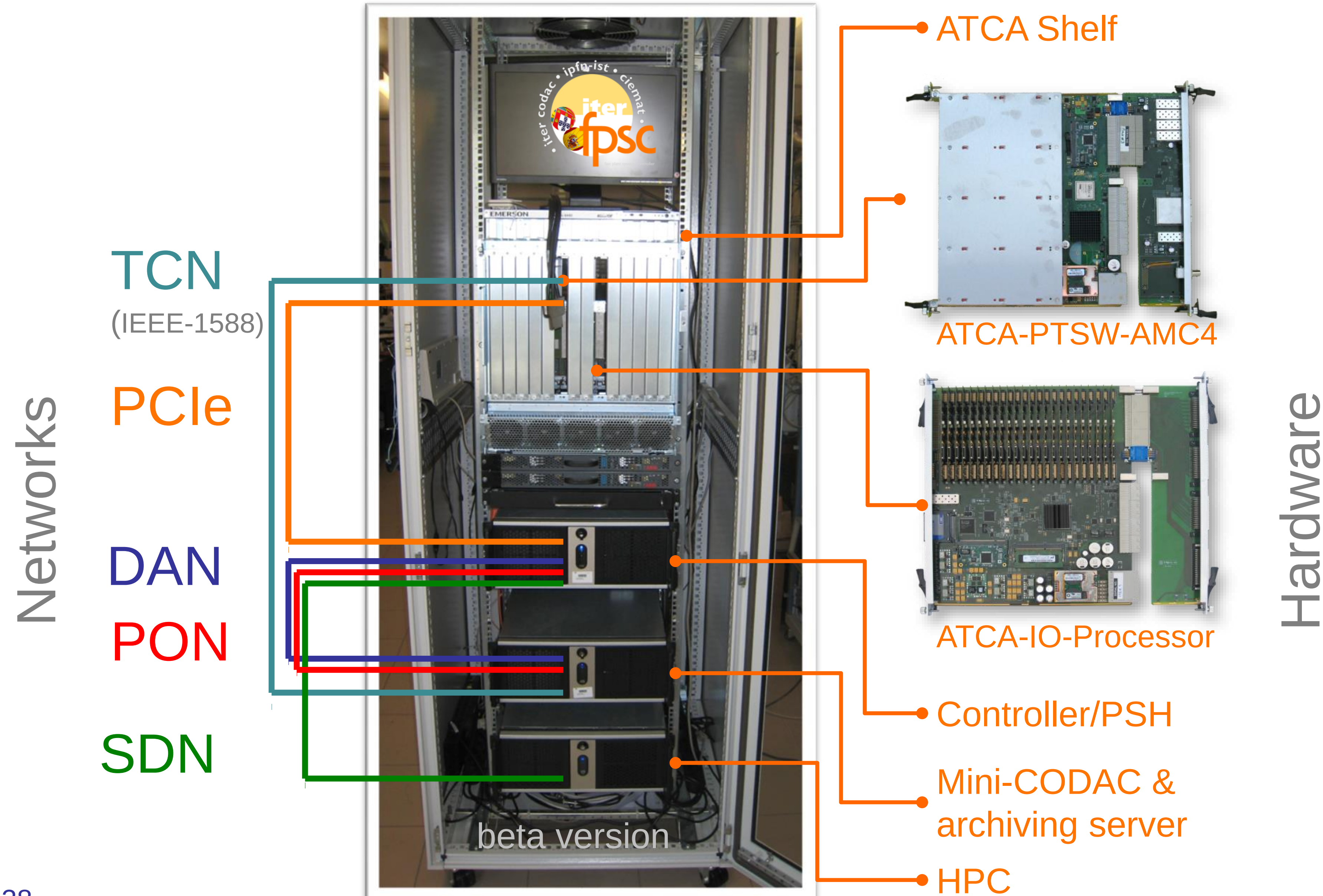
Redundant backplane interconnect

Redundant power supplies
Redundant fans



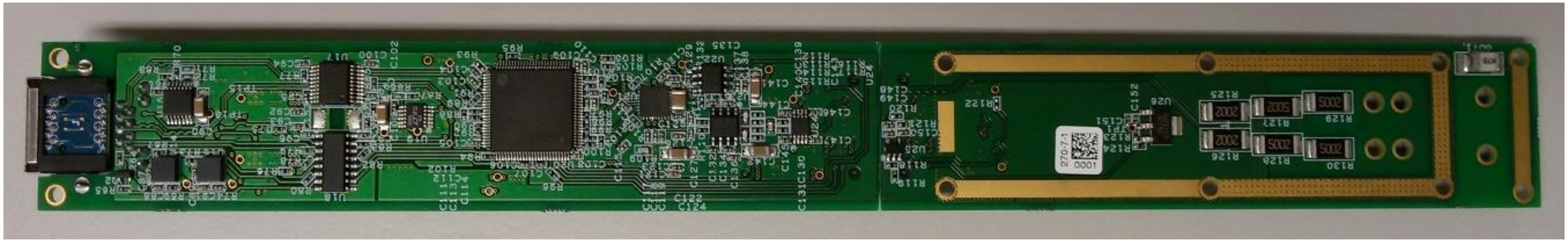
Redundant controller

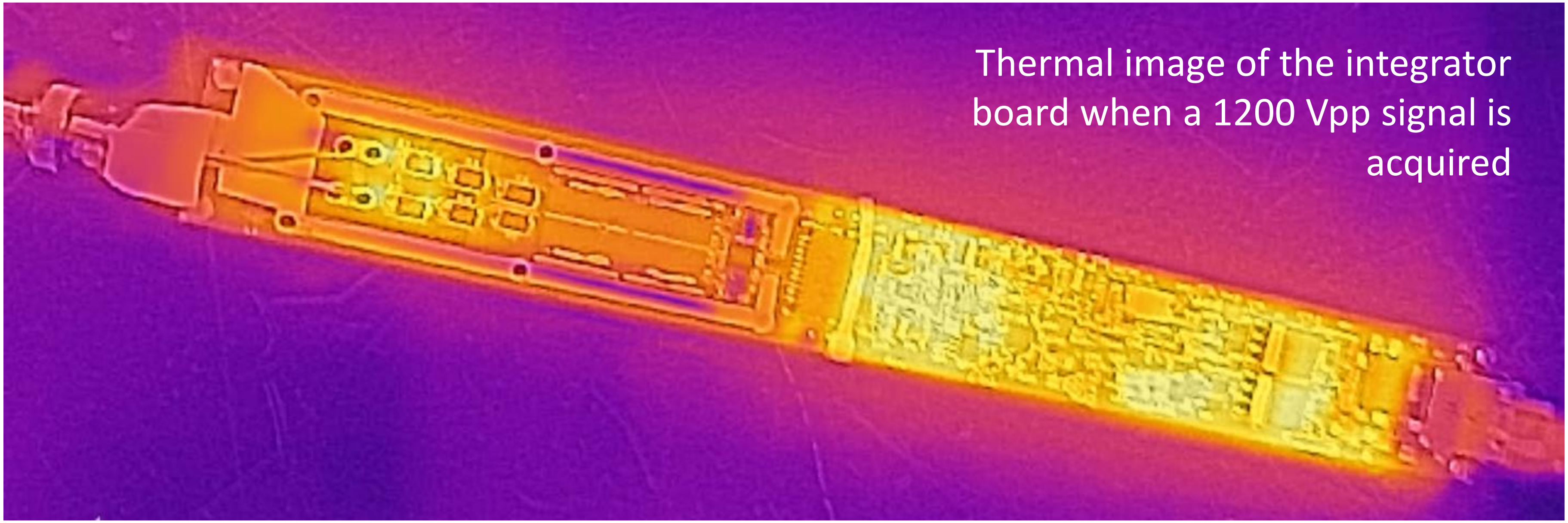
ITER prototype Fast Plant System Controller



Qualification tests of ITER low drift integrators prototype

Working for an industrial grade solution





Thermal image of the integrator board when a 1200 Vpp signal is acquired

Real-time data processing | JET Gamma ray spectroscopy

Intelligent modules (with FPGAs)

Pulse height analyzer; Pile-up rejection; and Pulse shape discriminator

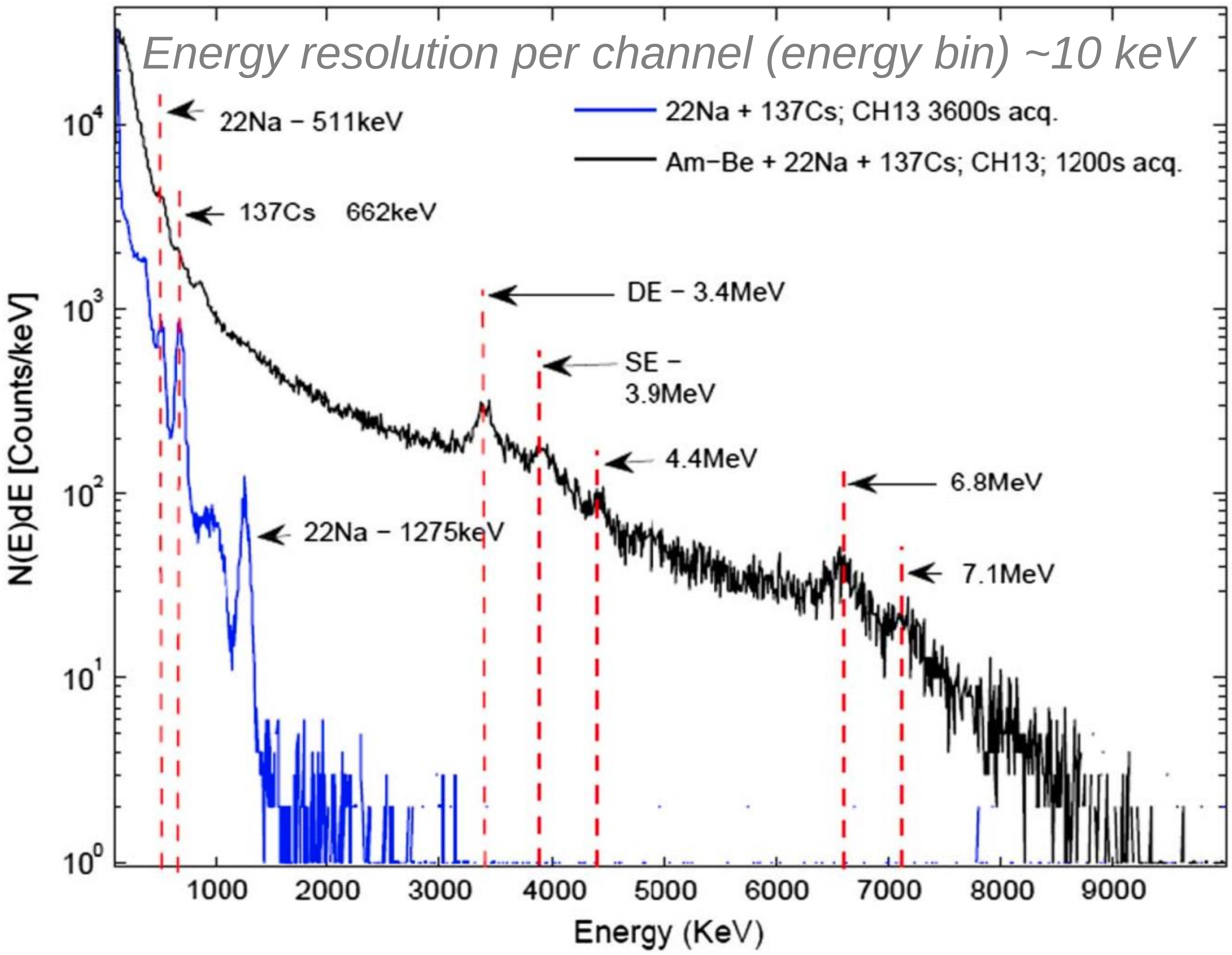
Digitizer modules centered around an FPGA:

- •controls ADCs and local memory,
- •provides the gigabit interconnections
- •runs DSP algorithms
- •Concurrent algorithms can be implemented on the FPGA and each one can be parallelized (e.g. 4 pipes at 250 MSPS ≡ 1 GSPS with reduced ENOB ~10-bit)

- • Data transfer rate of up to 800 Mbyte/s over x4 PCI Express to the host processor.
- • Choice of resolution
  - •250 MSPS @ 13-bit,
  - •400 MSPS @ 14-bit,
  - •500 MSPS @ 12-bit
- •Maximum pulse rate of 5 Mpulse/s;

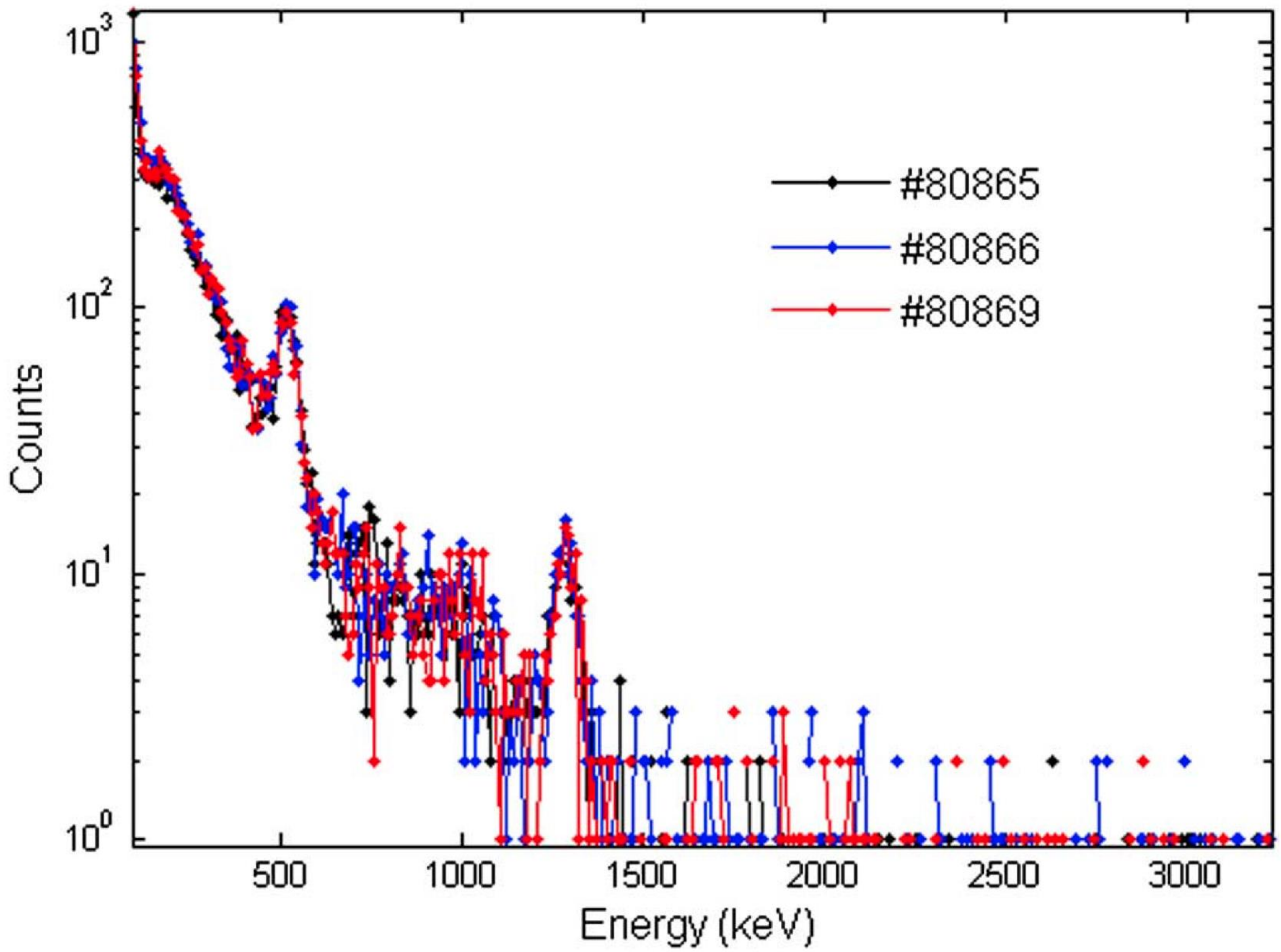
Data reduction rate of ~80% attainable with pulse height analysis

Spectra built with real time processed data inside FPGA using ^{22}Na, ^{137}Cs and ^{241}Am-Be radioactive sources



A. M. Fernandes *et al.*, *IEEE Transactions on Nuclear Science*, vol. 61, no. 3, June 2014, doi: 10.1109/TNS.2014.2312212

Spectra obtained during JET C28 campaign **(channel 11)**



CsI(Tl) scintillator coupled to a photodiode detector used to measure the gamma-rays and the hard X-rays in a range 200 keV - 6 MeV

ITER Radial Neutron Camera

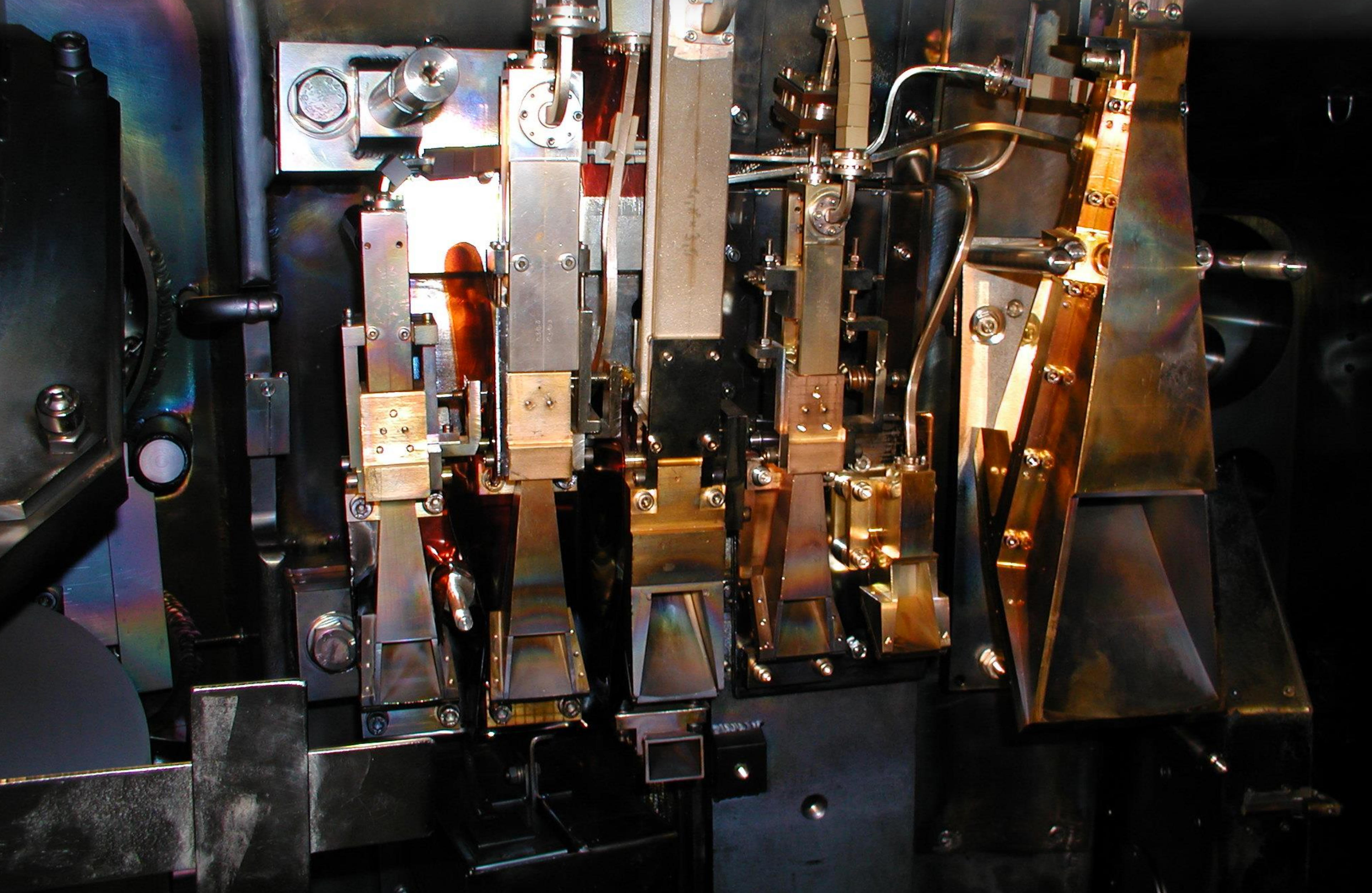
Design, development, and testing of a dedicated data acquisition prototype

including hardware, firmware and software to acquire, process, and store in real time the neutron and gamma pulses

Nuno Cruz et al., IEEE TRANS.NUCL. SCI., VOL. 66, NO. 7, JULY 2019
and several other articles by IPFN team

Why are diagnostics essential?

Microwave Reflectometry is a crucial diagnostic because it is a non intrusive remote sensor that enables probing deep into the plasma



Basic principles of reflectometry

Signal sent to plasma is reflected at the cutoff position

$$s_e(t) = A \cos(\omega t)$$

$$s_r(t) = A' \cos(\omega t + \phi)$$

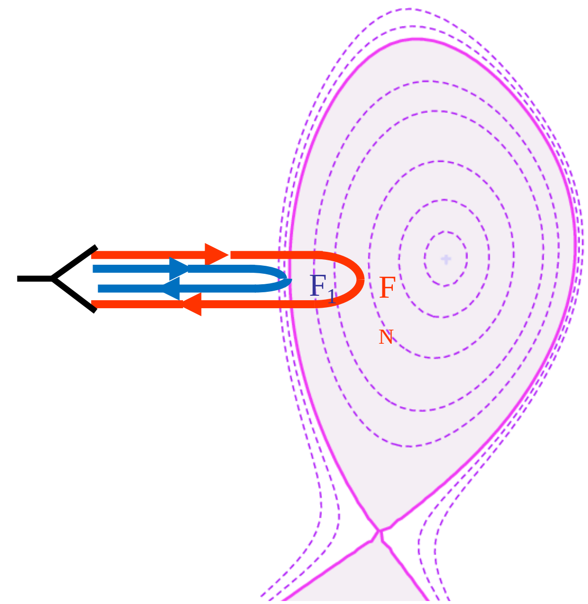
Reflected wave shows a phase shift ϕ due to propagation in the plasma

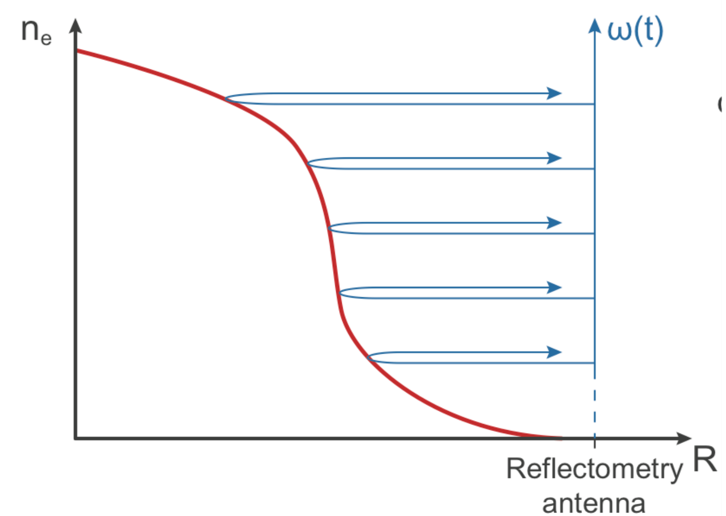
Electron density at cutoff obtained from wave frequency.

Cutoff position derived from integrated time delay due to wave propagation in the plasma

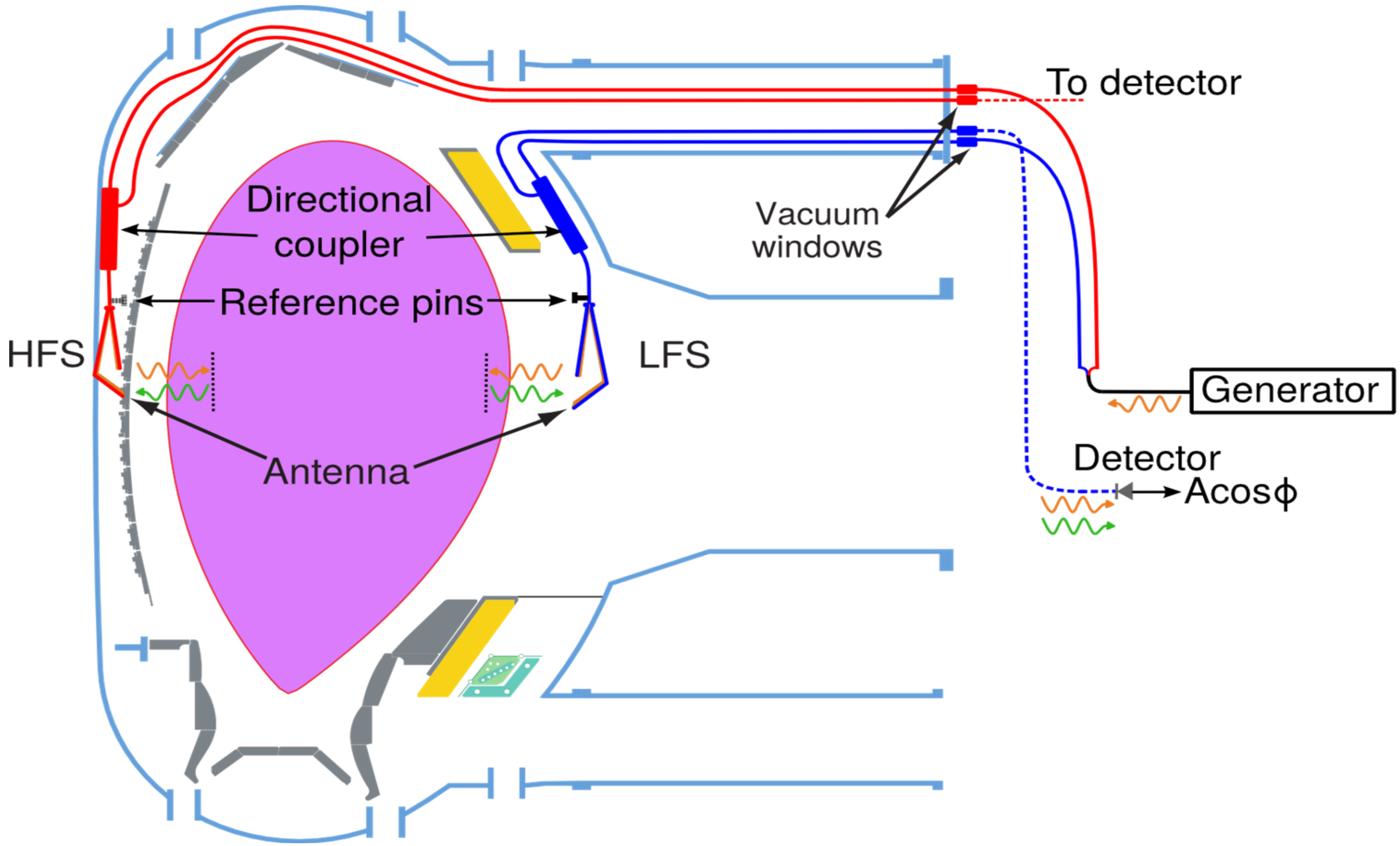
The phase reflects the propagation of the wave along a path described by a refraction index *N(r)*

Probing frequency can be swept (profiles) or fixed (fluctuations)

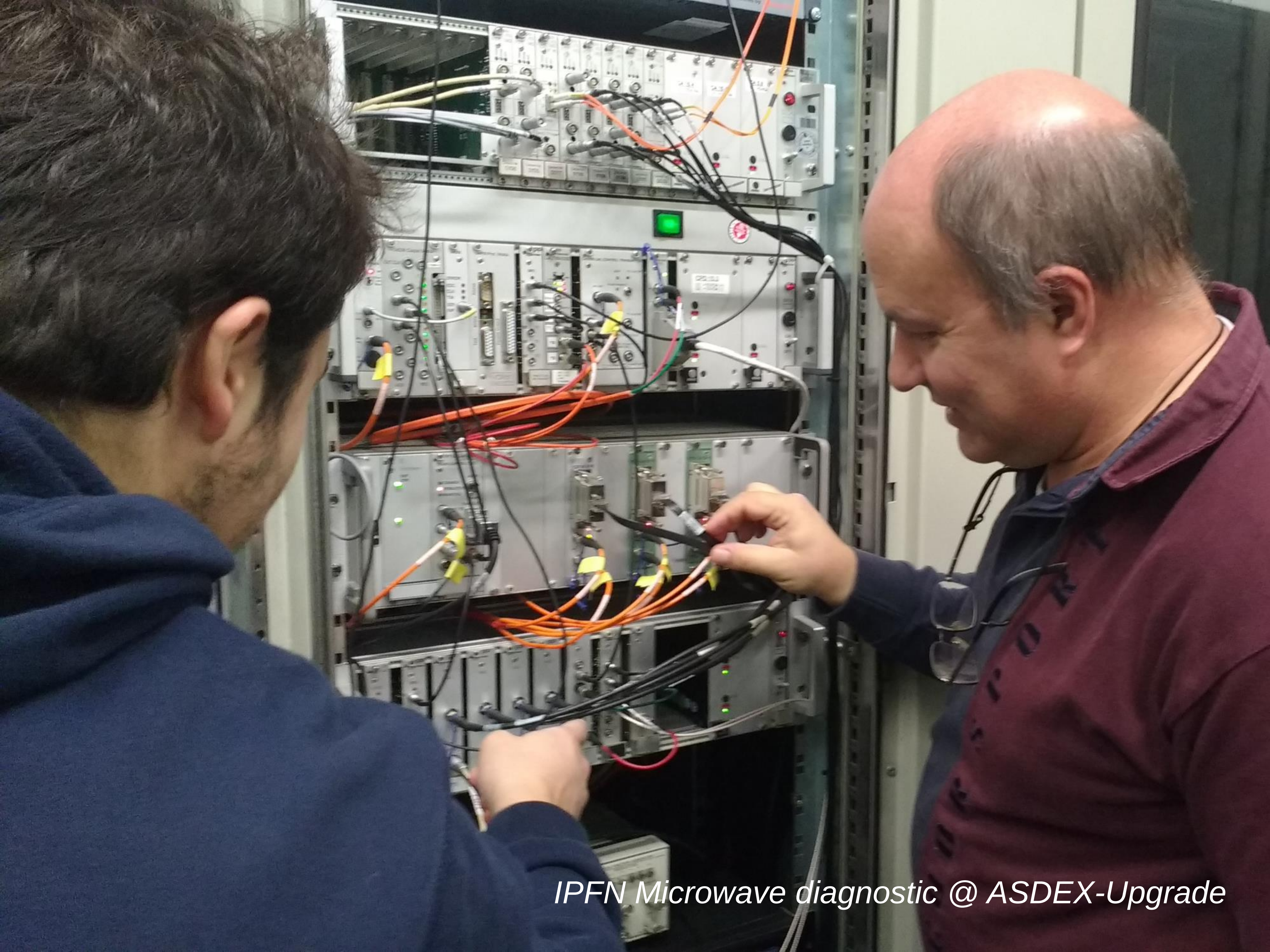




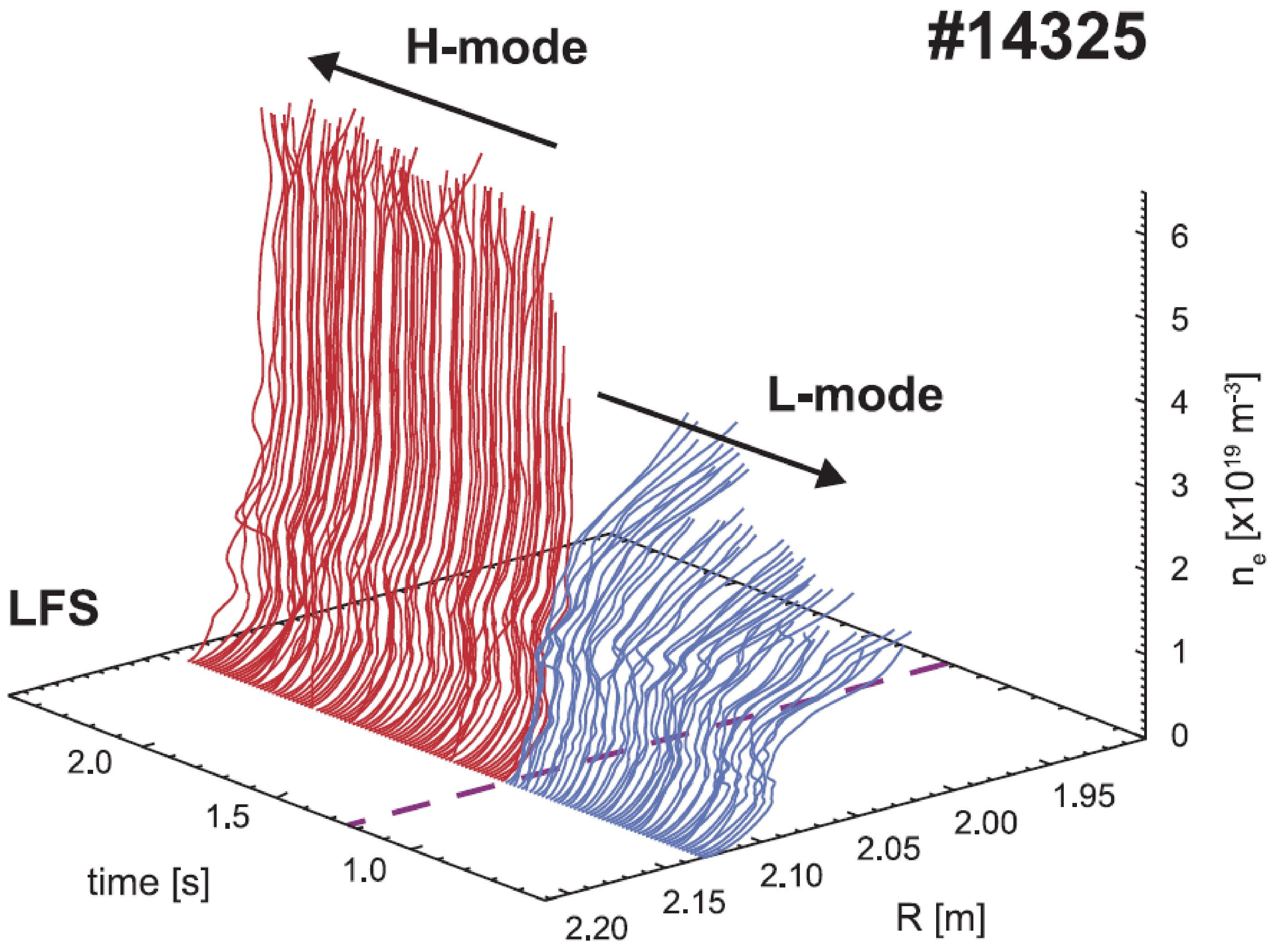
Reflectometer at ASDEX Upgrade



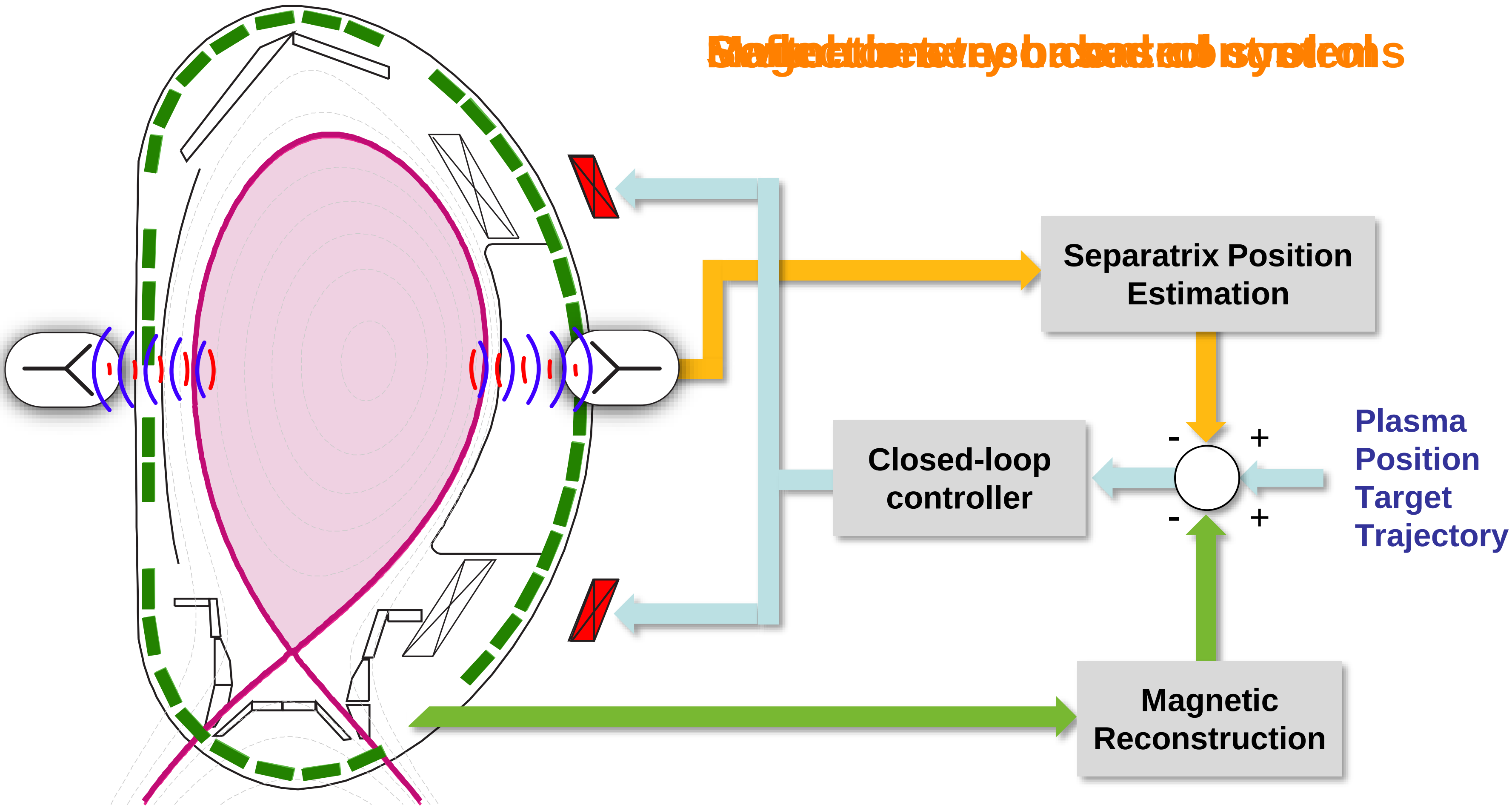
Band	**K:** 18-24 GHz	**Ka:** 24-36 GHz	**Q:** 33-49 GHz	**V:** 49-72 GHz
Density [$10^{19}m^{-3}$]	0.3-0.8	0.8-1.5	1.5-3.0	3.0-6.4


IPFN Microwave diagnostic @ ASDEX-Upgrade

Density profile evolution

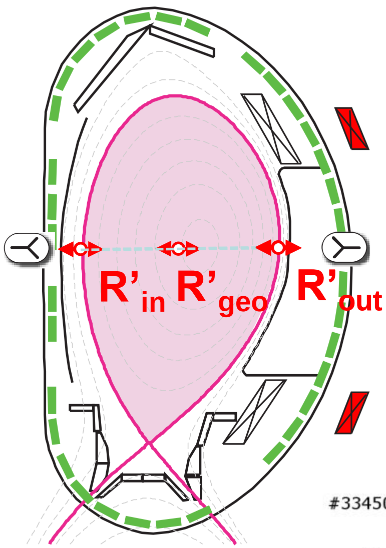


Example | Plasma Position Reflectometer

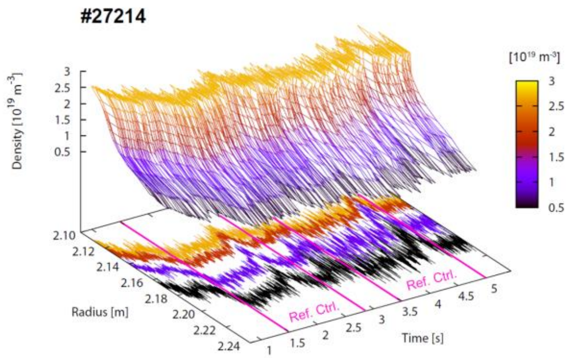


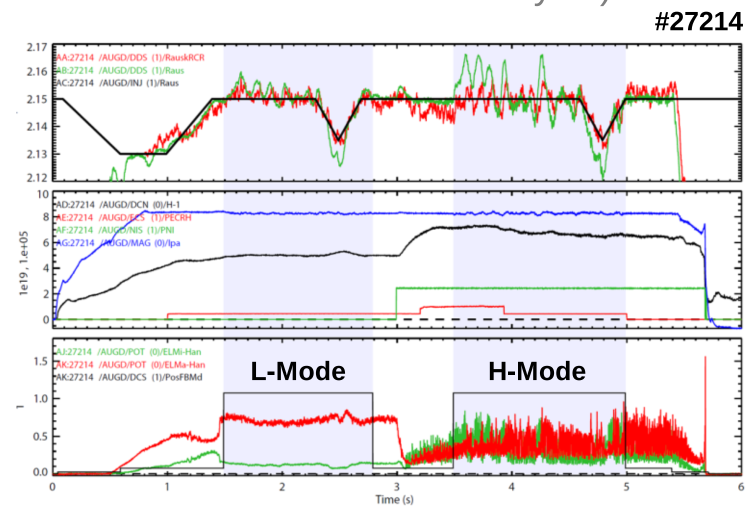
MW Reflectometry Plasma Position control @ AUG

Flawless control with reflectometry replacing magnetics radial measurements

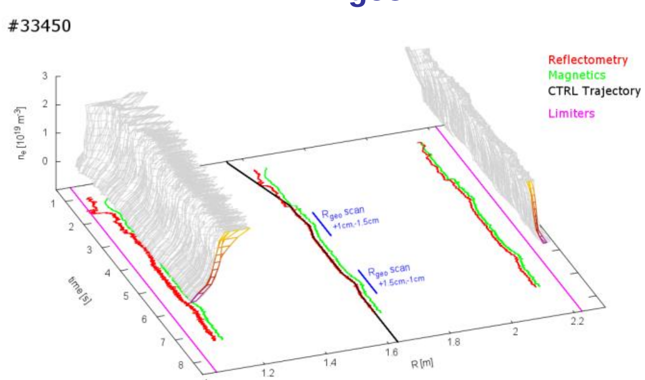


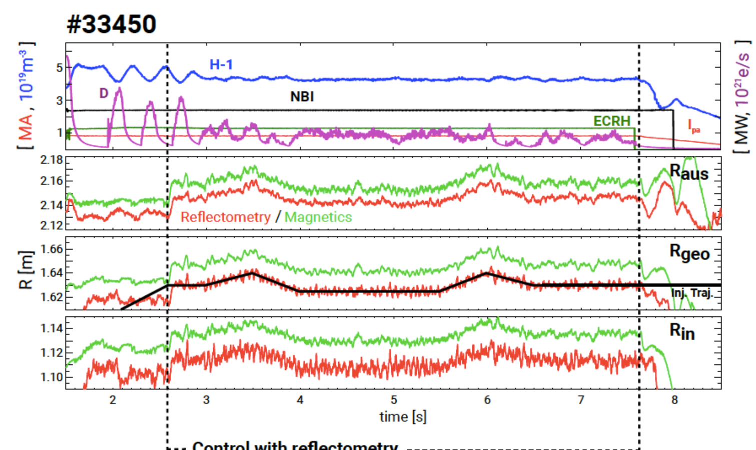
2011 - R'$_{out}$ control (1ms RT measurements & control cycle)





2016 - R'$_{geo}$ control (250 us RT measurements & 1 ms control cycle)





Santos, J., et al. Nuclear Fusion, 52(3), 032003

Santos, J. M., et al. Fusion Engineering and Design, 123(Nov.), 593–596

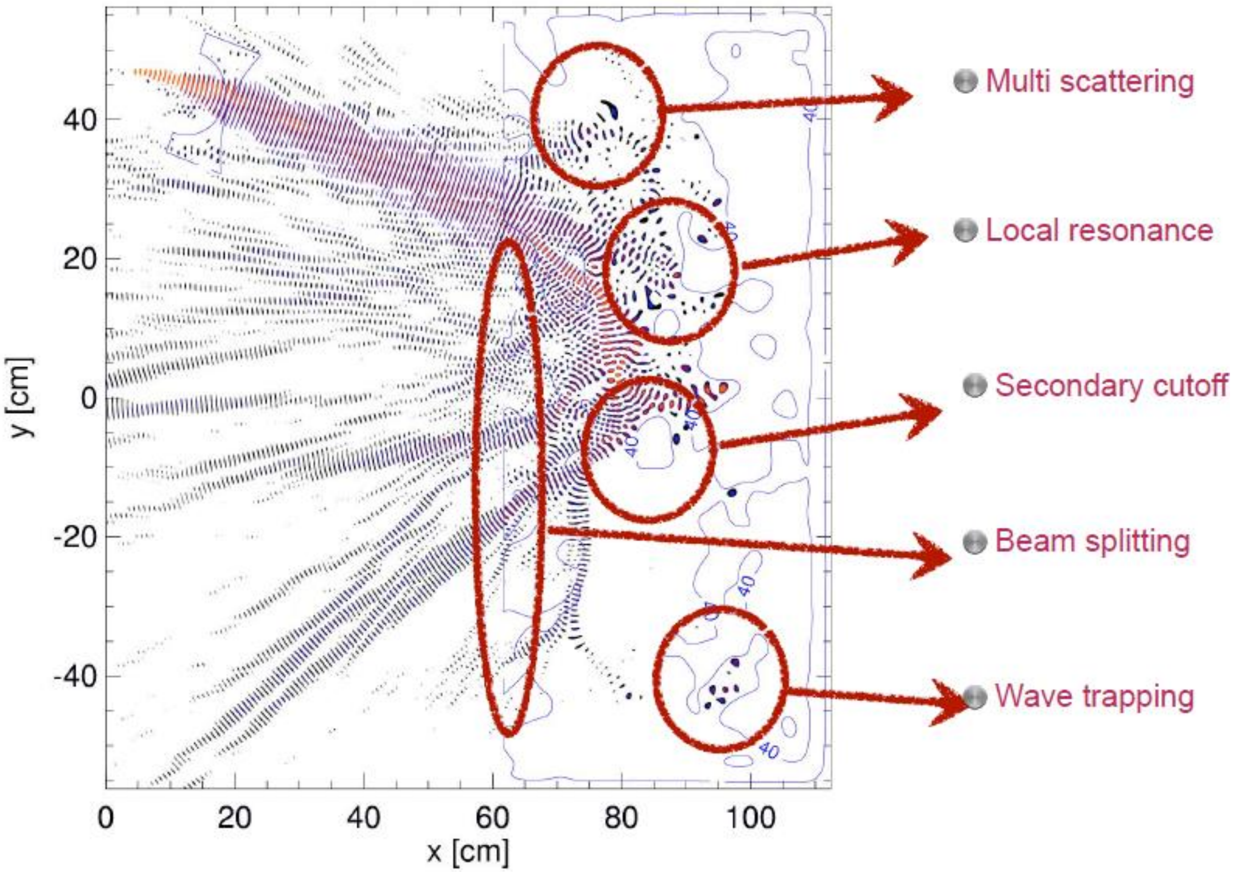
Propagation in plasma is complex

Full-wave simulations are crucial!

Plasma is extremely complex, non-homogeneous, non-stationary, anisotropic

Waves suffer the effects of turbulence, MHD, Doppler shifts, absorption, tunneling, mode conversion.

Requires a numerical full-wave treatment based on a simplified model which retains the fundamental physics



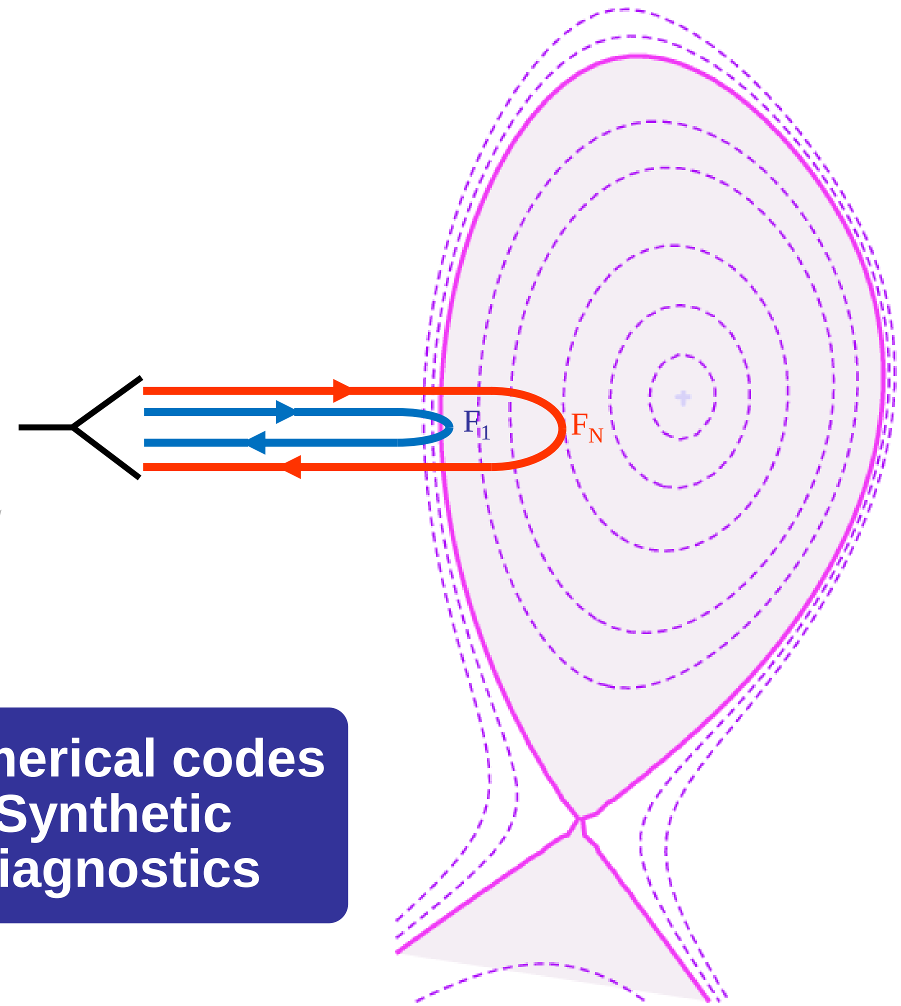
F. Silva, et al., J. Instrum. 14(08), C08003 (2019)
https://doi.org/10.1088/1748-0221/14/08/c08003

Developing reflectometry diagnostic systems requires an integrated approach

Microwave diagnostics
Physics & Engineering

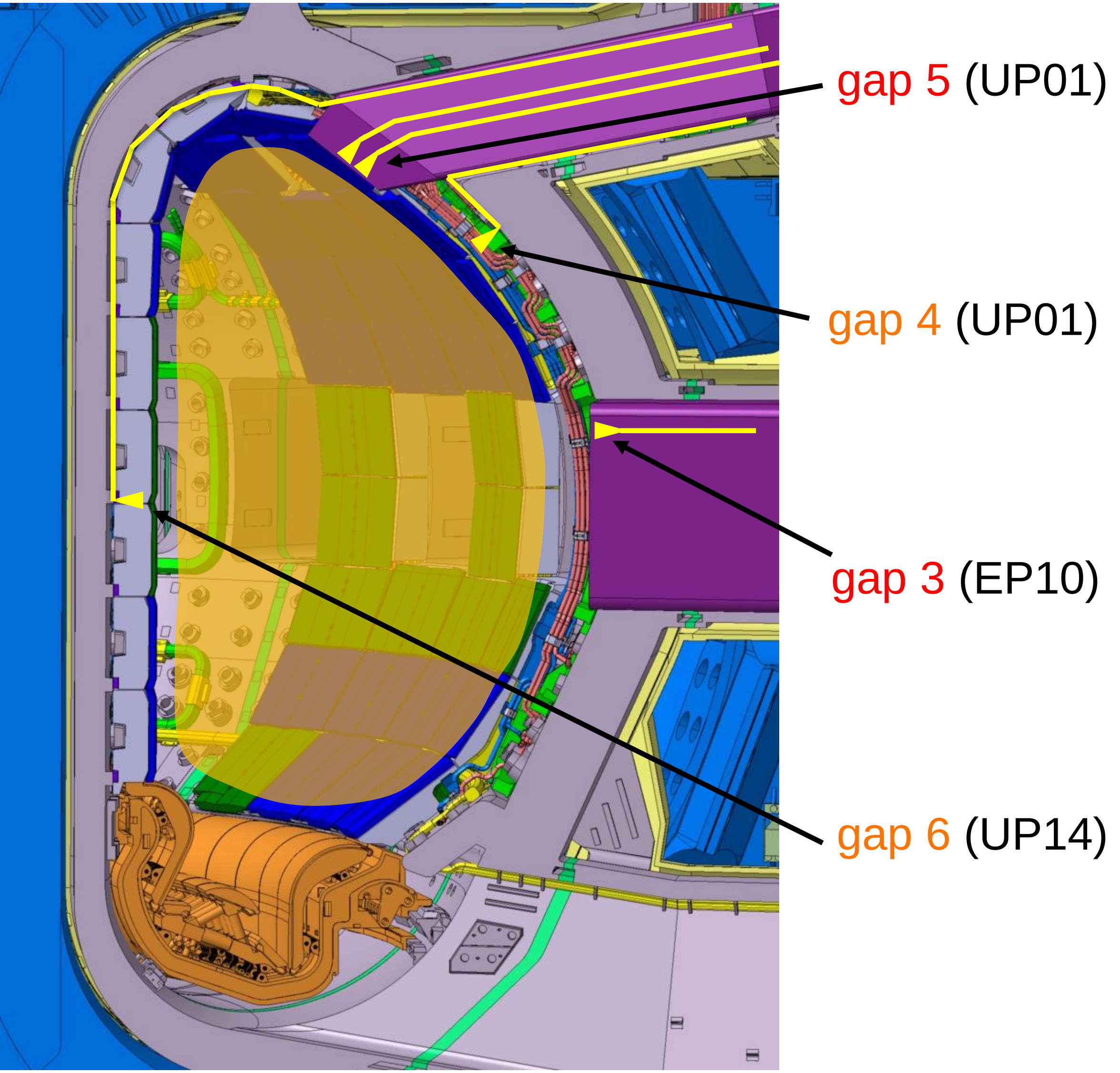
Data processing

Numerical codes
Synthetic diagnostics



ITER Plasma Position Reflectometry

CANCELLED
by F4E/IO



Measure edge electron density profile at four locations *aka* gaps 3, 4, 5, & 6 with high spatial (<1 cm) and temporal (100 µs) resolutions

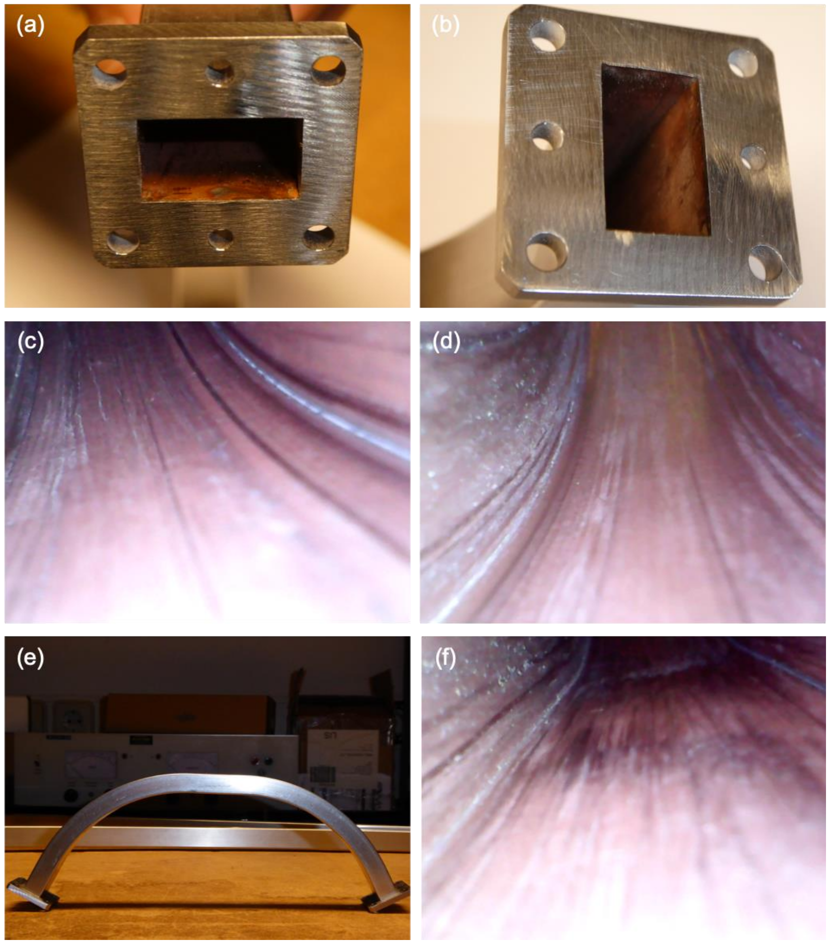
Main role in ITER

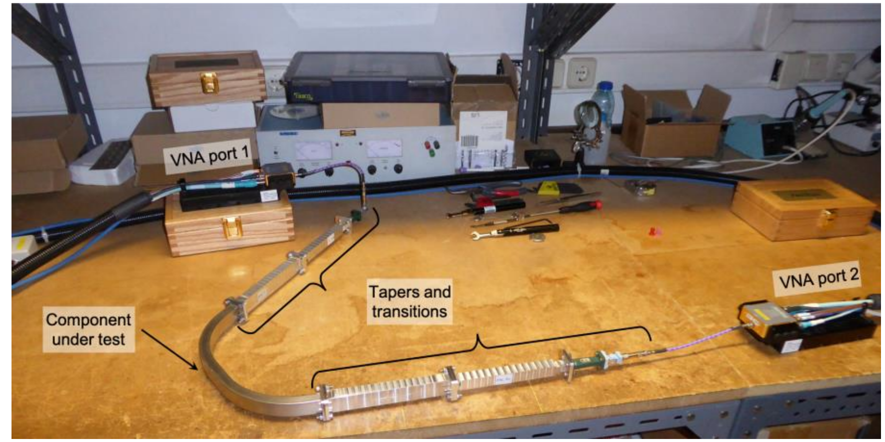
- Real-time supplementary contribution to magnetic measurements of the plasma-wall distance (correct drifts of the magnetics during long pulses)

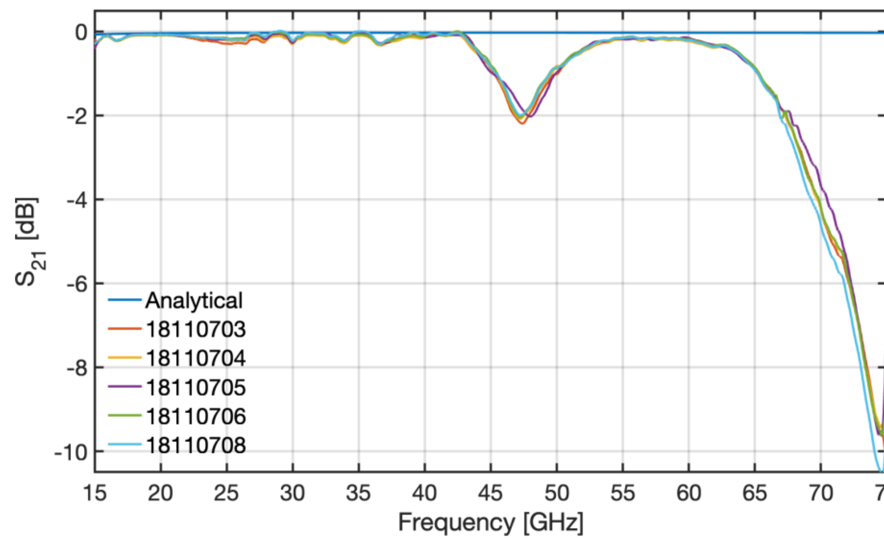
Baseline design

- 4 **FM-CW O-mode** reflectometers in **full bi-static configuration** covering the edge plasma up to **~7x10^{19} m^{-3}** (15 GHz to 75 GHz)

Test of waveguides design and materialsg



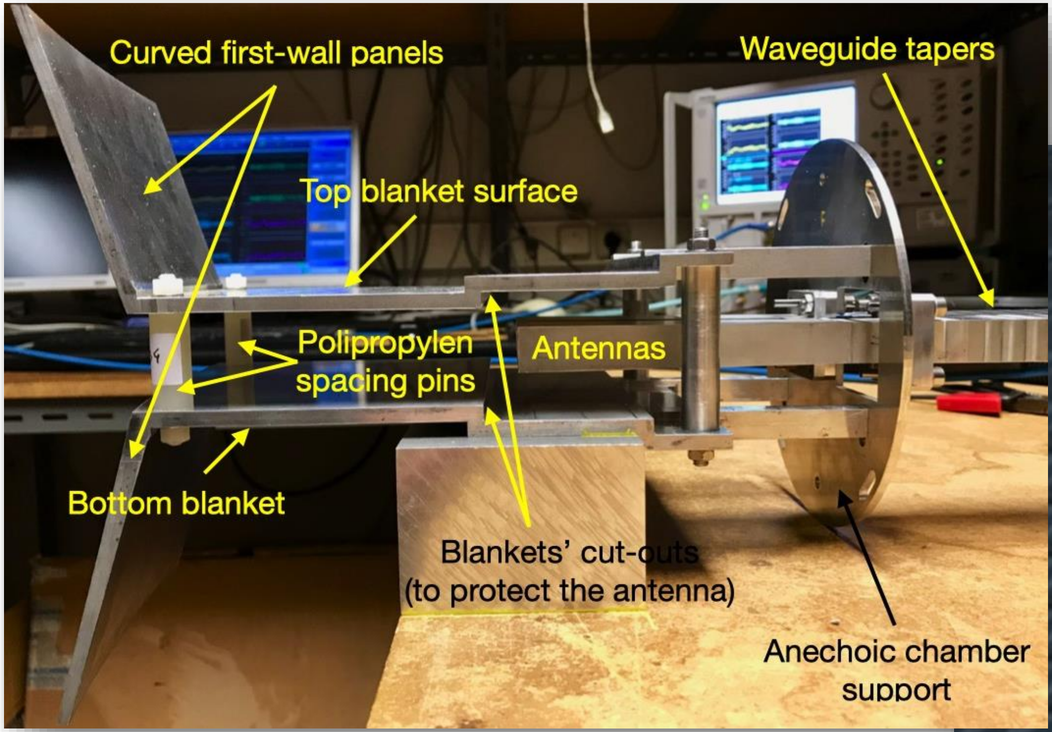


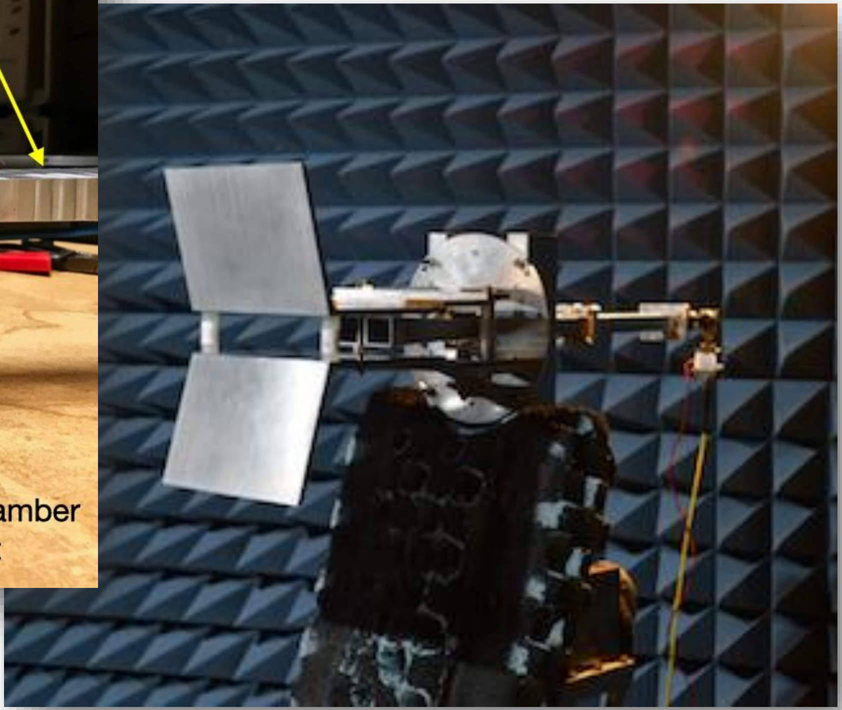


Lesson learned: Separate prototypes to validate models from prototypes to validate manufacture processes

Tests of gap 6 antenna assembly prototype

Mockup of antenna, waveguides and blanket module

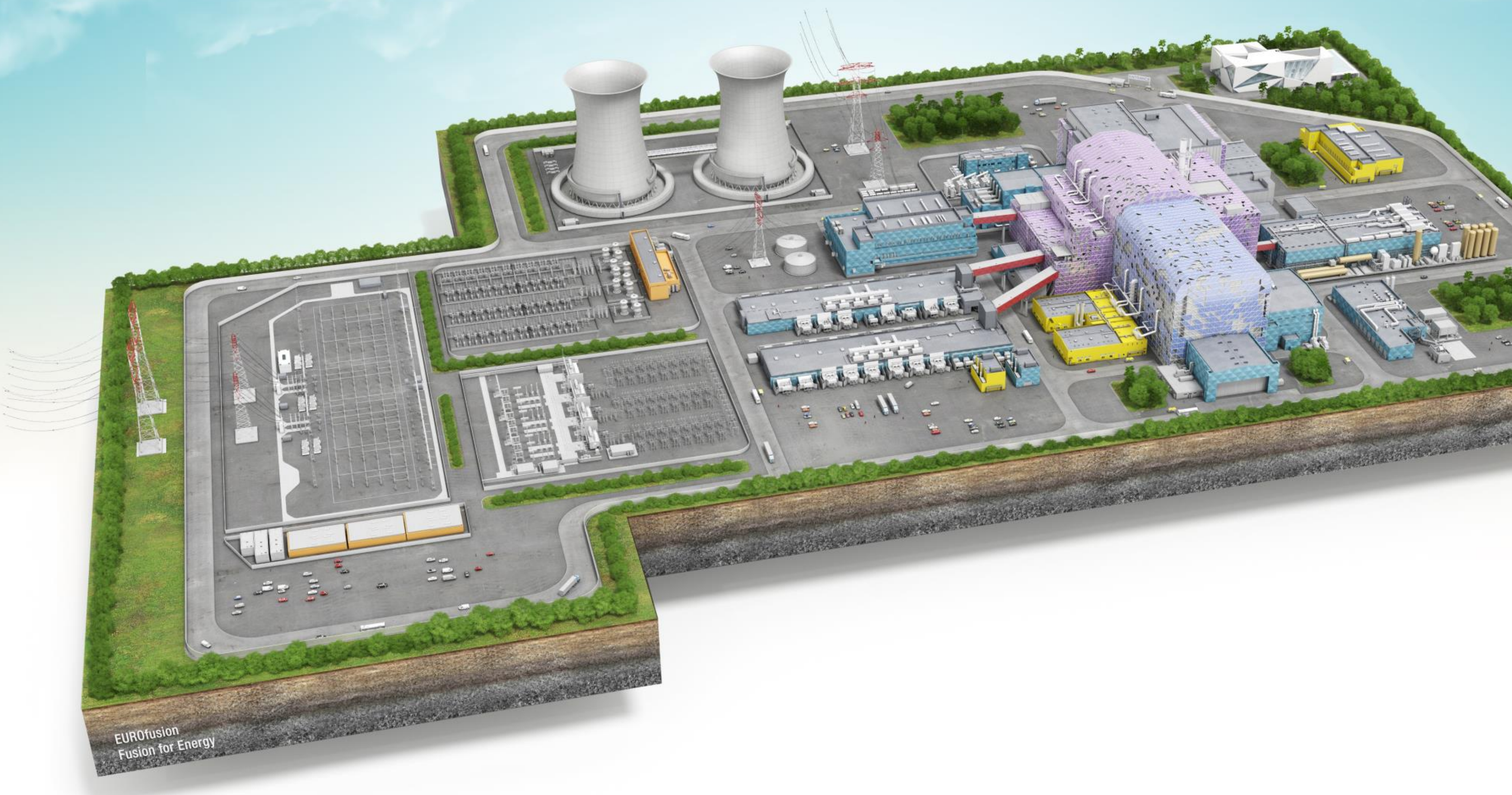




Antenna #1 (baseline): two parallel 115 mm long pyramidal horns with toroidal flare of ±2 mm and poloidal flare of ±1 mm.

Antenna #2: two parallel 115 mm long pyramidal horns with toroidal flare of ±2 mm and poloidal flare of ±4 mm.

DEMO
DEMONSTRATION POWER PLANT



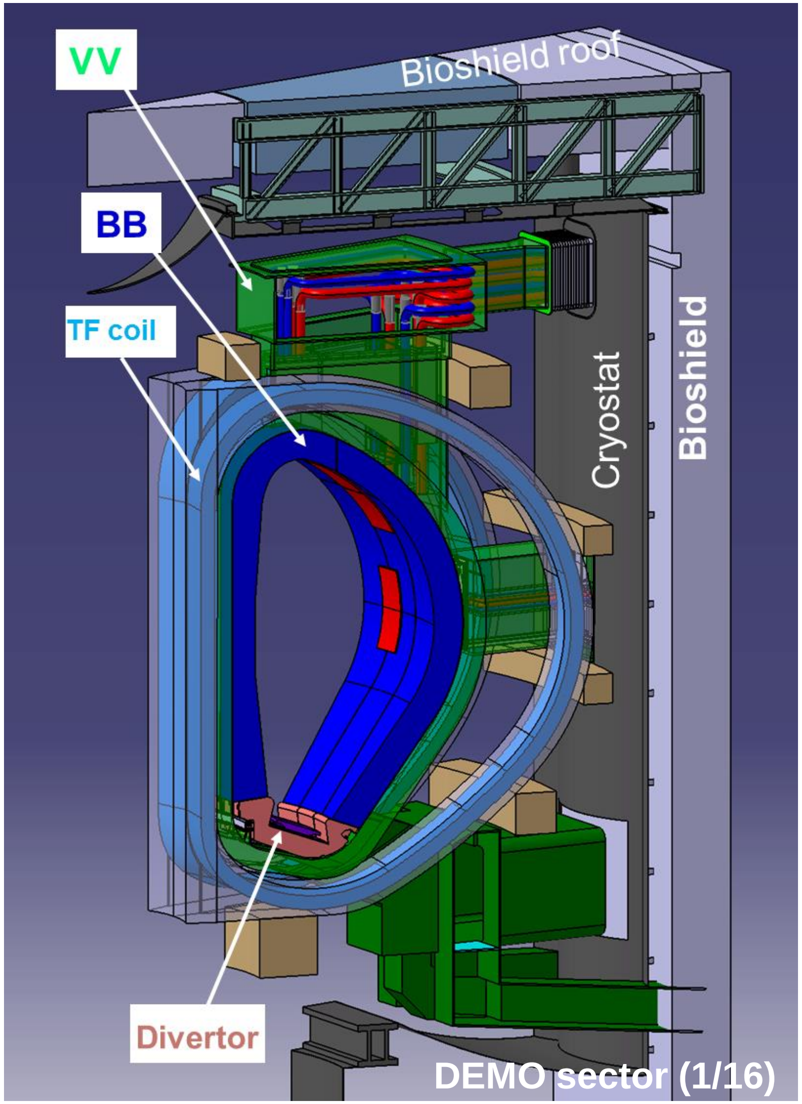
Challenges for diagnostic integration in DEMO

Space restrictions

- in Breeding Blankets (BB) (for sufficient tritium breeding: TBR>1)
- in Equatorial and Upper Ports (EP, UP)

Harsh conditions (radiation & heat loads, erosion)

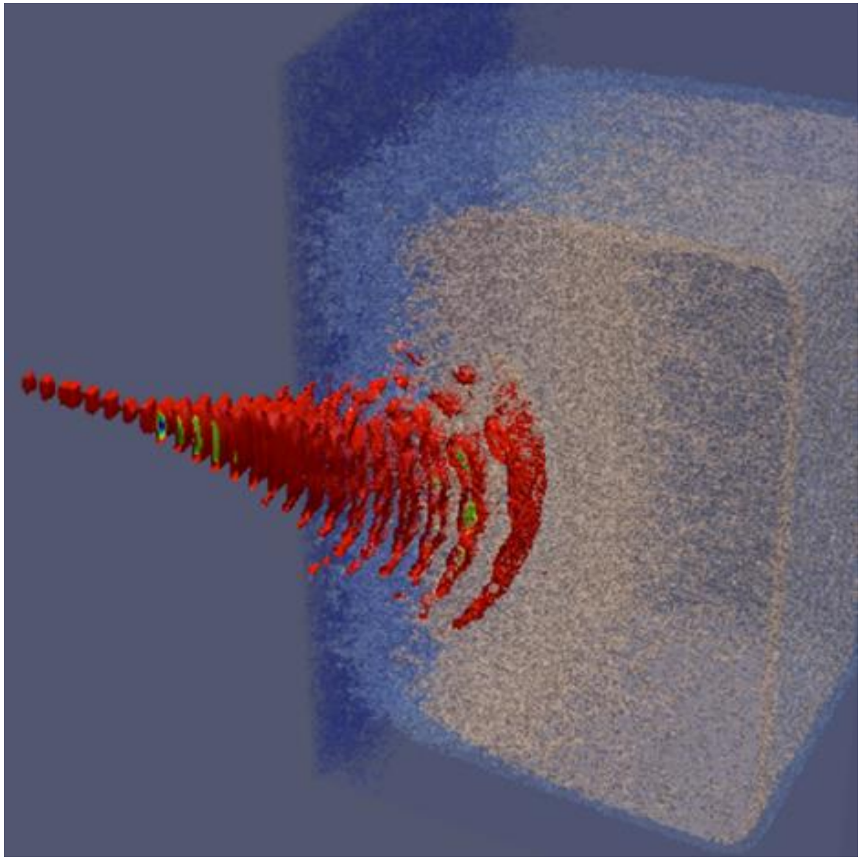
- Restrict choice of materials
  - metallic components in BB region
- Active cooling
  - for In-Vessel Components (IVC)
  - for Plasma-Facing Components (PFC)
    - BB first wall (FW), Divertor, Limiters
- Components retracted in protected locations
- Maintenance by Remote Handling (RH)
  - BBs substituted (at least) once during DEMO lifetime



MW reflectometry in DEMO

Candidate to

- measure the plasma density profile
- provide data for real-time feedback control of plasma position and shape
    - high spatial and temporal resolutions
    - high reliability
- backup solution to magnetics



Robust front-end

- metallic antennas and waveguides (WGs)
- able to withstand high radiation & heat loads
- no sensitive parts

Diagnostics Slim Cassette (DSC) innovative concept

Slim module dedicated to diagnostics

- Profile identical to the blankets, ~25 cm wide

Integrated with the Breeding Blanket

Made of solid EUROFER

Up to 80 pyramidal horn antennas and rectangular waveguides (EUROFER)

Clusters of up to 5 antennas, in 16 gaps

- 1 emitting antenna
- 1-4 receiving antennas

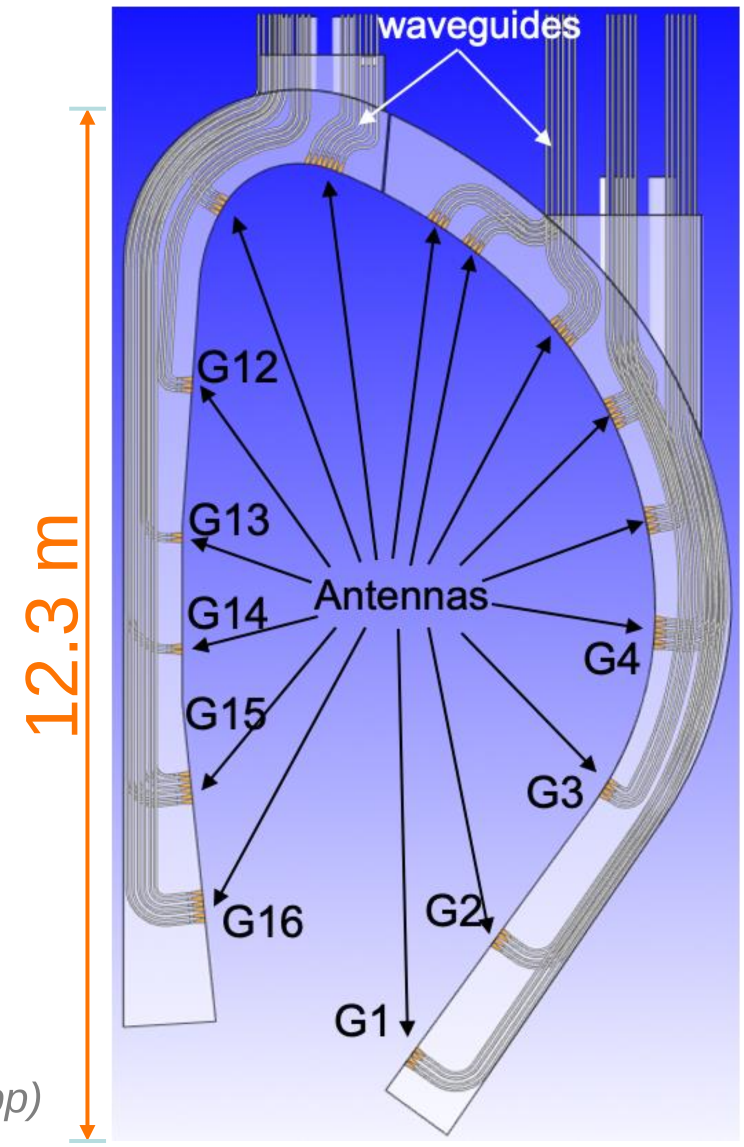
Eventually duplicated to provide redundancy

Waveguides routed through the UPs

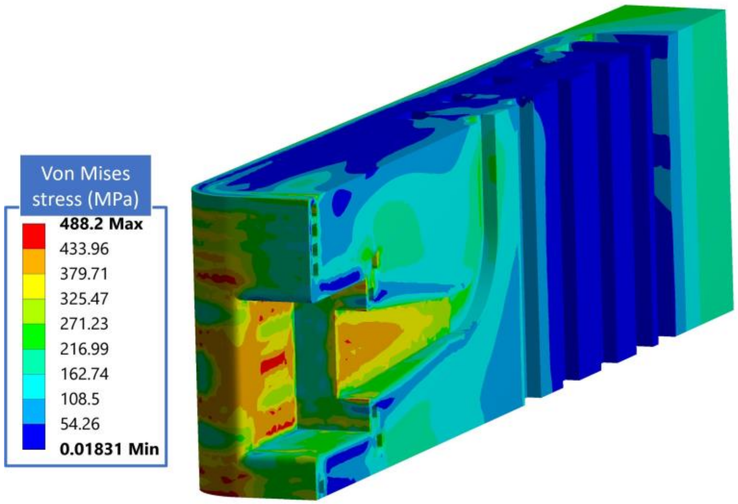
Actively cooled

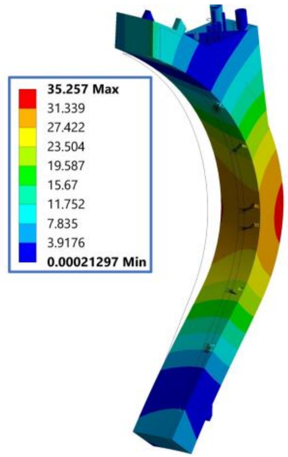
Designed with RM compatibility to facilitate a 'fast' exchange

*J. Belo et al., Nucl. Fusion **61** (2021) 116046 (28pp)*

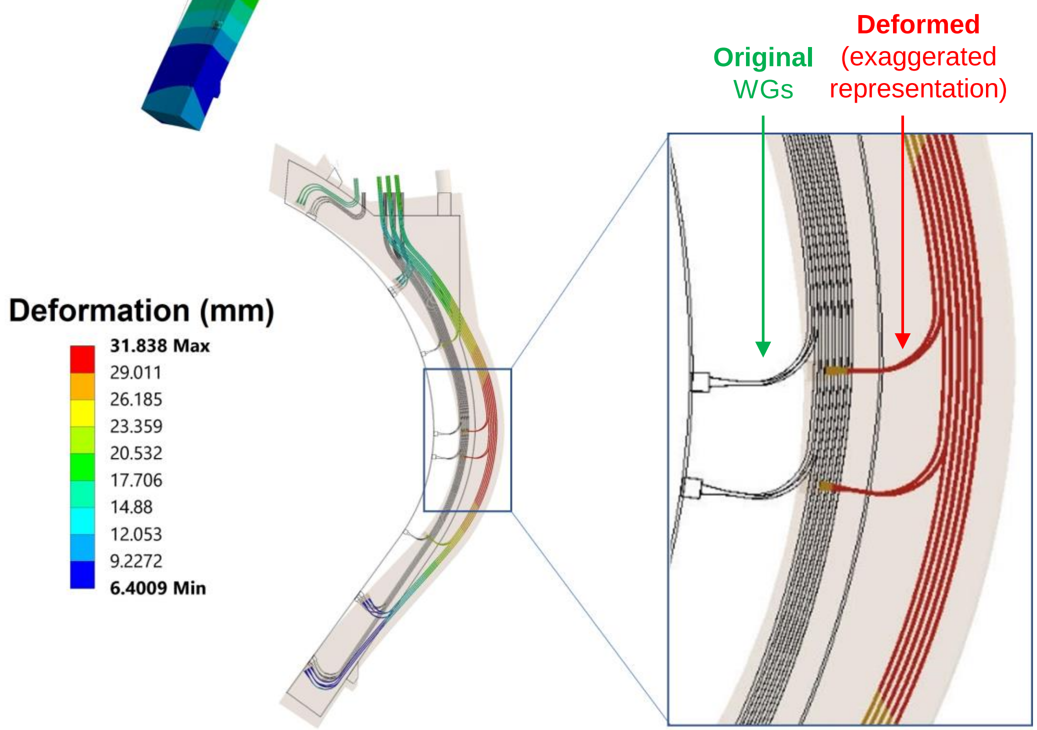


Nuclear and thermal loads have to be always considered in the design





Case	Gravity	Thermal map	EM load	EM moment
Case 1	✓	✗	✗	✗
Case 2	✓	✓	✗	✗
Case 3	✓	✗	✓	✓
Case 4	✓	✓	✓	✓



Max deformation (OB WGs): **3.2 cm**

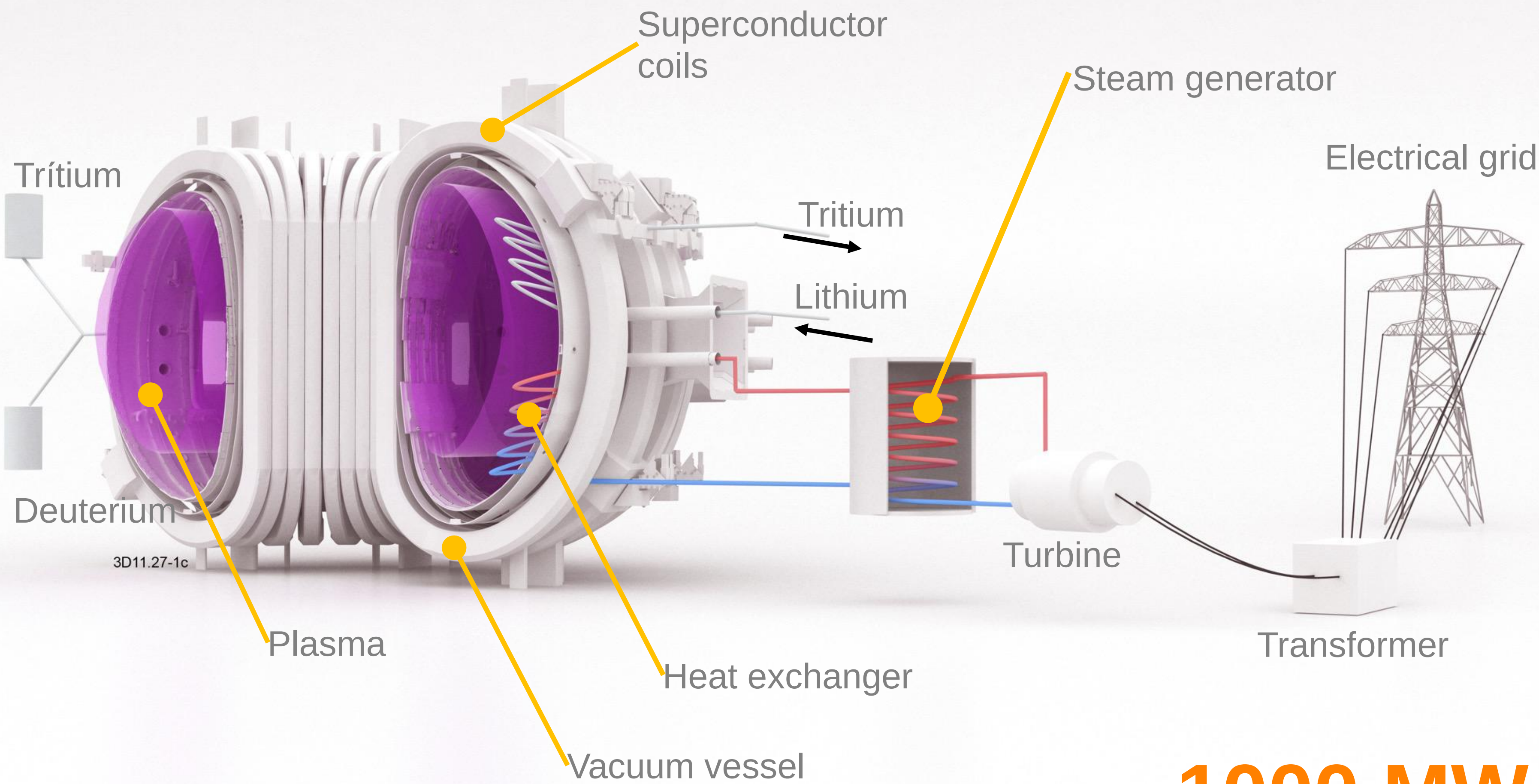
Current design of DSC is expected to withstand the loads without compromising its structural integrity

Complies with RCC-MR* level A criteria

*Design and Construction Rules for mechanical components of nuclear installations


To keep the lights on
Nuclear Fusion
Power Plant

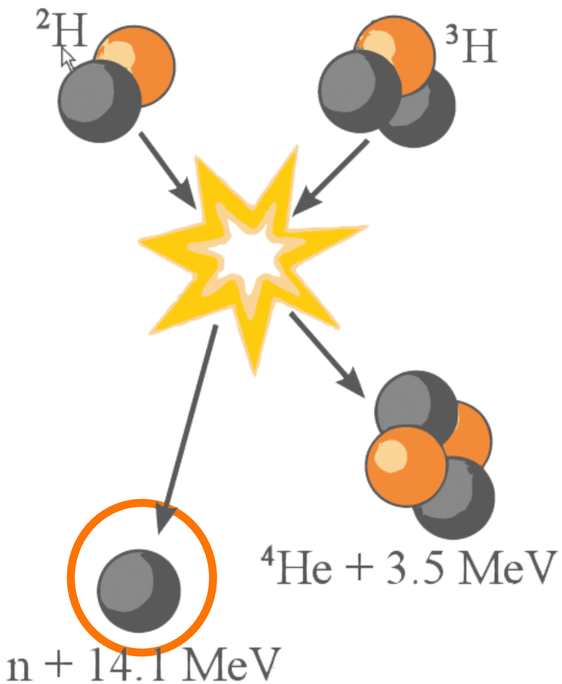
Nuclear Fusion Power Plant



1000 MW

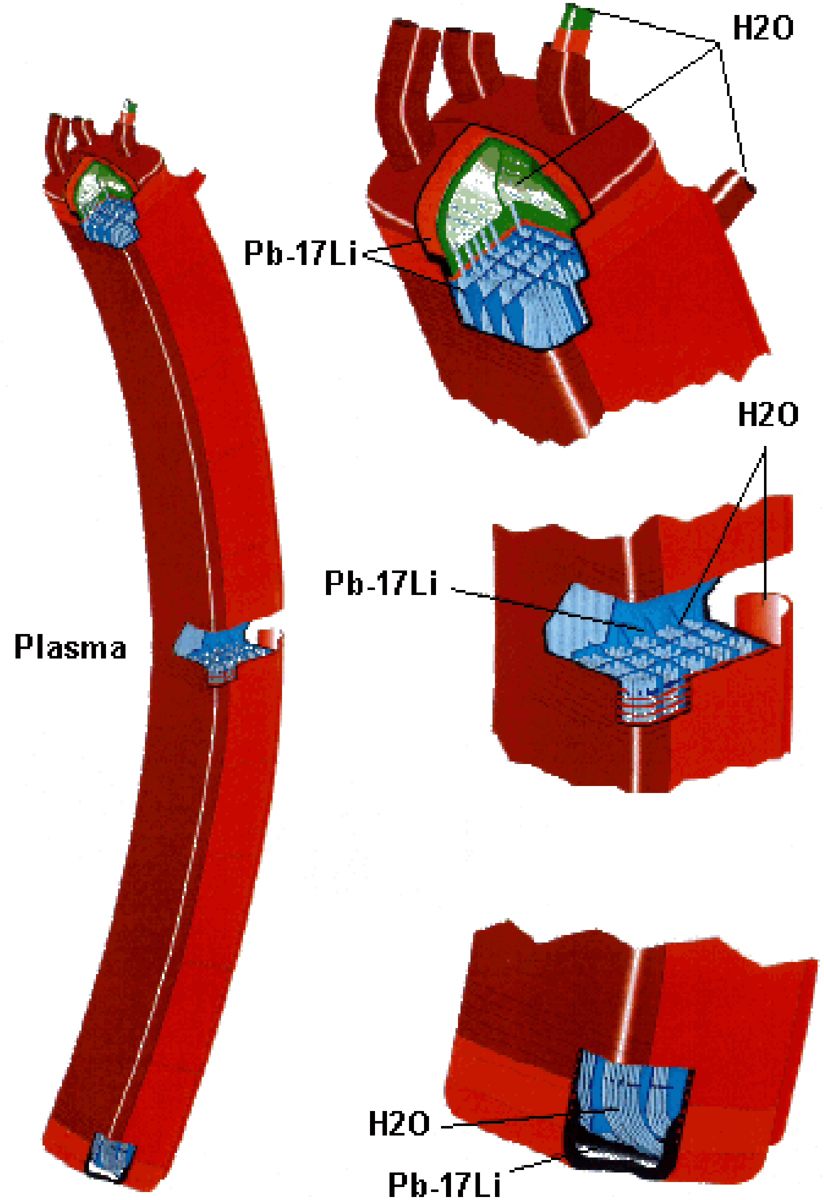
Continuous operation

Tritium Breeding Blanket



$$Li^6 + n \rightarrow T + He^4 + 4.8MeV$$

$$Li^7 + n \rightarrow T + He^4 - 2.5MeV$$



ChatGPT Oracle

When will nuclear fusion produce electricity?

Predicting an exact timeline for when nuclear fusion will produce electricity on a commercial scale is challenging. However, based on current research and development efforts, some estimates suggest that we could see the first operational fusion power plants within the next few decades.

The timeline depends on overcoming the technical challenges, refining fusion technologies, and securing sufficient funding and support for large-scale implementation.

While the path to practical fusion power is complex, scientists and engineers are dedicated to advancing the field, and steady progress is being made towards realizing the dream of fusion-generated electricity.

Nuclear fusion is in fashion!

PFW

"The Future Is Close": Gabriela Hearst On The Fusion Power That Inspired Her Chloé Show For SS23

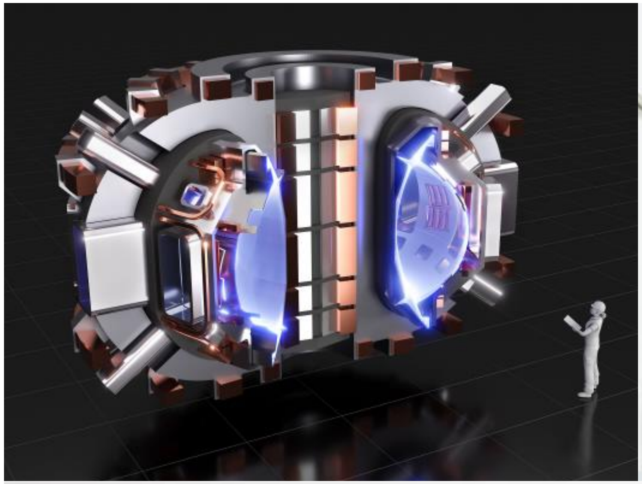
BY ANDERS CHRISTIAN MADSEN

30 September 2022

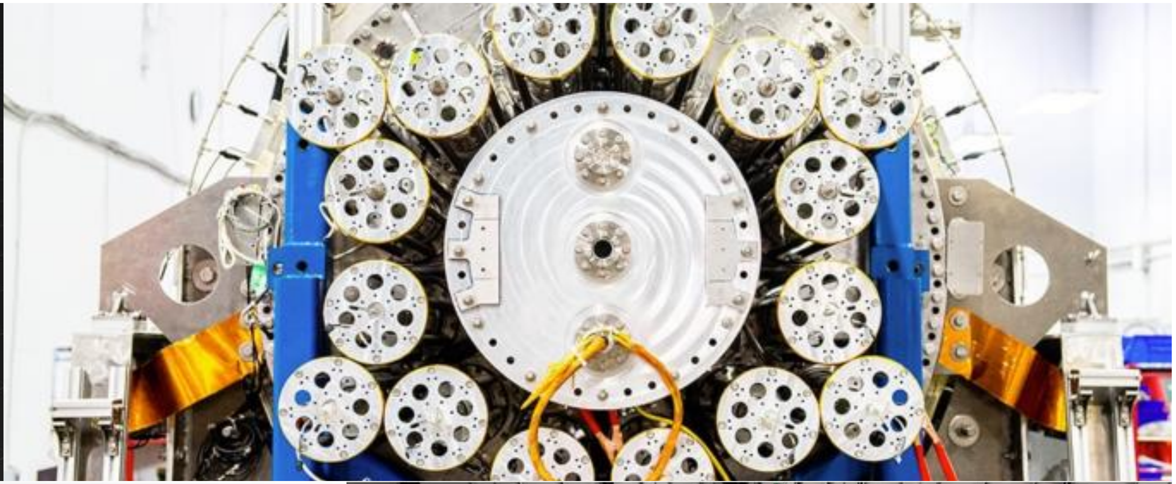
Nuclear fusion is in fashion!

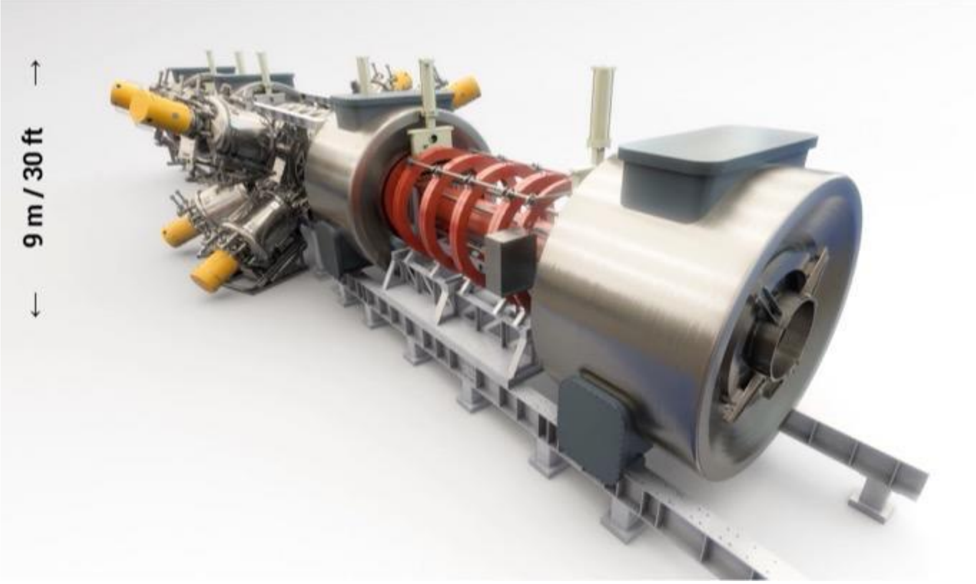
Also to investors in new projects / alternative concepts

SPARC



General Fusion

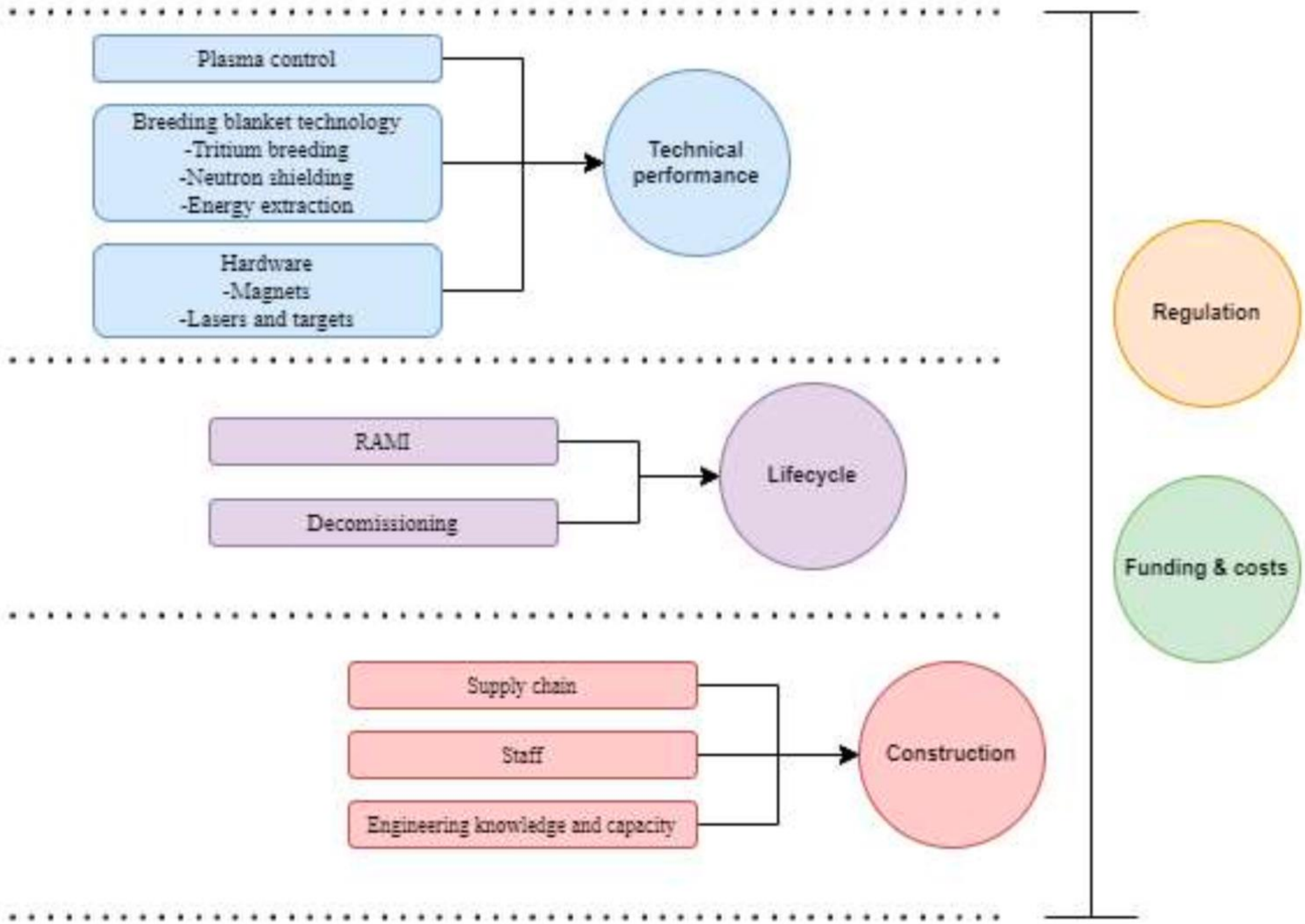




TAE Technologies

First Ligth Fusion

Main challenges for fusion energy are common to many of the new concepts



Foresight study on the worldwide developments in advancing fusion energy, including the small scale private initiatives, EU Commission Report Nov. 2022


Looking into
tomorrow’s
energy...