European Contributions to Enhancements in JT-60SA

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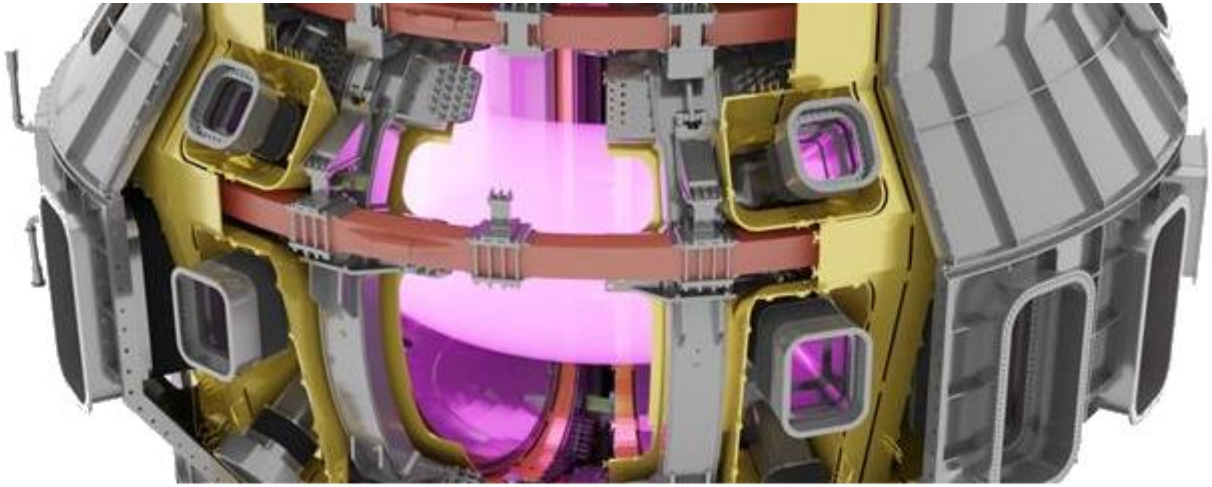
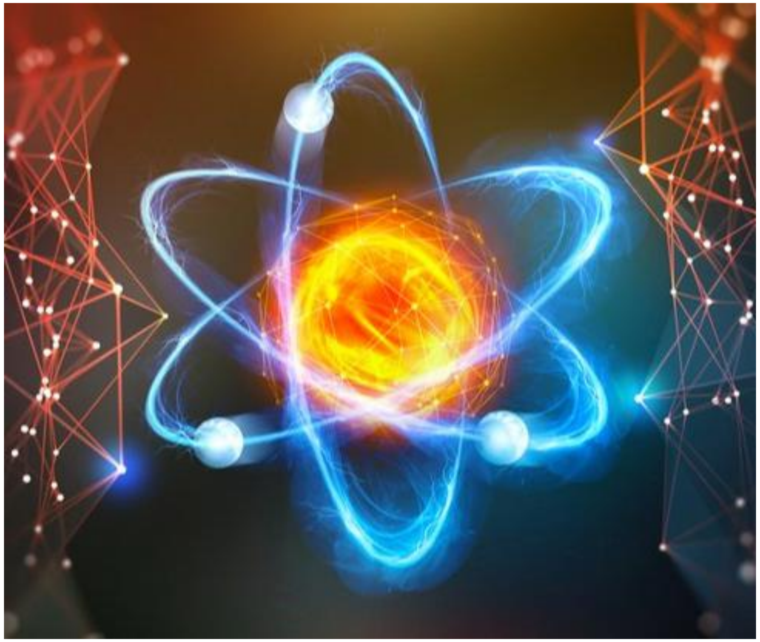
Outline

- Nuclear Fusion, Magnetic Confinement and Tokamaks
- The JT-60SA Project
- European contributions to JT-60SA
  - Ongoing Enhancement Projects
  - Future Enhancement Projects
  - JT-60SA International School



Harvesting Energy from Nuclear Fusion

- Clean and safe energy
  - No greenhouse gas emissions
  - Short-lived nuclear waste
- Highest power density per Kg
- Abundant fuel (hydrogen) – very delocalized



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  - Short-lived nuclear waste
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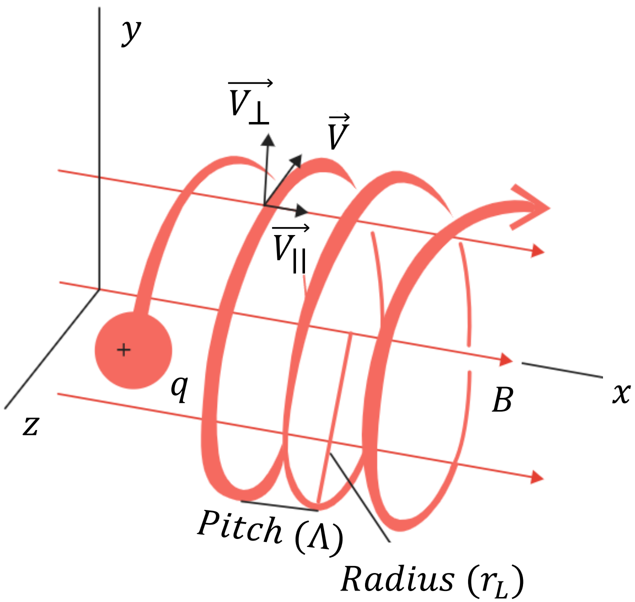
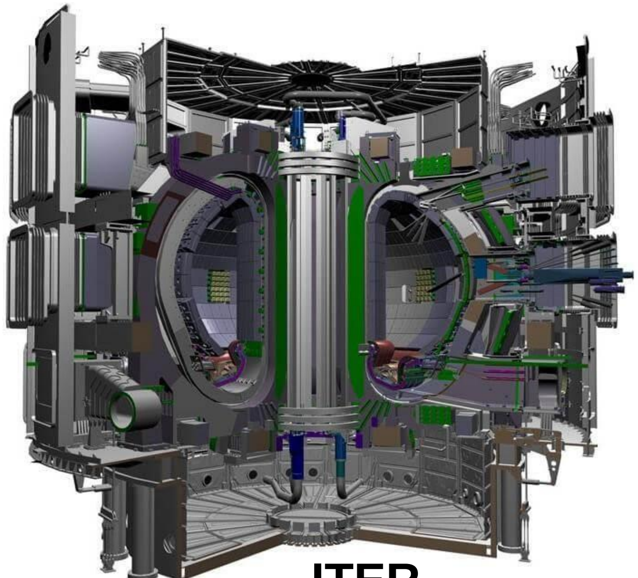
- Hard to achieve due to Coulomb barrier – reach nuclear strong force interaction
- Very high temperature needed – hotter than the sun – 100 MK despite quantum tunneling help
- Fuel in plasma state and must be confined
  - Gravitational – stars (not achievable in Earth)
  - Inertial – lasers (complex for steady-state)
  - Magnetic – EM properties of plasma (most extended)

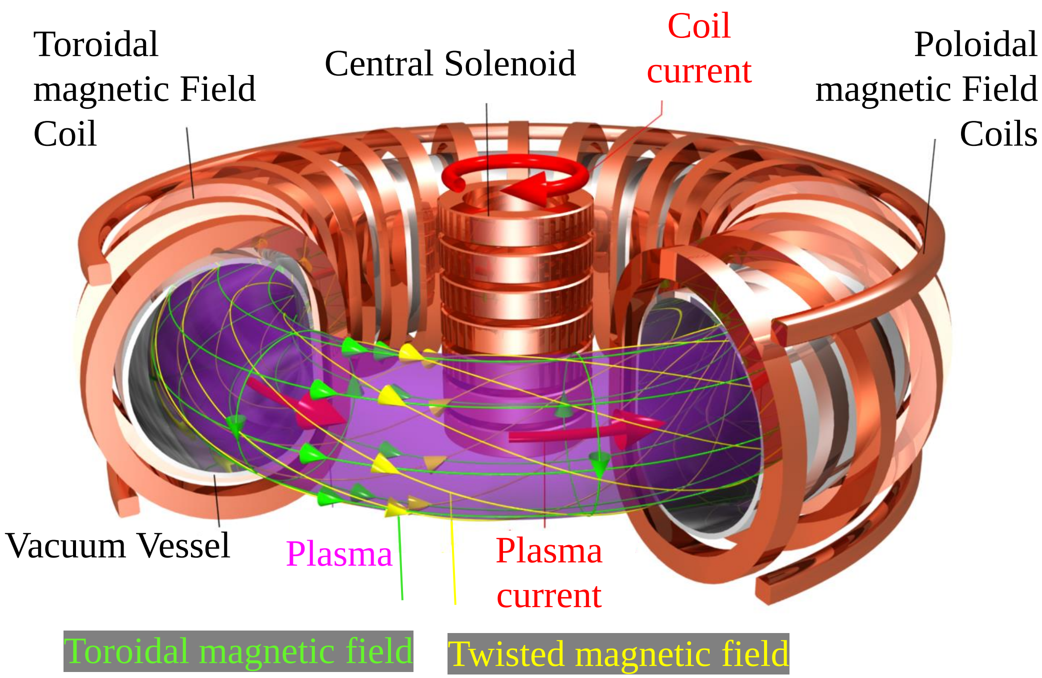




ITER

The Tokamak is the most Extended Concept for Plasma Magnetic Confinement

- Tokamak main components:
  - Vacuum Vessel – UHV conditions
  - Toroidal Field Coils (TFC) – Toroidal magnetic field
  - Central Solenoid (CS) – Induce the plasma current
  - Poloidal Field Coils (PFC) – Shape and control the plasma



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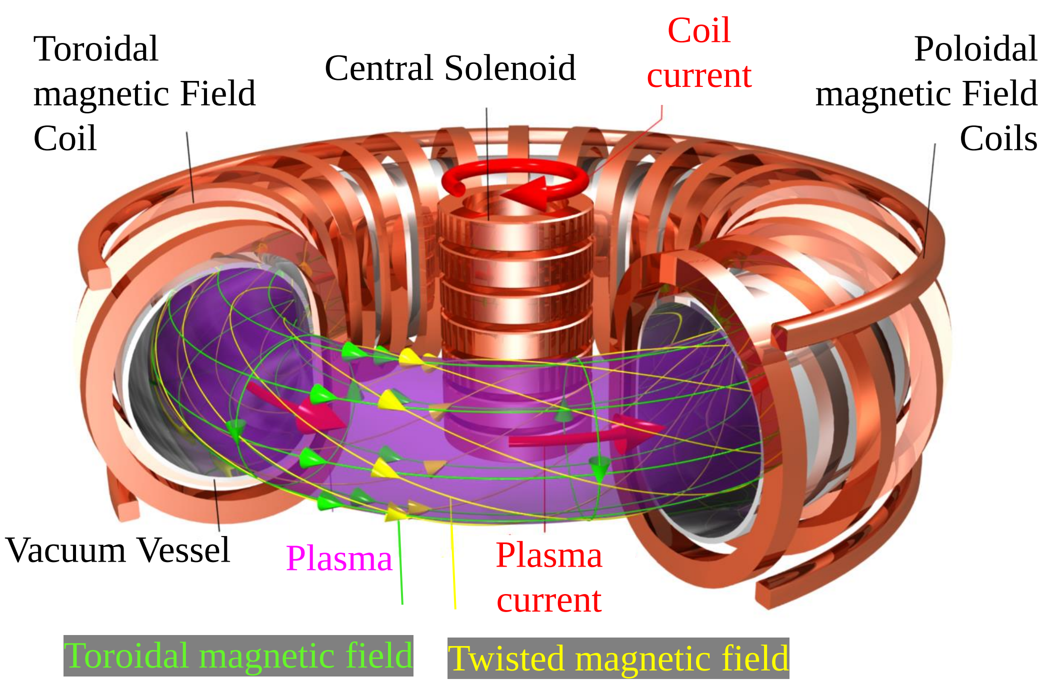
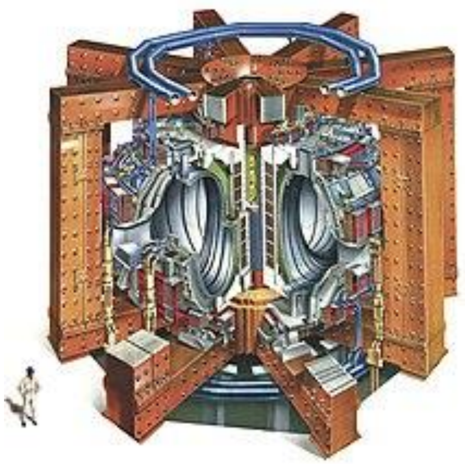
- Subsystems:
  - Heating systems – NBI
  - Power supplies
  - Cryogenics systems
  - Divertor
  - Vacuum pumps
  - Control and diagnostic systems

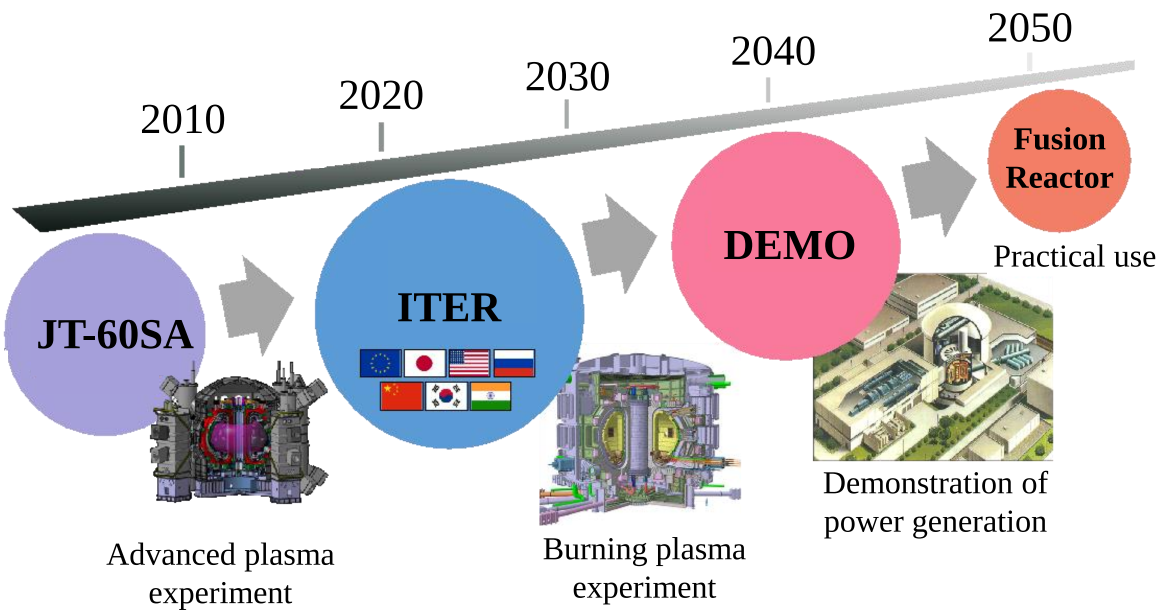


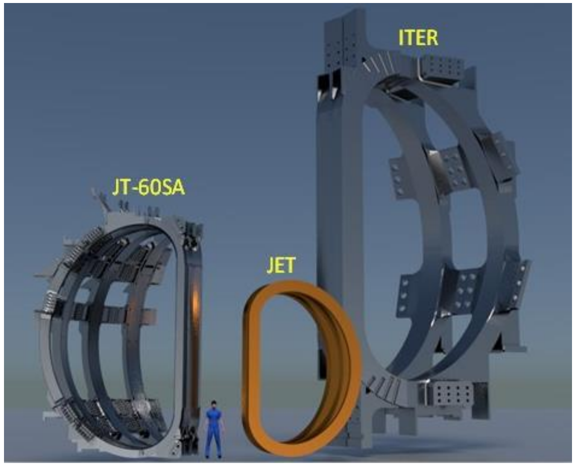
International Road-map to Obtain Fusion Energy in 2050

- Tokamak concept arose in 1950’s
- Machines grew bigger and more powerful
- Third generation machines reported good results but not enough
  - JET – Q ~ 1 (Break-even Q > 1)
- Present international road map:
  - JT-60SA → ITER → DEMO → Fusion reactor



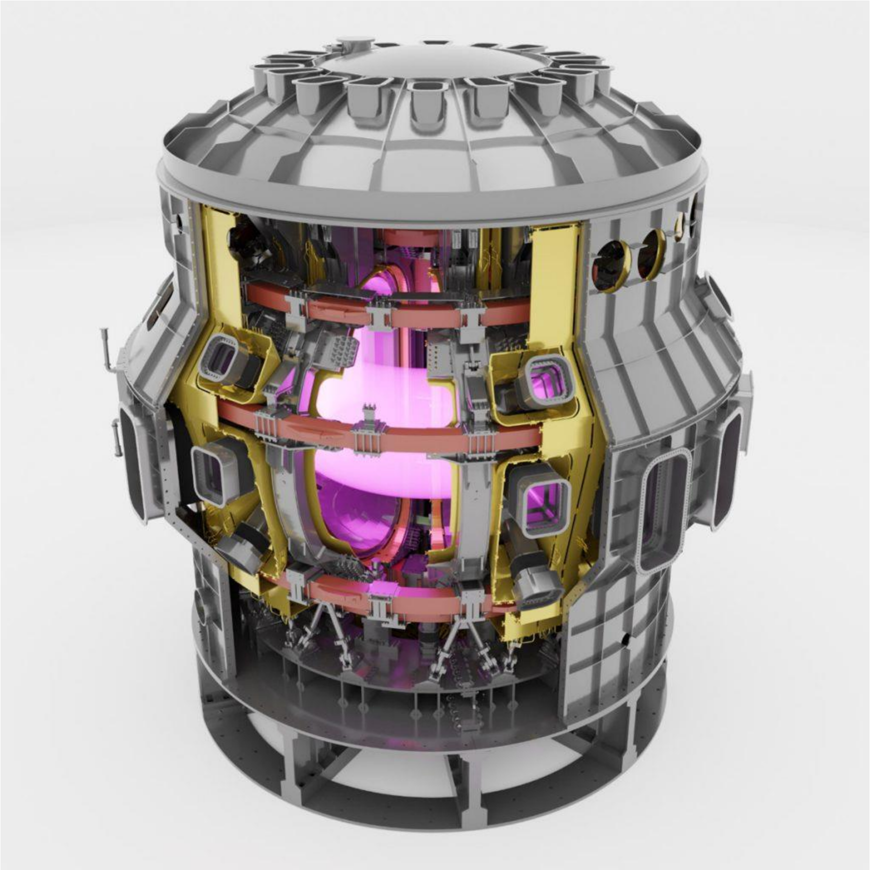
JET





The JT-60SA Tokamak

- World biggest tokamak until the ITER arrival
- Built in Naka (Japan): shared effort between Japan (QST) and EU (F4E, EUROfusion)
- Huge capabilities to shape the plasma – ITER-like plasmas
- Extended operation experiments (300s) – Steady state:
  - Superconducting tokamak
  - Non-inductive current drive capabilities



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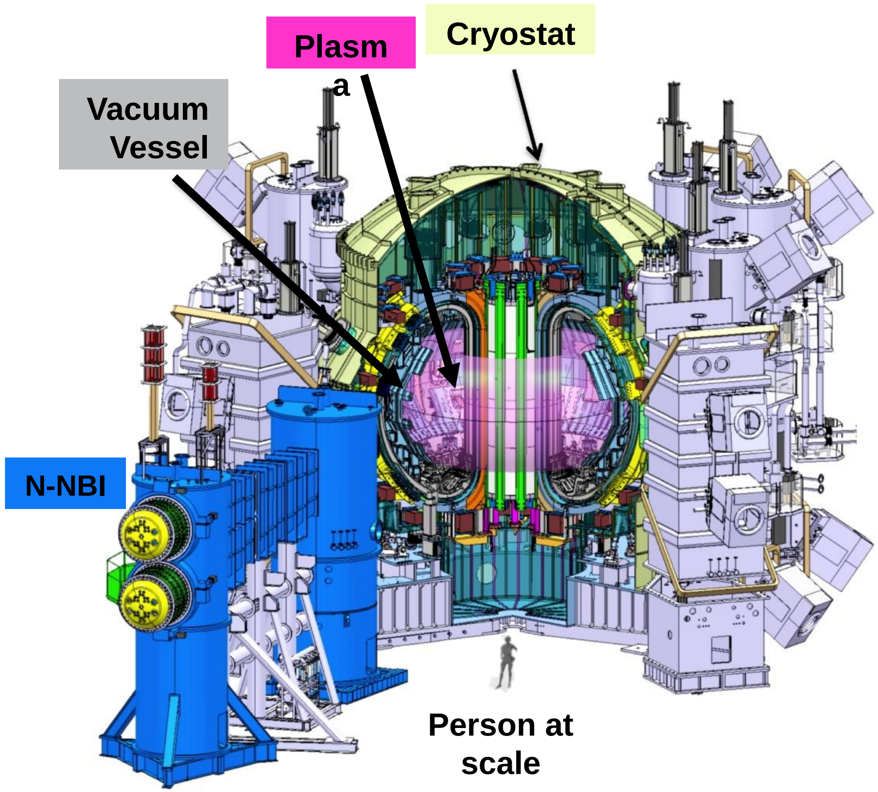
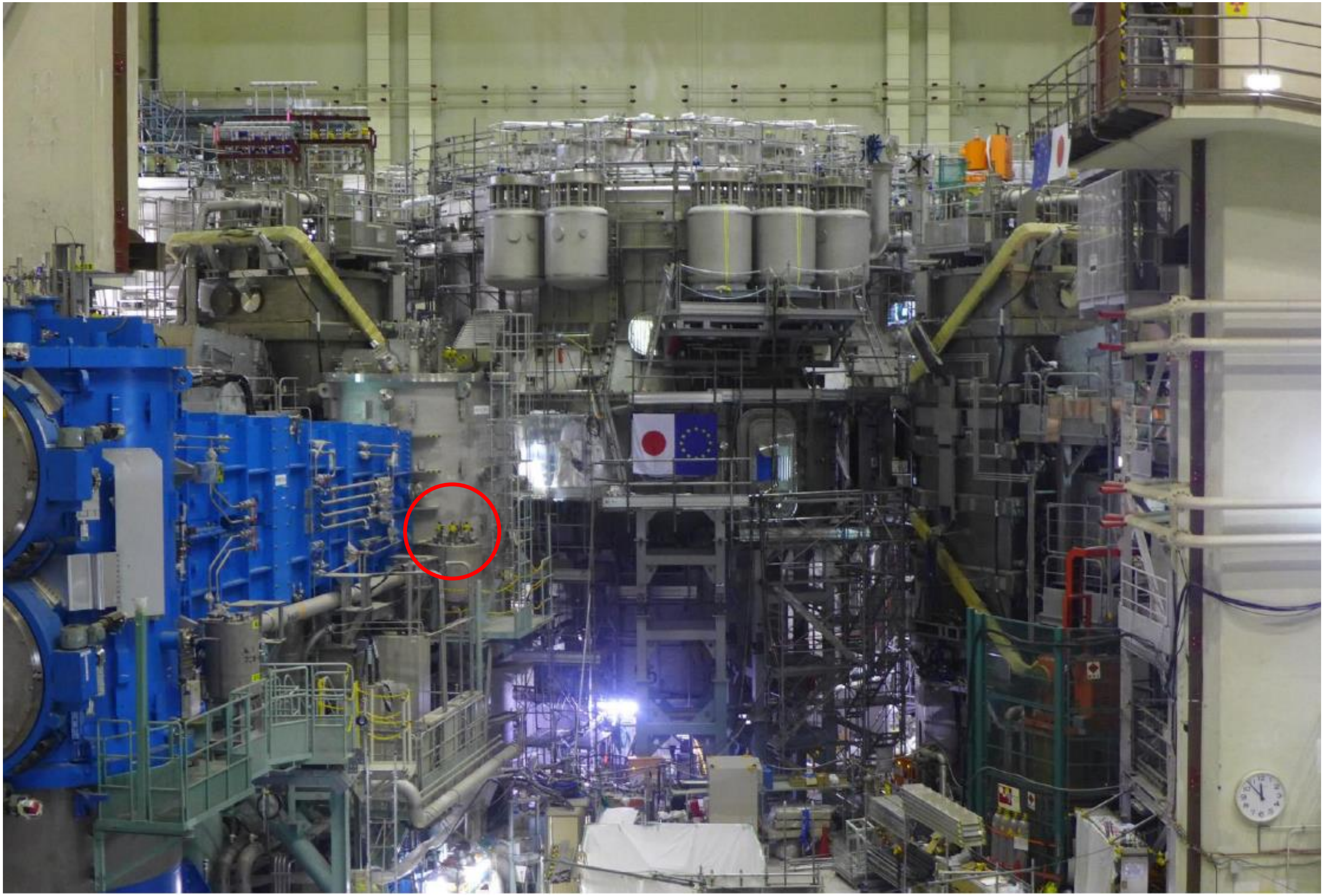
  - Non-inductive current drive capabilities
- Currently, more than 20 diagnostics installed/planned to perform cutting-edge research
- New enhancements being developed (QST, F4E and EUROfusion)



JT-60SA assembly completed in March 2020



JT-60SA Control Room… (back in 2019)

JT-60SA Control Room… (Currently)

EUROfusion participates in JT-60SA project through the WPSA workpackage

- Close collaboration with Fusion 4 Energy (F4E, implementing agency)
- WPSA divided into different areas
  - Scientific Exploitation
  - Code Management and Simulation
  - Machine and Plasma Operations
  - Enhancements
  - International Fusion School
  - Integrated Commissioning
- Enhancements area comprises procurement of different systems to improve JT-60SA performance

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  - Diagnostics

Ongoing

- EDICAM
- VUV Spectrometer
- TS Diagnostics
- FILD

Proposals

- TPCI system
- DR system
- EC Stray Detection system
- Neutron & Gamma diagnostics
- BES system
- IR imaging system
- Ultra-Fast Reflectometry system

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  - Diagnostics
  - Functional/auxiliary systems

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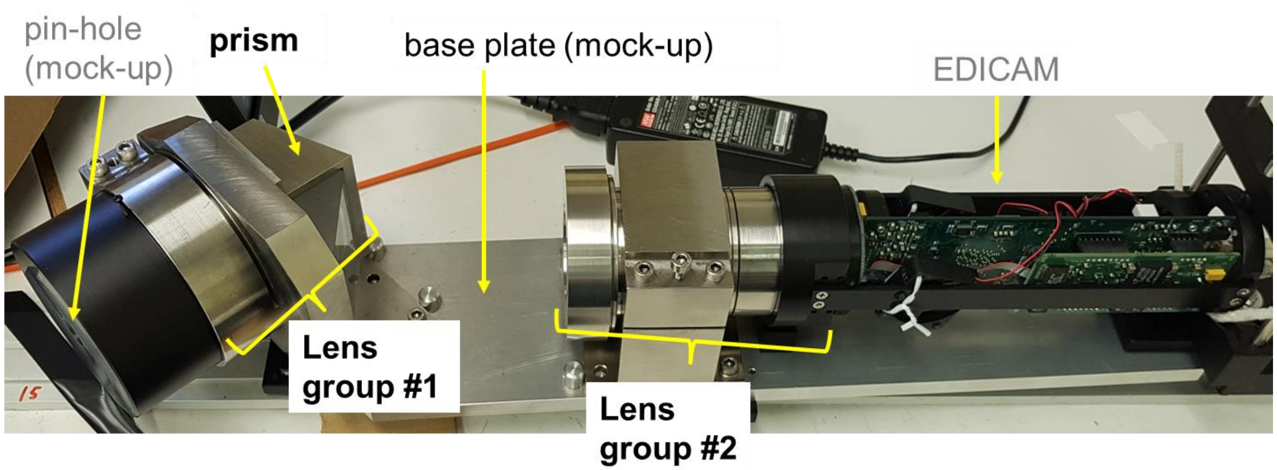
Ongoing

- Divertor Cryopumps
- Massive Gas Injection
- Pellet Launching System
- Remote Access Architecture

Find more: *G. Giruzzi et al. Plasma Physics and Controlled Fusion, 2020*

Event Detection Intelligent Camera (EDICAM)

- Fast wide-angle visible video diagnostic system
  - Recycling and impurity influx
  - Visible light emission associated with fast phenomena (plasma start up, disruptions, gas injection or even edge filaments)



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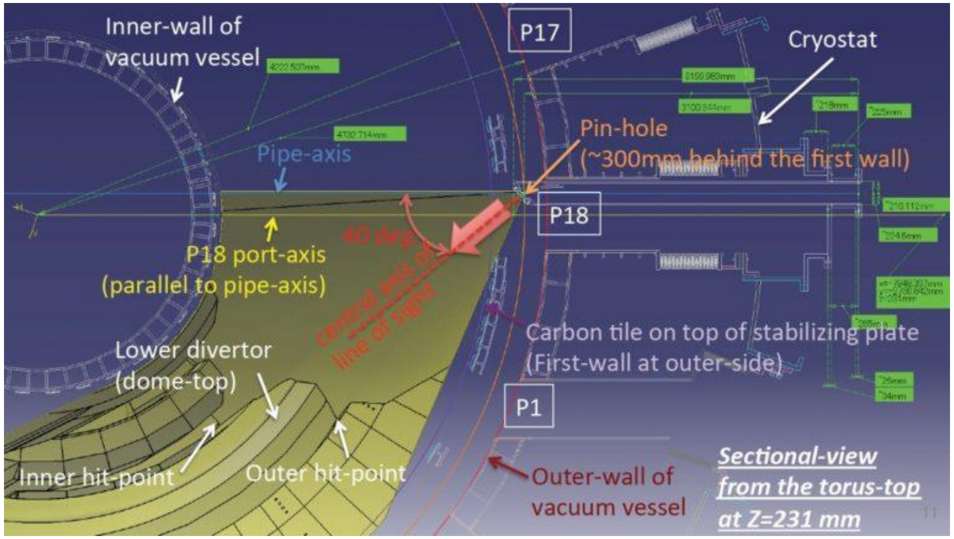
- Located in port P18: tangential view into torus
  - Wide-angle optics (FoV = 80°, 1/5 vessel)
  - Temporal resolution 100 Hz
  - Up to six ROIs simultaneously
  - Manual/On-event triggering



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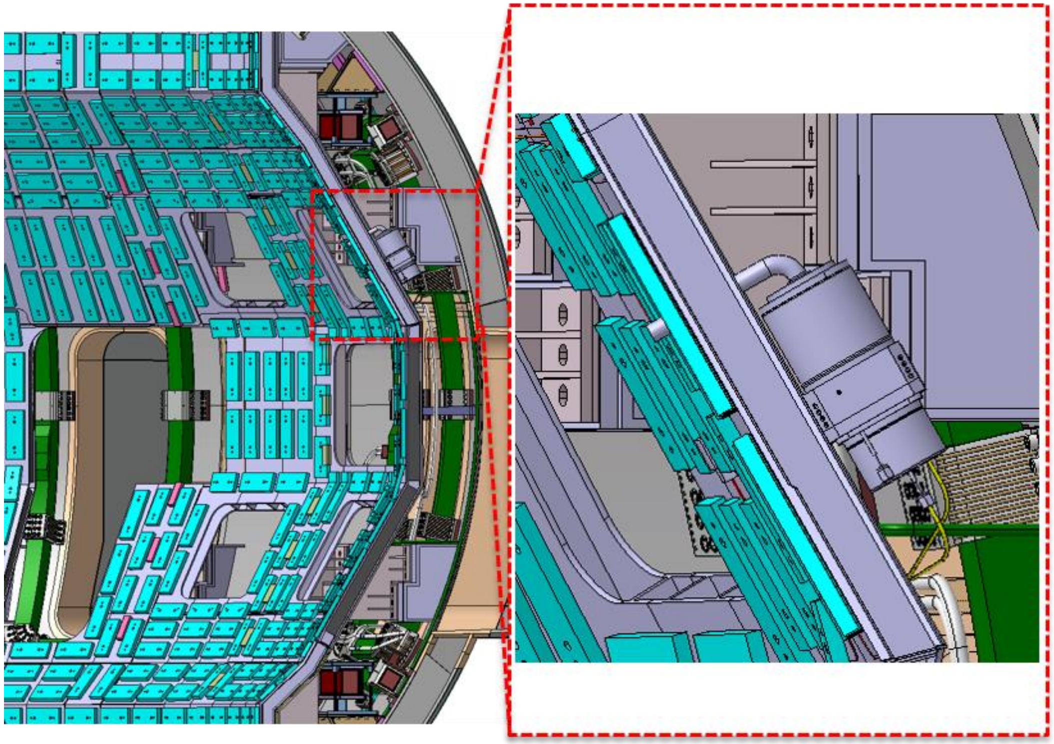
  - Temporal resolution 100 Hz
  - Up to six ROIs simultaneously
  - Manual/On-event triggering
- Project led by EK (Hungary) in collaboration with F4E and QST
- Installed in 2020 / Currently under commissioning

Find more: *T. Szepesi et al. Fusion Engineering and Design, 2020*

Massive Gas Injection System (MGI)

- Two valves in Ports 9&18, fixed against stabilizing plate
- Allows mixing different gas species and injecting it into the vessel
- MGI can be triggered
  - Manually
  - On a plasma event
  - At a predefined time



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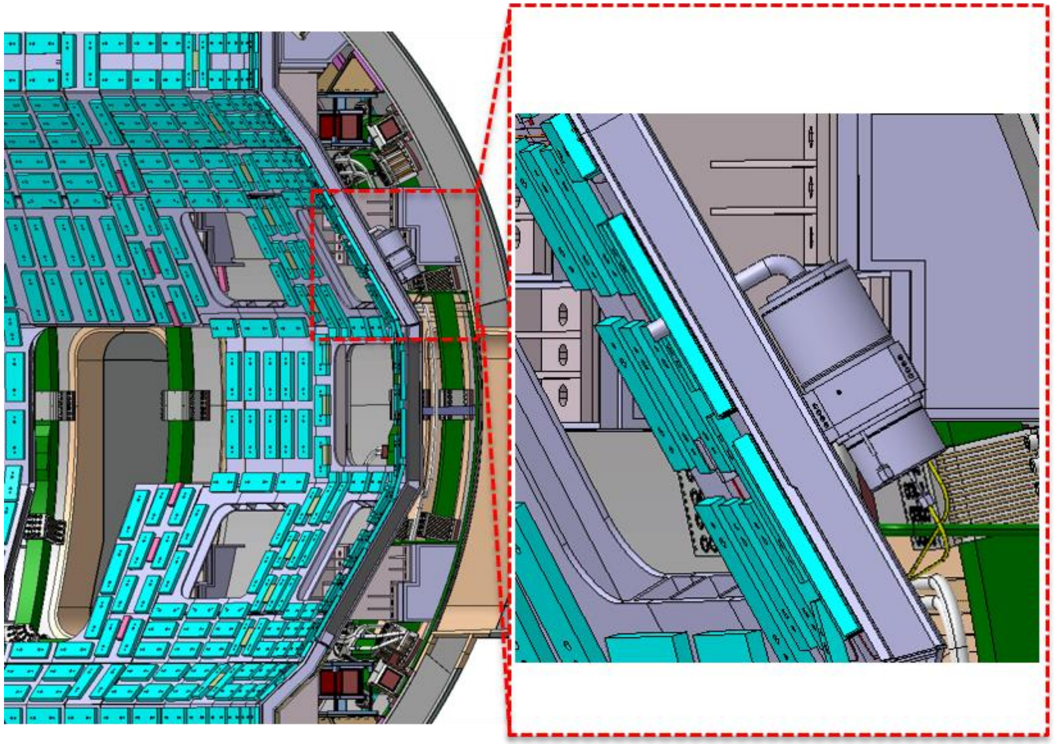
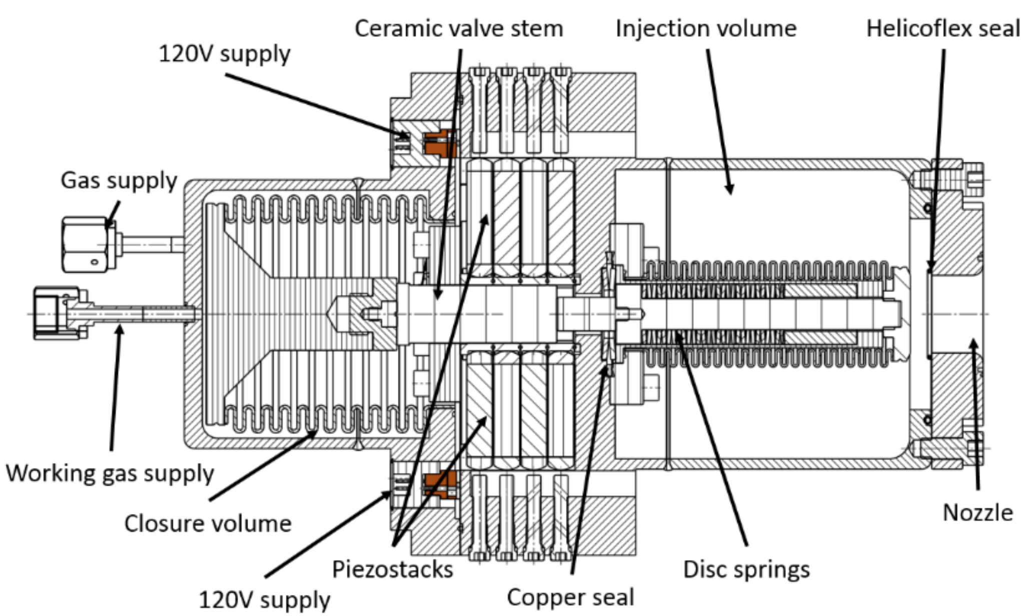
- Allows mixing different gas species and injecting it into the vessel
- MGI can be triggered
  - Manually
  - On a plasma event
  - At a predefined time
- Experimental tool used for
  - Plasma disruption mitigation
  - Study of heat load and force mitigation
- Project led by IPP Garching team (Germany)
- Manufacturing phase ongoing
- To be installed in 2022



Massive Gas Injection System (MGI)

- Piezoelectric stacks and springs for valve actuation
- Metallic bellows allow meeting UHV requirements
- Electronic control system for:
  - Automatic gas mixture
  - Injecting large gas quantities within ms
  - Different operation modes

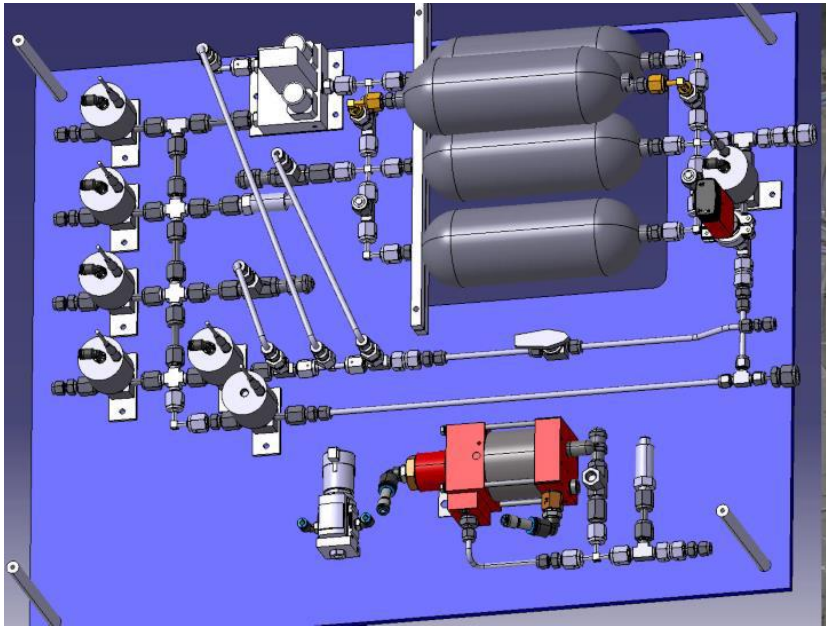


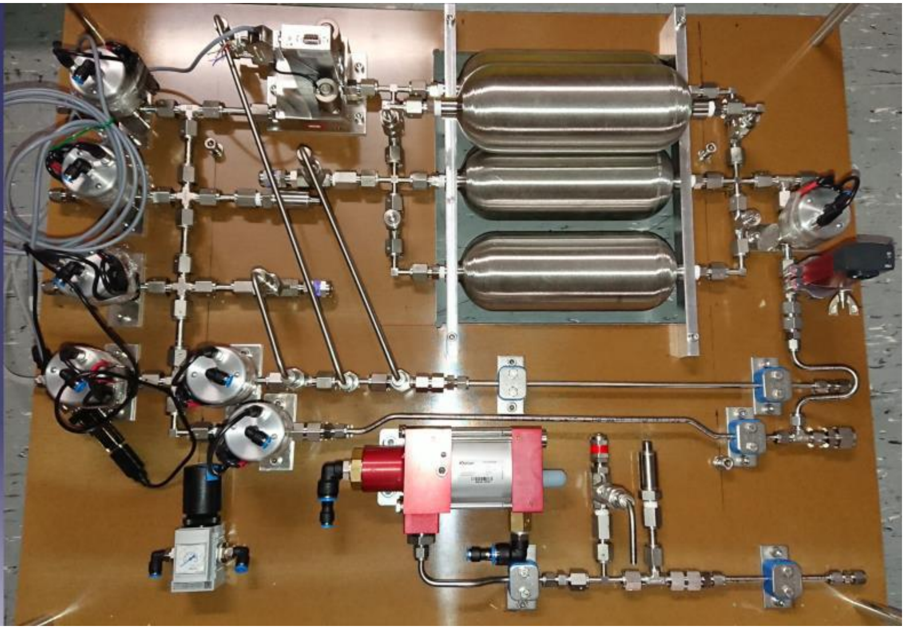
Gas reservoir [cm³]	815
Max. gas pressure [MPa]	7.2 (design pressure 8 MPa)
Max. gas amount [Pam³]	5868
Max. inj. Particles	$1.4*10^{24}$
Opening time [ms]	< 2
Valve plate lift [mm]	7
Nozzle diameter [mm]	28
Size l [mm] x b[mm] x h[mm]	140 x 110 x 292
Piezoelectric stacks	8
Required air pressure [MPa]	1.5 (design pressure 2 MPa)
Closure volume [cm³]	53

Massive Gas Injection System (MGI)

- Piezoelectric stacks and springs for valve actuation
- Metallic bellows allow meeting UHV requirements
- Electronic control system for:
  - Automatic gas mixture
  - Injecting large gas quantities within ms
  - Different operation modes
- Ex-vessel gas preparation system with electronic pressure controller for automated gas mixing

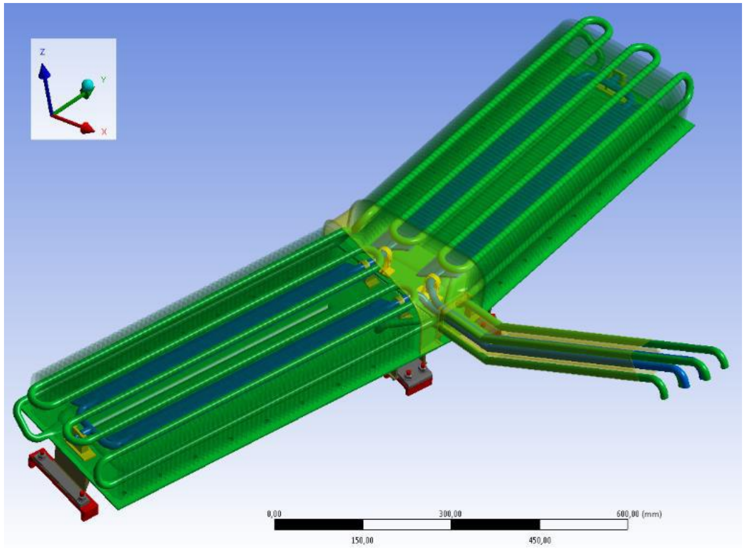
Find more: *M. Dibon et al. 46th EPS Conference on Plasma Physics, 2019*

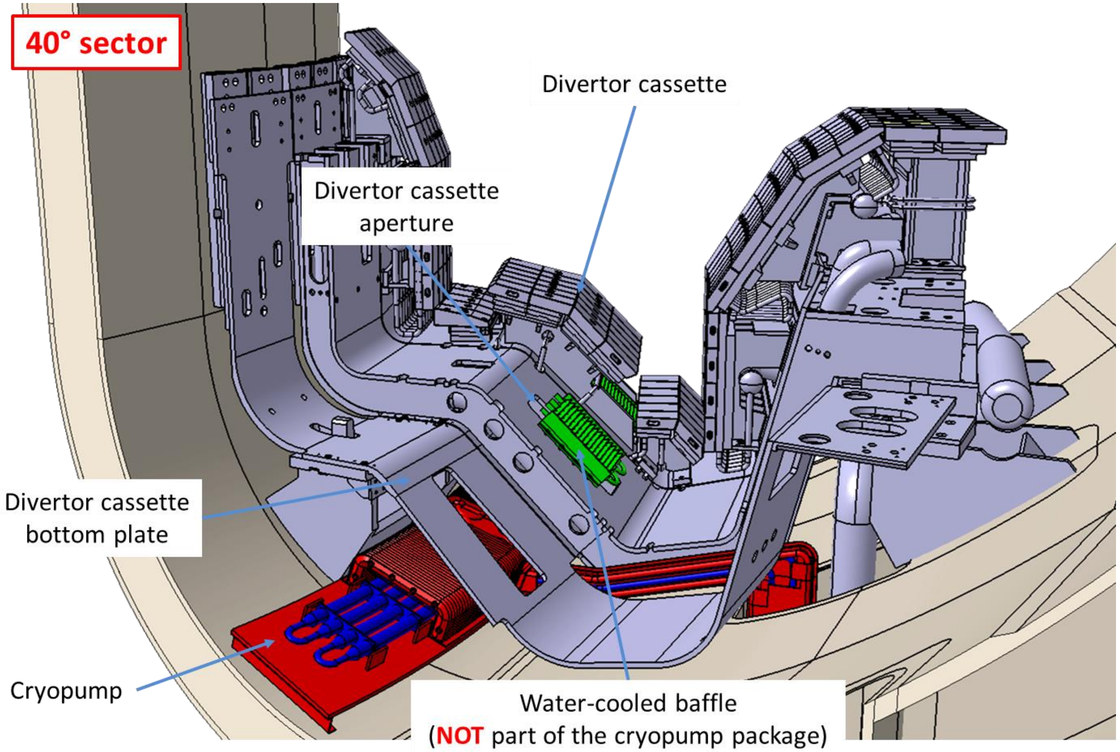




Divertor Cryopumping System

- Objective: evacuate neutralized hydrogen or deuterium fuel seeding gases (N2, Ar)
- Each cryopump unit consists of 2 sub-systems:
    - 3.7 K system: adsorption surfaces (cryopanels) cooled by supercritical helium
    - 80 K system: thermal radiation shield surrounding the cryopanel made of a base plate and an inlet baffle cooled by 80 K gaseous helium





Find more: *X. Luo et al. Fusion Engineering and Design, 2018*

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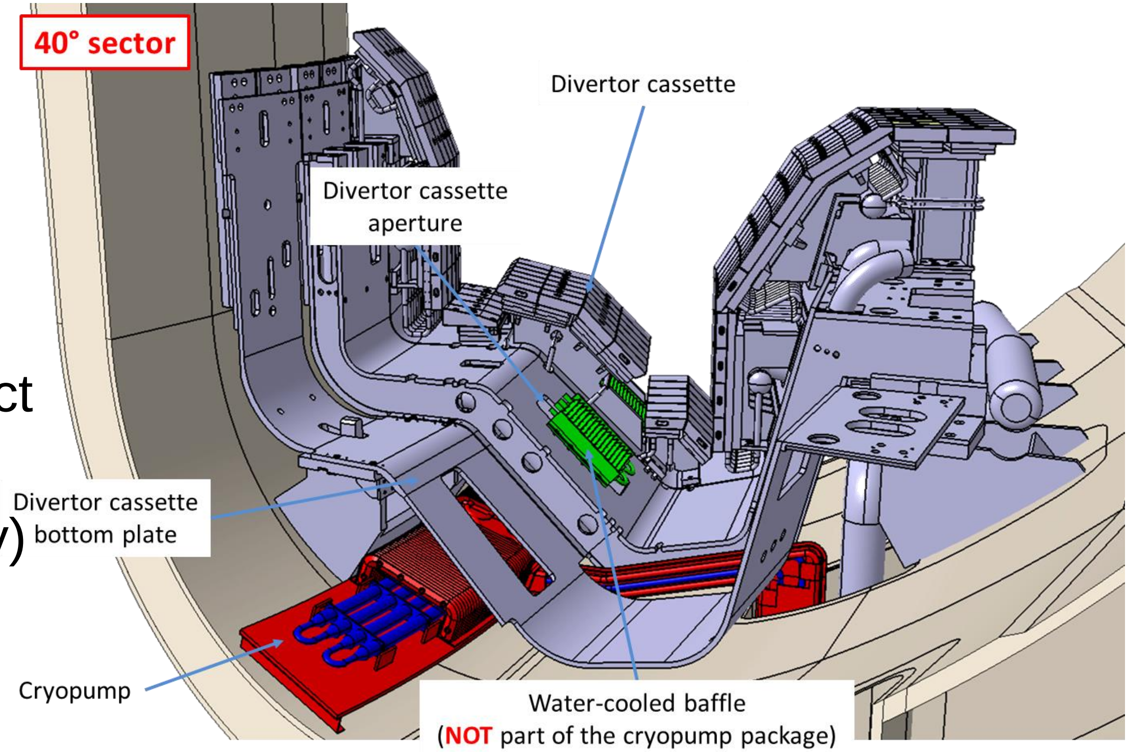
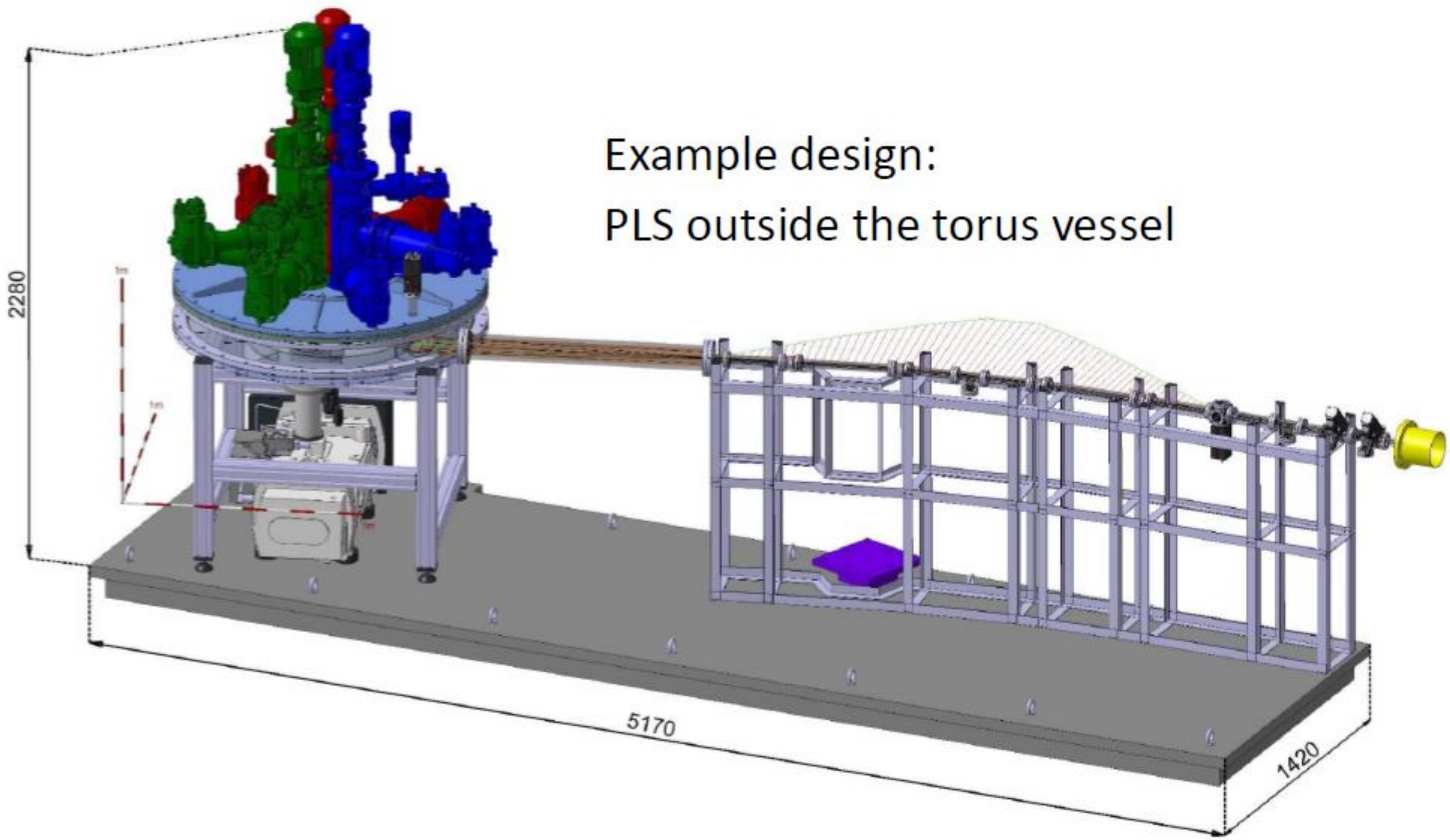
  - 80 K system: thermal radiation shield surrounding the cryopanel made of a base plate and an inlet baffle cooled by 80 K gaseous helium
- 9 identical units uniformly distributed
  - Located under divertor cassettes
  - Covering 40º sector
- Water-cooled baffle to protect from plasma radiation
- Design led by KIT (Germany) and procurement by F4E
- Delivered to Naka in 2022



Pellet Launching System (PLS)

- Produces frozen pellets of deuterium or hydrogen at a diameter of 2.4 mm
- Pellets dropped into a centrifuge: accelerated to 600 m·s-1 at a rate of 100 Hz
- Guiding tube to deliver pellets to inboard side entering the plasma



Example design:

PLS outside the torus vessel

Find more: *P.T. Lang et al. Fusion Engineering and Design, 2019*

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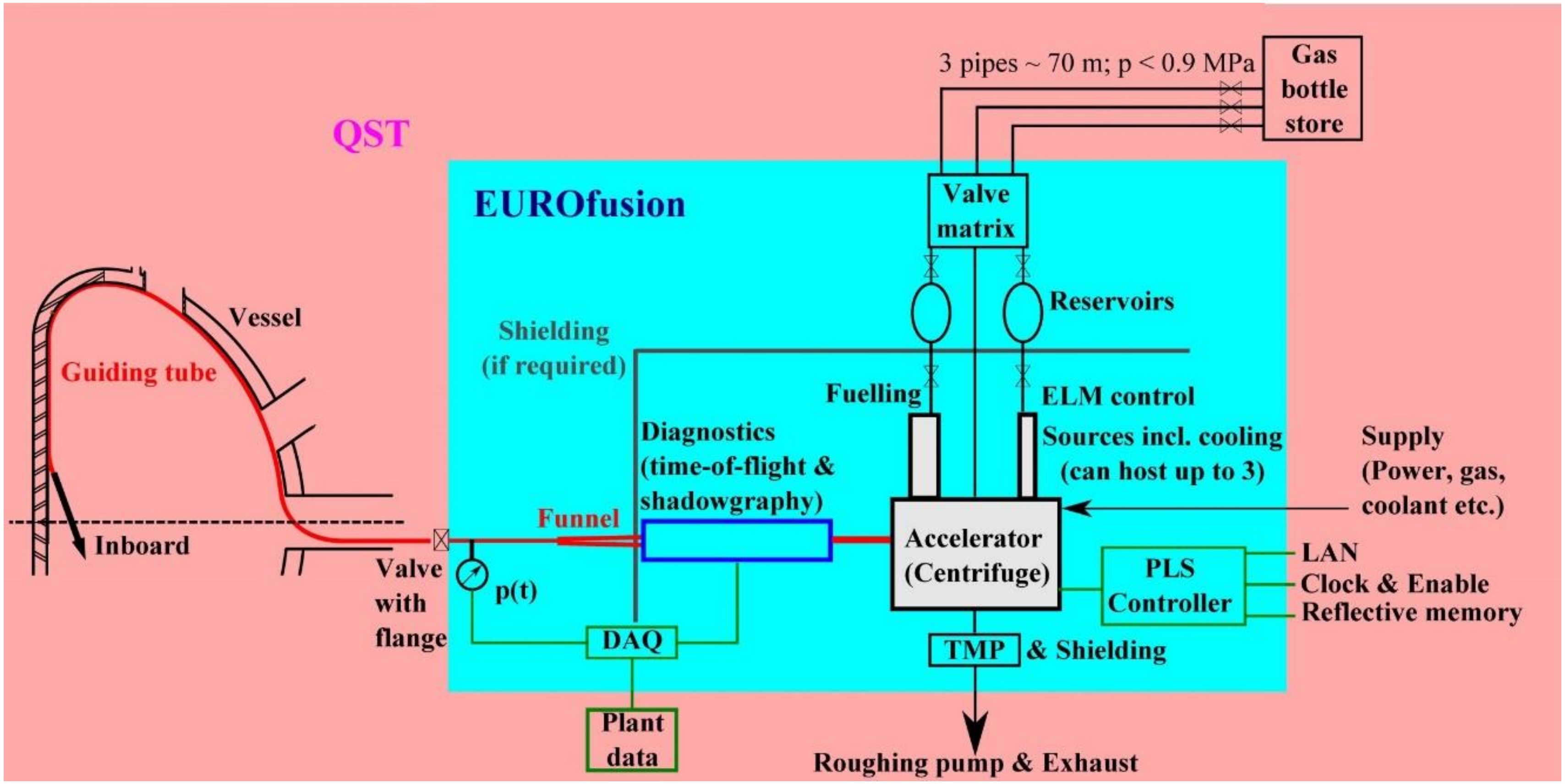
- PLS includes shadography and ToF pellet diagnostics



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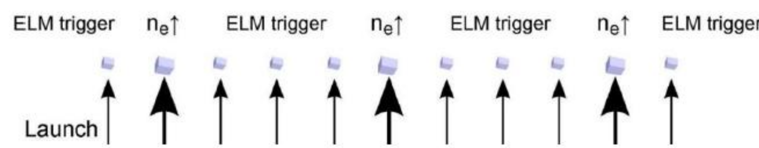
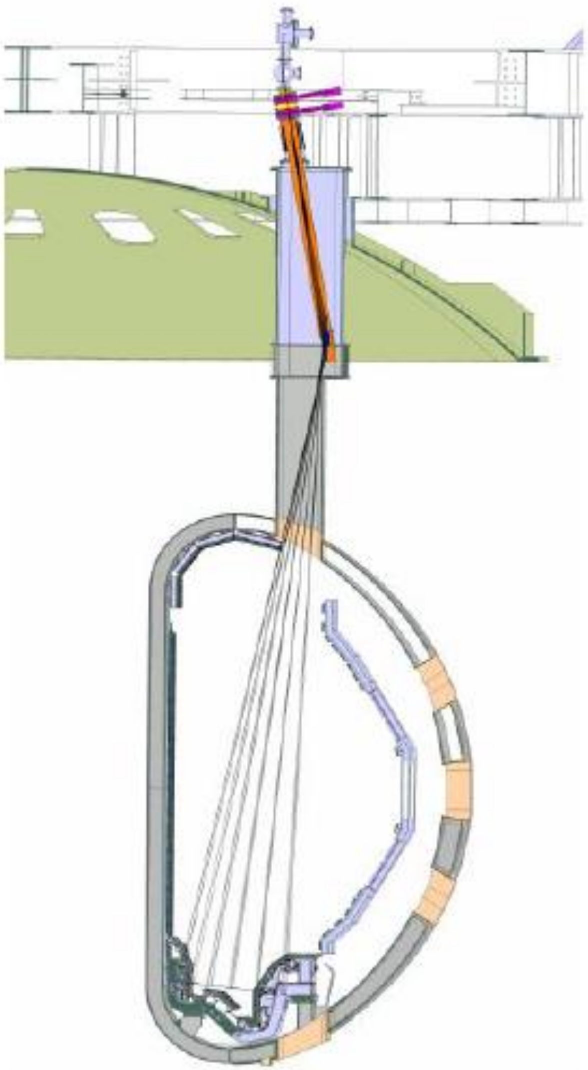
- Guiding tube to deliver pellets to inboard side entering the plasma
- PLS includes shadography and ToF pellet diagnostics
- Almost steady state injection of precisely timed different pellets
- Serving different purposes:
    - Fueling
    - ELM pacing and control
    - Investigate power exhaust
    - Particle balance studies
- Project led by IPP Garching team (Germany)
- Manufacturing phase ongoing
- To be installed in 2022



Vacuum Ultraviolet Spectrometer System (VUV)

- Resolve emission from intrinsic (C, O , Ni, Cr ….W) and extrinsic (N, Ar, Ne , Kr) impurities: evaluate relative/absolute contribution to plasma radiation losses
- Resolve C and Ne lines: able to detect volume recombination processes (in the proximity of detachment)
- Contribute to divertor physics studies: distinguish radiation from plasma X-point and inner and outer legs



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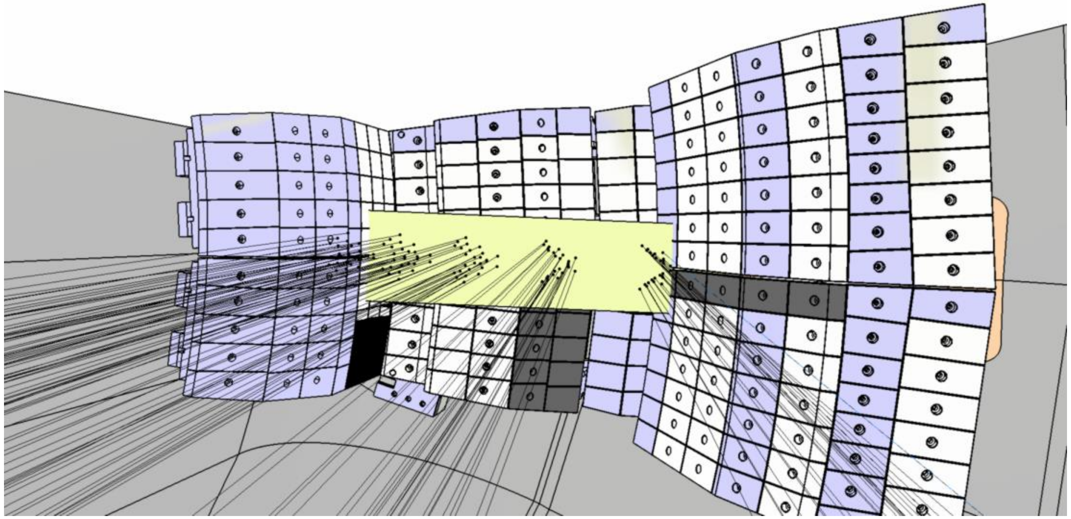

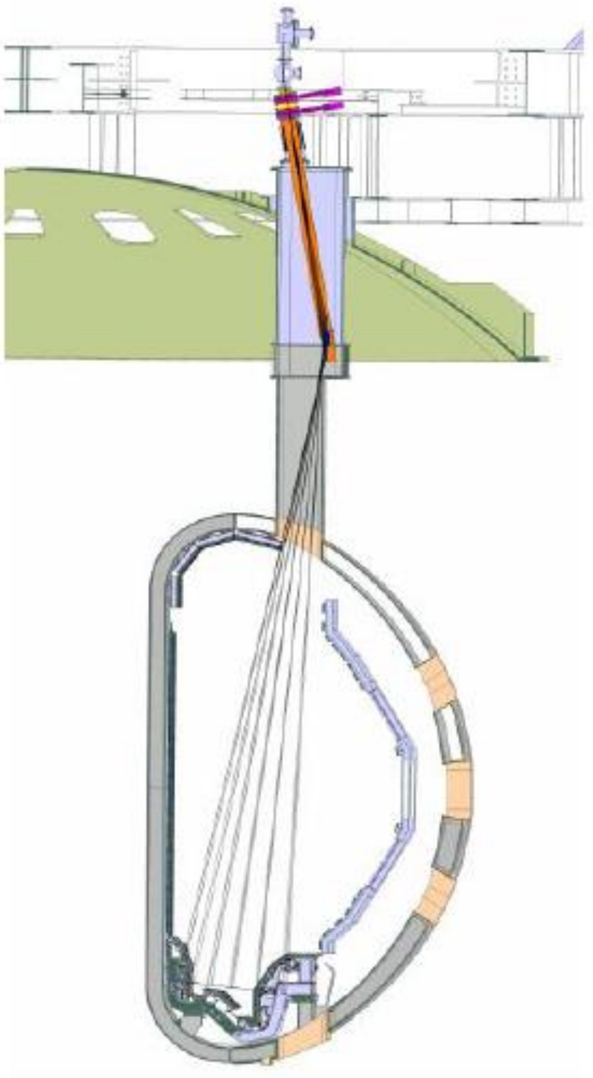

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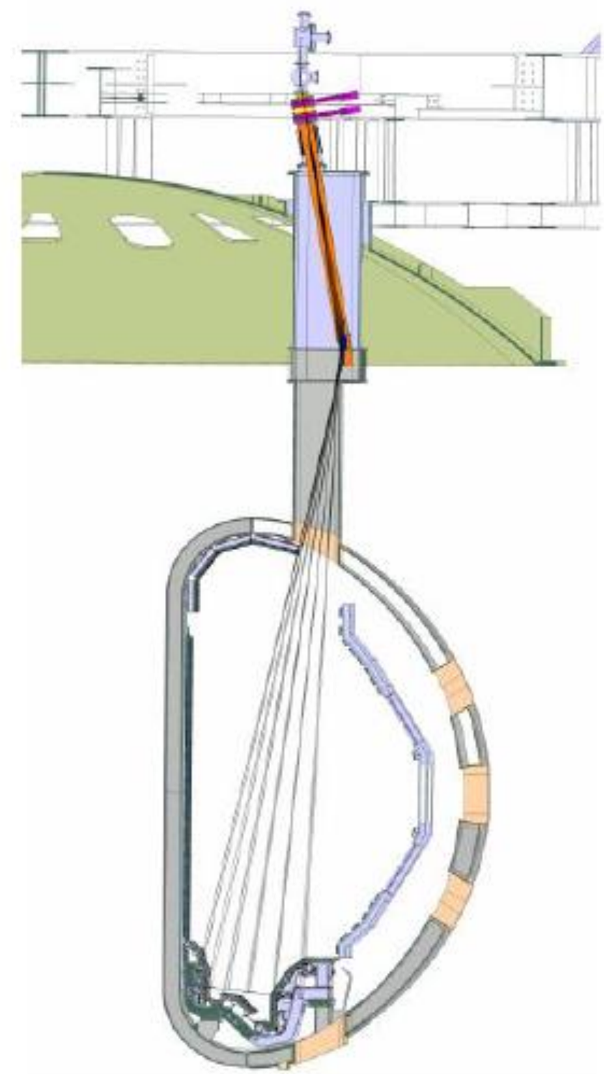


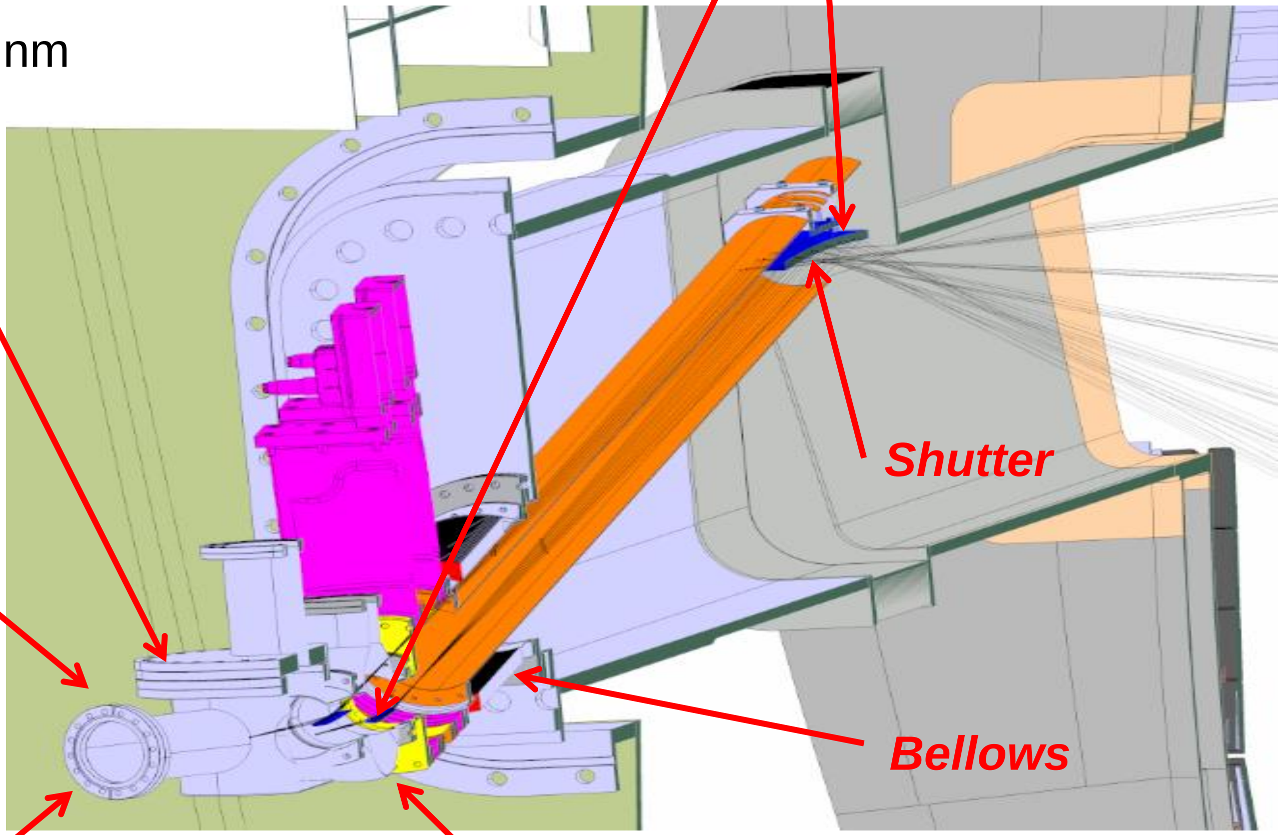
Find more: *M. Valisa et al. 46th EPS Conference on Plasma Physics, 2019*

Vacuum Ultraviolet Spectrometer System (VUV)

Gratings: Custom toroidal holographic
(design by W Biel)
l resolution: 0.1 and 0.2 nm
/respectively

Collecting mirrors: Toroidal mirrors

Spectrometer:
modified
Double SPRED
251 McPherson

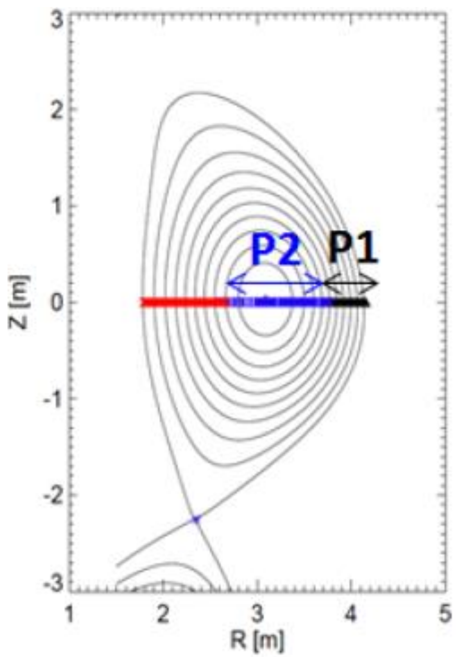


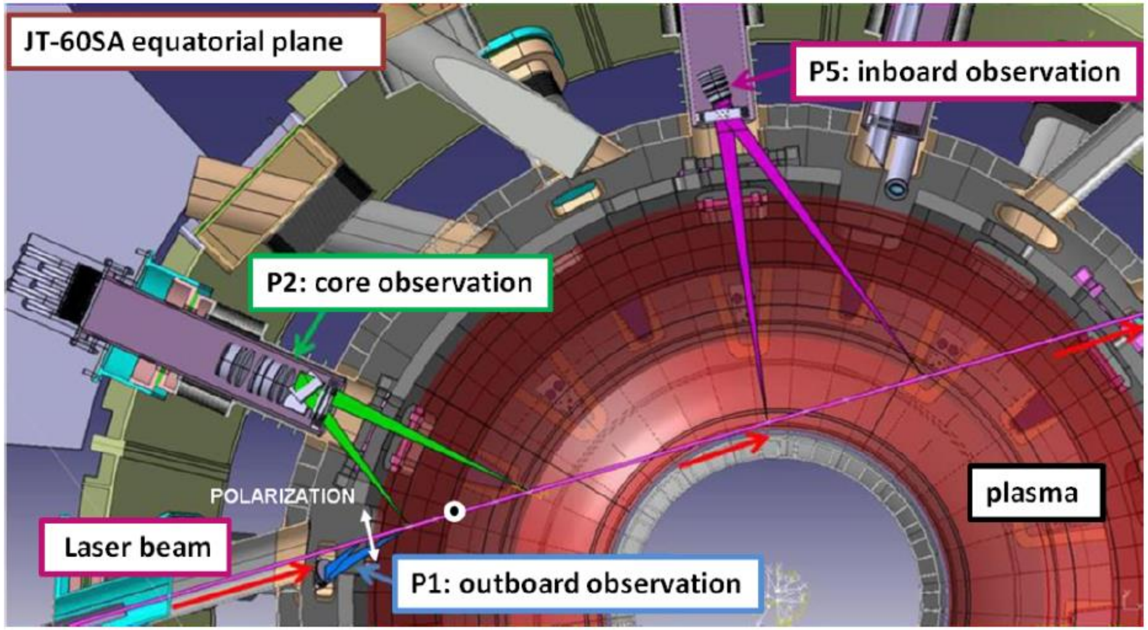
Detectors:
2D CCD 2048x512
(13 mm pix.) / raw
shift time < 5 ms

Find more: *M. Valisa et al. 46th EPS Conference on Plasma Physics, 2019*

Thomson Scattering Diagnostics (TS)

- Measuring plasma electron temperature (Te) and density (ne) profiles with high accuracy (detecting Thomson scattering effect of a high-intensity pulsed laser beam)
  - P2 plasma core observation
  - P1 plasma edge observation (Low field side and plasma boundary)
  - P5 plasma inboard observation (High field side, future implementation)
- Common 1064 nm Nd:YAG laser beam path: passing torus equatorial plane tangentially to inner wall and exiting vessel towards external beam dump





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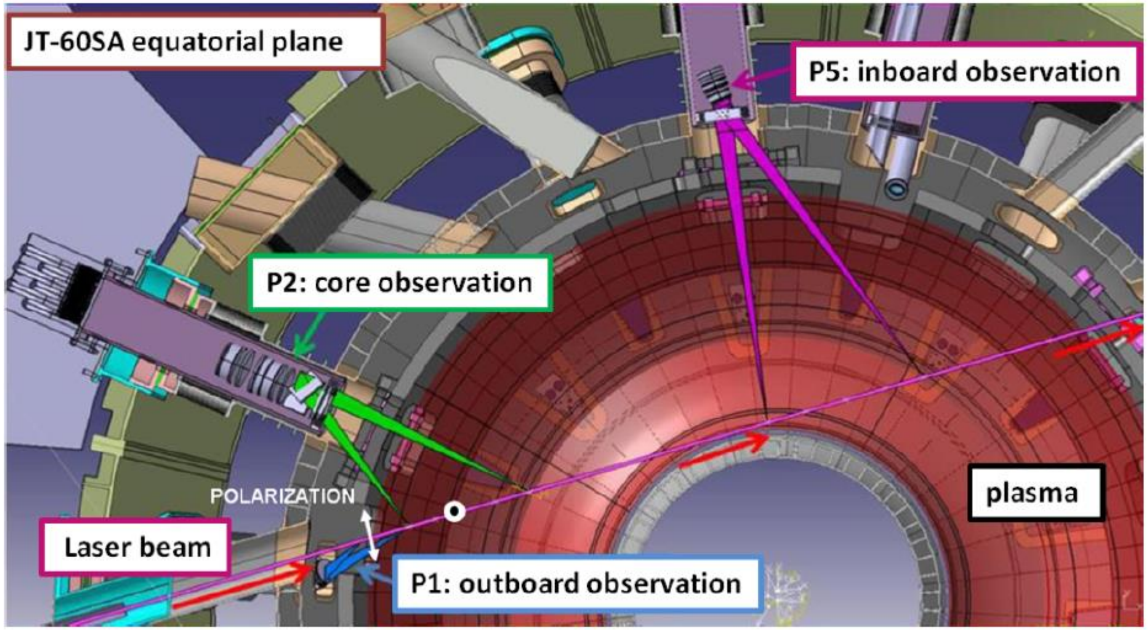
- Manufacturing/procurement phase ongoing
- To be installed in 2022



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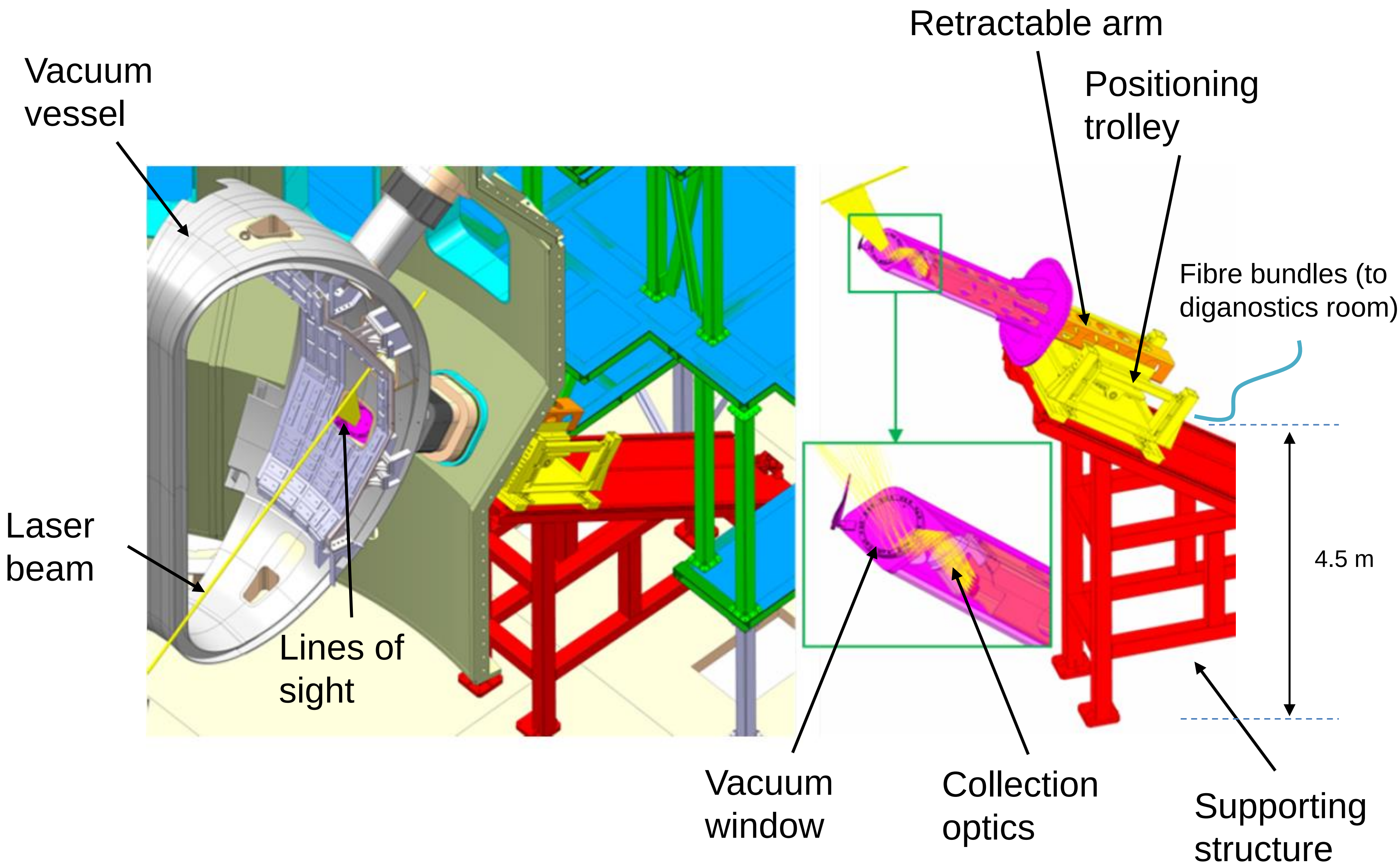

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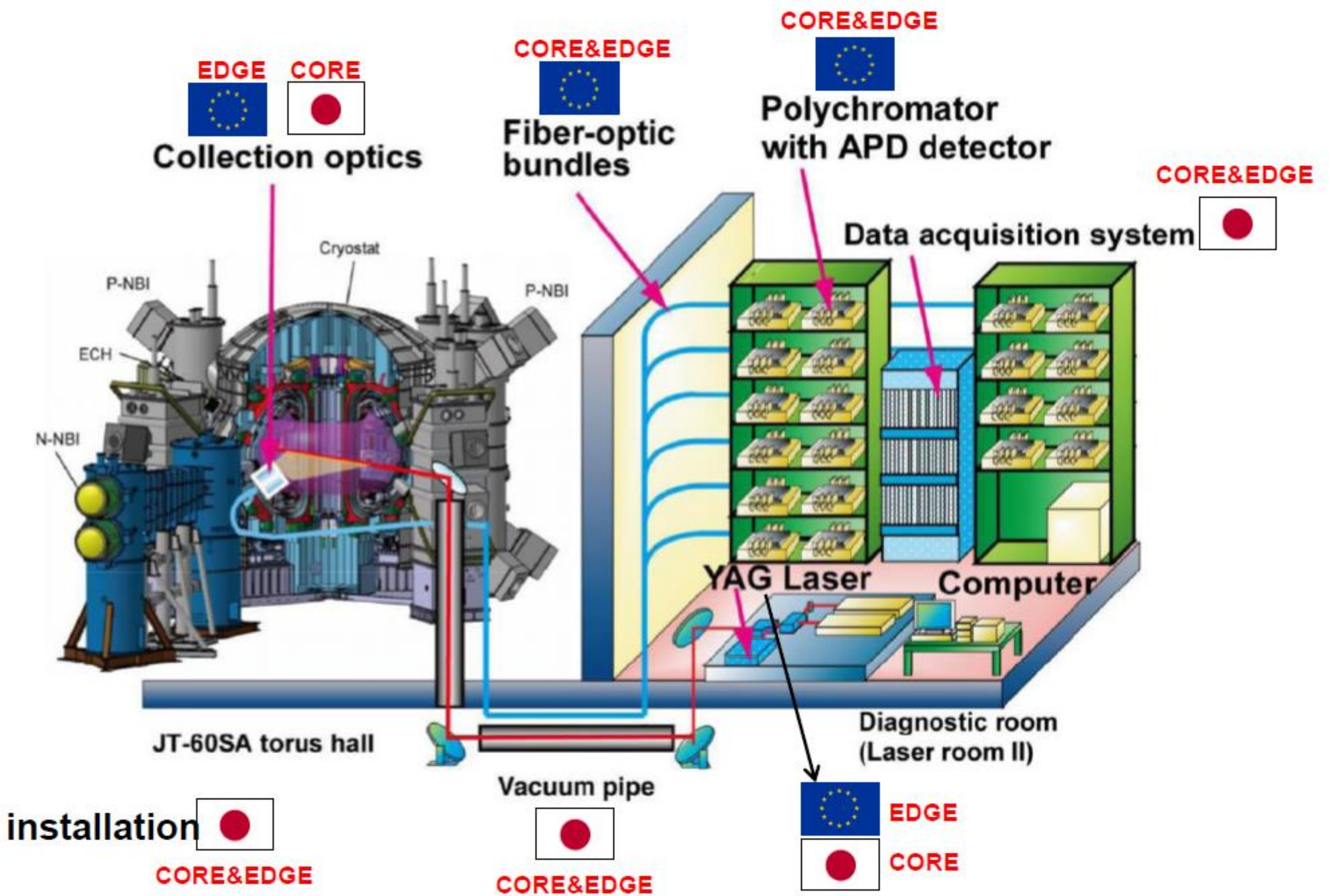
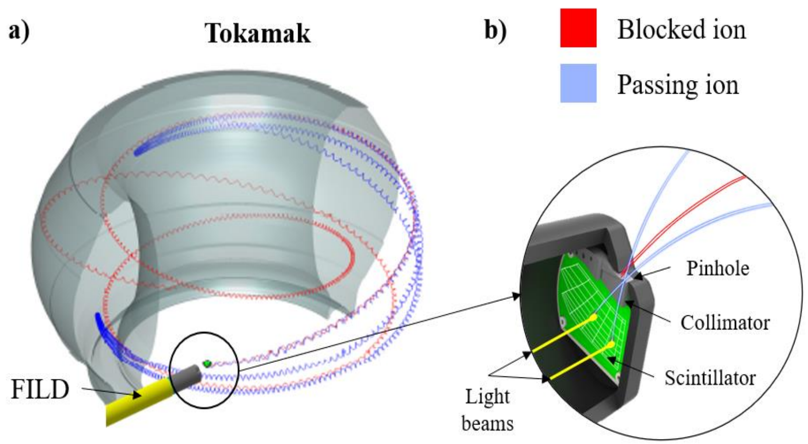
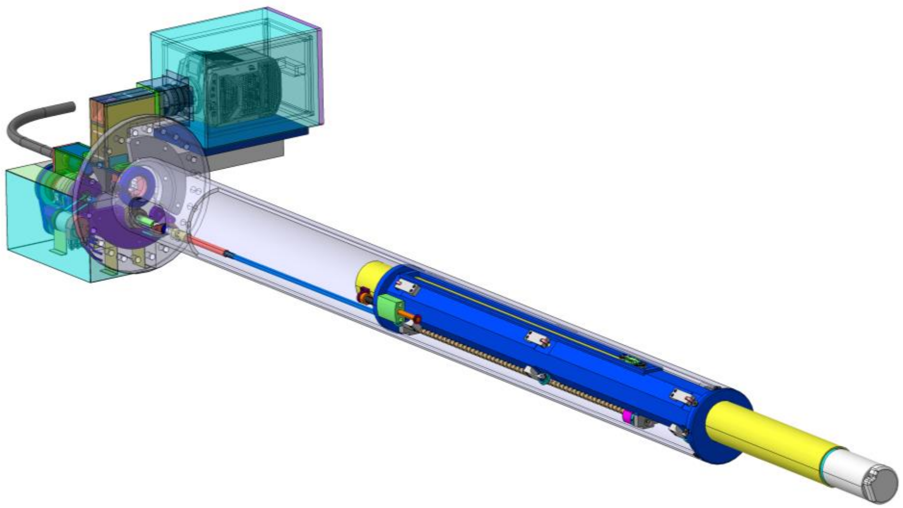


Find more: *H. Tojo et al. Review of Scientific Instruments, 2021*

Fast-Ions Loss Detector (FILD)

- Used in tokamaks for characterizing fast ions escaping plasma confinement
  - Study mechanisms provoking fast ions losses (e.g., plasma instabilities)
  - Contribute to develop mitigation strategies (e.g., externally applied magnetic fields)
- Works as a magnetic spectrometer dispersing ions onto a scintillator plate
- Strike points recorded using image acquisition system with high temporal and spatial resolutions





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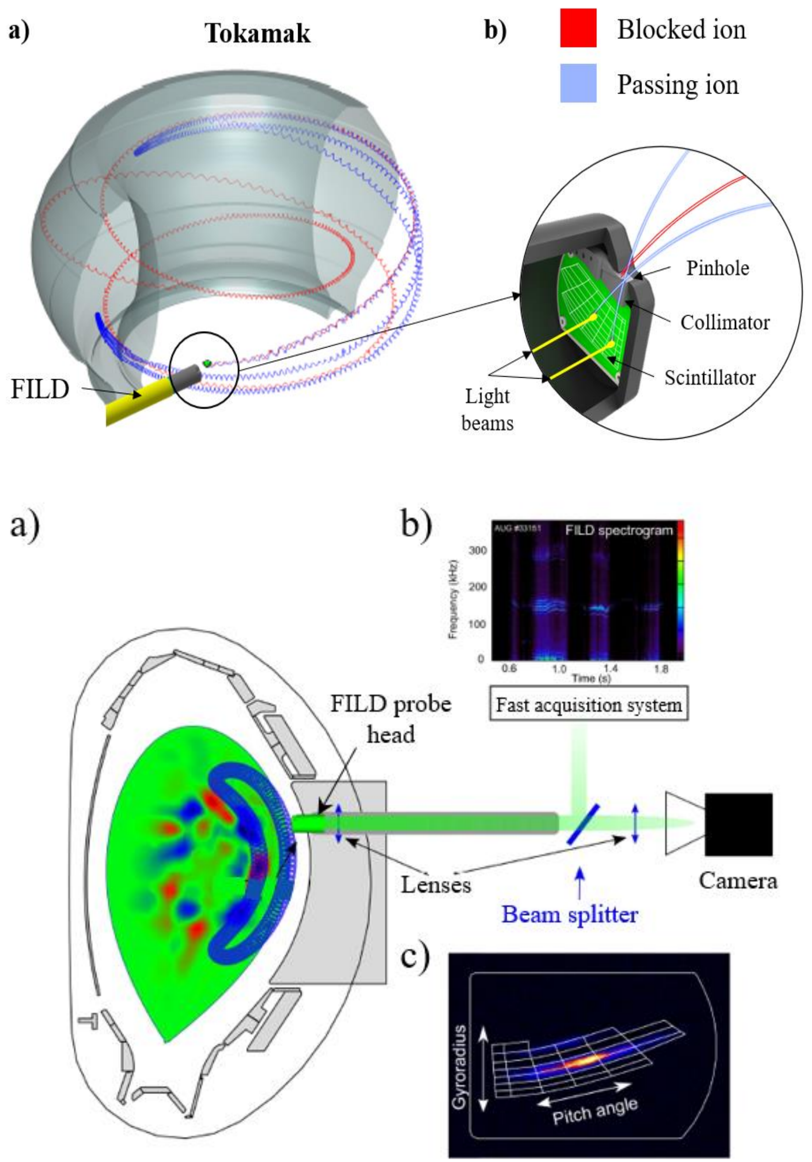
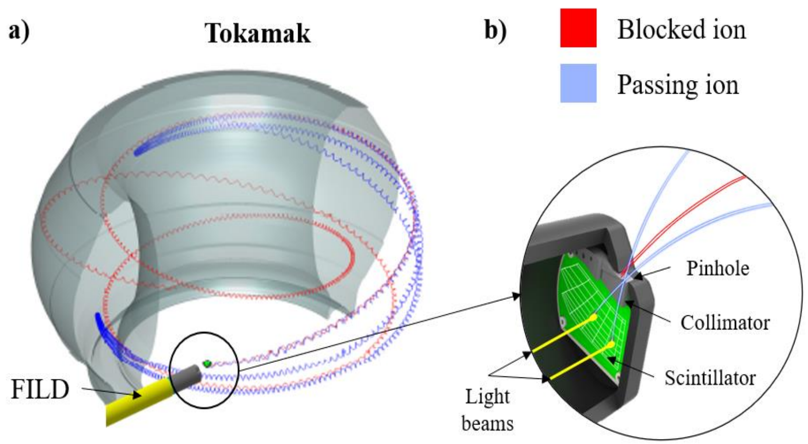
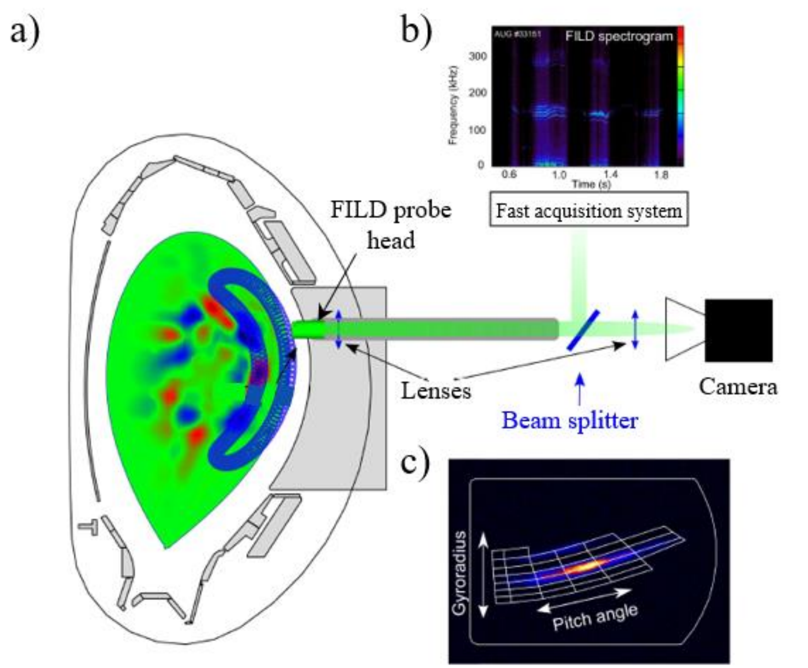


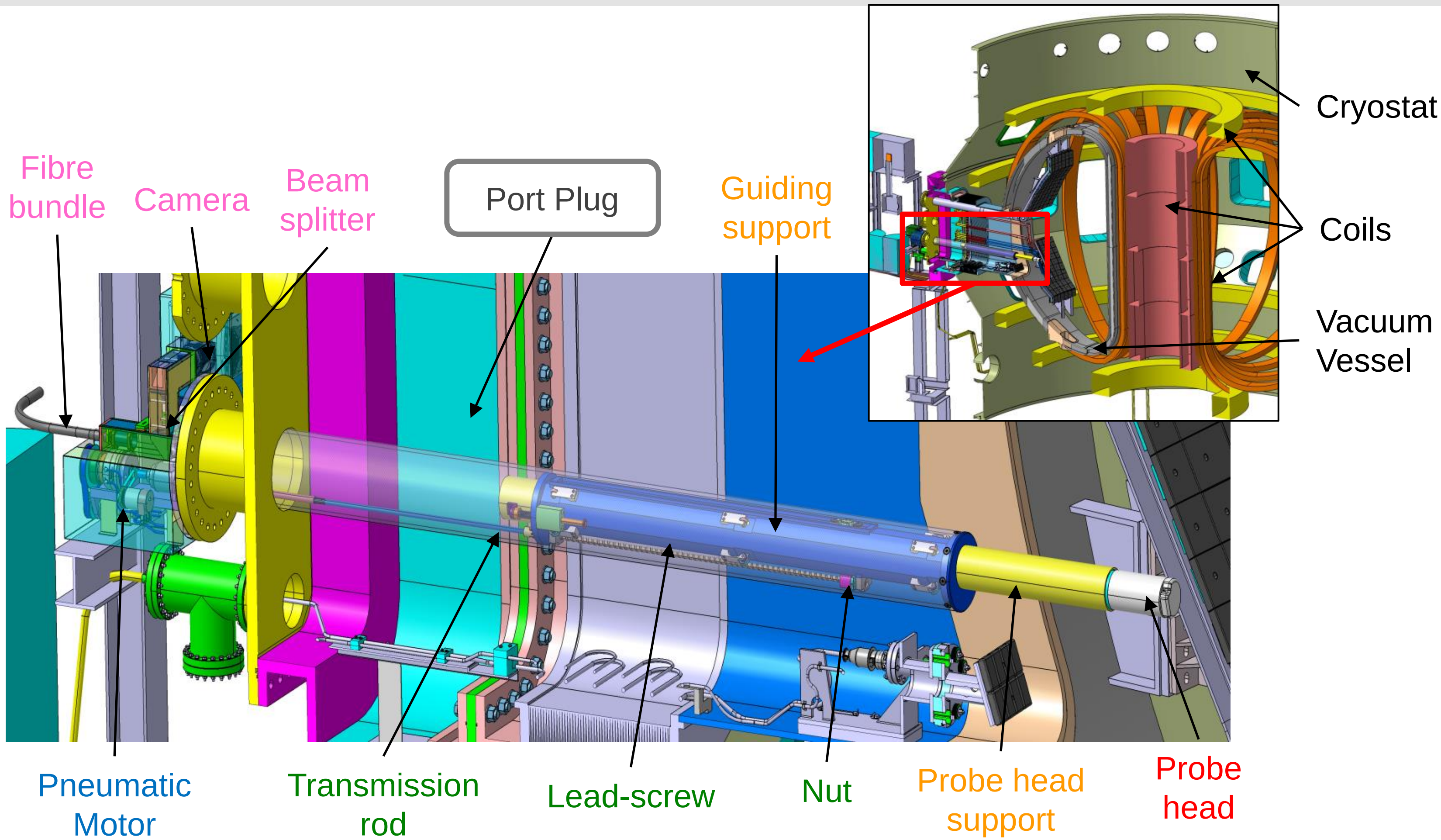
Fast-Ions Loss Detector (FILD)

- Used in tokamaks for characterizing fast ions escaping plasma confinement
  - Study mechanisms provoking fast ions losses (e.g., plasma instabilities)
  - Contribute to develop mitigation strategies (e.g., externally applied magnetic fields)
- Works as a magnetic spectrometer dispersing ions onto a scintillator plate
- Strike points recorded using image acquisition system with high temporal and spatial resolutions
- Project led by University of Seville (Spain) with collaborations from ENEA (Italy)
- Final design to be concluded in 2021
- To be installed in 2024





Fast-Ions Loss Detector (FILD)



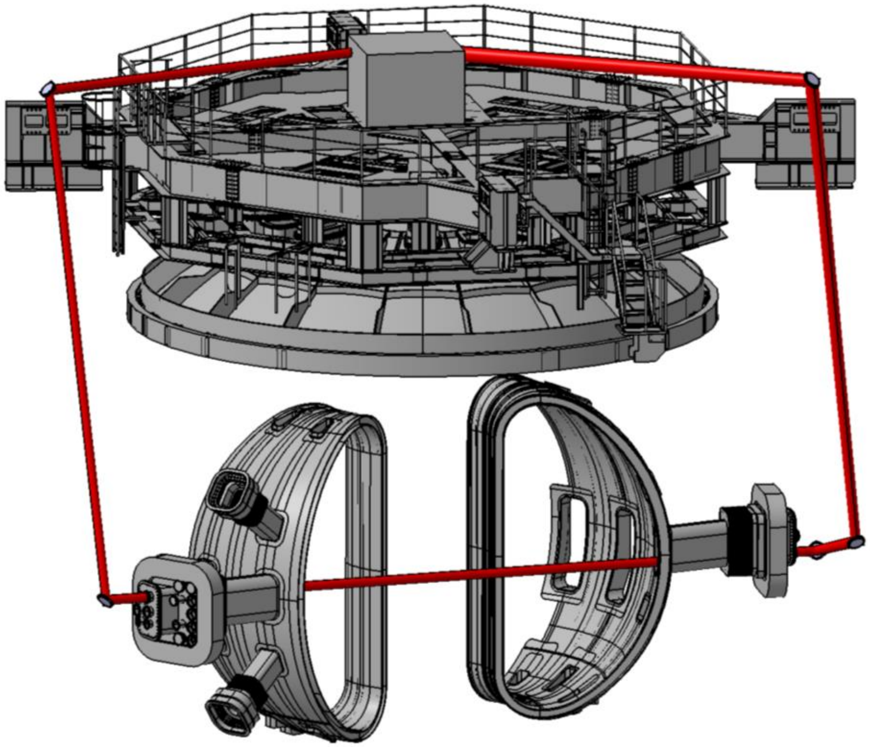
Motion drive unit ⇒ Transmission ⇒ Guiding system ⇒ Probe head ⇒ Light acquisition system

Find more: *J. Ayllon-Guerola et al.*
Fusion Engineering and Design, 2021

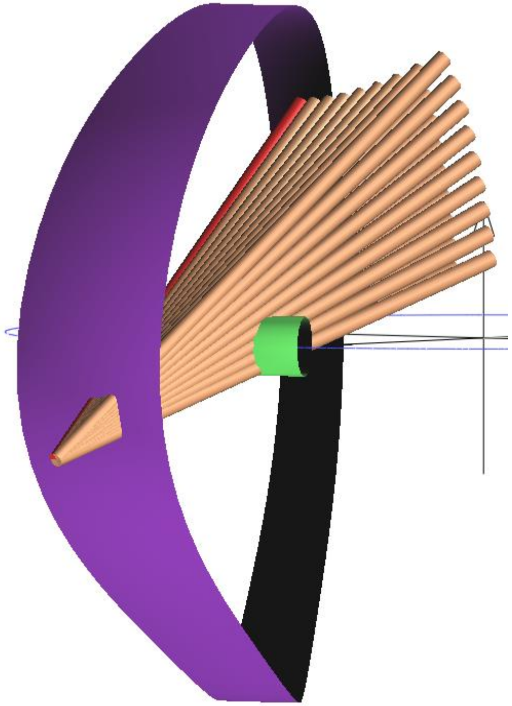
Several Enhancement Projects Selected for Period 2021-2025 by EUROfusion

- Two diagnostic proposals being prepared for consideration by experimental/scientific teams

Tangential Phase Contrast Imaging (TPCI) system



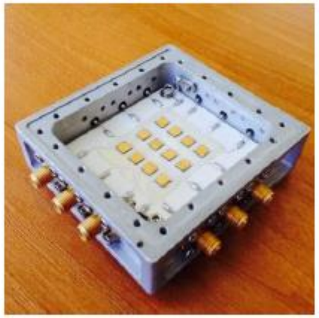
Doppler Reflectometry (DR) system



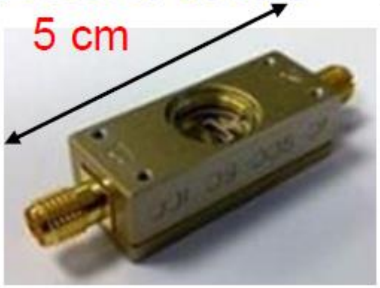
Several Enhancement Projects Selected for Period 2021-2025 by EUROfusion

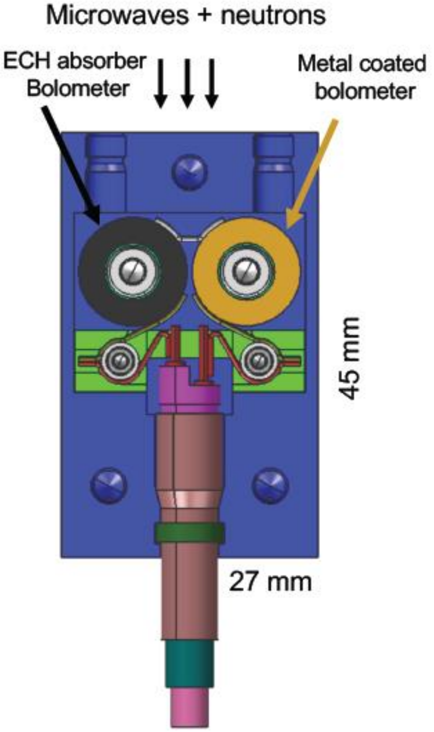
- Several diagnostic proposals in feasibility study phase
  - Neutron and Gamma diagnostics
  - EC Stray Detection system

VNS matrix at JET



Standalone oblique diamond detector at JET

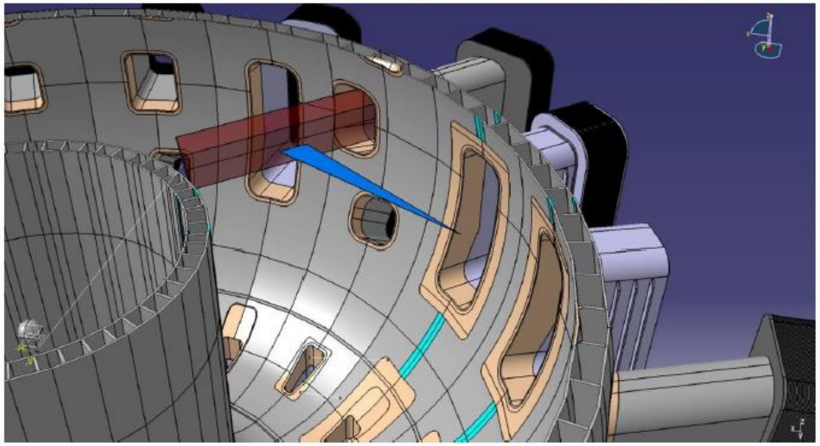




Several Enhancement Projects Selected for Period 2021-2025 by EUROfusion

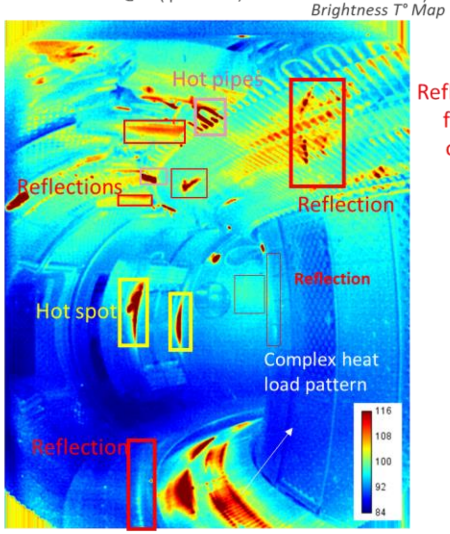
- Several diagnostic proposals in feasibility study phase
  - Neutron and Gamma diagnostics
  - EC Stray Detection system
  - Beam Emission Spectroscopy (BES) system
  - Ultra-Fast Reflectometry system
  - IR imaging system

D-BES – Set-up 8B beam on port 16. Observation on P-17



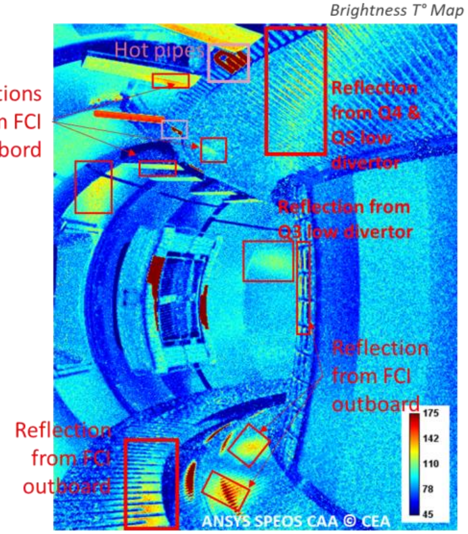
Experimental IR Image

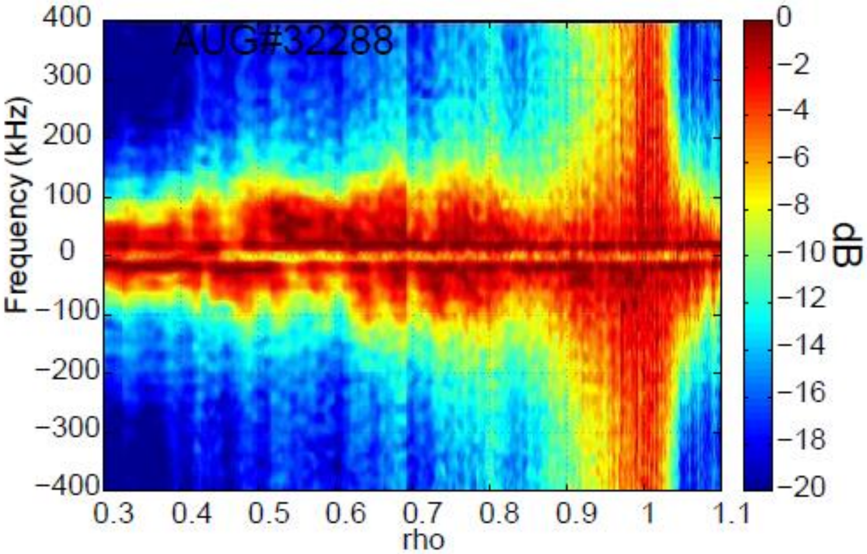
#Pulse 55210 @ 7s(Ip=500 kA, 4.4MW LH + 0.7MW FCI)



Reflections from FCI outbord

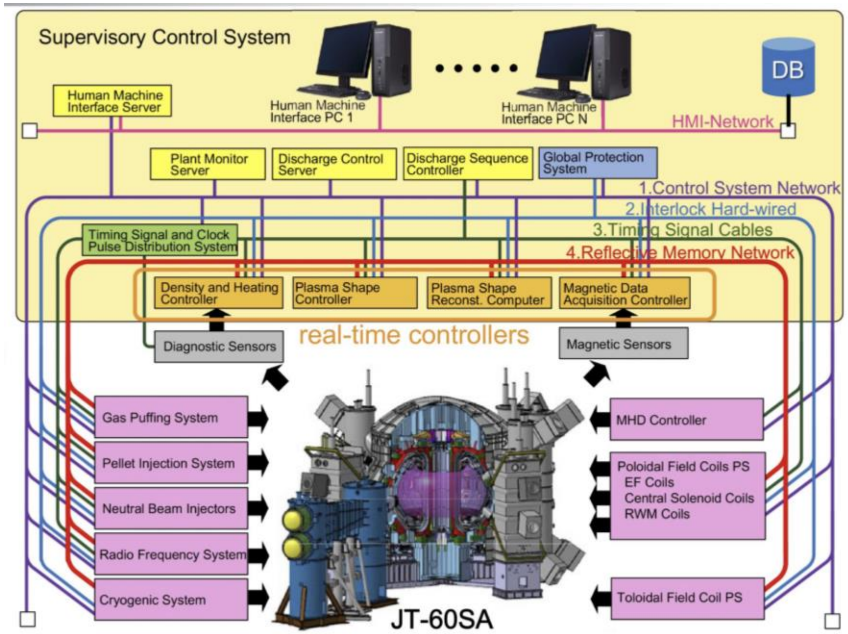
Simulated IR Image





Several Enhancement Projects Selected for Period 2021-2025 by EUROfusion

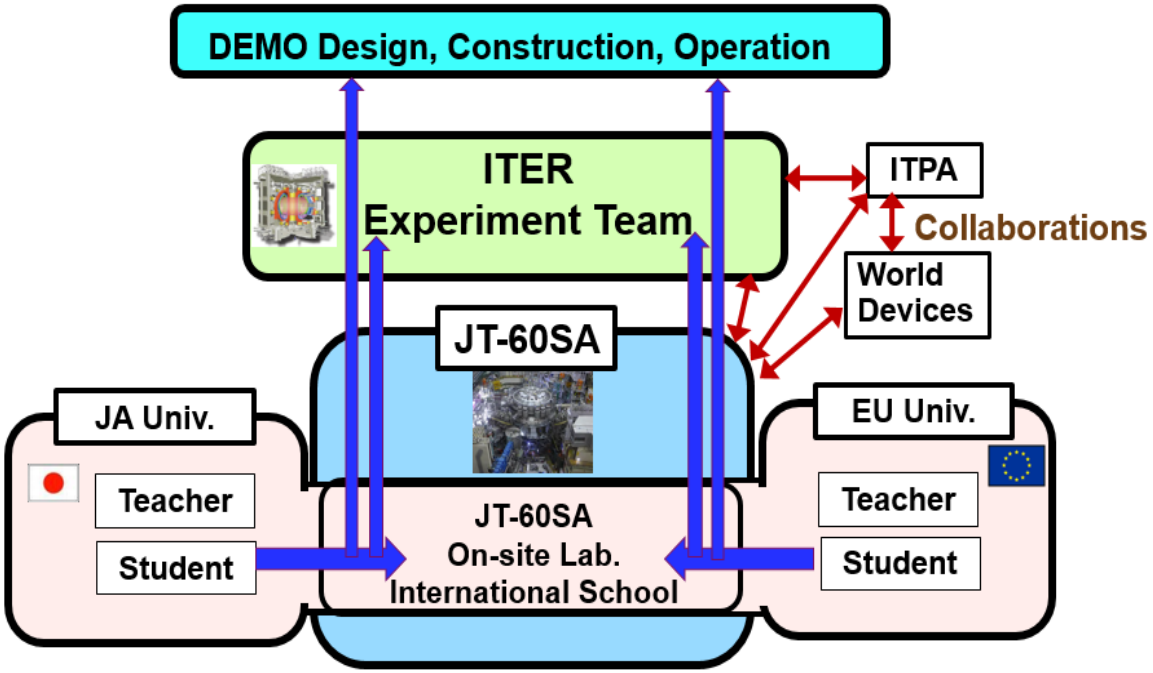
- Remote Access Architecture design and implementation
  - Conceptual design phase
  - Based on previous experience in other tokamaks
  - Coordination with EU-REC activities
  - Technology solutions to run complex experiments remotely



JT-60SA International Fusion School (JIFS)

- JT-60SA missions:
  - Supporting ITER exploitation
  - Contributing to DEMO machine and scenario design
  - Fostering new generations of fusion physicists and engineers

  $\Rightarrow$ Connect the project with training initiatives



courtesy: Y. Kamada

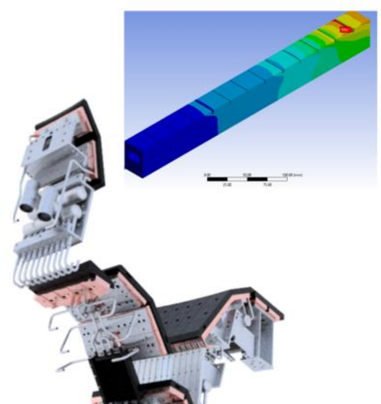
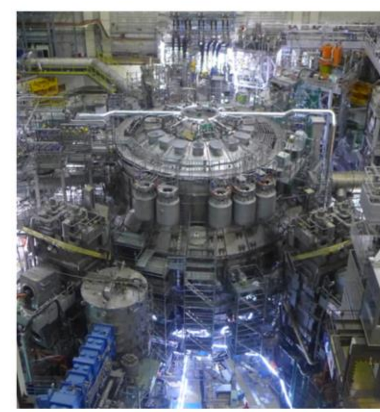
JT-60SA International Fusion School (JIFS)

- Completing the training of selected students & young professionals by:
  - Lectures on fusion physics, engineering, operation
  - Group work using the JT-60SA facility, laboratories, modelling tools and data as an ideal playground for practical examples and applications

- Creating links between students and young professionals from Japan and Europe*, who could then:
  - Participate in JT-60SA operation, scientific exploitation and upgrades
  - Be involved in Japanese and EU participation in the ITER programme.

*Note: here Europe means EU + countries associated to the EURATOM fusion programme



Summary

- Nuclear fusion is a promising energy source for humanity
- Crucial experiments being prepared and run in the next 10 years: exciting field for physicist and engineers
- Tokamaks are the most used machines to experimentally study nuclear fusion
- JT-60SA Tokamak built in Naka (Japan) by Japan and EU: operation started in 2021
- New enhancements (diagnostics, functional and auxiliary systems) being developed (QST, F4E and EUROfusion)
- JT-60SA International Fusion School (JIFS) upcoming