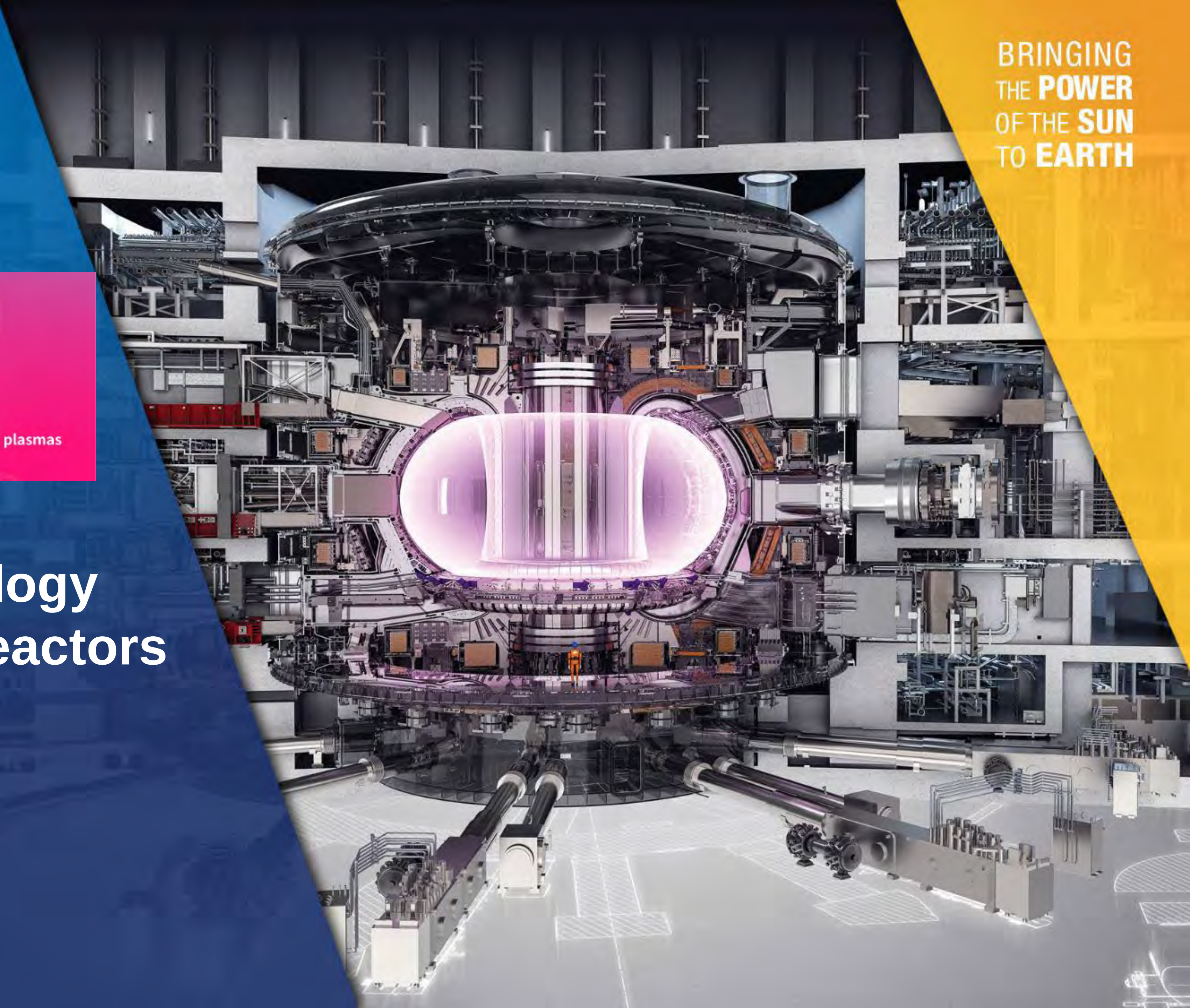
FUSION FOR ENERGY

BRINGING THE POWER OF THE SUN TO EARTH

IIS2026

ITER International School

Physics and engineering of heating and current drive systems for magnetic fusion plasmas



L-15: H&CD technology challenges in fusion reactors

Paco SÁNCHEZ
Fusion for Energy, F4E

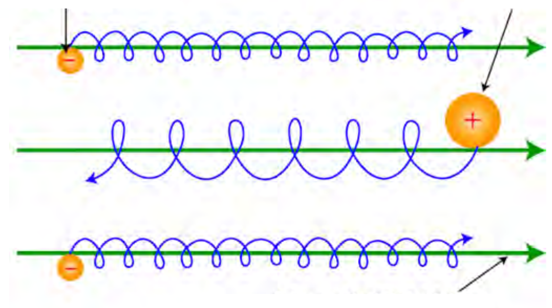
乐山 24.07.2026

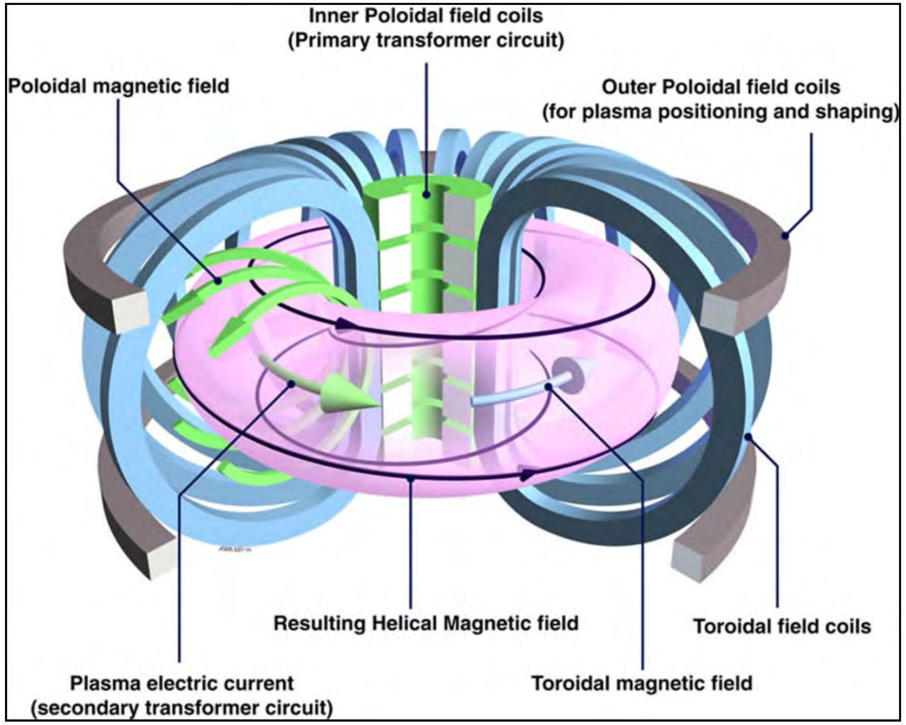
Outline of Talk – H&CD Challenges in Fusion Reactors

- **Heating & Current Drive (H&CD) Systems and Technologies**
- Heating Neutral Beam (HNB)
  - The ITER HNB system
  - Main parts and challenges
- Ion Cyclotron Resonance Heating (ICRH)
  - The ITER ICRH system
  - Main parts and challenges
- Electron Cyclotron Resonance Heating (ECRH)
  - The ITER ECRH, from the plasma to the microwave source
  - EC Launchers, parts and challenges
  - EC Gyrotrons, parts and challenges
  - EC Power Supplies, parts and challenges

Fusion Reaction and Control

Confinement: The plasma electrons and ions (D^+ and T^+) are **charged** and thus follow helical trajectories around magnetic field lines ➔ **magnetic fields** are used to **confine the particles** avoiding the loss of energy by collisions with the Tokamak walls





In a Tokamak like ITER, the **magnetic confinement** is created by a combination of **toroidal** and **poloidal** magnetic **fields / coils**

Heating plasma up to the **required 150 millions ºC** can be done with **EM waves** and/or with **neutral beams:**

The **Hot Side of Fusion**!

Thermal equilibrium

Some time for your feedback ☺

A. Why not “using” **Ohmic heating** to reach fusion-relevant plasma temperatures?

B. For the ITER target Q = 10 and P_{fus} = 500 MW, how much **external power** is required? Does it match with the ITER installed power?

Thermal equilibrium

A. Why not "using" **Ohmic heating** to reach fusion-relevant plasma temperatures?

*Contrary to what happens in metals, resistivity in plasmas **decreases** with **increasing** temperatures! As a result, Ohmic heating is relatively small for the required high temperature plasmas.*

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*$P_{ext} = P_{fus} / 10 = 50$ MW → neglecting Ohmic heating, injected power shall equal 50 MW. **However**:*

- higher additional power needed to access the "H-mode" confinement, and

- installed power shall be higher (losses ~20% for EC, availability)

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In steady-state, the plasma temperature and density are the result of the thermal equilibrium equation (x, y, z, t): if the losses increase, the temperature decreases and thus the alpha power decreases, so additional heating power was required (→ Baseline 2024)

H&CD Systems and Technologies

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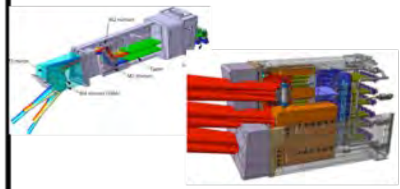
ITER BASELINE 2016 (old)

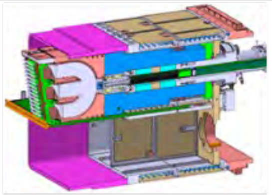
EC (170 GHz)
Electron Cyclotron



20MW

- Direct Electron Heating
- MHD control
- Current Drive profile control
- Impurity control
- Current Drive

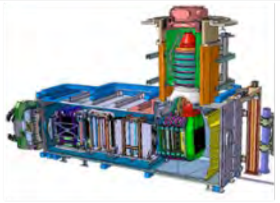
IC (40-55 MHz)
Ion Cyclotron



20MW

- Direct Ion Heating
- Extra "kick" to Q=10
- MHD control
- Impurity control

NB
Neutral Beam



33MW

- Both Ion and Electron Heating
- Bulk heating
- Bulk Current Drive
- Plasma rotation

EC System designed to these strengths

Courtesy Caroline Darbos, IO

ITER BASELINE 2024 (current)

EC
- 40 MW for Start of Research Operation (SRO)
- 60 MW (*optional to 66.7 MW*) for DT-1 operations

IC
- 10 MW (for IC wall conditioning + test heating performance)
- *20 MW of potential upgrade*

NB
- 33 MW (*16.5 MW* → *50 MW*)

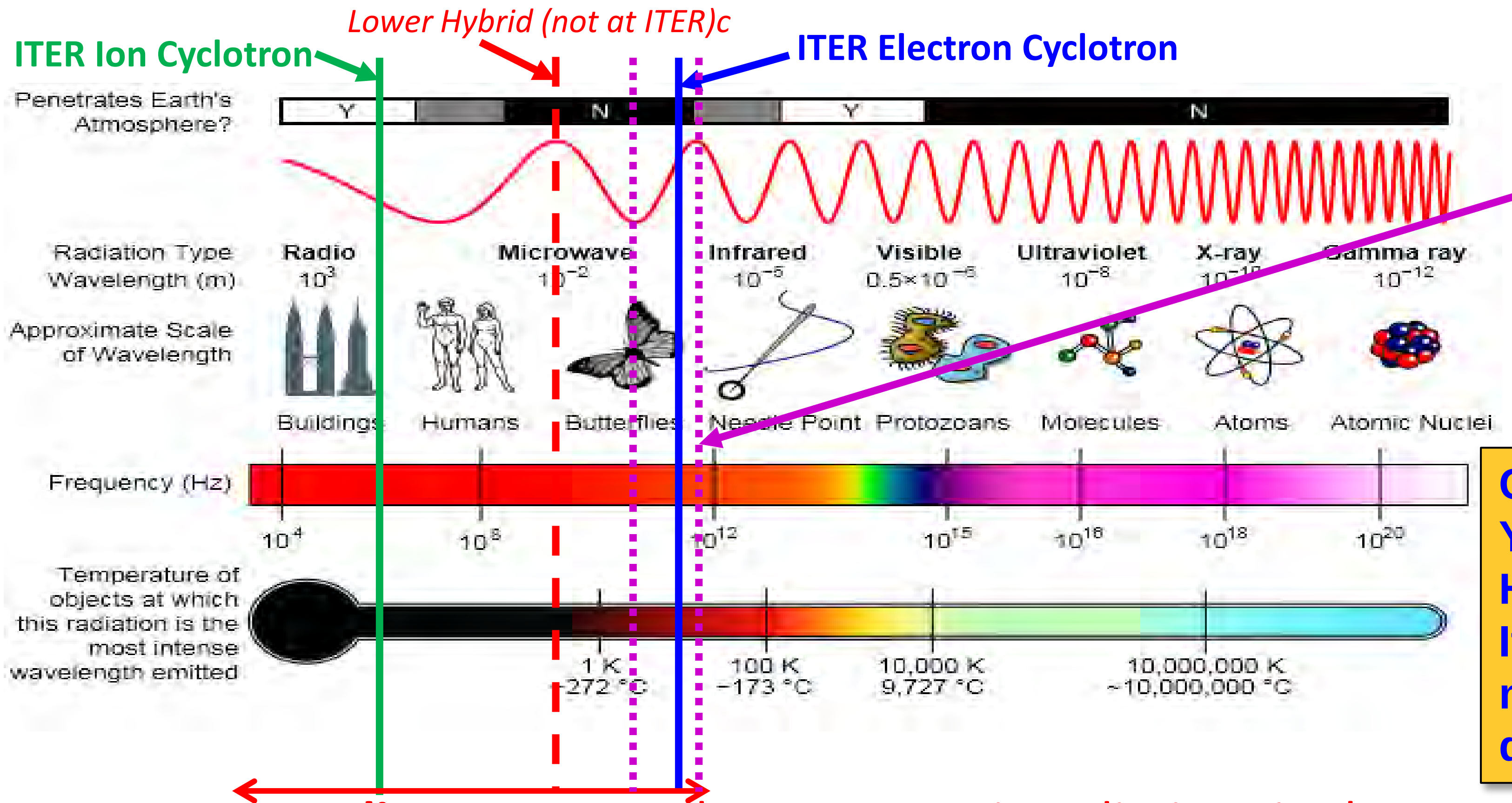
Other H&CD systems not foreseen at ITER:

<u>LHCD</u>: Lower Hybrid Current Drive (in the range between IC and EC)

<u>EBW</u>: Electron Bernstein Waves, no density cut-off and effective CD, ideal in low-B machines (Spherical, Stellarators)

Electromagnetic Spectrum

EC (& IC and LH) are using electromagnetic radiation, a form of radiant energy, propagating through space via electromagnetic waves (or photons) at the speed of light



EBWs (not at ITER) can operate in a large range ~10-200 GHz:

MAST : 28GHz (start) and 60 GHz (Heating)

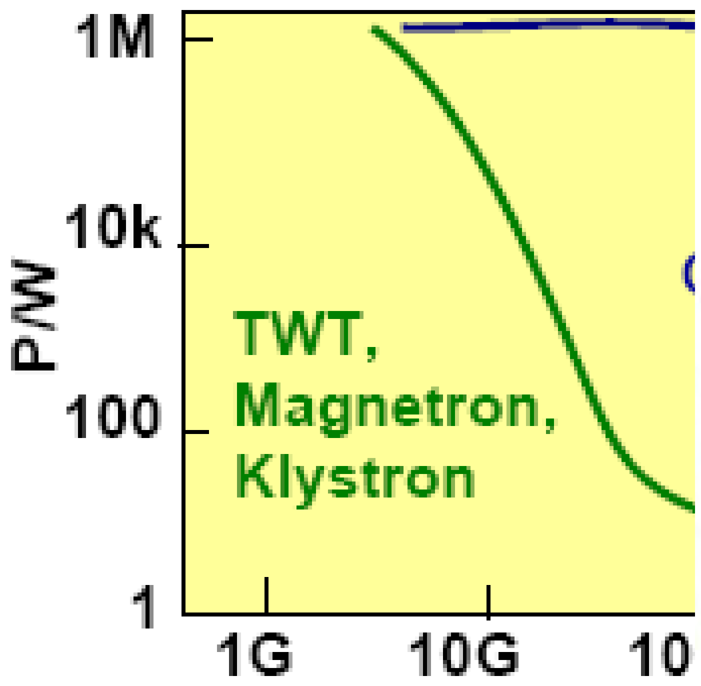
TST-2: ~20 GHz

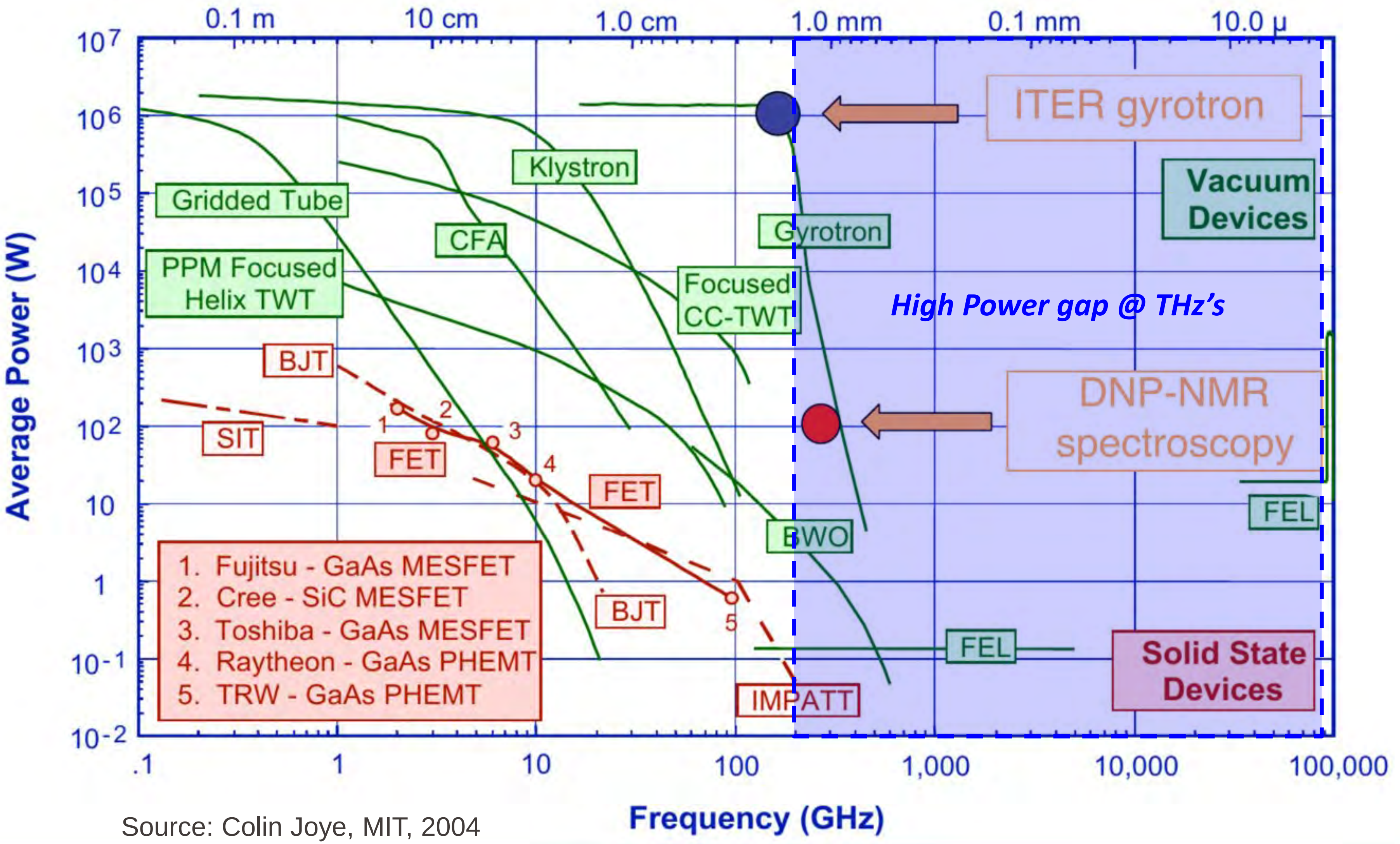
STEP: 140-170 GHz

Can ECRH be the only heating system?
Yes → STEP & DEMO baseline,
However, …
It depends on machine field, so other methods are required and useful depending on the machine!

Radio waves are electromagnetic radiations in the range of about 3 Hz to 300 GHz. They are usually produced by accelerated (change of speed/direction) electrons

Technology Spectrum: the THz Gap





Source: Colin Joye, MIT, 2004

General Schematics – "The H&CD Model"

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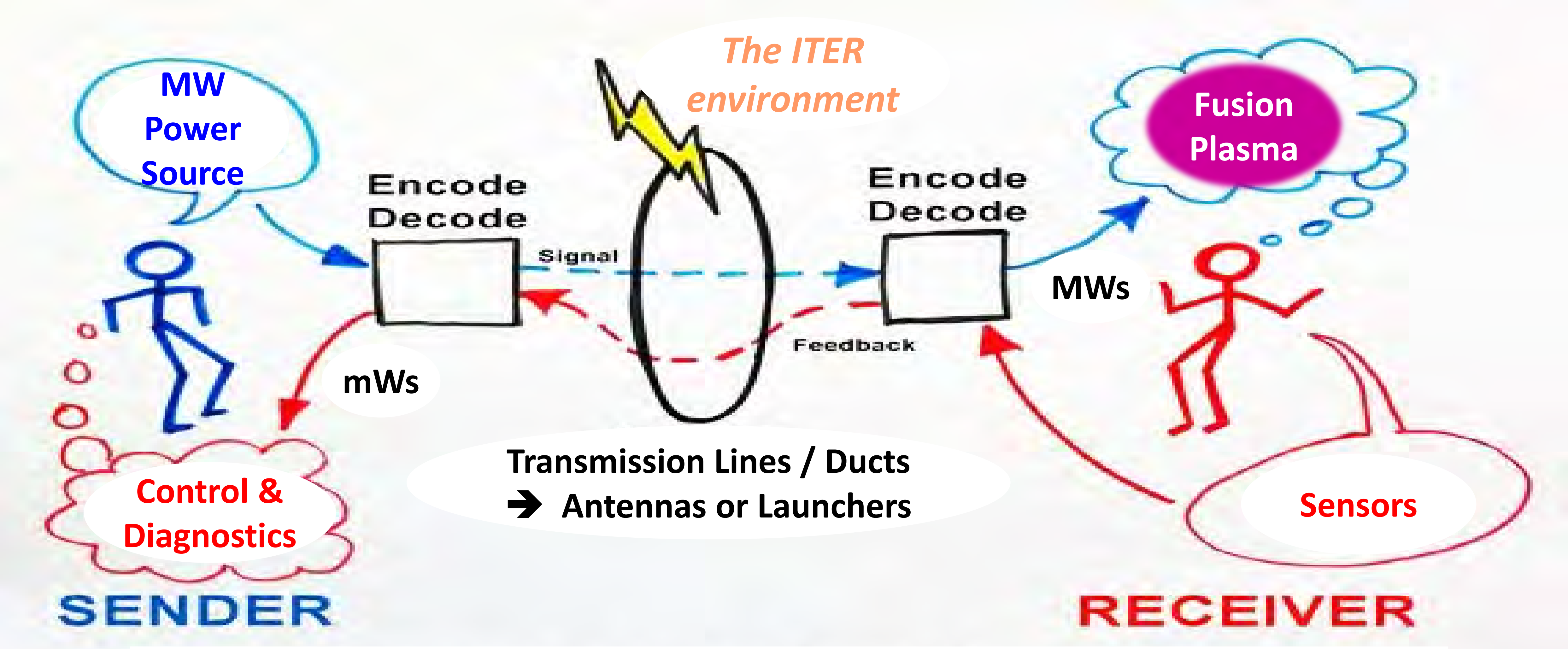

The "Leshan" model of the ITER H&CD (HNB, ICRH and ECRH)

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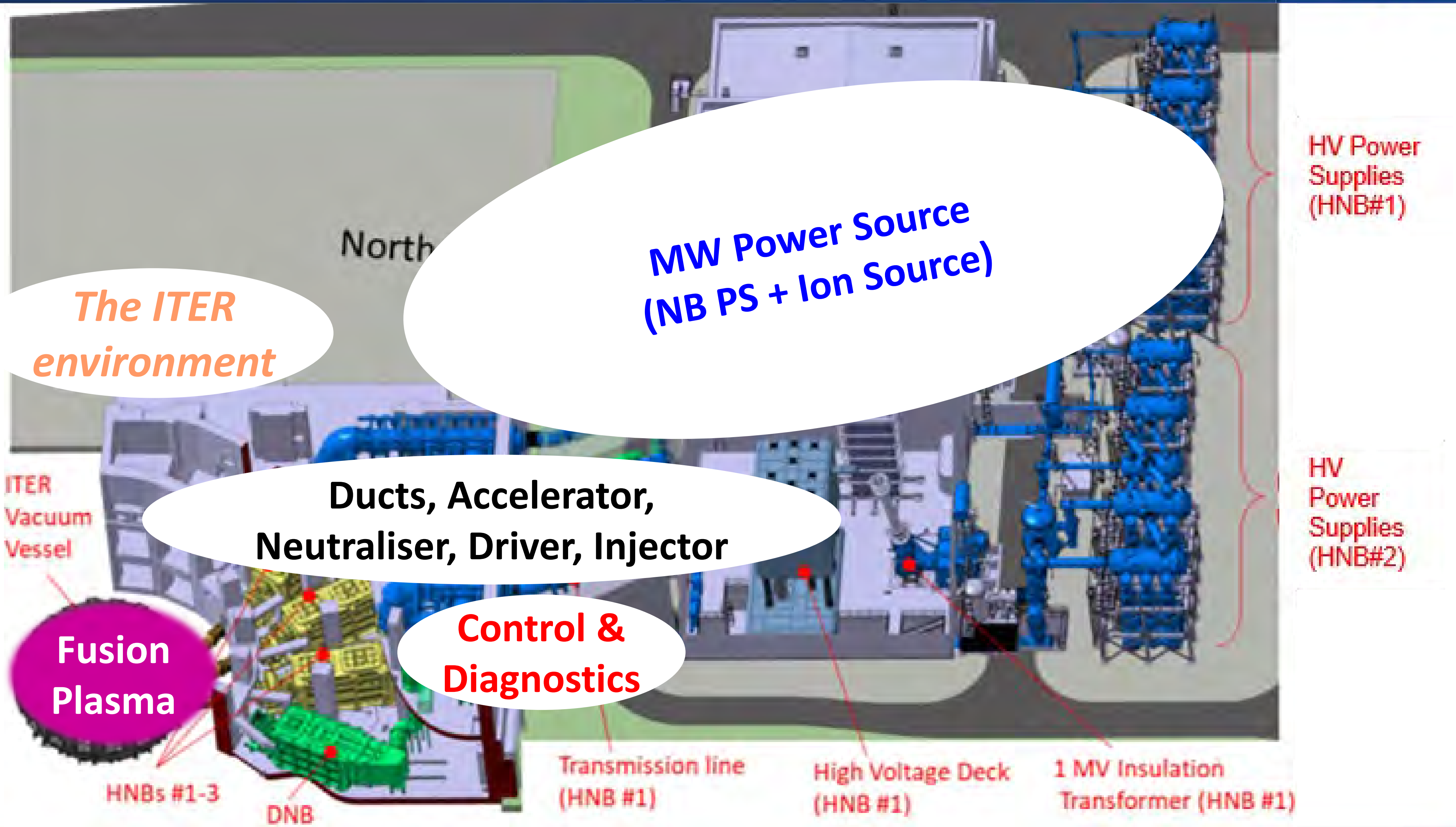
The ITER HNB model

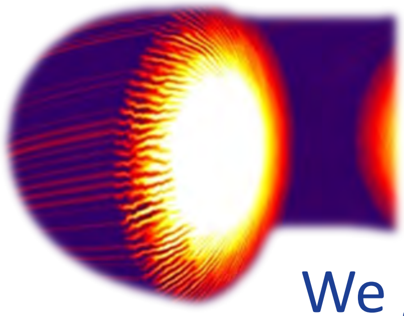


Neutral Beam (HNB) H&CD System

Basics: If we were able to inject a beam of **high energy ions** into the Tokamak plasma, they would be **confined by the magnetic fields**; would circulate around the Tokamak and **heat the plasma by collisions with the ions and electrons present in the plasma**. **The higher the speed of ions collision, the higher the probability of a fusion reaction**

Unfortunately, we cannot inject **ions from outside** into the plasma, as they would be **reflected out** of the machine by the confining (magnetic) fields

Then, we inject **high energy neutral particles**, which do not "see" the magnetic fields, and, once inside the plasma, many reactions will lead to **ionisation of the neutral beam**, such as:



NB	Present in the plasma		Resulting particles within the plasma	
D^0	$+ (D^+ \text{ or } T^+)$	$\Rightarrow$	$D^+ + (D^0 \text{ or } T^0)$	*charge exchange*
D^0	$+ (D^+ \text{ or } T^+ \text{ or } e)$	$\Rightarrow$	$D^+ + (D^+ \text{ or } T^+ \text{ or } e) + e$	*ionisation*

We got a **high energy ion beam** inside the Tokamak plasma which **heats the plasma,** and also contributes to maintaining good **confinement** and **density** of the plasma

Neutral Beam – How to create it?

Create ions

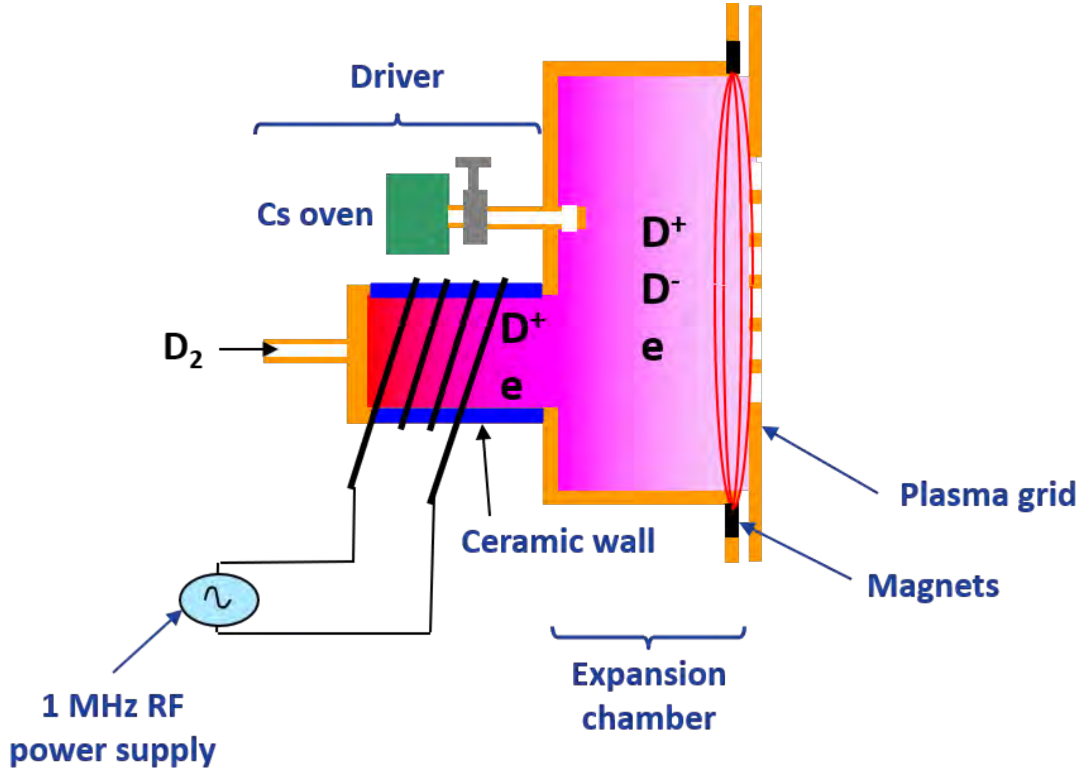
Accelerate the ions

Neutralise the ions

Drive this beam of neutral particles

Injection to the plasma

Ion Source



Source: Introduction to Neutral Beam Injection (NBI) , R. Hemsworth, ITER Org., January 2009

Neutral Beam – How to create it?

Create ions

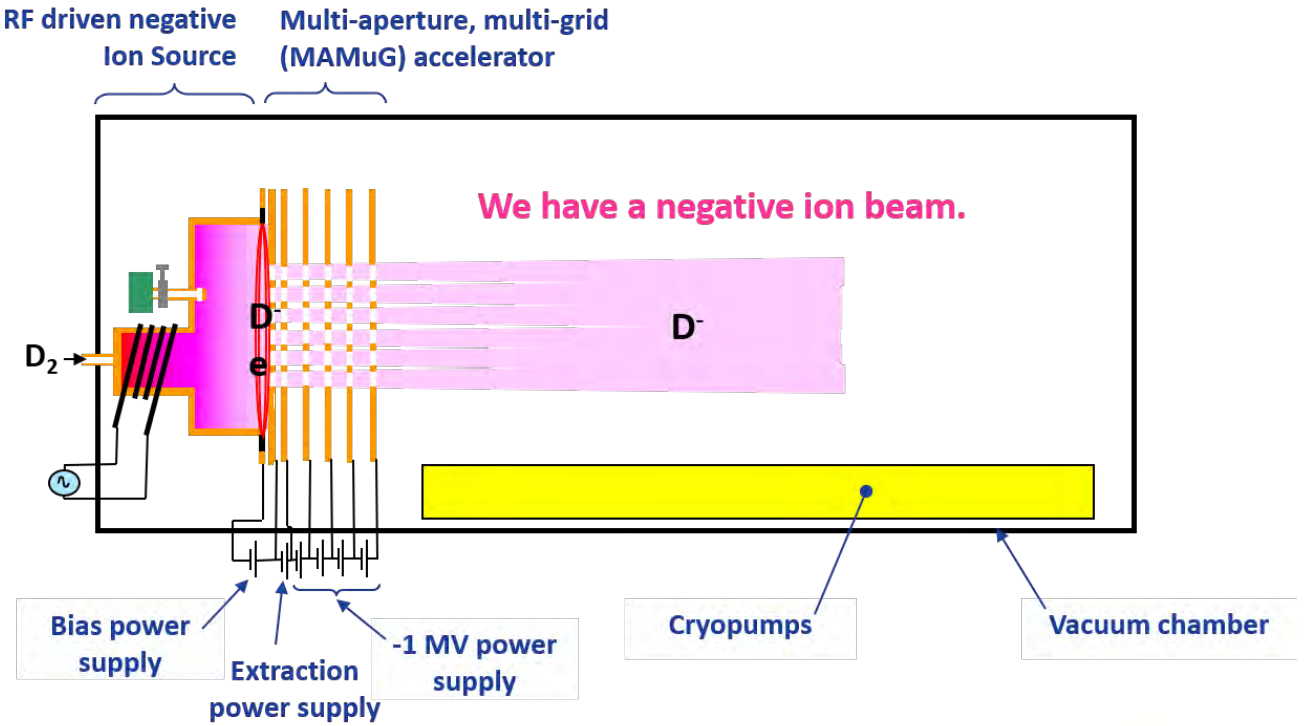
Accelerate the ions

Neutralise the ions

Drive this beam of neutral particles

Injection to the plasma

Accelerator (+ Power Supplies, inside Vacuum Chamber with Cryopumps) **giving energy to ions**



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Neutral Beam – How to create it?

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Create ions

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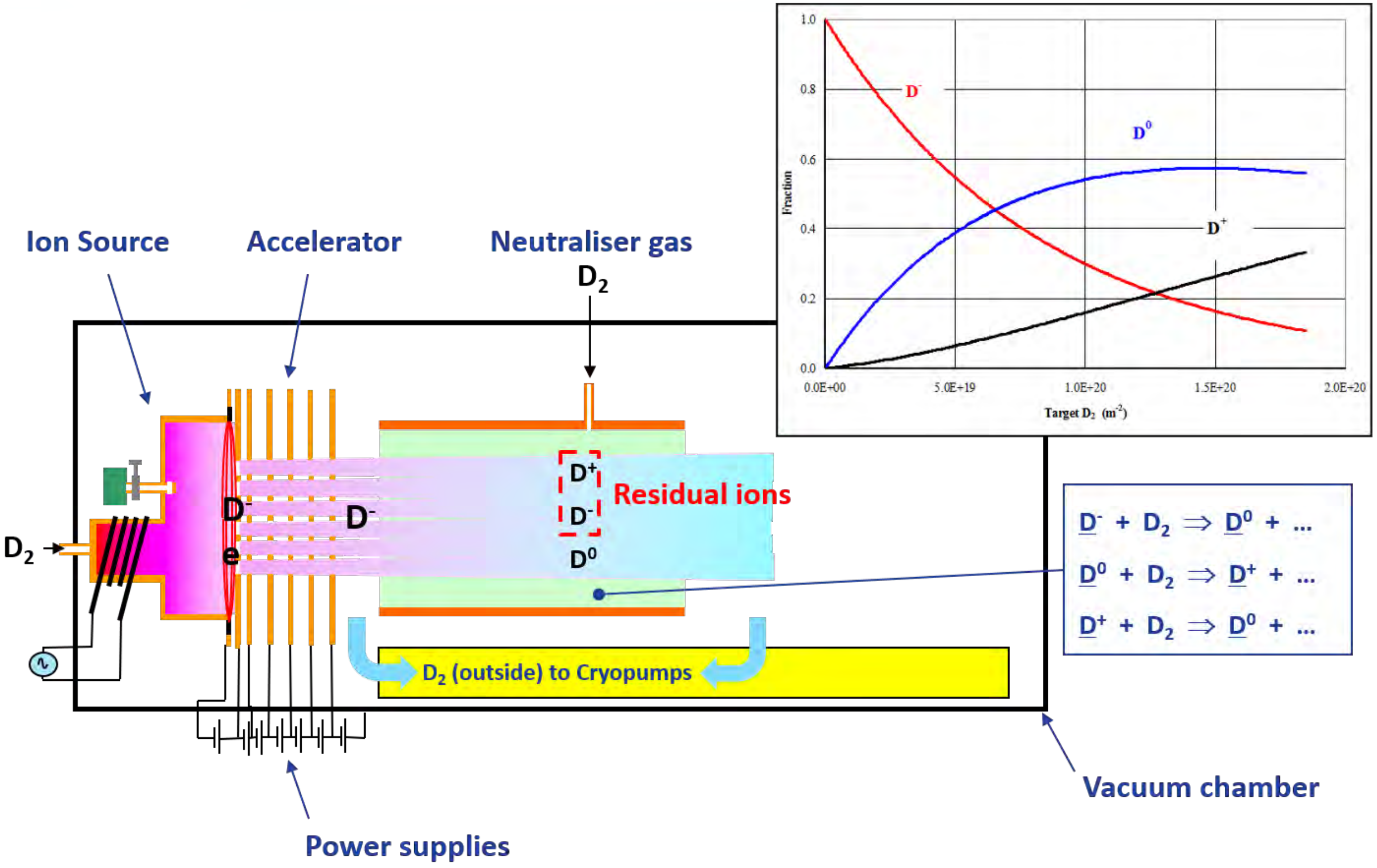
Neutralise the ions

Drive this beam of neutral particles

Injection to the plasma

Beam Neutraliser and…



Source: Introduction to Neutral Beam Injection (NBI) , R. Hemsworth, ITER Org., January 2009

Neutral Beam – How to create it?

Create ions

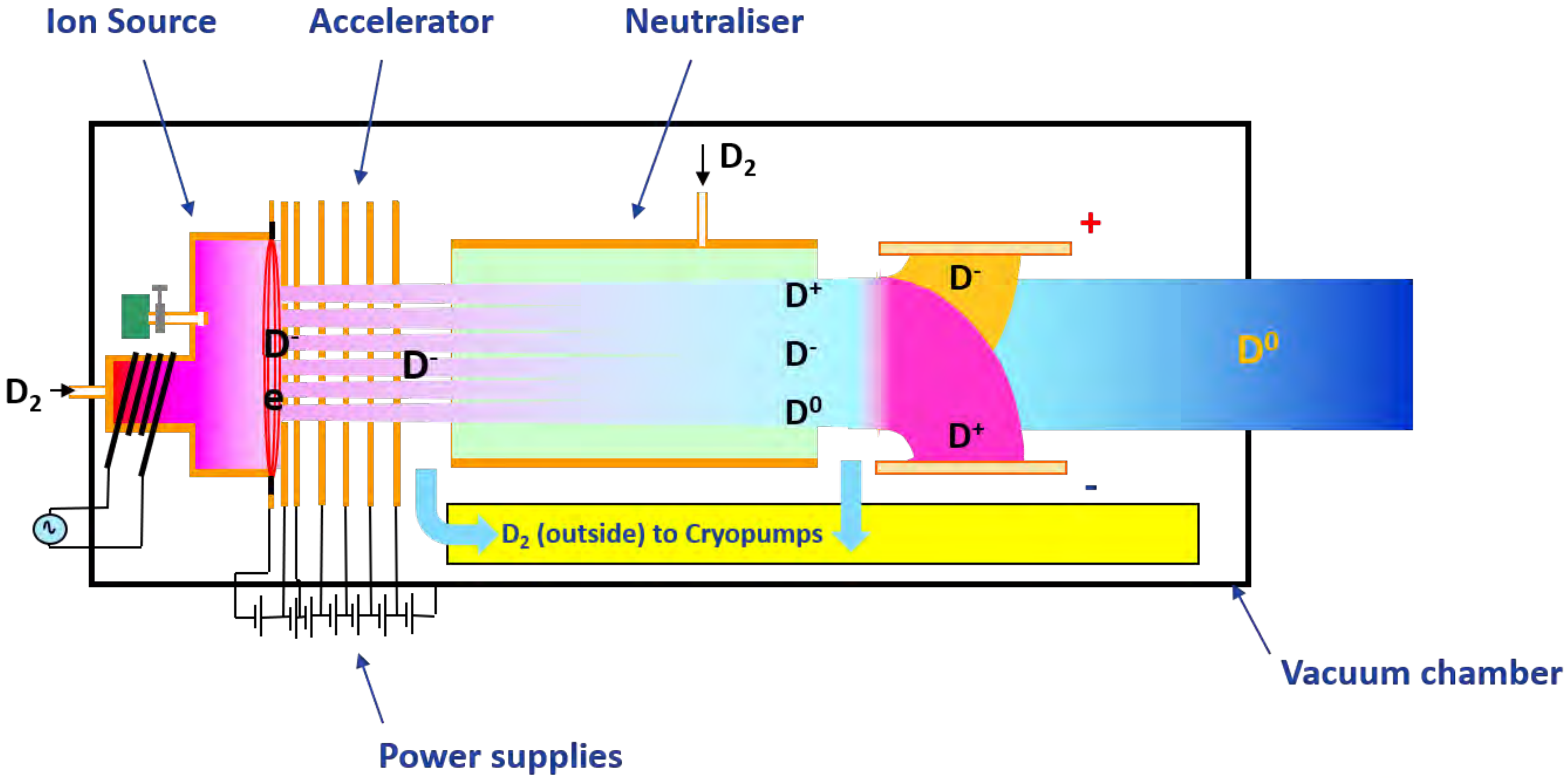
Accelerate the ions

Neutralise the ions

Drive this beam of neutral particles

Injection to the plasma

… remove residual ions



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Neutral Beam – How to create it?

Create ions

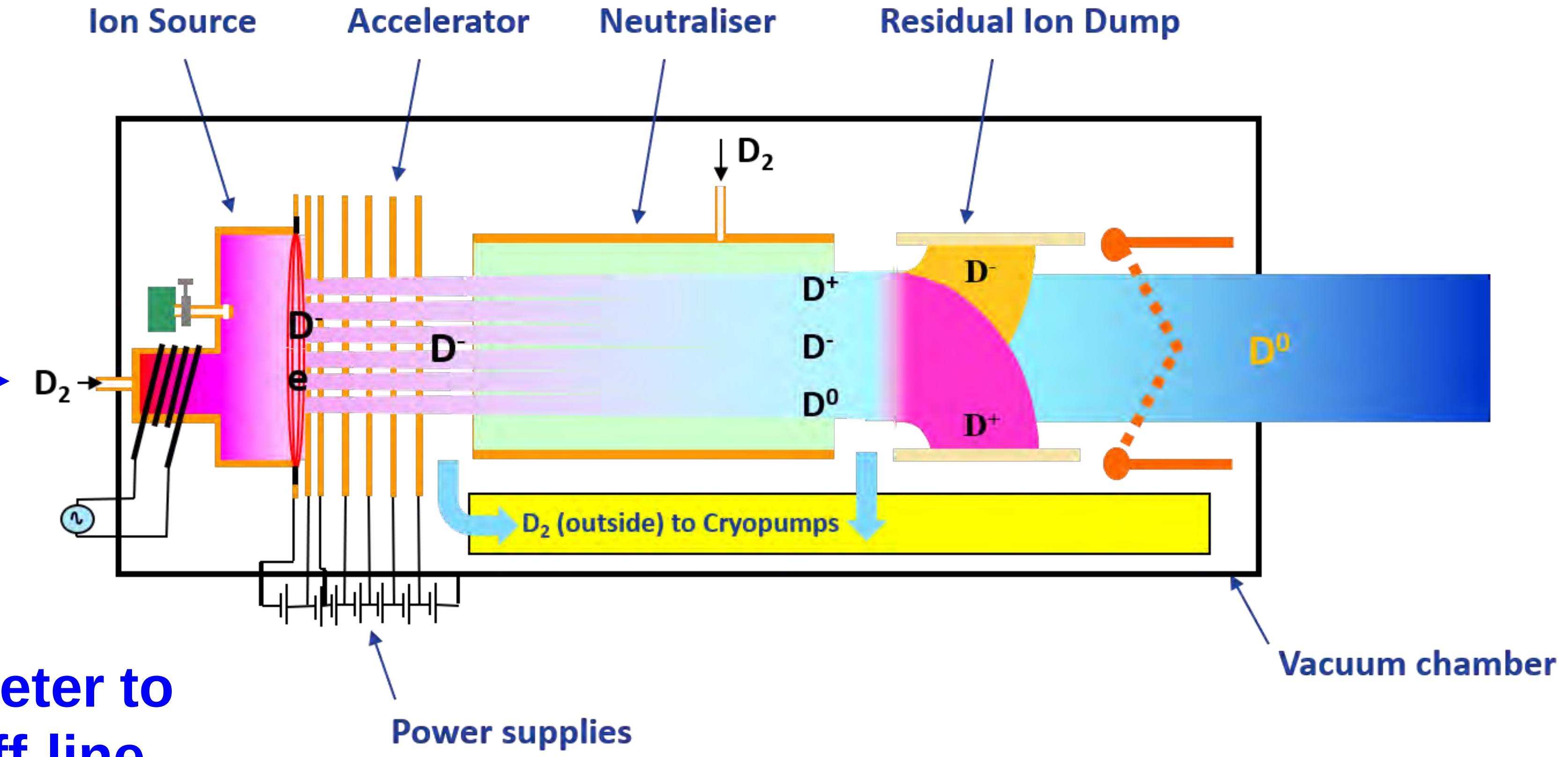
Accelerate the ions

Neutralise the ions

Drive this beam of neutral particles

Injection to the plasma

Add calorimeter to allow off-line commissioning



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Neutral Beam – How to create it?

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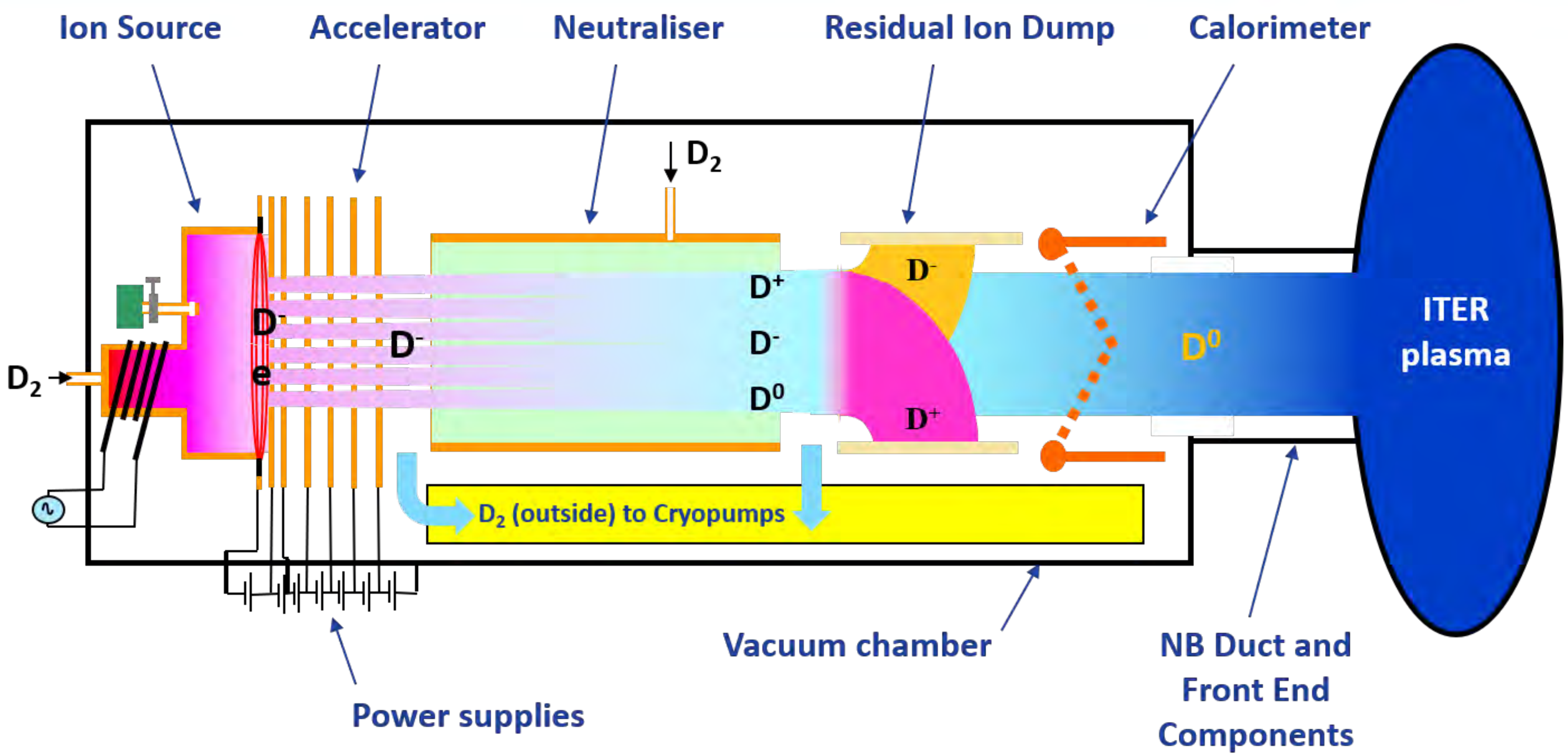
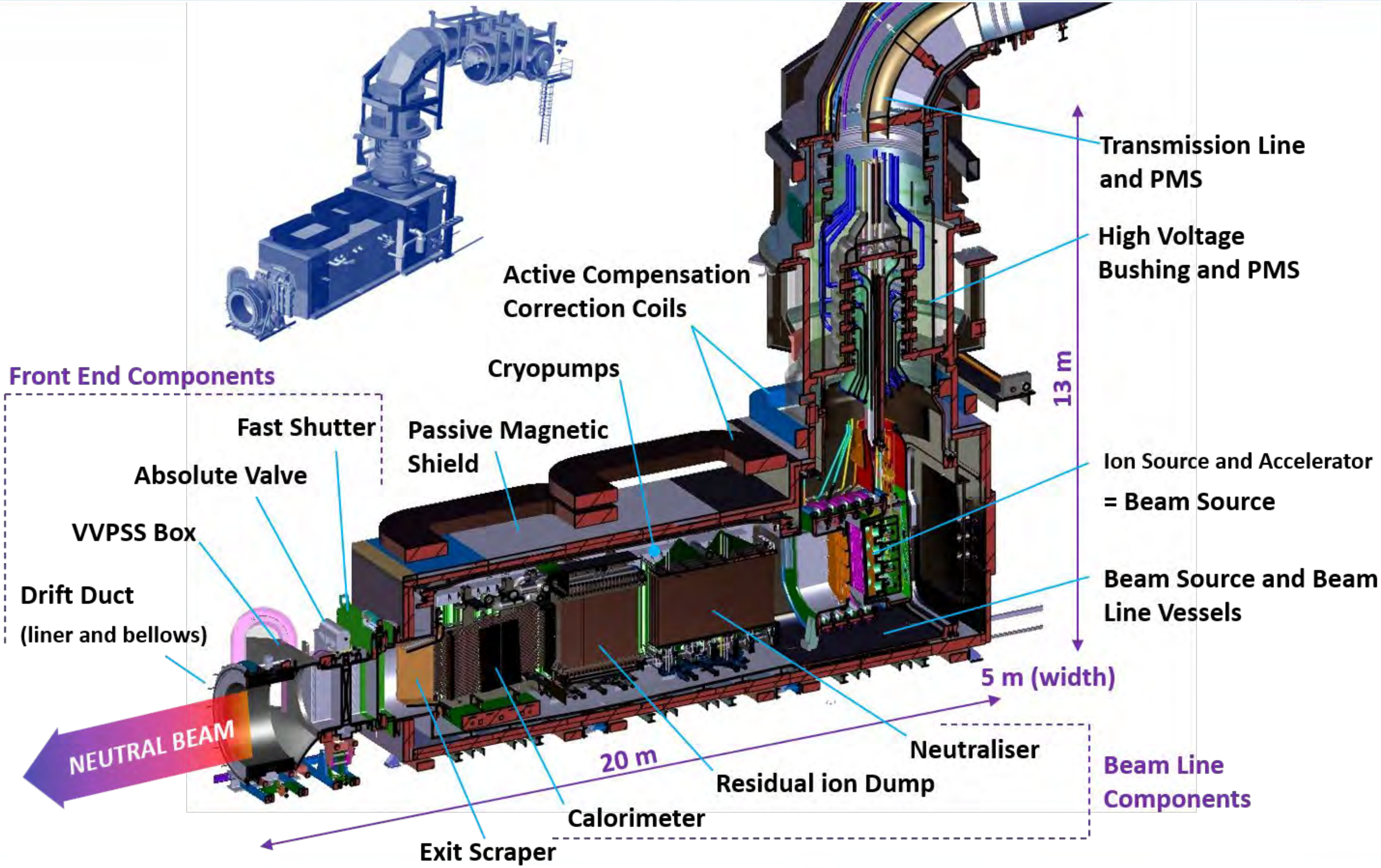
Injection to the plasma



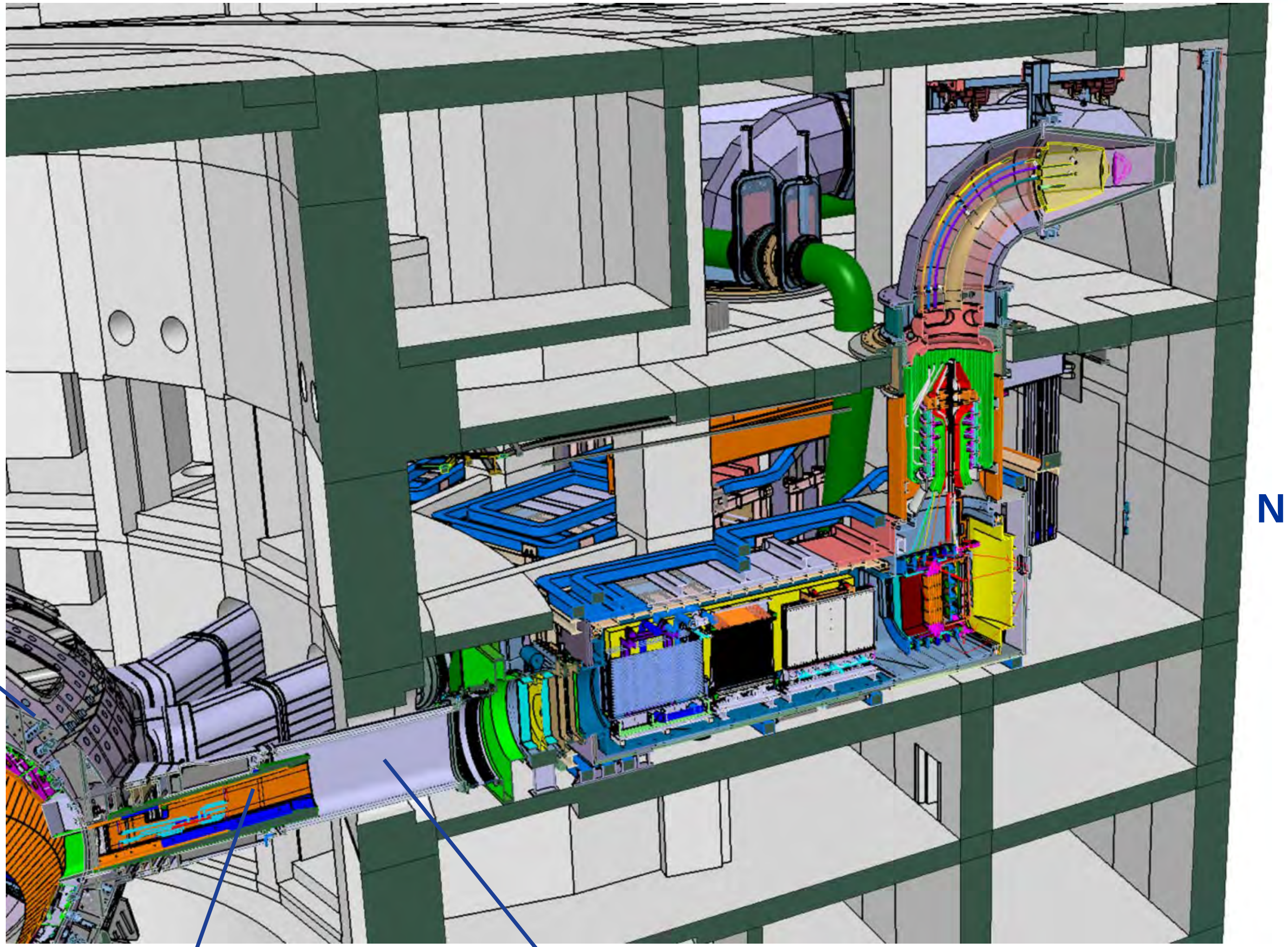
Connect to the Tokamak

Source: Introduction to Neutral Beam Injection (NBI) , R. Hemsworth, ITER Org., January 2009

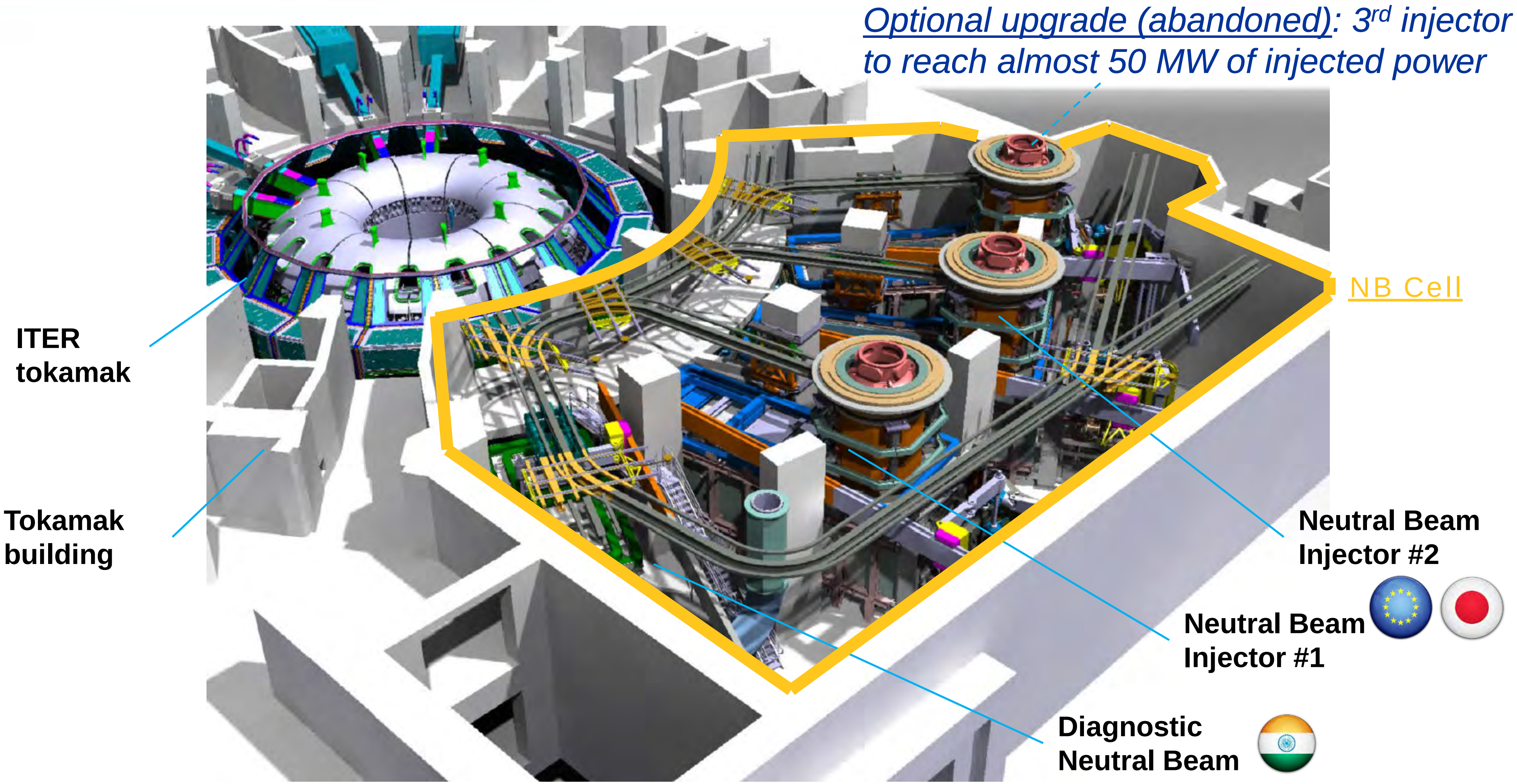
The ITER HNB (Heating Neutral Beam) – Overview



The ITER HNB Integration in the Tokamak Complex



The ITER HNB – Neutral Beam Injectors



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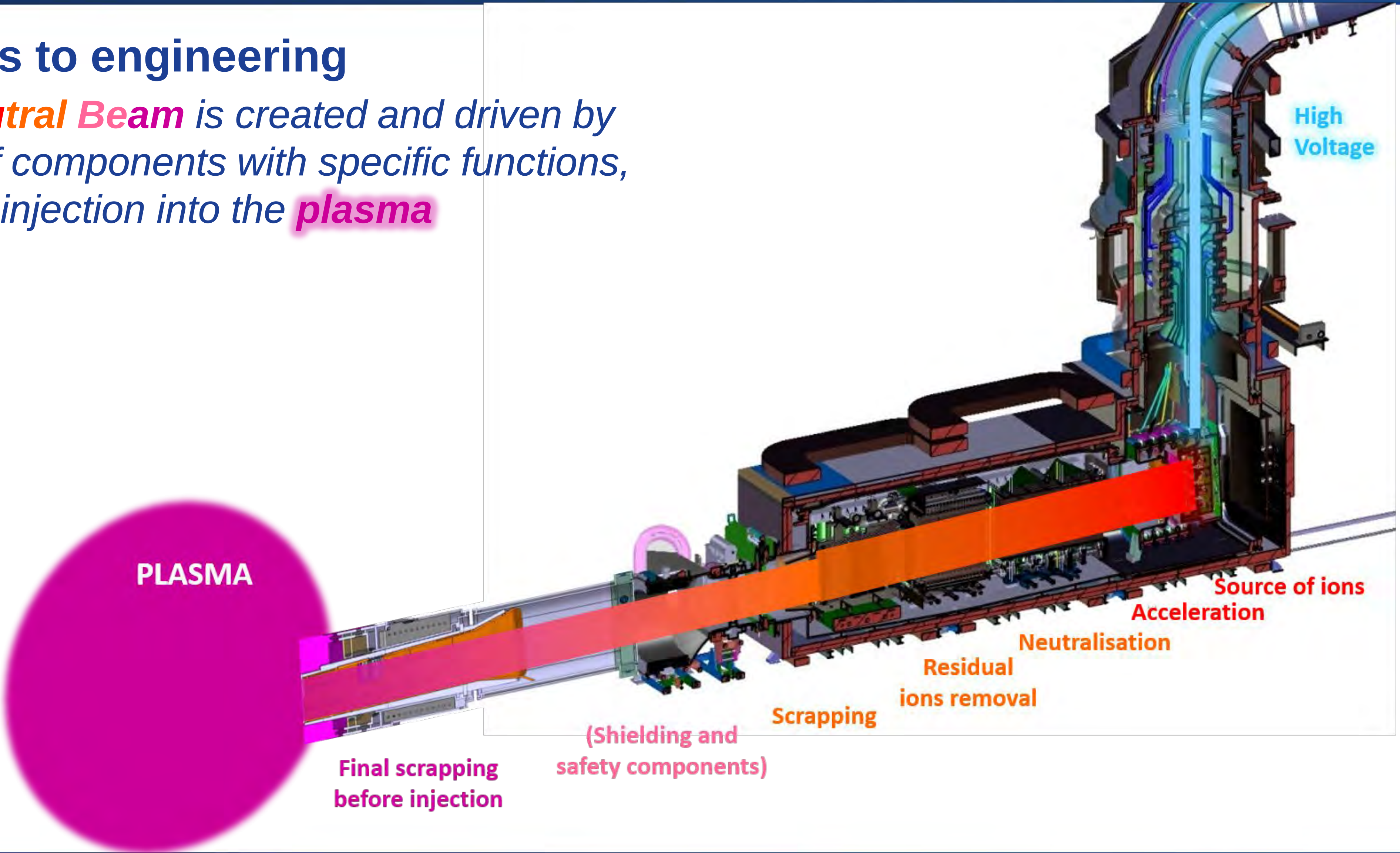
Physics to engineering

*The **Neutral Beam** is created and driven by series of components with specific functions, until the injection into the **plasma***

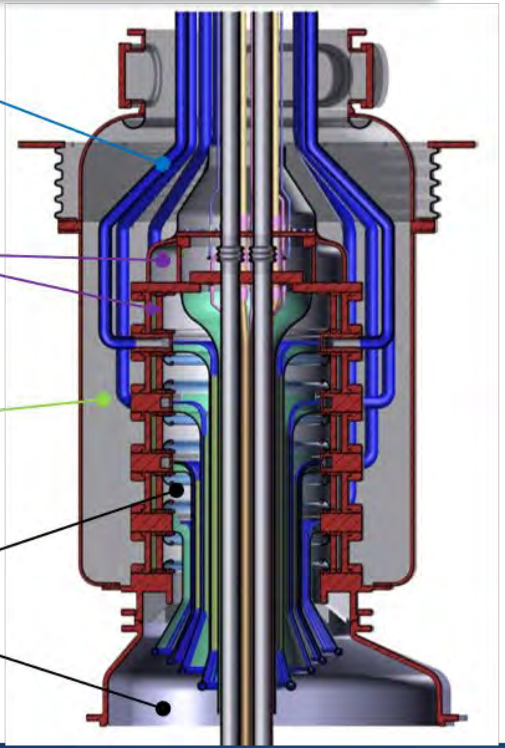


Neutral Beam – Components (HVB and TL)

High Voltage Bushing (HVB) & Transmission Line (TL)

Key function

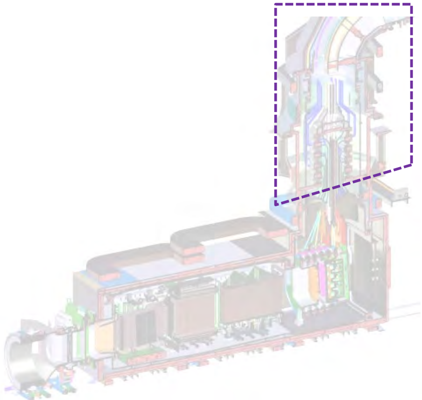
Ensure the transfer of the different **electrical potentials** and **cooling water** from the TL (under SF_6 gas pressure) to the NB Ion Source and Accelerator (under vacuum).



Height ≈ 6.7 m

Diameter ≈ 3.9 m

Weight ≈ 48 t

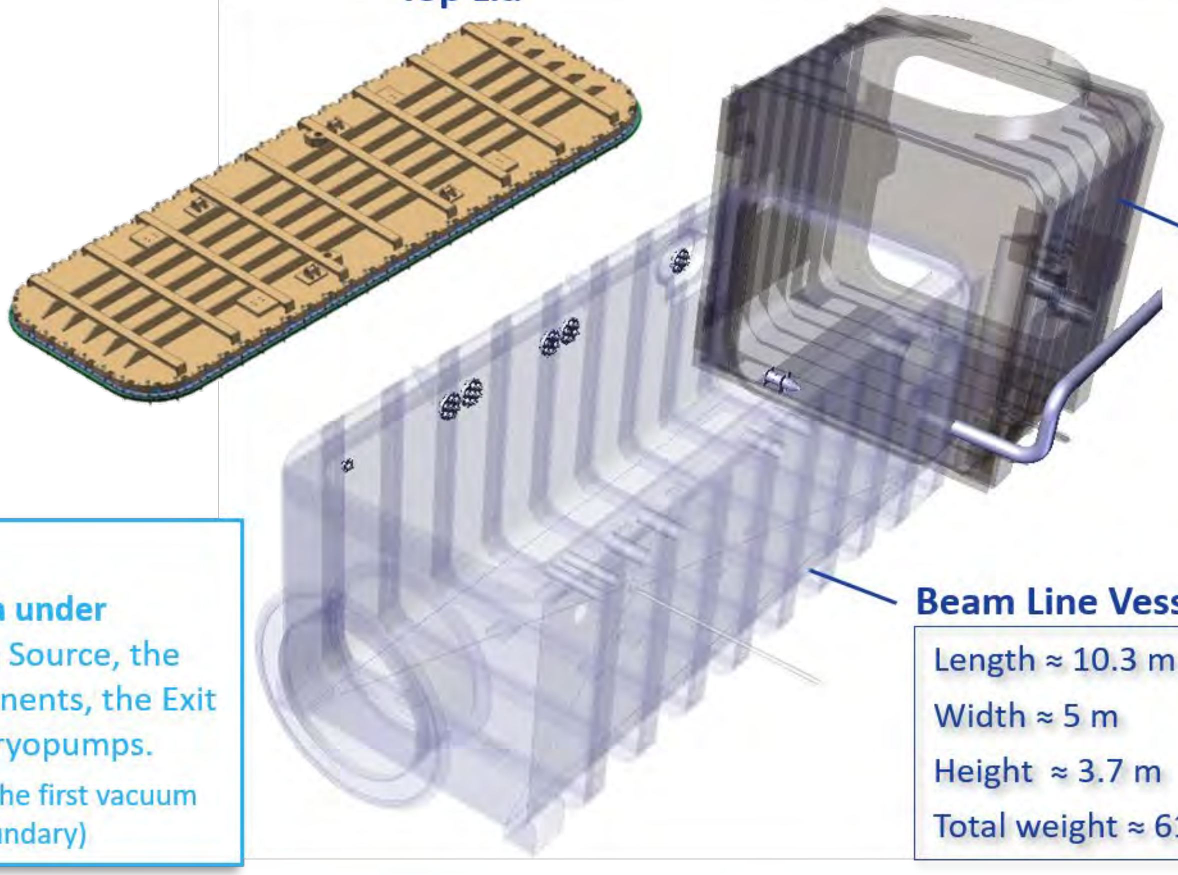


Neutral Beam – Components (BLV and BSV)

Beam Line Vessel (BLV) &
Beam Source Vessel (BSV)

Top Lid

Rear Lid



Beam Source Vessel

Length ≈ 4.3 m
Width ≈ 5.4 m
Height ≈ 5.5 m
Total weight ≈ 41 t

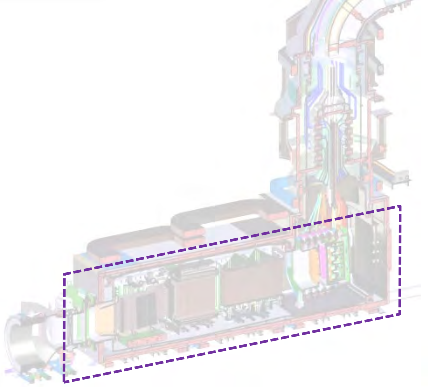
Beam Line Vessel

Length ≈ 10.3 m
Width ≈ 5 m
Height ≈ 3.7 m
Total weight ≈ 61.3 t

Key function

Host and **maintain under vacuum** the Beam Source, the Beam Line Components, the Exit Scraper and the Cryopumps.

(Hence actuating as the first vacuum and confinement boundary)

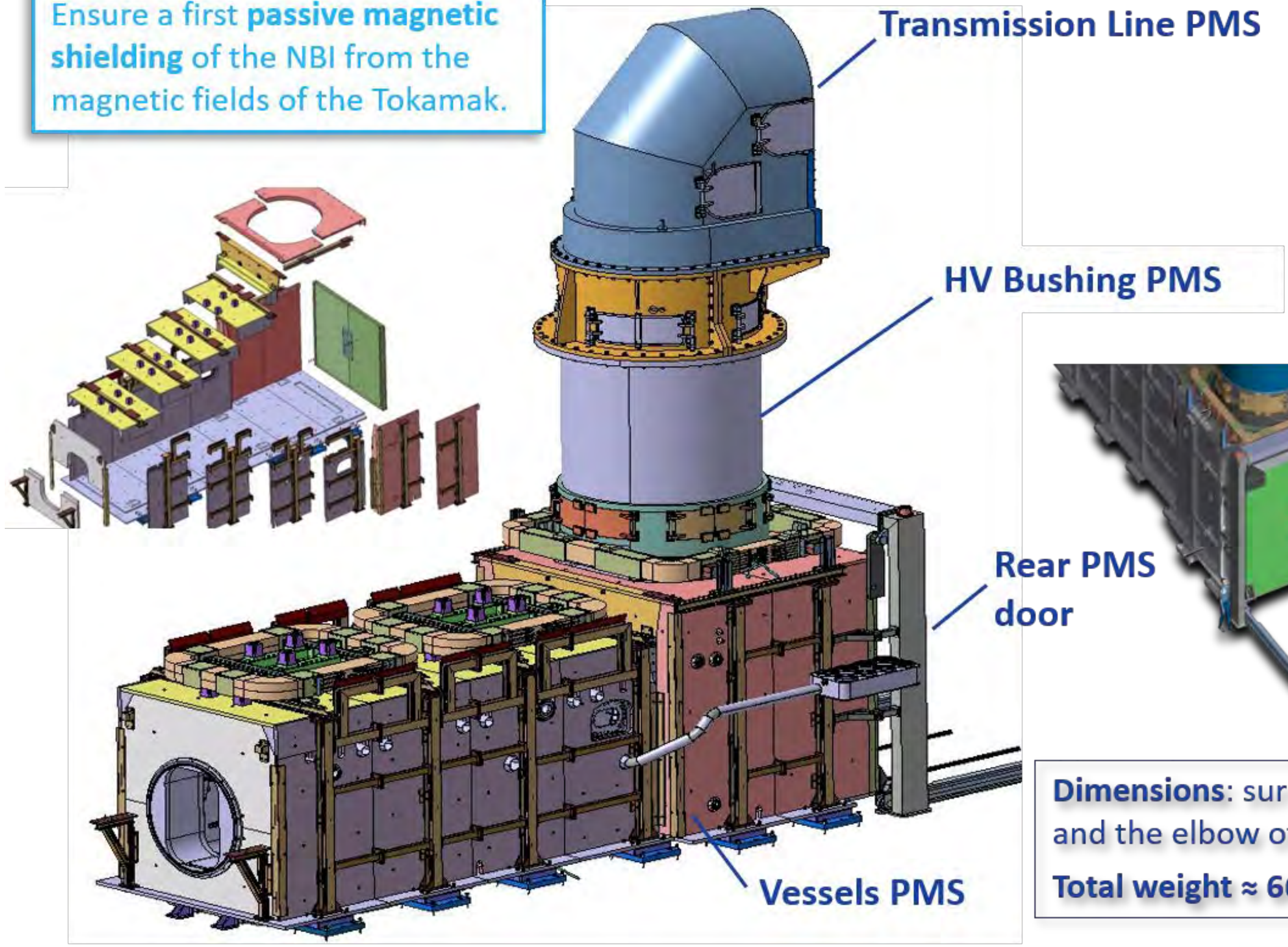


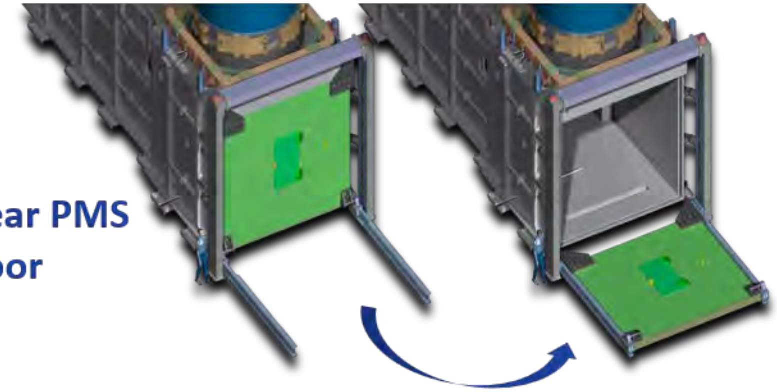
Neutral Beam – Components (PMS)

Passive Magnetic Shield (PMS)

Key function

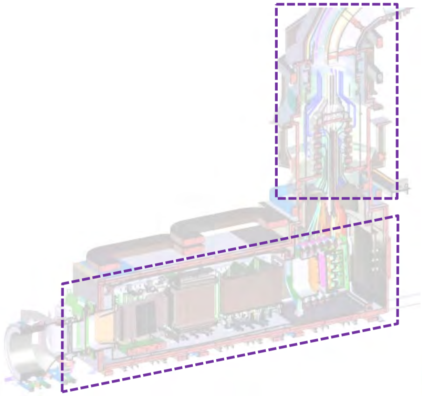
Ensure a first **passive magnetic shielding** of the NBI from the magnetic fields of the Tokamak.





Dimensions: surrounding the Vessels, HV Bushing and the elbow of the Transmission Line.

Total weight ≈ 662 t



Neutral Beam – Components (ACC Coils)

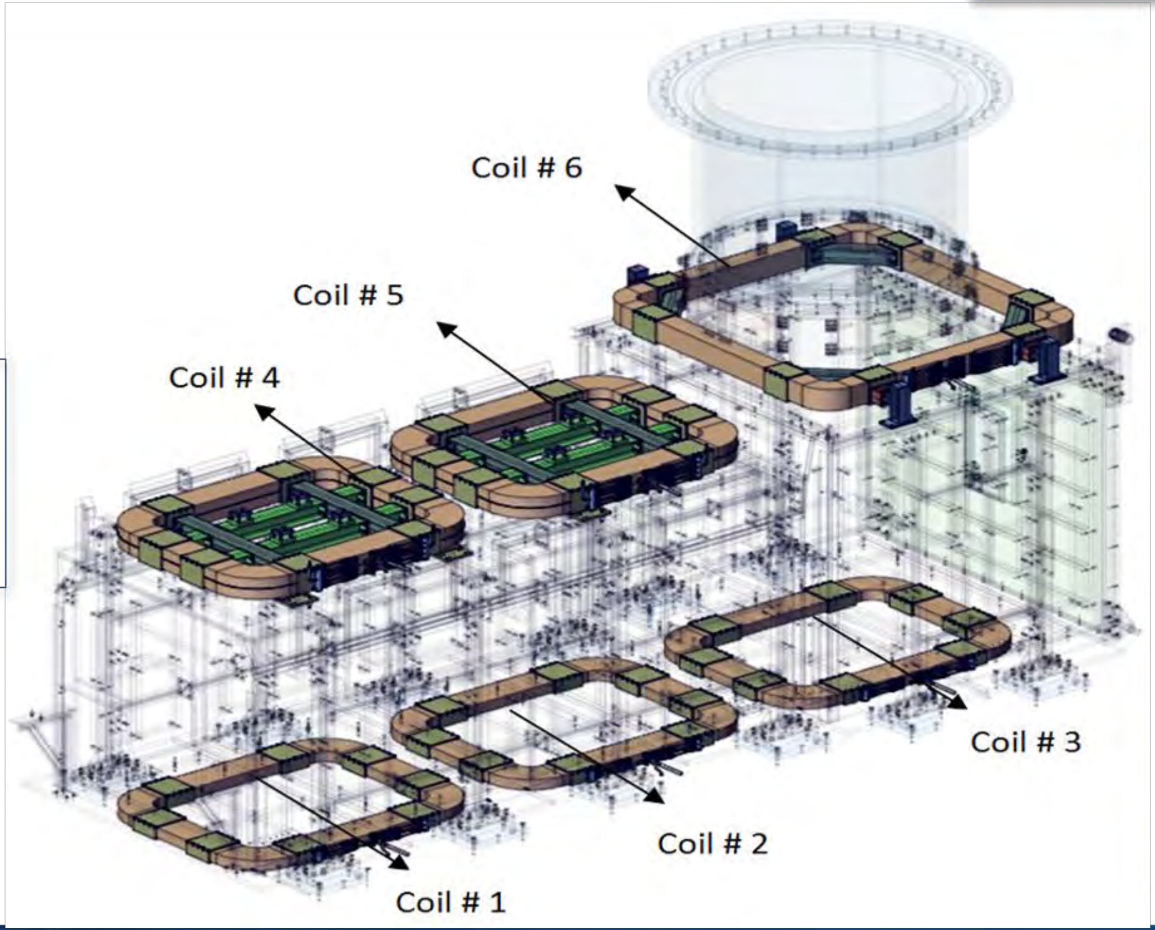
Active Compensation Correction Coil (ACC Coils)

Key function

Ensure a complementary **active magnetic shielding** of the NBI from the magnetic field of the Tokamak.

Top coils (each)

Length ≈ 4.3 m
Width ≈ 4 m
Height ≈ 53 cm
Weight ≈ 18 t

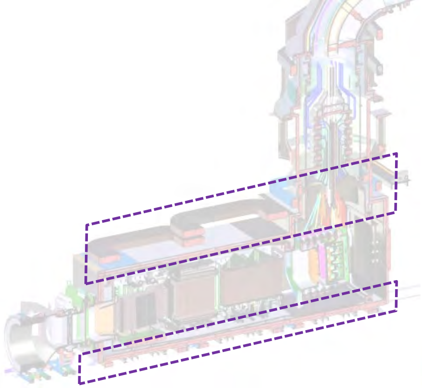


HV Bushing coil

Length ≈ 4.7 m
Width ≈ 5.6 m
Height ≈ 45 cm
Weight ≈ 16 t

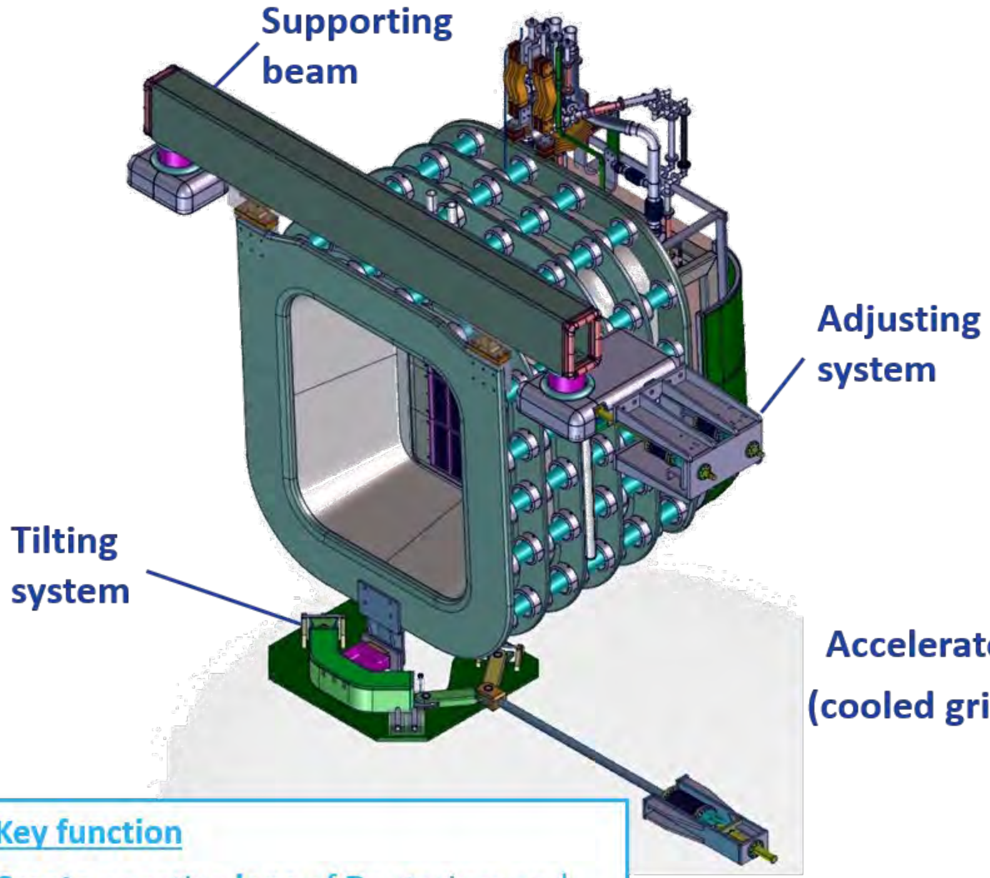
Bottom coils (each)

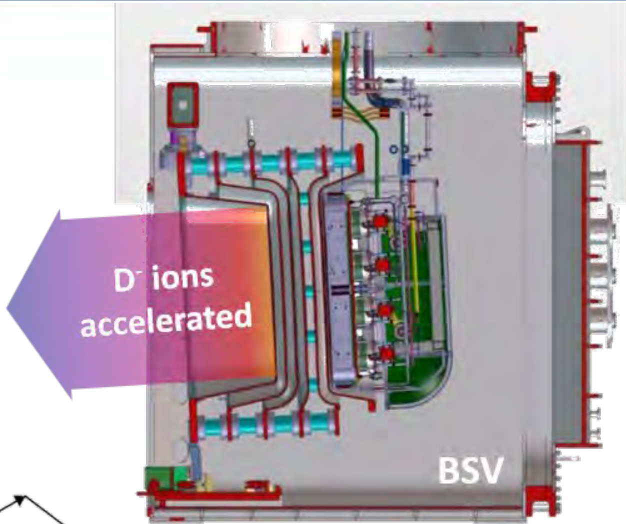
Length ≈ 5 m
Width ≈ 3.7 m
Height ≈ 32 cm
Weight ≈ 11 t

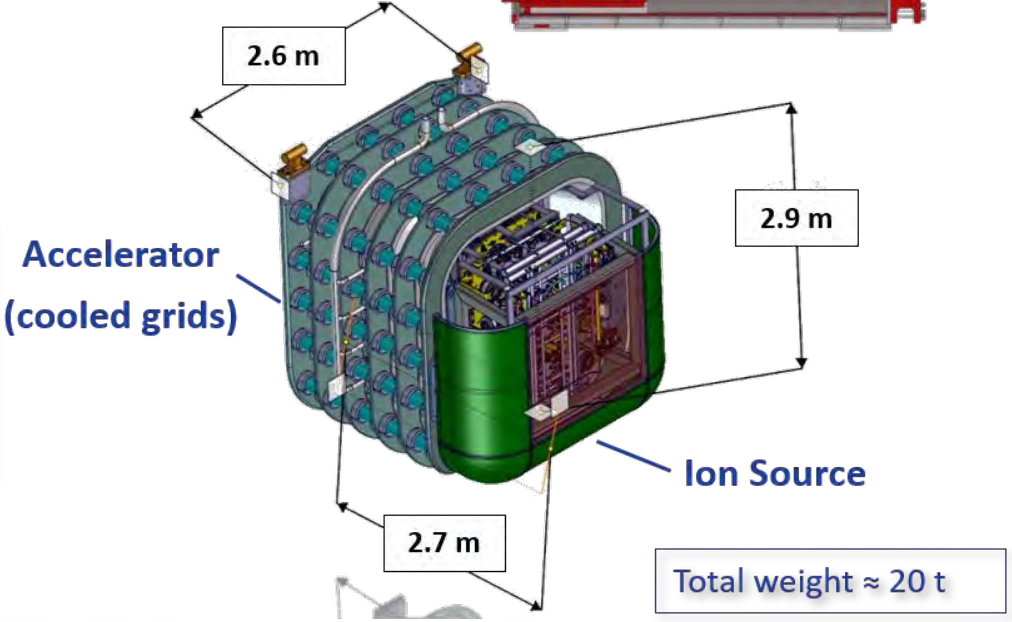


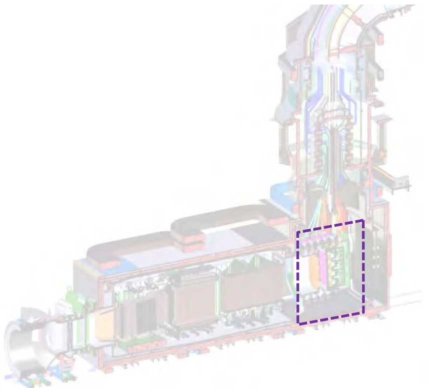
Neutral Beam – Components (Beam Source)

Beam Source (Ion Source + Accelerator)









Key function

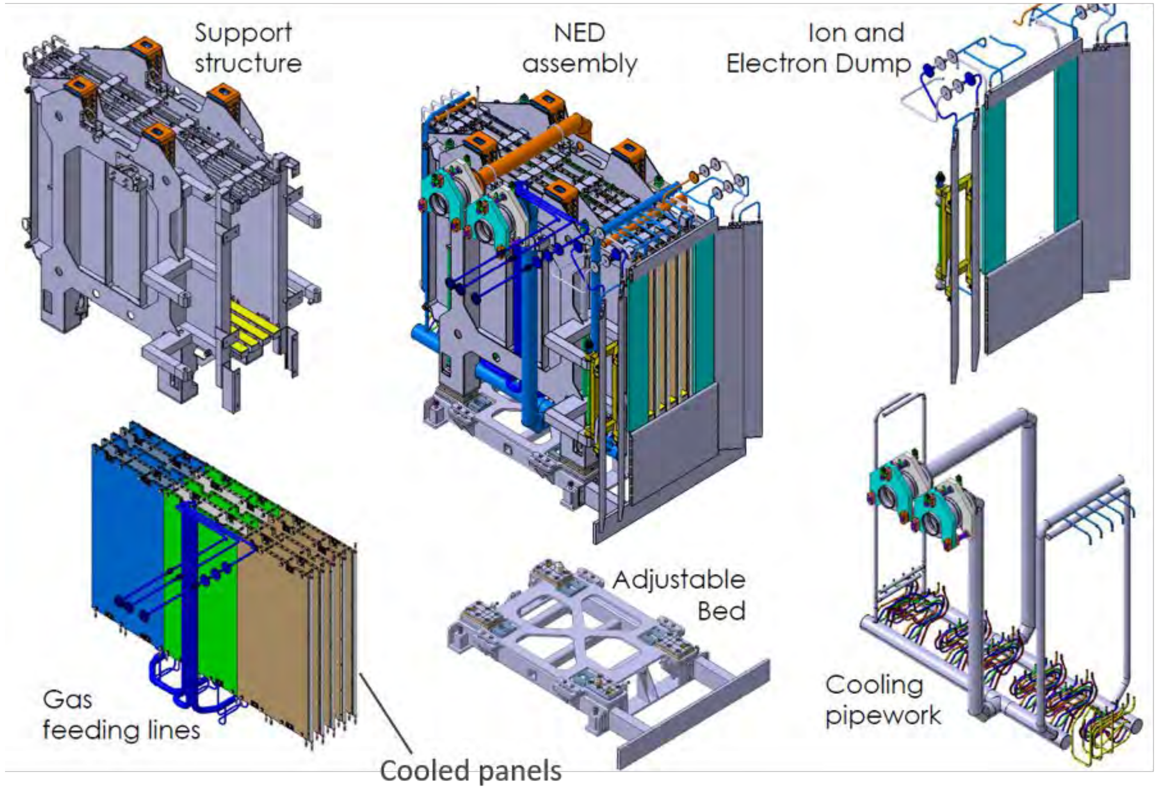
Create negative **ions** of **Deuterium and accelerate** them to the required energy with electrical fields.

Neutral Beam – Components (NED)

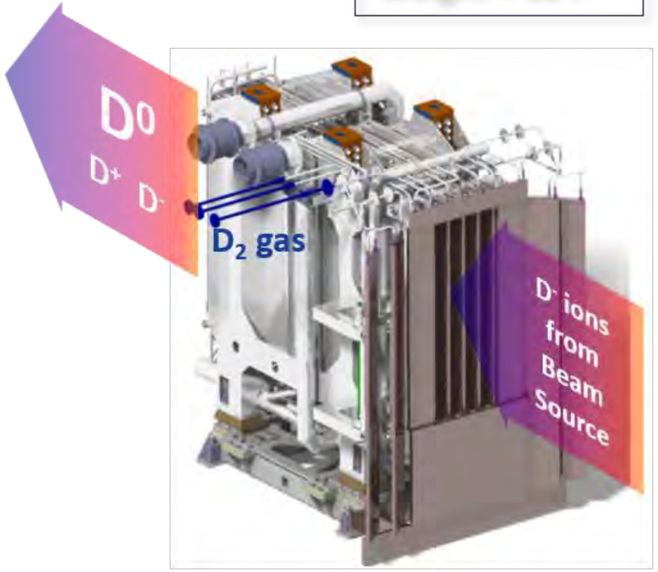
Key function

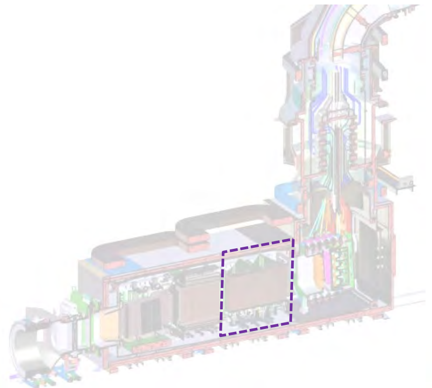
Neutralise (with D_2 gas) the accelerated **Deuterium ions** coming from the Beam Source.

Neutraliser – Electron Dump (NED)



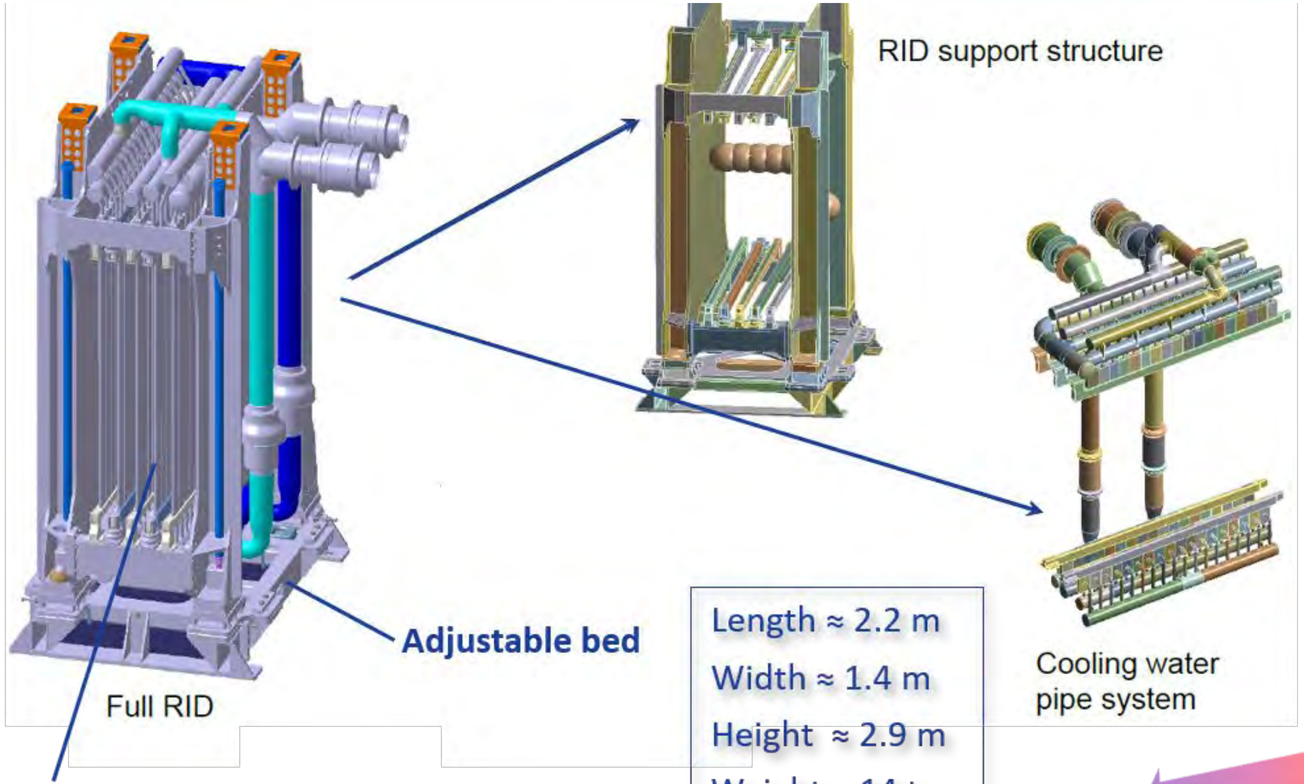
Length ≈ 3.2 m
Width ≈ 2 m
Height ≈ 2.9 m
Weight ≈ 12 t



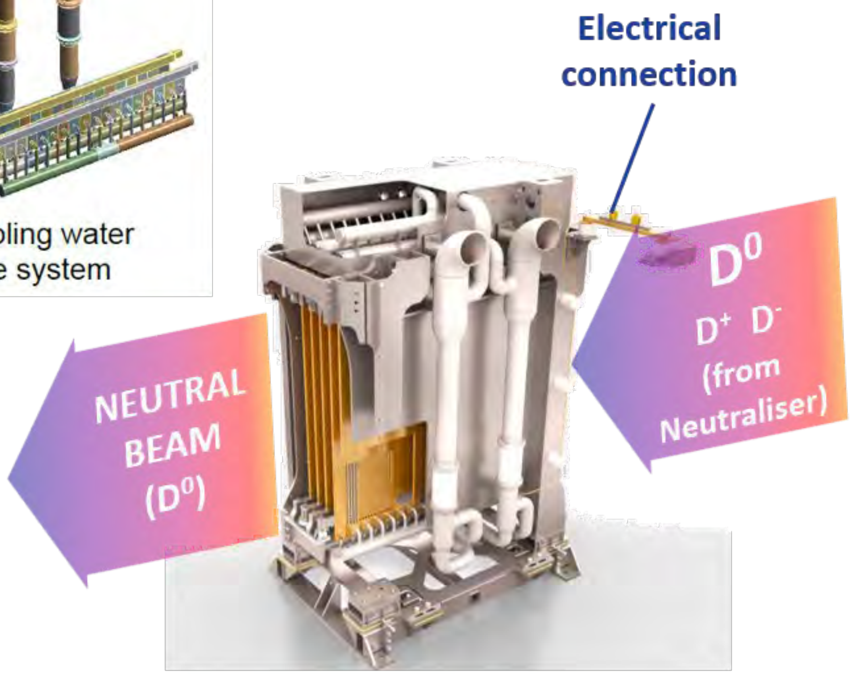


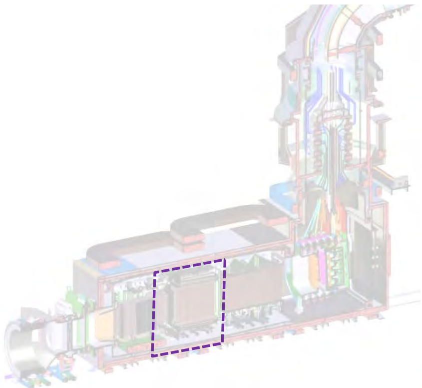
Neutral Beam – Components (RID)

Residual Ion Dump (RID)



Length ≈ 2.2 m
Width ≈ 1.4 m
Height ≈ 2.9 m
Weight ≈ 14 t





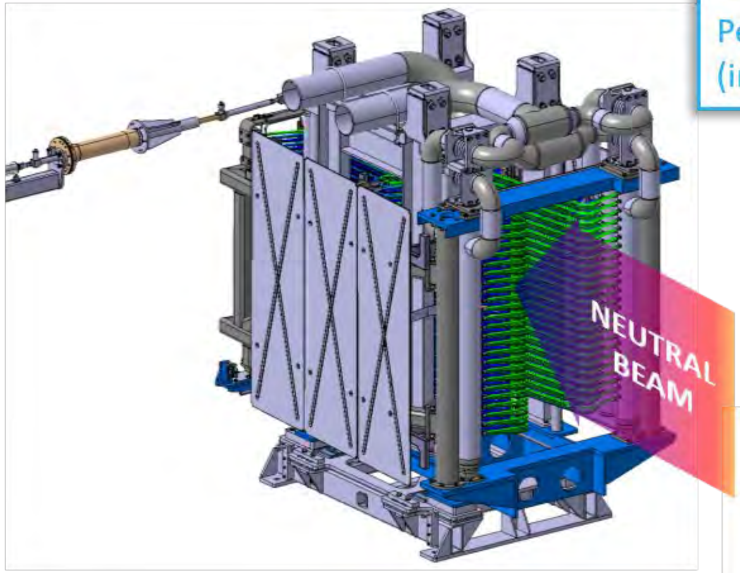
Key function

Capture (with electrical fields) the **residual ions** from the Neutraliser to **leave only a neutral beam.**

Neutral Beam – Components (Calorimeter)

Key function

Perform the **commissioning** of the Neutral Beam (in closed position ⇒ no injection into the plasma).

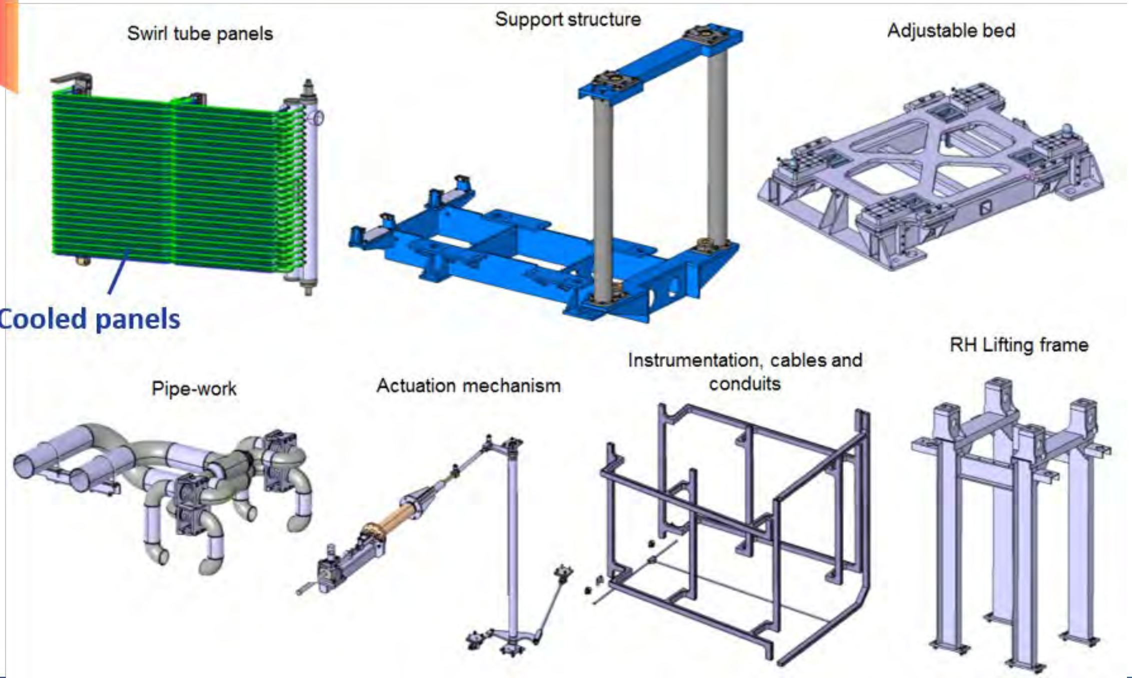


Length ≈ 3.3 m

Width ≈ 2.7 m

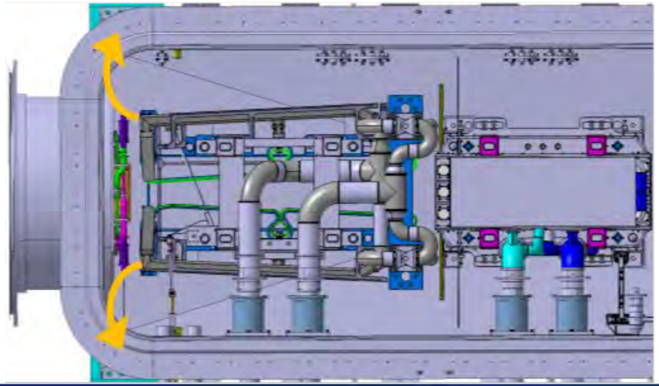
Height ≈ 3.2 m

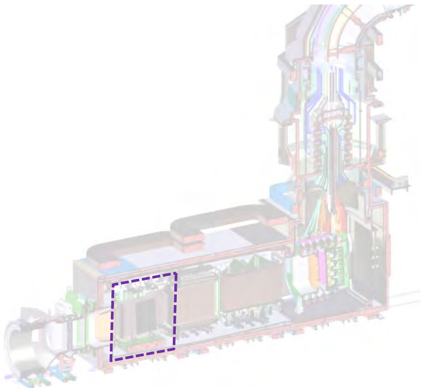
Weight ≈ 5 t



Open position: beam injection

Closed position: beam commissioning



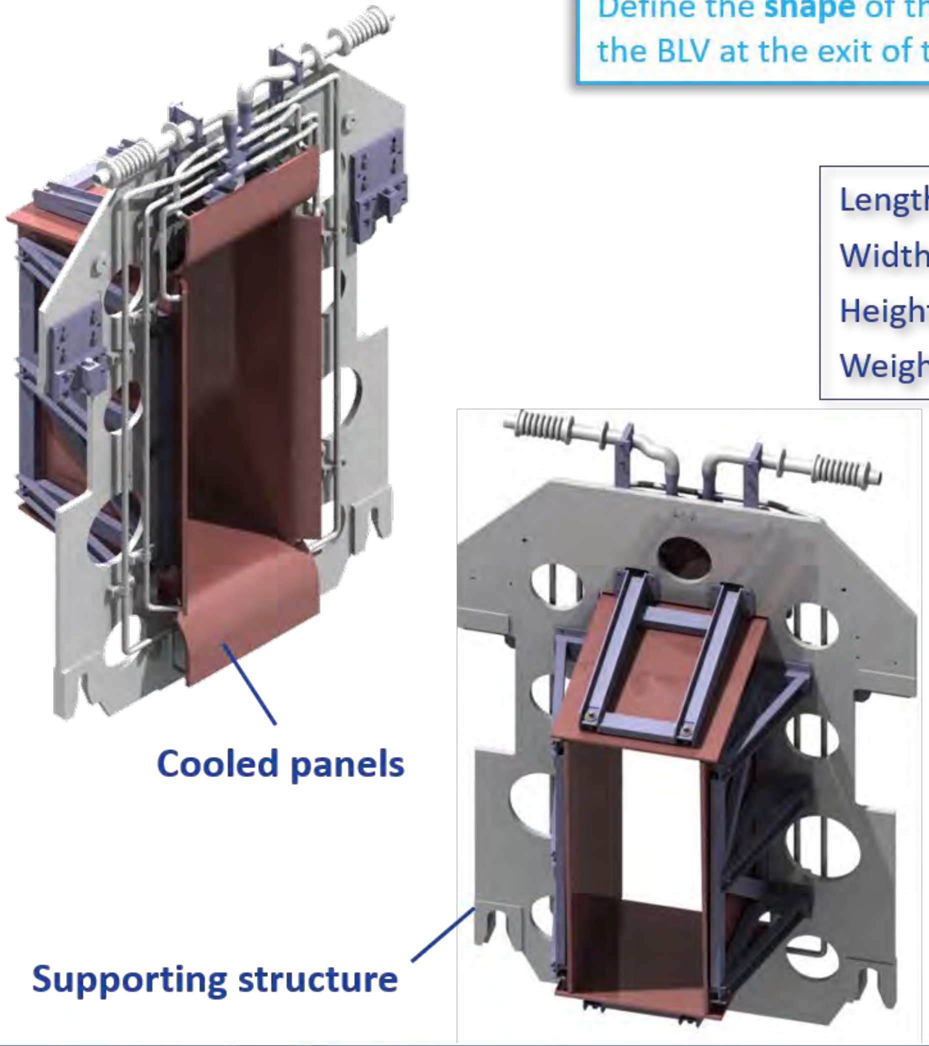


Neutral Beam – Components (ES)

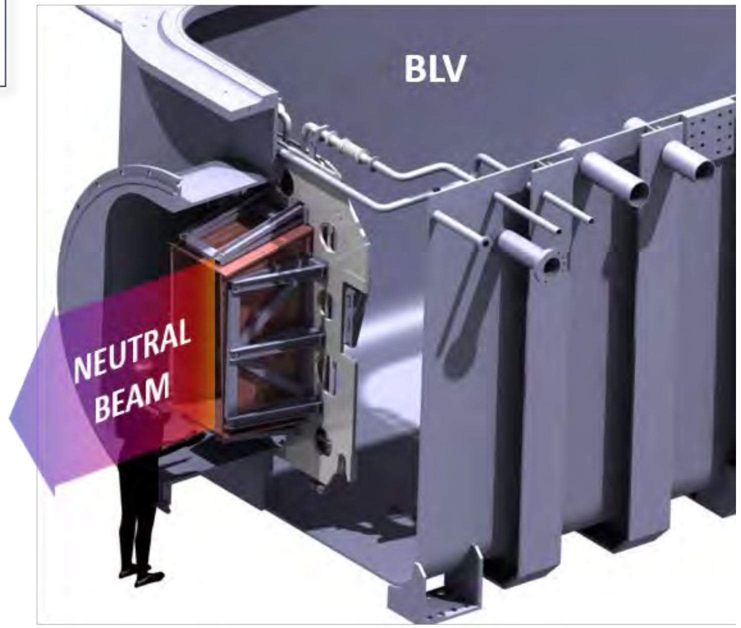
Exit Scraper (ES)

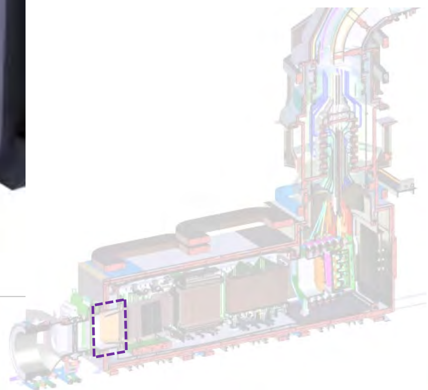
Key function

Define the **shape** of the Neutral Beam and **protect** the BLV at the exit of the Calorimeter.



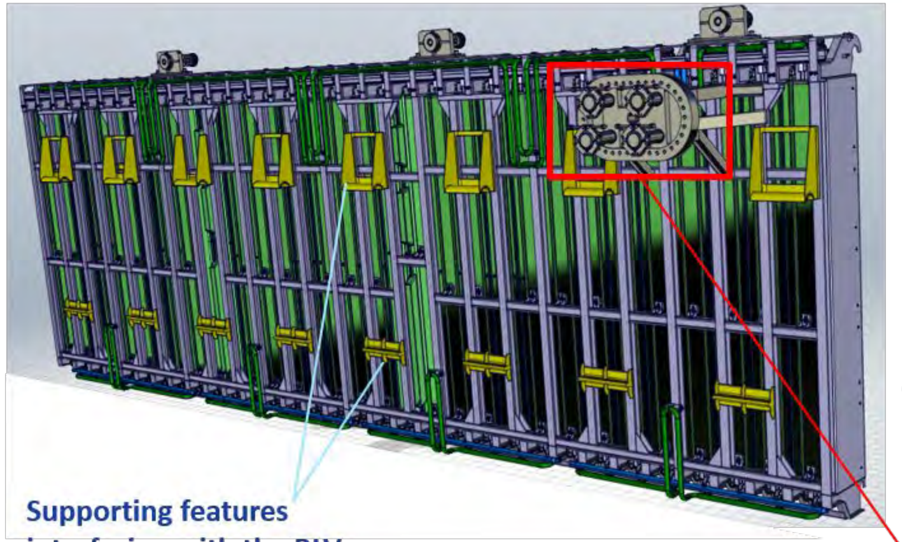
- Length ≈ 1 m
- Width ≈ 1.9 m
- Height ≈ 2.8 m
- Weight ≈ 1.7 t





Neutral Beam – Components (Cryopumps)

NB Cryogenic pumps (Cryopumps)



Key function

Vacuum pumping inside the BLV-BSV by absorption:

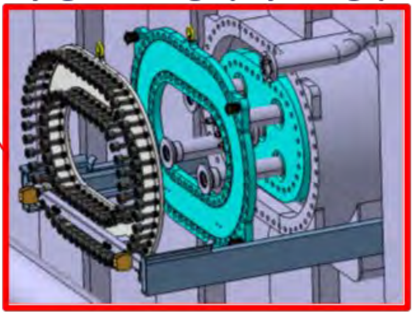
of Deuterium, starts at ≈ T < 18 K

of Hydrogen, starts at ≈ T < 14 K

of Helium, starts at ≈ T < 10 K

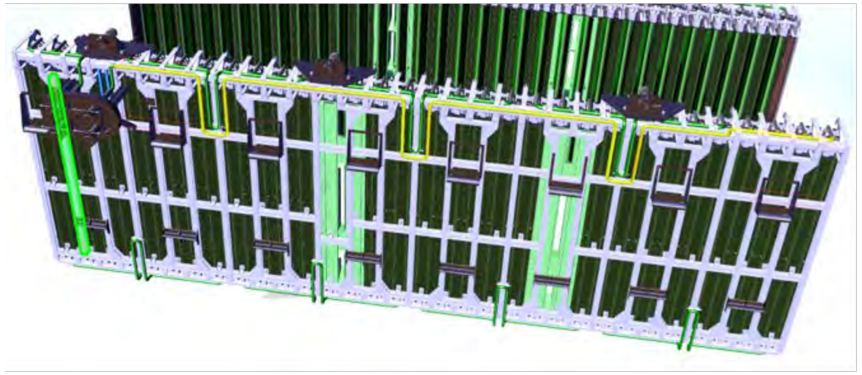
Absolute Zero = 0 K (Kelvin) = - 273,15 °C (Celsius)

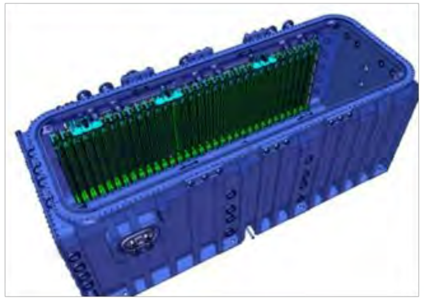
Cryogenic flange (Cryoflange)

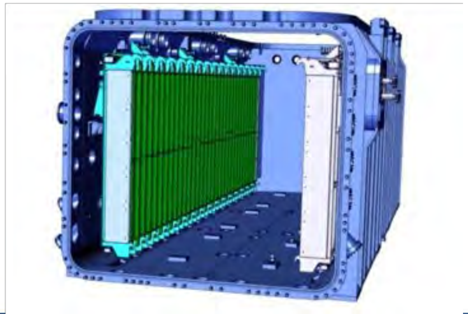


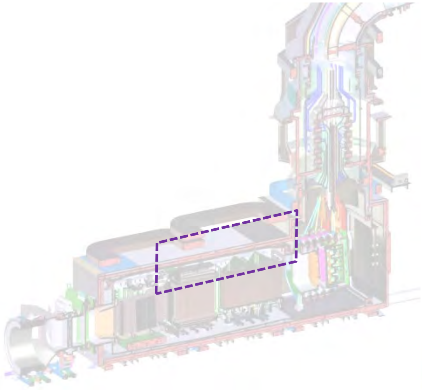
One Cryopump on each side of the BLV

- Length ≈ 8 m
- Width ≈ 48 cm (without flange)
- Height ≈ 2.9 m
- Weight ≈ 5 t



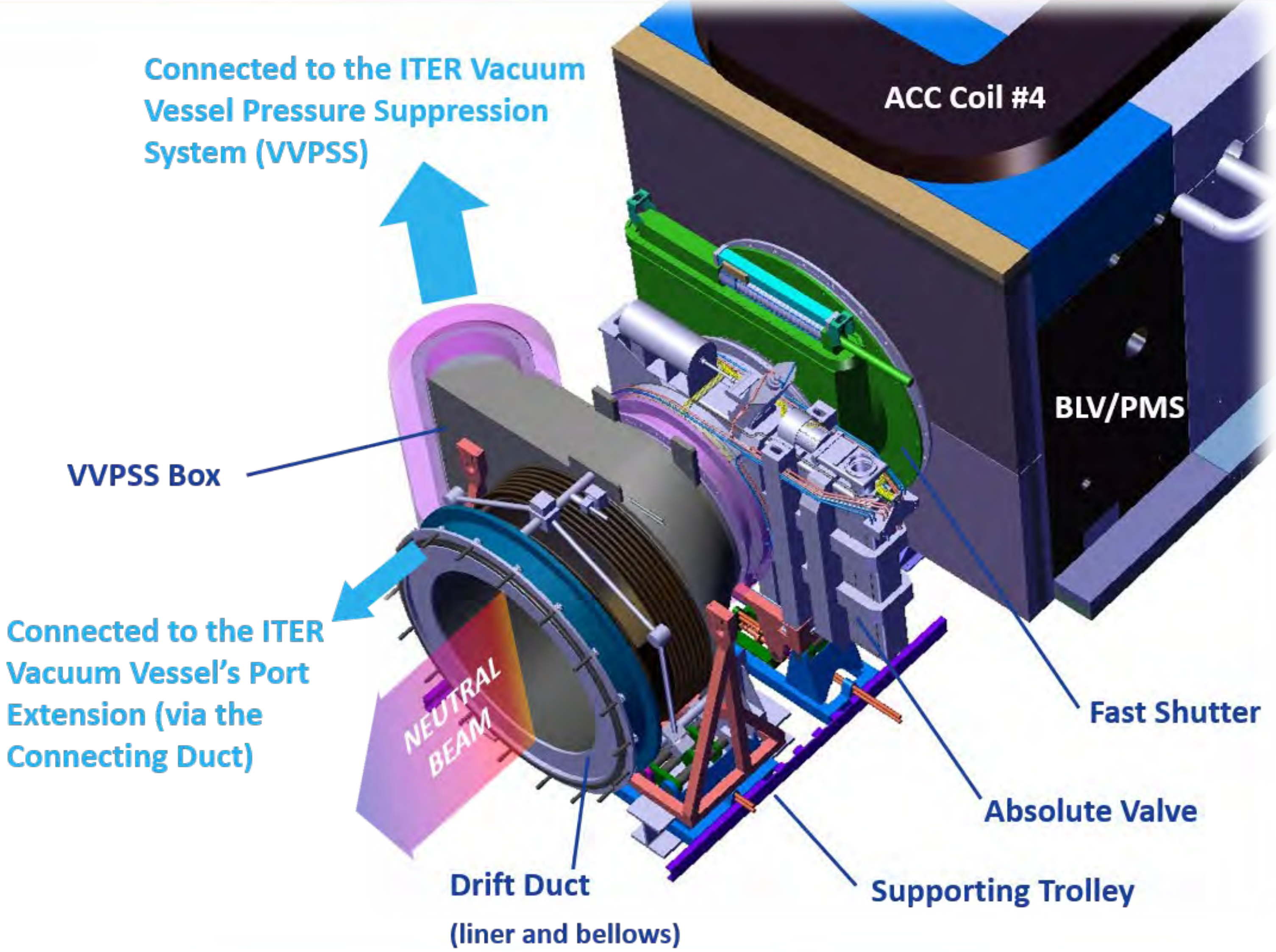


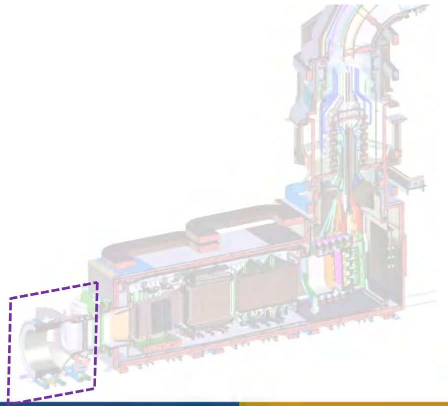




Neutral Beam – Components (FEC)

Front End Components (FEC)

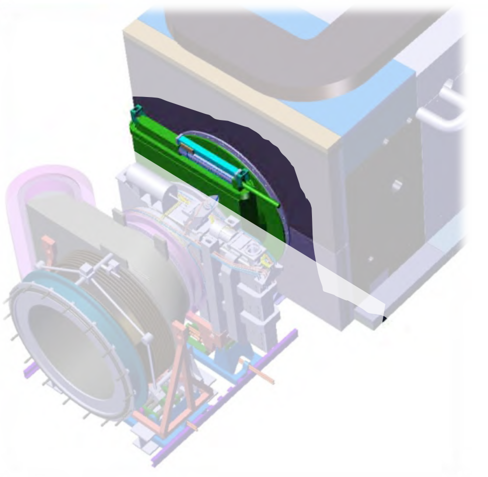


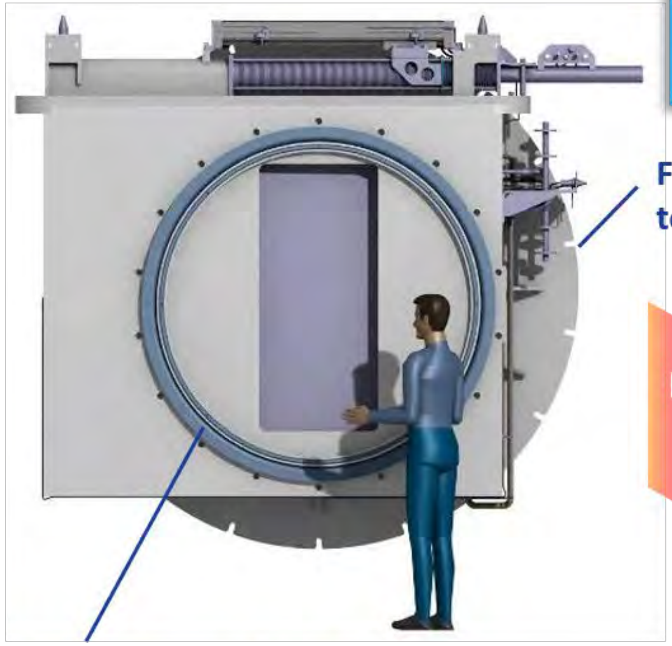


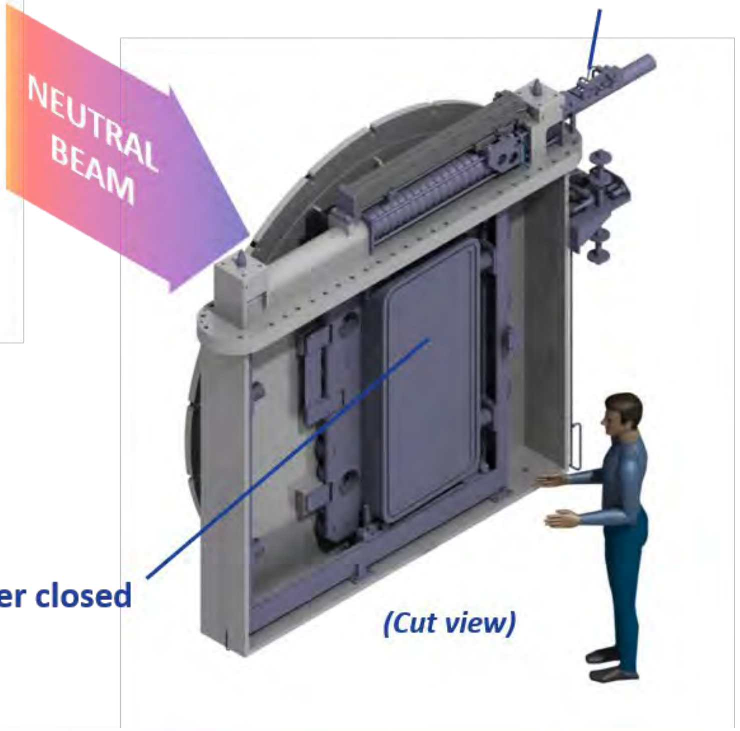
Fast Shutter (FS)

Key function

Shut quickly (< 1 s) in order to **protect** the NBI from an accident inside the Tokamak (pressure increase).





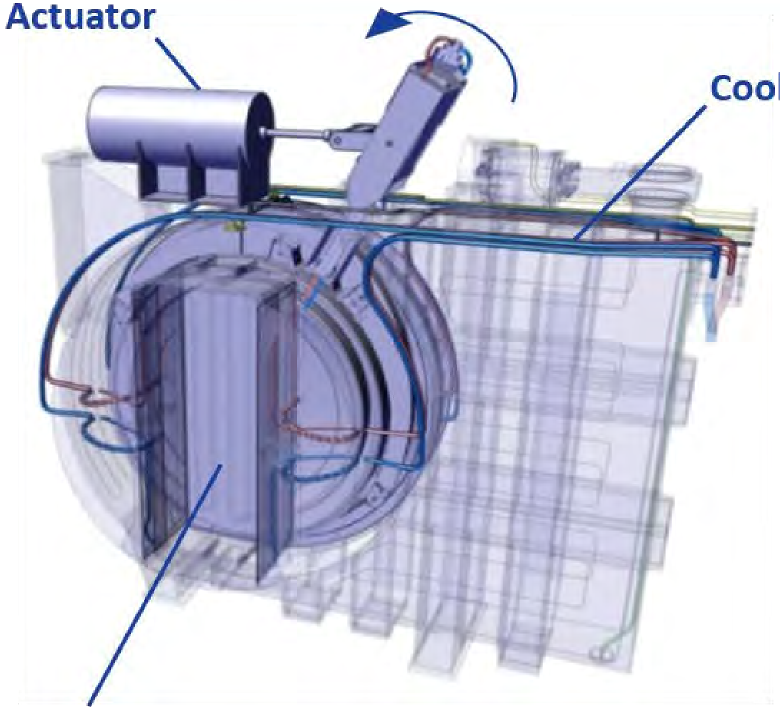


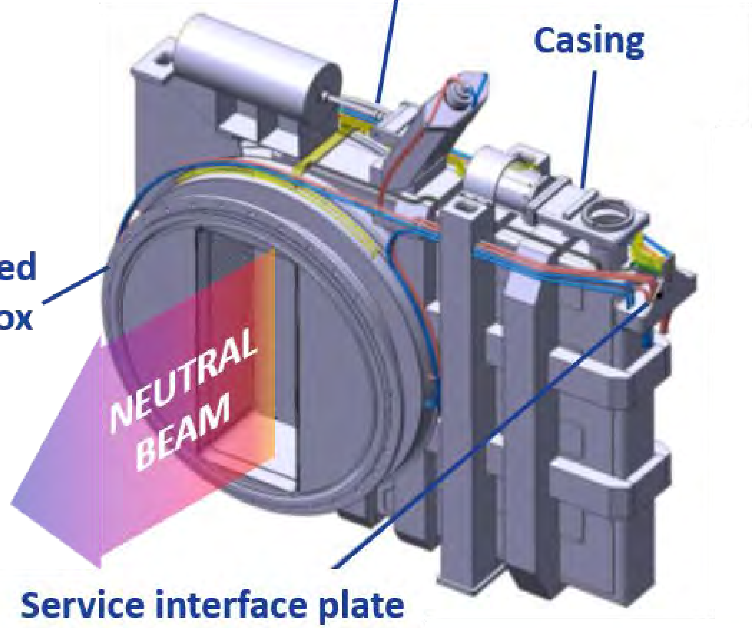
Length ≈ 70 cm
Width ≈ 3.3 m
Height ≈ 2.8 m
Weight ≈ 13.1 t

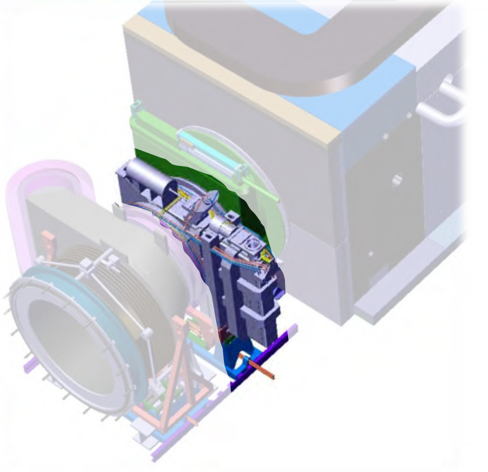
Neutral Beam – Components (AV)

FUSION FOR ENERGY

Absolute Valve (AV)







Key function

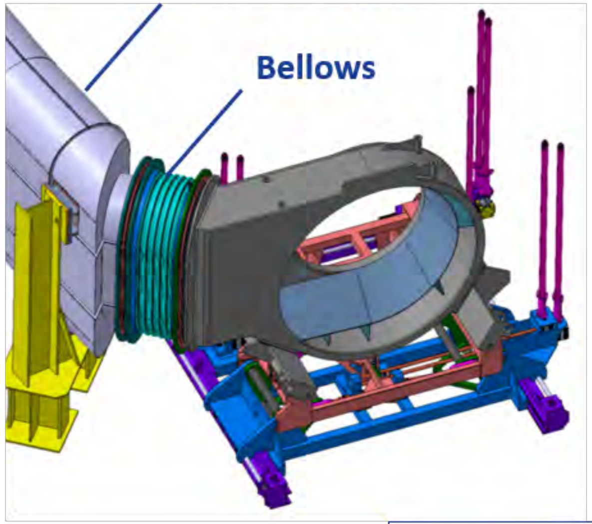
Maintain two different levels of **pressure** between the NBI and the Tokamak (in case of maintenance or accident).

Length ≈ 1.2 m
Width ≈ 3.3 m
Height ≈ 2.9 m
Weight ≈ 16 t

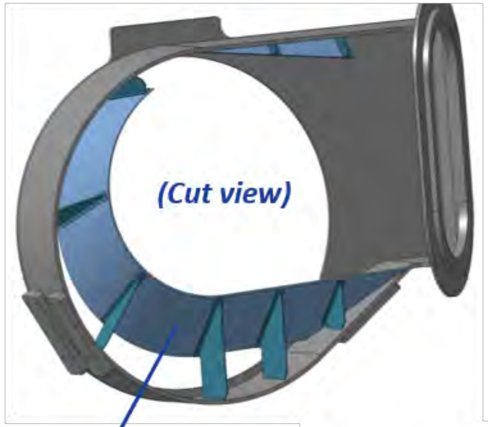
Neutral Beam – Components (VVPSS)

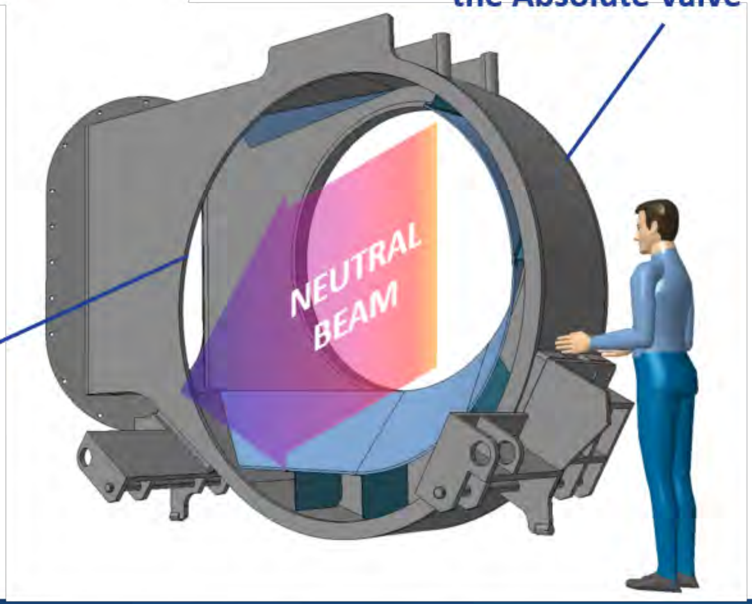
FUSION FOR ENERGY

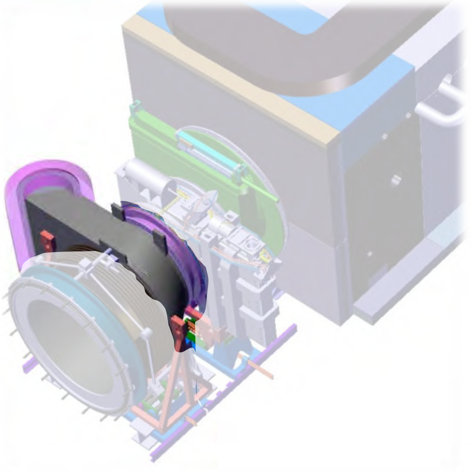
Vacuum Vessel Pressure Suppression System (VVPSS) Box



Length ≈ 1.3 m
Width ≈ 3.7 m
Height ≈ 2.6 m
Weight ≈ 4.7 t







Key function

Connection of the Tokamak (via the NB equatorial port) to the ITER VVPSS.

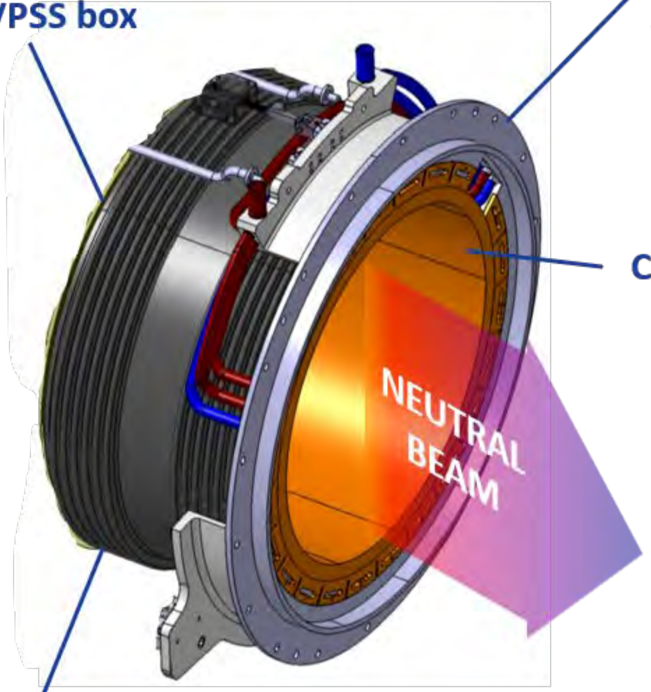
Neutral Beam – Components (Duct Drift)

FUSION FOR ENERGY

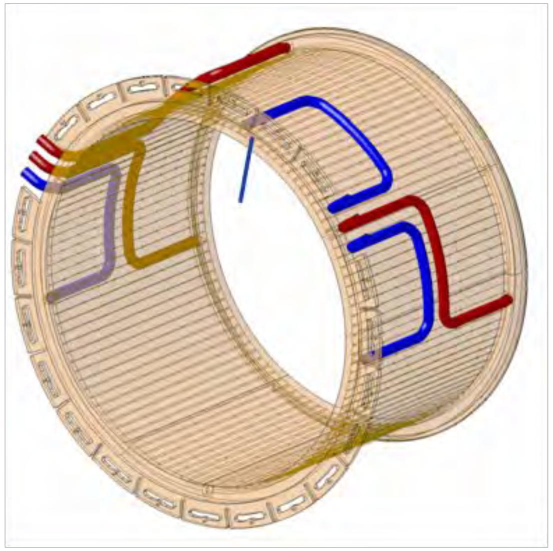
Drift Duct (bellows + liner)

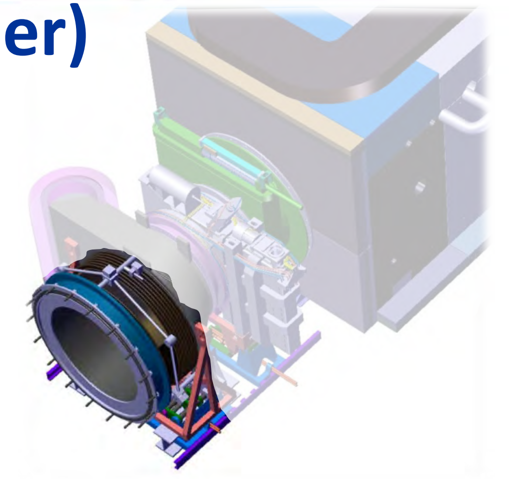
Bellows welded to the VVPSS box

Flange connected to the Connecting Duct (interface with the ITER Vacuum Vessel)

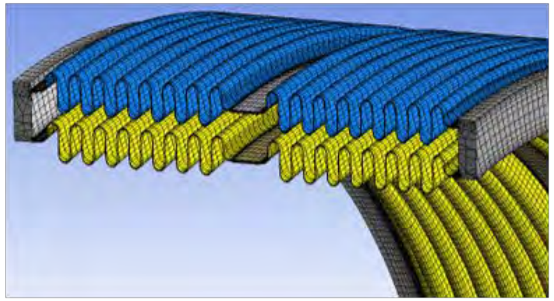


Cooled liner





Double bellows (vacuum and confinement boundary)



Length ≈ 1.4 m
Width ≈ 3.2 m
Height ≈ 3 m
Weight ≈ 5.7 t

Key function

Recover the assembly **misalignments** and **thermal expansions** between the NBI and the Tokamak.

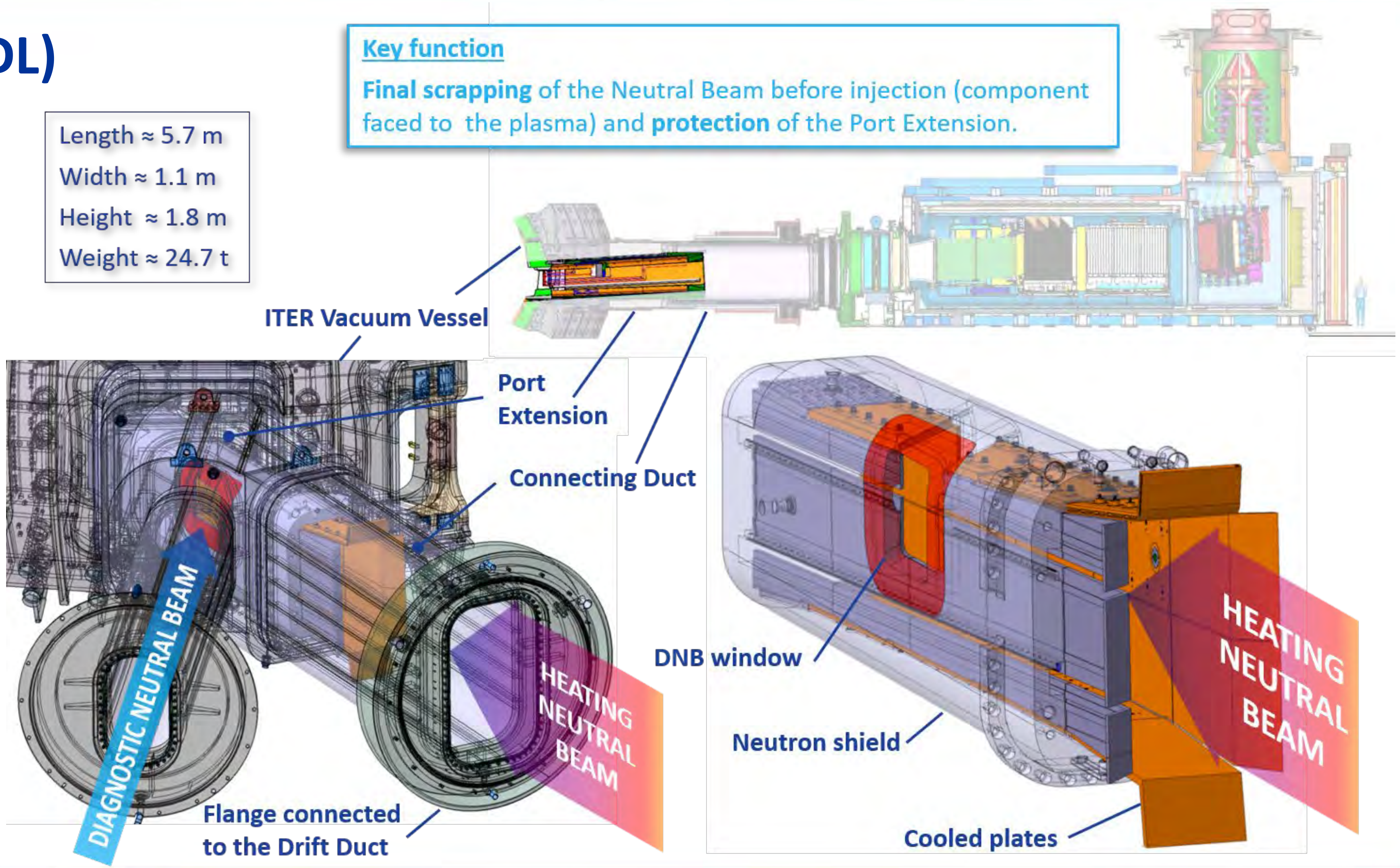
Neutral Beam – Components (DL)

Duct Liner (DL)

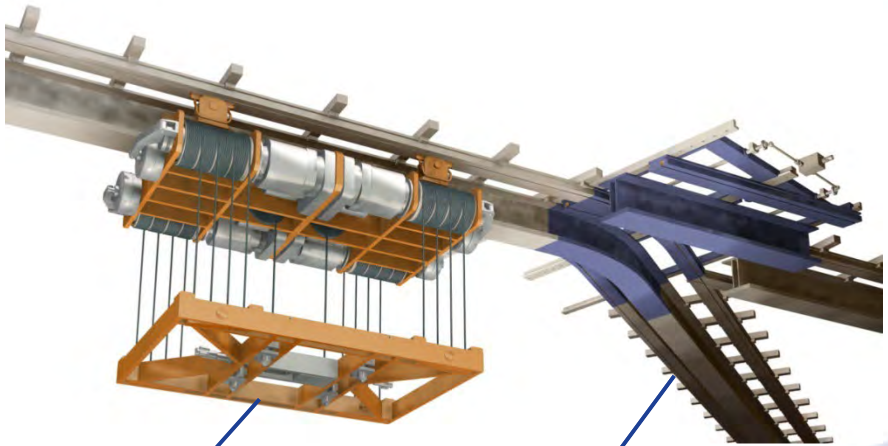
Key function

Final scrapping of the Neutral Beam before injection (component faced to the plasma) and **protection** of the Port Extension.

Length ≈ 5.7 m
Width ≈ 1.1 m
Height ≈ 1.8 m
Weight ≈ 24.7 t



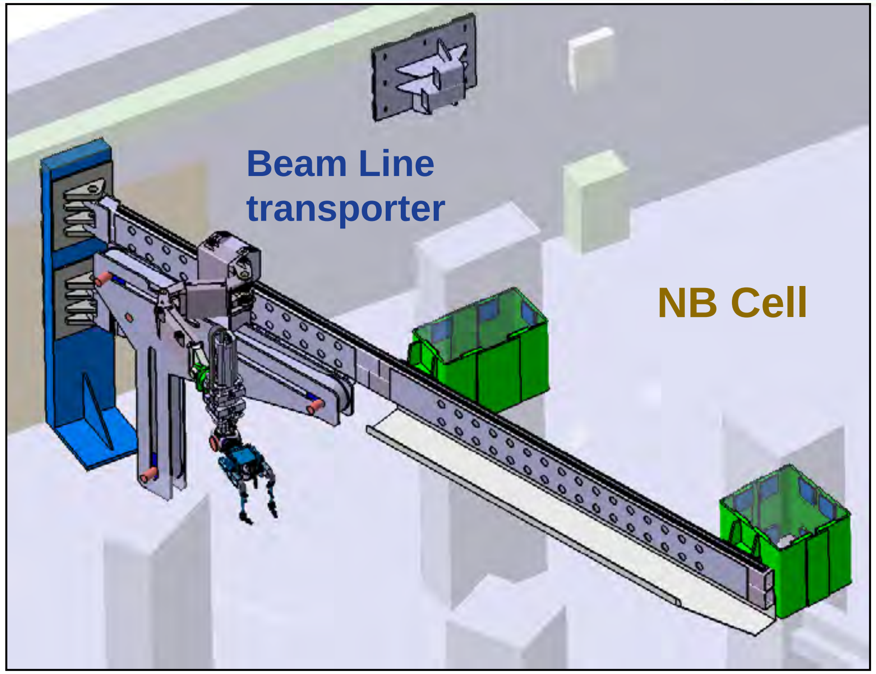
Neutral Beam – Remote Handling Tools

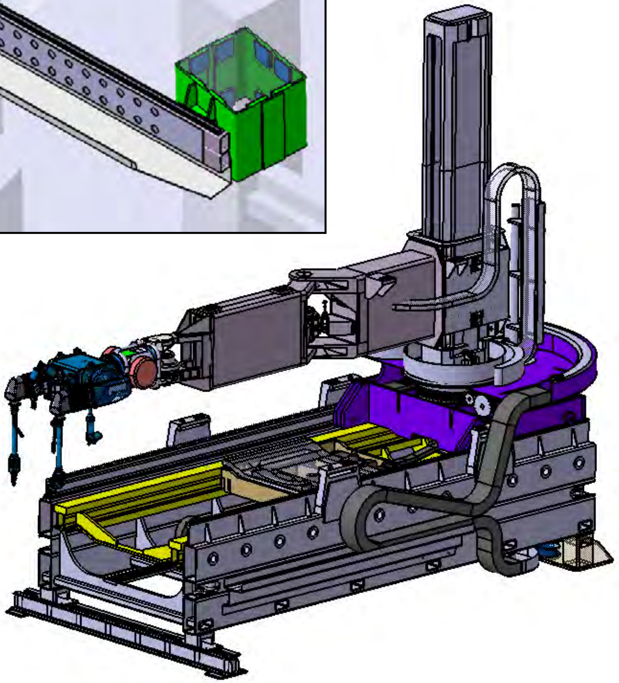


RH crane

RH monorail

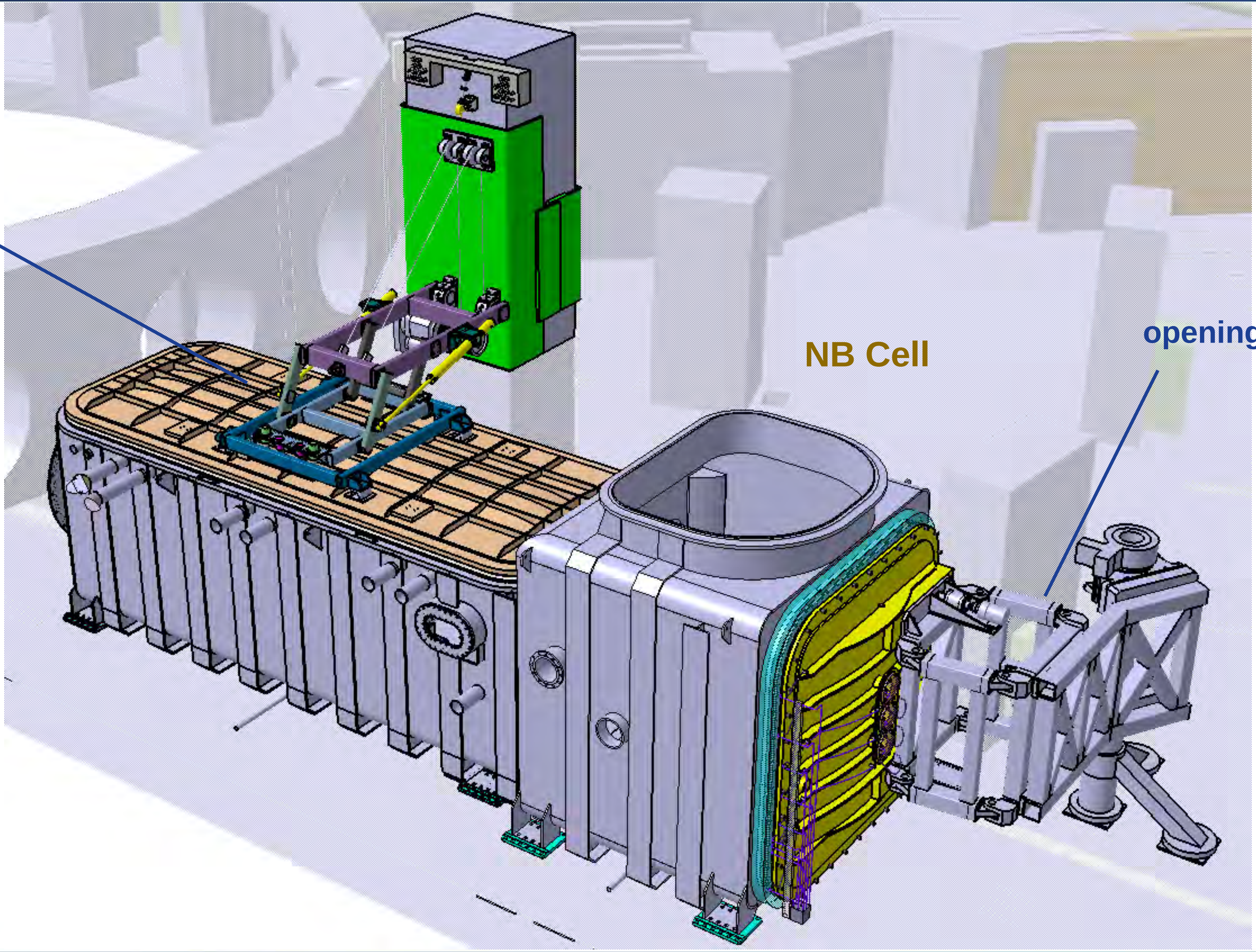
RH tools layout in the NB Cell





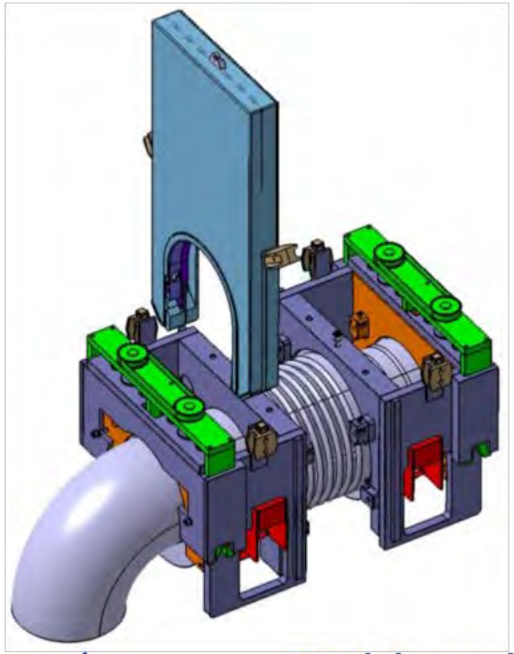
Beam Source manipulator

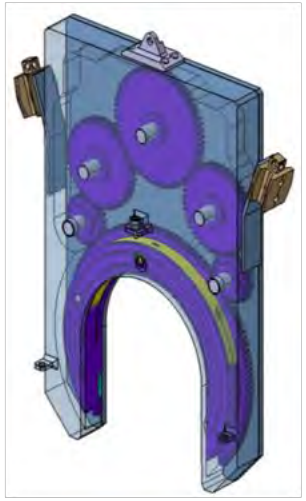
Neutral Beam – Remote Handling Tools

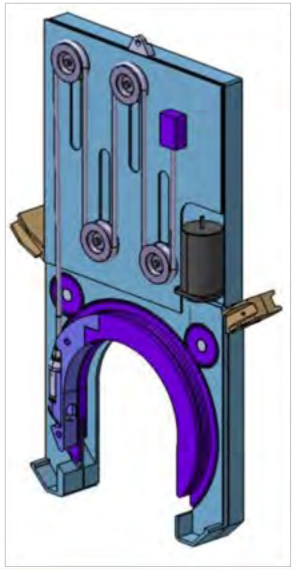


Neutral Beam – Remote Handling Tools

FUSION FOR ENERGY

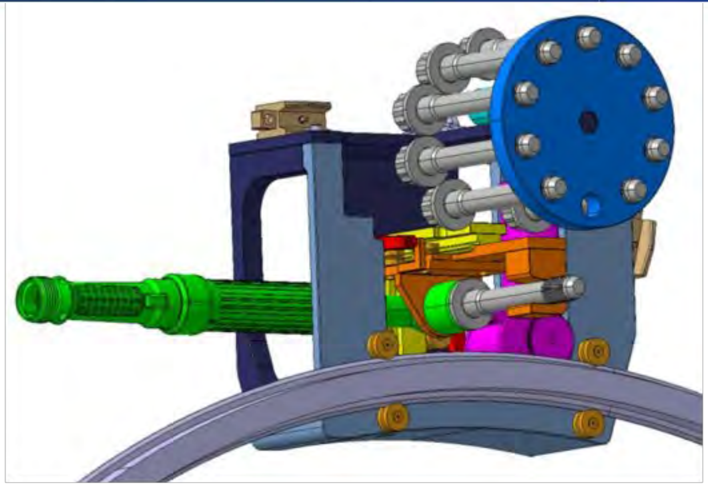




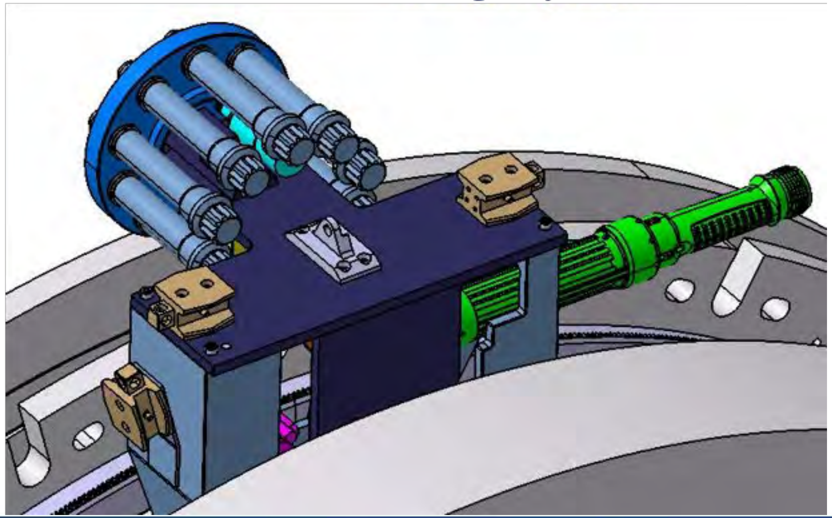


RH piping tool:
alignment, welding,
cutting, inspection

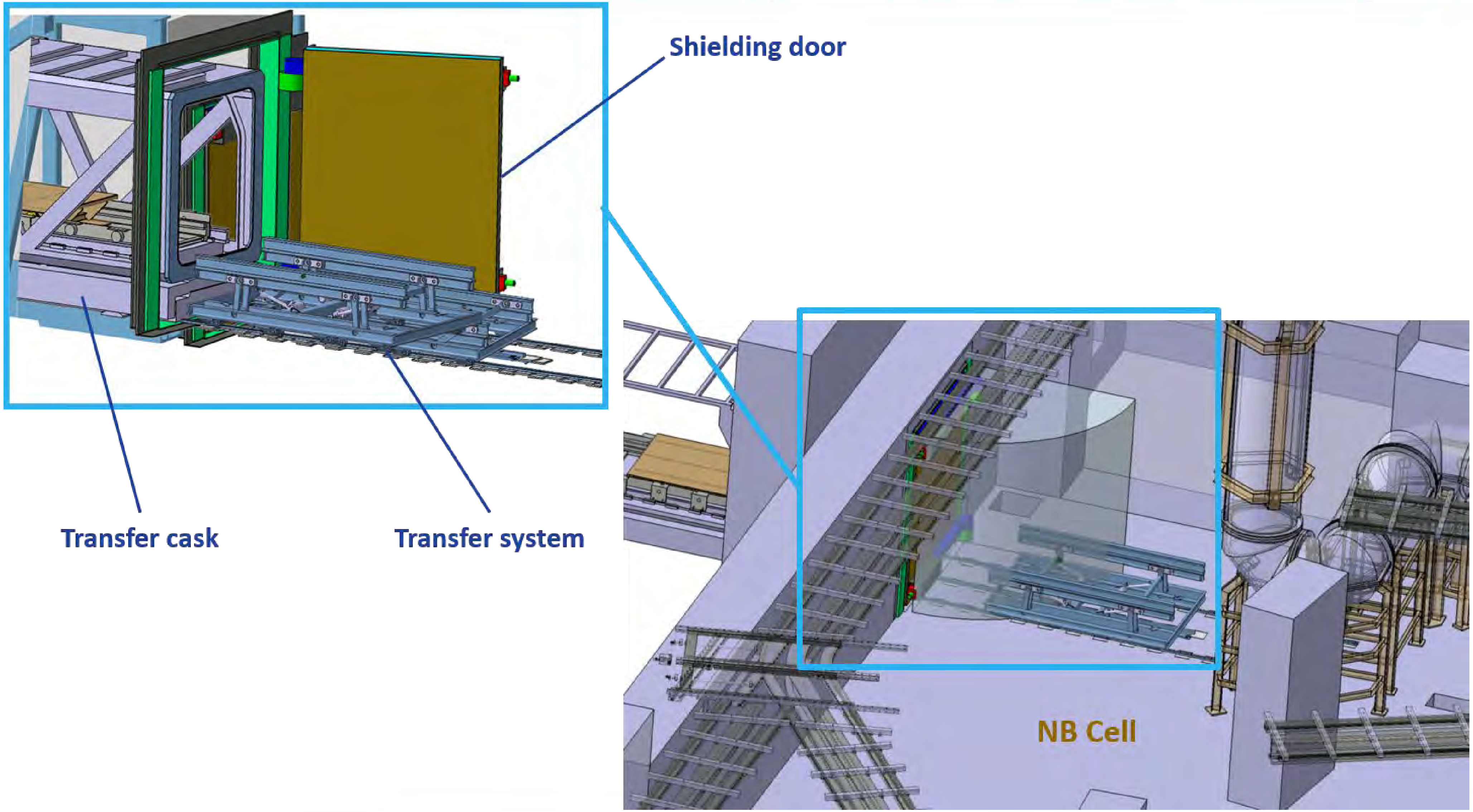
BLC cooling pipe



RH flange tool:
bolting, inspection

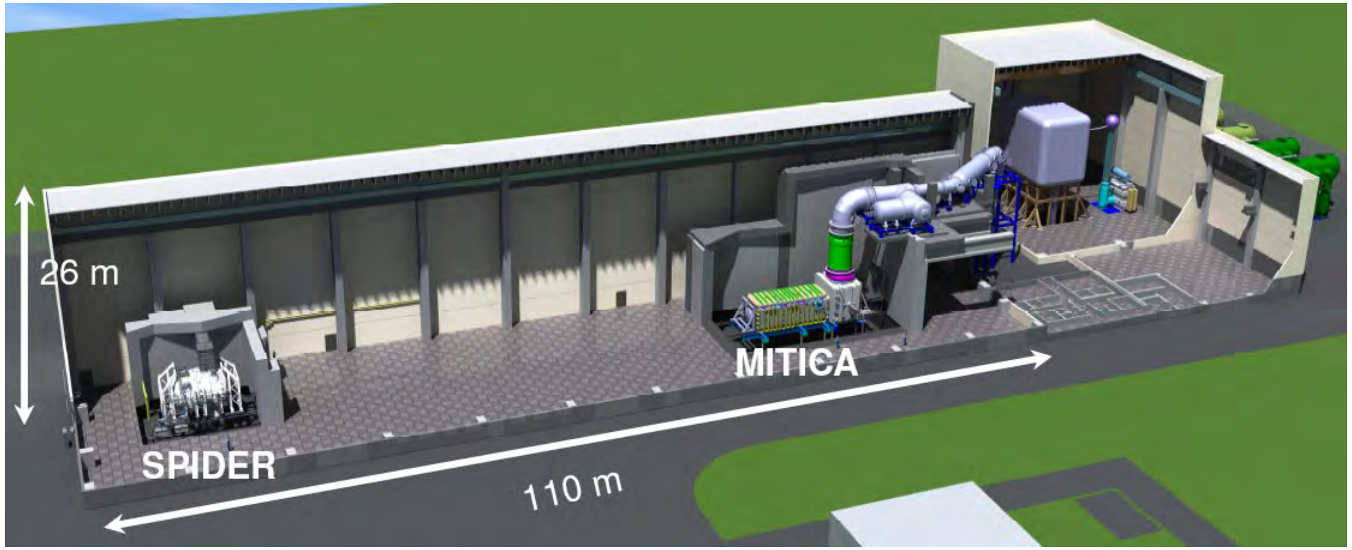


Neutral Beam – Remote Handling Tools

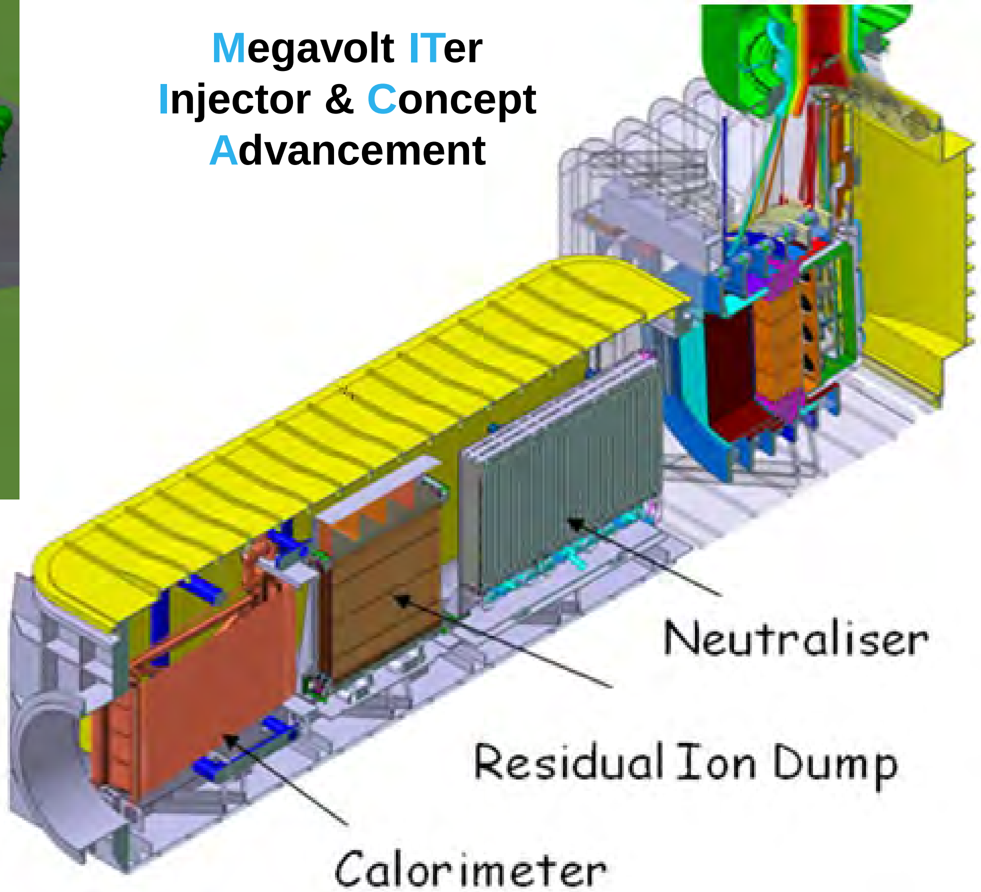


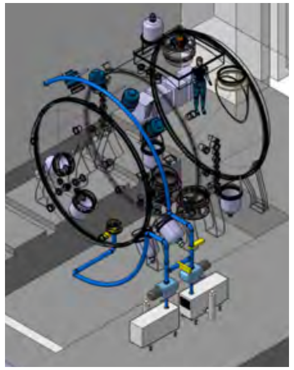
Neutral Beam – Challenges (SPIDER & MITICA)

Main challenges: Diversity of FOAK parts and components, i.e., complexity on fabrication, installation and operation → **SPIDER** and **MITICA** experiments at Consorzio RFX, Padova (Italy)



Megavolt ITer Injector & Concept Advancement

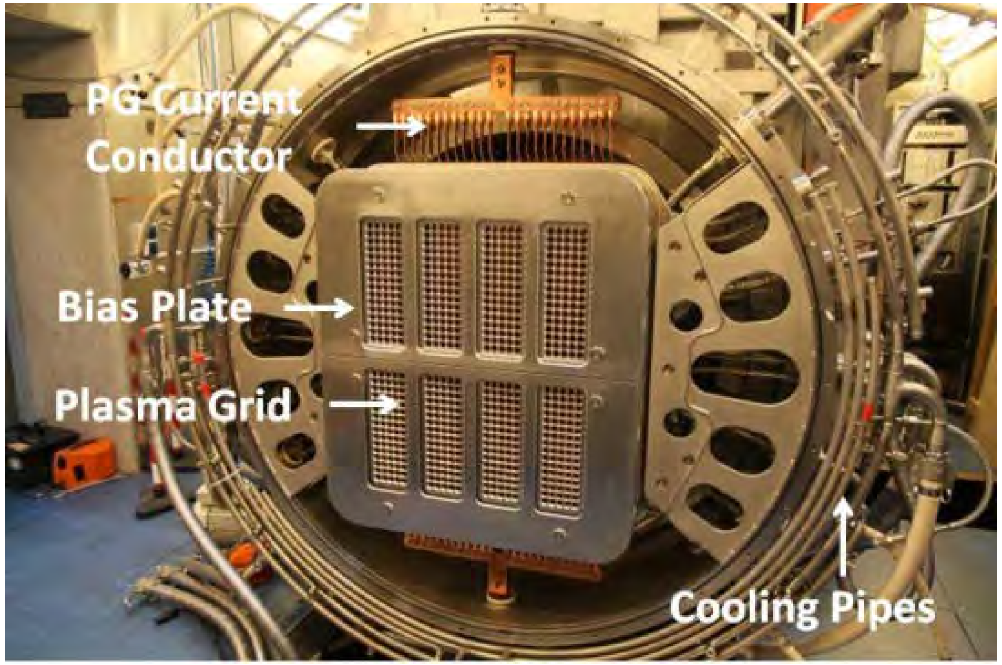




Source for Production of Ion of Deuterium Extracted from Radio frequency plasma

Neutral Beam – Challenges (ELISE & Injector)

Main challenges: Diversity of FOAK parts and components, i.e., complexity on fabrication, installation and operation ➔ **ELISE** *(+ BATMAN + RADI)* experiment(s) at IPP-Garching (Germany)



Extraction from a Large Ion Source Experiment

Experimental campaigns on a half-size ITER-type source with extraction of negative ion beams. Experimental tests in ITER relevant conditions

In addition: The combined "**energy x current x pulse duration**" of the **NB ITER injector** represents an extrapolation of **three orders of magnitude (x1000)** from the existing NB systems

Neutral Beam – Challenges (Components)

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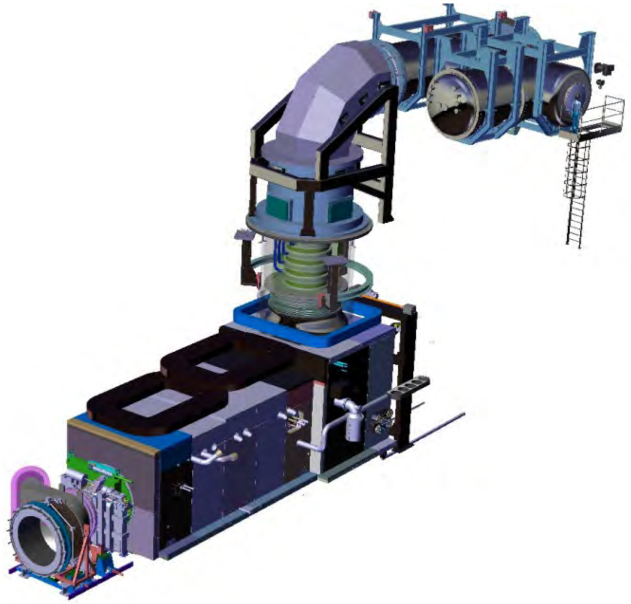
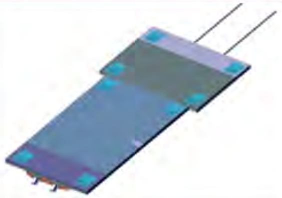
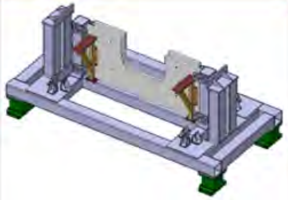
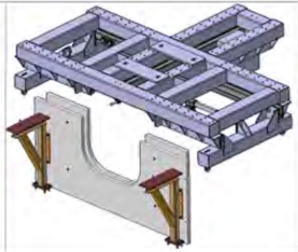
<u>Main challenges</u>: Assembly procedure with of parts (number of components) and procedures (number of steps) with attention to coordinate with other intervening PBS (e.g., RH tools)



Neutral Beam – Challenges (Assembly)

Main challenges: Assembly procedure with of parts (number of components) and procedures (number of phases/steps) with attention to coordinate with other intervening PBS (e.g., RH tools)

STEP		ASSEMBLY STEP DESCRIPTION & ILLUSTRATION		TOOL(S) / EQUIPMENT(S)	COORDINATION	SPECIFICATIONS	DURATION	TIME SCALE
	6	Setting and fixation of BLV and BSV feet interfaces on lower PMS plates		Laser Tracker System Fixation equipment				
	7	Alignment checking of BLV and BSV feet, according to BLV & BSV metrology (measured in factory)		Laser Tracker System				
6		Front PMS plate (1/2 lower part) installation						
	1	Transportation of front PMS plate (1/2 lower part) to the NB Cell		PMS trolley				
	2	Unloading from PMS trolley, setting and fixation to lower PMS plates		Industrial monorail crane PMS lifting tool Fixation equipment				
	3	Clearances checking between PMS plates, according to magnetic requirements		Laser Tracker System (or other measurement system if LTS is not needed)				

Neutral Beam – Main Challenges (Summary)

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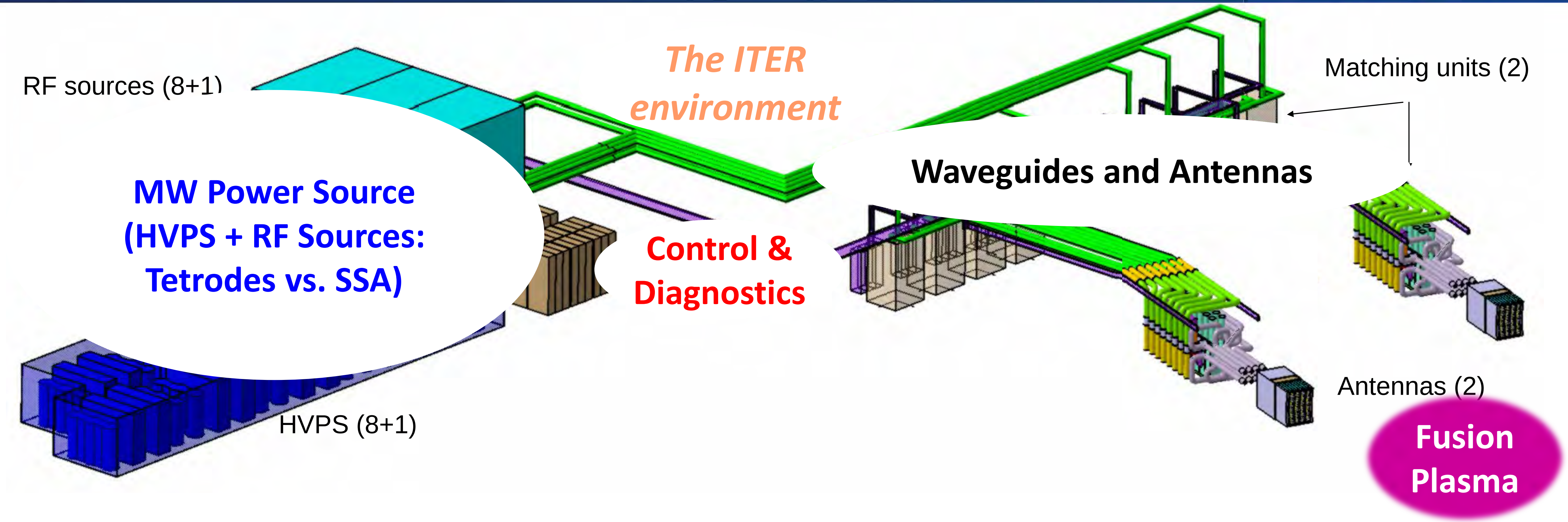
- Many FOAK parts & components → complexity on fabrication, installation and operation
- NBTF, real-scale prototyping (NTBF, MITICA, SPIDER) → improvements, **years of experience**
- Pending R&D tasks, while completing procurement specifications and operational parameters
- Interfaces management, internal (between NB sub-systems) and external (ITER environment)
- Assembly time constraints & ITER phase coordination → Keeping schedule under control
- Alignment & tolerances, as per physics & engineering constraints → short time for alignment
- Operation & Maintenance, considering complexity, number of parts, weights and dimensions
- ITER environment, neutron fluence, and high heat loads (e.g., accelerator) → cooling!
- Risk mitigation actions + Unknown challenges → possible increase of cost

Outline of Talk – H&CD Challenges in Fusion Reactors

- Heating & Current Drive (H&CD) Systems and Technologies
- Heating Neutral Beam (HNB)
  - The ITER HNB system
  - Main parts and challenges
- **Ion Cyclotron Resonance Heating (ICRH)**
  - **The ITER ICRH system**
  - **Main parts and challenges**
- Electron Cyclotron Resonance Heating (ECRH)
  - The ITER ECRH, from the plasma to the microwave source
  - EC Launchers, parts and challenges
  - EC Gyrotrons, parts and challenges
  - EC Power Supplies, parts and challenges

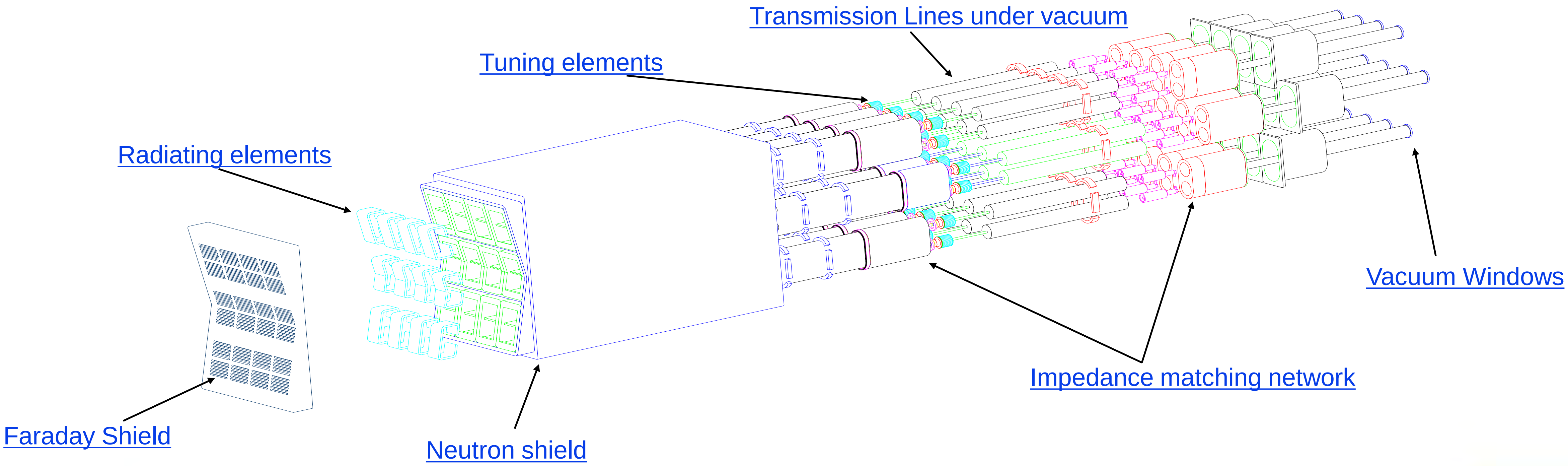
The ITER ICRH (IC Resonance Heating)



The ITER ICRH system shall be designed to couple 10-20 MW of power in quasi-CW operation (pulses up to 3600s) in the frequency range 40 to 55 MHz, which covers other ITER HCD plasma scenarios

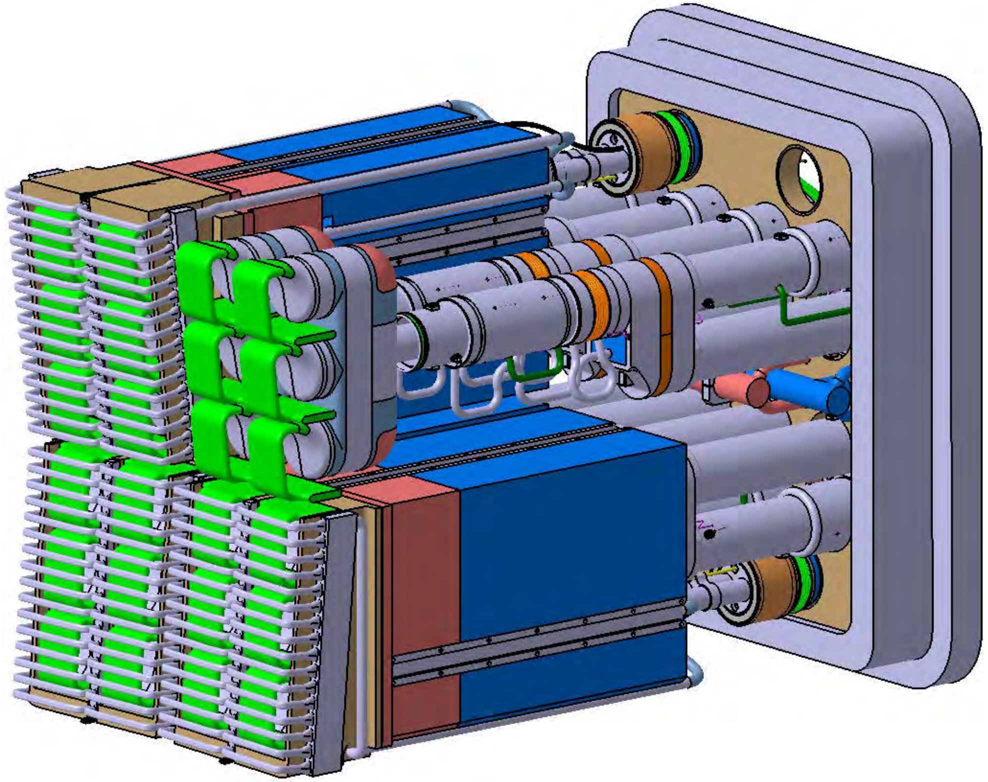
ICRH Technological Challenges – Launchers

***IC Launchers* (in-vessel):** Faraday shield, directly facing the plasma; support structure, including primary vacuum closure plate; twelve antennas, with their neutron shielding, mechanically assembled in a single array;
and twelve sections of coaxial transmission lines sealed at the closure plate by dielectric vacuum windows



ICRH Technological Challenges – Antennas

IC Antennas: Each antenna copes with very high-power density (~9 MW / m^2) and they shall be insensitive to rapid changes in coupling conditions, as per presence of rapid changes in loading resistance, produced by ELMs



3D view of the antenna plug facing the plasma

Main challenges:

- Efficient cooling of antennas to evacuate the heat load ~9 MW / m^2 ➔ high power density test at the test facility
- Faraday Screens to protect the current-carrying antenna strap (Be/CuCrZr/Stainless-Steel prototype bar) ➔ high power density test too
- Water cooled RF Vacuum Windows in Alumina ➔ Prototype under RF test with water in operating and baking conditions (i.e., 150 ^{o}C and 240 ^{o}C)

ICRH – Main Challenges (Summary)

- HVPS & Control → PWM vs. PSM, and electronic modules (maintenance, replacement)
- RF sources → Tetrode (cathode lifetime)
- RF Sources → SSA (transistors obsolescence, maintenance and replacement)
- RF Sources → Tetrode vs. SSA, check CERN lessons learned (workload, cost)
- Transmission lines and RF Windows → Losses reduction and vacuum sealing
- Matching system (stud tuners) → real time adaptation (tested ASDEX-U)
- Launcher → Faraday shield, directly facing the plasma (neutron fluence)
- Antennas → Efficient cooling to evacuate the heat load ~9 MW / m^2
- ITER environment, neutron fluence, also with high heat loads
- New building at ITER site → schedule constraints, long time scales

Outline of Talk – H&CD Challenges in Fusion Reactors

- Heating & Current Drive (H&CD) Systems and Technologies
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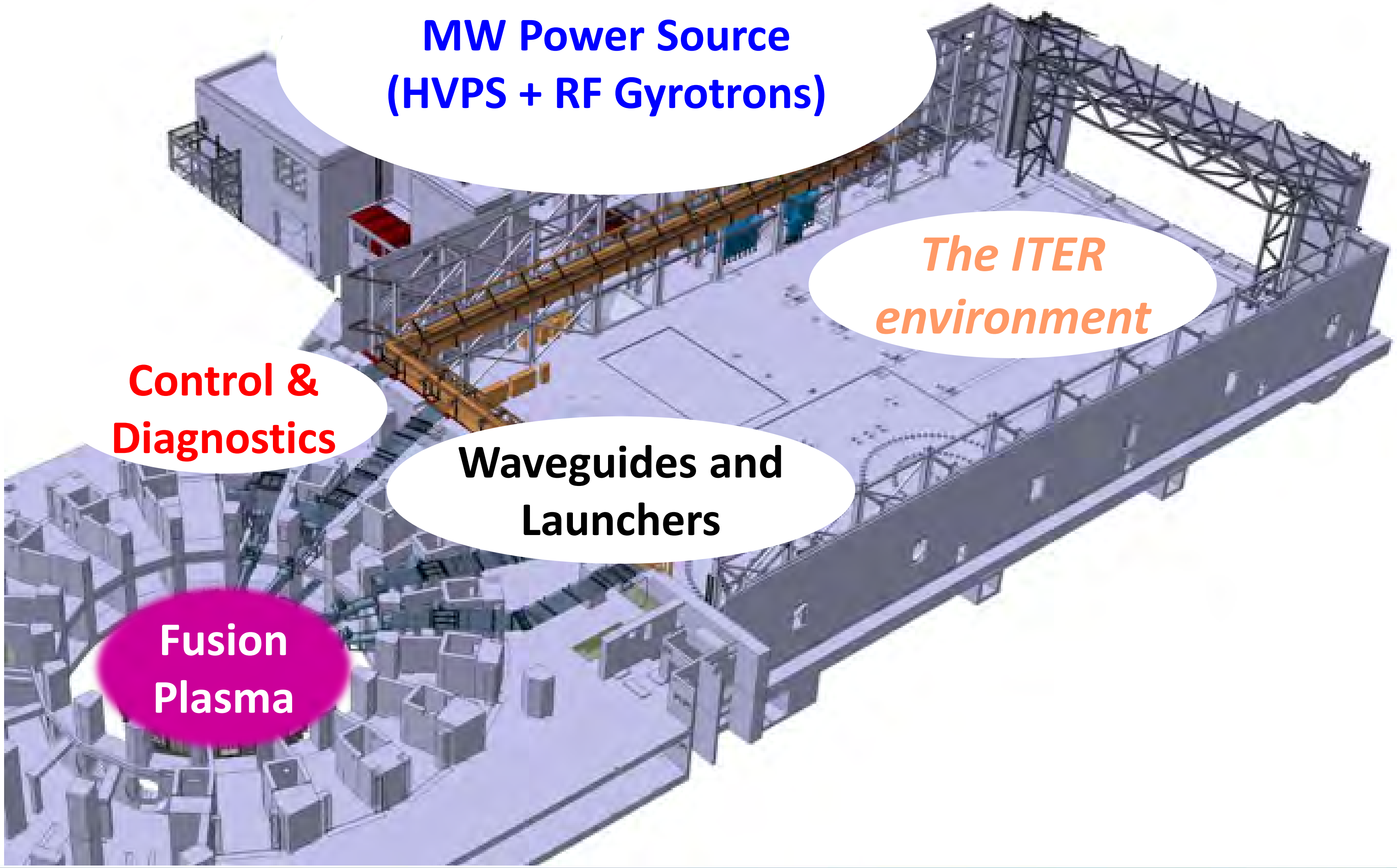
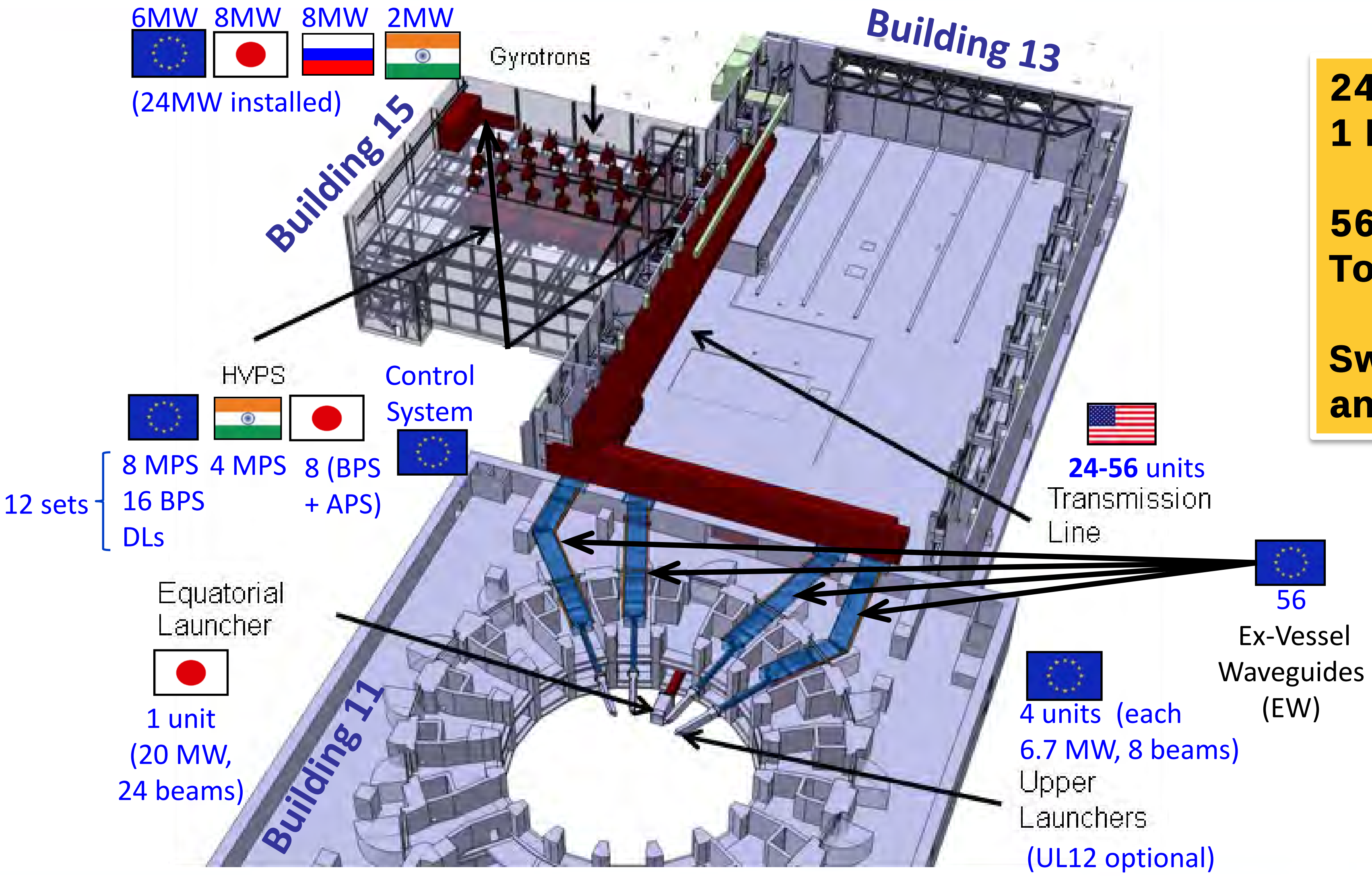
  - **EC Launchers, parts and challenges**
  - **EC Gyrotrons, parts and challenges**
  - **EC Power Supplies, parts and challenges**

The ITER ECRH (EC Resonance Heating)



ITER ECRH System (Baseline 2016)

FUSION FOR ENERGY



24 gyrotrons
1 MW @ 170 GHz up to 3600 s

56 transmission lines (EW) in Tokamak building (B11)

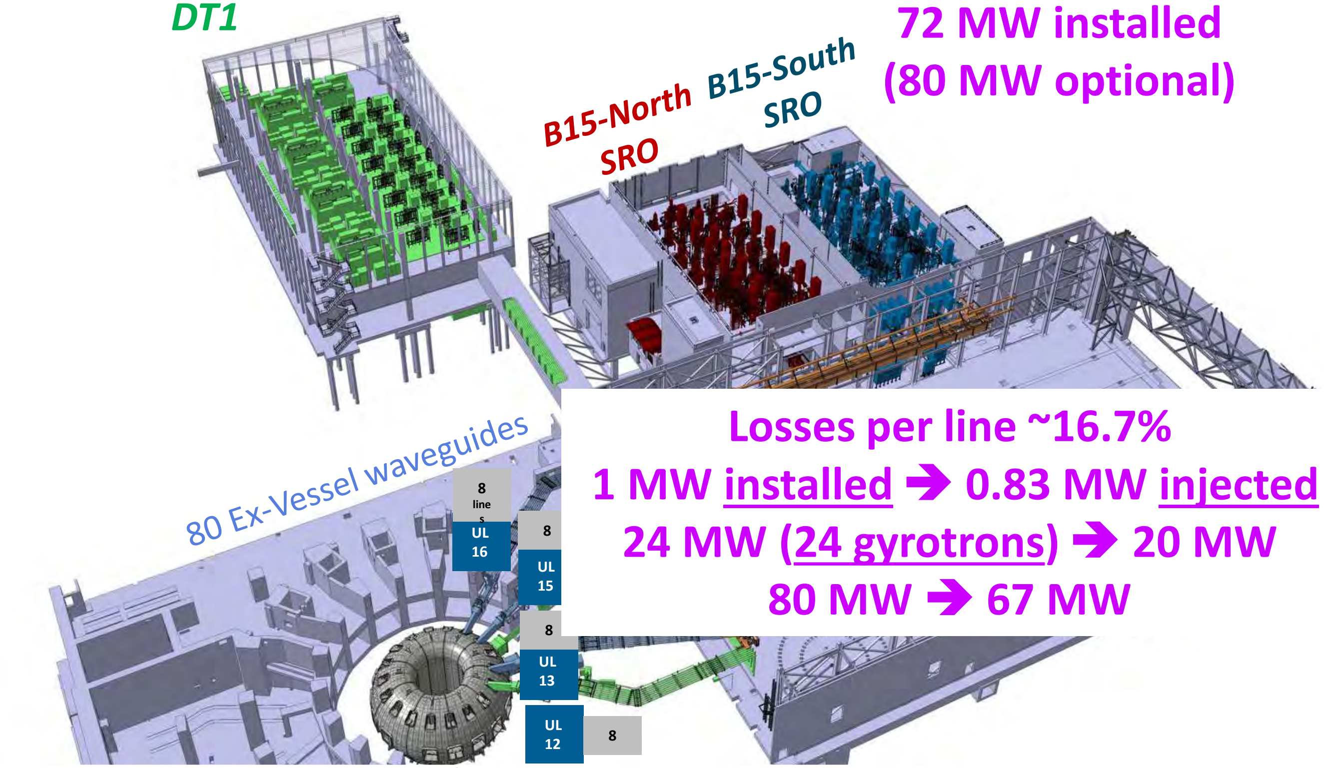
Switches between upper launchers and equatorial launcher

ITER ECRH System (Baseline 2024: SRO + DT-1)

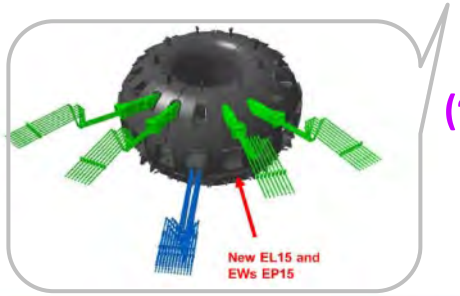
FUSION FOR ENERGY

B18 (New Building with Bridge)
DT1

TOTAL POWER =
72 MW installed
(80 MW optional)



Losses per line ~16.7%
1 MW installed ➔ 0.83 MW injected
24 MW (24 gyrotrons) ➔ 20 MW
80 MW ➔ 67 MW



~60 MW
(~67 MW optional)
plasma injected

In general, same technology, with some adaptations and new building

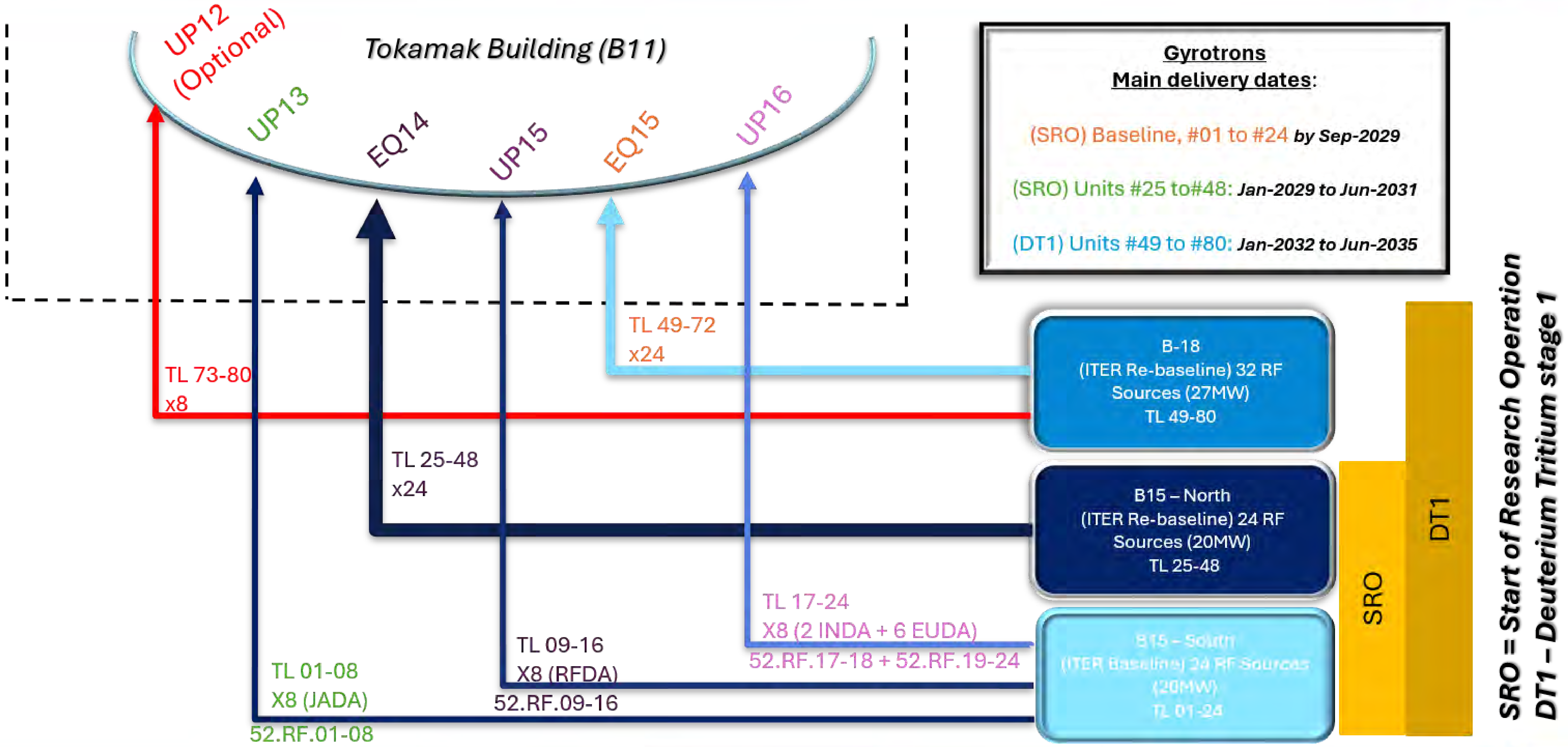
Baseline and SRO		DT1
24	+ 24	+ 24 RF Sources (+8 optional)
12	+ 12	+ 12 High Voltage PS (+4 optional)
24	+ 24	+ 24 Transmission Lines (+8 optional)
1		+ 1 Equatorial Launcher (EL15)
4		*(UL12 remains optional)*
56		+ 24 Ex-Vessel Waveguides
		+ Control cubicles
		+ Ancillaries, supports

Implications:

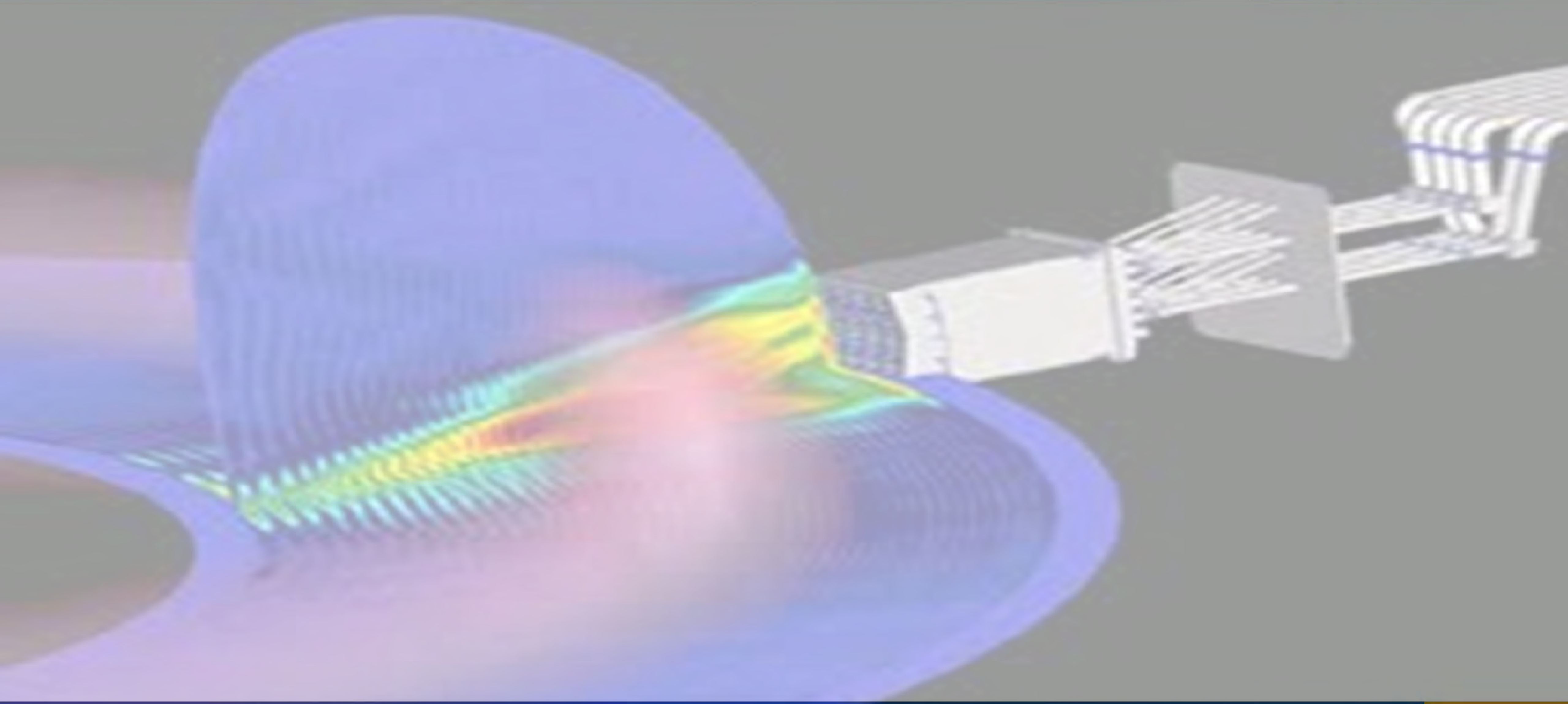
- Retrofitting of B15 North (penetrations, reinforcement)
- Logic for keeping same B15 services (water & electricity)
- Construction of new building with bridge
- New transmission line routing in (for SRO and DT-1)
- **Removing switches**
- New cooling annex and cooling loop (CCWS-2F/H4)
- Significant implications in SSEN/PPEN
- New equatorial launcher (EL15) in B11
- New ex-vessel waveguides in B11
- Associated services (e.g vacuum, adaptation of CCWS-1A)

ITER ECRH System (Baseline 2024: Schematics)

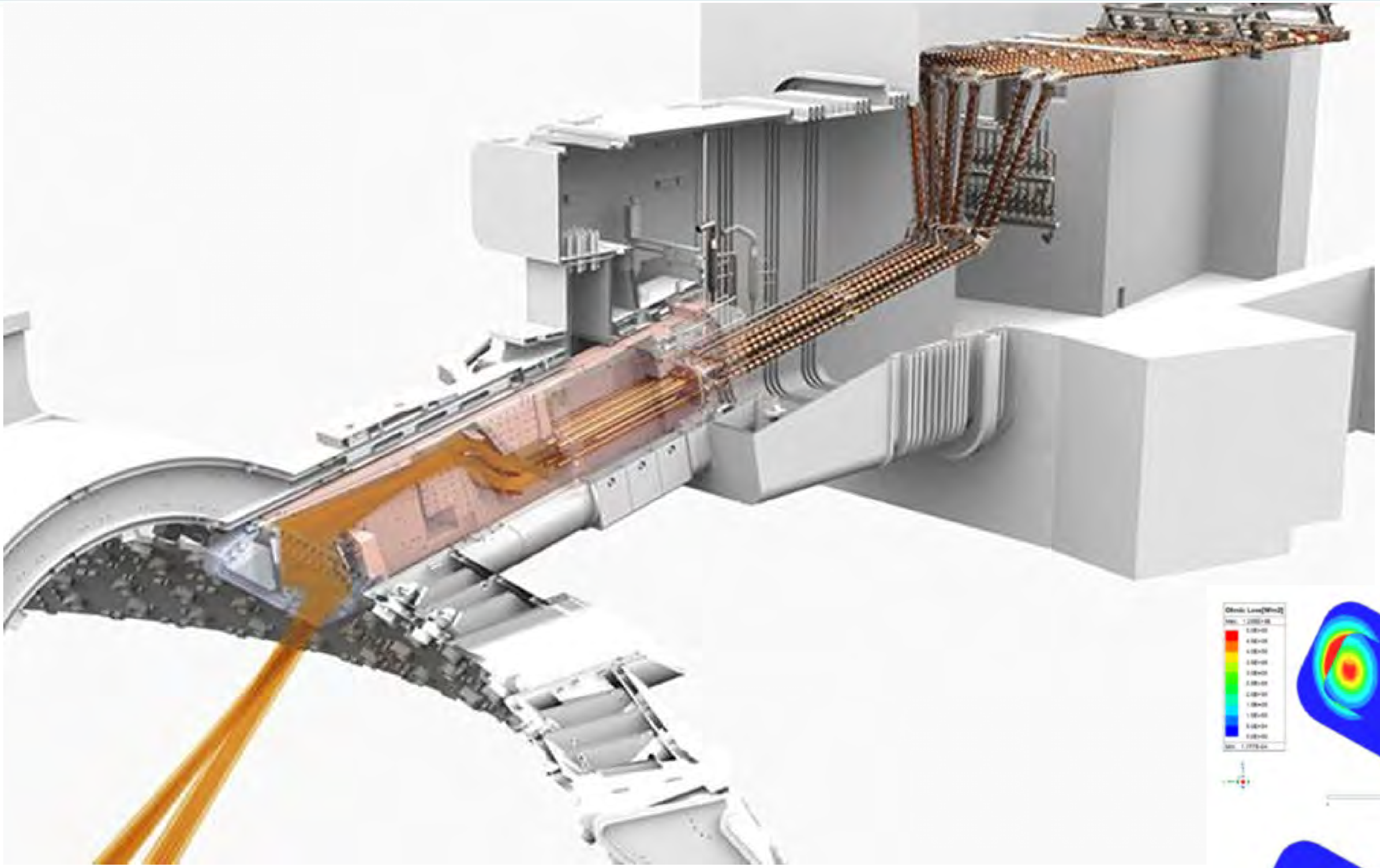
FUSION FOR ENERGY



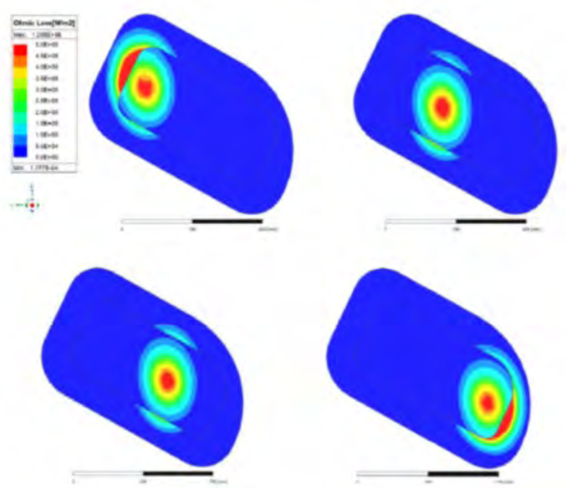
The ITER ECRH ‘from plasma to μw source’

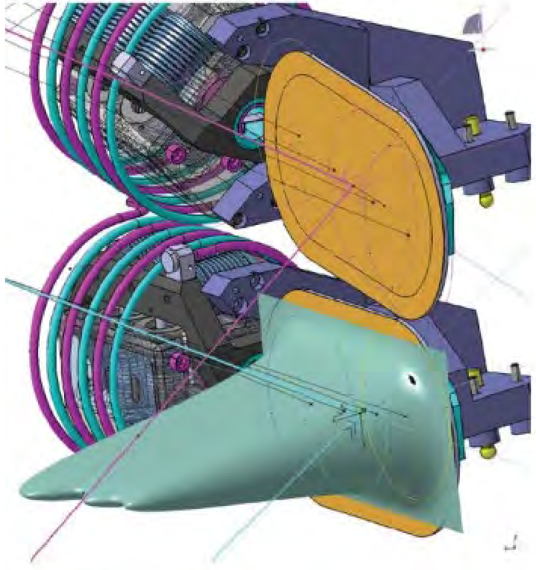


EC Upper Launchers – Parts and Challenges

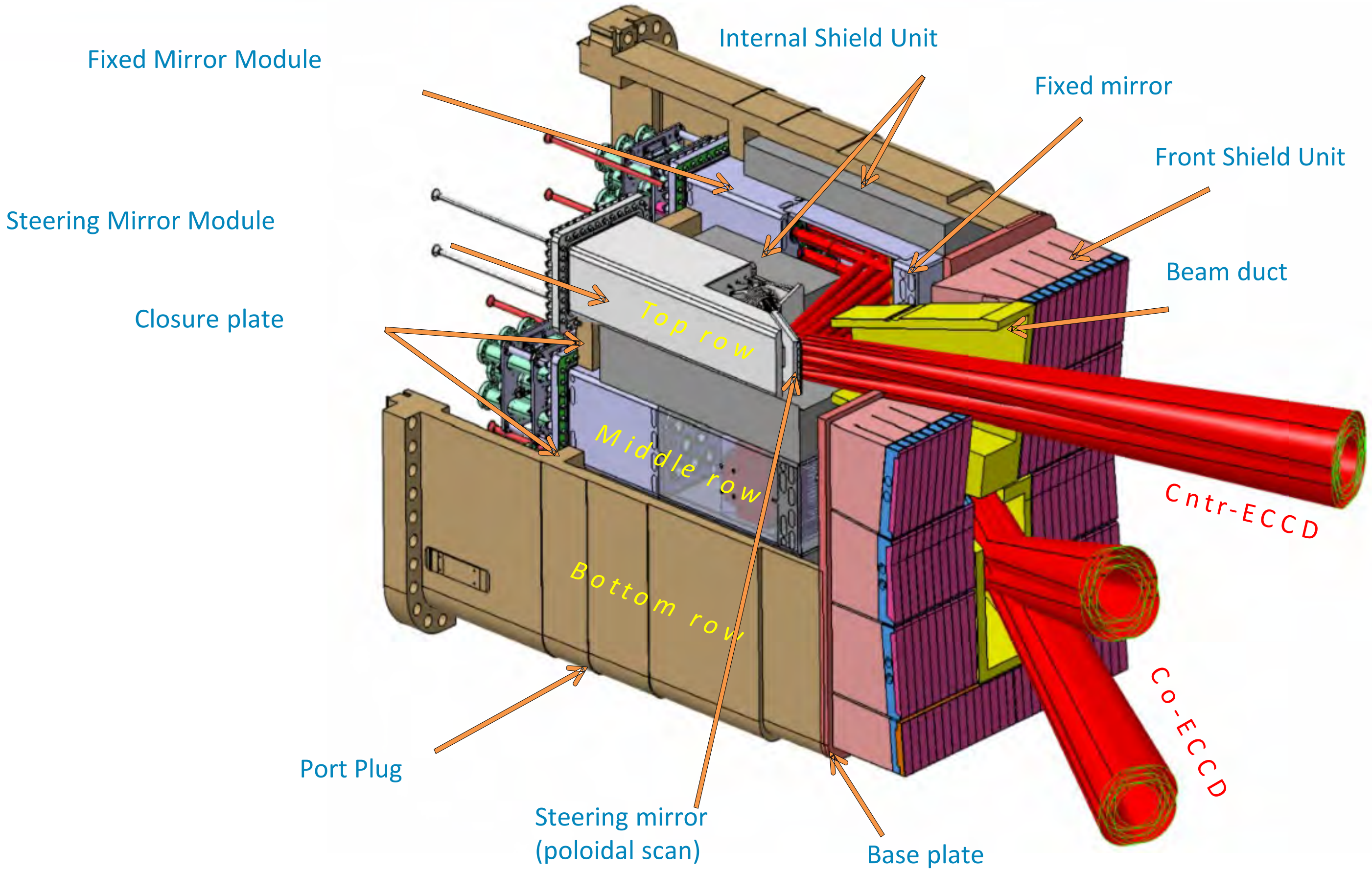


- 4 upper launchers from EUDA
- Poloidal steering beam injection
- 20 tons (max.), 8 beam inlets, 2 steering mirrors, 3 fixed mirrors sets
- Designed for whole ITER lifetime
- High neutron flux and RF loads
- Mirrors heat load: **~ 1-6 MW/m^2**



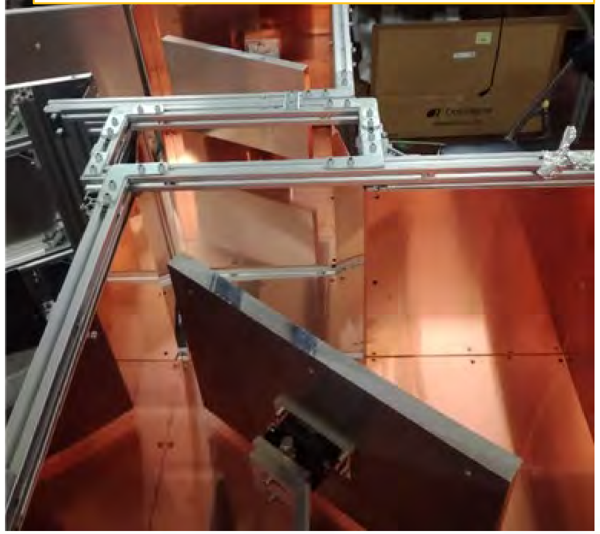


EC Equatorial Launchers – Parts and Challenges



- 2 Equatorial launchers: JADA (x1) and EUDA (x1)
- Poloidal steering beam injection
- 48 tons (max.), 6 modular structures
- 24 beam inlets (8 x 3 slots)
- Designed for whole ITER lifetime
- High neutron flux and RF loads

EL Mock-up - QST



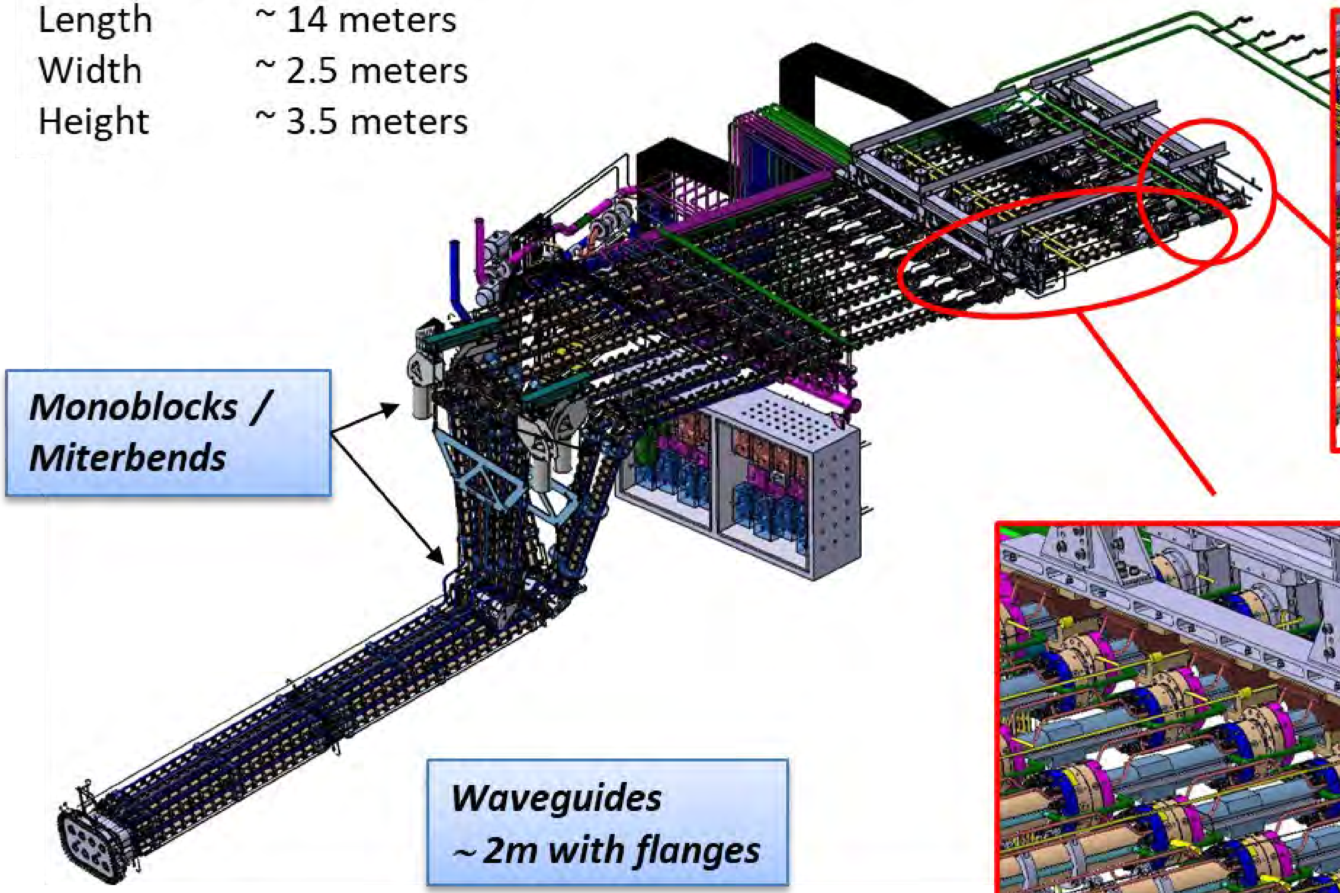
EC Ex-vessel waveguides – Parts and Challenges

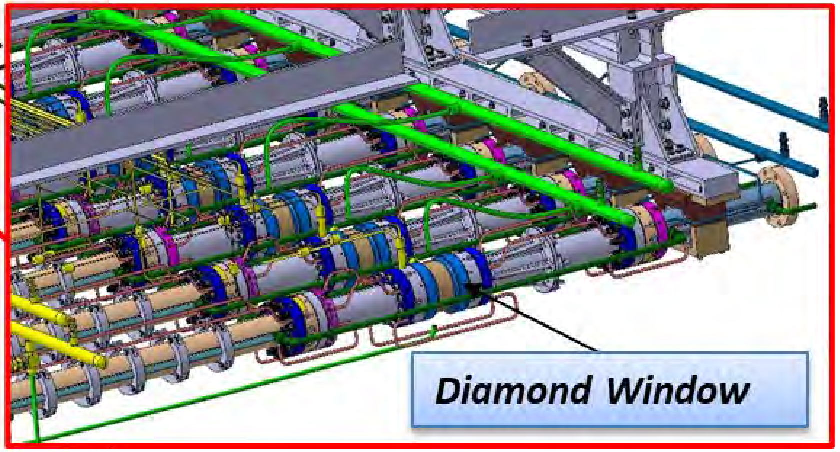
FUSION FOR ENERGY

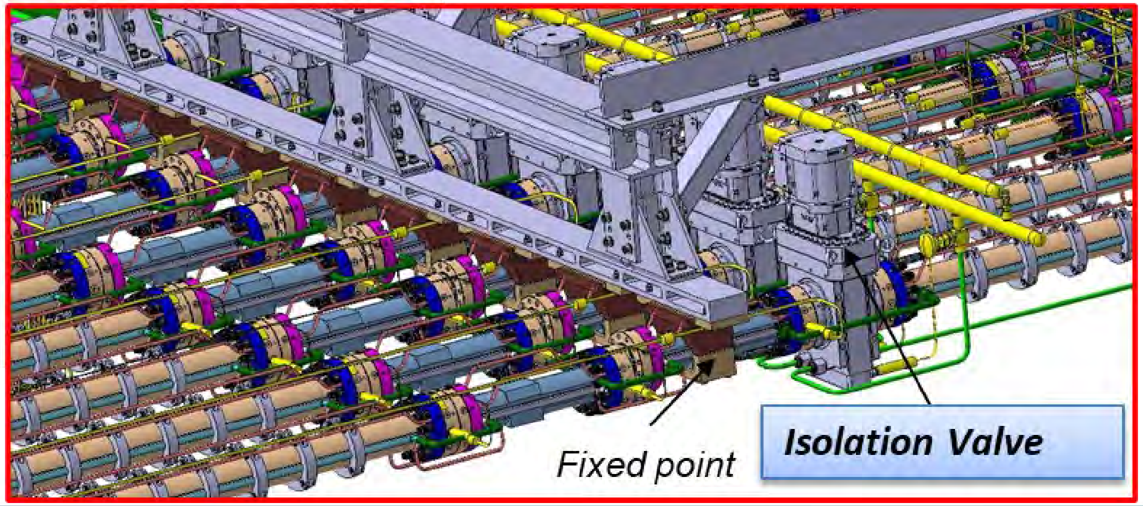
- Diamond windows and valves qualification for neutronics and RF loads

Dimensions

Length	~ 14 meters
Width	~ 2.5 meters
Height	~ 3.5 meters



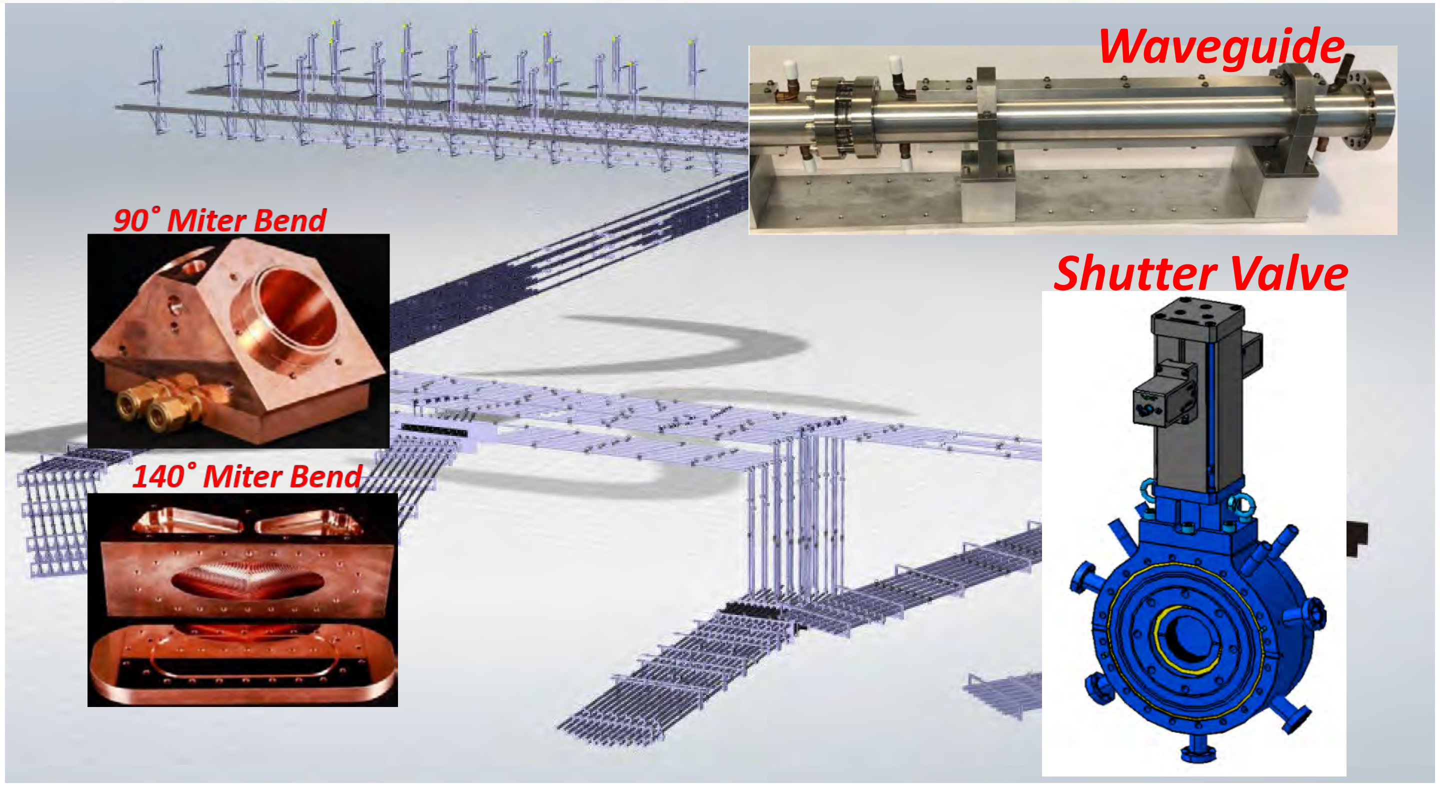




EC Transmission Lines – Parts and Challenges

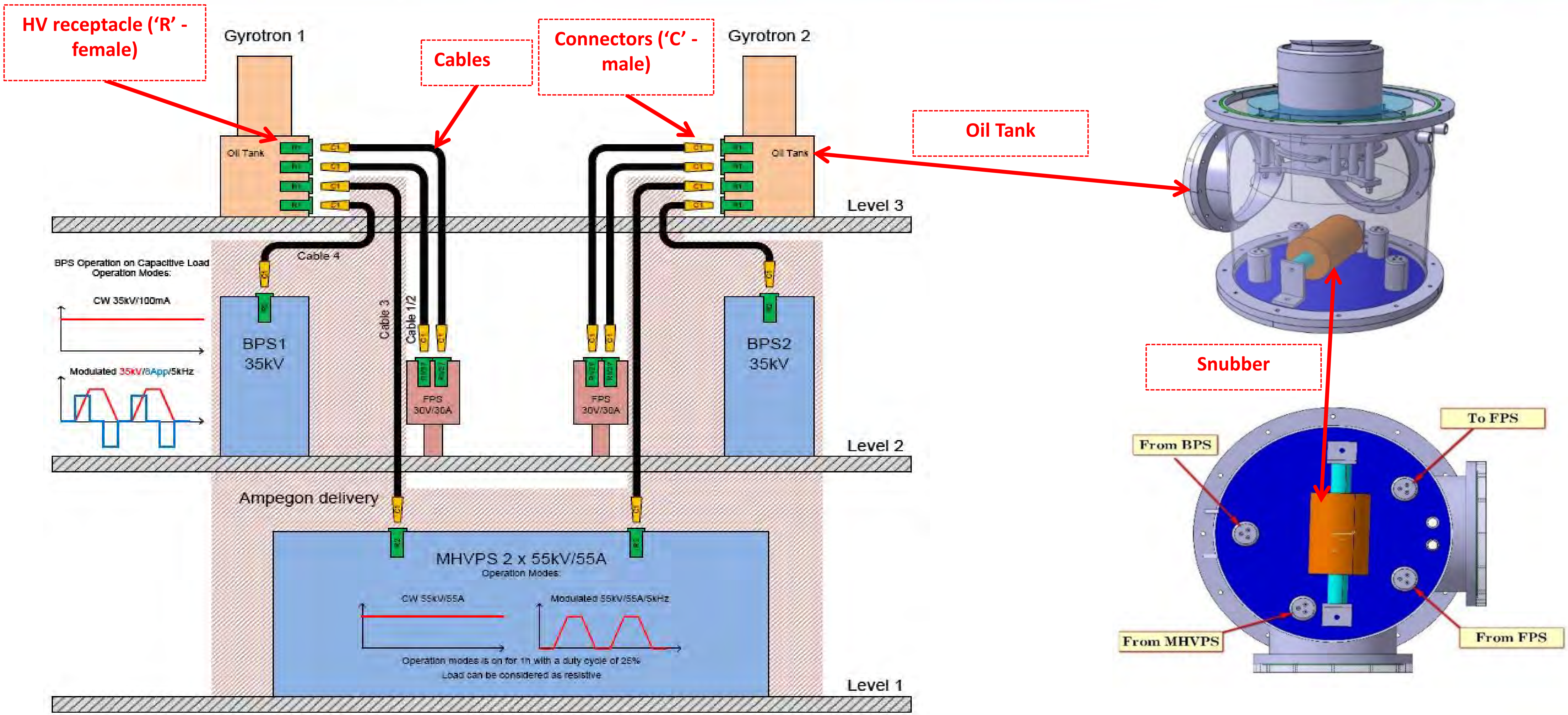
FUSION FOR ENERGY

- Corrugated WGs 50 mm diameters
- Up to 3 m straights to cover length ~160m
- Alignment 0.1mm/m
- Power Handling 1.25 MW
- Pulse length 3600 s (25 % duty cycle)
- Power Transmission Efficiency ≥90 % ;
  HOM <7 % at 1 MW
- Design finalized (except pending tests for polarizers, shutter valves, I&C and building penetrations: sleeves/bellows)



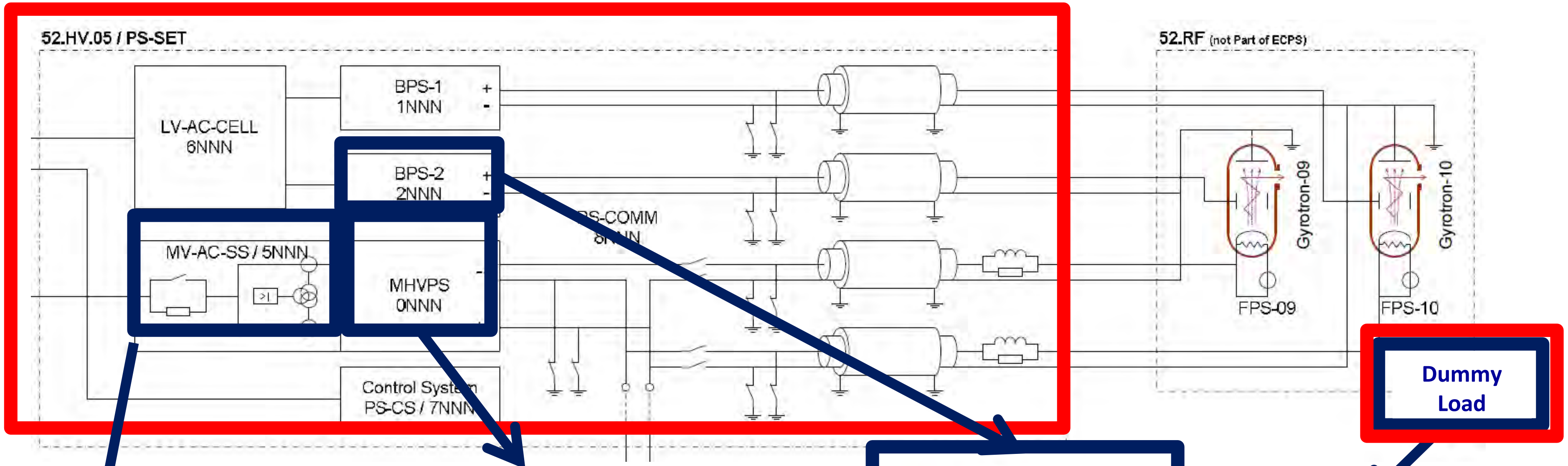
- Supports have been delivered on site. Tender process for waveguides manufacturing on going (selection from 2 qualified vendors) and manufacturing about to start
- Main challenge on site installation: 3 different buildings, coactivity, tight space (requirement: 0.25 mm from support to support ➔ avoid deformations and to maintain target mode conversion efficiency ≥ 93%
- Isolation Shutter valve (COTS UHV from VAT): pending nuclear and RF qualification tests

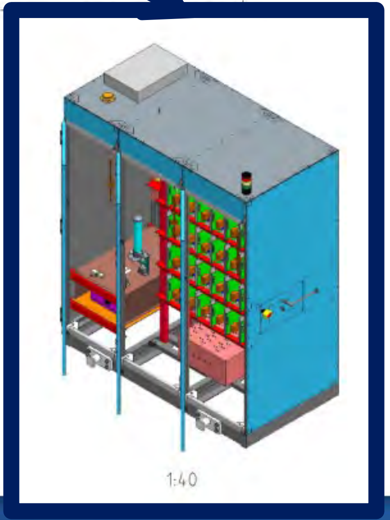
EC RF Sources: HV Power Supplies and Gyrotrons

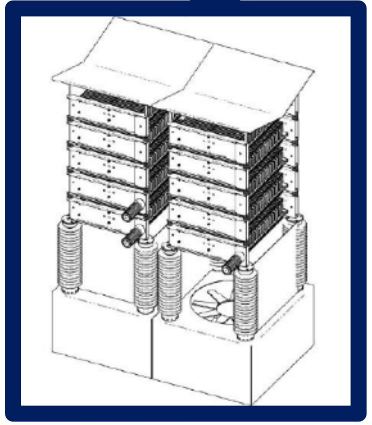


EC HV Power Supplies

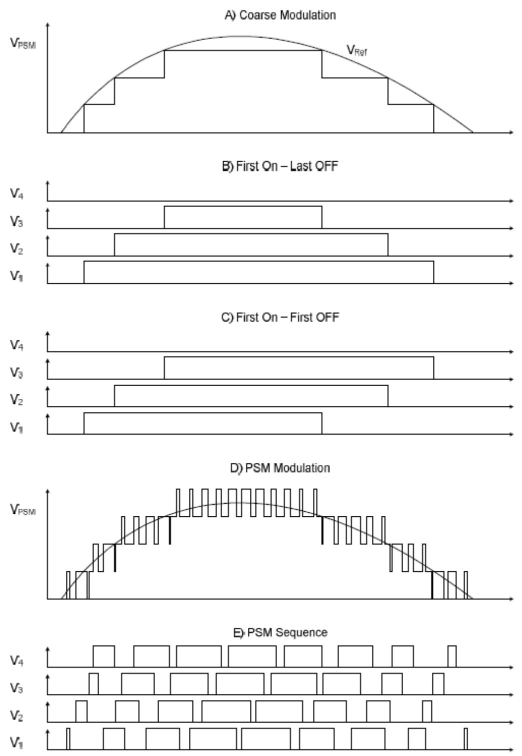
Block diagram ➔ MV (22kV) ➔ 1 Main HVPS (MHVPS) + 2 Body PS (PBS) + 2 Anode PS (APS) for Triode type







PSM design topology



EC Power Supplies at ITER site – Challenges

EUDA:

- 8 MHVPS and 16 BPS installed at ITER B15 (L1 and L2) (feeding EU+RF+IN gyrotrons)
- Commissioning tasks completed on the first unit (1 MHVPS + 2 BPS)
- Adaptation done for site tests & commissioning of JADA gyrotrons (requires connection to BPS/APS)
- Rest of units (7 units) commissioning on-going, to be tested on Long Pulse Dummy Load (B15 annex)



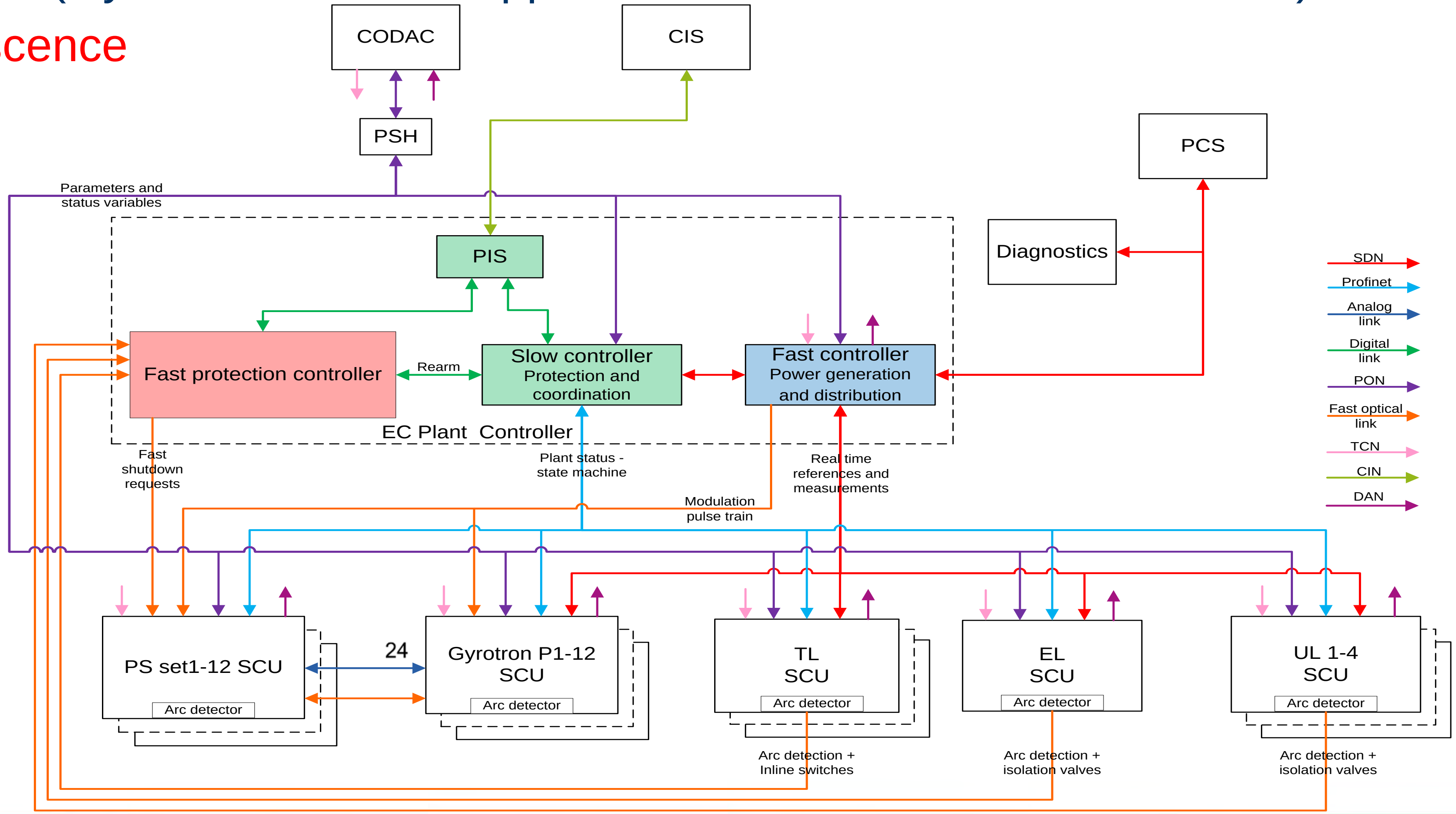
INDA (MVHPS) / JADA (BPS + APS): feeding JA gyrotrons

- 4 MHVPS under construction (to be installed in B15 L1)
- 8 sets (BPS + APS) delivered and installed at ITER site B15 L2

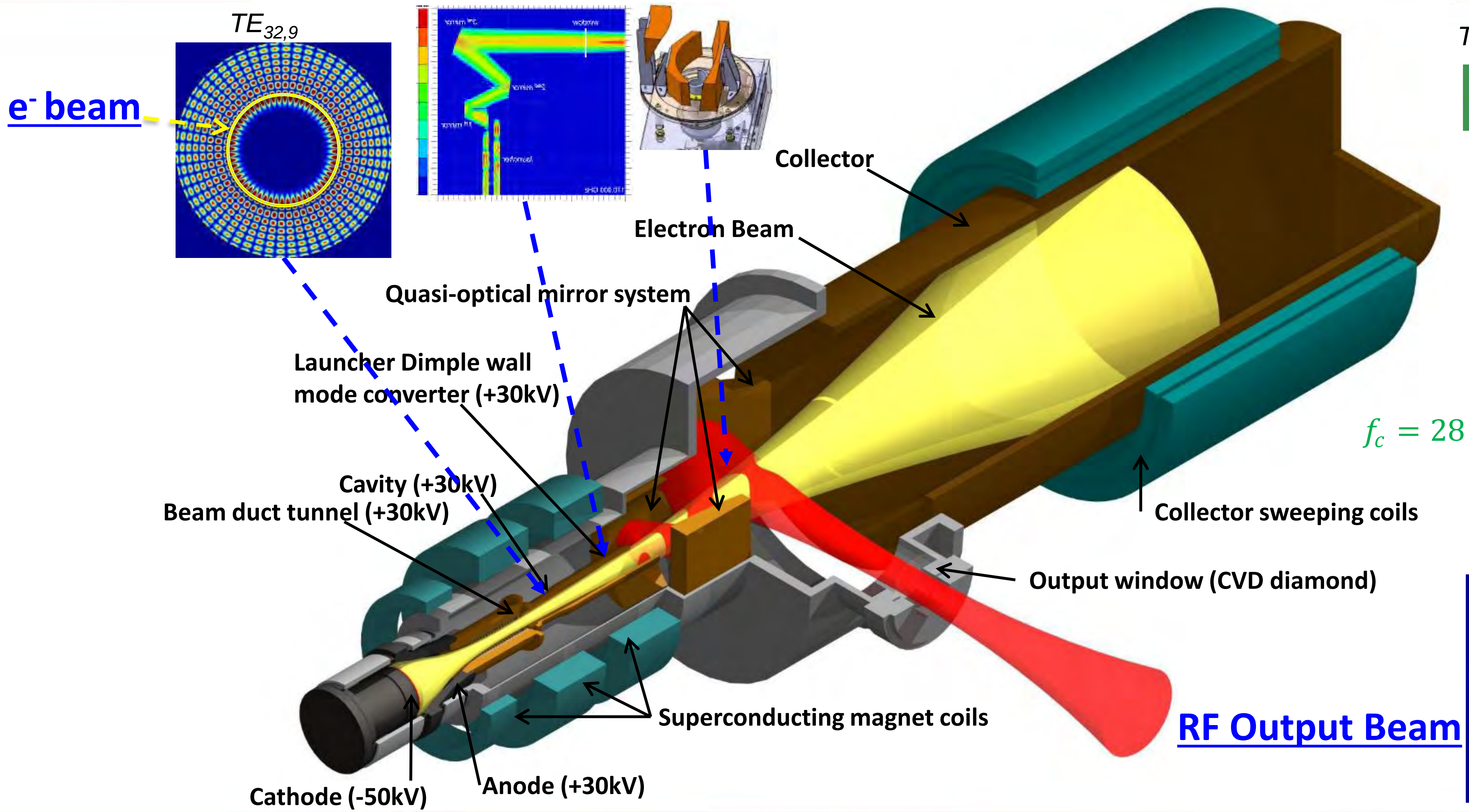
- **Challenge** on long time installed before operation and electronic obsolescence

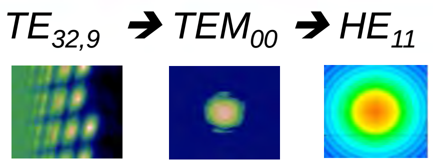
EC Control System – Parts and Challenges

- ITER Control system of the Electron Cyclotron Plant is modular ➔ adapted to different local controls
- Includes a supervisory system plus a set of local controllers normally provided by the DA providing the system components (Gyrotrons, Power Supplies, Transmission Lines, Launchers)
- Electronic obsolescence



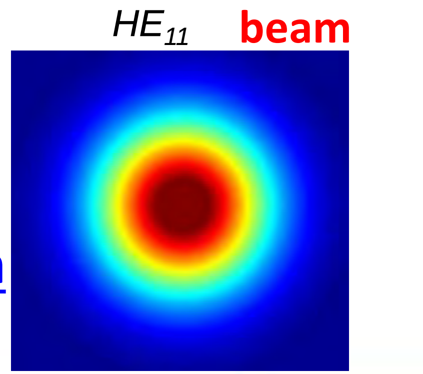
EC Gyrotrons – What is a gyrotron?





ITER Gyrotrons

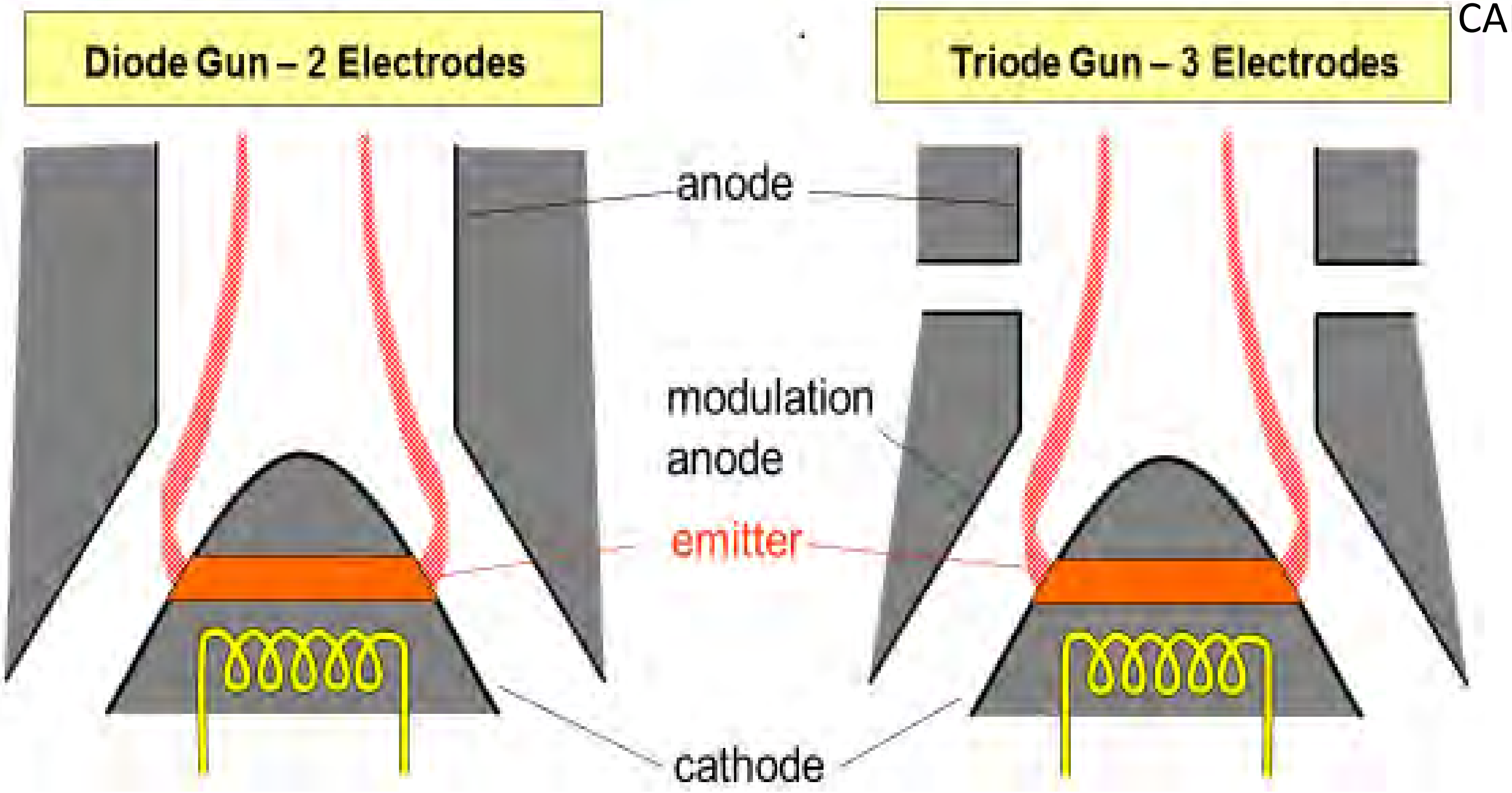
$$f_c = 28 \cdot \frac{6.666}{1,097556} = 170\ GHz$$



EC Gyrotrons – Magnetron Injection Guns (MIGs)

GYCOM
MPP
THALES

CANON



α is a function of the magnetic field angle and the acceleration voltage (V_{acc})

$\alpha = v_{\perp}/v_{||}$

more complicated, but independent control over α

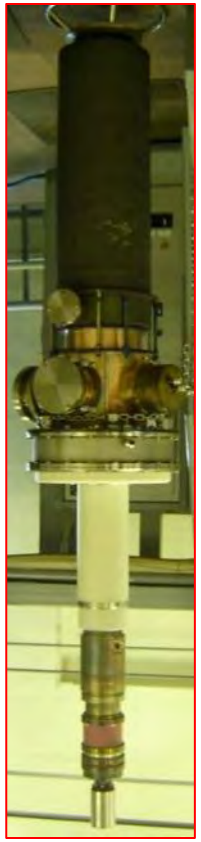
EC Gyrotrons manufacturers

FUSION FOR ENERGY

JADA | RFDA | | EUDA = Fusion for Energy (F4E)

Triode type

Canon



Gycom

MPP (former CPI)

Thales

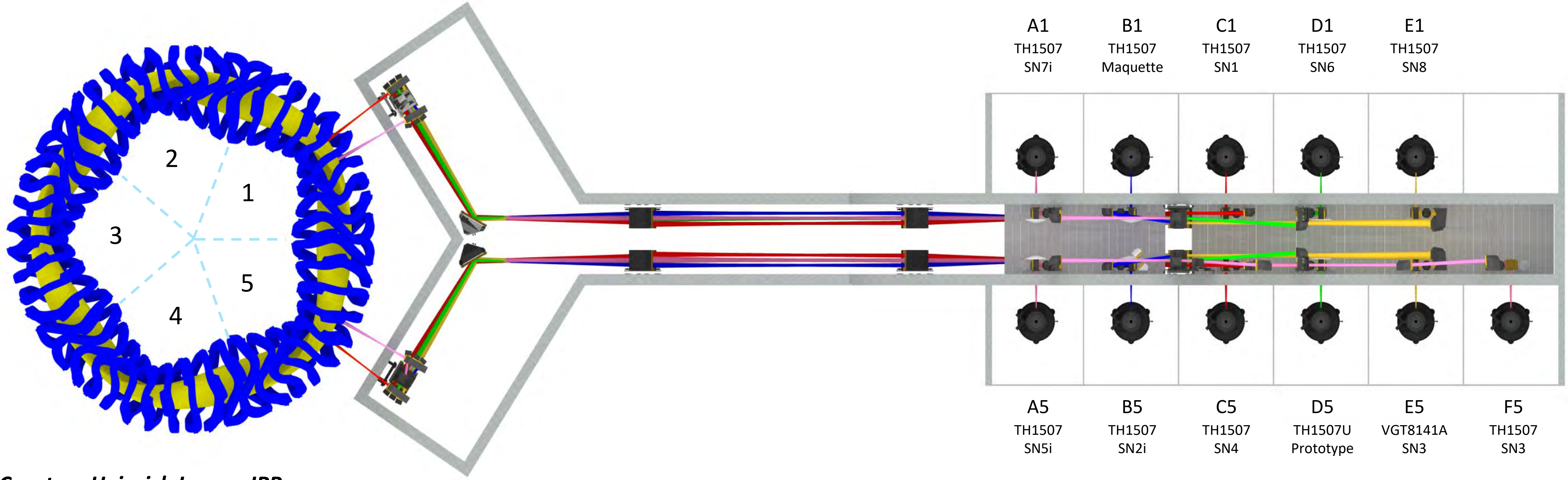
- ➔ Design and R&D programmes by the different DAs were completed, with future evolutions (challenges)
- ➔ MPP delivering gyrotrons for **W7-X** and **DIII-D** (see next slides), not qualified for ITER Gyrotrons

EC Gyrotrons @ Wendelstein 7-X

Designed for 12 gyrotrons (currently 11 are used)

Total installed ECRH power: 8.6 MW

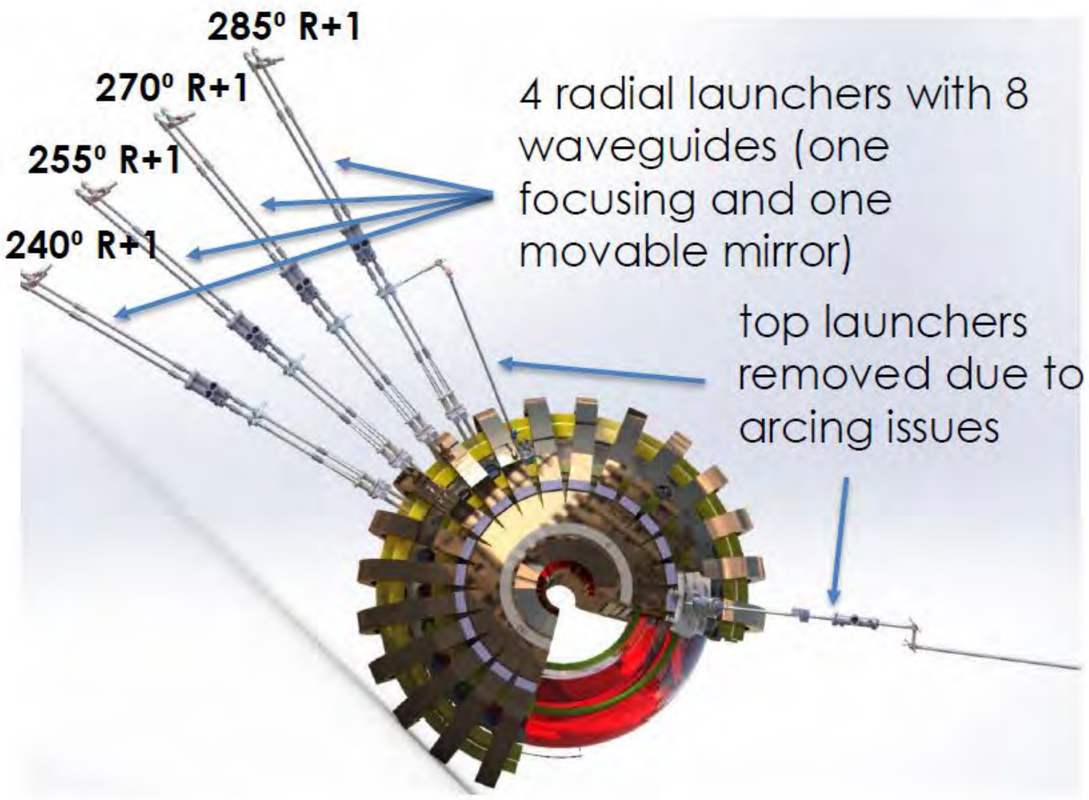
Fully quasi-optical transmission to plasma vessel

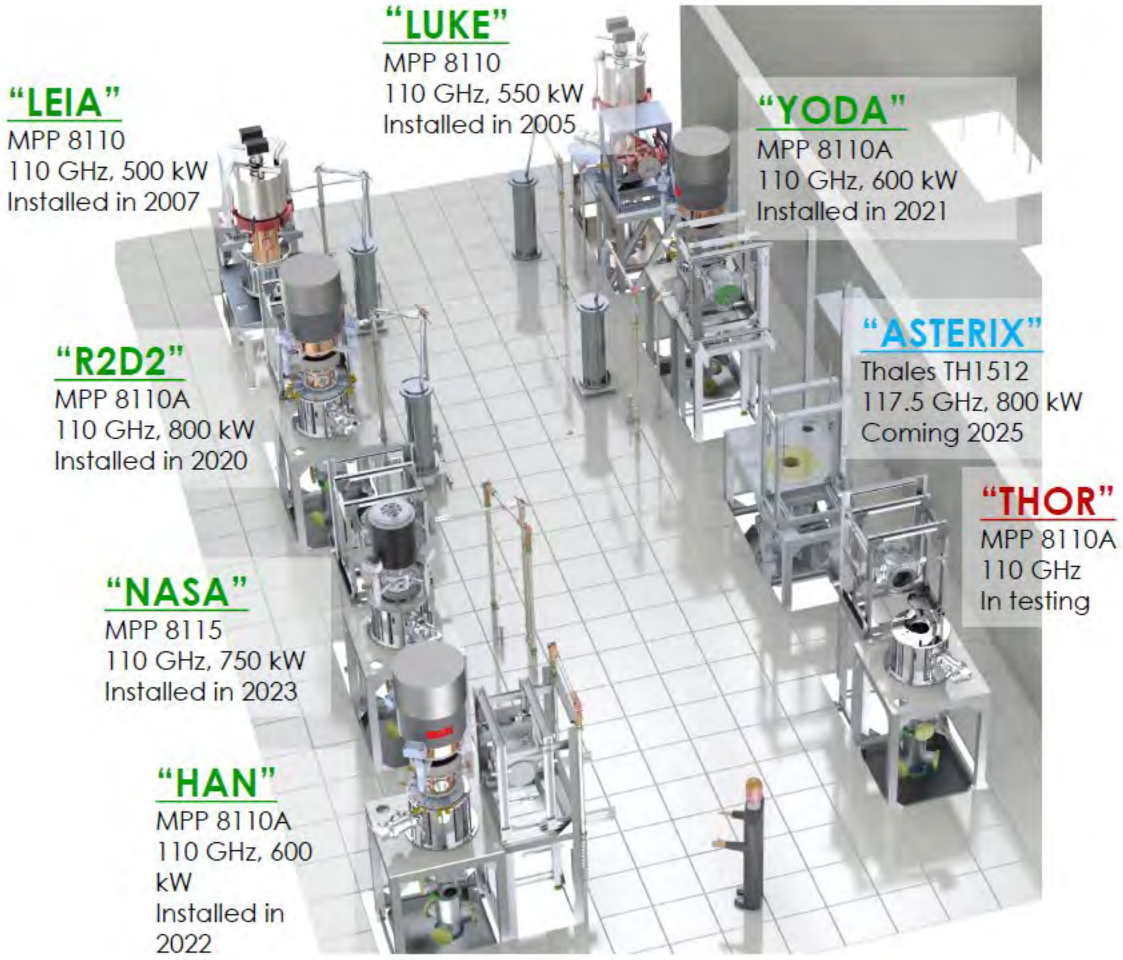


Courtesy Heinrich Laqua, IPP

EC Gyrotrons @ DIII-D

- Eight gyrotron positions and launchers installed
- Gyrotrons planned from 3 vendors (KF included)





DIII-D NATIONAL FUSION FACILITY

Courtesy Jared Squire, GA

GENERAL ATOMICS

DIII-D Electron Cyclotron Heating and Current Drive (ECH/ECCD) Systems

ECRH Planned Needs Worldwide (non-exhaustive)

FUSION FOR ENERGY

In 2004

Short time for your feedback ☺

TABLE I. Toroidal devices with EC systems in the MW power range. All systems are either operating or in active construction, except for the ITER system which is planned. The powers specified are installed source powers.

Device	Power (MW)	Frequency (GHz)	Mode
ASDEX Upgrade	2.0	140	X2
COMPASS-D	2.0	60	X1, O1, X2
DIII-D	5.0	110	X2
FTU	1.6	140	O1
JT-60U	4.0	110	O1, X2
T-10	1.6	140	X2
TCV	3.0	82.7	X2
	1.5	118	X3
TEXTOR	0.4	110	X2
	1.0	140	X2
TORE SUPRA	1.0	118	O1, X2
LHD	2.5	84	O1
	1.5	170	X2
Wendelstein 7-X	10.0	140	X2
ITER	20.0	170	O1

R. Prater, "Heating and Current Drive by electron cyclotron waves", in *Phys. Plasmas,* Vol. 11, No. 5, May 2004

~50 MW

Any guess for 2026?

Growing factor?

ECRH Planned Needs Worldwide (non-exhaustive)

FUSION FOR ENERGY

In 2004 (2026 update)

TABLE I. Toroidal devices with EC systems in the MW power range. All systems are either operating or in active construction, except for the ITER system which is planned. The powers specified are installed source powers.

Device	Power (MW)	Frequency (GHz)	Mode
ASDEX Upgrade	2.0 (8)	140	X2
COMPASS-D	2.0	60	X1, O1, X2
DIII-D	5.0 (11)	110	X2
FTU	1.6 (4)	140	O1
JT-60U	4.0	110	O1, X2
T-10	1.6	140	X2
TCV	3.0 (6.5)	82.7	X2
	1.5	118	X3
TEXTOR	0.4	110	X2
	1.0	140	X2
TORE SUPRA	1.0	118	O1, X2
LHD	2.5	84	O1
	1.5	170	X2
Wendelstein 7-X	10.0 (12)	140	X2
ITER	20.0 (72-80)	170	O1

R. Prater, "Heating and Current Drive by electron cyclotron waves", in *Phys. Plasmas,* Vol. 11, No. 5, May 2004

... from ~50 MW ➔ ~500 MW !

In 2026:

	[MW]	[GHz]	Modes
ASDEX Upgrade	6 + 3 (by 2027)	105/140 + 112/140/168	O1, O2, X2, X3
BEST	15	170	
CFEDR (CFETR)	30	170	
Compass	2	105/140,170	
DTT	16-32	170	
EAST	4	105/140	
HL-3	4.5	68, 105	
JT-60SA	7	83, 110, 138	O1, X2, O2
KSTAR	6	105/140,170	
LHD	6.2	77, 82.7, 84,154	O1,X2,X3
MAST-U	1.8	28,34.8	EBW
STEP	300	different frequencies	
TCV	6.5	82.7/84/118/126	X2, X3
WEST	3	105	O1

EC Gyrotrons challenge: Industrialisation

FUSION FOR ENERGY

Industralisation: High increase on gyrotrons demand (**x10** from 2004), represents a huge opportunity for vendors, and also a big challenge to industrialise facilities and increase production / deliveries. Industrial compromise: performance improvement vs. financial gain (short when selling few units)

Gyrotrons: Normal production rates, so far, **~2-4 units per year**, and adaptations are done / required to produce **6-10 units per year:**

- ➔ duplicating baking station, hiring and training new personnel, production on shifts
- ➔ required new conditioning/testing facilities
- ➔ easy performance improvement when multiple iterations and "massive" production
- ➔ path to be paved, it would help **other applications** or **new manufacturers** (see next slide)

Automobile: BYD Produces up to 4400 cars per day at its largest Xi'an facility. In China, a total of **80000 to 95000 cars are produced per day** ➔ Wonderful industrial performance, cars sold worldwide

🚗 🚗

EC Gyrotrons challenge: Industrialisation

FUSION FOR ENERGY

New Manufacturers:

EU endeavour launched by Guerric de Crombrugghe → MWB Gyrotron Industries GmbH

China: SWIP showed a gyrotron during our visit to Chengdu on Wednesday:

105 GHz, ~500 kW, > 1s pulse → promising performance

Other Gyrotron Applications: Thermal Energy (Quaise @ ~95 GHz), rocket propulsion via thurst generation *(~28 GHz),* material sintering (~24-300 GHz), food preservation treatments,…

Quaise and MIT drilling 20 miles (~32 km) for thermal energy → https://www.quaise.com/

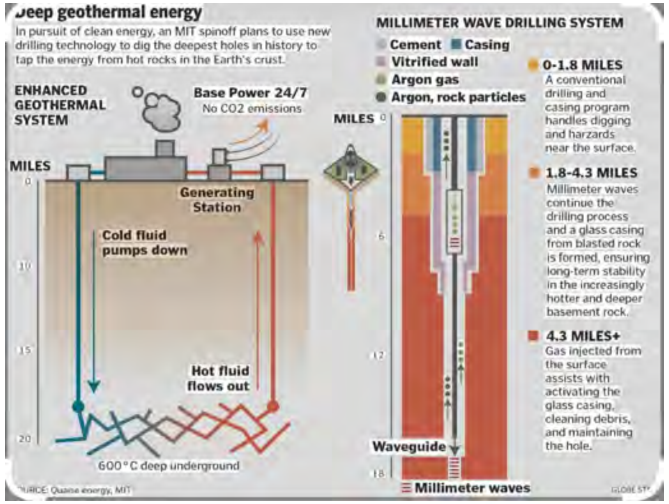
Paul Woskov at MIT: melting granite by Gyrotron beam

Quaise schematics on the drilling →

Different concepts by other actors:

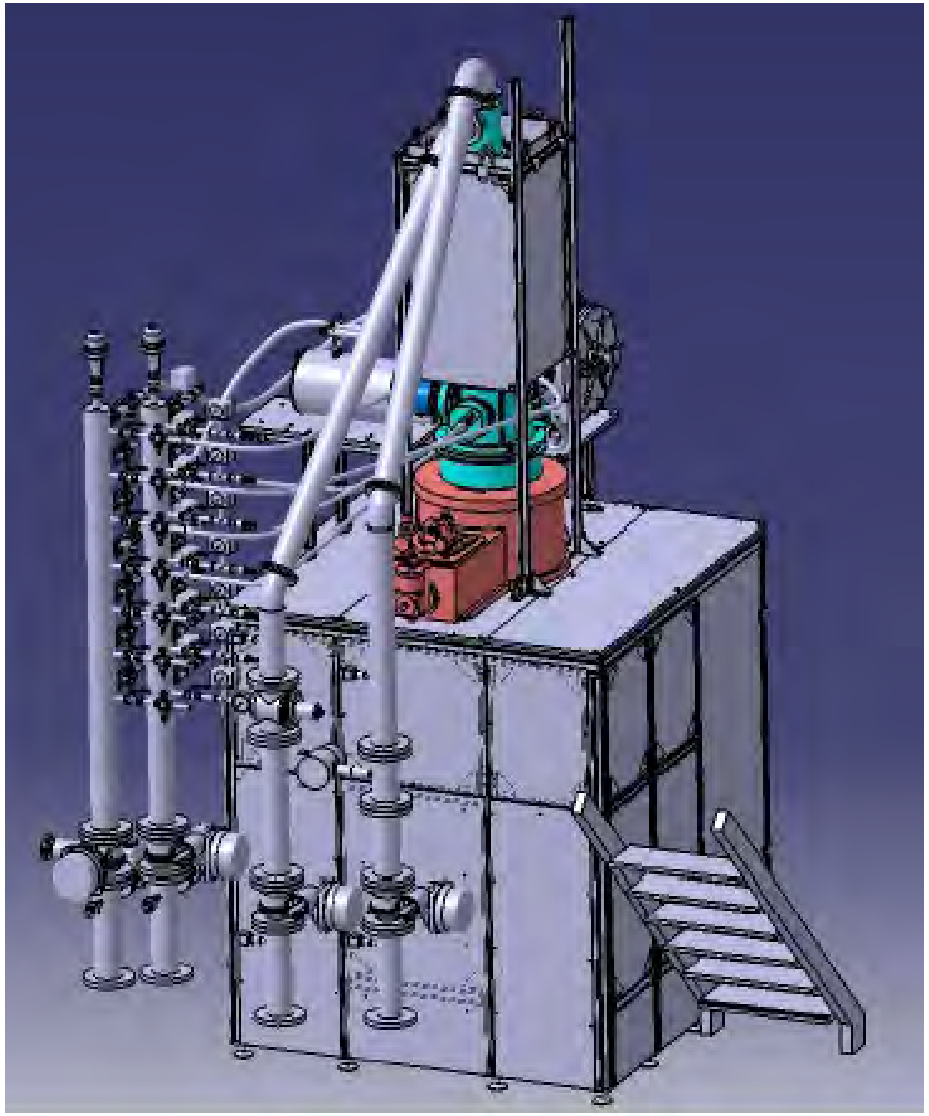
Melting vs. Crashing stone-grave

(i.e., shorter pulses, easier removal)



EC Gyrotrons – ITER Specification

Item	Specification
Nominal output power	≥ 0.96 MW , the power being measured at MOU output.
Nominal frequency	170±0.3 GHz including initial transient phase.
Pulse length	≥ 3600 sec
Duty cycle	≥ 25%
Reliability	≥ 95% (95% of successful pulses for 50 pulses done at pulse length of 500 s)
RF power generation efficiency	***≥ 50 % (with collector potential depression)***
HE_{11} content	> 95 % at MOU output waveguide (50 mmϕ)
Modulation from 0-5 kHz	100% power depth modulation



EC Gyrotrons – Performance for ITER

- JADA & RFDA manufactured gyrotrons ➔ FAT completed @ 1 MW / 50% eff / ≥ 95 % reliability
- INDA Final Design Review (FDR) to be completed in 2026, Manufacturer TBC (diode-type chosen)
- EUDA FDR completed in 2026, Prototyping phase completed with 1 MW / 46% eff / ≥ 95 % reliability

Electrical Efficiency ➔ $\eta[\%] = \frac{P_{out}[kW]}{V_k[kV] * I_b[A]}$

For instance, for the giving **Pout = 1 MW**, Vk = 50 kV and Ib = 43 A ➔ $\eta[\%] = \frac{1000}{50 * 43} = 46{,}5\ \%$

In this case, the HVPS delivers 50 kV * 43 A = **2150 kW**, and **1.15 MW goes to the collector**

If efficiency falls to $\eta[\%] = \frac{1000\ \text{kW}}{50\ \text{kV} * 50\ \text{A}} = 40\ \%$ ➔ HVPS delivers **2500 kW**, **1.5 MW goes to the collector**

If efficiency increases to $\eta[\%] = \frac{1000\ \text{kW}}{50\ \text{kV} * 30\ \text{A}} = 67\ \%$ ➔ HVPS delivers **1500 kW**, **0.5 MW to the collector**

$$Reliability[\%] = \frac{Number\ of\ consecutive\ successful\ pulses}{Number\ of\ total\ consecutive\ pulses}$$

(e.g., 19 consecutive successful pulses over 20 total pulses = 95 %)

EC Gyrotrons – Challenges

- **Short term** for EUDA gyrotrons ➔ Increase efficiency to the required ITER level (46 ➔ 50 %)
- EUDA program in two parallel actions:
  - **Action 1**: modify cavity mode from TE32,9 to TE32,11 ➔ increase 3-4 points ➔ ~50 %
  - **Action 2**: Produce new prototype to include additional improvements ➔ increase 4-5 points ➔ ~55 %
- Validation analysis on-going, manufacturing to be launched end-2026, tests to be completed Q1-2028

- **Medium term** action ➔ Increase efficiency to the 60-70 % levels (aiming to reduce electrical bill)
- Prototyping actions planned

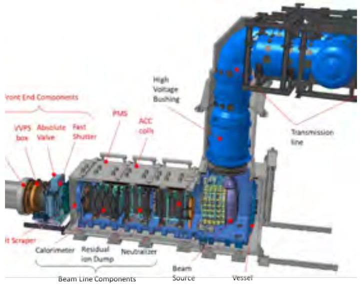
  *For the new ITER baseline or STEP, 80-300 gyrotrons, big savings if **electrical power** goes from 2.15 MW (46.5 %) down to 1.5 MW (67 %) per gyrotron: **e.g., for 100 gyrotrons, savings of 65 MW***

- **Other** actions ➔ Simplification on manufacturability (modular designs, synergies between models)
- **Other** actions ➔ Simplification on repairability (flanged designed to replace filament heater & cathode)
- **Other** actions ➔ Revise and improve procedure for LONG TERM STORAGE
- **Other** actions ➔ Workforce, recruitment and training of early careers (due to time scales)

EC Gyrotrons – Challenges

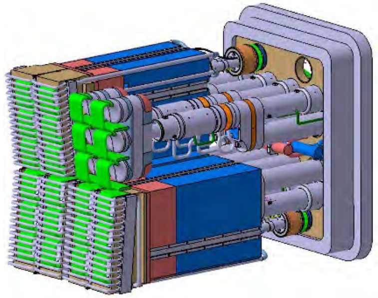
- Despite its relatively simple concept, the gyrotron involves many state-of-the-art features:
  - High voltage (~80 kV, depressed collector) and High current (~ 40 A)
  - High magnetic field (~7T) and large temperature gradients
  - MW level CW beam with ca. 20 mm cross-section, passing through a diamond window.
  - Need of efficiency water cooling systems
- As of today, for the ITER case: 170 GHz, 1MW, CW is state-of-the-art
- R&D programs to get > 1.5 MW and multi-frequency tubes and higher efficiency, and industrialisation
- **Extremely high ohmic loads in the cavity** (cylinder ~150 mm long, ~20 mm radius) ➔ **COOLING!**

NBI



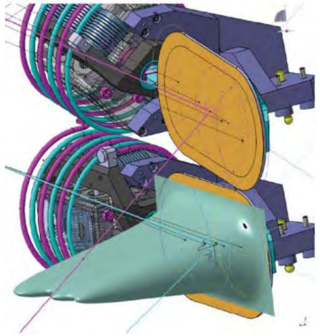
~0.3-2.2 MW/m²

IC Antena



~9 MW/m²

EC Launcher Mirrors



~1-6 MW/m²

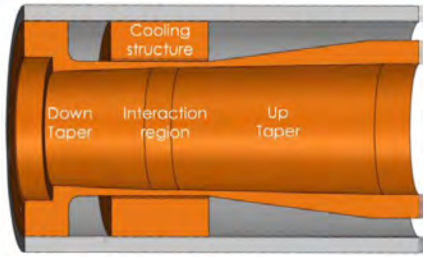
Gyrotron collector

~5 MW/m²

Space Shuttle

~1-2 MW/m²

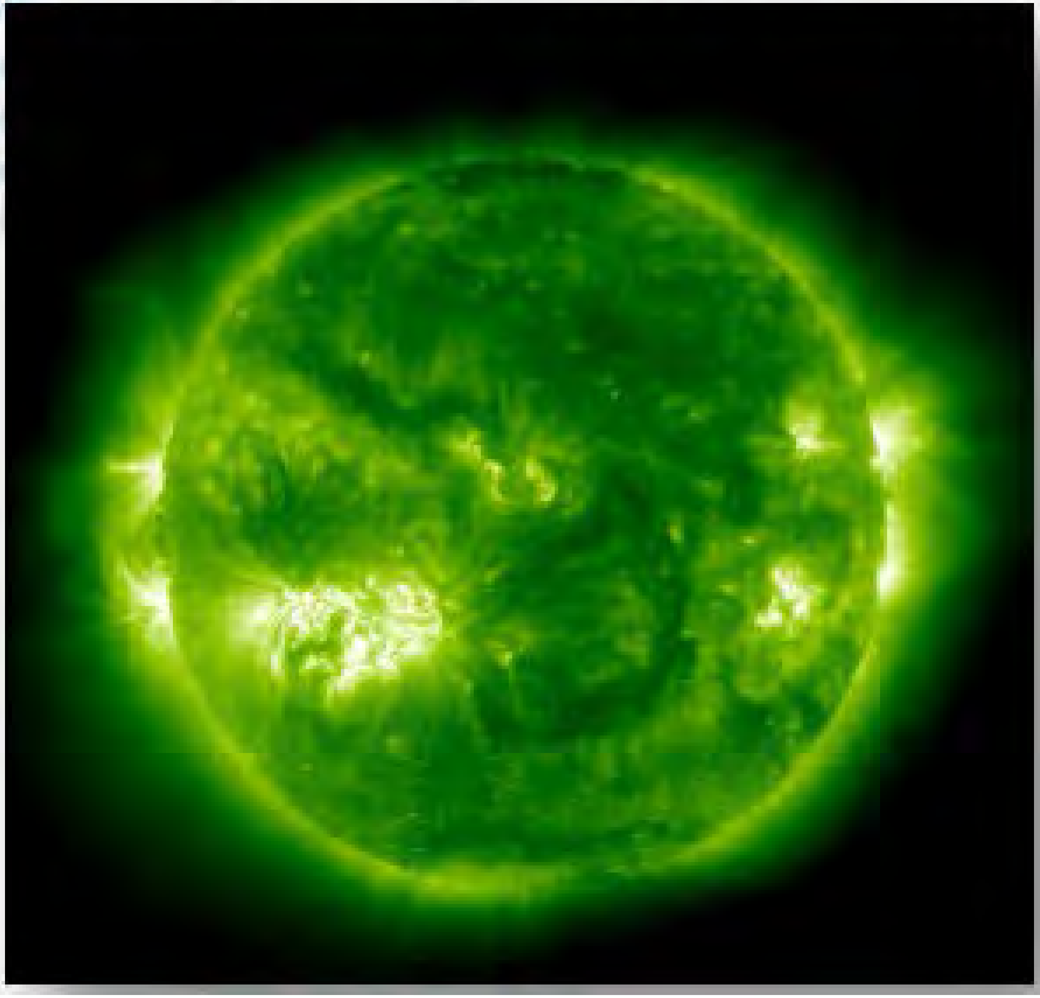
Gyrotron Cavity



~25 MW/m²

EC Gyrotrons – Challenges

~60 MW/m² at the sun surface



#ITER Gyrotrons: Status in Building 15 – Level 3

FUSION FOR ENERGY

B15 – L3

1st Gyrotron (JADA)

Courtesy Satoshi Ito-San, ITER Organisation

ITER Gyrotrons: Status in Building 15 – Level 3

ECRH Summary Challenges

FUSION FOR ENERGY

- EC Launchers: High neutron flux and RF loads, steering beams, design for whole ITER lifetime
- Ex-vessel WGs and TLs: diamond windows & valves qualification for neutronics and RF loads
- EC HVPS & Control System: long time installed before operation and electronic obsolescence
- EC Gyrotrons: Industrialisation as per increase demand (consider other applications)
- EC Gyrotrons: higher power and efficiency (electrical consumption)
- EC Gyrotrons: Extremely high ohmic loads in the cavity, **improve cooling techniques**
- Simplification on manufacturability (modular designs, synergies between models)
- Simplification on repairability (e.g., flanged designed to replace filament heater & cathode)
- Revise and improve procedure for LONG TERM STORAGE
- WORKFORCE → recruitment and training of early careers (due to very long time scales)

Summary Conclusions – Challenges

ECRH, ICRH, HNB → see previous slide, #51, #56

Workforce and ITER time scale!

SPECIAL THANKS !

Presentation prepared with the help of the F4E HCD teams 👏

Many thanks to all Lecturers, as they allowed me to simplify my presentation 👌

Special thanks to the organisers, and their efforts to facilitate our lives 🎉

And …. all the best for the STUDENTS, remember, we need you !!! 🙌 👐

QUESTIONS ?

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Thank you for your attention

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