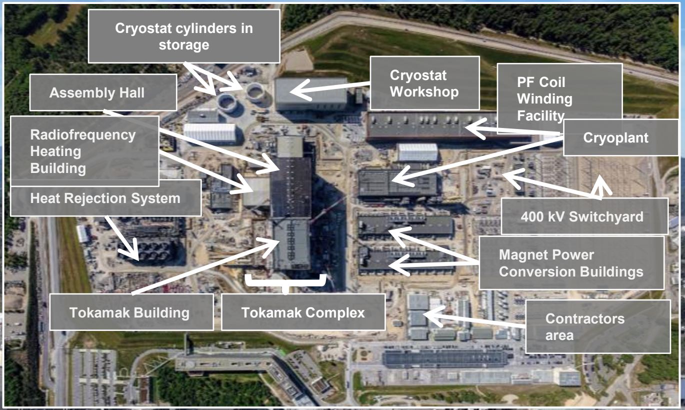
# Engineering of ITER H&CD systems

C. Darbos on behalf of ITER HCD team

# OUTLINE

- ❑ Context
- ❑ ITER NBI
- ❑ ITER ICRH
- ❑ ITER ECRH
- ❑ Common generic concerns

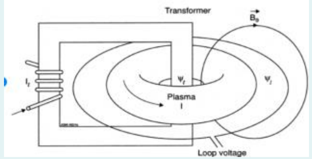



*The views and opinions expressed herein do not necessarily reflect those of the ITER Organization.*

# Heating & Current Drive Systems

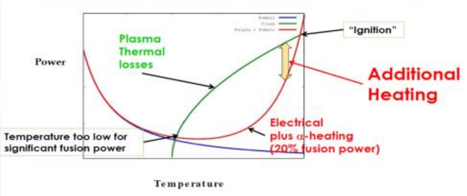
- ✓ Context
- ❑ ITER NBI
- ❑ ITER ICRH
- ❑ ITER ECRH
- ❑ Common concerns

Tokamak is a toroidal transformer: Induced plasma current heats plasma (joule effect)

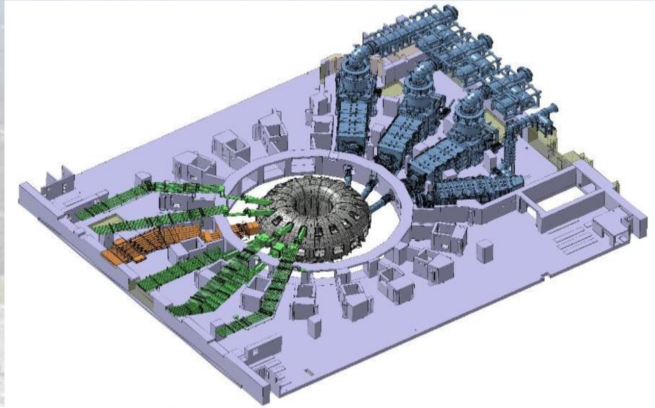


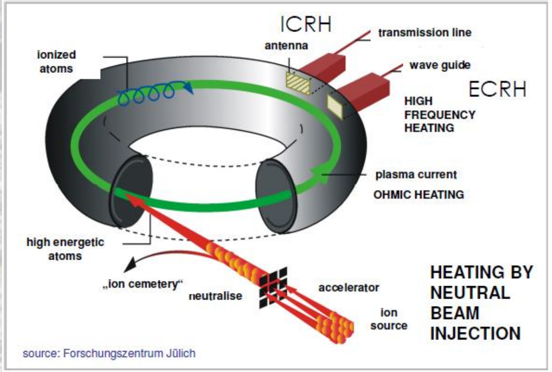

Resistivity (and power) drops with temperature

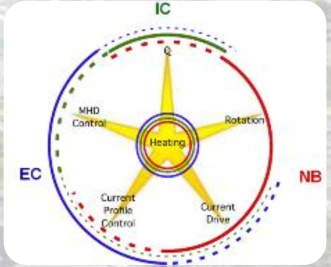
- $P_{ohmic}$ becomes progressively less and less efficient in heating the plasma
- Alpha (fusion) power increase with temperature




Gap filled by additional heating power





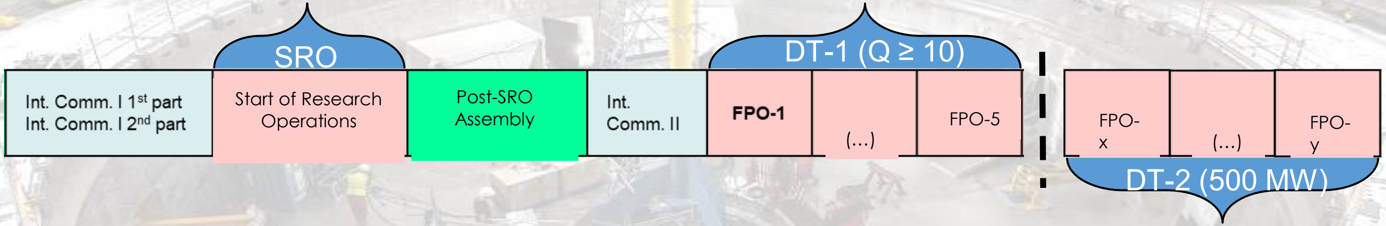




Steady-state tokamak reactor requires auxiliary Heating & Current-Drive systems (electromagnetic + other such as Neutral Beam Injectors).

# New baseline machine configuration

- 40 MW EC heating power (3 Upper + 1 Equatorial Launchers)
- 10 MW of ICWC & ICH
- Boronization system (Glow Discharge Cleaning + *dropper*)
- Full in-vessel coil system (ELM control and VS)
- 4 Pellet injectors (fueling + ELM control)
- W divertor (water cool.) + inertially cooled W wall in key areas

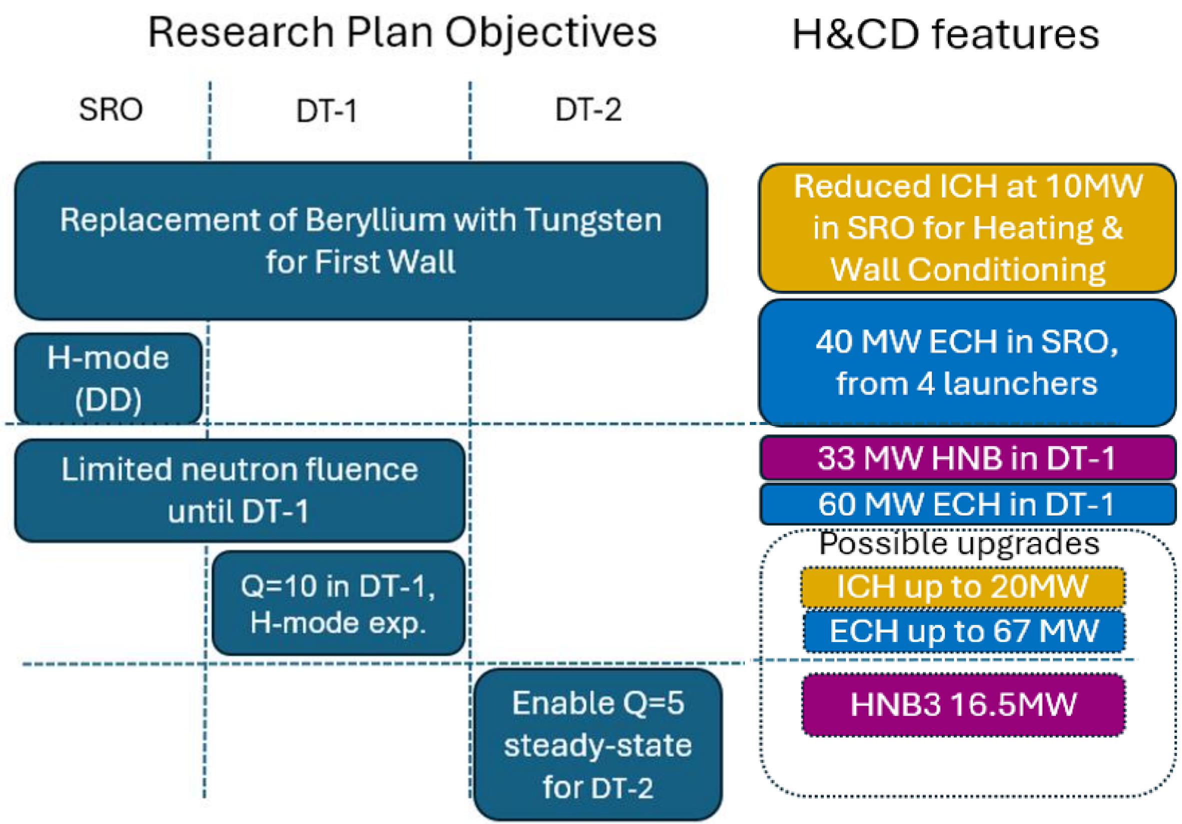
- All SRO systems, plus …
- 60 MW EC heating power (3 Upper + 2 Equatorial Launchers)
- 33 MW Neutral Beam (NB) heating power
- 10 → 20 MW IC heating (depending on SRO test results)



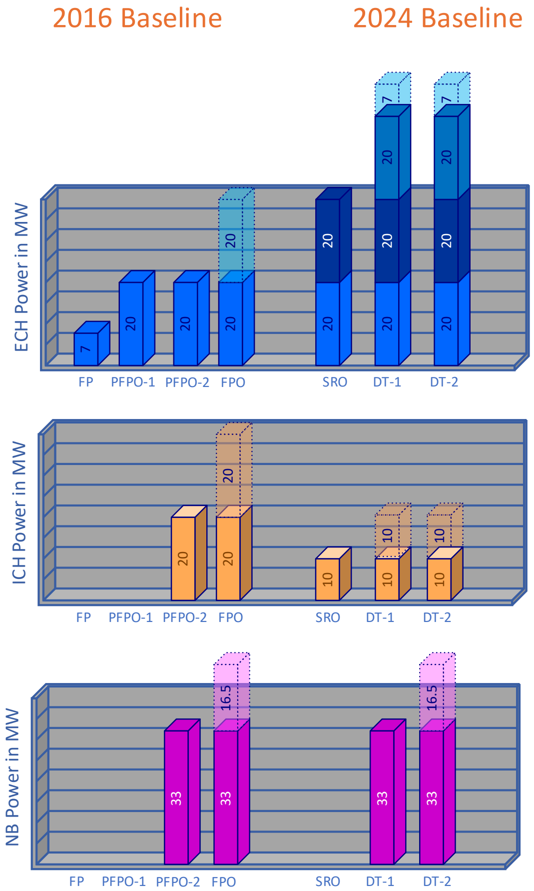

- Be to W → Changes in both the heating power requirement and the heating mix.
- Some uncertainty on ICRH-specific sputtering in a full W environment:
  - ✓ Reduced ICRH power (10 MW) for Start of Research Operation (SRO) for ICWC and tests of ICRH.
  - ✓ Based on experimental results, possible upgrade to 20MW system in DT-1.
- ECRH:
  - ✓ 40 MW for SRO (compensates for reduced ICRH power).
  - ✓ 60-67 MW for Q=10 in DT-1 (gives total of 100 MW of heating power, as requested by ITER Research Plan, together with NBI).

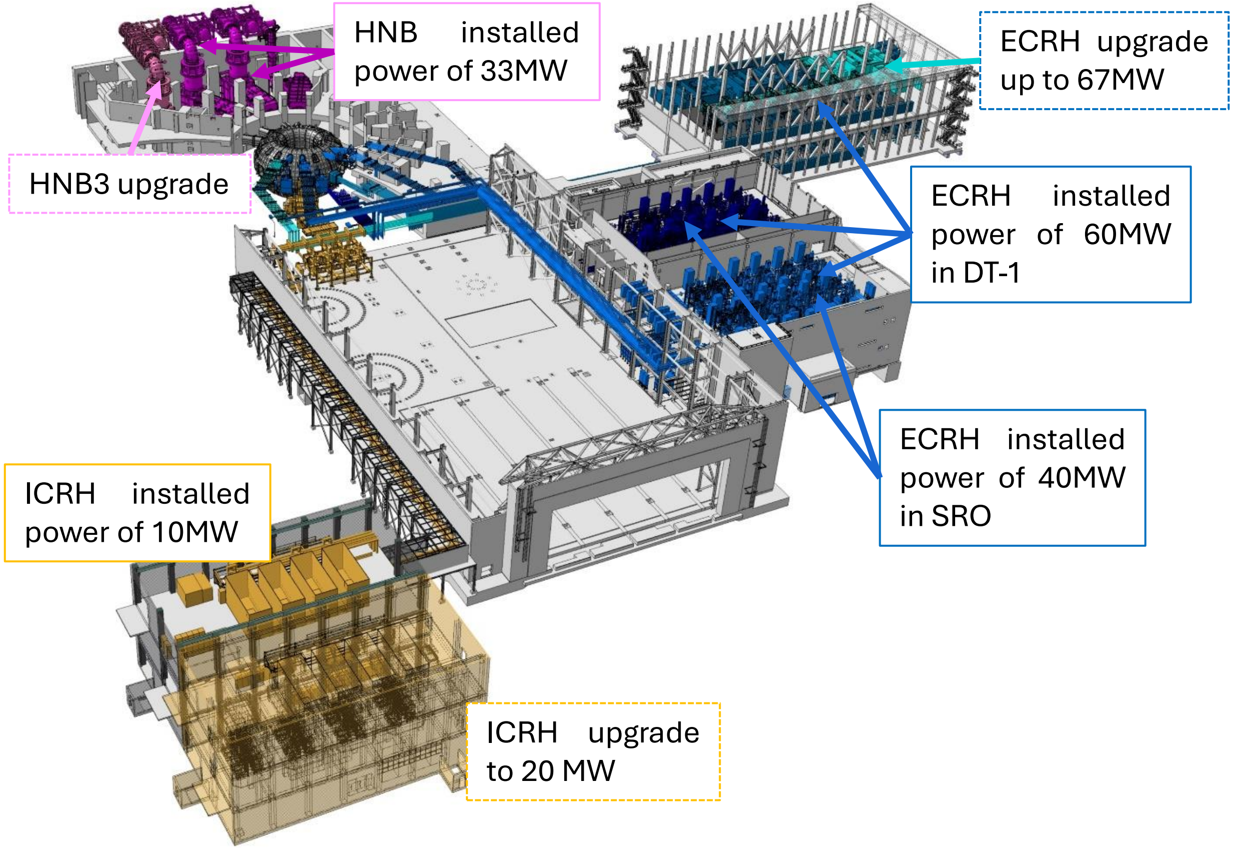
- All DT-1 systems, plus …
- Possible upgrade to 50 MW NB heating
- Possible upgrade to 67 MW EC heating
- Other upgrades required to meet DT-2 goals (e.g. increased shielding, etc.)

# Heating mix and power adaptation for SRO, DT-1 & DT-2



# Heating mix and power adaptation for SRO, DT-1 & DT-2



# Scenario development pathway in SRO and DT-1

Use of W wall favours $B_T$ values that provide effective central heating.

→ Scenario development at 2.65 and 5.3 T.

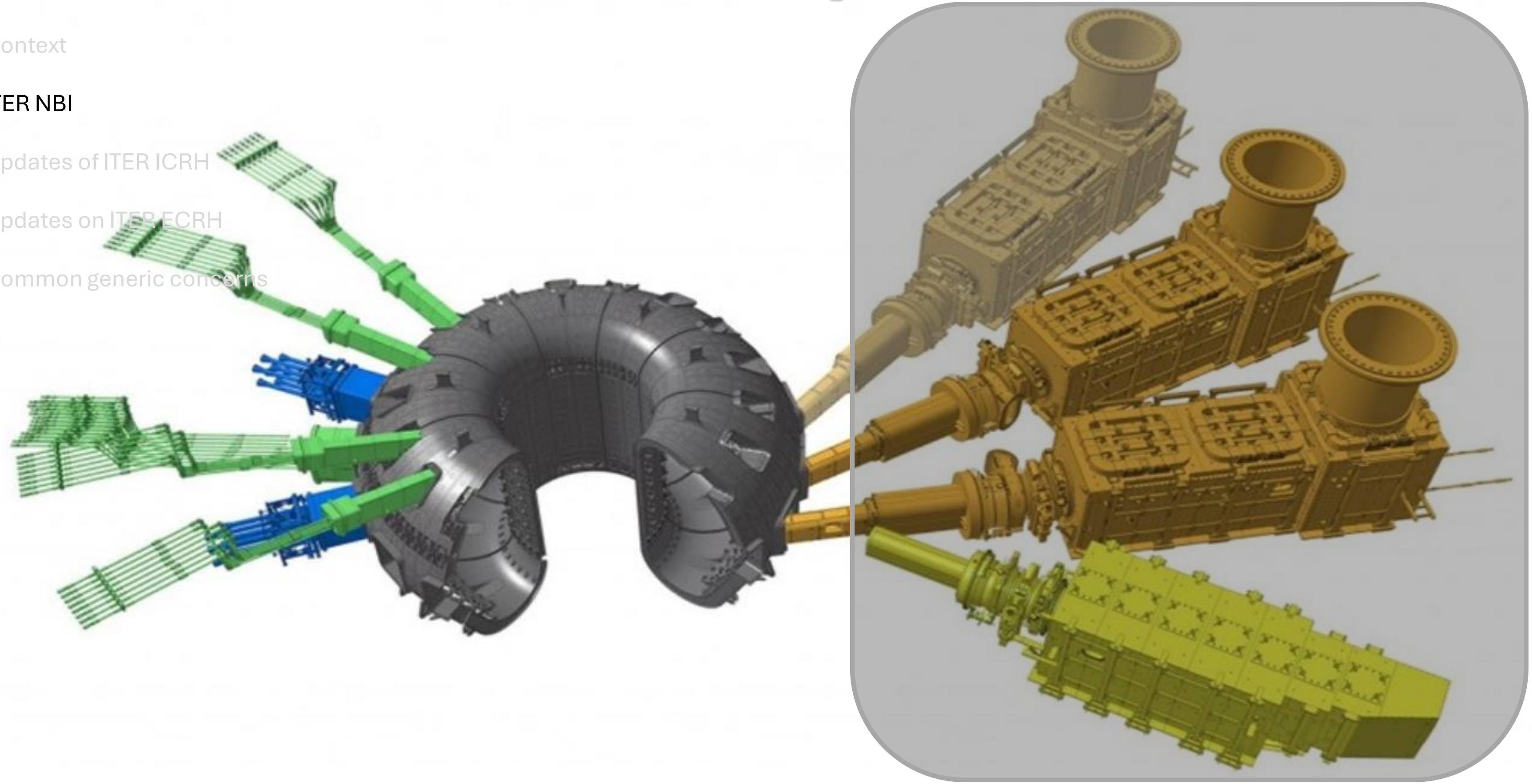
| | SRO | | DT-1 | |
|---|---|---|---|---|
| **ECRF** | 40 MW | 2.65 T<br>X2 in L-mode, O2 in H-mode. | 60-67 MW | 2.65 T<br>X2 in L-mode, O2 in H-mode. |
| | | 5.30 T<br>O1. | | 5.30 T<br>O1. |
| **ICRF** | 10 MW | 2.65 T<br>• In D at ~42 MHz:<br>H minority (N=1), or,<br>D majority (N=2).<br>• In H:<br>No efficient scheme. | 10-20 MW | 2.65 T<br>• In D and DT at ~42 MHz:<br>H minority (N=1), or,<br>D majority (N=2).<br>• in H:<br>No efficient scheme. |
| | | 5.30 T<br>• In D or H at ~53 MHz:<br>$^3$He minority (N=1).<br>*Assess coupling & ICRF-specific sputtering.* | | 5.30 T<br>• In D or H at ~53 MHz:<br>$^3$He minority (N=1).<br>• In DT at ~53 MHz:<br>$^3$He minority (N=1),<br>T majority (N=2). |
| **NBI** | | | 33 MW | Up to 0.87 MeV H beams.<br>Up to 1.00 MeV D beams. |

# Common challenges

- In-kind procurement
- First of a Kind for many components
- Different levels of maturity between the ITER systems and between sub-systems
  - Assumptions taken for the interfaces definition
  - Adaptations made following the developments
- Pushing beyond limits a wide spectrum of engineering and physics technology
- Nuclear environment with stringent safety requirements

# ITER NBI system

- ❑ Context
- ✓ ITER NBI
- ❑ Updates of ITER ICRH
- ❑ Updates on ITER ECRH
- ❑ Common generic concerns

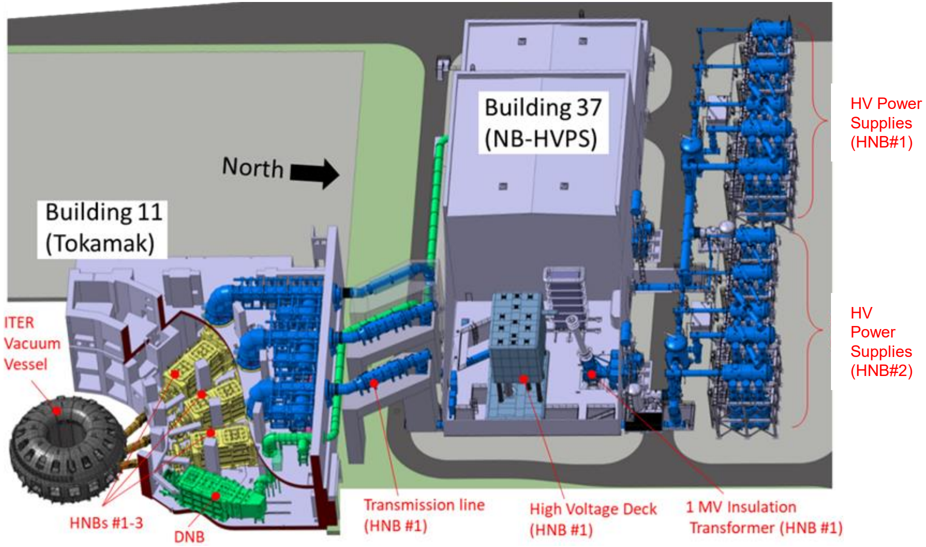


# Overview of NB Systems at ITER

2+1 Heating Neutral Beams (HNBs) + 1 Diagnostic Neutral Beam (DNB)

**Diagnosing He ash content (CXRS)**

- 33 (50) MW of Power injected
- Also provide current drive, rotation.
- Mostly procured In-kind, via PAs with Europe, Japan (HNBs) and India (DNB)

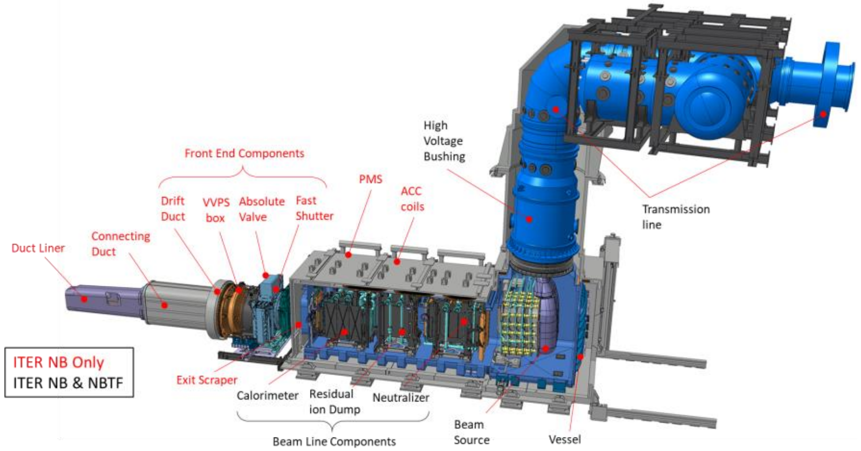



| Parameter | HNB (H/D) | DNB (H) |
|---|---|---|
| Injected power (MW) | 16.5/beamline | 1.7 |
| Beam energy (MeV) | 0.87/1 | 0.1 |
| Accelerated current (A) | 46/40 | 60 |
| Beamlet divergences (mrad) | <7 | <7 |
| Pulse length/duty cycle (s) | 3600/25% | 3 s ON, 20 s OFF or 0.1s ON 1.4s OFF |

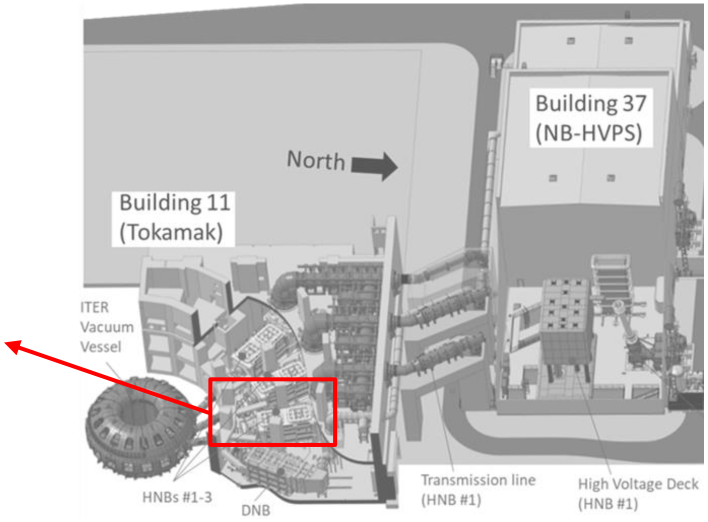
# Overview of HNB System at ITER

- ✓ Based on production and neutralization of <u>negative</u> ions.
- ✓ High Voltage, large heat fluxes;
- ✓ High Vacuum;
- ✓ Compensation of ITER B field;
- ✓ Nuclear Confinement,
- ✓ RH

→ >10 large FOAK components involved; large extrapolation from existing NBI→ NBTF

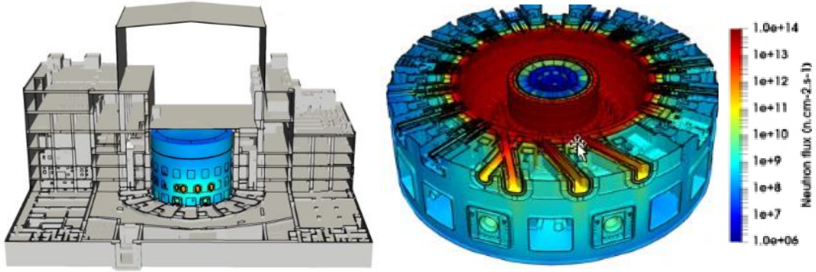



CAD view of HNB#1. DNB has a similar configuration, and almost identical components



# NUCLEAR ENVIRONMENT

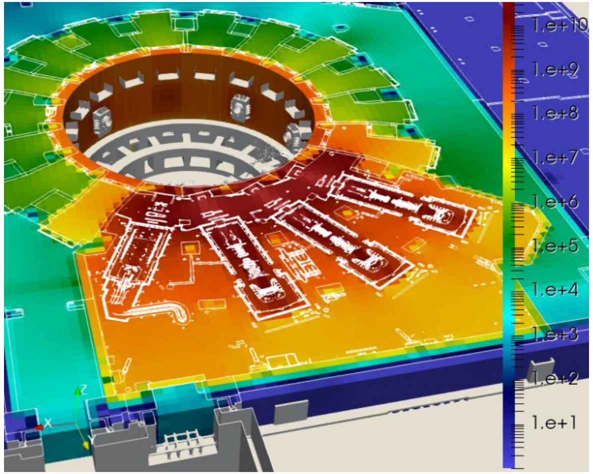
- Nuclear environment at ITER has a strong impact on design choices for the operation and maintenance




Report ITER IDM 2RLM3G

- Compliance with Nuclear regulation (Confinement Functions, redundancy,…)

- Electronic, will not survive in NB cell. Reliable operation requires neutron flux < 100 n/cm$^2$/s



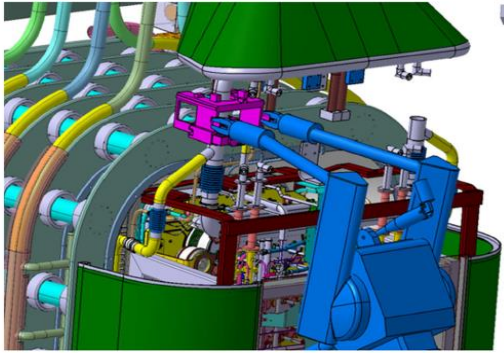

*Credits: E. Polunovskiy, IO*

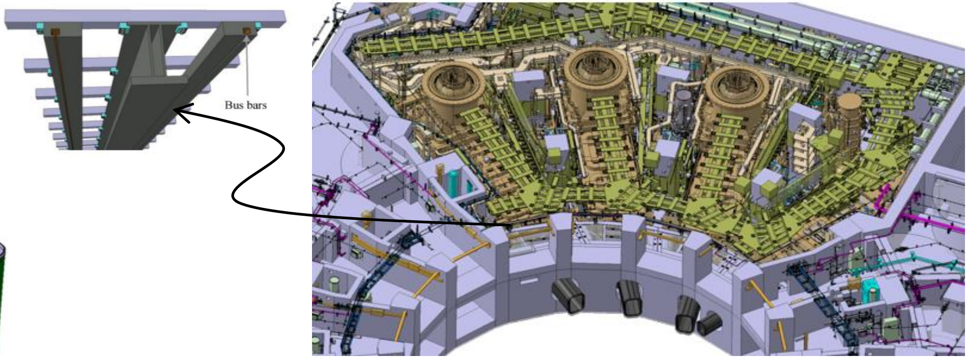
- Careful design of radiation protections allowed to keep the Shutdown dose rate* in the NB cell to<100 µSv/h where human access is required.
- Radiation levels in the NB cell will preclude any extensive manned interventions
- Most Operation can only be done by Remote handling

*Any maintenance in ITER only allowed after 2 week time. The Radiation dose after this period is called shutdown dose rate

# NUCLEAR ENVIRONMENT: REMOTE HANDLING

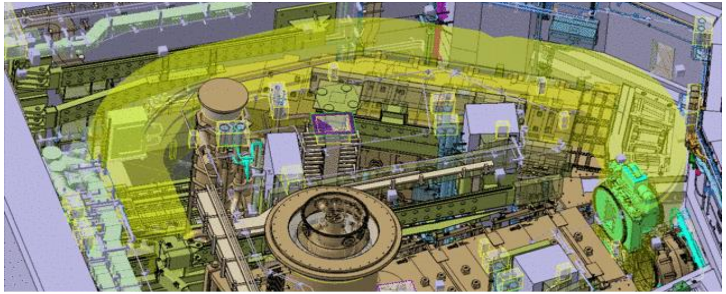
- In the Design of NB cell, accessibility for all the RH tools shall be granted.
- Activated components need to be transferred to the hot cell building for storage/disposal
- Pillars in NB cell preclude the use of a standard bridge crane → monorail crane






- All Components have to be designed to be compatible with monorail transport (mass, gravity center,…) also in accidental scenarios (earthquakes)
- Automatic cutting and welding devices →Need space reservation
- Substitution of Cs oven is the only maintenance operation presently planned

- Test in the RH "cold test facility" (Ready for mid-2034, useful to develop custom solutions for NB RH)



*Credits: K. Roux, IO*

# NB Main Challenges

1. Generation of required negative ion densities at ITER relevant parameters while simultaneously keeping the co extracted electron currents to acceptable levels.
2. High voltage holding, up to 1MV in the accelerator, TL and vessel.

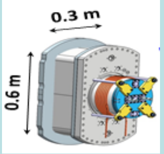
The program, designed to address these challenges is broken down as follows:

1. Ion source development program
2. HV development program

Development of a dedicated test facility (NBTF "PRIMA") leading to MITICA a full scale HNB Prototype

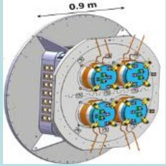
# NB Development program

## Ion source development program



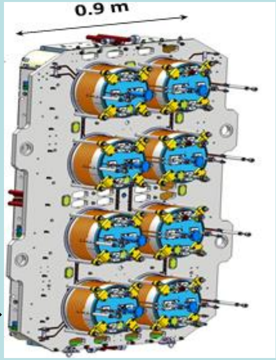

x4

BATMAN – 100 kW




ELISE – 400 kW

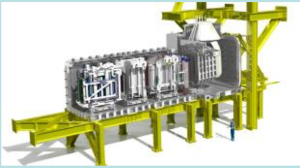
x2




SPIDER, MITICA beam sources
800 kW

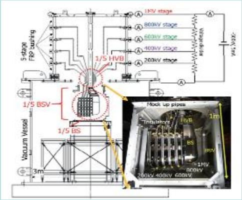
Starts with Elise in 2012, half size ITER type source with beam extraction.
Creation of a dedicated test bed to host 2 experiments SPIDER & MITICA.

## HV development program



MITICA

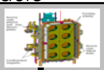
HVPTF




HV Tests

Accelerator physics studies to 1MV to enhance understanding and benchmarking of the codes.

*Reference schedule*



2018: SPIDER — *Integration & Operation*

2027: MITICA — *Integration & Operation*

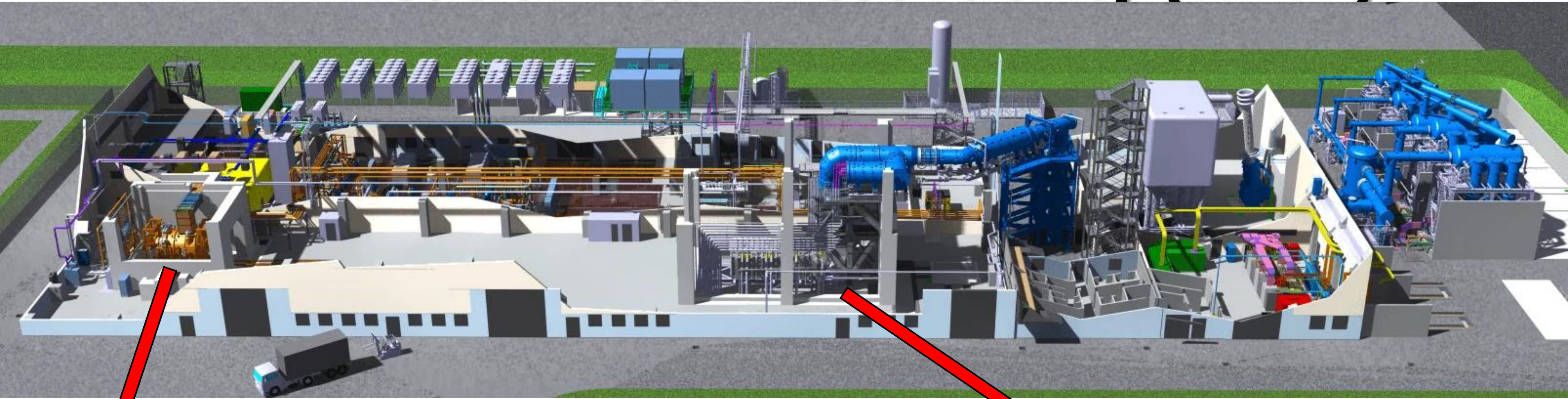
DT-1 — *HNBs to inject into DT-1 plasma*

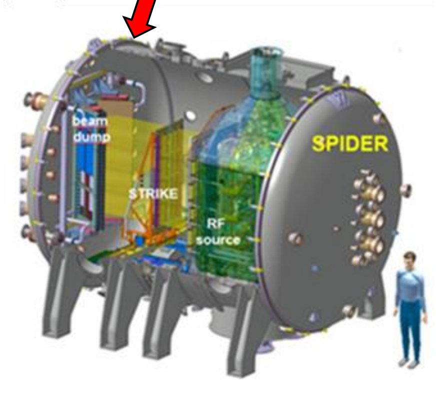
The schedule outlined provides a full 1 MV prototype injector operational experience of several years prior to HNB/DNB operation at ITER during DT-1.
MITICA will operate in double shift with single shift of SPIDER in parallel.

Sufficient time to ensure the confidence in the:

- Design
- Technology
- Beam Characterization
- Performance – modulation and power variation
- Component Lifetime

# ITER Neutral Beam Test Facility (NBTF)



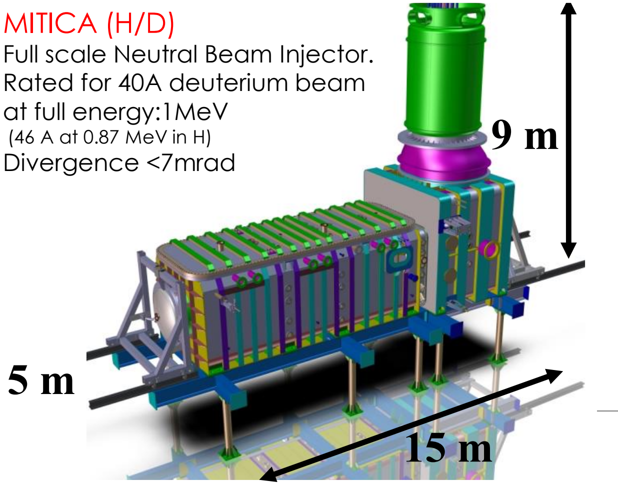



**SPIDER (H/D)**
Full scale negative ion source,
Rated for 56A deuterium
beams (70A in H) at $^1/_{10}$ of ITER
NBI beam energy

J=355/285 A/m2 *
E=0.1 MeV
P=0.3 Pa
Ele/Ion < 0.5/1
Uniformity ±10%
Beam on time=1000/3600s

*DNB Relevant

MITICA (H/D)
Full scale Neutral Beam Injector.
Rated for 40A deuterium beam
at full energy:1MeV
(46 A at 0.87 MeV in H)
Divergence <7mrad



# NBTF experiments requirements for ITER NBI[1]

## SPIDER (HNB/DNB source)

| Parameter | In H | In D |
|---|---|---|
| Beam energy (keV) | 100 | 100 |
| **Extracted current dens. ($A/m^2$)** | **>330/355** | **>285** |
| Max. beam source pressure (Pa) | 0.3 | 0.3 |
| **Uniformity (%)** | **±10** | **±10** |
| Beam-on time (s) | 3600 | 3600 |
| Co-ext. electron fraction | <0.5 | <1 |

[1] SRD-53-PR,-MI,-MP,-SI,-SP – NBTF System Requirements Document

## MITICA (full HNB prototype)

| Parameter | In H | In D |
|---|---|---|
| **Beam energy (keV)** | **870** | **1000** |
| Accelerated current (A) | 46 | 40 |
| Max. beam source pressure (Pa) | 0.3 | 0.3 |
| **Beamlet divergence (mrad)** | **<7** | **<7** |
| Beam-on time (s) | 1000 | 3600 |
| Co-ext. electron fraction | <0.5 | <1 |

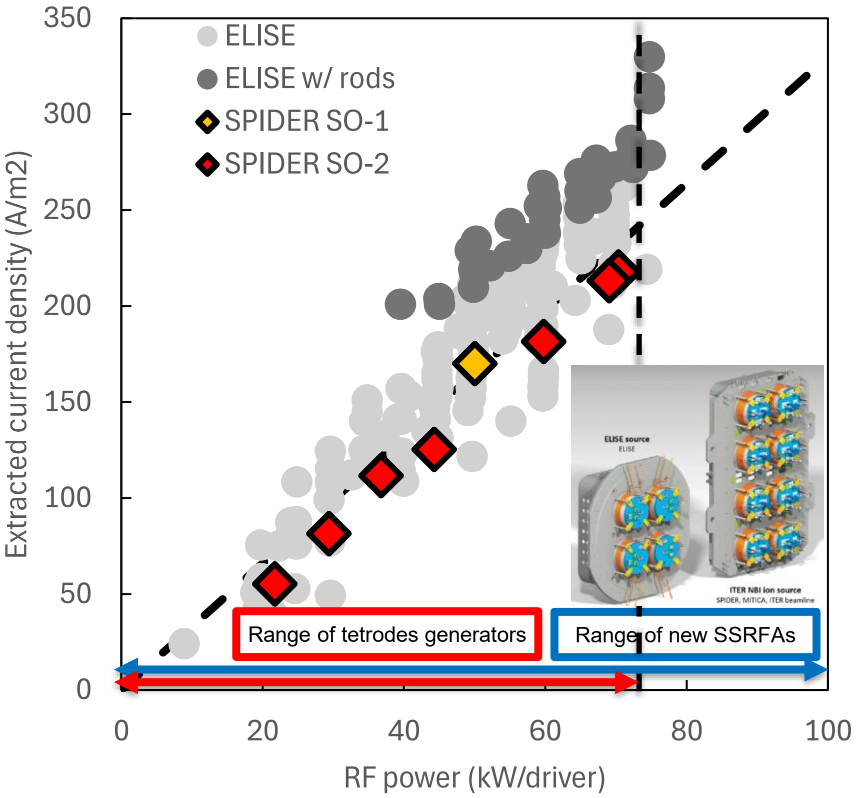
These 4 major challenges will be described in the next slides, including the recent results and progresses associated.
The NBTF will test all aspects of the HNB system, except the components downstream of the NB vessel (beamline exit scraper, fast shutter, absolute valve and duct liner). Most aspects of the beam source for the DNB will also be tested in the SPIDER test bed.

# Extracted current density

- ❑ **<u>Scaling of extracted current with RF</u>**
  - ✓ Demonstrated in ½ size prototype sources ELISE at IPP (100% for short pulses, 90% for long pulses)
- ❑ Scaling at full beam size to be demonstrated in SPIDER. Status: Scaling at perveance match up to 70kW/driver In line with IPP results (considering single segment operation)

- ❑ **<u>Upgrades foreseen for next campaign</u>**
- Replacement of tetrodes with solid-state amplifiers (FAT passed, delivered to NBTF)
- SPIDER Vacuum Enhancement Module ready for installation

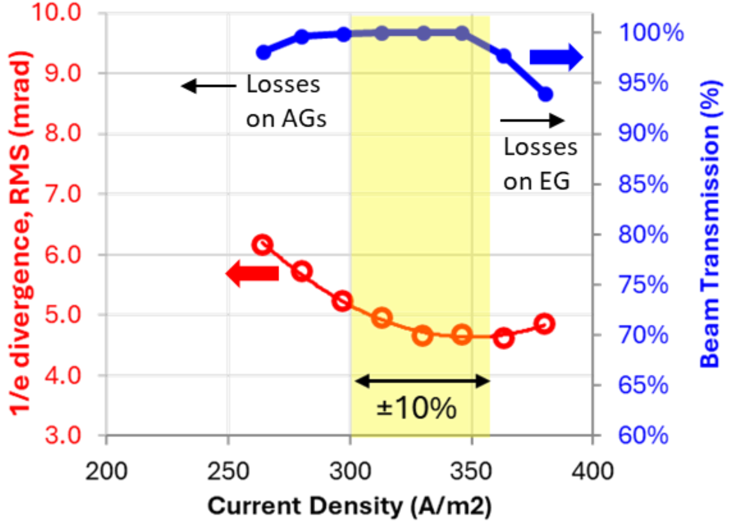
→Targeting full power operation (>90kW/driver) mid July

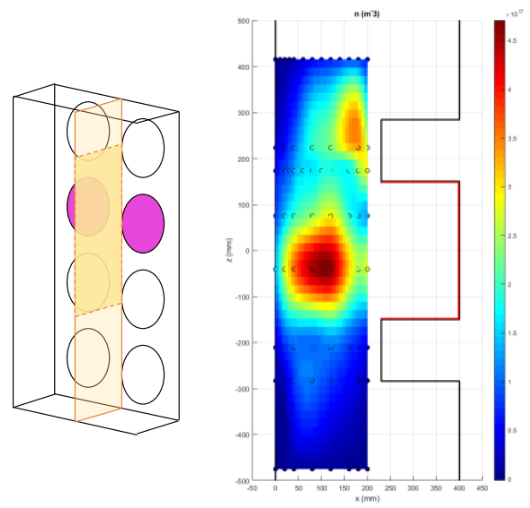


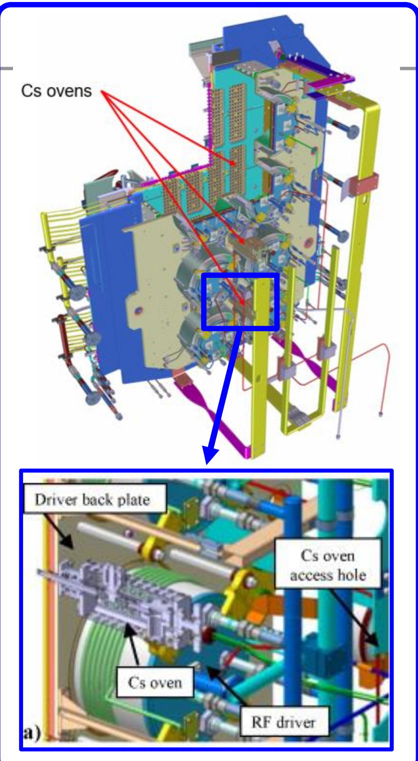

[1] Fantz et al. (2024), Nuclear Fusion, Vol. 64, No. 8, p. 086063
[2] Sartori et al. (2022), Nuclear Fusion, Vol. 62, No. 8, p. 086022
[3] SPIDER 2024 single segment campaign SO-2 (preliminary data)

# Non-uniformity < ±10%

- Requirement driven by heat loads
- Beam uniformity Depends on negative ions uniformity (plasma+Cs)






Heat-loads on grids → Beam uniformity (±10%) ↔ Plasma uniformity

Perveance $\pi = I/V_{EG}^{3/2}$

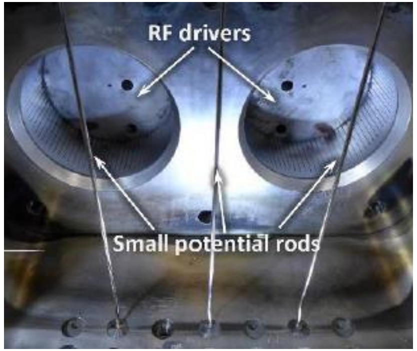
Beam uniformity (±10%) → Uniform Cesium distribution

# Non-uniformity < ±10%

- Requirement driven by heat loads
- Beam uniformity Depends on H- uniformity (→ plasma uniformity and Cs distribution)
- Active area of research in giant ion sources for fusion
- Improvements achieved recently on both plasma uniformity and Cs distribution.

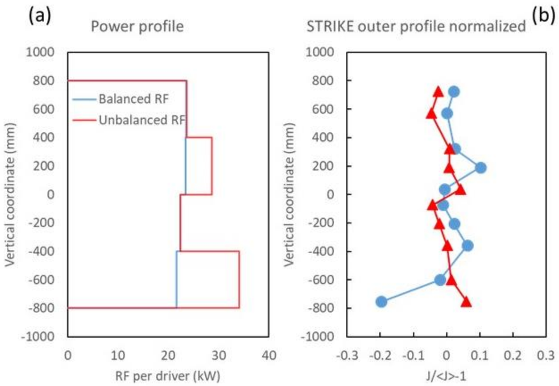
**Examples:**

Use of additional electrodes in the plasma can stabilize the co-extracted electron current (like rods in ELISE)



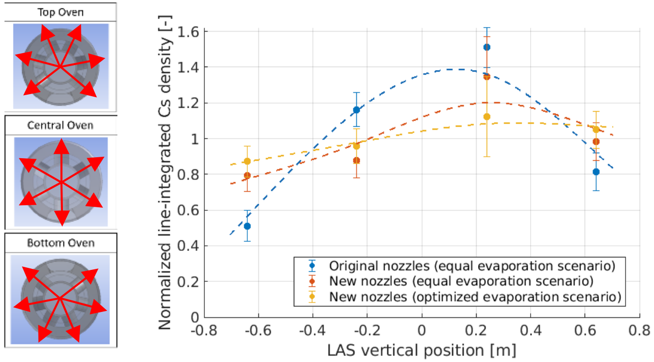

D. Wünderlich et al., J. Phys.: Conf. Ser. 2743 012026 (2024)

Tuning of RF power in each pair of driver, compensate the plasma E x B drift




Increase of the heat-load of the co-ext. electrons to be expected

Improved Cs distribution with tuning of nozzles and calibrated emissions. Dedicated 3D models, and Test stand (CATS)



# Beam optics: divergence < 7 mrad

**Beam Power=$I_{ACC} \cdot V_{ACC} \cdot Y_N \cdot (1-T_R) \cdot$ $T_G$**

$I_{ACC}$=Accelerated current =40 A

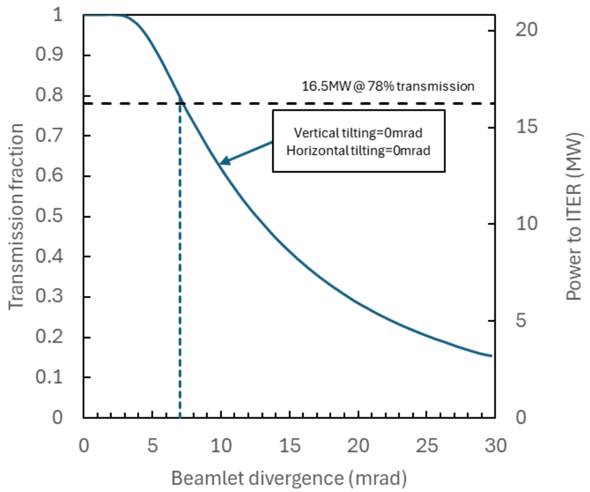
$V_{ACC}$=Acceleration Voltage =1 MV

$Y_N$=Neutraliz. Yield=56%

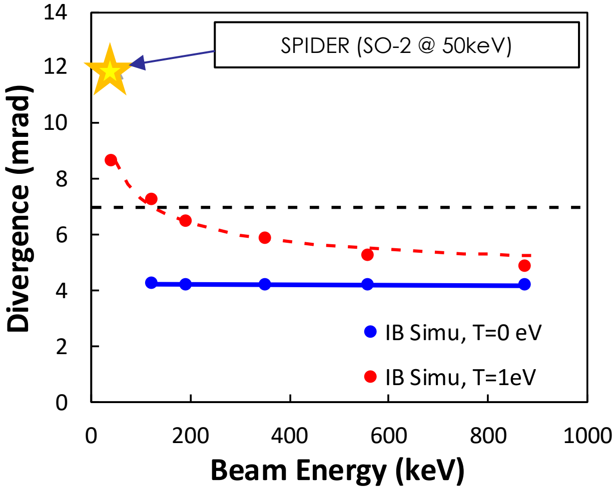
$T_R$ =Re-ionization Losses=4.8%

$T_G = T_G$ (**divergence,** aiming, tilting)

**Beam Power ≥ 16.5 MW ⟹ $T_G \geq 78\%$**




**To assure the required injected power to be injected in ITER, the HNB requires divergence <7 mrad**




- Divergence depends on the electrostatic lens and on the initial transversal velocity $v_\perp$ of the H-/D-
- The temperature dependent term scales with $\frac{v_\perp}{v_{beam}} \sim \frac{v_\perp}{\sqrt{E_{beam}}}$
- The HNB target of <7 mrad is expected to be reached in MITICA for $E_{beam} > 200keV$

# NBTF experiments requirements for ITER NBI[1]

## SPIDER (HNB/DNB source)

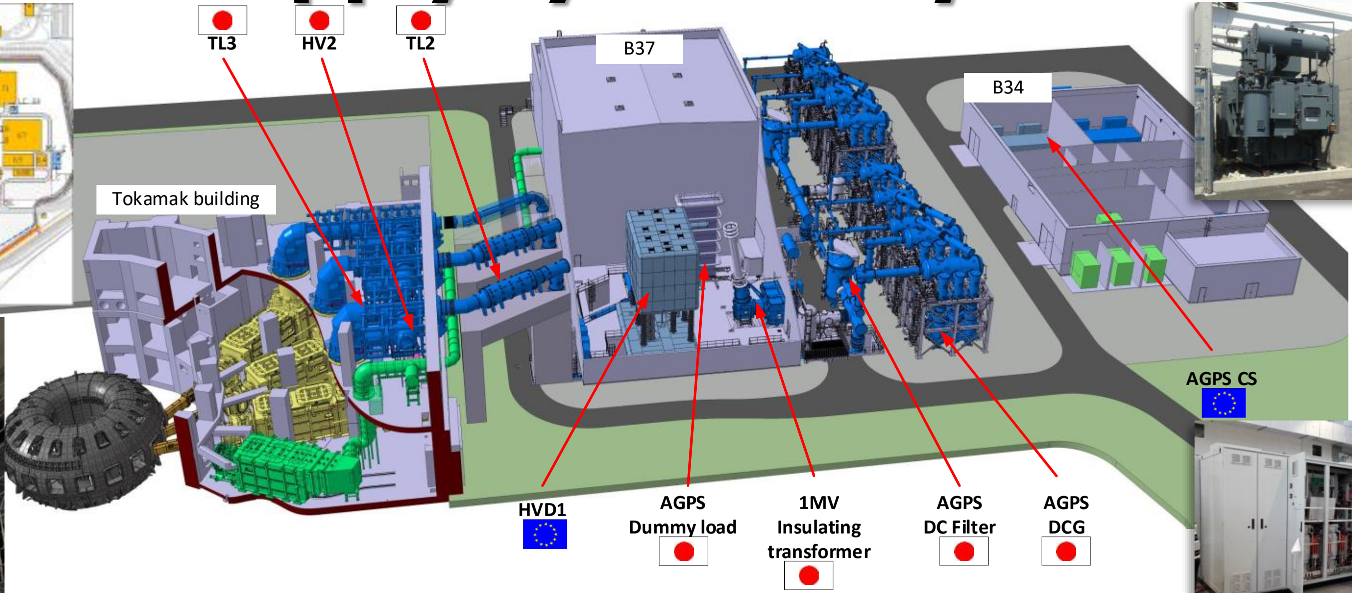
| Parameter | In H | In D |
|---|---|---|
| Beam energy (keV) | 100 | 100 |
| **Extracted current dens. (A/m²)** | **>330/355** | **>285** |
| Max. beam source pressure (Pa) | 0.3 | 0.3 |
| **Uniformity (%)** | **±10** | **±10** |
| Beam-on time (s) | 3600 | 3600 |
| Co-ext. electron fraction | <0.5 | <1 |

[1] SRD-53-PR,-MI,-MP,-SI,-SP – NBTF System Requirements Document

## MITICA (full HNB prototype)

| Parameter | In H | In D |
|---|---|---|
| **Beam energy (keV)** | **870** | **1000** |
| Accelerated current (A) | 46 | 40 |
| Max. beam source pressure (Pa) | 0.3 | 0.3 |
| **Beamlet divergence (mrad)** | **<7** | **<7** |
| Beam-on time (s) | 1000 | 3600 |
| Co-ext. electron fraction | <0.5 | <1 |

# NB Power Supply system Layout in ITER

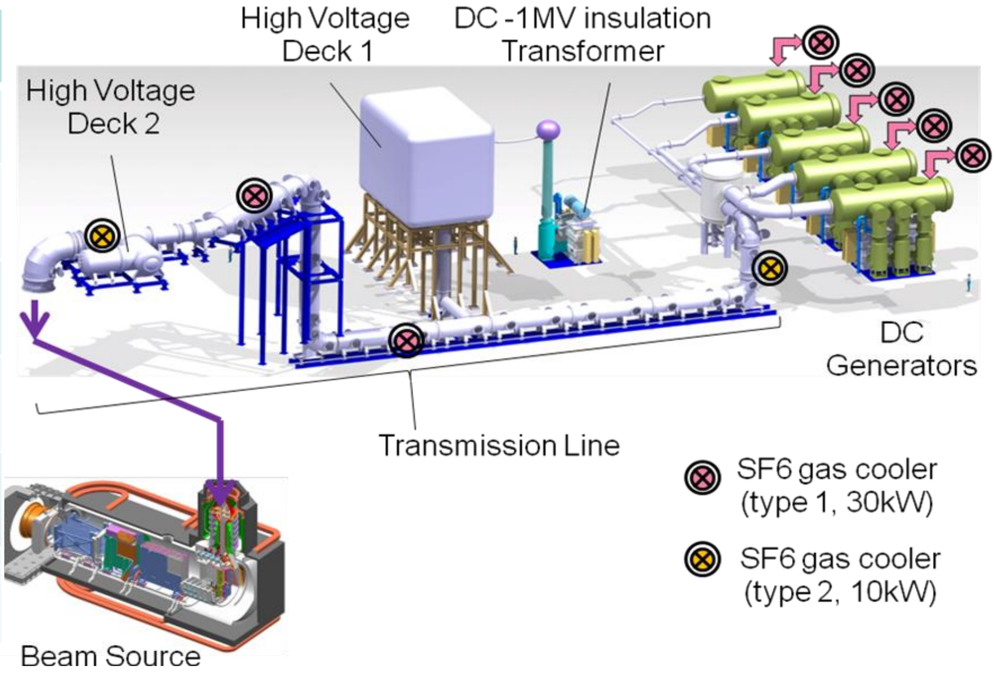



Main challenges:

- The mega volt generation and maintainability for 3600s the ramp up in 80ms.
- The SF6 management.

# Schematic of the SF6 gas cooler

| ITEMS | SPECIFICATIONS |
| --- | --- |
| SF6 Gas pressure | 0.6 MPa (abs) |
| Maximum operating gas pressure | 0.75 MPa (abs) (for pressure design) |
| Minimum guarented gas pressure | 0.55 MPa (abs) (for electric field design) |
| SF6 gas cooler shall be installed | 30kW, 8m3/min |
| SF6 Temperature rise in the Diode tanks | Average 73°C (upper limit 80°C) |
| SF6 Temperature in the DC Filter and TLs | 150°C Max. |



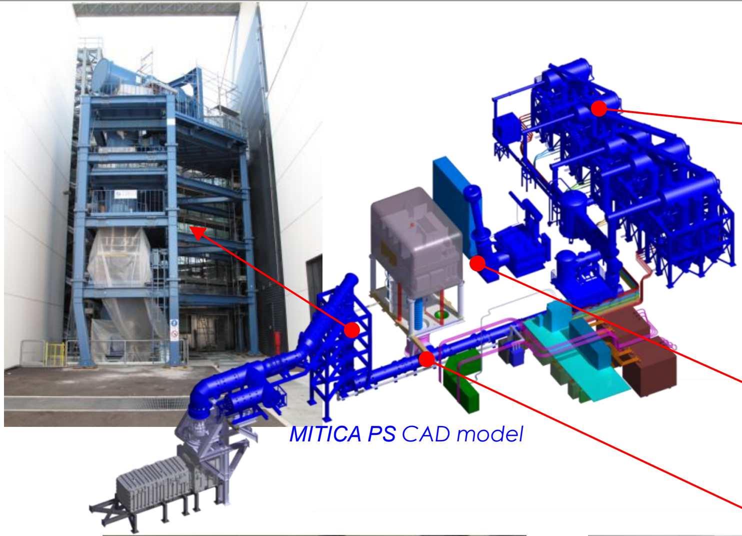

- The $SF_6$ gas coolers are used for cooling of $SF_6$ gas filled in the DC generators, DC filter, Transmission line 1&2, transmission line 3 and High voltage deck 2.
- There are two types of $SF_6$ gas cooler depend on the heat exchange capabilities (30kW and 10kW).

# Heating Neutral Beam Power Supply (MITICA) installed in Padua (Italy) by JADA

The Heating Neutral Beam injector are supplied at ultra high DC voltage (-1MV dc) to fixe the potential of the RF ion source and for the acceleration grid.

The qualification and tests will be performed at the, Neutral Beam Test Facility, Prima site in Padua (Italy)

The Installation at ITER site is on-going.



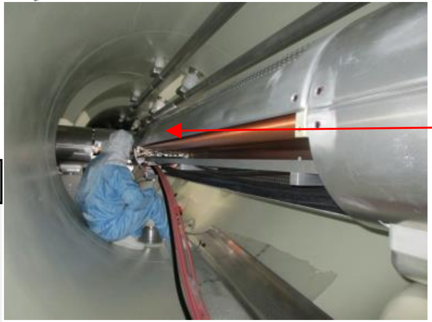
*MITICA PS CAD model*

*AGPS DCG, 200kV step up transformer*

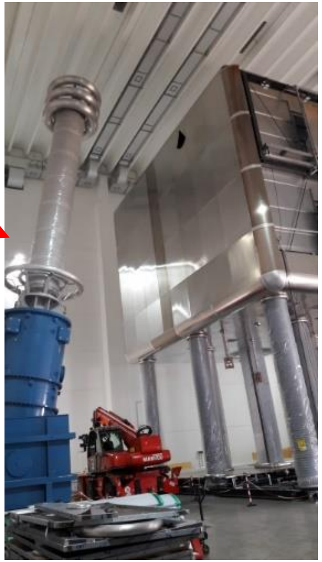
**AGPS-DCG**

Main characteristics

- Input section: 6.5 kV 150 Hz
- Output section: 200kV, 400kV, 600kV, 800kV and 1MV DC.



*The -1MV dc Transmission Line*



*The HV-Deck &*
*The -1MV insulating transformer*

**1MV DC Transmission Line**

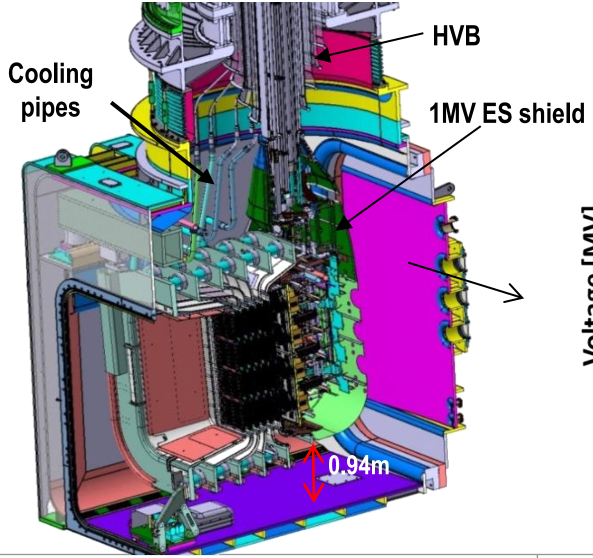
Supply the electrical power to the accelerator and the RF ion source

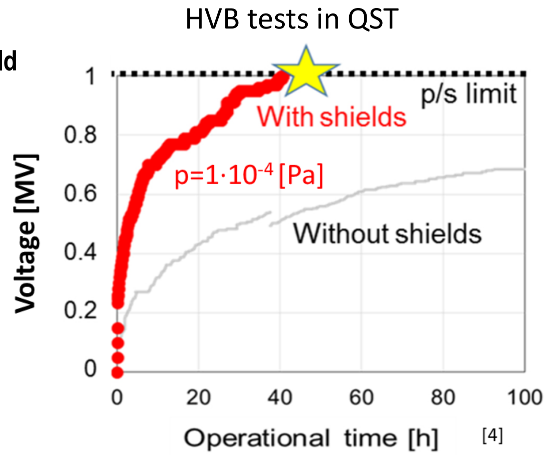
Main characteristics

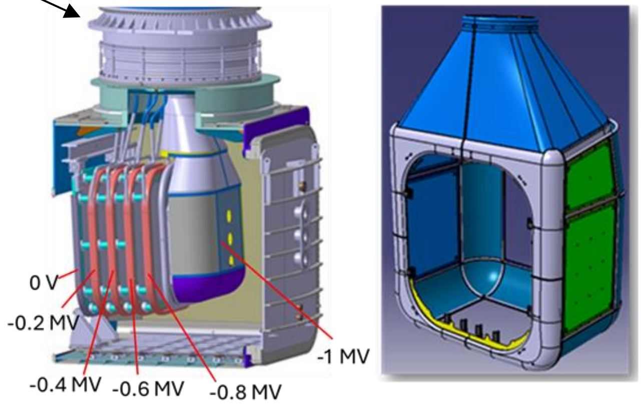
- Insulation: 1 MV dc
- 2.5 m diameters
- Filled with 6 bar of SF6

# High voltage holding

- Existing HV beam sources rely on gas insulation ($SF_6$) → not possible in ITER due to Radiation Induced Conduction
- Extrapolations from old experiments suggested ~1m insulation distance, in case of vacuum insulation (MITICA, HNBs)
- Later Experiments (HVB tests in QST, and 1/5th mock-up) show the beneficial effect of intermediate shields,
- A series of tests could be conducted in 2024 (JADA-NBTF collaboration)
  - Full-scale beam source mock-up tested using a Testing Power Supply (-1MV, 10mA) with voltage divider
- Two configurations tested: <u>full ion source without shield</u>, and with a -<u>600kV intermediate shield</u>

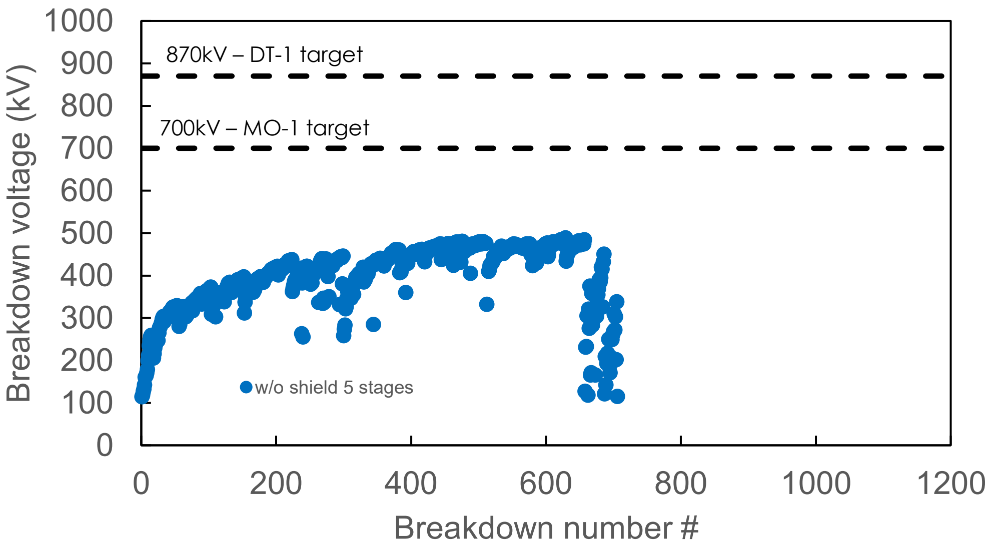


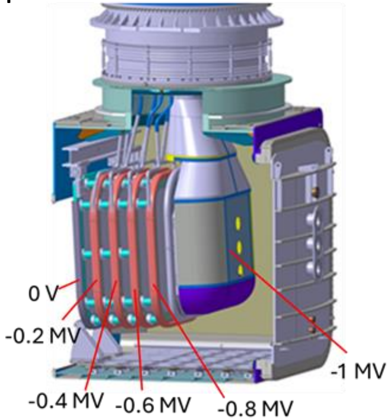



# High voltage holding

- ❑ **<u>HV test experiments</u>**
  - ➢ No-shield campaign: 420kV maximum voltage over 5 stages → additional shield is necessary
    - ➢ Scattering of data due to the reliability of vacuum spark-gaps



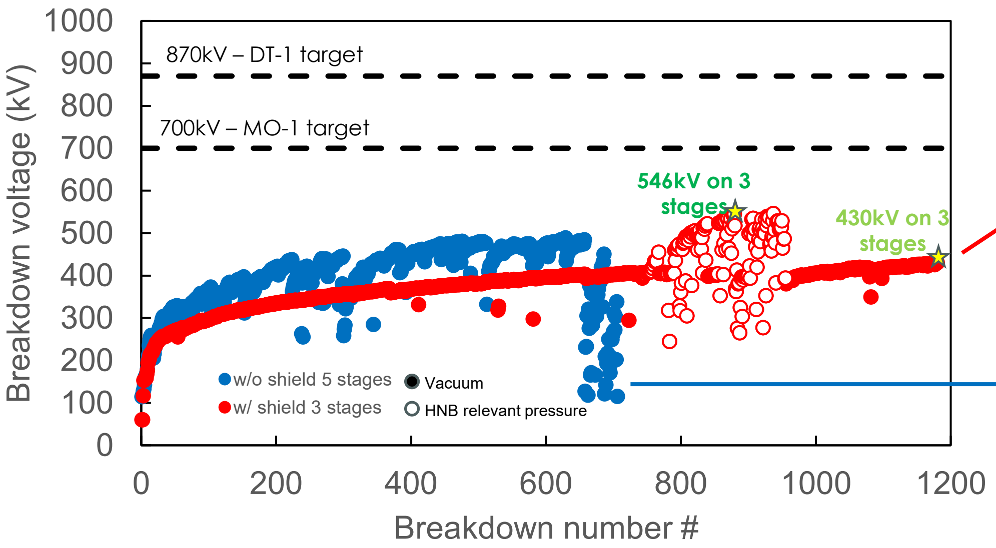



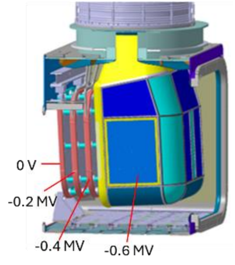


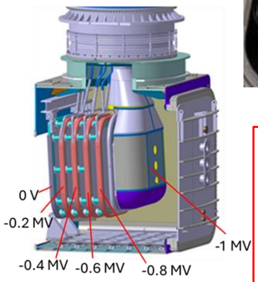
# High voltage holding

## ❑ HV test experiments

- ➢ No-shield campaign: 420kV maximum voltage over 5 stages → additional shield is necessary
  - ➢ Scattering of data due to the reliability of vacuum spark-gaps
- ✓ -600kV shield campaign: 200-400-600kV stages polarized, 800-1000kV stages short-circuited to 600kV stage
  - ✓ Good indications in terms of operating procedures in view of the first MITICA campaign
  - ✓ 546kV on 3 stages with HNB relevant pressure and 430kV on 3 stages in high vacuum



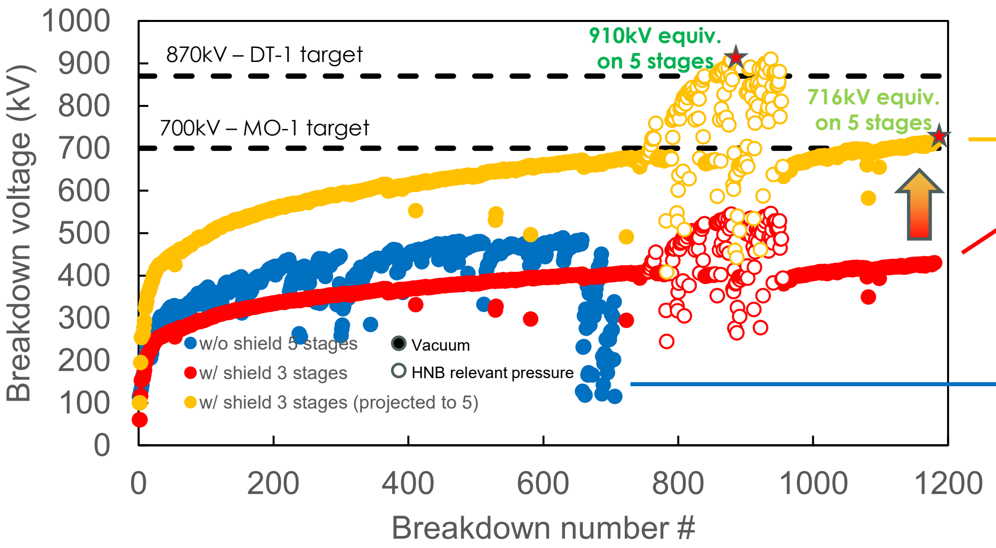



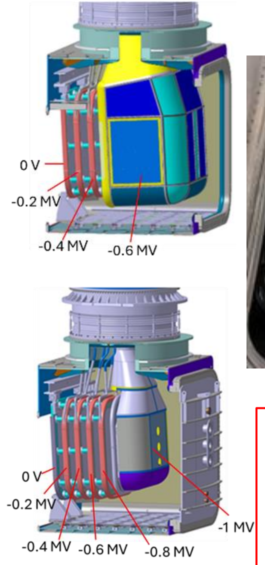

**N.B.** The intermediate shield fully separates the vessel in two electrostatically independent regions. Its voltage holding toward vessel was the most difficult to hold (600 kV vs 400 kV)

# High voltage holding

## ❑ HV test experiments

- ➢ No-shield campaign: 420kV maximum voltage over 5 stages → additional shield is necessary
  - ➢ Scattering of data due to the reliability of vacuum spark-gaps
- ✓ -600kV shield campaign: 200-400-600kV stages polarized, 800-1000kV stages short-circuited to 600kV stage
  - ✓ Good indications in terms of operating procedures in view of the first MITICA campaign
  - ✓ 910kV equivalent voltage with HNB relevant pressure and 716kV equivalent voltage in high vacuum




**N.B.** The intermediate shield fully separates the vessel in two electrostatically independent regions. Its voltage holding toward vessel was the most difficult to hold (600 kV vs 400 kV)

# CHALLENGES FOR NBTF

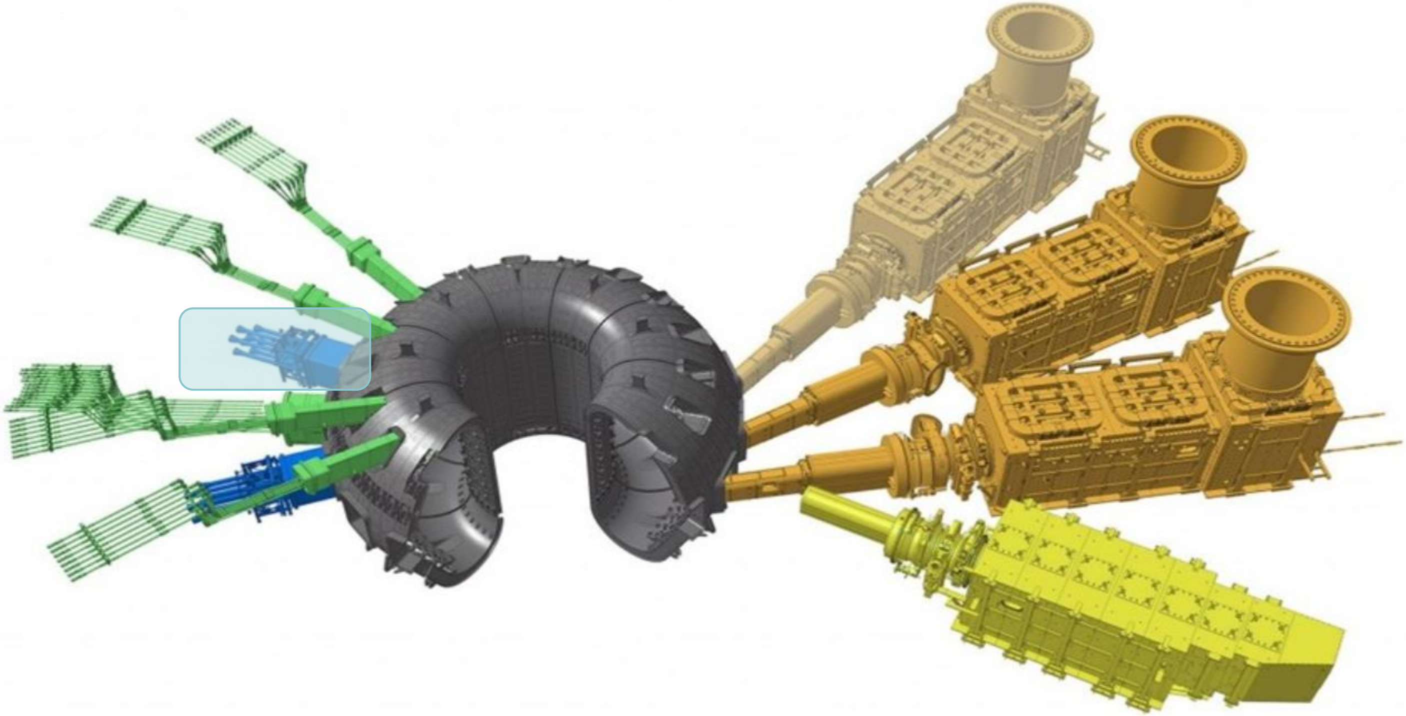
- **Current density** and **Beam divergence** **doesn't seem prohibitive**.
- The target **Uniformity** of the beam is likely more challenging. Active research, including collaboration with other laboratories is underway to address it.
- **Voltage holding** is also a key aspect. Recent tests at MITICA have yielded encouraging results, supporting the expectation that a single 600 kV shield shall assure full 1 MV insulation

| | HNB | DNB |
|---|---|---|
| **Current density** | ✓ | ✓ |
| **Beam divergence** | ✓ | ✓ |
| **Uniformity** | ✓ | ✓ |
| **Voltage holding** | ✓ | ✓ |

**NBI system is clearly highly complex, and achievement of required performance pose many challenges. Nevertheless, no risk has been identified as a true showstopper**
**The planned research at NBTF represents the most credible mitigation strategy to achieve the expected results.**

# ITER ICRH system

- ❑ Context
- ❑ ITER NBI
- ✓ ITER ICRH
- ❑ ITER ECRH
- ❑ Common generic concerns



# ITER ICRH system

## 2016 baseline

**8+1 RF sources and their HVPS**

**8 Transmission Lines**

**2 antennas**

**4 RF sources and their HVPS**

3.0 MW @ VSWR 1.5:1, 40-55 MHz, CW

**4 Transmission Lines**

<u>ICWC/ICRH with 10MW for SRO:</u>

- No technical requirements modified for the individual components of the ICRH system.
- New location for the RF sources & HVPS (B15N allocated to ECRH).
- 1 antenna (instead of 2, second port allocated to ECRH).
- The system is compatible with ICWC (needing 2-2.5 MW coupled to plasma → 5 MW installed). 10 MW installed power relaxes constraints on ICWC and allows proper testing of ICRH.
- The system is upgradable to 20 MW.

# CW high power RF system and harsh multiphysics constraints

- High vacuum ($10^{-4}$-$10^{-5}$ Pa) & high temperature (~250°C) environment.
- Large forces & torques ($10^5$ N & $10^5$ N.m in $10^{-4}$s, ex: plasma transients).
- Large E-fields ($10^6$ V/m) + need for protections such as arc detection.
- Large heat fluxes outgoing from the plasma ($10^6$ W/m$^2$, ex: plasma radiation, charge exchange, etc.) & high neutron fluxes ($10^7$ W/m$^3$) → Active cooling.
- Nuclear-safety constraints.
- HV 40-50kV.

*[Helou, et al. CWRF2018]*
*[ITER_D_46WNQW v1.1]*
*[Load Specification for the IC H&CD Antenna (ITER_D_33CETP v6.1)]*

# Main challenges

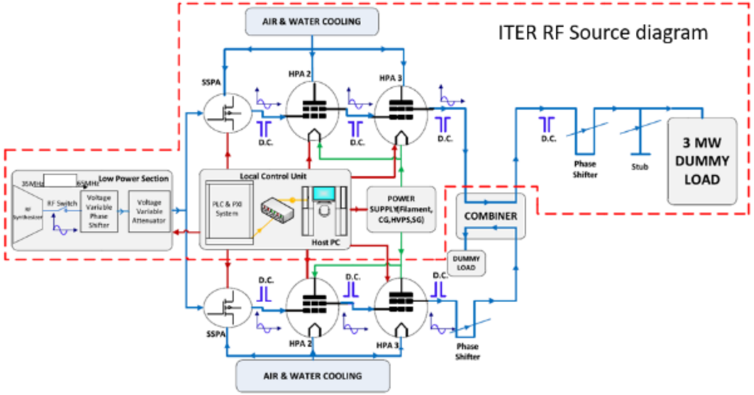
- RF sources: 3 MW CW each between 40 and 55 MHz
    - ***3MW test facility with mismatched load condition***
- Modification of the antenna environment constraints:
    - Reduction in port volume
    - Reduction in the port plug dimensions
    - Technical issues to be solved
        - Difficulty in manufacturing a SIC1 window with both structural and safety functions: Manufacturing of windows / vacuum TL design (Power tests to be done)
        - The structural behaviour of the antenna, in particular the front face.
        - Faraday screen (coating)
        - Reconciliation RF design and manufacturing tolerance (prototyping)
            - **Several steps in antenna design (prototyping phase at present)**
            - **Now optimization of the design**

# RF sources development

**4 RF sources each 3 MW CW between 40 and 55 MHz**

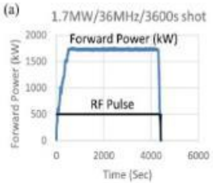
One source is composed of 2 parallel amplifier chains with a combiner circuit

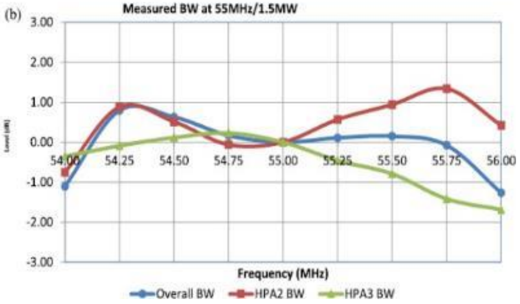
- R&D program performed by IN-DA to demonstrate ITER grade performance for one chain: 1.7 MW/3600s, 36 MHz with VSWR up to 1.5; full RF source will be developed with supplier
- Combiner circuit tested up to 1.5 MW/2000s under splitter configuration, 35-65 MHz
- RF detection using direct sampling advanced techniques developed by IO; test facility based on 10kW amplifier implemented in CEA to perform tests on RF control loops




IN-DA test facility

Thales Diacrode TH 628

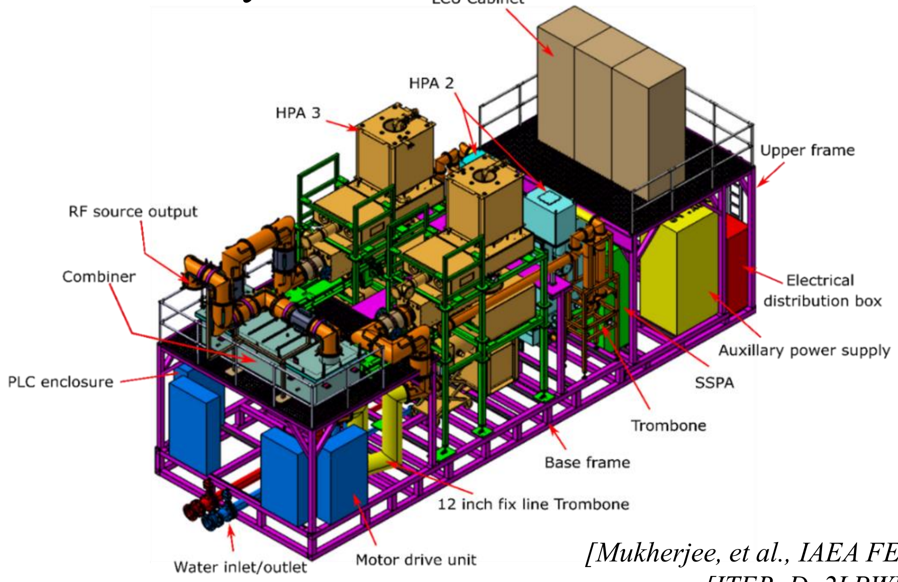



Performance test on single chain: 1.7 MW/3600s and +/- 1MHz bandwidth

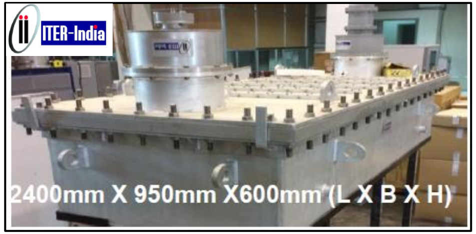
# RF sources as per baseline (i.e. 10 MW / antenna)

## RF source layout

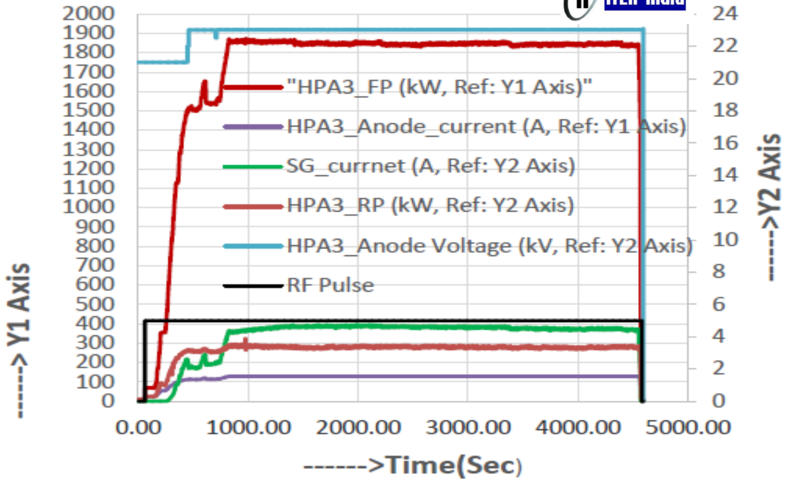



*[Mukherjee, et al., IAEA FEC 2016]*
*[ITER_D_2LPWUT v4.2]*
*[ITER_D_5ELB22 v1.0]*

## Combiner:




## Validation tests for ½ source chain

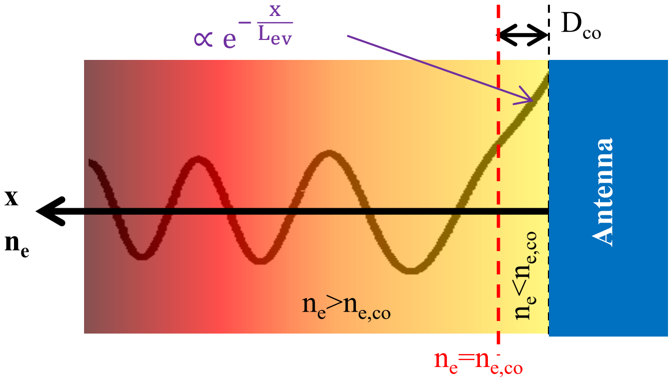



| | |
|---|---|
| 1.5MW / 2000s / 35-65 MHz on matched load including 1dB BW test | Demonstrated at 36 MHz, 45 MHz, 55 MHz & 65 MHz |
| Design capability test at 1.7MW/3600s on matched load | Performed at 36 MHz |
| 1.5MW/2000s at 65 MHz on mismatched load at 5 phase angles | Demonstrated at 0, 45, 90, 135 & 180 degrees |
| Max. output harmonic level: < -20 dBc | Achieved |
| η ~ 50% - 60% | 55% - 65% |
| Emergency power cut-off response: <10µs | Achieved |

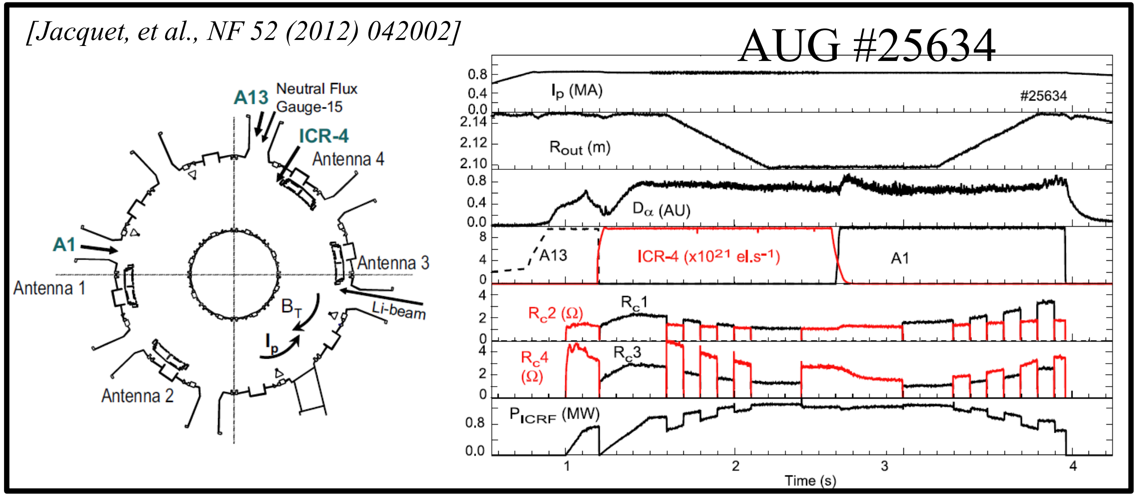
# CW high power RF system and harsh multiphysics constraints

- ❑ Fast wave is typically below cut-off at the antenna mouth.
- ❑ Compact phased arrays of electrically small loops (or straps): $Z_{strap}=R+jX = R+j\omega L$ with $\omega L/R >> 1$

→ Sensitive matching, in particular due to presence of strong mutual couplings.

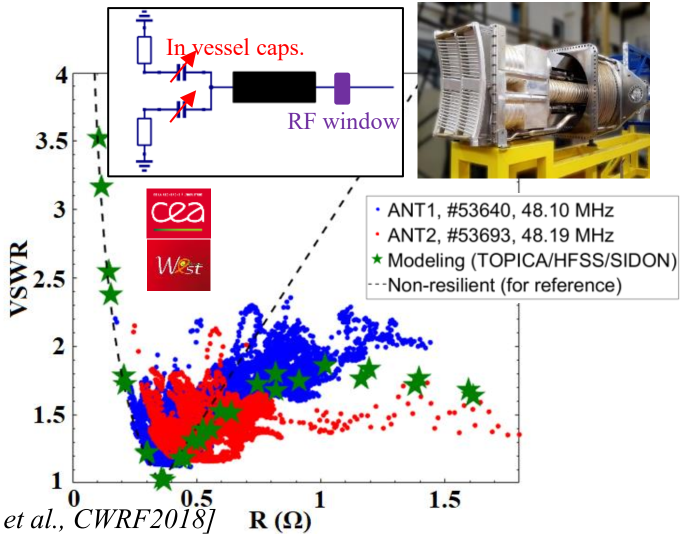



- o In antenna design phase: straps optimization to R ↗ (& $R/X^2$ ↗) & optimize antenna feeding circuit → V ↘, I ↘ & P ↗.
- o Scenario optimizations: plasma position, plasma shape, local gas injection, etc. to R ↗ & P ↗.

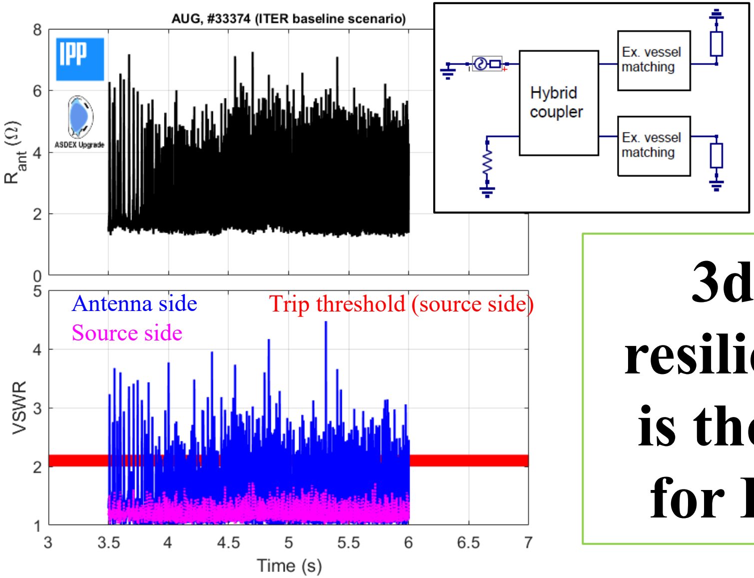


# CW high power RF system and harsh multiphysics constraints

- ❑ Sensitive impedance matching + harsh non-stationary plasma loading. Need for:
  - o Reconfigurable matching circuit (+ need to cover wide band, 40-55 MHz for ITER IC).
  - o Real-time controlled matching. But electromechanical tuning elements cannot cope with very fast ($< 10^{-3}$ s) plasma loading variations (×2 - ×5, or more).
  - o Load-resilience (ex: Conjugate-T, 3dB splitters, etc.).




*[Helou, et al., CWRF2018]*
*[Helou, et al., RFPPC2019]*
*[Hillairet, et al., NF 61 (2021) 096030]*

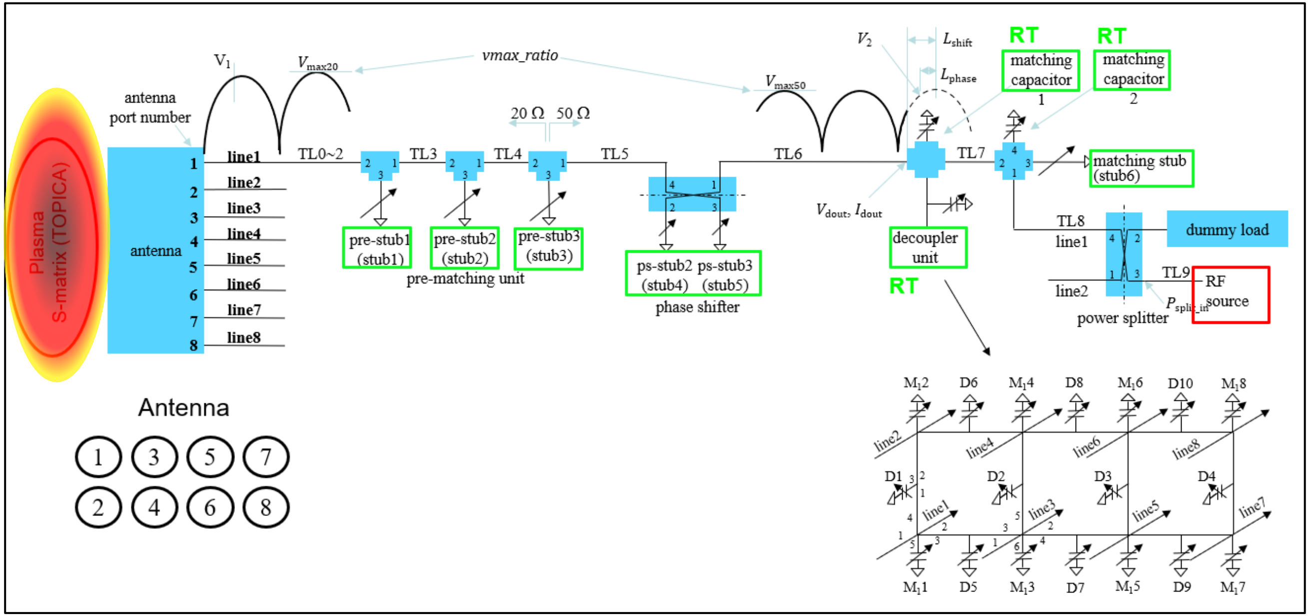



**3dB load-resilient circuit is the baseline for ITER IC.**

*Acknowledgments: V. Bobkov, IPP-Garching*

# The Transmission Line & Matching System (TL&MS)

## Variety of 20Ω & 50Ω components. Ex:



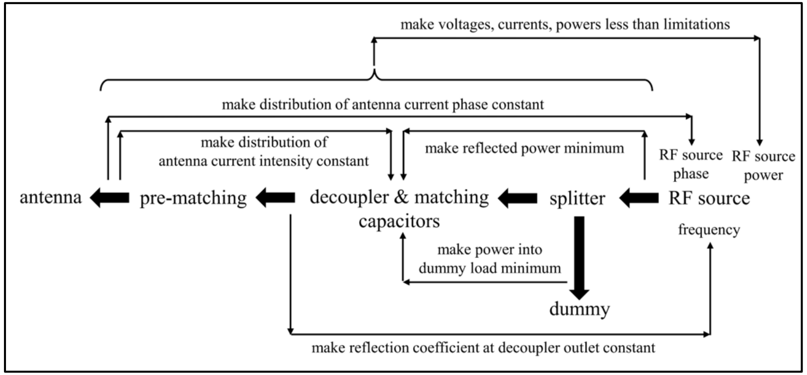

- 20Ω & 50Ω 12” lines,
- 20Ω & 50Ω elbows, with/without cooling gas inlets,
- 20Ω DC blocks,
- RF contacts in 20Ω pressurized lines,
- 50Ω gas barriers,
- Variable length stubs,
- Hybrid couplers,
- Hybrid phase shifters,
- Variable capacitors,
- Bellows,
- Spoke Ring Assemblies (center conductor supports),
- Etc.

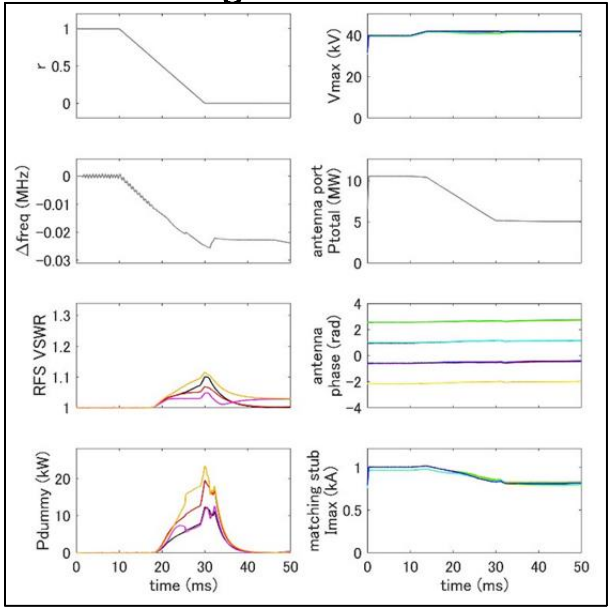
Feedback control algorithms (stub + expansion joint + gas barriers)

# Matching algorithms development ongoing

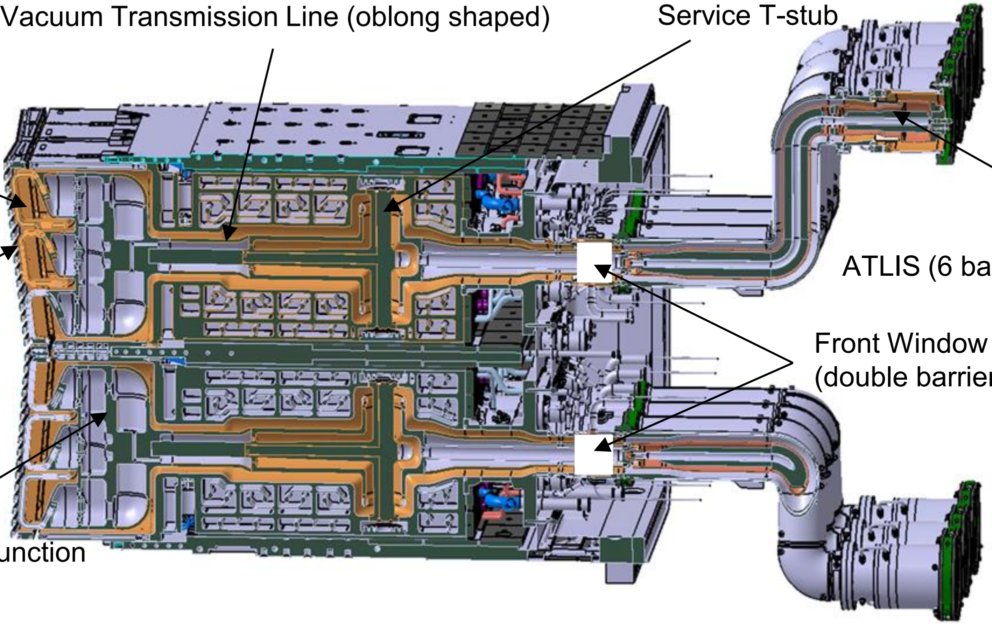
*[K. Saito, ITER_D_CHY9GQ v1.1]*

- Example of matching algorithm with:
  - Static stubs (ex. much less reduced risks of failure because of triboelectric aspects at the RF contacts).
  - Addition of matching capacitors in main matching.
  - Real-time controlled capacitors and frequency.



# The ITER ICRH antenna



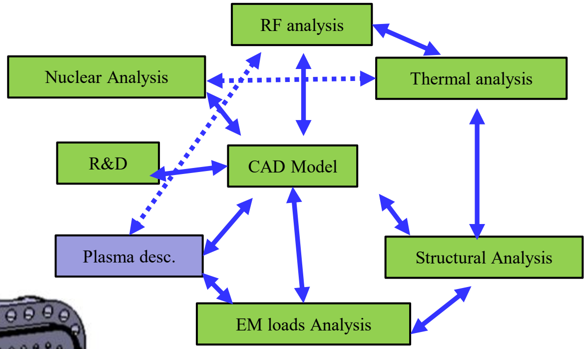

- 3.5 m × 2.0 m × 1.5 m, 45 tons.
- 24 straps array grouped in 8 triplets.
- 8 inputs. Flexibility for antenna array excitation.
- 4 RF modules.

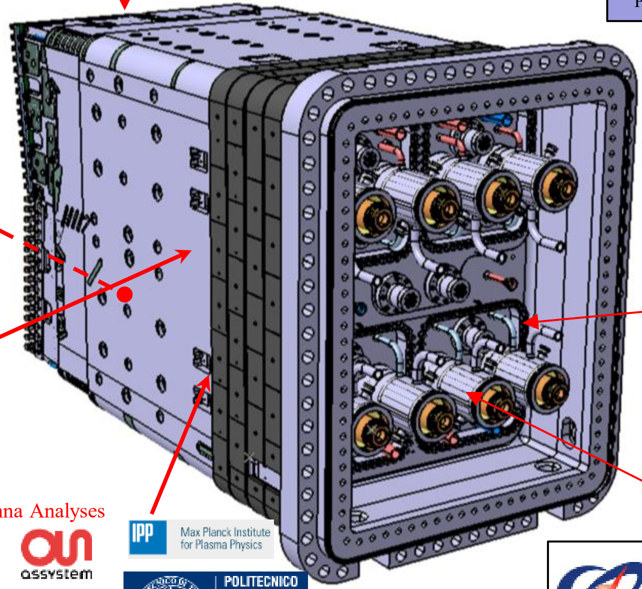
- 45 kV peak nominal voltage.
- $E_{max}$=2-3 kV/mm (depending on direction, and location).
- Optimized for 40-55 MHz.
- 10 MW CW, compatible with 20 MW CW.
- RF modules designed to maximize coupled power + provide neutron shielding and compliance to multiphysics requirements.

# Design steps

- Proper modelling (electrical, thermal etc…)
- Prototypes manufacturing
- Tests
- Retro-engineering if necessary
- Working from design with manufacturers

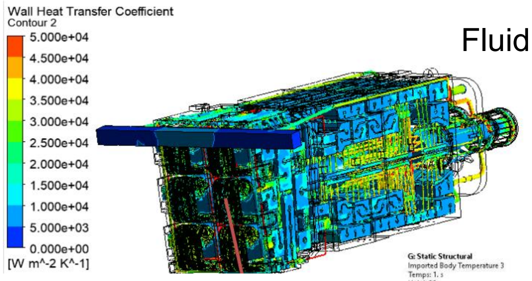
**Iterative design process**



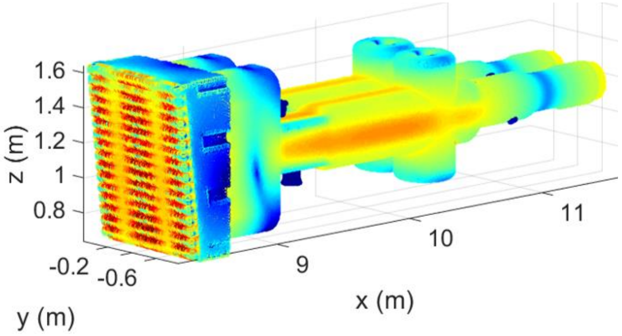
# Example Analysis process

- ❑ Integrated modelling covering: RF, electromechanical, thermomechanical, seismic, nuclear, 3D development & integration, etc.
- ❑ Example: RF loss densities from detailed full-wave modelling campain → Input for thermo-mechanical calculations (considered: impact of material temperature, surface roughness, safety factor, etc.).

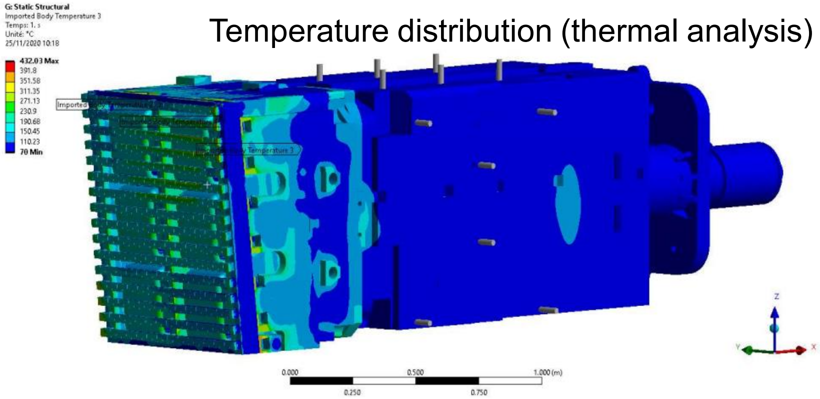



Fluid analysis

$\log_{10}(\delta^2 P)$ [W/m$^2$] at 55 MHz



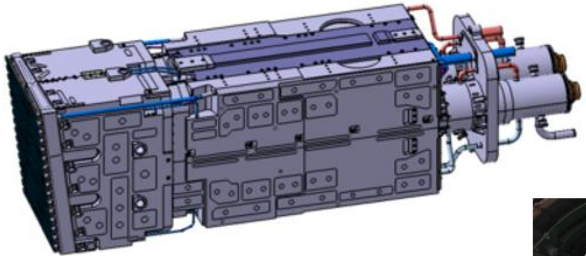

Temperature distribution (thermal analysis)



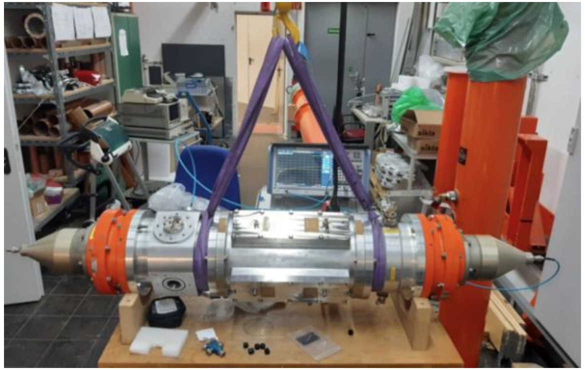

*[ITER_D_44M4QS v2.1]*

# Examples of prototyping activities & testbeds under development

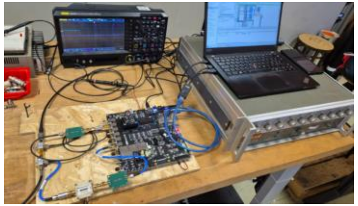
- R&D contract for manufacturing a quarter Antenna prototype in underway.
  - Validate manufacturing, assembly, etc.
  - Lower power characterizations.
  - High CW power validation tests under High RF voltages and currents.



- Arc Detection system RADAR.

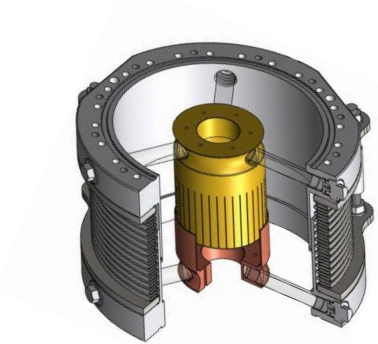


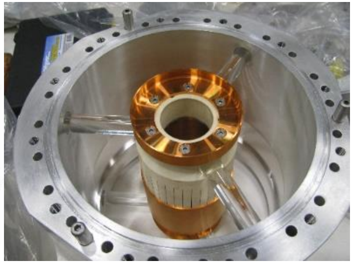
  - RF response validated by modeling
  - Prototype fully tested in laboratory, compliant with modeling
  - Installed in ASDEX and EAST for test with plasma

# The Transmission Line & Matching System – Example of tests

## ❑ 6 MW Assembly Bellows:





- Purpose: enable assembly and disassembly of TL sections, by provide length trimming (80 mm total stroke).
- Approach: bellows does not carry RF current but only serves as pressure seal. Uses sliding joints with RF contacts.
- Outer conductor and centre conductor are cooled by flowing gas. No water cooling.

## Lower power test (max allowable VSWR: 1.02)

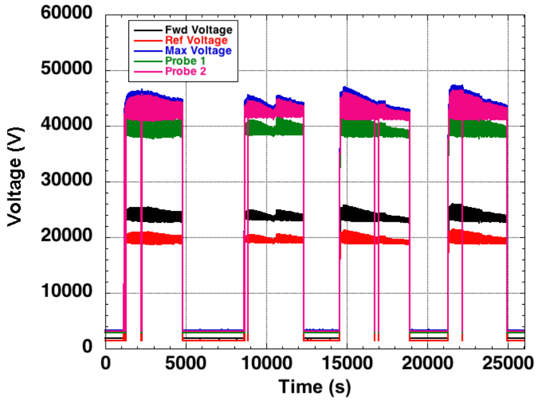
| Frequency | Fully extended | 76 mm compression | Fully compressed |
|---|---|---|---|
| 40 MHz | 1.008 | 1.0027 | 1.0042 |
| 55 MHz | 1.011 | 1.0036 | 1.0062 |

*[ITER_D_5H3HSM v1.0]*
*[R. H. Goulding, et al., RFPPC2017]*

## High power tests

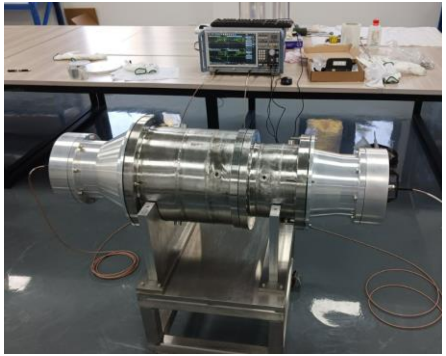
- Bellows from 2 suppliers tested for high voltage and high current handling.
- Both designs met ITER high power test requirements:

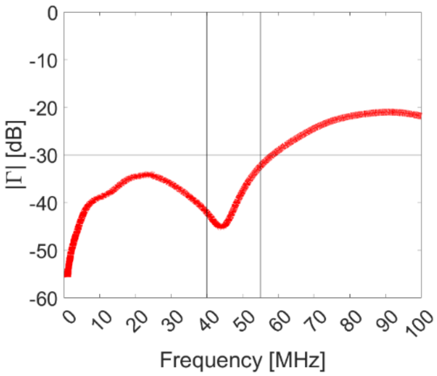
- $V \geq 35$ kV peak for 3600 s
- $V \geq 40$ kV peak for 0.1 s, 10% duty factor
- $I \geq 680$ A peak for 3600 s.

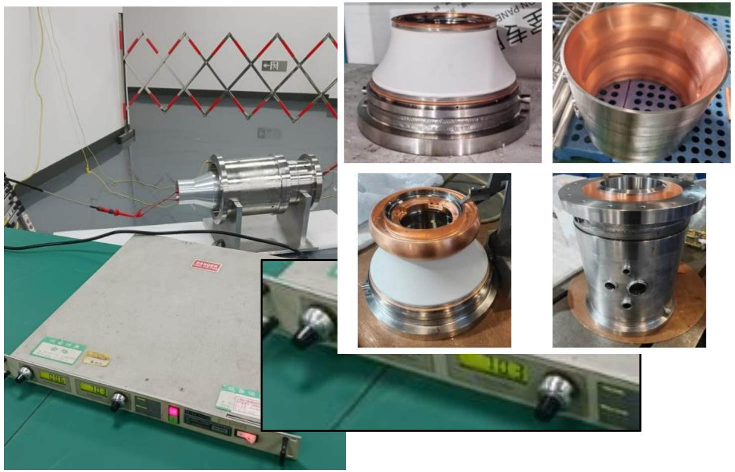


# RF windows test articles

- ❑ RF windows (Front Window and Rear Windows) progressing. Contracts with ASIPP & Alevion
- ❑ Example for ASIPP windows: VNA tests for prototype RW Test Article, and Hipot tests.



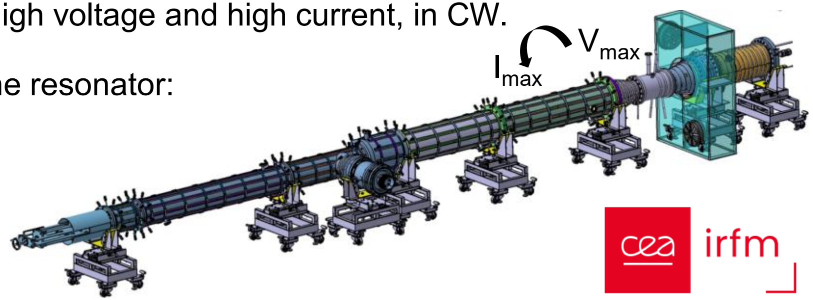


- ❑ Next steps, tests at high voltage and high current, in CW.

Modular design of the resonator:

- $V_{max}$ and $I_{max}$.
- FW & RW.




cea irfm

# CHALLENGES FOR IC

- High Voltage and RF current test of the RF windows remain to be completed (2026 and 2027 test campaign), long pulse at high current or voltage is still a challenge. The final design of the window shall be finalized following the high-power test results.

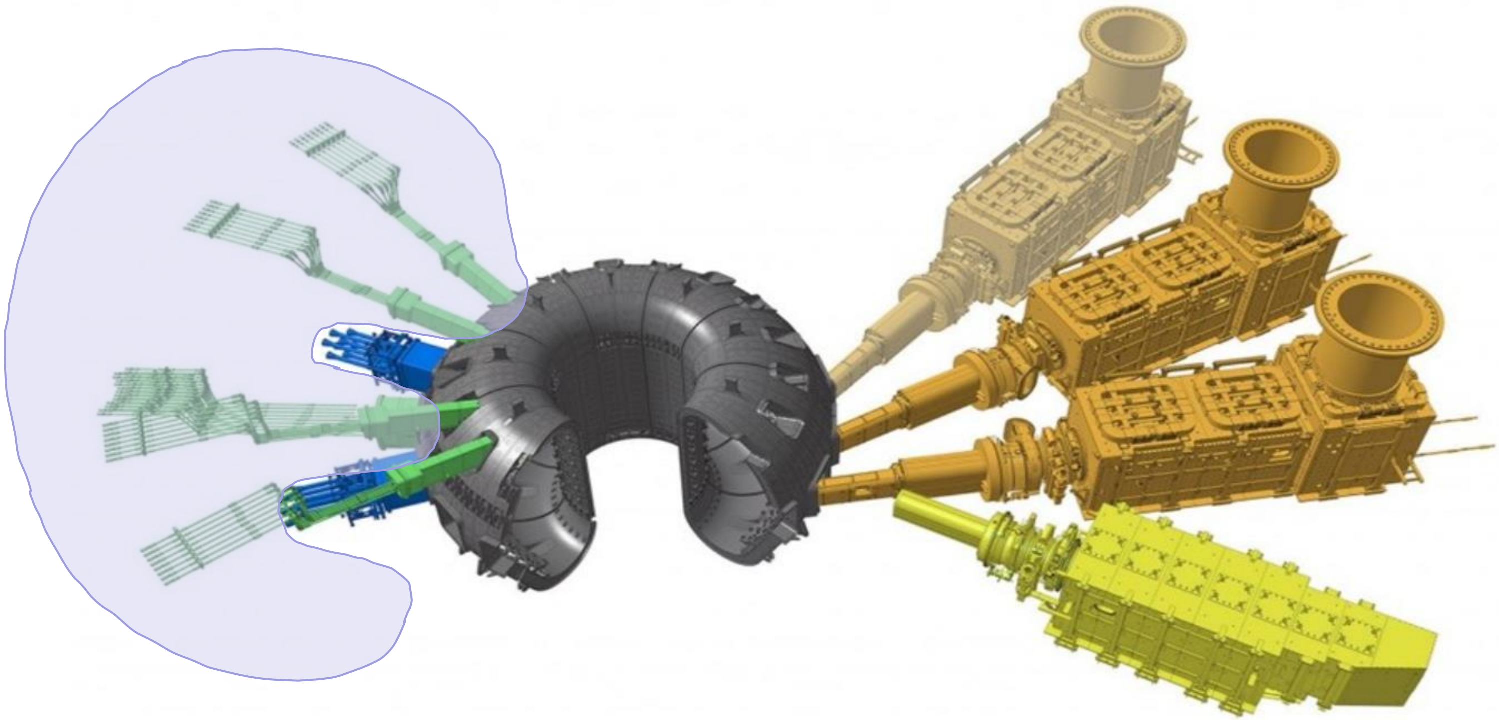
- Final design of the faraday screen has been produced by IO, but the final prototype for manufacturing demonstration is not yet completed, the final choice of the coating material for the PFC is not stabilized. HFT needs to be completed in less than 16 months, implying the manufacturing of the prototype and the completion of the different low Z coatings.

- The high-power test of the Antenna prototype is under preparation, after having designed the facility to perform the test, the ICRH team shall procure the different component and shall install the facility in the Building 55 (various call for tender ongoing)

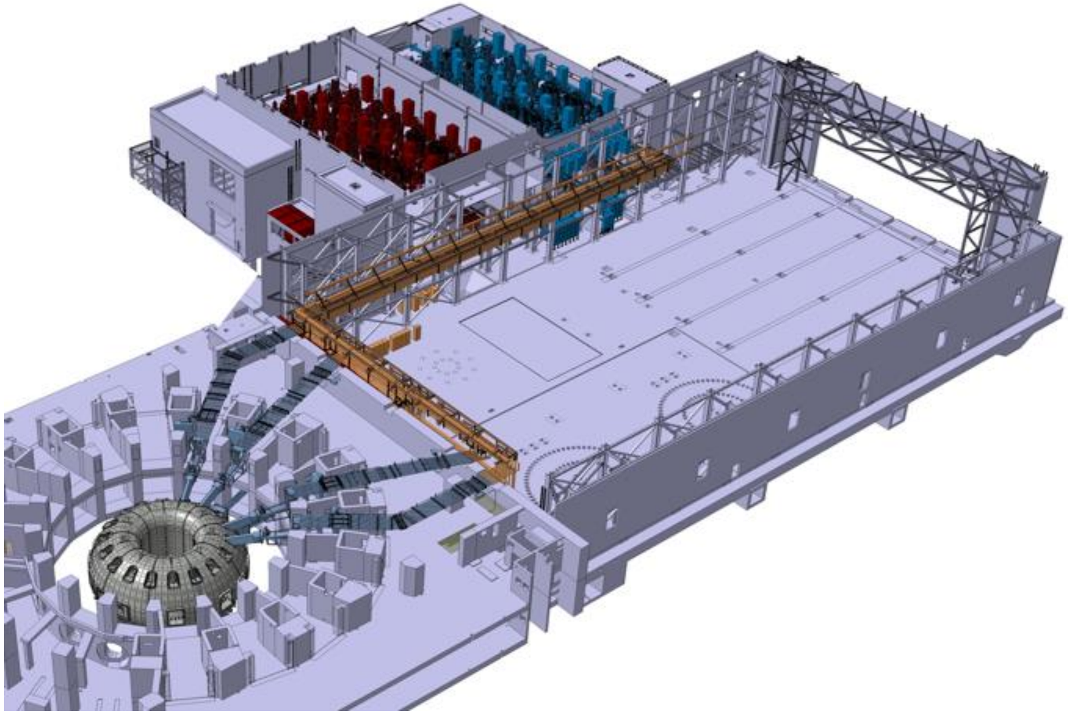
- Manufacturing of the Antenna prototype is progressing, while the biggest challenge is to ensure consistent manufacturing design choices with respect to the final design model used for the final analysis package (structural, fluid, electromagnetic and nuclear analyses). The manufacturing is underway and the validation of the different manufacturing technics (coating, selective laser melting and welding) will be completed by end 2026.

# ITER ECRH system

- ❑ Context
- ❑ ITER NBI
- ❑ ITER ICRH
- ✓ ITER ECRH
- ❑ Common generic concerns



# ECH system in the baseline 2024 (Phase 1 - SRO) +20MW

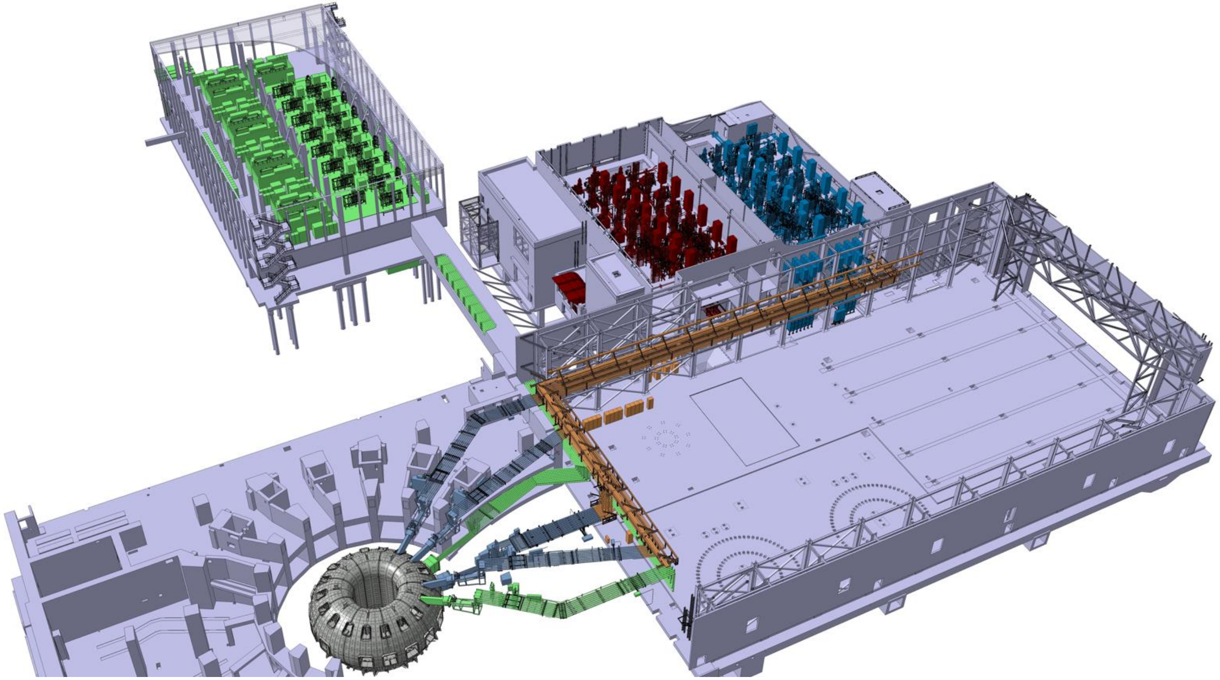


New hardware (**based on baseline**):
+ 24 1MW RF sources (Gyrotrons)
+ 12 High voltage Power supplies (HVPS)
+ 24 Transmission lines (TL)
+ Ancillaries, supports, etc.

Implications:
- Retrofitting of B15 North (layout, new penetrations with potential reinforcement, etc)
- New transmission line routing in B13 and associated supporting structures and platforms
- New cooling annex and cooling loop (CCWS-2F/H4)
- No changes in B11
- Logic for upgrade to keep B15 unchanged

***New baseline → Same technology as per in the current baseline***

# ECH system in the baseline 2024 (Phase 2 - DT-1) 60MW (+7MW compatibility)



New hardware:

+ 24 (8 opt) 1MW RF sources (Gyrotrons)
+ 12 (4 opt) High voltage Power supplies (HVPS)
+ 24 (8 opt) Transmission lines (TL)
+ Building A with Bridge
+ Ancillaries, supports, etc.

Implications:

- Construction of new building with new bridge
- New transmission line routing in addition to ones from SRO
- Uses the same cooling loop CCWS-2F/H4 (already designed for SRO)
- 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)

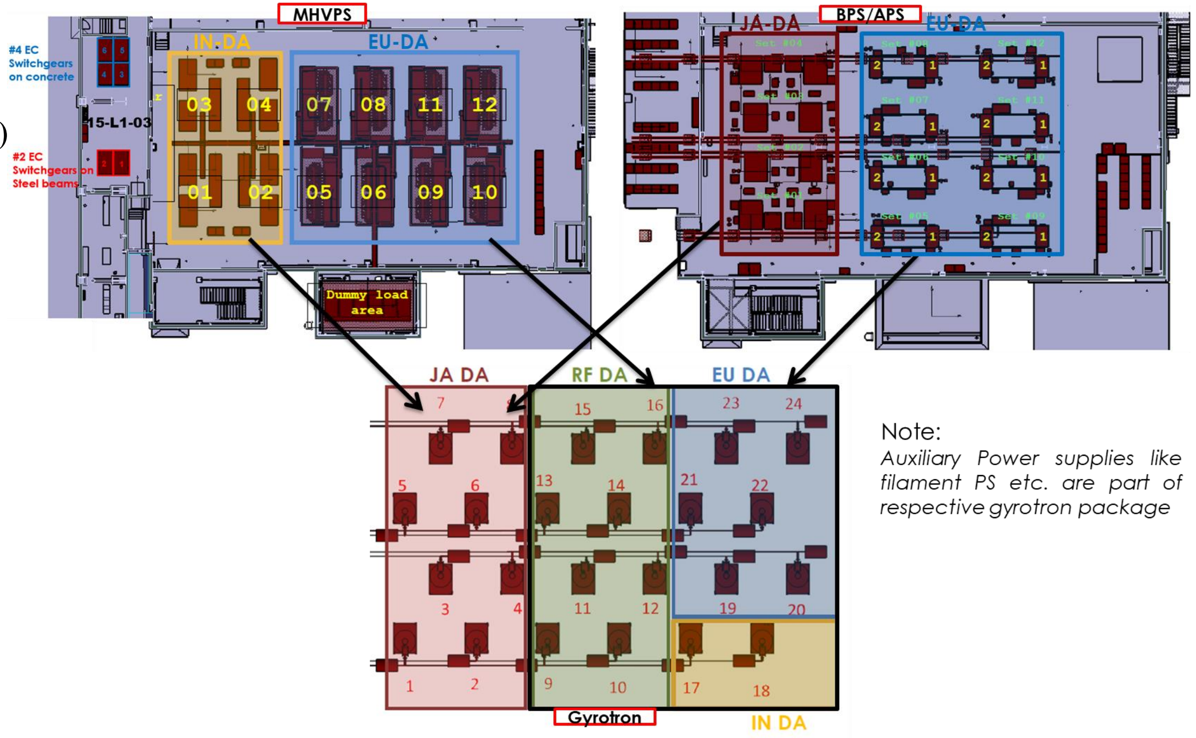
***New baseline → Same technology as per in the current baseline***

# High voltage power supplies (HVPS)/Gyrotrons

- **24 gyrotrons** (diode and triode)

Procurement:

- RFDA Gyrotrons (8 units) – GYCOM (Diode)
- JADA Gyrotrons ( 8 units) – QST/CANON (Triode)
- EUDA Gyrotrons (6 units) – THALES (Diode)
- INDA Gyrotrons (2 units) – TBD (Diode)



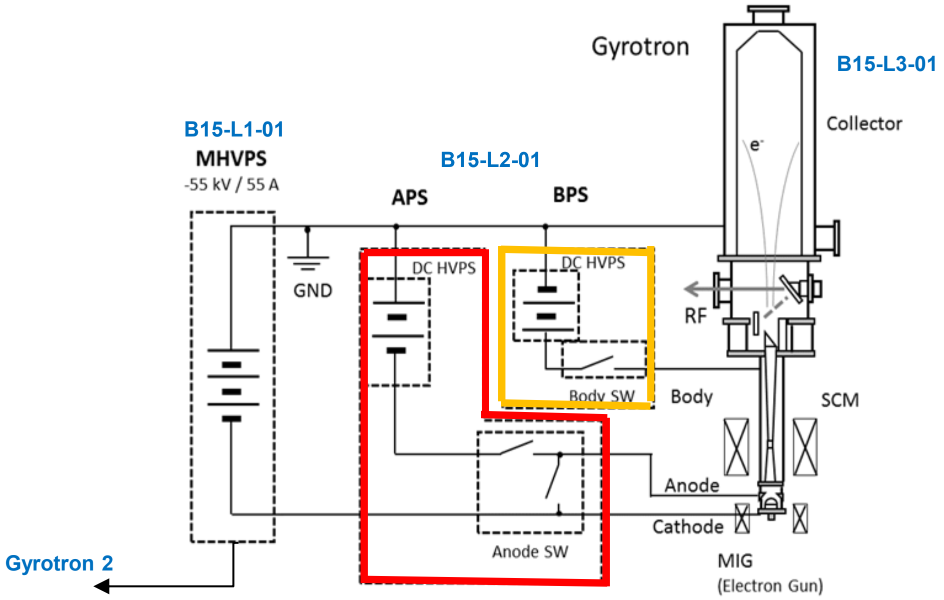

Note:
*Auxiliary Power supplies like filament PS etc. are part of respective gyrotron package*

- **12 Main High Voltage power supplies**

Two types of power supplies (same basic technology, different interfaces):
- HVPS from INDA (4 units) – Triode gyrotrons
- HVPS from EUDA (8 units) – Diode gyrotrons

# HVPS system - overview

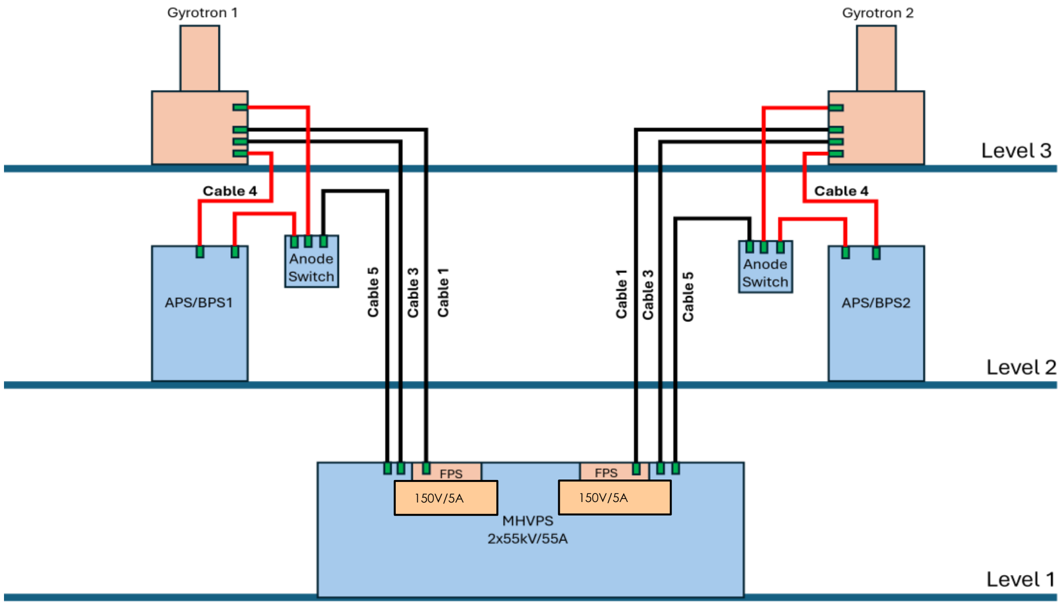
| Item | Description |
| --- | --- |
| **MHVPS** | Providing power to the gyrotron's Cathode (**-55 kV, 2x55 A**) |
| **BPS** | Providing power to the gyrotron's Body (**40 kV, 125 mA**) |
| **APS** | Providing power to the gyrotron's Anode (**10 kV, 600 mA** or **-20 kV, 750 mA**) |
| FPS | Providing power to the gyrotron's filament (up to 150 V and 30 A) |
| MHVPS and APS/BPS Dummy Loads | Testing the power supplies before connecting to the gyrotron |
| Feeder Lines | Connecting all the MHVPS with the long-pulse dummy load |
| Fences | Safety |
| HV triaxial/coaxial cables | Connecting power supplies and gyrotrons |




*DTG have no APS

# HVPS system – Main engineering challenges

- **High-Voltage environment**: all components have to be sized to operate in a high voltage environment (55 kV), which means proper clearance between them has to be respected.
- Relatively **long HV cables**: cable length is proportional to the parasitic/stray parameters. These elements are to be taken into account during the design process.
- **Testing setup**: testing high-voltage system often needs custom testing setups. The MHVPS requires a dedicated building annex to house its long-pulse dummy load.
- **Maintenance**: this aspects should be considered during the design. Faults will occur during the testing phase, and minimizing the time for troubleshooting/replacing the damaged parts is essential. Accessibility to all parts should be maximized.
- **Procurement of spare parts**: components should be chosen based on the market availability and should be easily replaceable by similar parts - if out of stock - to avoid long waiting time for procuring them.

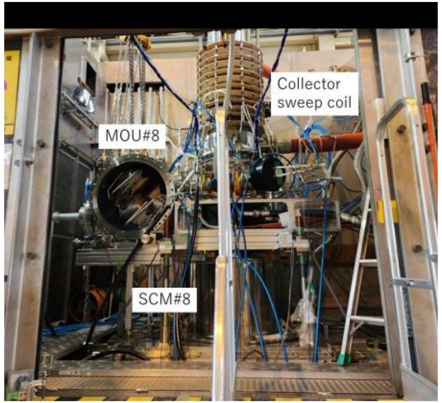


# Gyrotrons – RFDA and JADA

- 8 gyrotrons manufactured each (16 tubes)
- Factory acceptance testing completed for 7 units. Last FATs are on going
- Successful pulses from 1s to 300s and up to 1000s at 1MW (0,96MW at the output of the MOU) at the frequency around 169.9 GHz (within the specifications) and with an efficiency ~50% for long pulse operation:
  - between 52 and 57% (RFDA) ; 48.1-51.1 % (JADA)
- Reliability more than 90% on all tubes
- HE11 mode purity more than 95%: 96.8% (RFDA) and 95.2% (JADA)
- Modulation tested:
  - RFDA: at 100Hz, 500Hz and 1kHz (due to limitation of the HVPS, the maximum modulation is 1kHz) with more than 800 kW.
  - JADA: Modulation tested at 1kHz, 3kHz and 5kHz with more than 800 kW.
- 12 units delivered on site each (4 from RFDA and 8 from JADA)
- The installation started. First units finalized. Commissioning started on 1st unit from JADA. SP test on going. First HE11 beam on 02/06/2026 with JADA tube

***RF-DA Test Stand***

***JA-DA Test Stand***




***JADA gyrotrons at ITER site***

# Gyrotrons – EUDA/INDA

- Final design review for EUDA gyrotrons completed.
- Final design review for INDA gyrotrons almost completed.
- Framework contract with Thales for both ITER and DTT machine signed → The pre-series DTT gyrotron is being tested at the Swiss Plasma Center (SPC) and already demonstrated high power for 1000s.
- INDA will procure 2 EC RF sources from existing manufacturers and has developed a full test-bed. A gyrotron tube manufactured by Gycom has been extensively tested and demonstrated full power 1000s.

- The remaining work is focused on the integration of the mechanical components (support structures, cooling manifolds etc…) in the existing environment at ITER


EUDA (Falcon)

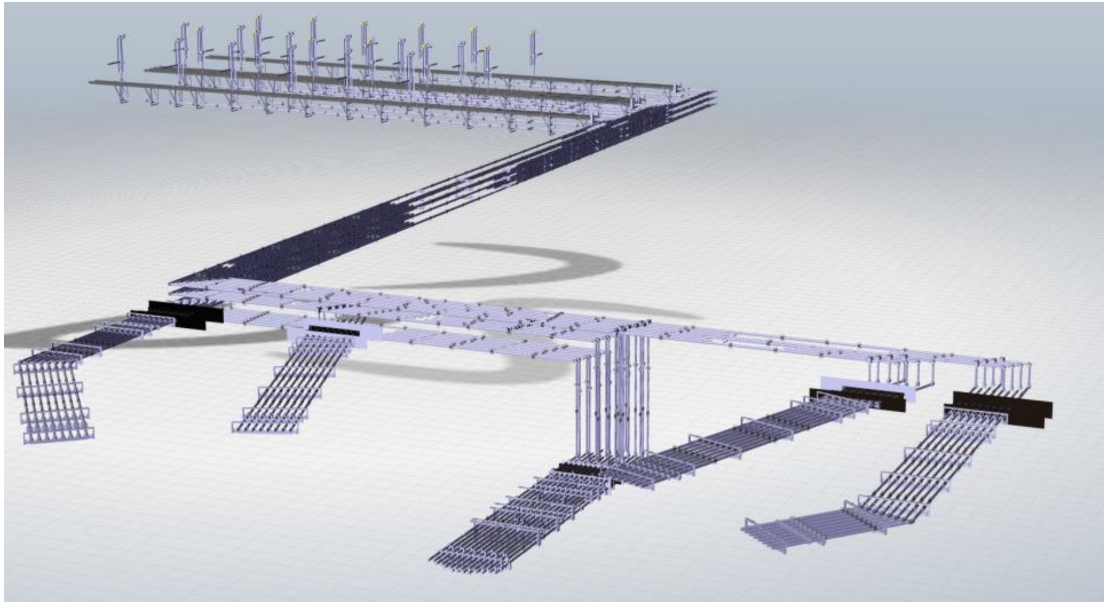
*Prototype being tested 1MW, 1000s*

INDA test fac.

*Prototype (GYCOM tube) fully tested 1MW /1000s / 50% on INDA test bed.*

# Transmission line

- Length ~160m
- **50 mm WGs, up to 3m long**
- **0.1mm/m**
- Power Handling 1.25MW
- Pulse length 3'600s (25% duty cycle)
- Power Transmission Efficiency ≥90%
- Design is finalized
- Manufacturing on-going for 1st phase



- Manufacturing of waveguides and non-PIC equipment finalized and manufacturing on going.
- Next step is installation on site: 3 different buildings

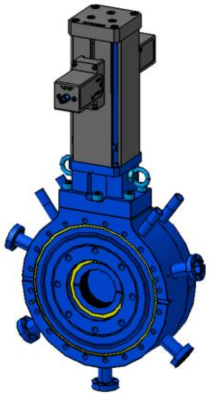
# Transmission line

**TL requirements:**

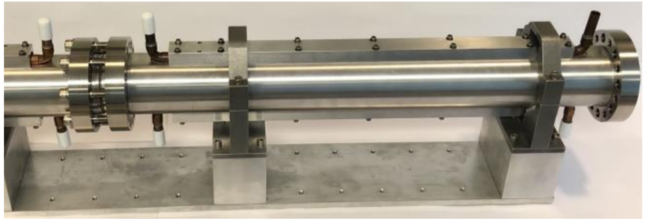
- **Power transmission efficiency better than 90% (in average)**
- **$HE_{11}$ mode purity better than 93% (in average)**

- Prototypes for all main components have been finalized via 2 different vendors
- Polarizer prototype (adaptation from GA design) have been manufactured, tests on going

*Shutter Valve*

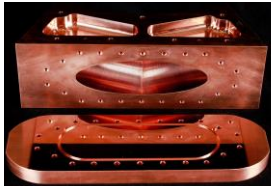


*Waveguide*

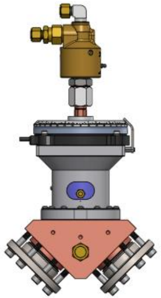


*90˚ Miter Bend*

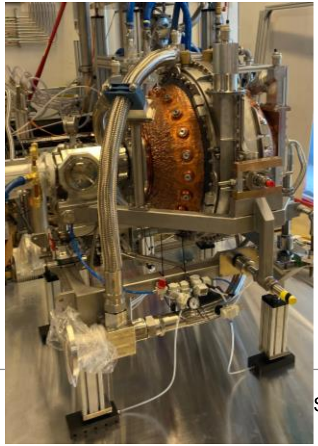
*140˚ Miter Bend*



*Polarizer*

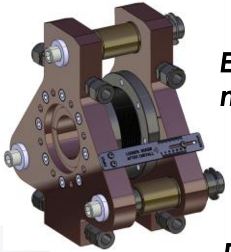


*Dummy loads*

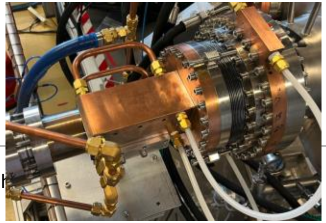


*Pump-out*

*Expansion Unit*



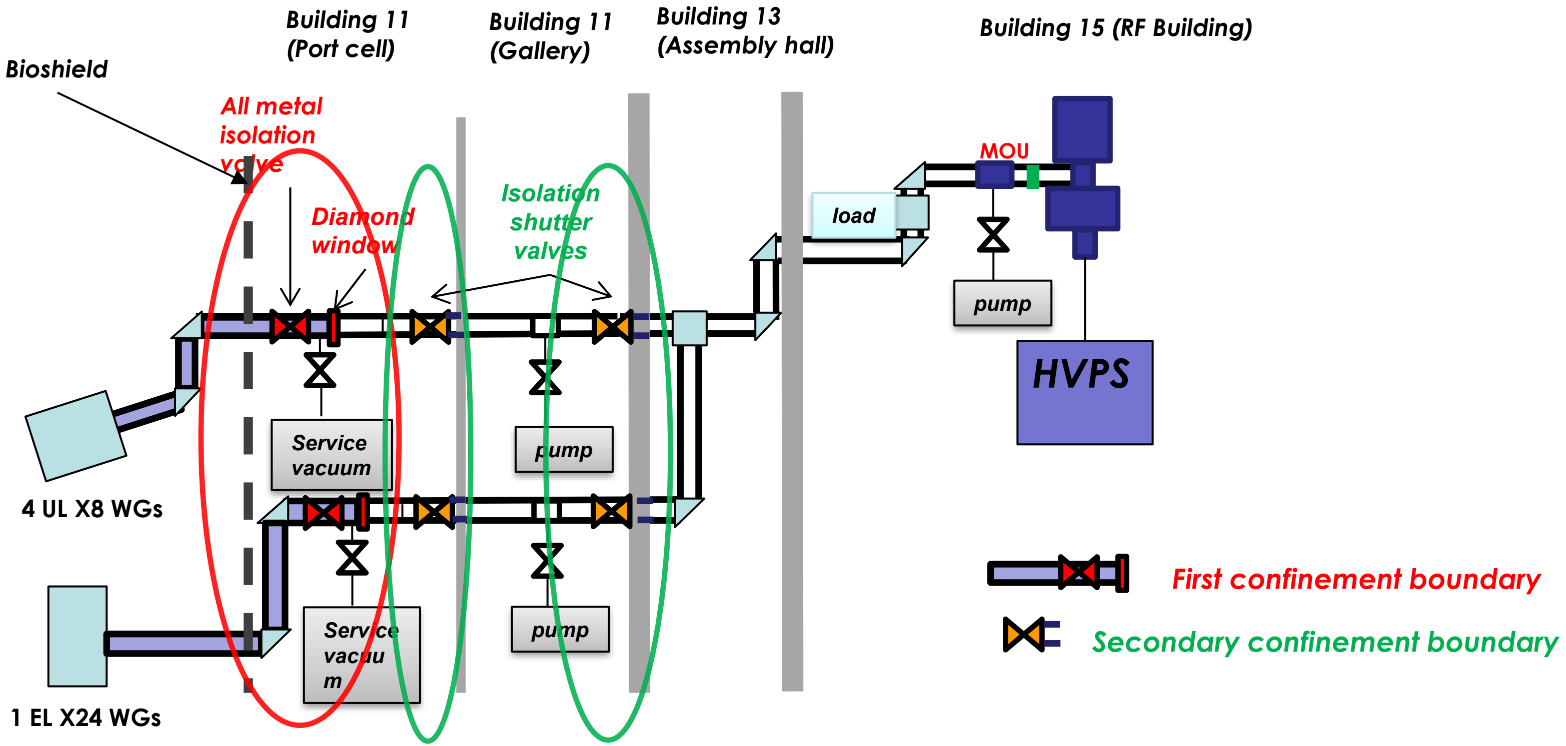
*MOU-TL adapter*



*Switch*

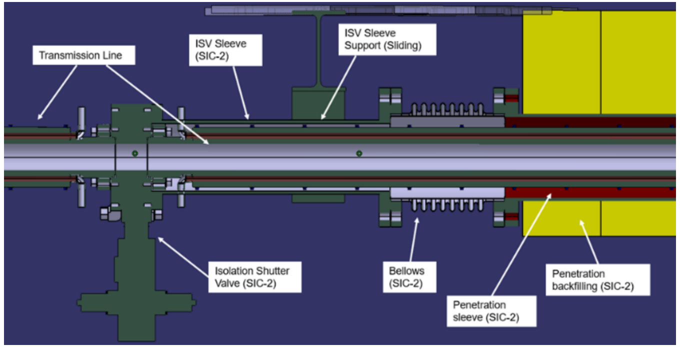
*DC Break*

# EC System Confinement



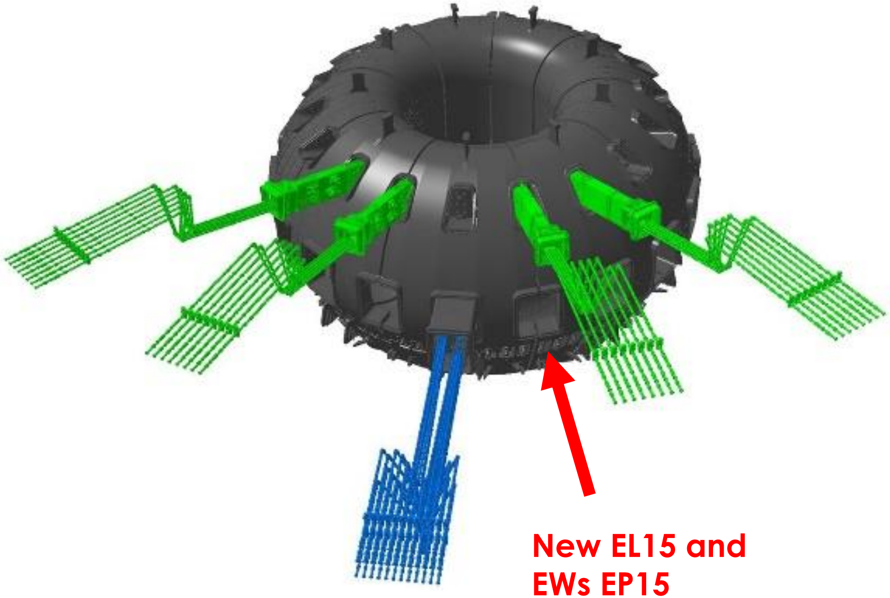
# Transmission line

Transmission line crosses the secondary confinement → PIC → SIC-2
Isolation valves, sleeves and bellows.
Isolation Shutter valve: Adaptation from COTS UHV VAT valve. Nuclear Qualification completed.




- Whole layout of the TL routing has been analyzed, using manufacturing tolerances as free parameter of a Montecarlo-based set of analysis codes. The outcome of the analysis has been used to set the main manufacturing parameters: waveguide's straightness; tilt and offset at components interfaces; manufacturing accuracies; mirrors planarity, offset and tilt; cooling parameters (to minimize the thermal stresses, expansion, mirror bowing, etc.).
- For example, the waveguide maximum bending radius has to be in the order of 1 to 2 km, to minimize mode conversion:
  - The previous waveguide manufacturing technology made use of extruded tubes that made practically impossible to achieve such level of straightness.
  - The new developed manufacturing technique start from solid rod, deep drilled, pull bored and finally internally corrugated and externally machined. This process proved capable to produce routinely waveguides with the required tolerance: flatness and perpendicularity of the mating surfaces 0.01 mm and 0.02 mm, respectively; straightness 0.10 mm/m and roundness 0.05 mm

# Global view and architecture for EC launchers




**Location: UP12, 13, 15, 16 and EP14, EP15**

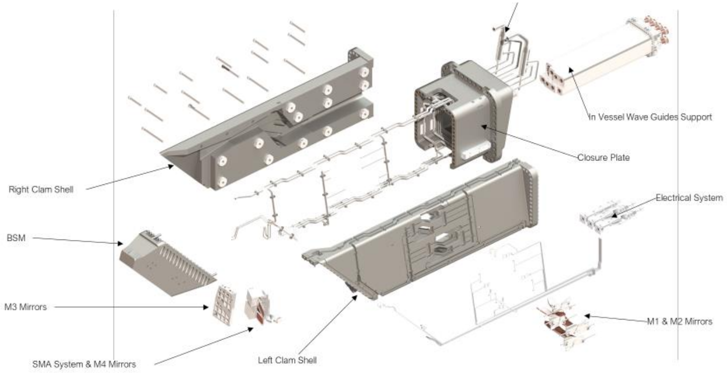
→ 56 + 24 (80) Ex-vessel Waveguides (last part of waveguides connecting to Launchers)

→ 4 Upper Launchers

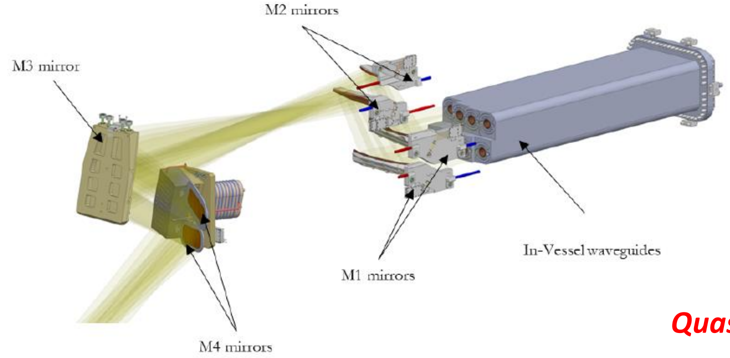
- Each with 8 entry beams split into 2 sets of 4 beams each with USM (upper steering mirror) and LSM (lower steering mirror)

→ 1+1 Equatorial Launchers, 24 entries organized in 3 groups

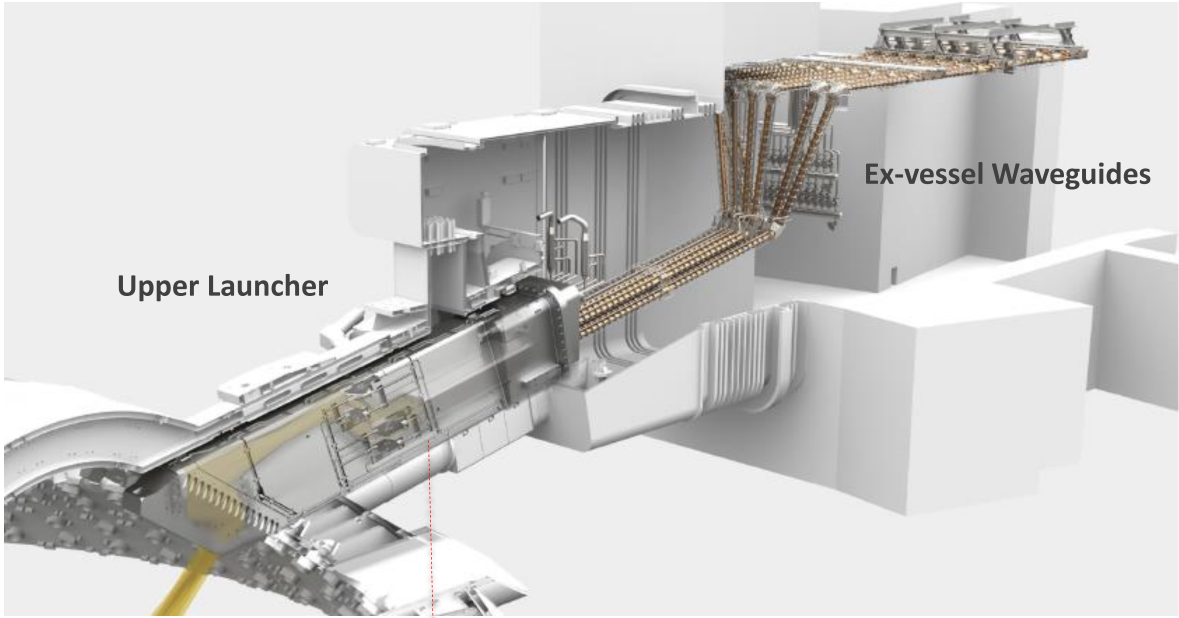
# Global view and architecture




Upper Launcher breakdown




UL quasi-optical system

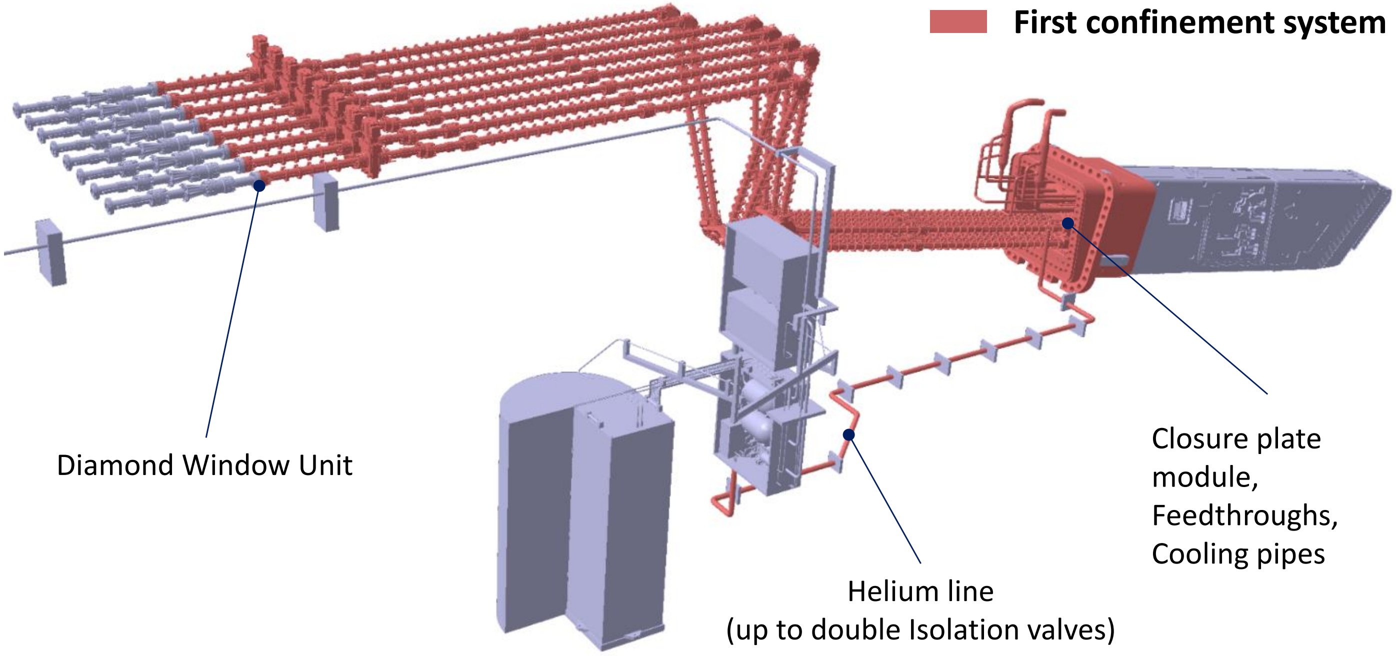



***Quasi-optical microwave transmission*** ← ***Guided microwave transmission***

# Main functions

**Defined requirements**

**Primary safety functions**
- The confinement of radioactive and hazardous inventory in the Vacuum Vessel;
- the confinement of water containing radionuclide;
- the shielding to limit neutron streaming and dose rate at the Port cell.

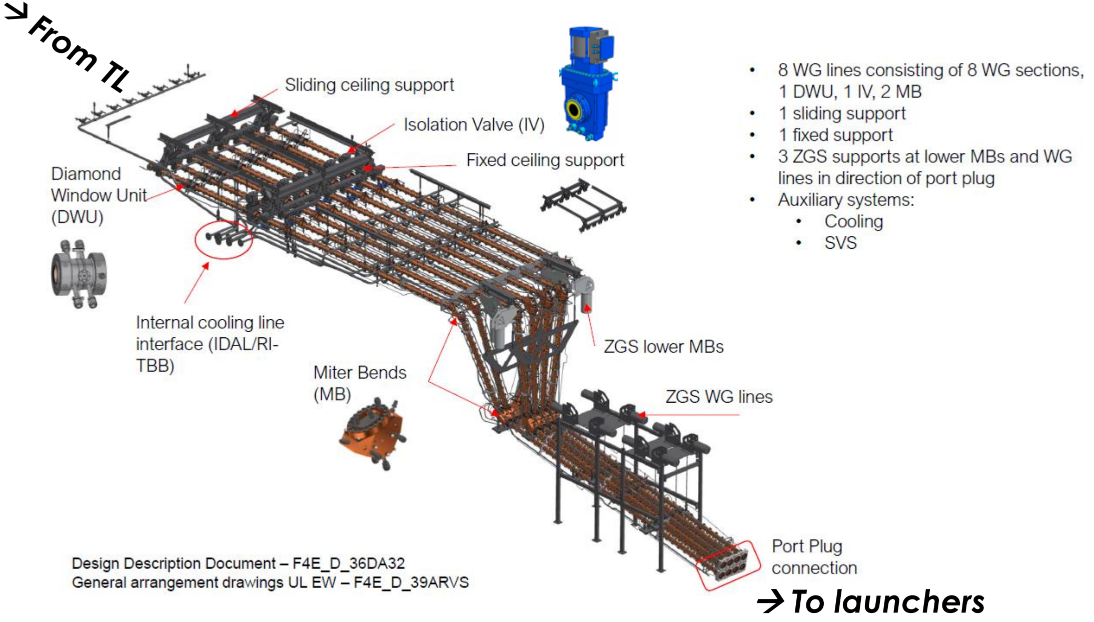



**EW primary function**
- Ensure a correct propagation of the microwave power reducing losses and HOM generation

**UL/EL primary function**
- contribute to plasma heating
- assist in the plasma breakdown & burnthrough
- **provide neoclassical tearing modes (NTM) control and current profile tailoring** (localized power deposition on specific range of plasma locations)

# Ex-vessel waveguides

- Design under EUDA almost finalized.
- EW forms the first confinement barrier:
  - Isolation Valve
  - Window (disk under manufacturing)
- Diamond disks are under manufacturing Integration of the disk is under study and prototyping.
- Isolation valve. Adaptation of COTS valve from VAT (RF inserts, double confinement). Design has been developed. Optimizations potentially required to increase the thermal transfer to RF insert. Prototype not yet launched (work on going)
- Detail thermal structural analysis are on going

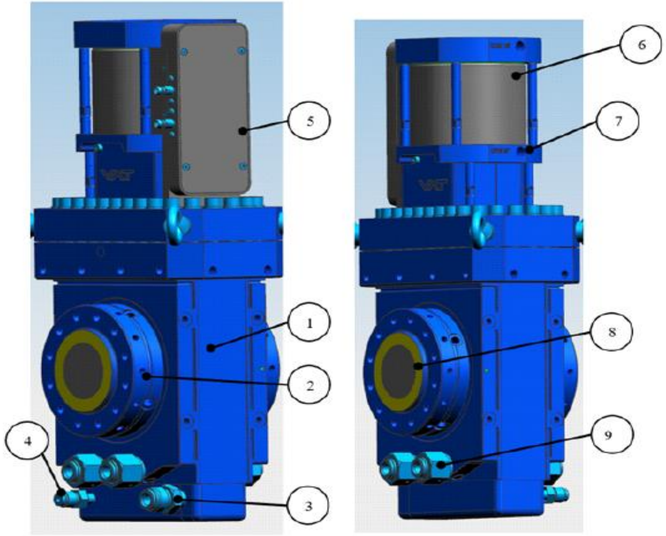



<u>Main characteristics:</u>

- 50 mm
- CuCrZr (mechanical properties)
- Double confinement boundaries (double seals, monitoring)

# Ex-vessel waveguides design

## Isolation valve




1 Double shelled Body
2 ITER Flange
3 Pumping port
4 Interspace pumping port
5 Position indicator

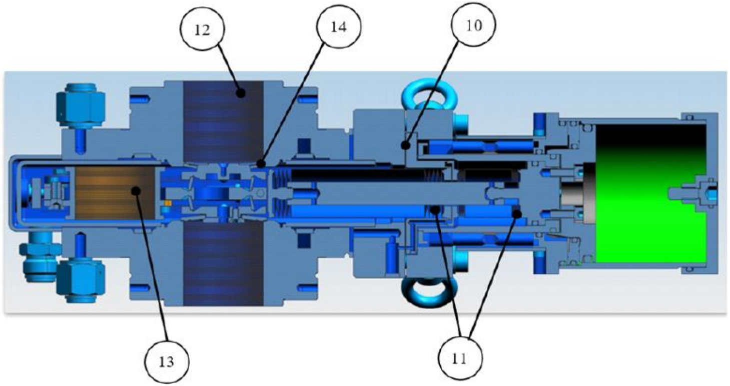
6 Actuator
7 Compressed air connection
8 Sealing surface
9 Water cooling connection

Figure 98: Isolation Valve Components

To actuate the valve there is a double acting pneumatic actuator (6) on top of the valve.

In order to achieve the intermediate vacuum between the two housing shells, there is a VCR ¼” vacuum connection (7).

To keep the heat loss as low as possible, this valve has a corrugated waveguide (13) that bridges the distance from flange (2) to flange in the open state. Apart from the waveguide, both flanges (12) are also carried out with the corrugation. Flanges on both sides, designed for the ITER double metal seals.




Cross section - Valve in closed position

10 Double bonnet seal
11 Double bellows

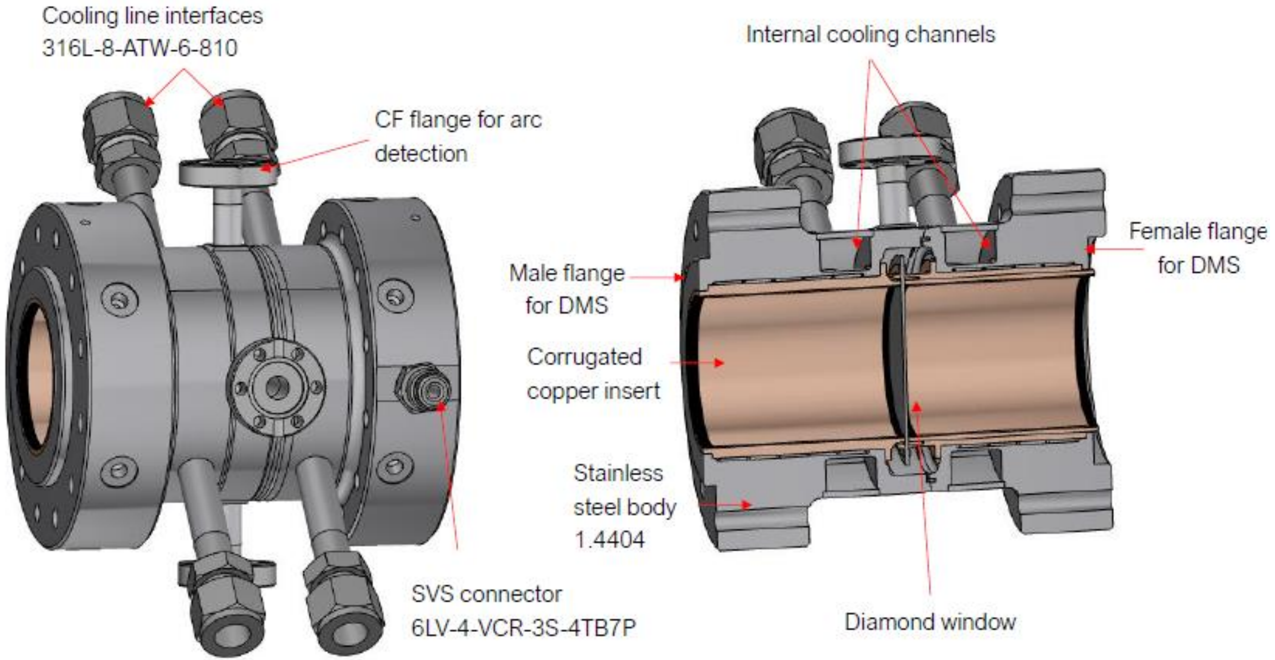
12 & 13 Waveguide
14 VATRING

Figure 99: Isolation Valve Closed Position

To connect the water cooling with the valve there are two Swagelok VCR ½” connector (9) implemented in the valve

# Ex-vessel waveguides design

Diamond Window Unit (DWU) – First confinement separation between Tokamak and Gyrotron vacuum

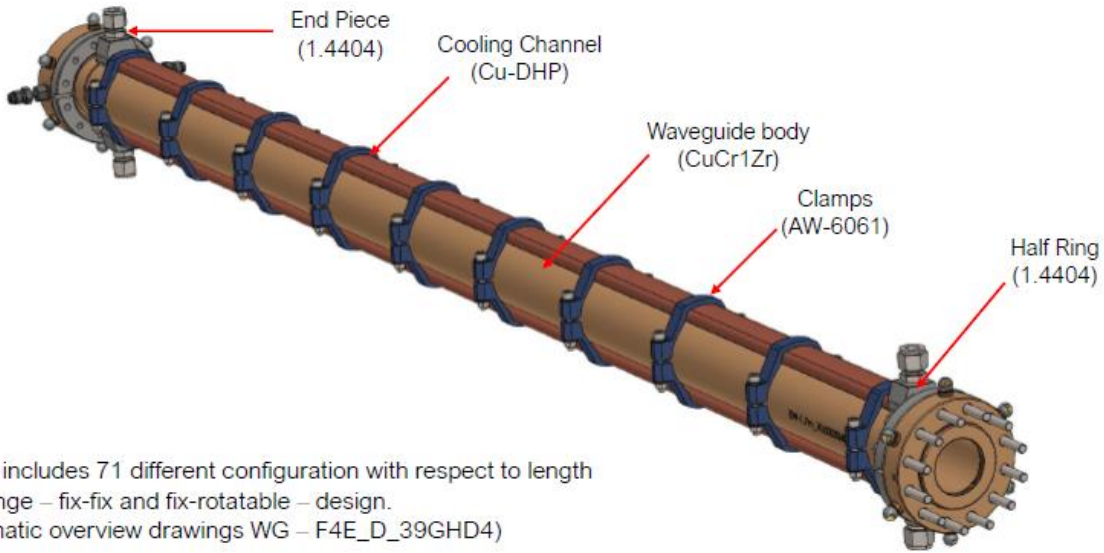



Schematic Overview Drawing DWU – F4E_D_39GHD4

# Ex-vessel waveguides design

RF COMPONENTS DESIGN

Ex-Vessel Waveguide (EW) – Standard assembly – Transmission of RF power from TL interface to PP

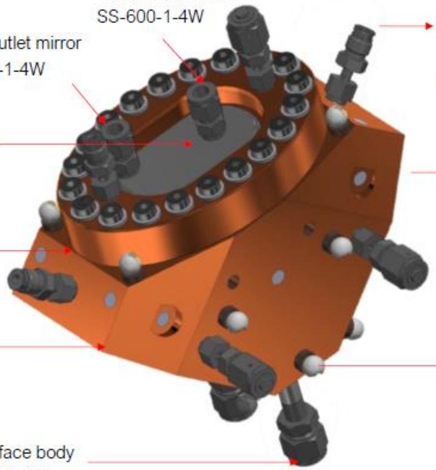


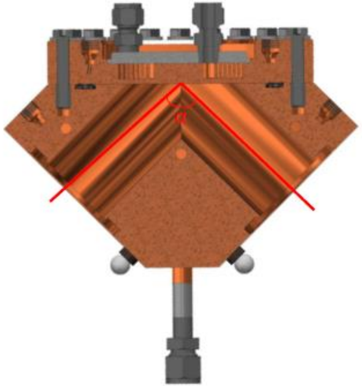

Design includes 71 different configuration with respect to length and flange – fix-fix and fix-rotatable – design.
(Schematic overview drawings WG – F4E_D_39GHD4)

Rotatable flanges only at connections to Miter Bends to simplify assembly.

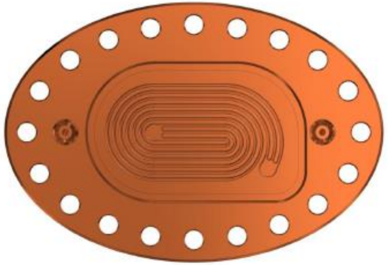
# Ex-vessel waveguides design

Miter Bends – Beam redirection



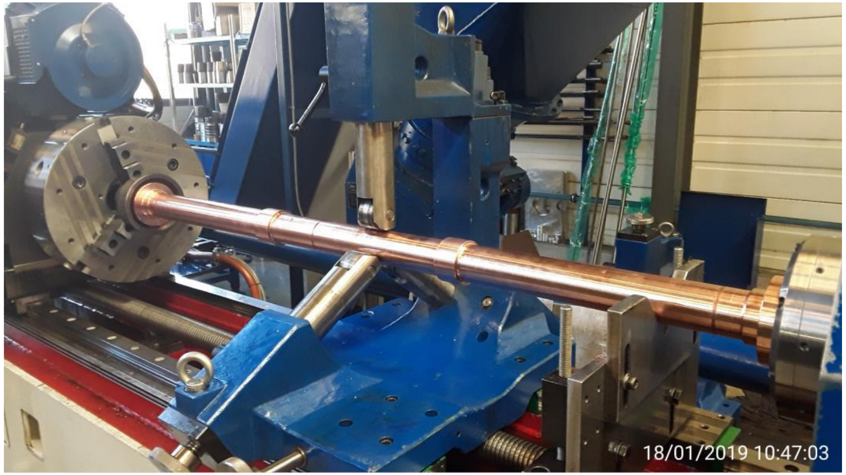



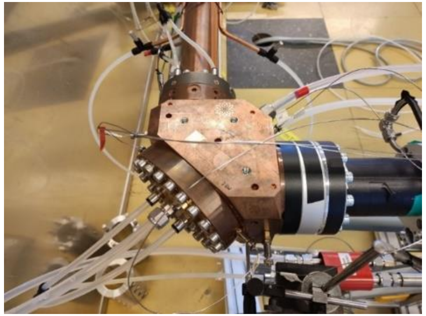
Schematic Overview Drawing MB – F4E_D_39GHD4



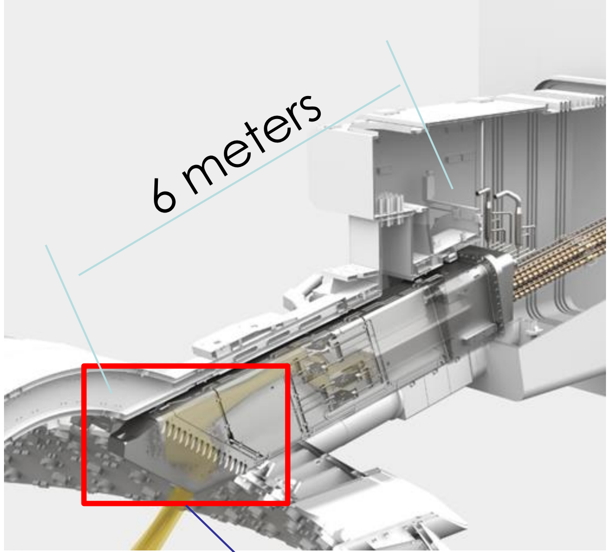
# Ex-vessel waveguides prototypes

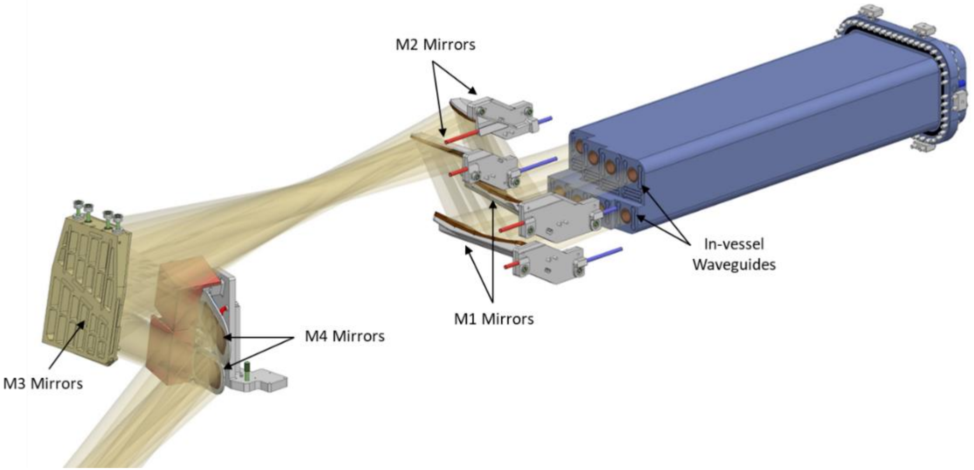
- Some test articles have been done (e.g. diamond window, miter bend and CuCrZr waveguides)
- No showstoppers found with manufacturing of CuCrZr pieces
- Some qualification plans have been prepared and approved.
- Some qualification activities already started on the DWU and other components



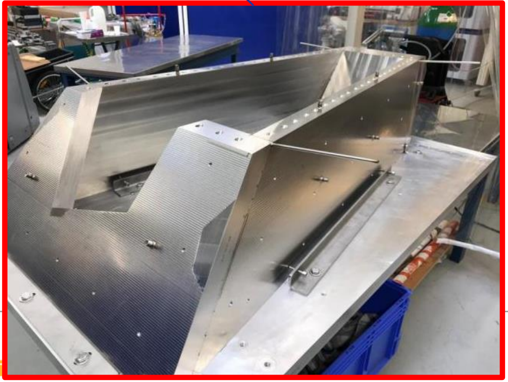



# Upper Launcher




**Design almost finalized with EUDA (IDAL consortium).**



*Full scale BSM prototype*

# Upper Launcher Design

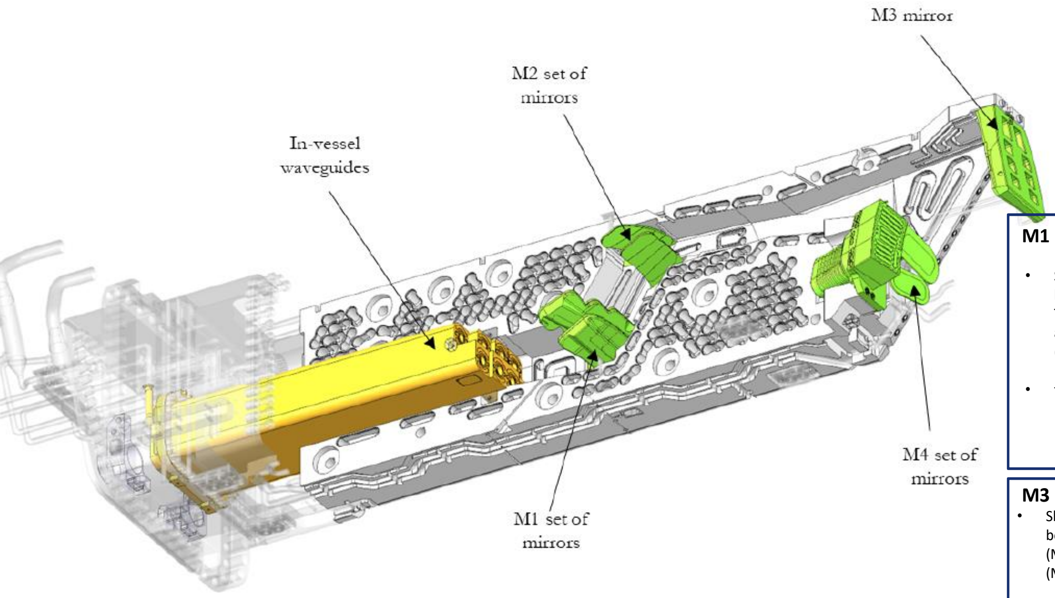
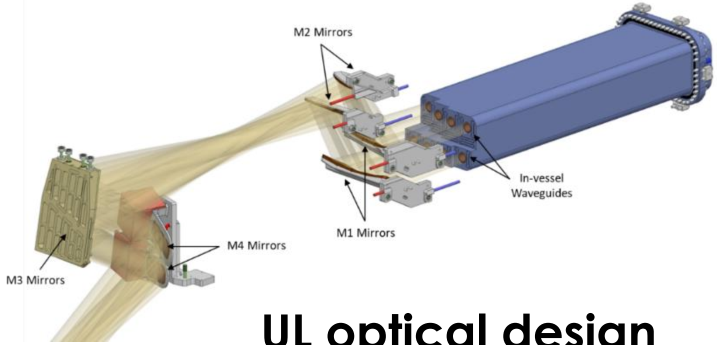


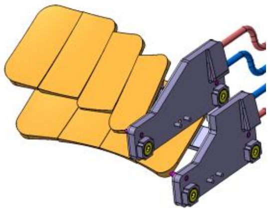

Figure 3-10. UL Optical System mirror sets detail




## UL optical design

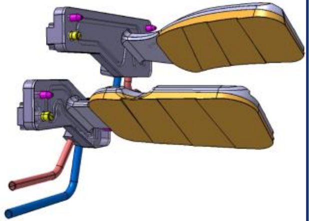
**M1**

- Submirror per beam line TL5-8 (UM1) and TL1-4 (LM1).
- f=602.26mm Ellipsoidal



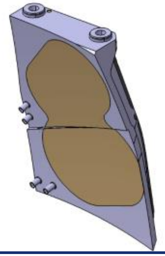
**M2**

- Submirror per beam line TL5-8 (UM2) and TL1-4 (LM2).
- f= ∞



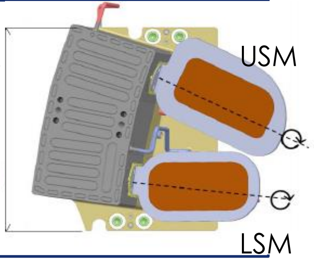
**M3**

- Shared mirror per beamline row: TL5-8 (M3 lower) and TL1-4 (M3 upper)
- Shared mirror support
- f=1280.48mm for TL1-4 (M3 upper) - Ellipsoidal
- f=1235.70mm for TL5-8 (M3 lower) - Ellipsoidal



**M4**

- Two independent steering assemblies per beamline row TL1-4 (USM) and TL5-8 (LSM)
- Rotating mirror system with Δγ of 13 deg.
- f= ∞



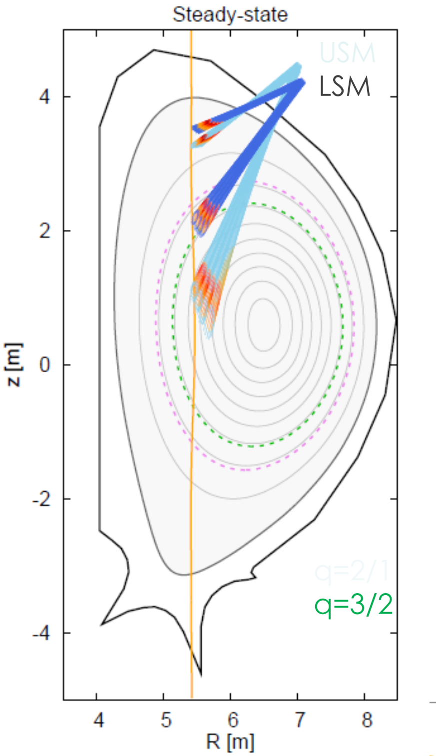
# Main functions

*Each Upper Launcher will be optimized for NTM control over the range of 0.6≤ρT ≤0.88 and assist in current profile tailoring over the range of 0.4≤ρT≤0.6*

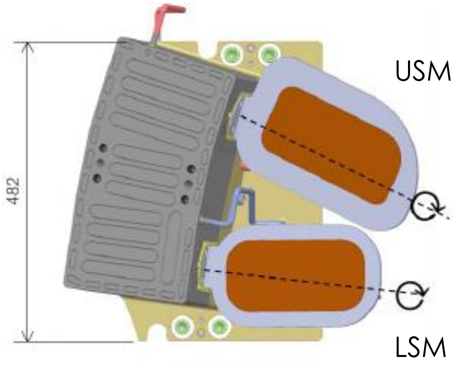
Plasma locations are referred in terms of ρ *(typically $\rho_T$ or ρT)*

ρ = 0 is the magnetic axis

ρ = 1 is the last closed magnetic surface




## Steering function critical for NTM control



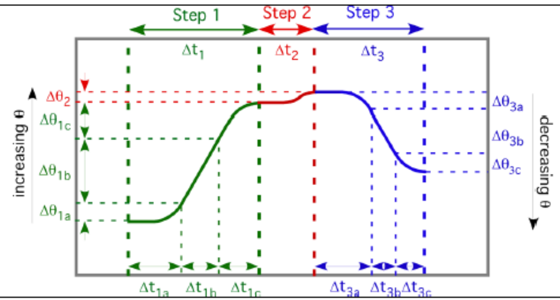



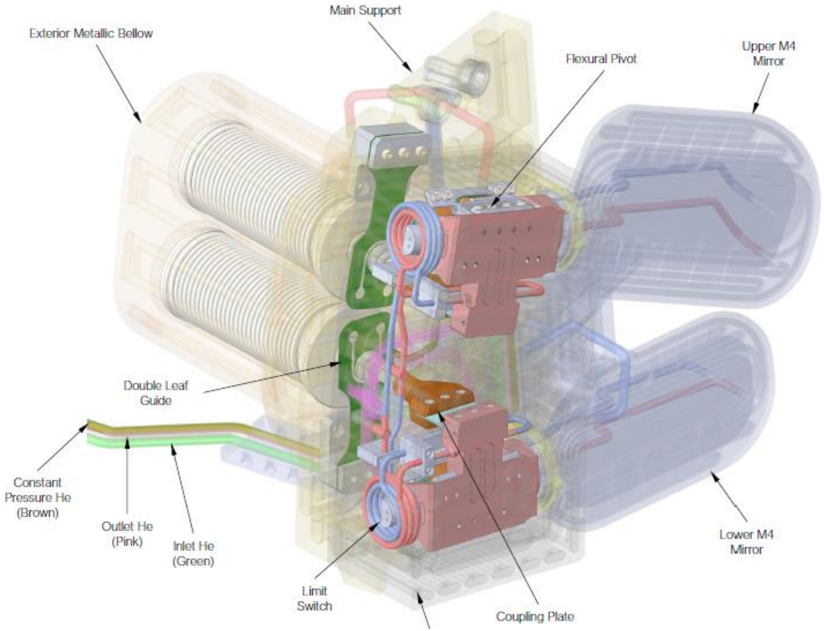

Figure 1: A hypothetical time trace of the SMA rotation (θ), which characterizes the three types of movements used to define the rotation requirements of the SMA.

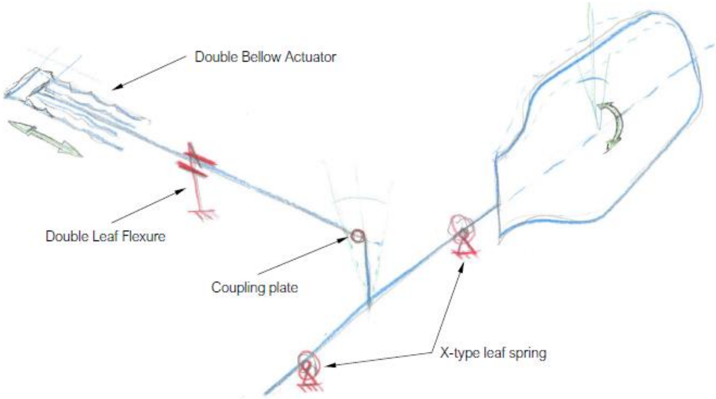
Rotation speed: 5.2°/s

Angular rotation accuracy: 0.025°

Rotation range: 13 °

# M4 Steering Mechanism

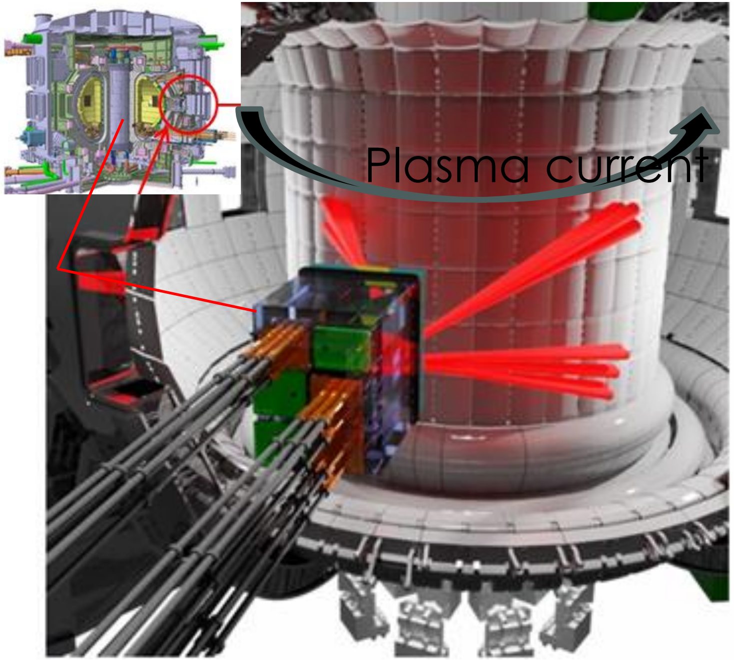


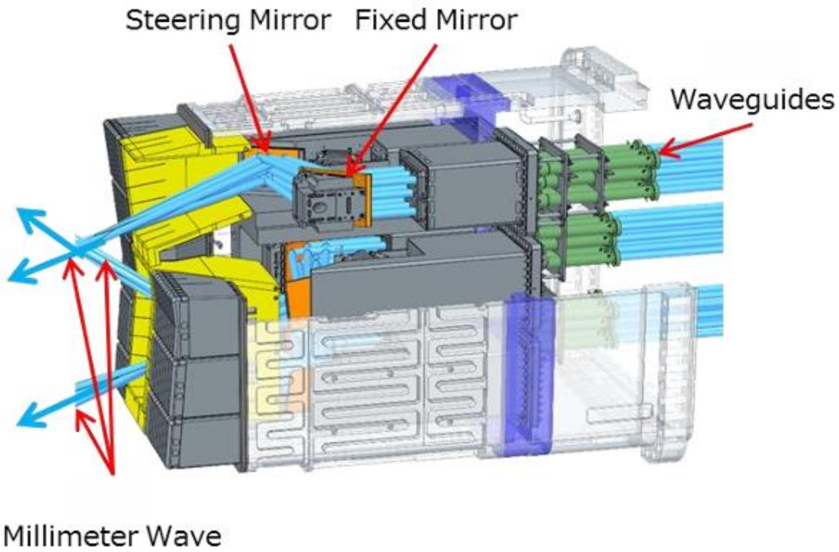

**Frictionless pneumatic He actuated mechanism**
**Double bellow actuator + flexure plates/pivots**

# Main architecture of Equatorial Launcher

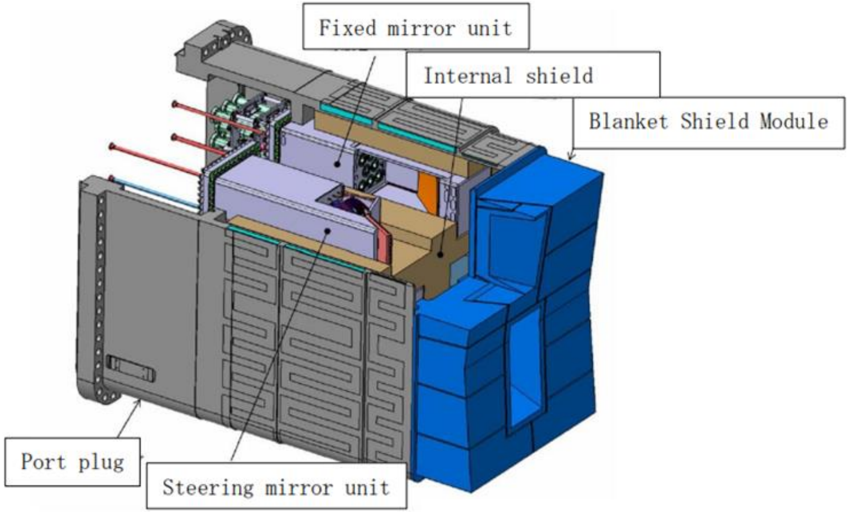
24 MW at gyrotron side → 20 MW at plasma in **3 bunches of 8 beams**



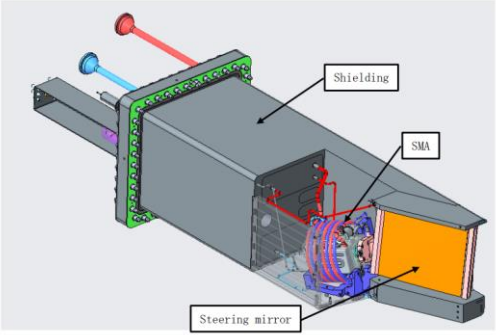

- 8 beams in Counter-current → Used during plasma initiation
- 16 beams in Co-current



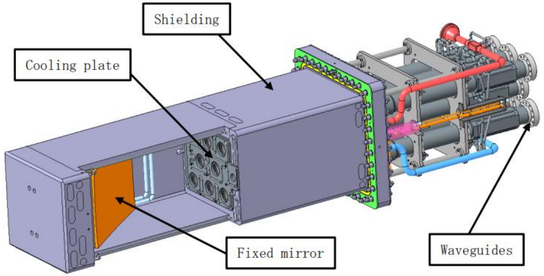
# Equatorial Launcher




The design finalization is currently at JADA.
Final design review almost finalized.




3X 8 waveguides



# Main challenges

Ex-vessel waveguides system: connected to points with different relative movements: VV and building → needs to be flexible enough to absorb those relative movements for all events, and at the same time minimize deformations during operation to minimize the losses and HOM generations, which is a threat for the performance and for the integrity of the launcher

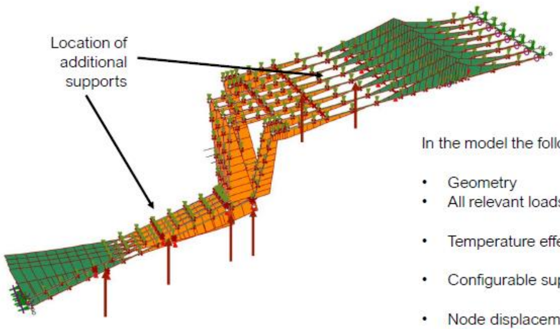
*implemented system flexible enough including ZGS (zero gravity supports)*

*Implemented enough intermediate supports to reduce deflection*

**Supporting strategy:**

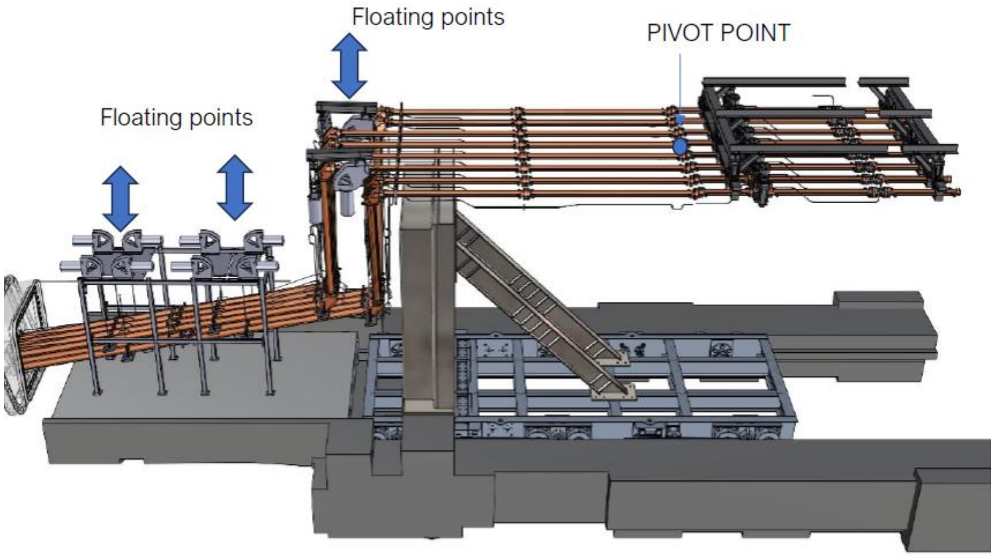
For the supporting strategy, a parametric model has been built that will allow to check multiple scenarios in a fast frame.

The model is similar to the parametric tool used for the HOM assessment in the UL



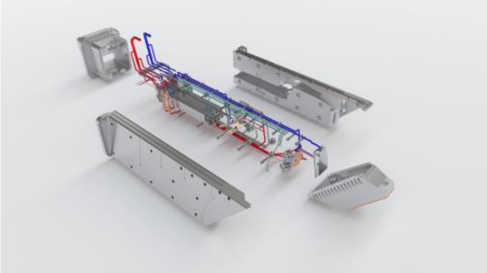

In the model the following aspects are modelled:

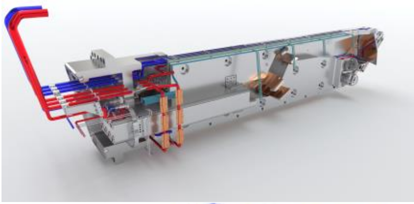
- Geometry
- All relevant loads & boundary conditions
- Temperature effects
- Configurable supports
- Node displacement to simulate VV movement

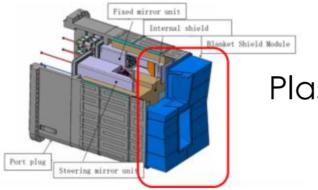


# Main challenges

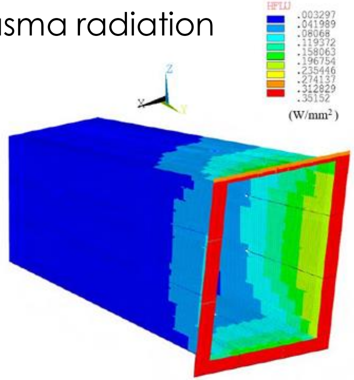
- Launchers inserted in the VV Port → very harsh environment: neutronic loads, plasma radiation loads, EM loads. → *very robust design*
- Launchers to be designed for the whole ITER life (RHC3) → *very robust and reliable design*
- Very high RF loads → 8MW/Upper Launcher in reduced volume → RF power density very high (peak ohmic losses above 1MW/m2 and stray load peaks of several 100s KW/m2 → *very well cooled design (mirrors and plug)*
- Launchers → quasi-optical system → minimize thermal deformations → thermal management is critical to ensure thermal stability (deformations induce higher losses which induce higher deformation) → *very well cooled design (mirrors and plug)*
- Nuclear shielding function: in order to reduce both shutdown dose rate in the interspace and port cell for human access and minimize the nuclear heating on the superconductive magnets
  - → *Combination of massive steel and water*
  - → *Dogleg configuration*








Plasma radiation



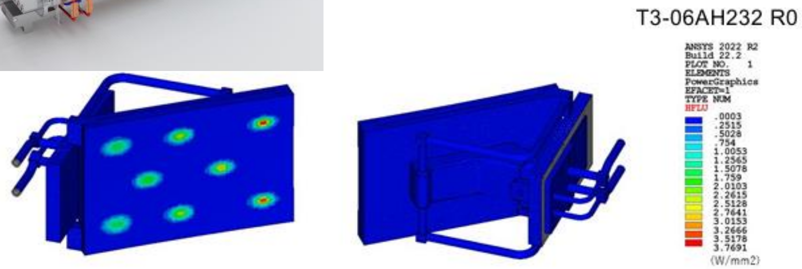
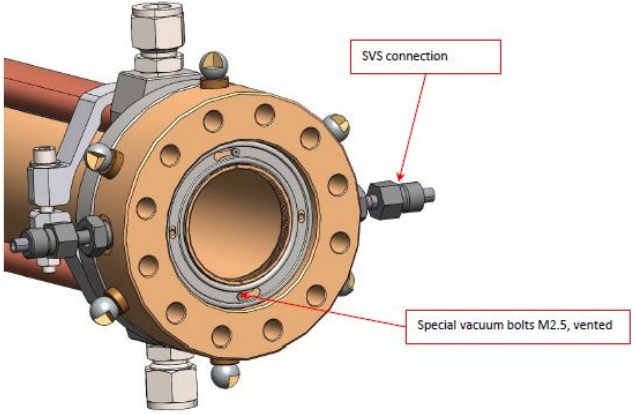



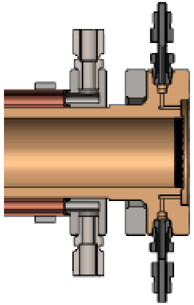

Figure 6.15 – Heat Loads from Direct RF and Stray RF Applied to Fixed Mirror

**0.35 MW/m2**

# Main challenges

- Cooling
- Ultra-high vacuum environment (main vacuum of the machine) → *selection on materials, minimize outgassing, minimize trap volumes…*
- Steering mechanism reliable enough in the closest area to the plasma → *SMA frictionless mechanism*
- UL/EL closure plate and Ex-vessel waveguides are part of first confinement barrier → safety classification SIC-1:
  - → Strict Nuclear qualification via tests
  - → Confinement monitoring via implementation of double barriers – i.e: double helicoflex seal with interspace monitoring by SVS



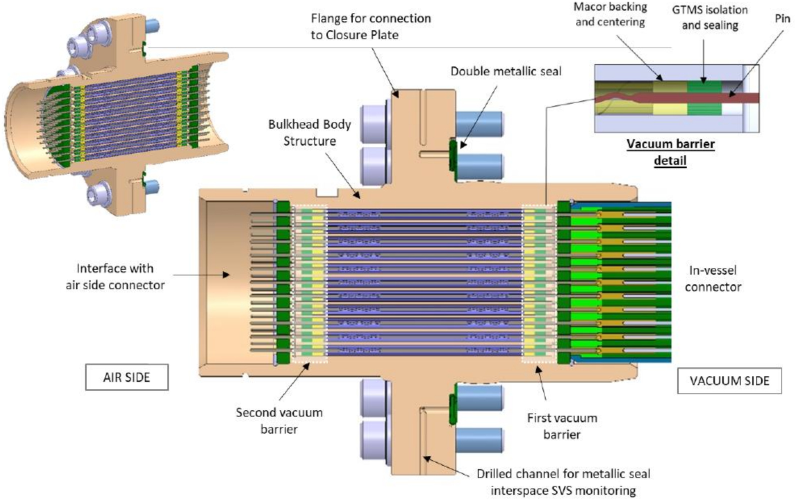
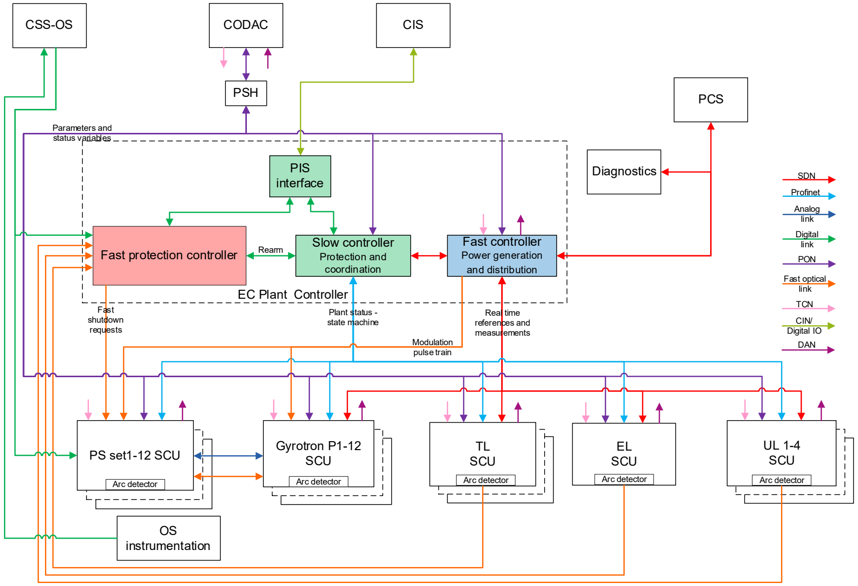



Figure 6-66 Cross section of Main EFT bulkhead, showing the vacuum barriers GSTMS concept

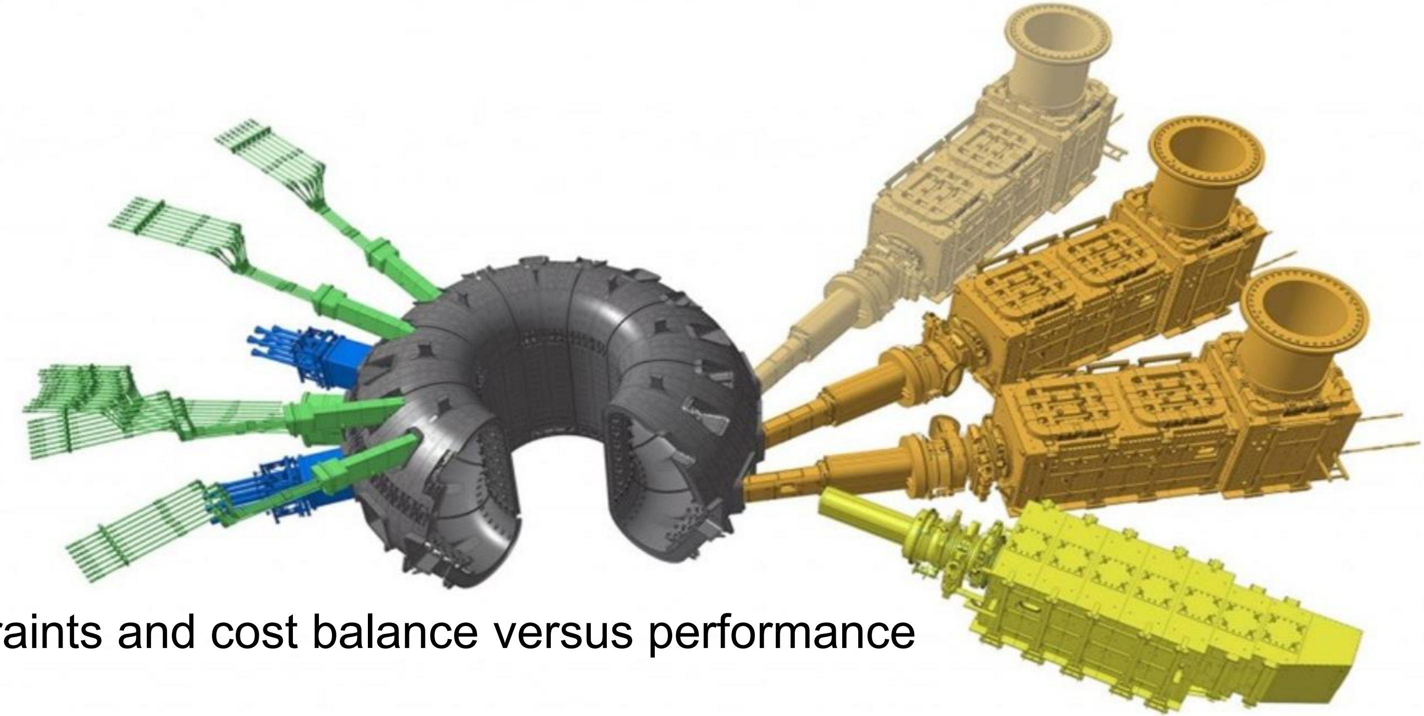
# Control System

- The EC control system is made of two different layers:
- the EC Plant Controller (ECPC) → interface with CODAC, PCS, CIS and supervision of SCU
- and the Subsystem Control Units (SCU)→ implements the control, safety (via direct interface with central system) and protection functions
- Design finalized after all the EC system subcomponents completed design
- Development in stages:
  Stage 1: simplified system for commissioning of HVPS and gyrotrons (mimic all functions). System delivered and tested
  Stage 2: integration of all system
- Generally, the SCUs are delivered with the different subsystems and a large work of integration is envisaged.



# Common concerns

- ❑ Context
- ❑ ITER NBI
- ❑ ITER ICRH
- ❑ ITER ECRH
- ✓ Common generic concerns



✓ Integration constraints and cost balance versus performance

✓ Assembly activities & Co-activities between assembly and commissioning

✓ Schedule constraints and how to mitigate delays

# ITER Organization

## On the Way to Fusion Energy

Thank you for your attention!

Questions?