EUROfusion

IAEA Technical Meeting on Tritium Breeding Blankets and Associated Neutronics

2-5 September 2025, Vienna

Progress in the concept development of the VNS - a beam-driven tokamak for component testing

Ivo Moscato and the VNS design team

EUROfusion Programme Management Unit – DEMO Central Team

Acknowledge the contribution of DCT and WPDES contributors and the support of STAC

This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.

Rationale for a Volumetric Neutron Source

Need a Risk Mitigation Strategy

Provide credible and attractive plan to deliver fusion

The new strategy needs to consider the following

1. **Lack of external Tritium supplies** to provide sufficient Tritium startup and operational inventory required for any major fusion facility beyond ITER
2. **Large uncertainties in Breeding Blanket achieving Tritium Self-Sufficiency**
3. **Huge uncertainties in RAMI, and blanket failure modes and failure rates.**
4. **Complex multiple/synergistic effects need to be studied under representative nuclear conditions in sufficiently large volumes**
5. **Need to establish a qualification database** (presently almost inexistent)

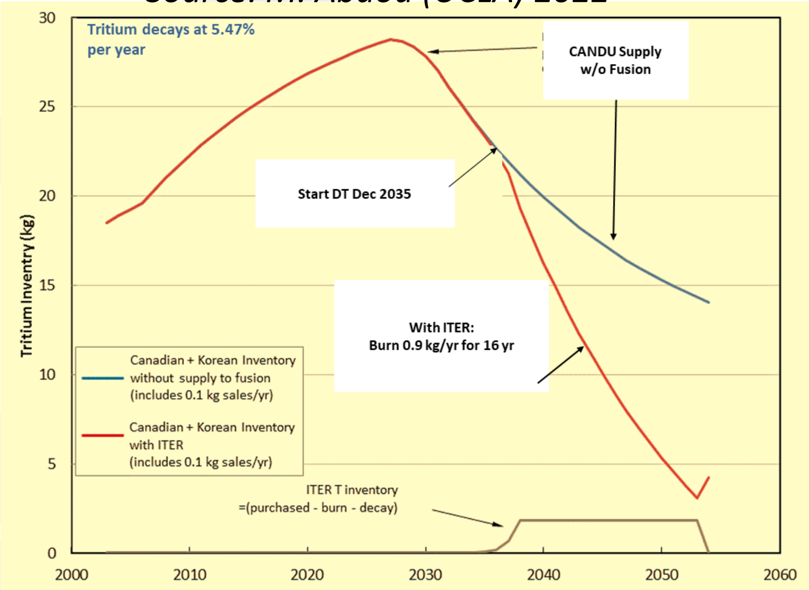
Issues 2, 3, and 4 can be adequately addressed only in the fusion nuclear environment of a DT plasma-based facility

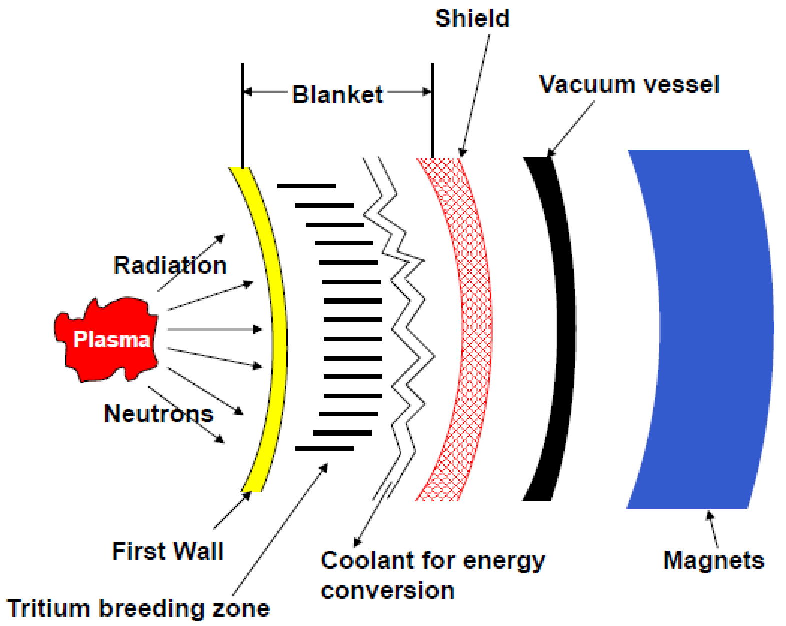
(1), (2) mandate that the DT facility must be a small fusion power (< 50 MW)

EUROfusion launched in 2023 a feasibility study of a VNS.
This was successfully completed in Dec. 2024

G. Federici - ***Testing Needs for the Development and Qualification of a Breeding Blanket for DEMO***, Nucl. **Fusion 63 (2023) 125002.**

Source: M. Abdou (UCLA) 2022

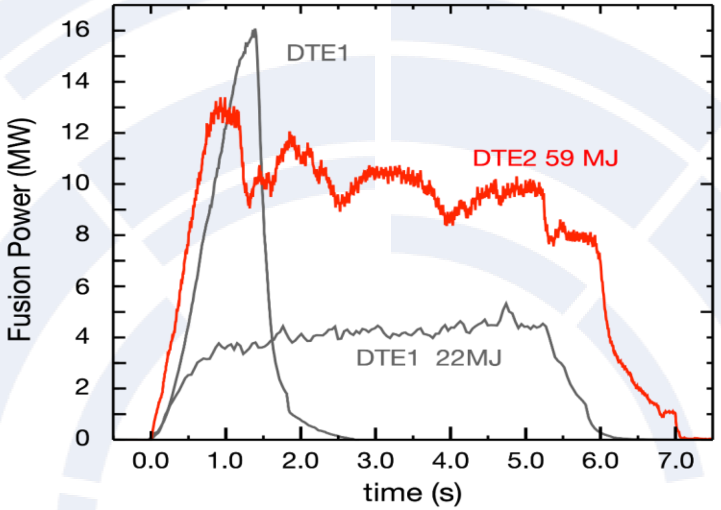




Why a 14 MeV Plasma-Based VNS?

High Level Objectives
1. To be build in parallel to ITER -- > <u>physics must be known</u>
2. Nuclear technology mission (DT plasma)
3. Breeding blanket: concept validation, testing, qualification
4. Show that the fuel cycle can be closed, by using tritium from external supplies
5. Remote maintenance demonstration
6. Adequate level of plant availability

Physics well established and demonstrated (JET, TFTR)



The JET record shot is an example for such a plasma, but NWL is too small

Requirements/ Design Operation Constraints
- **(from 1)** it must rely on a demonstrated physics ($Q \leq 1$) (JET, TFTR) – decouple from ITER physics/ scenarios
- **(from 2, 3)** Sufficient high level of n-flux → must achieve a relevant $\boxed{NWL \geq 0.5\ MW/m^2}$
- **(from 2, 3)** Must achieve relatively high fluence levels F= NWL x Irradiation time = NWL x time xAv → $\boxed{(20\text{-}50\ dpa)}$
- **(from 4)** Operate with tritium from external supplies (non self sufficient) → must minimize $\boxed{P_{fus} < 50\ MW}$

Additional requirements that could be further addressed (some preliminary number are available)
- Demonstration of electricity production
- Production of tritium and radioisotopes (as byproduct*)

***i.e., w/o affecting the testing mission**

VNS Testing approach

- TBMs: "similar systems", can increase TRL to 6-7, not qualify the component.

  ➯ **Testing of TBMs must provide information on validation of design tools and early-life failures → "Low fluence".**
- Segments: "identical" systems, can increase TRL to 8 and qualify the component.

  ➯ **Testing of Segments must provide information on performance and reliability of the component →"DEMO relevant" fluence.**

Goals for TBM testing

- Detect unforeseen failures due to the abrupt changes of material properties at in early irradiation phase.
- Detect early failures due to residual stresses introduced during manufacturing/effects of stress concentration in singular zones (ex. welds).
- Validation of integrated operation of auxiliary systems
- Validate nuclear data (cross sections) in a representative spatially varying neutron flux spectra (tritium production, transmutations, activation…).
- Validation of modelling tools used for design (T permeation / T retention, MHD flows, pebble-bed thermo-mechanics, etc…).
- Validation of corrosion laws.
- Check for initial changes in DBTT, (position and temperature dependent).

VALIDATION

(& early life failures)

Goals for Segment testing

- Qualification of C&S w.r.t. DEMO relevant damage modes (also) in irradiated conditions (irradiation creep, creep-fatigue interaction, fatigue crack growth, swelling…).
- Qualification of representative manufacturing and assembly techniques.
- Collection of statistical data on failure modes/frequencies for reliability analyses.
- Check for long term effects of n-irradiation on breeder/multiplier materials (irradiation creep, swelling, T burn-up factor, dust formation…).
- Check for additional effects of swelling/He embrittlement/changes in DBTT that appear at higher doses.
- Qualification of performances of auxiliary systems (T extraction).
- Check for long-term corrosion effects (IA-SCC, corrosion fatigue, thinning).
- Validation of ACP codes and radioactive source terms.

QUALIFICATION

Engineering design of the VNS

Concept Definition: VNS Design

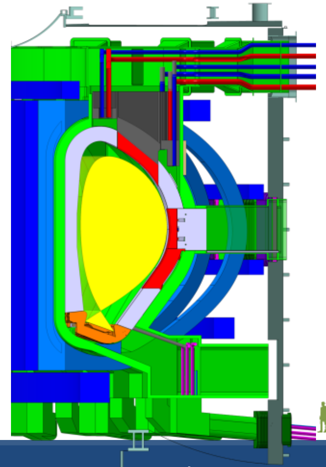
- **VNS volume 50 times smaller than ITER**
- **Fluence achievable in VNS is 100 times more than ITER and sufficient to qualify blankets**

The smallest VNS we could find:

R = 2.63m, B_0 = 5.6 T	
A=4.25	High aspect ratio to create space on the inboard side while minimising the surface
CS	Nb_3Sn, sized to ramp up the plasma, I_p = 2.55 MA
TF coil	Nb_3Sn, B_{max} =13.2 T – trading-off B with TFC size
n-shield (inboard)	Comparable to ITER
P_{fus} / $P_{NBI + EC}$	38 MW / 42 + 8 MW

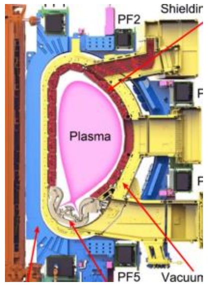
DEMO
42,000 tons

20 m



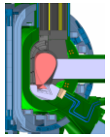
ITER
23,000 tons

10 m

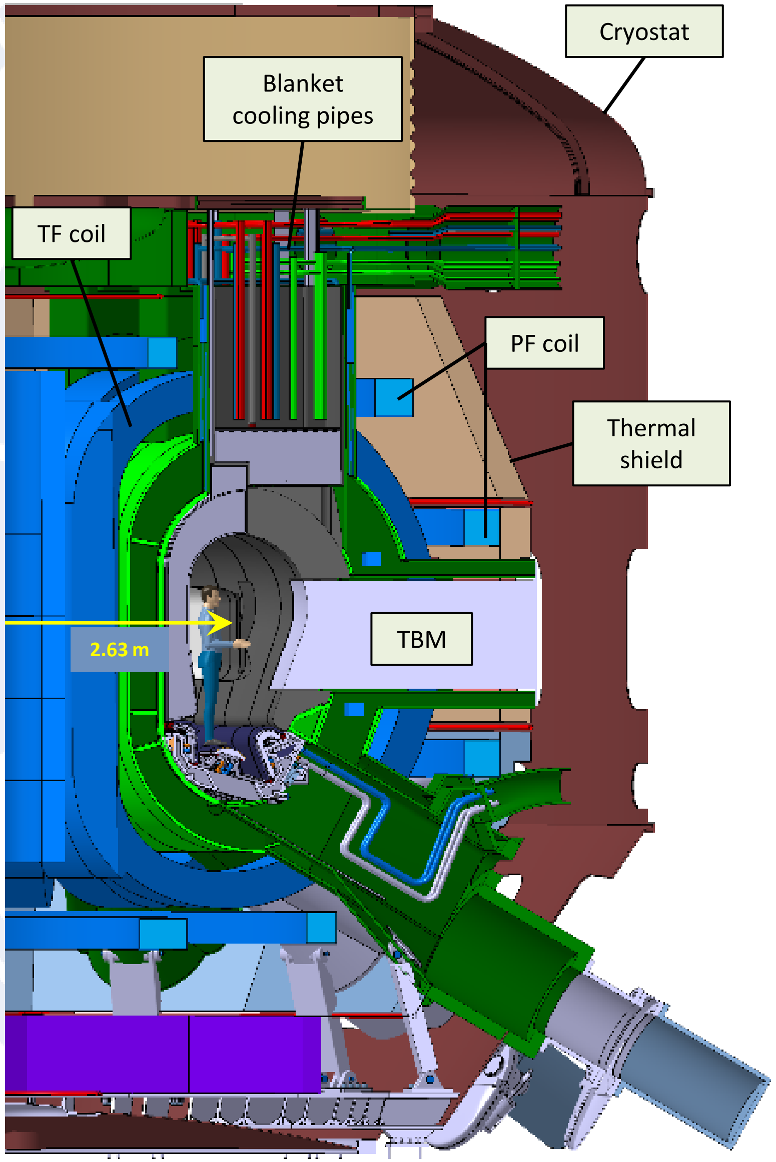


VNS
2,000 tons

5 m



The smallest VNS we could obtain



Allocation of systems to ports and RM

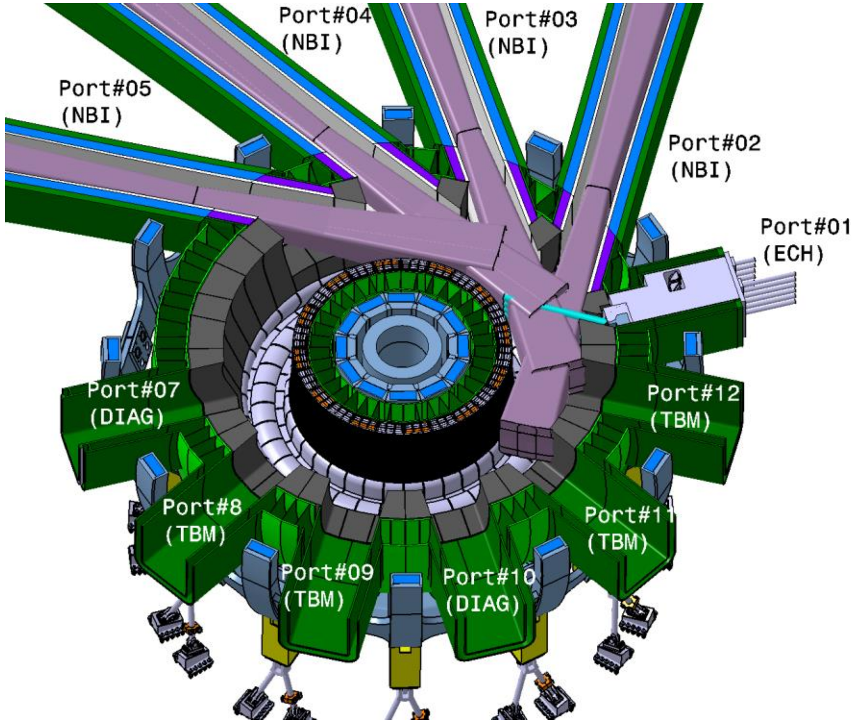
VNS tokamak is Remote Maintenance compatible.

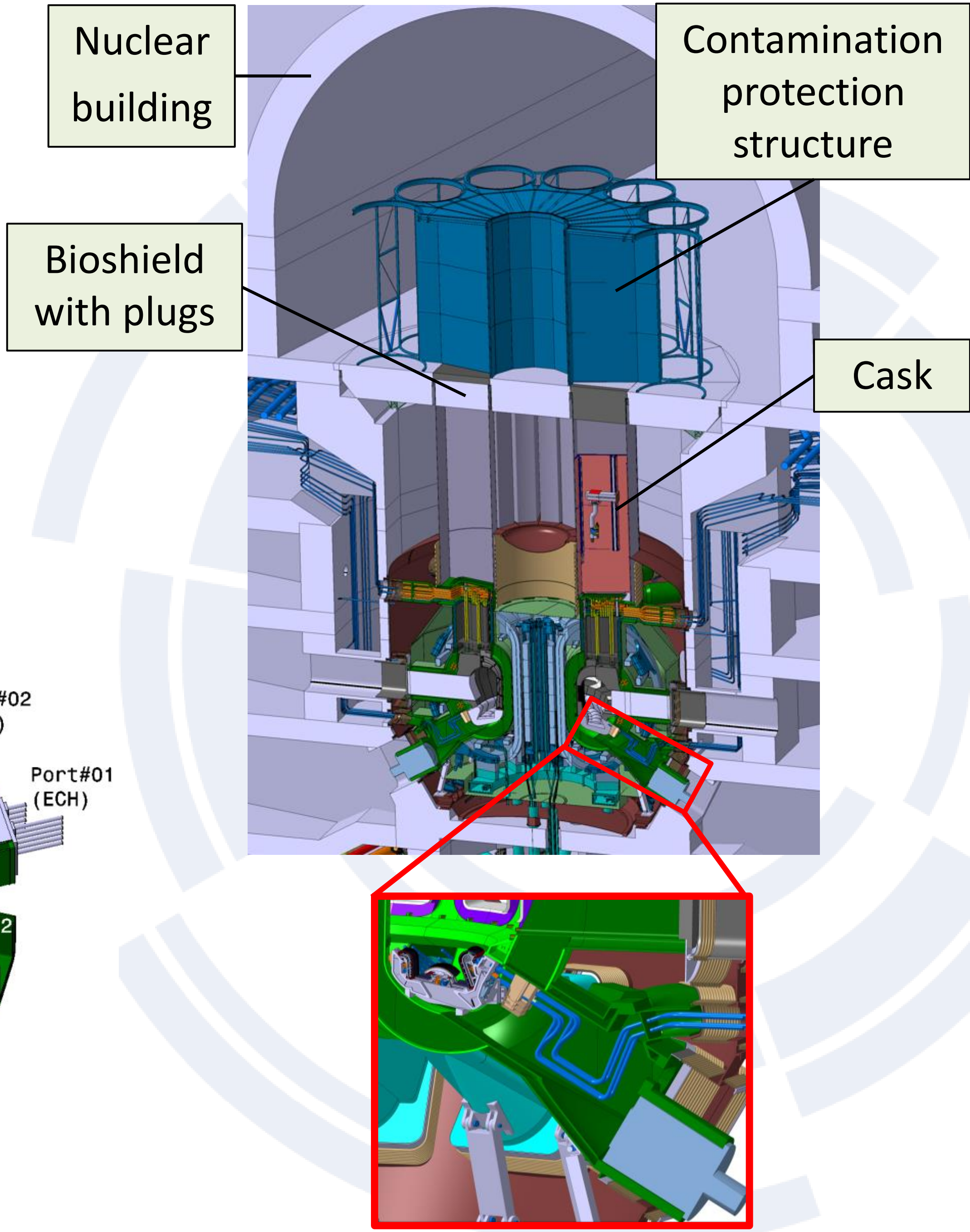
Good access to blankets from the top.

The contamination protection structure divides the hall above the bioshield into 12 port cells for independent access to each port.

Adapted ITER divertor RM concept: Pipes in non-RM ports accessible through separate closure plate.

Port	Upper	Equatorial	Lower
#1	Blanket RH	EC	Divertor RH
#2	Blanket RH	NBI	Pumping
#3	Blanket RH	NBI	Pumping
#4	Blanket RH	NBI	Divertor RH
#5	Blanket RH	NBI	Pumping
#6	Blanket RH	blocked	Pumping
#7	Blanket RH	Diagn.	Divertor RH
#8	Blanket RH	TBM	Pumping
#9	Blanket RH	TBM	Pumping
#10	Blanket RH	Diagn.	Divertor RH
#11	Blanket RH	TBM	Pumping
#12	Blanket RH	TBM	Pumping

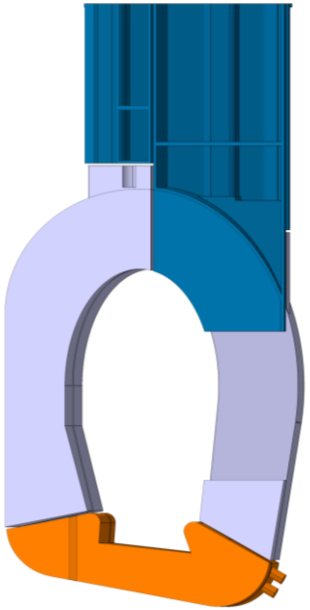


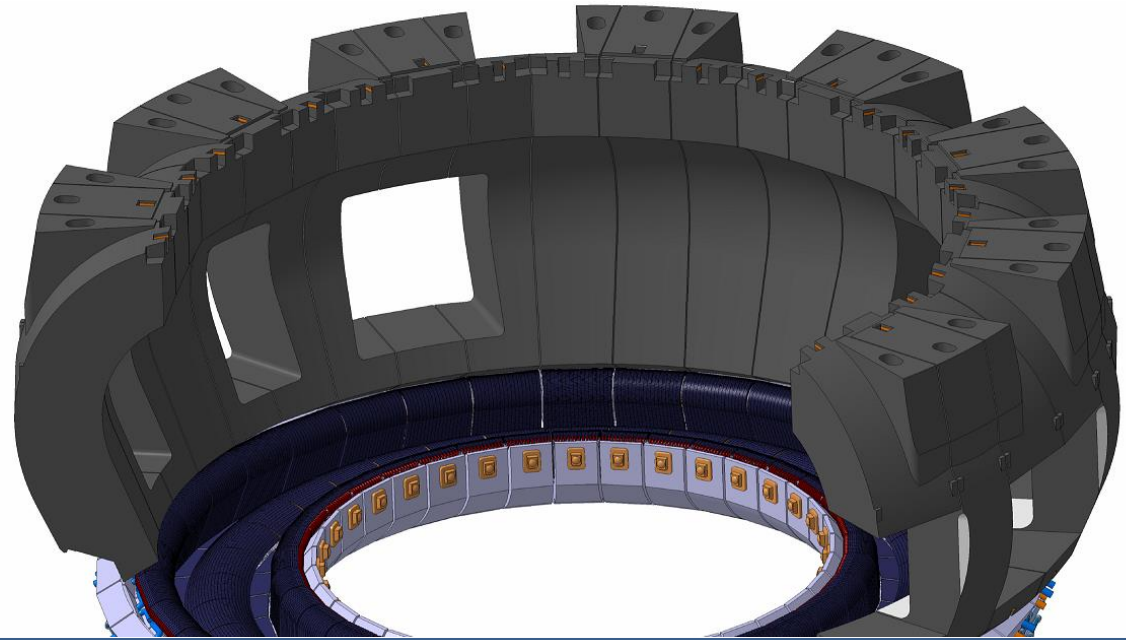


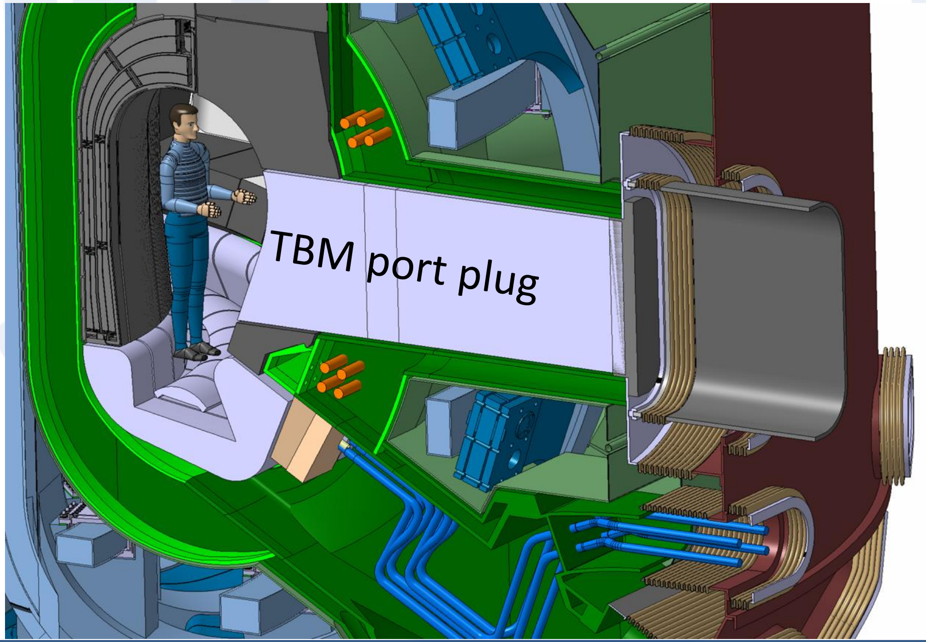
Segmentation of in-vessel components and testing opportunities

- **Four equatorial ports** and around 2/3rd of outboard wall to provide **up to 25 m²** of testing surface
- Ability to test **several candidate blanket**/coolant concepts

Identification	FW surface	Services
Inboard segments – n-shielding	n-shield blankets	Coolant
20 outboard segments (undivided)	~17 m²	Coolant + purge gas
8 upper parts of central outb. segments	$8 \cdot 0.34$ m² = 2.7 m²	Coolant + purge gas
4 TBM port plugs and/or 12 Full test segments	$4 \cdot 1.2$ m² = 4.8 m² $12 \cdot 0.87$m² = 10.4m²	Coolant + purge gas + instrumentation
Divided lateral outb. segments (NB ports) - 8 upper parts - 8 lower parts	n-shield blankets n-shield blankets	Coolant Coolant







Segmentation of in-vessel components and testing opportunities (cont'd)

Capability to test both:

- **full-blanket segments**
- **segments with cut-outs**

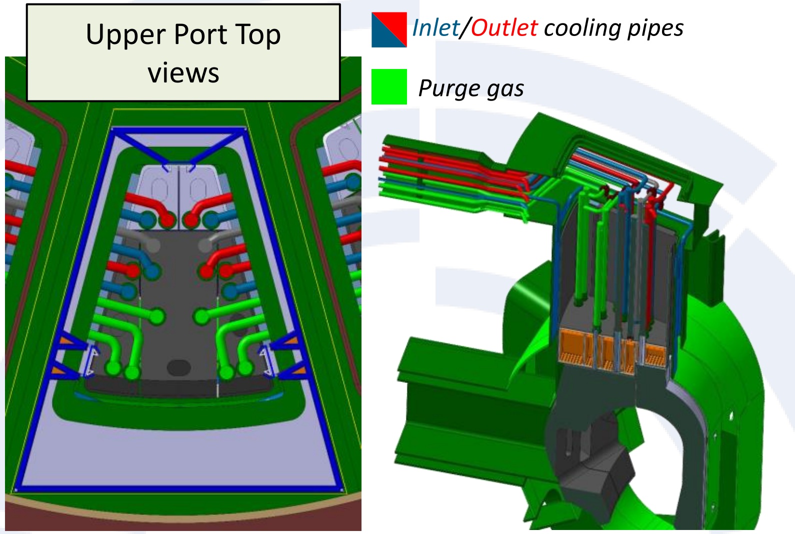
as in upscaled FPPs

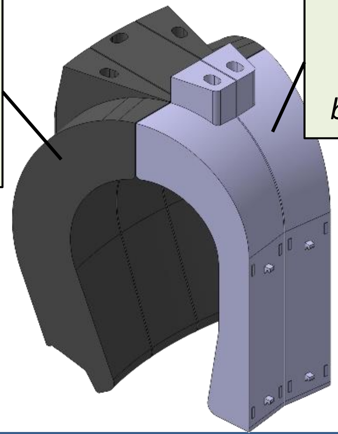
Outboard blankets served by:

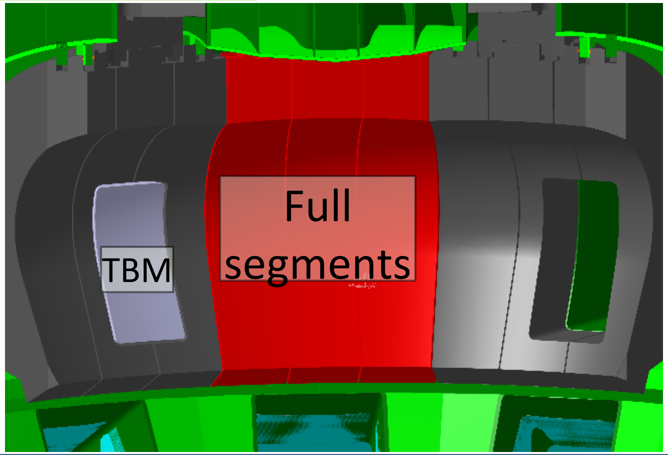
- cooling pipes
  - **water** (up to 330 °C and 15.5 MPa)
  - **gas coolant** (up to 520 °C and 8 MPa)
- tritium purge gas pipe

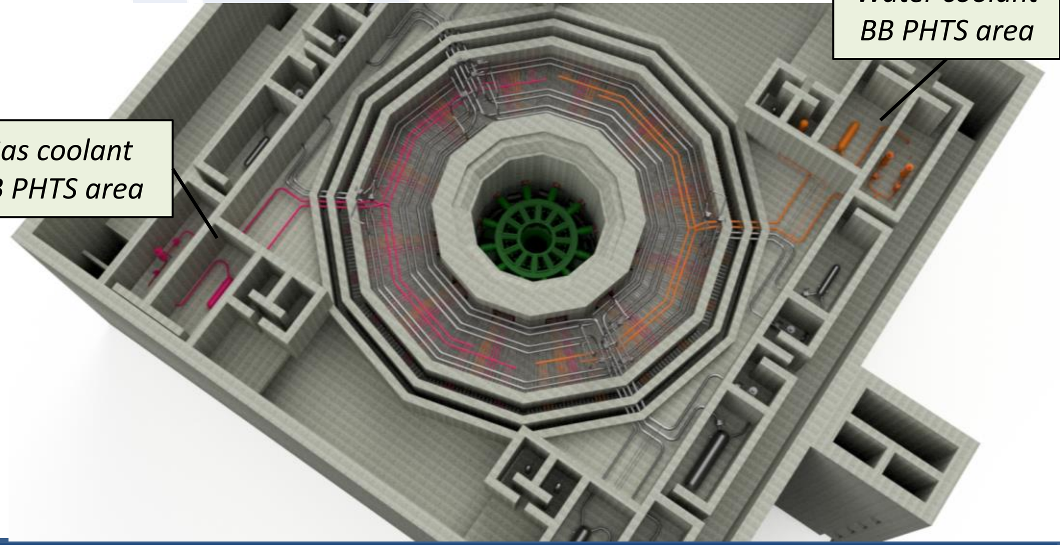
Flexibility is built-in to VNS facility **to accept breeding blanket <u>segments</u>** from **early** nuclear operation **phases**.

Supporting systems and services are being integrated into the plant and buildings.





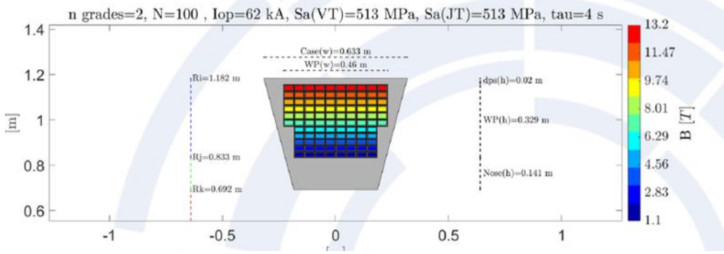


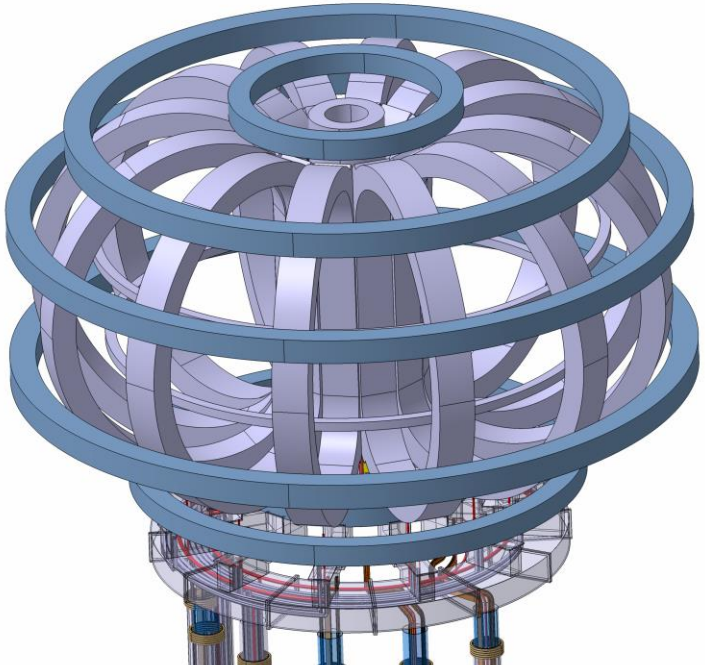


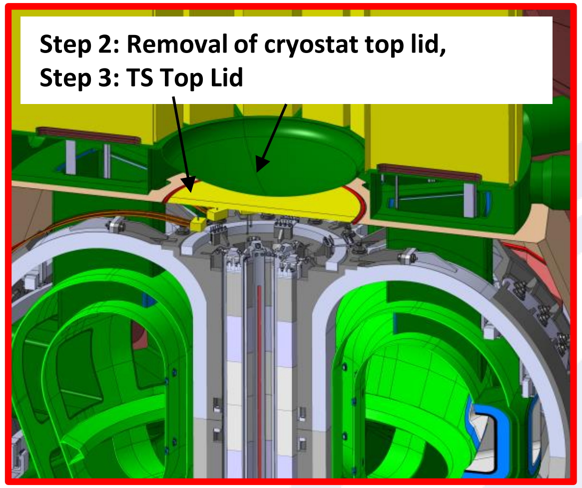
Magnet

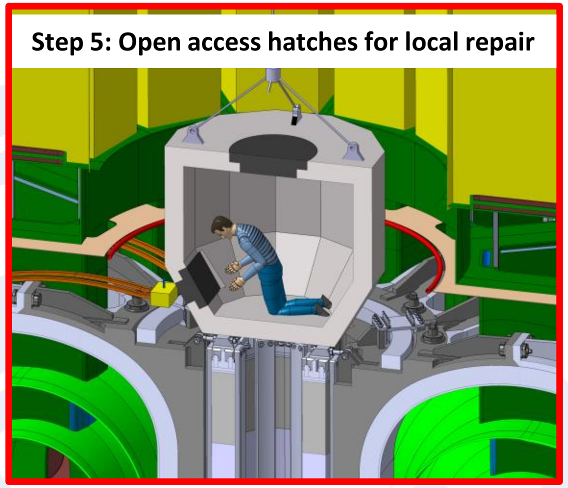
Magnet Coil Design Highlights

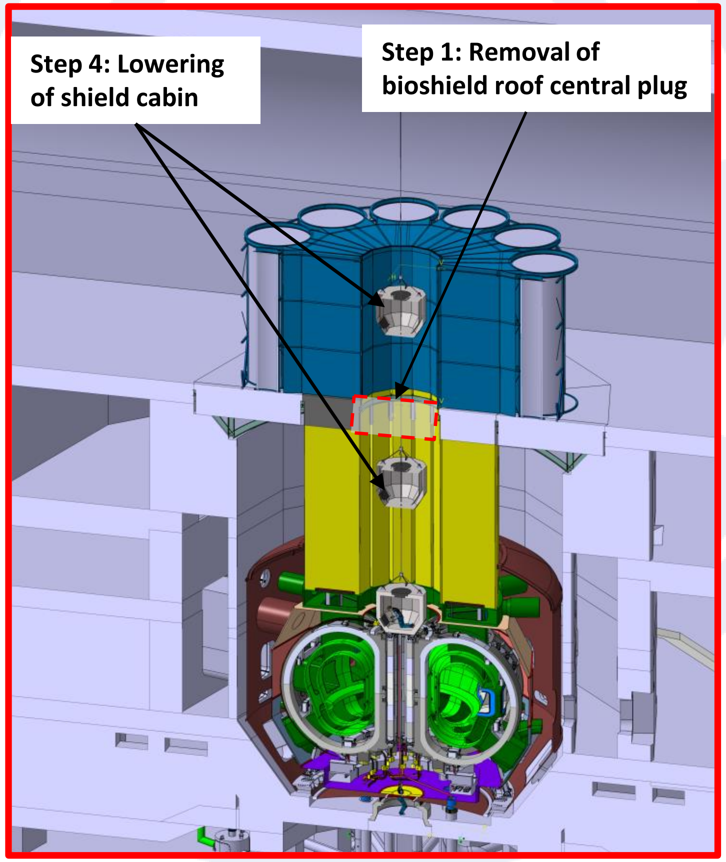
- **Performance:**
  - Maximum field: 13.2 T
- **Manufacturing**:
  - PF coils outside TF coils → no in-situ winding
  - Coils can be individually produced and heat-treated
  - TF coils' size ~1.5 times those of DTT
- **Material Choice**:
  - Nb_3Sn selected for TF coils (mature technology)
  - HTS use depends on future development
- **Maintenance & Accessibility**:
  - Joints placed above/below CS for easy access
  - Radiation-protected zones
  - Reachable via special-purpose cabins



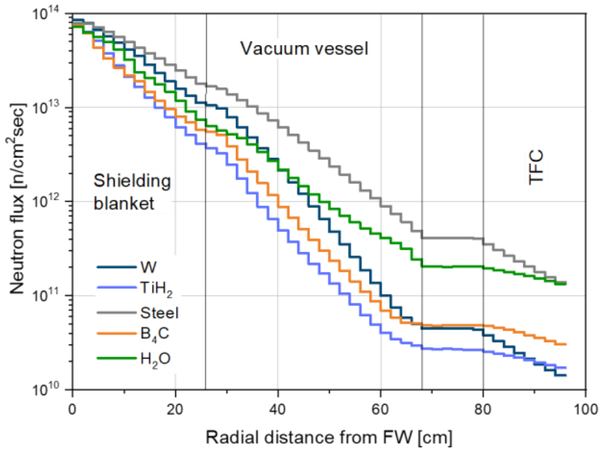


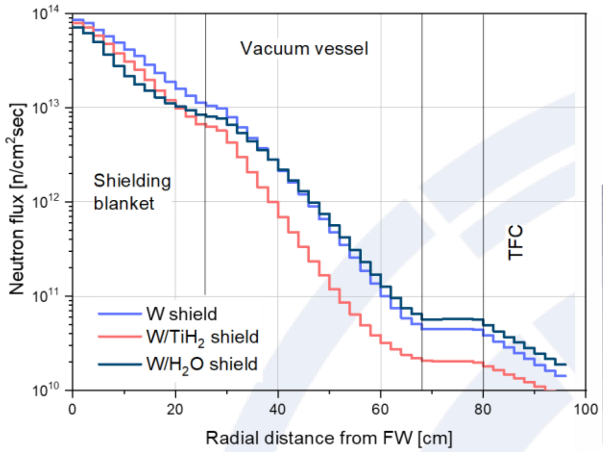


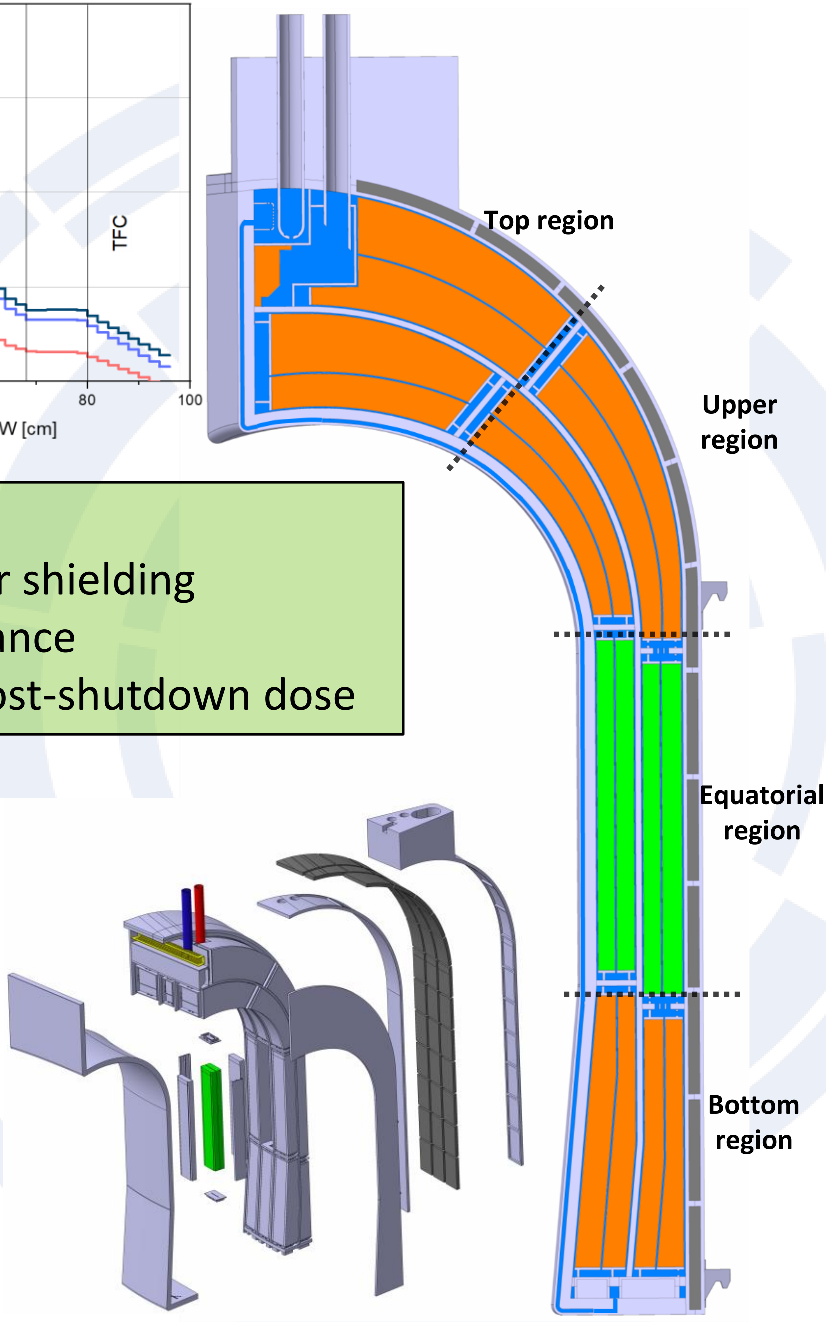




Shield blanket







Design:

- ➢ Welded box, HIPed FW, 316Ti
- ➢ Water 50-70° @ 10 bar

Tailored Shielding:

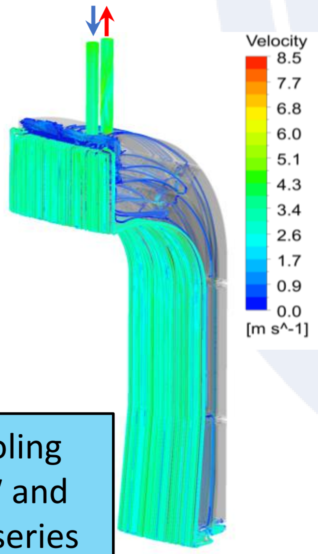
- ➢ 5 radial layers, 4 poloidal zones
- ➢ High-performance materials needed at IB equator

Material Selection:

- ➢ Equatorial region - IB
  - **W**: Core shield (neutron/gamma absorption)
  - **TiH_2**: Enhances shielding, lowers weight/activation
  - **B_4C**: Thermal neutron absorber, electrical insulator
- ➢ Above/Below equatorial region - IB
  - **Steel/Water**: low load zone, ferritic steel aids blanket attachment via inward magnetic forces
- ➢ Outboard regions
  - **TiH_2/B_4C:** replace W to reduce neutron leakage, activation, and post-shutdown dose

Design goal:

- Optimize material mix for shielding performance & maintenance
- Reduce activation and post-shutdown dose

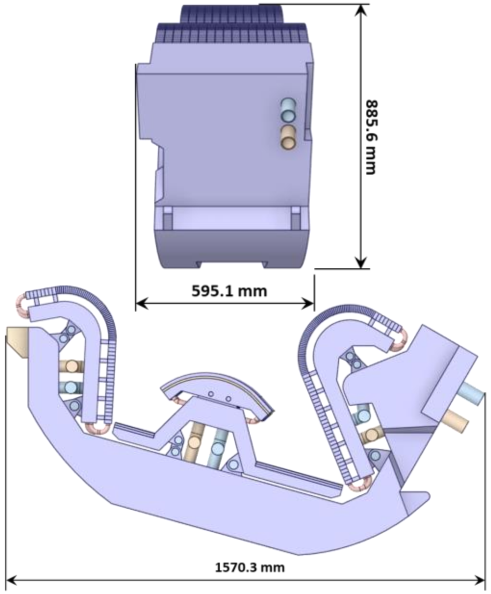


U-shaped cooling path with FW and SB cooled in series

Divertor

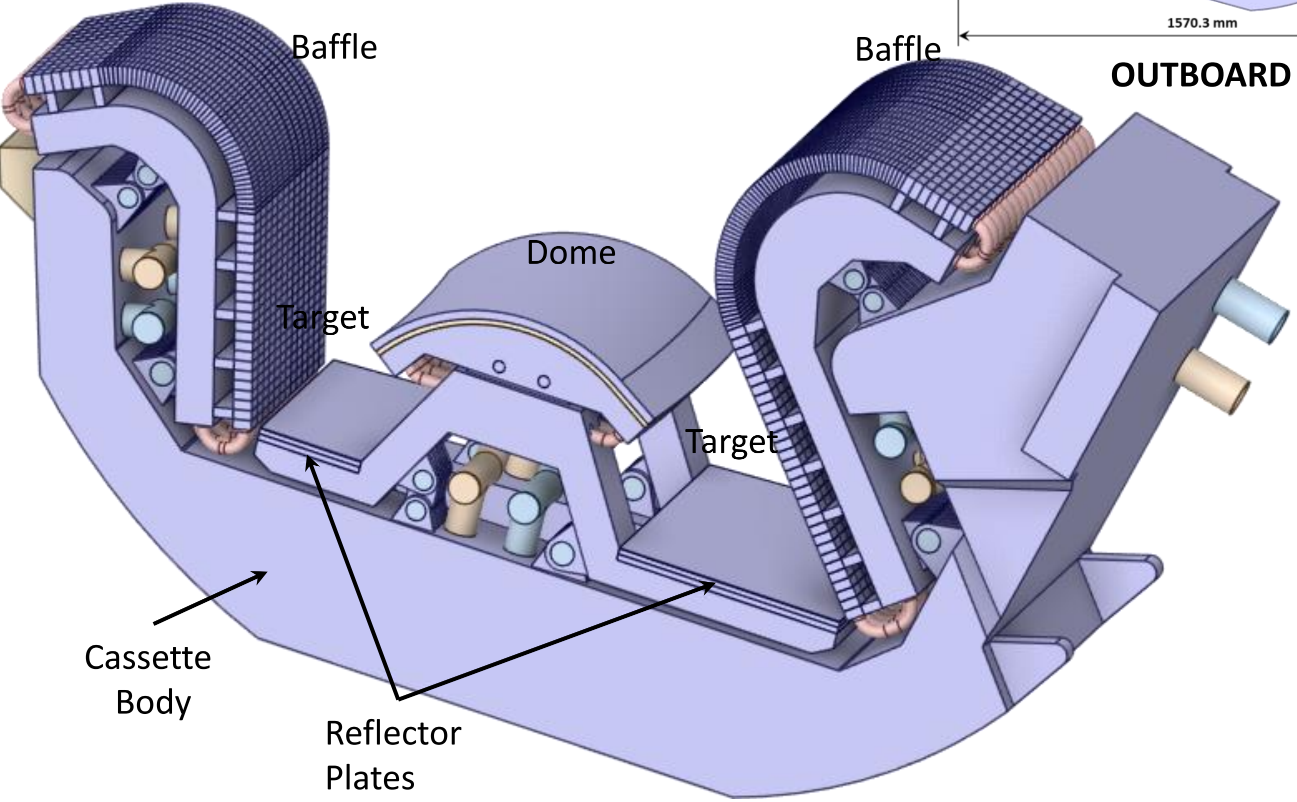
Design:

- Structural material: 316Ti
- Water coolant: T_{in} = 50 °C and p_{in} 3.5 Mpa
- ITER-like PFCs:
  - Targets with W-monoblocks
  - Dome with Hypervapotron



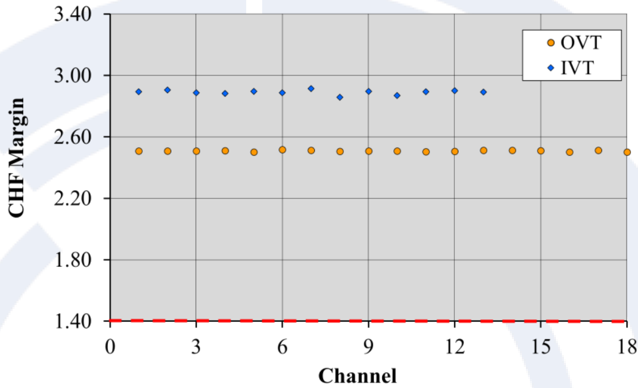
OUTBOARD

INBOARD



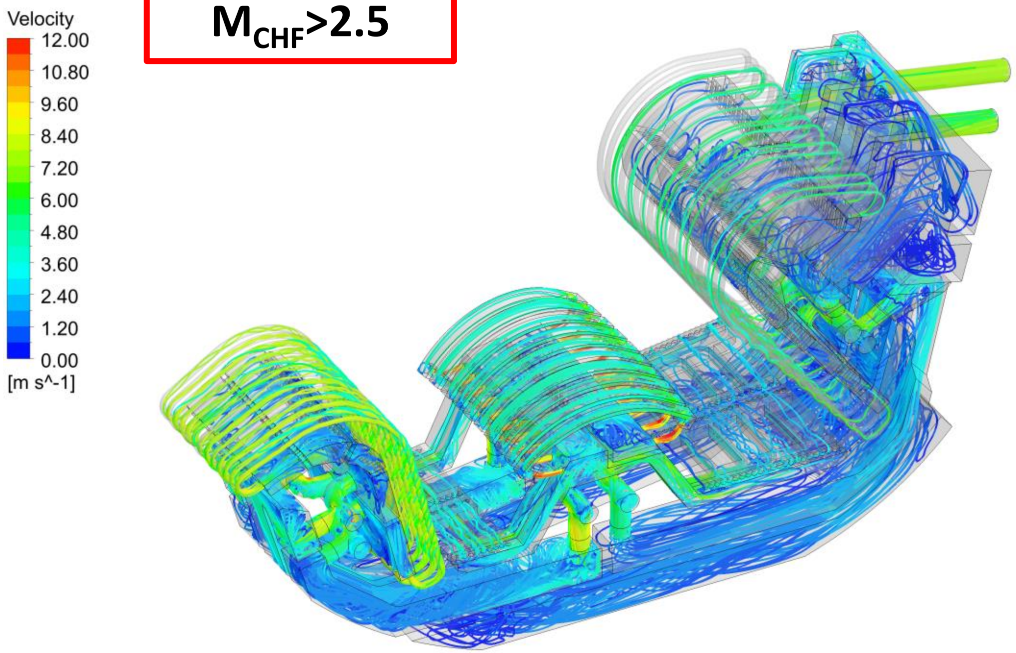
IVT and OVT

- Tested **against 10 MW/m²**
- Expected SS heat fluxes around 6 MW/m²



p_{in}=35 bar
ṁ=9 kg/s
T_{ave}≈70°C

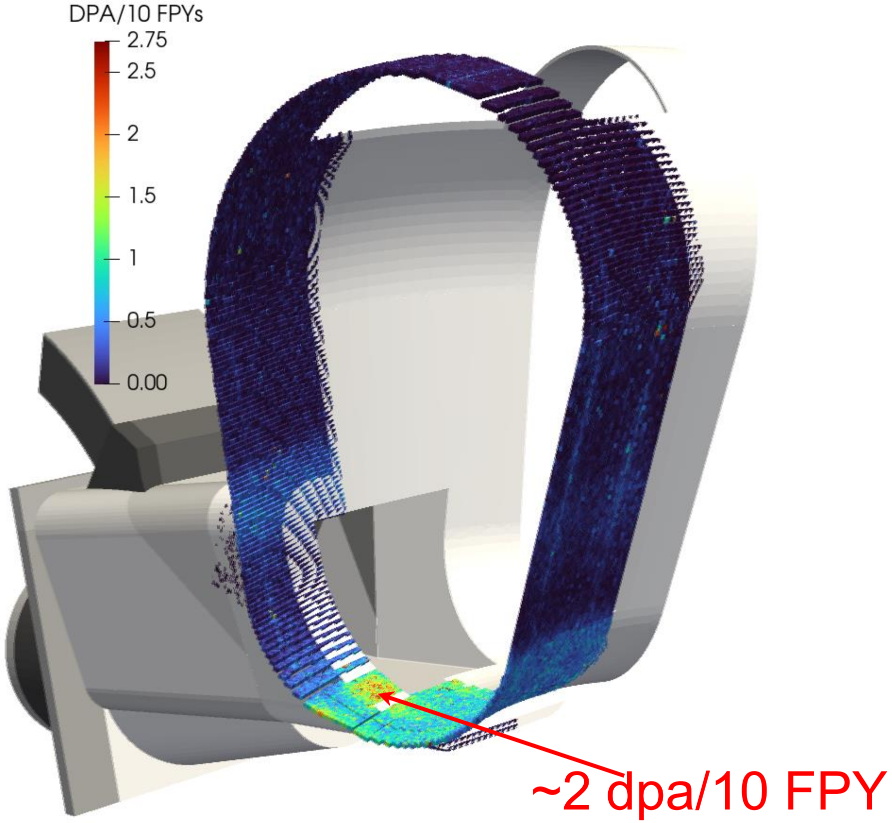
Δp=7.4 bar
M_{CHF}>2.5

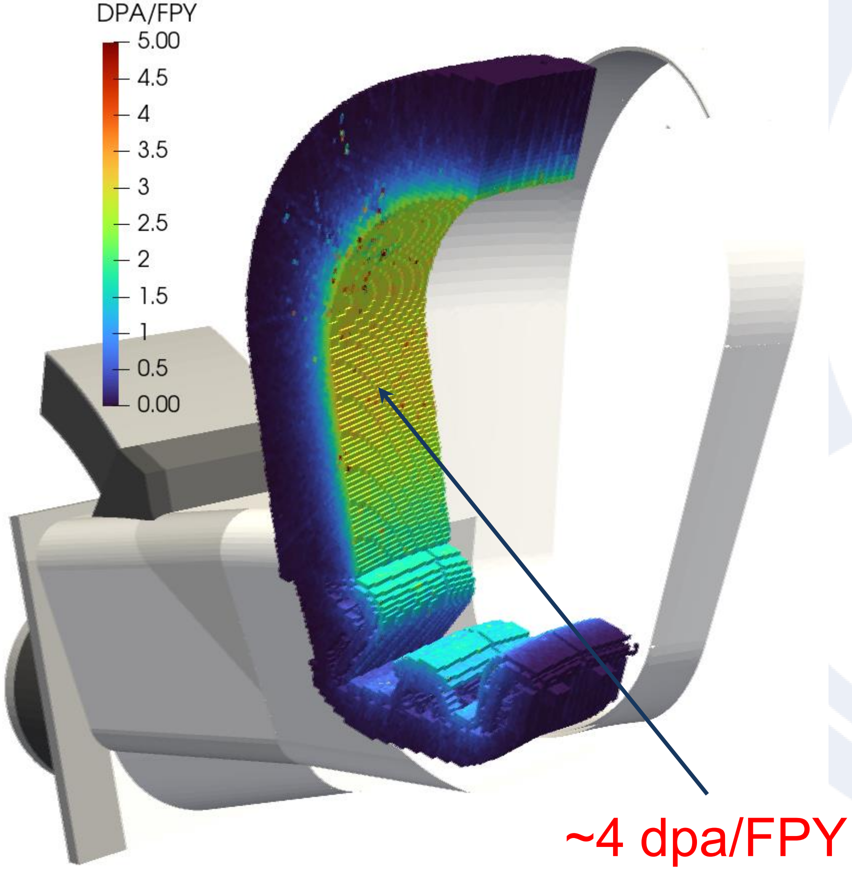


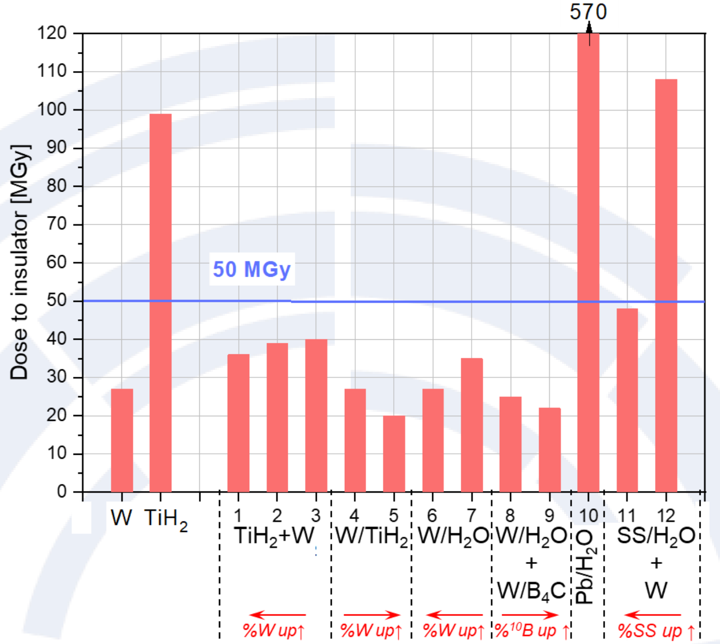
Nuclear shielding of critical components

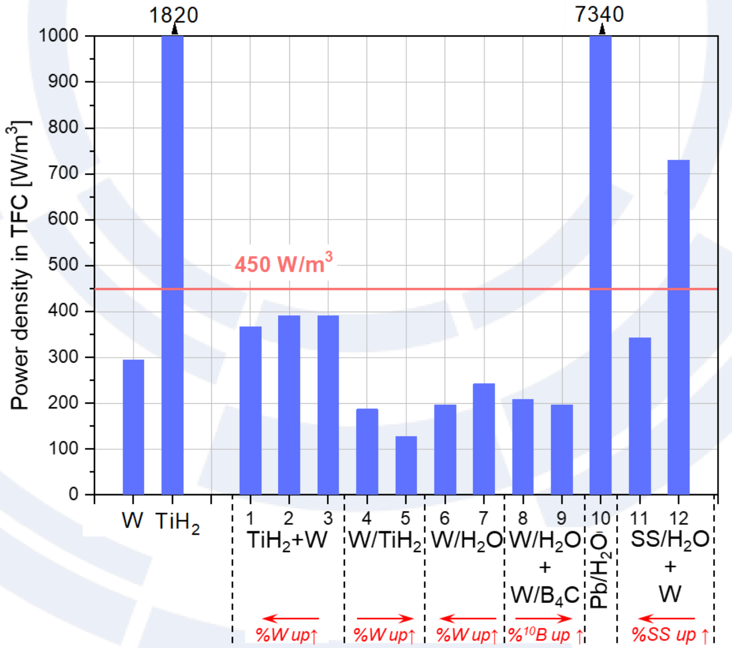
- W-based materials provide the best solutions with a sufficient safety margin
- Mixed materials, W + moderator, could give additional margins

- The TFC in the inboard side can be reliably protected against radiation
- VV can operate for the whole lifetime within the negligible irradiation damage window









Fuel Cycle

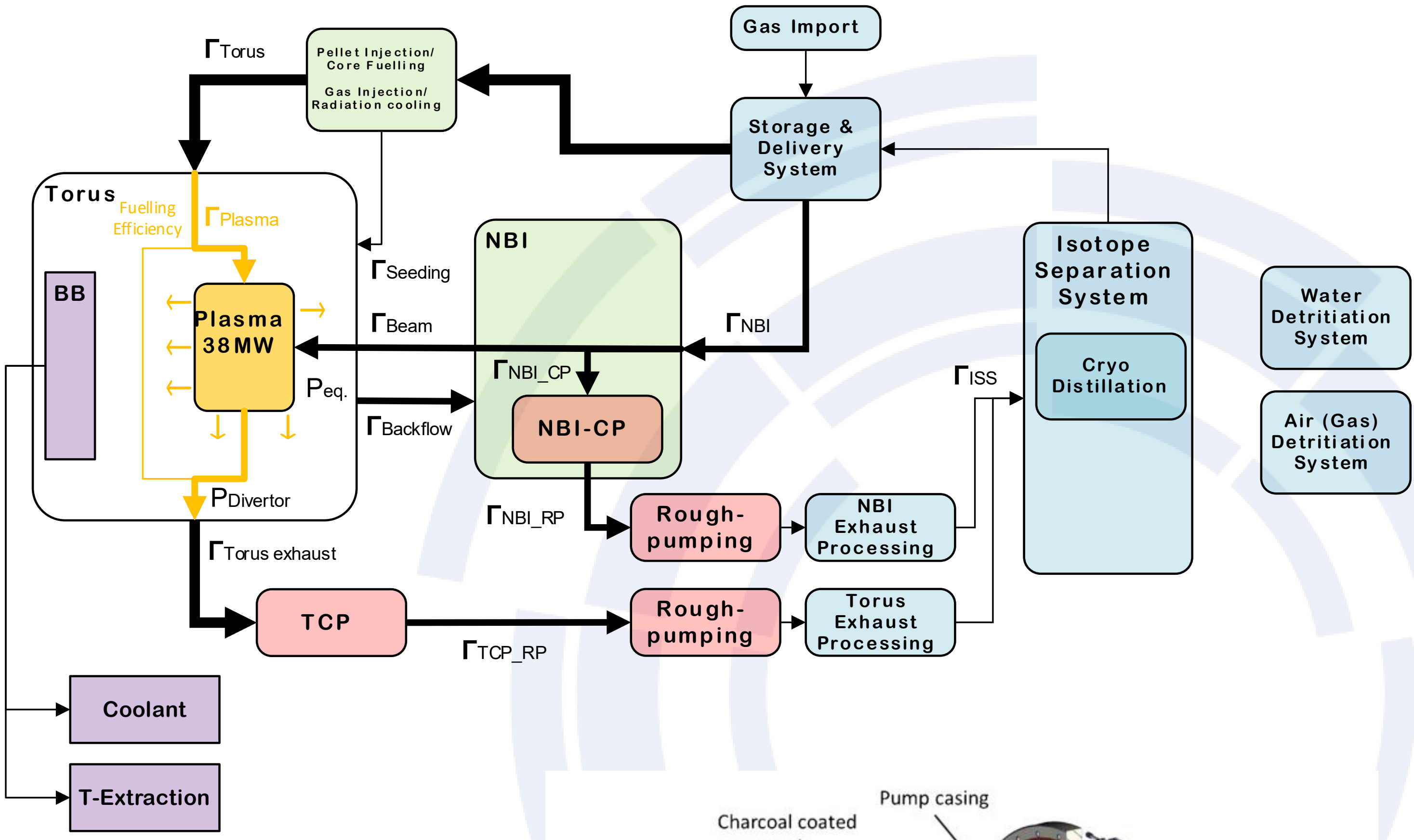
Fuelling technology:
- Pellet for core fuelling
- Gas puffing for “impurities”

Pumping technology:
- Torus: Cryo-sorption (charcoal coated)
- NBI: Cryo-condensation (stainless steel surface)

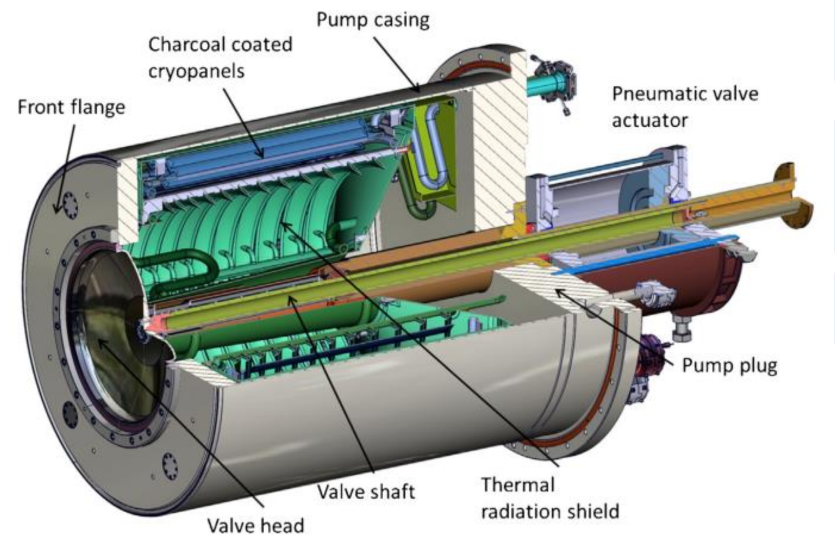
Reference Scenario:

Tritium Plasma with Deuterium Beam:
- High concentrated Tritium Plasma fuelling (95%)
- High concentrated Deuterium beam (95%)
- Seeding Gas Krypton

Tritium inventory [g]	
Torus Cryo-pump	85
NBI Cryo-pump	19
Pellet Injector	23
1st Confinement	127
Isotope Separation System	386
Total T	**513**



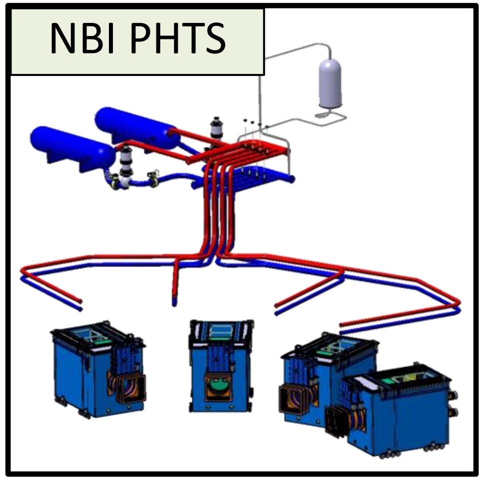
Fuel Cycle technology can rely on adaptation of many ITER developed technology like ITER Model-pump for Torus vacuum

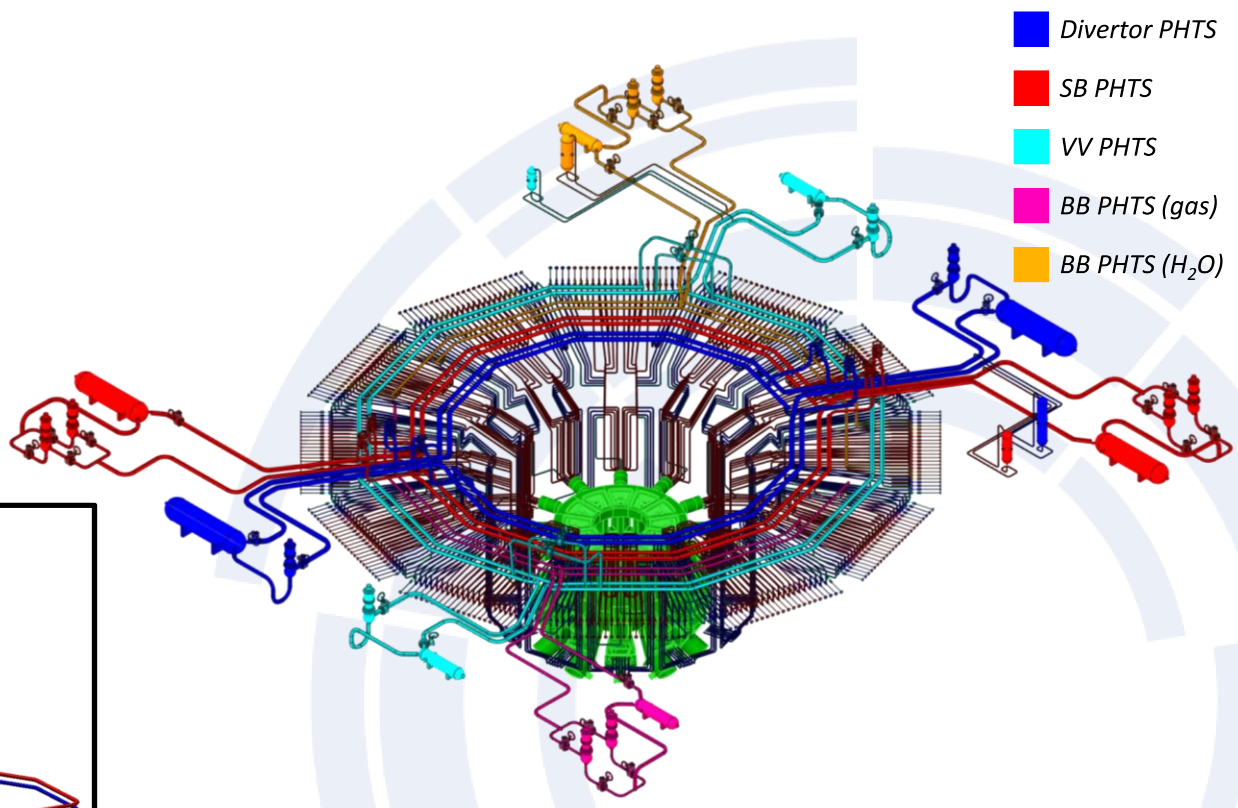


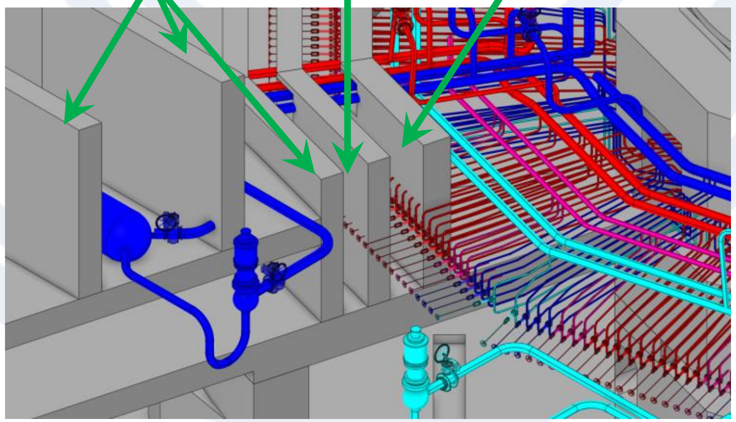
Tokamak Cooling Systems

Target T/H conditions						
	SB	Divertor	VV	NBI	BB (water)	BB (gas)
Inlet Temp.[°C]	50	50	50	50	>285	>300
Outlet Temp. [°C]	<70	<75	≈51	<70	<328	<550
Pressure [MPa]	1.0	3.5	1.0	1.4	15.5	<8.0

Heat to different clients* [MW]	
Shielding Blanket	**35-36**
Divertor	**52-53**
Vacuum Vessel	**1**
Breeding Blanket	**<15**
NBIs	**60**
TBMs (each)	**<1.5**
Total heat to remove	**≈160**







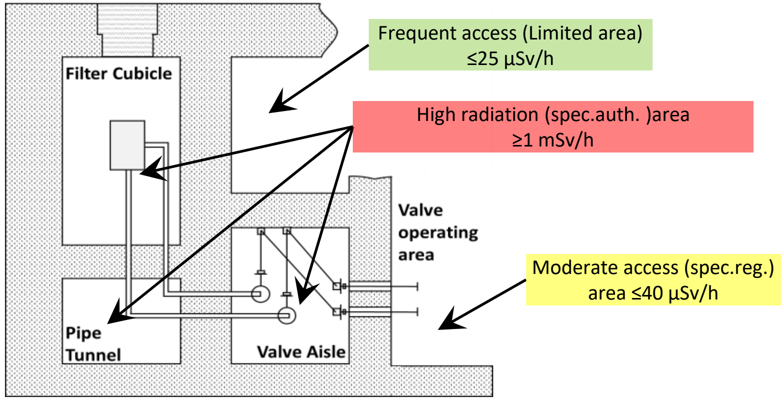
Secondary shielding requirements:

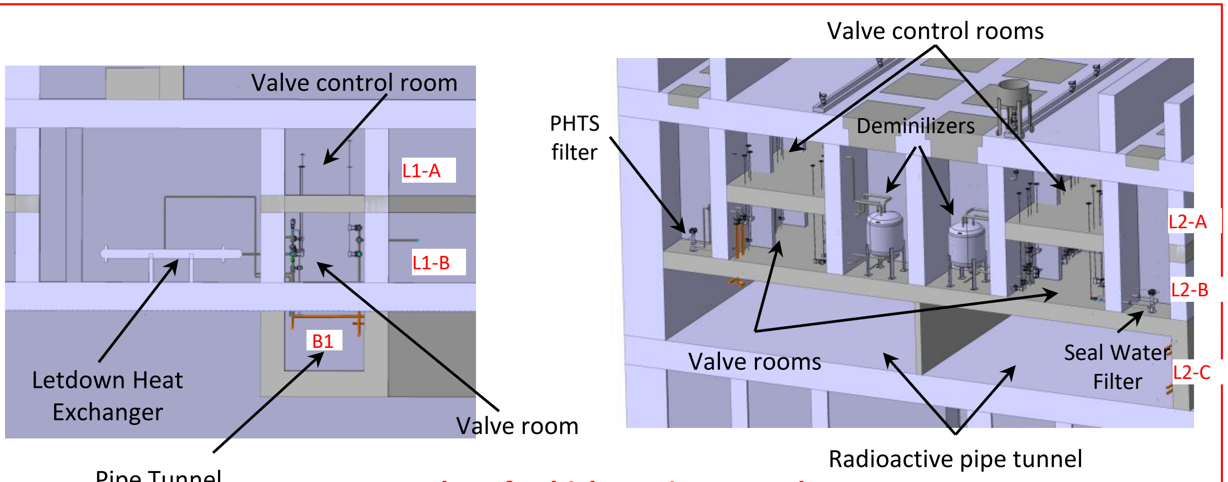
- Dose outside the tokamak building walls ≤2.5 µSv/h
- In fission plants secondary shielding ~0.8-1.2 m.
- In VNS N-16 specific activity can be more than 100 times higher than NPPs.
- Increase of concrete thickness needed to keep same dose level (+30-40 cm)

Nuclear auxiliary building – overall layout for radiation protection

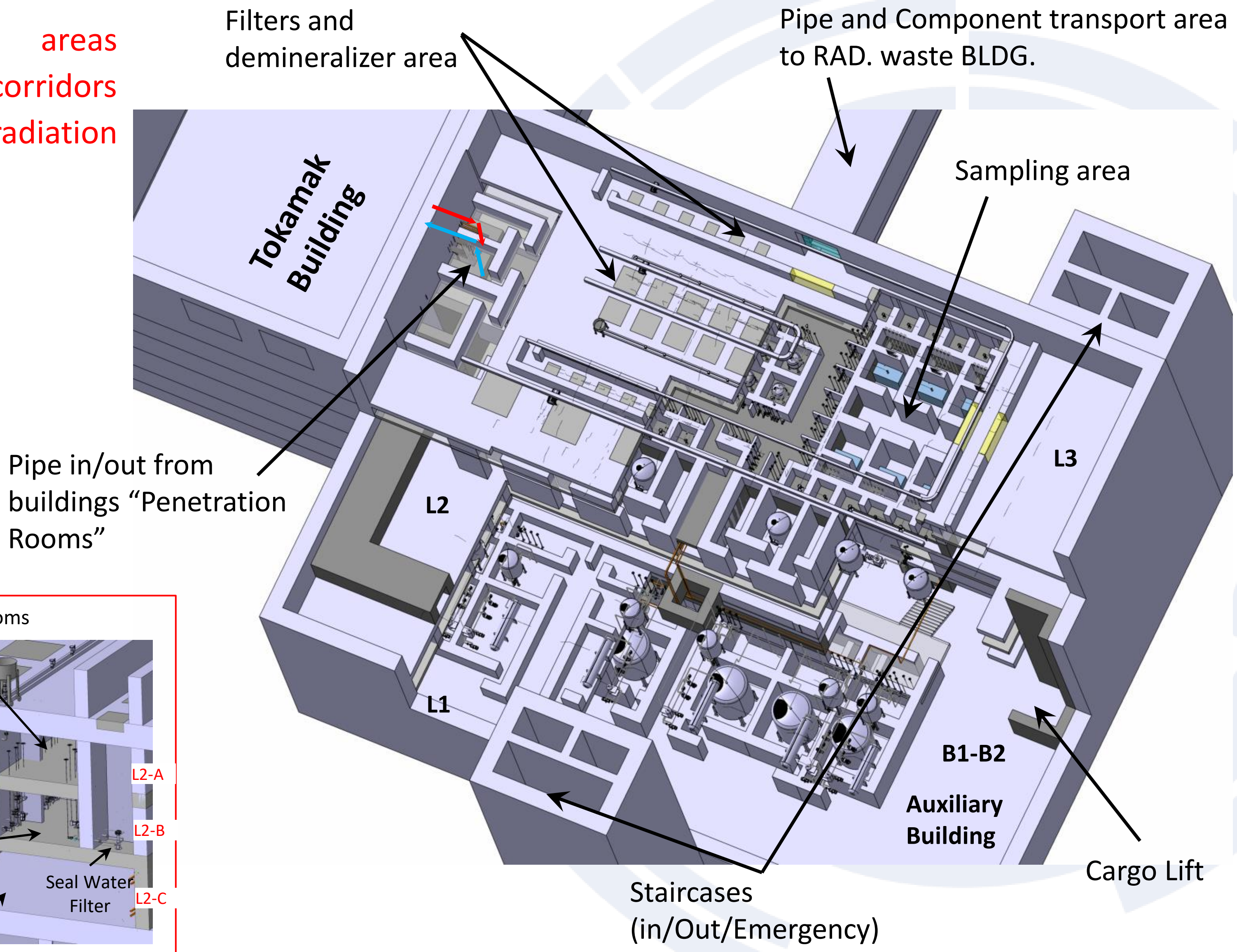
- Separation of radioactive and nonradioactive pipe tunnels
- Valve operated from well shielded areas
- Frequently access areas (40hr/week) like corridors are shielded so that radiation level is ≤25 µSv/h

Schematic of layout for radioactive equipment segregation





Examples of cubicles as integrated



Various CVCS Component Cubicle.

Summary

VNS technologies:

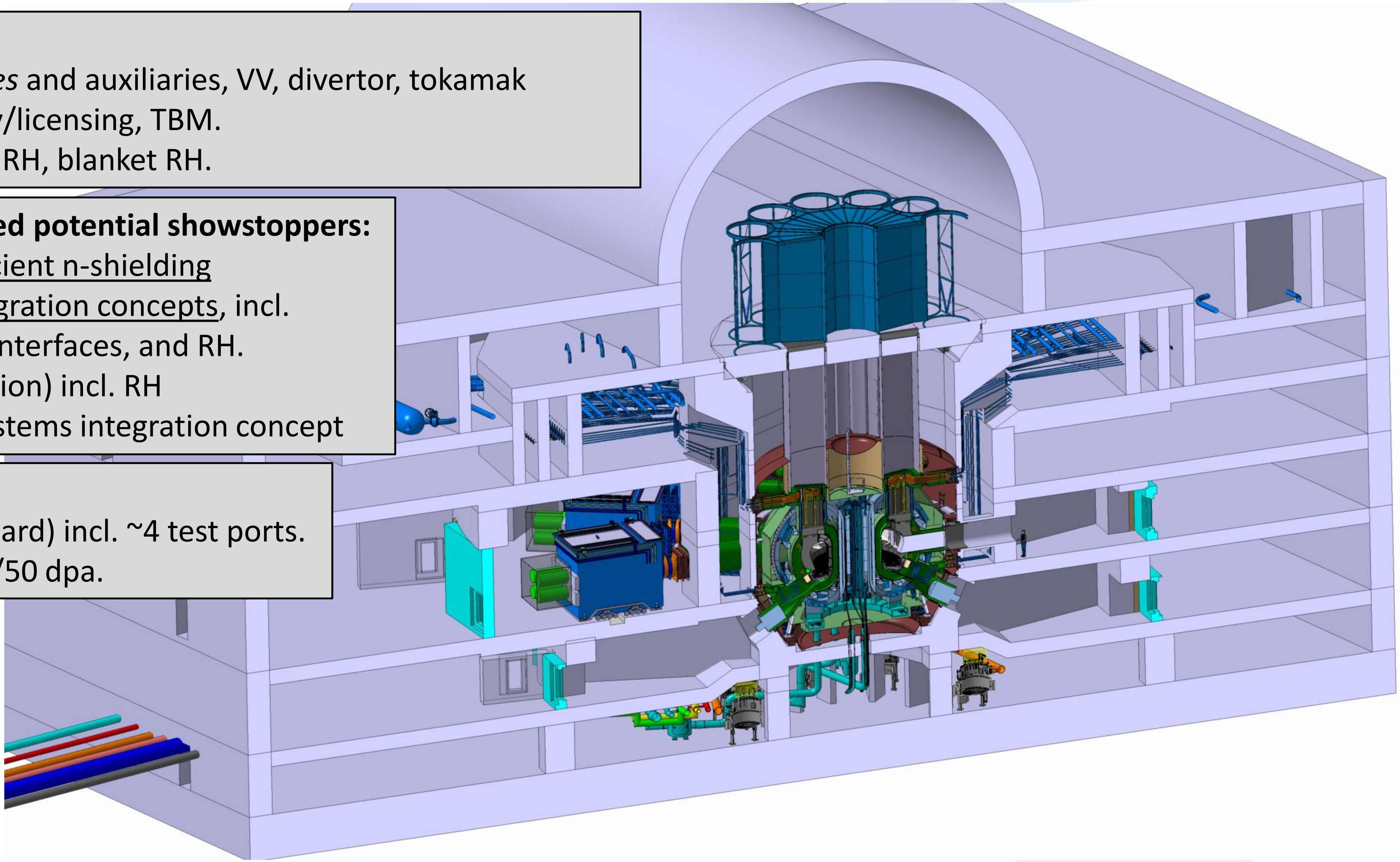
- ITER-like: Magnet *structures* and auxiliaries, VV, divertor, tokamak cooling, T-fuel cycle, safety/licensing, TBM.
- New: steady-state NBI, NB RH, blanket RH.

Concepts for initially identified potential showstoppers:

- Tokamak design with sufficient n-shielding
- In-vessel components integration concepts, incl. electrical and mechanical interfaces, and RH.
- NBI (steady-state, positive ion) incl. RH
- Activated cooling water systems integration concept

Testing opportunities:

- ~25 m² testing area (outboard) incl. ~4 test ports.
- 10 full power years to ~40/50 dpa.



Thank you

FAIRNESS

Transparency
Collaboration
Loyalty

OPENNESS

Open doors
Open hearts
Open minds
Open ears

COMMITMENT

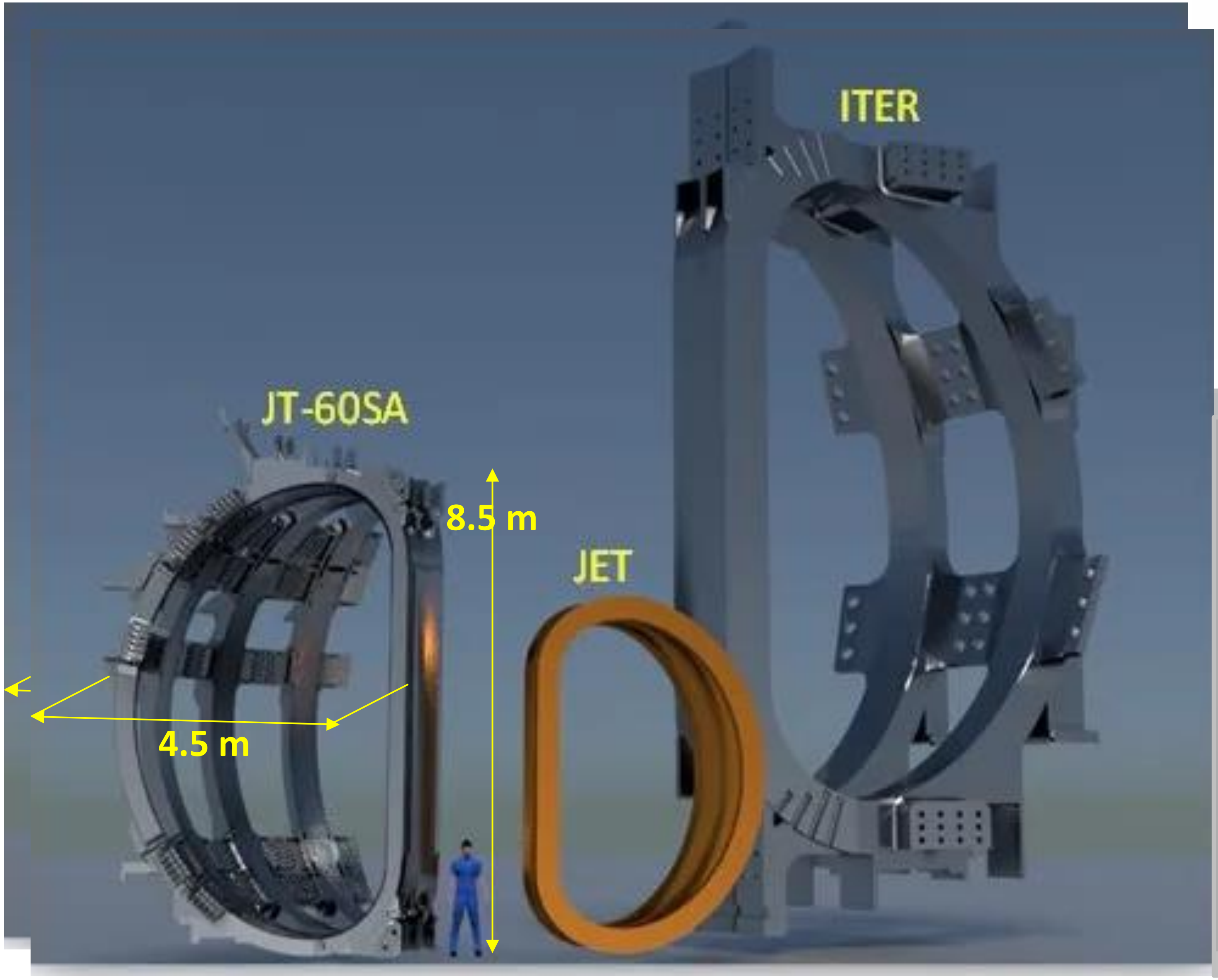
Ownership
Critical thinking
Determination
Respect

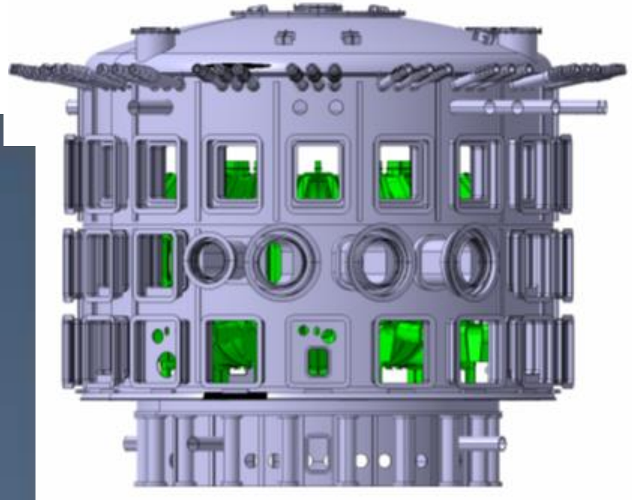
DIVERSITY

Cooperation
Equal opportunities
Inclusion

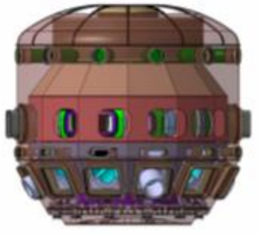

BACKUP SLIDES

Concept Definition: **VNS Design**

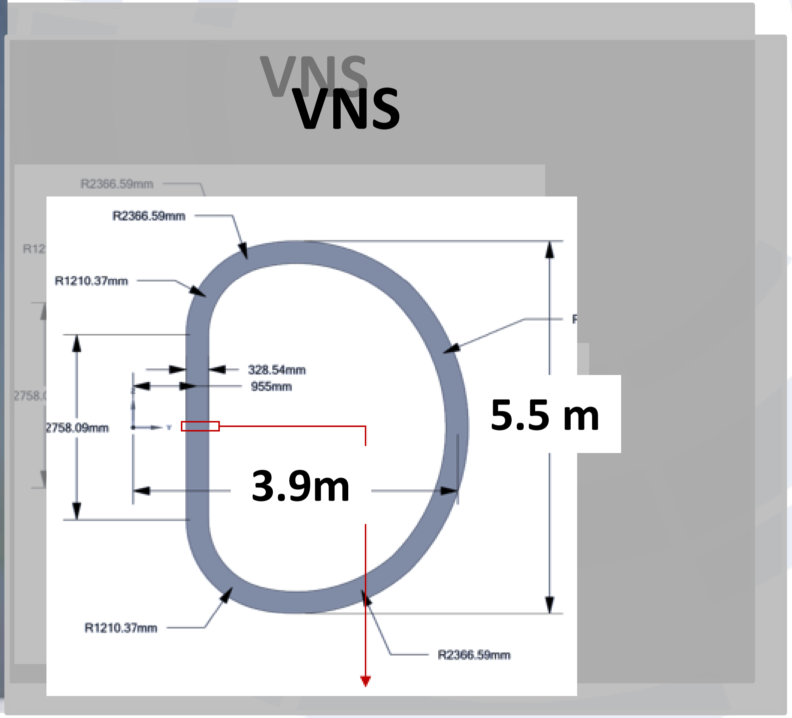




„ITER“ CRYOSTAT



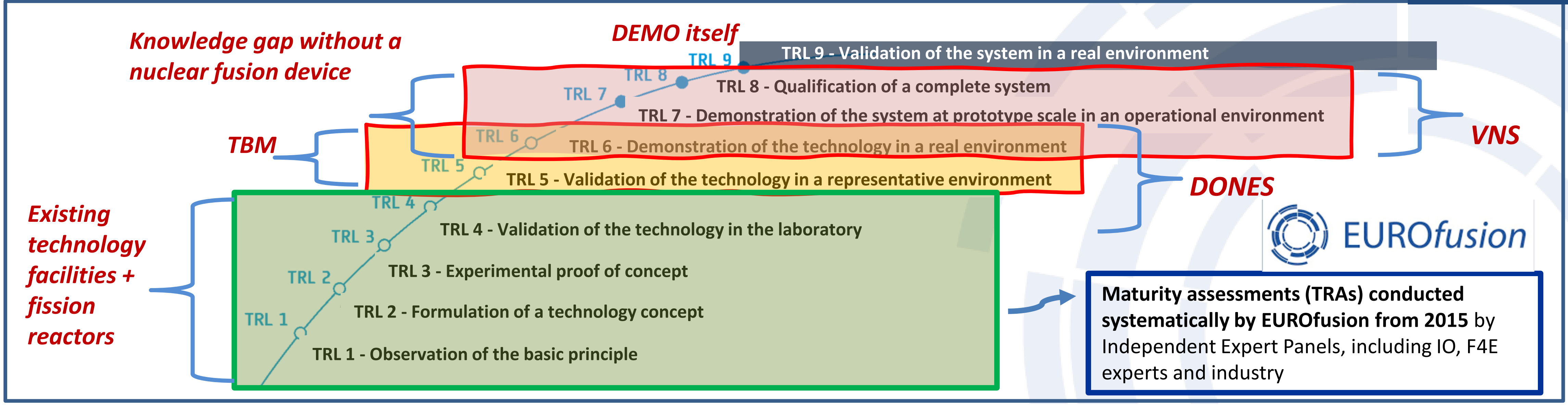
„VNS“ CRYOSTAT



Motivation: How to fill the main technology gaps beyond ITER

Performance and reliability of the breeding blanket is essential for the deployment of future fusion reactors

G. Federici - *Testing Needs for the Development and Qualification of a Breeding Blanket for DEMO*, Nucl. Fusion 63 (2023) 125002.



Maturity assessments (TRAs) conducted systematically by EUROfusion from 2015 by Independent Expert Panels, including IO, F4E experts and industry

The qualification of fusion nuclear technologies:

1. is a prerequisite for the safe and successful development of fusion power.
2. is also a requirement for licencing fusion nuclear systems.

➔ **We need a dedicated nuclear facility that brings the TRL from 4 to 8.**

Table 4: Contribution of the different facilities in achieving TRL goals.

Facility	TRL 4	TRL 5	TRL 6	TRL 7	TRL8
DONES					
ITER-TBM (*)					
VNS-TBM					
VNS-Segment					

(*) Considering DT-2 phase. Without DT2, ITER-TBM contribution is insufficient to achieve TRL6 and a VNS-TBM program becomes mandatory.

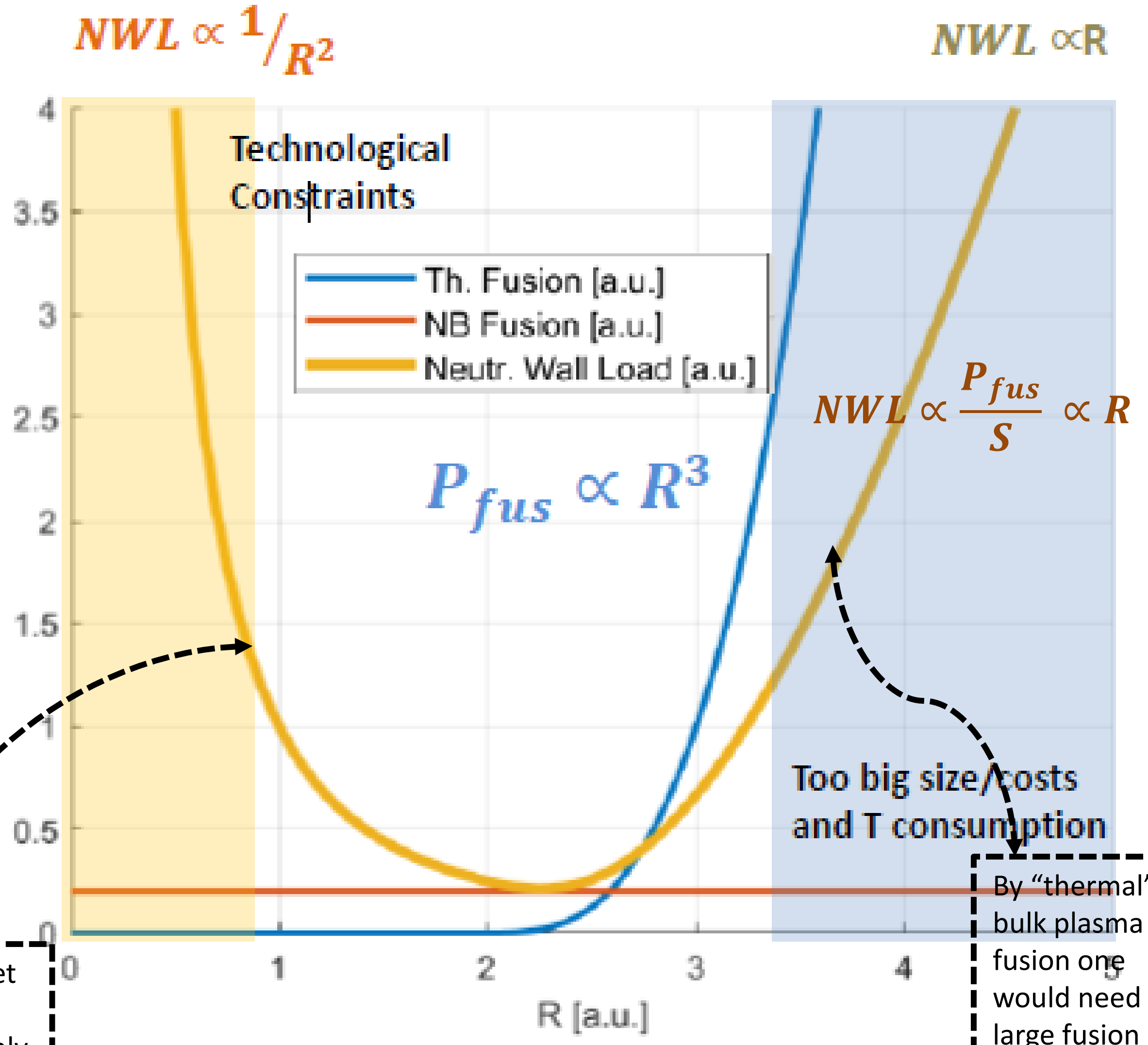
Essential in reaching the TRL
Can contribute in reaching the TRL
No relevance in reaching the TRL

Recent EUROfusion assessment
The roles of different facilities for the nuclear qualification of the breeding blanket
https://idm.euro-fusion.org/?uid=2SFVCY

Concept Definition: **VNS Design Point and Physics Basis**

- **Low T-consumption (no breeder requirement): $P_{fus} \leq 50$ MW**
- **Nuclear performance: Peak neutron wall load ≥0.5 MW/m²**
- **Fluence: lifetime neutron fluence > 20...50 dpa**
- **Availability: Steady-state plasma operation**

	DEMO	VNS
P_f (MW)	2000	30
NWL (MW/m²)	1	0.5
fpy to reach 20 dpa	2	4
T (kg) consumed to reach 20 dpa	224	6.8



With beam – target fusion. Fusion power depends only on beam power – no volume dependence

By "thermal", bulk plasma fusion one would need a large fusion power to get a sufficient NWL. **Not OK!**

Current Roadmap: Lessons learned

The current EU fusion roadmap is articulated on 3 main devices: **JET, ITER, and DEMO** supported by R&D

- **Significant resources have been devoted, in Europe, to DEMO design and R&D during the last 10 years**
- **A major milestone was the DEMO G1 Gate held in 2020**

1 Still large plasma physics uncertainties that heavily constrain the design space and affect the performance and the operation of future devices. **ITER Mission is fundamental**

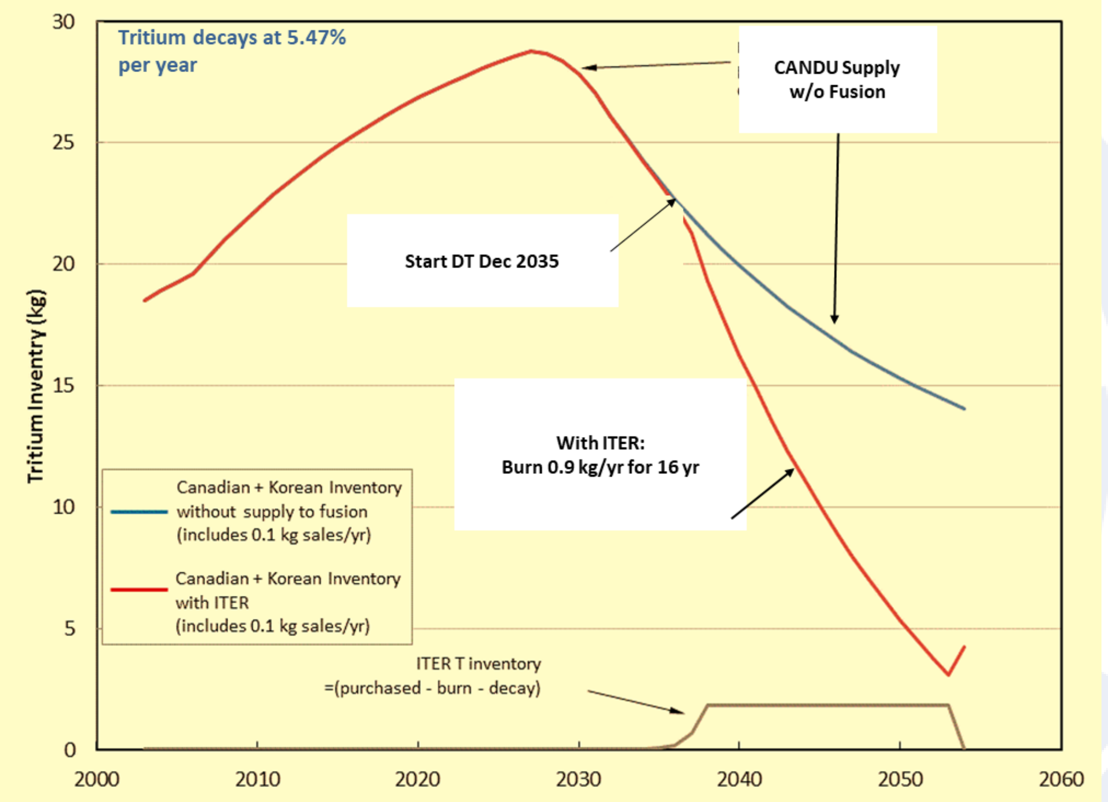
2 DEMO was conceived to have **two distinct phases** of operation: a **qualification phase DEMO phase 1 (20 dpa),** to qualify technologies and processes in a fusion nuclear environment, and **a nuclear operation phase DEMO phase 2 (50 dpa**), to demonstrate the feasibility of fusion as a source of energy. **This introduces a high failure risk**

3 Tritium fuel consumption in fusion is huge. **55.8 kg per 1000 MW fusion power per year.** This tritium will not be available from external sources, which means that **must breed effectively (TBR>1) from day-1 during the qualification phase**. **This introduces a high failure risk**

4 To qualify components and processes, DEMO will have to operate with a relatively high availability already during phase 1. However, because none of the DEMO components will have previously been qualified in a representative fusion nuclear environment. **This introduces a high failure risk.**

Tritium Consumption and Production

- **Tritium Consumption in Fusion Systems is huge:**
  - **55.8 kg per 1000 MW fusion power per year**
  - **For 2000 MW Fusion Power Plant (~500 MWe): 112 kg/year;** 0.31 kg/day; 0.012 kg/hour
- **Tritium Production in Fission Reactors is much smaller (and cost is very high)**
  - LWR (with special designs for T production): ~ 0.5 kg/year ($84M-$130M/kg per DOE Inspector General*)
  - Typical CANDU produces ~ 130 g per year (0.2 Kg per GWe per full power year) (T is unintended by product)
  - CANDU Reactors/Ontario Hydro: 27 kg from over 40 years, $30M/kg (current), CERNAVODA (158 M€ / kg)



Note: Fission reactor operators do not really want to make tritium because of permeation and safety concerns. They want to minimize tritium production if possible

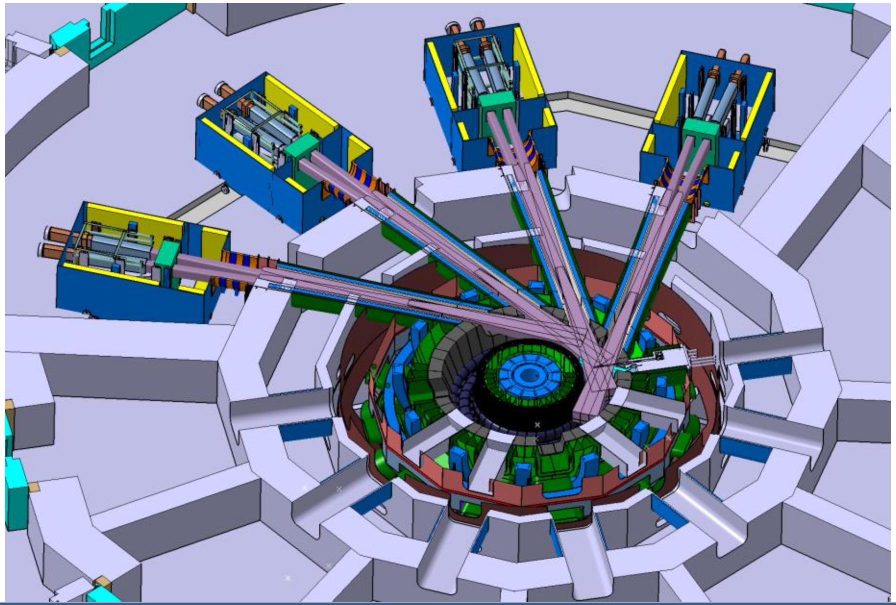
Source: M. Abdou (UCLA)

M. Abdou, Invited Lecture, MaPLE-U Inauguration, KIT 10-14-2022

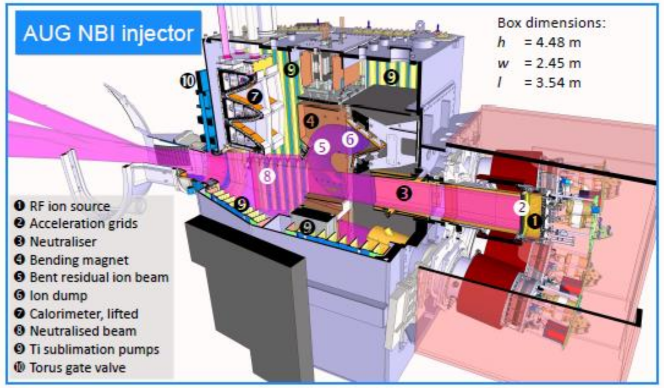
Issue: With ITER DT start in 2040, there will be not much external non-fusion supply of tritium left to provide "Start up" T inventory for any major DT Fusion facility beyond ITER

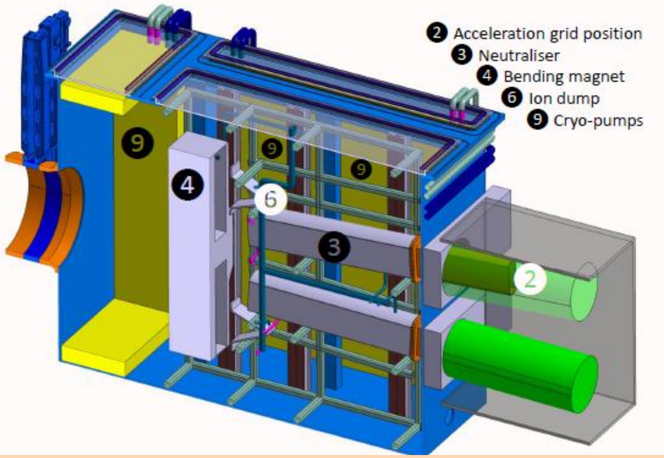
Neutral Beam Injector

- **NBI System**:
  - D-injection into T-rich plasma
  - Tangential injection, 120 keV positive ion beams
  - 42 MW total power (14 MW per injector)
  - 4 injectors: 3 operating, 1 regenerating
  - 4 sources/injector, 3.5 MW each (vs. AUG: 2.5 MW)
- **Operation**:
  - Steady-state, non-inductive current drive
  - Pulse length: 3–6 hours
  - Regeneration time: pulse length ÷ 3



FEATURE	VNS	AUG
Beam Power/Source	3.5 MW	2.5 MW
Total Power	42 MW (3 injectors active)	~20 MW
Beam Energy	120 keV	60–93 keV
Pulse Length	3–6 hours	~10 seconds
Operation Mode	Steady-state (non-inductive)	Pulsed
Injector Setup	4 injectors (3 active, 1 regen)	2 injectors



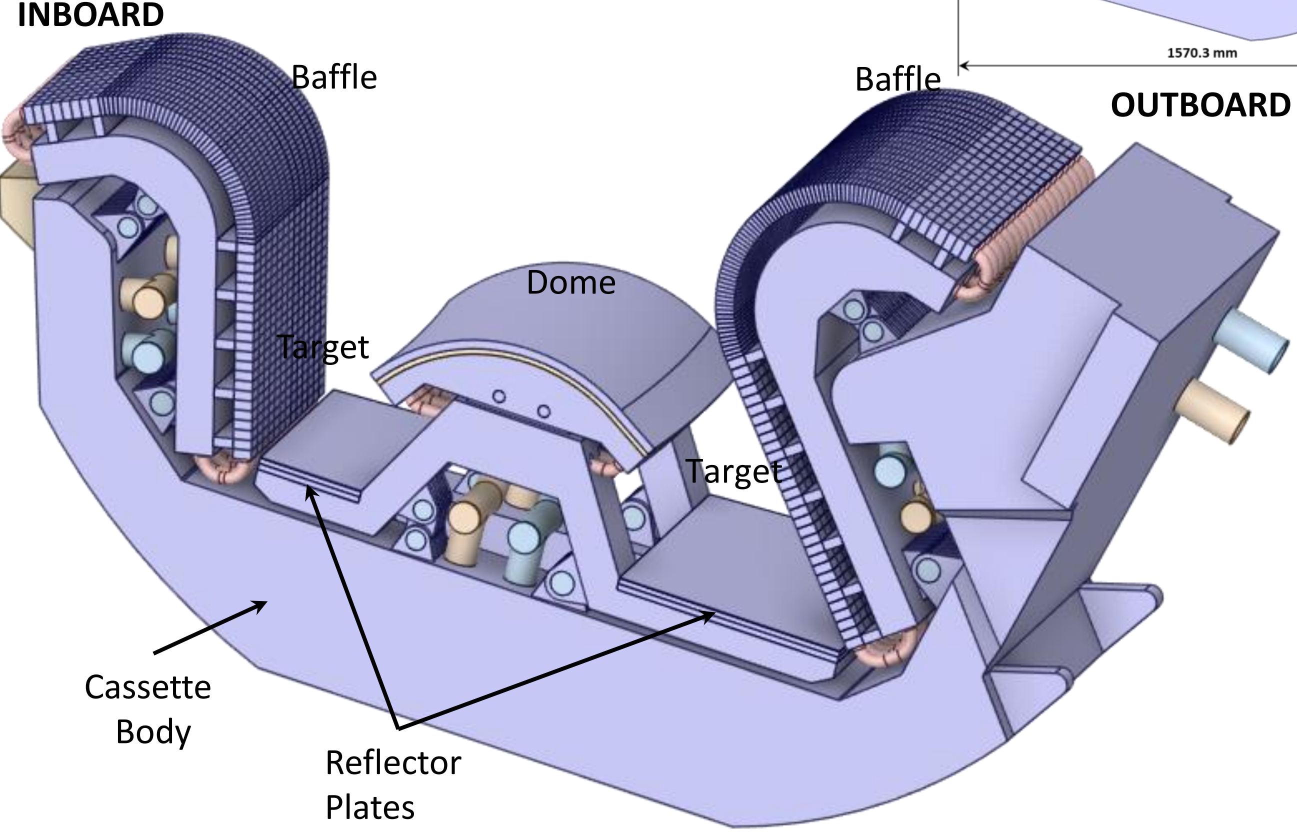


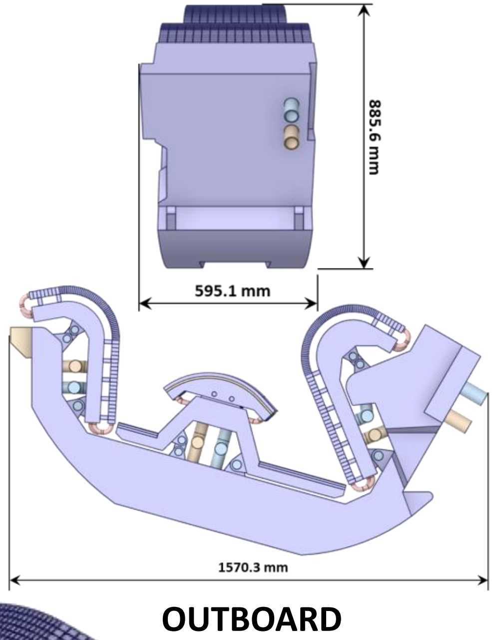
C. Hopf et al., Neutral Beam Injection for a Tokamak-based Volumetric Neutron Source, FED,213 (2025), 114870

- **12 TF coils allow the integration of an ITER-like NB duct in-between TF coils.**
- **Endurance performances and overall reliability to be demonstrated via tailored R&D program**

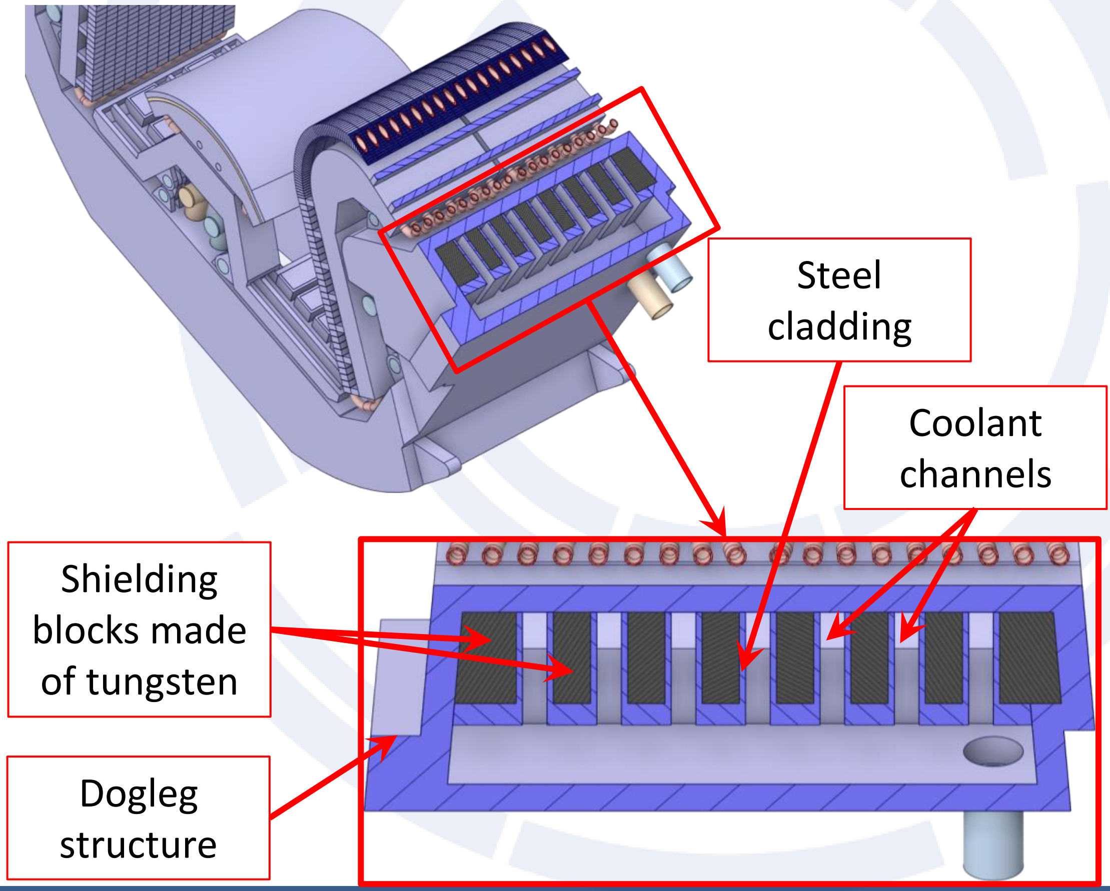
Divertor

Design:
- Structural material: 316Ti
- Water coolant: T_{in} = 50 °C and p_{in} 3.5 Mpa
- ITER-like PFCs: Targets with W-monoblocks





- The **VNS Divertor Design has been adapted to the VNS new design point**, available since March 2025.
- To **improve neutron shielding**, dogleg structures have been added at the outboard, together with box-like tungsten inserts both at the outboard and below Reflector Plates.

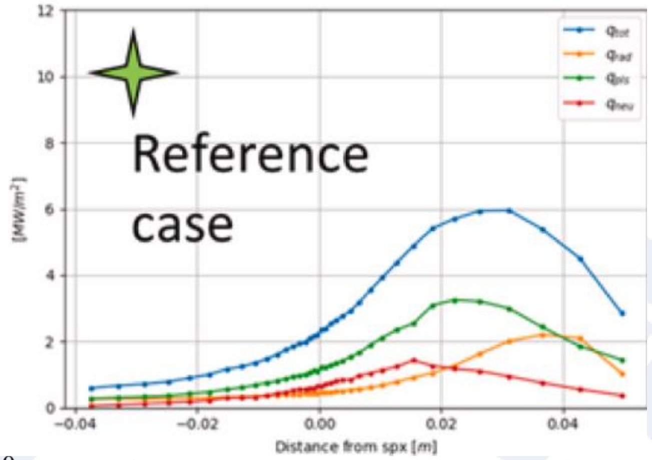


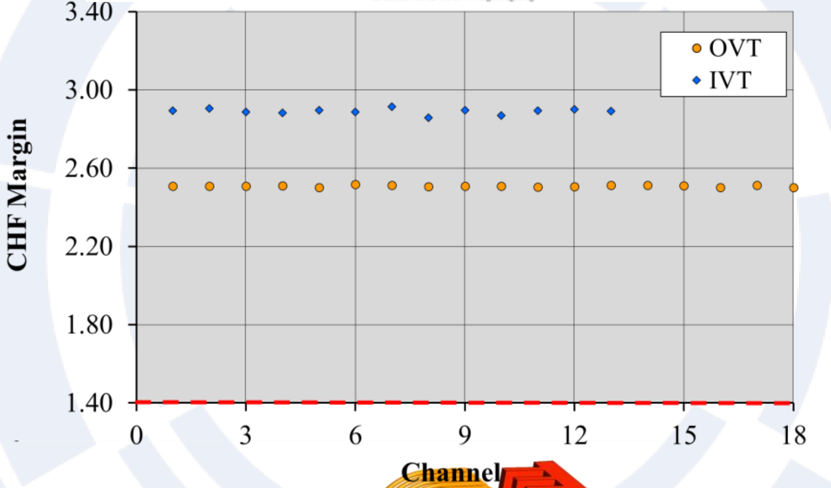
Divertor (cont’d)

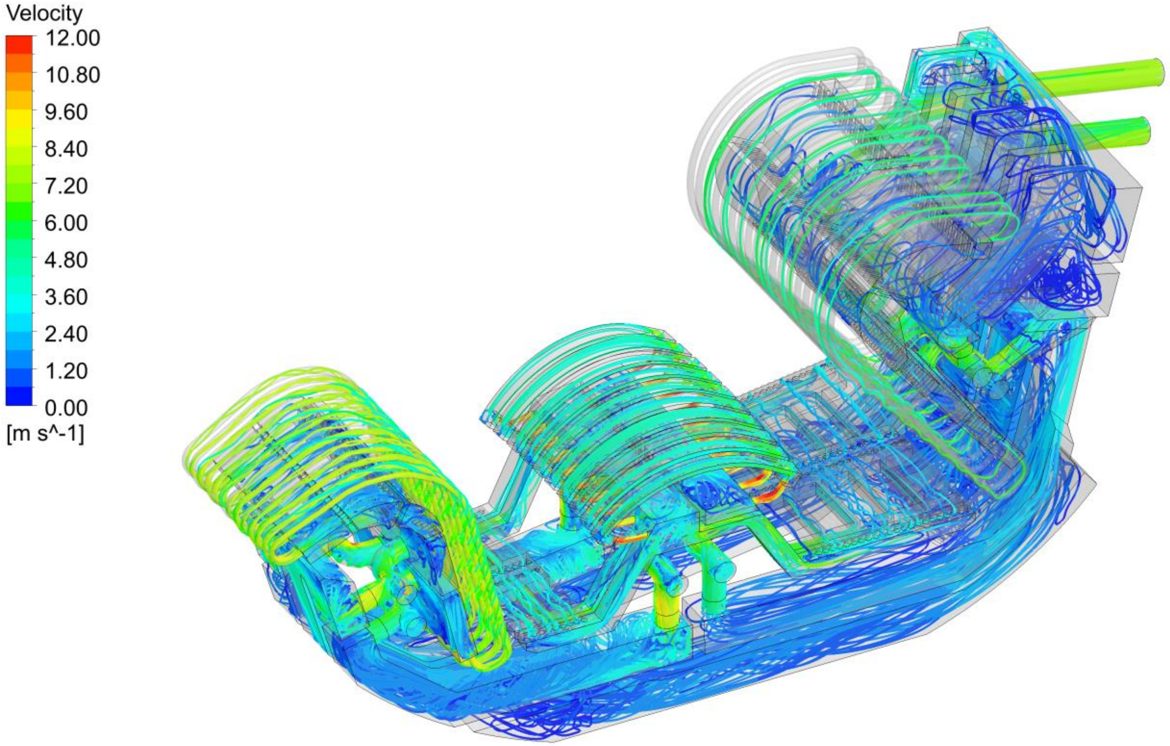
3D CFD analyses to test behaviour of the divertor cassette under relevant design scenario

IVT and OVT

- Tested **against 10 MW/m²**
- Expected SS heat fluxes around 6 MW/m²

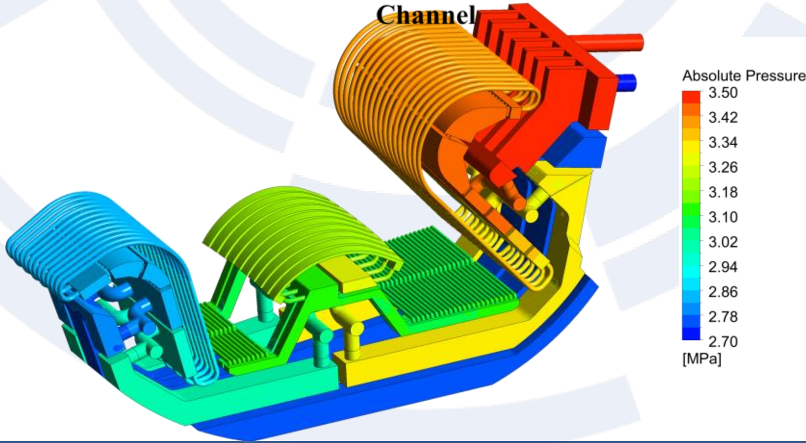






p_{in}=35 bar
$\dot{m}$=9 kg/s
T_{ave}≈70°C

Δp=7.4 bar
M_{CHF}>2.5



Recent EUROfusion VNS – related publications

1 G. Federici - Testing Needs for the Development and Qualification of a Breeding Blanket for DEMO, Nucl. Fusion 63 (2023) 125002.

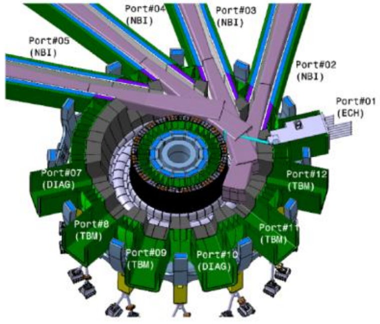
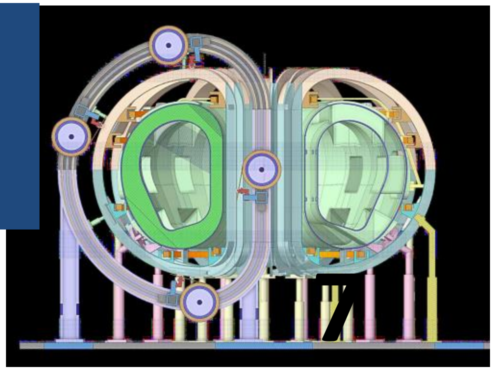
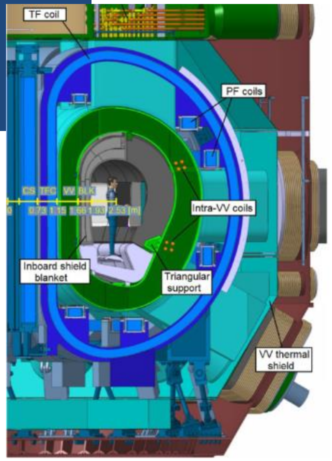


Fig. 2. System allocation to equatorial ports.

2 L. Giannini et al. – Innovative Coil Fabrication and Assembly Concept Integration of an Inverted Magnetic Cage for the VNS Magnet System, Fus. Eng. Des. 205 (2024) 114530.



3 D. Leichtle – Pre-conceptual neutronics and shielding assessment of a beam-driven tokamak VNS, to appear in Fusion Technology

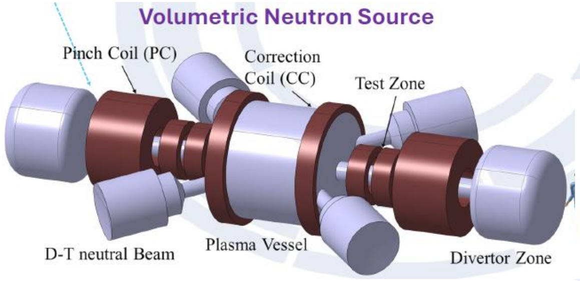


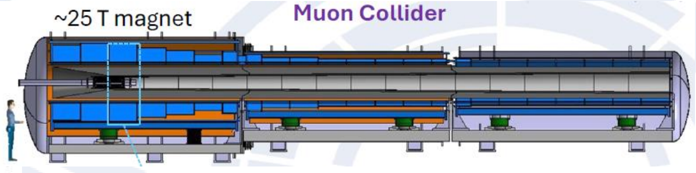
4 C. Bachmann et al. – Engineering concept of the VNS - a beam-driven tokamak for component testing , Fus. Eng. 211 (2025) 114796.

5 C. Hopf et al. – Neutral Beam Injection for a Tokamak-based VNS, Fus. Eng. Des. 213 (2025) 114870

6 M. Siccinio et al. – Physics Basis for a Volumetric Neutron Source for component testing and qualification , to be submitted to Nucl. Fusion

7 L. Giannini et al., Advances in Magnet and Shielding Designs for Fusion and High Energy Physics Applications, 214 (2025) 114899.





+ others still in review process