

ITER TCWS Tokamak Cooling Water System

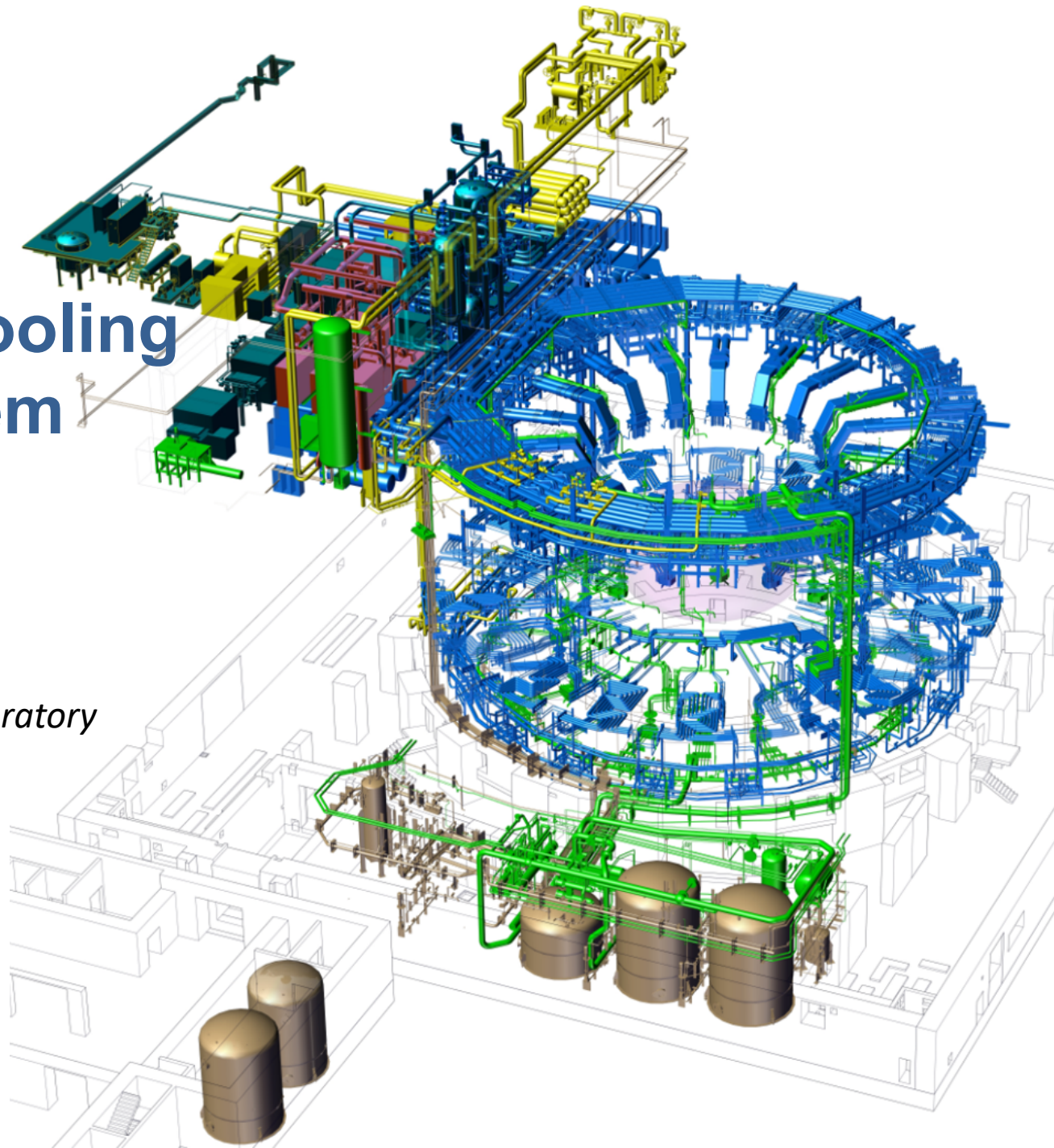
Walter Van Hove

US ITER Project

Oak Ridge National Laboratory

BNS Evening Lecture

February 25, 2021



- ITER project
- Overview of the TCWS
- Unique challenges for the TCWS
- Manufacturing and installation

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ITER project



- Collaborative effort between 7 partners
- Build and operate a Tokamak
- Demonstrate the technical feasibility of fusion as an energy source
- Build in Cadarache, France



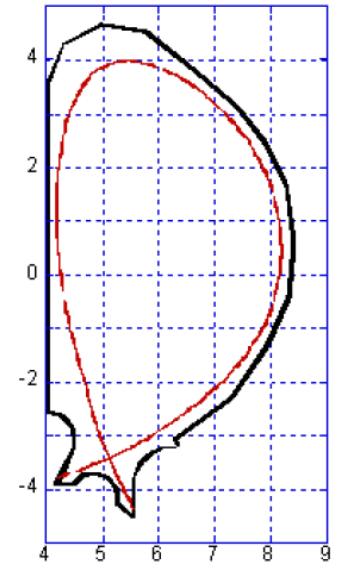
ITER site



ITER project - objectives



- Experiment with burning plasmas
- Realize fusion of D-T
$${}^2_1\text{H}^+ + {}^3_1\text{H}^+ \rightarrow {}^4_2\text{He}^{2+} (3.6 \text{ MeV}) + n (14.1 \text{ MeV})$$
 - 500 MW of fusion power during 450 sec
 - $Q \geq 10$
 - Short pulses up to 700 MW
- Some performance parameters
 - Major radius 6.2 m, minor radius 2 m
 - Plasma volume 816 m³
 - Magnetic field 5.3 T
 - Plasma current 15 MA
 - Additional plasma heating up to 73 MW by high frequency electromagnetic waves (ICH, ECH) and Neutral Beam Injection (NBI)

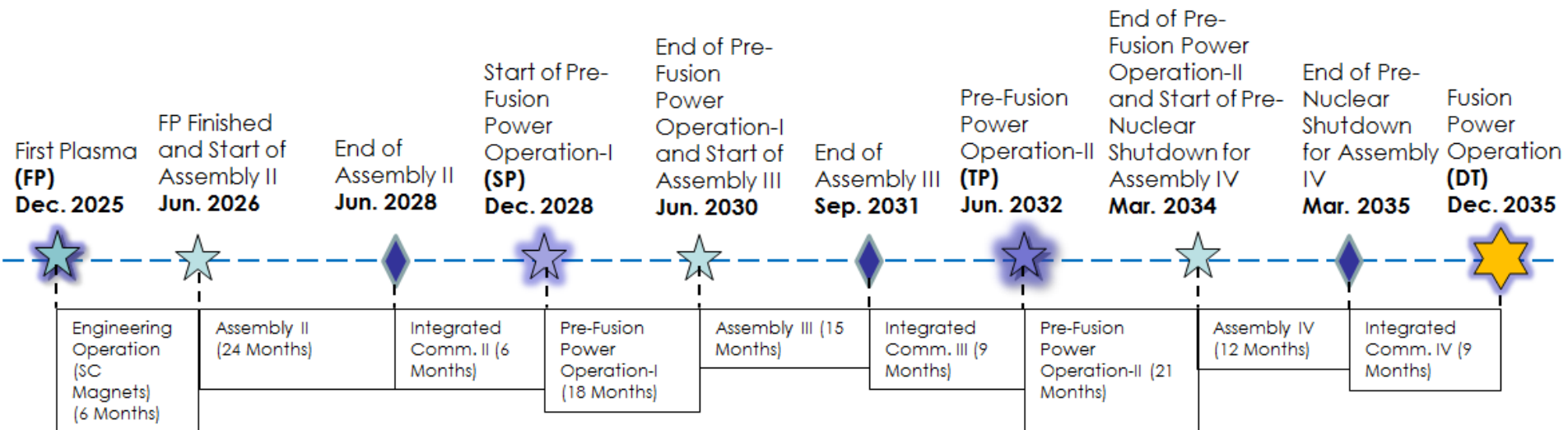


ITER Staged approach

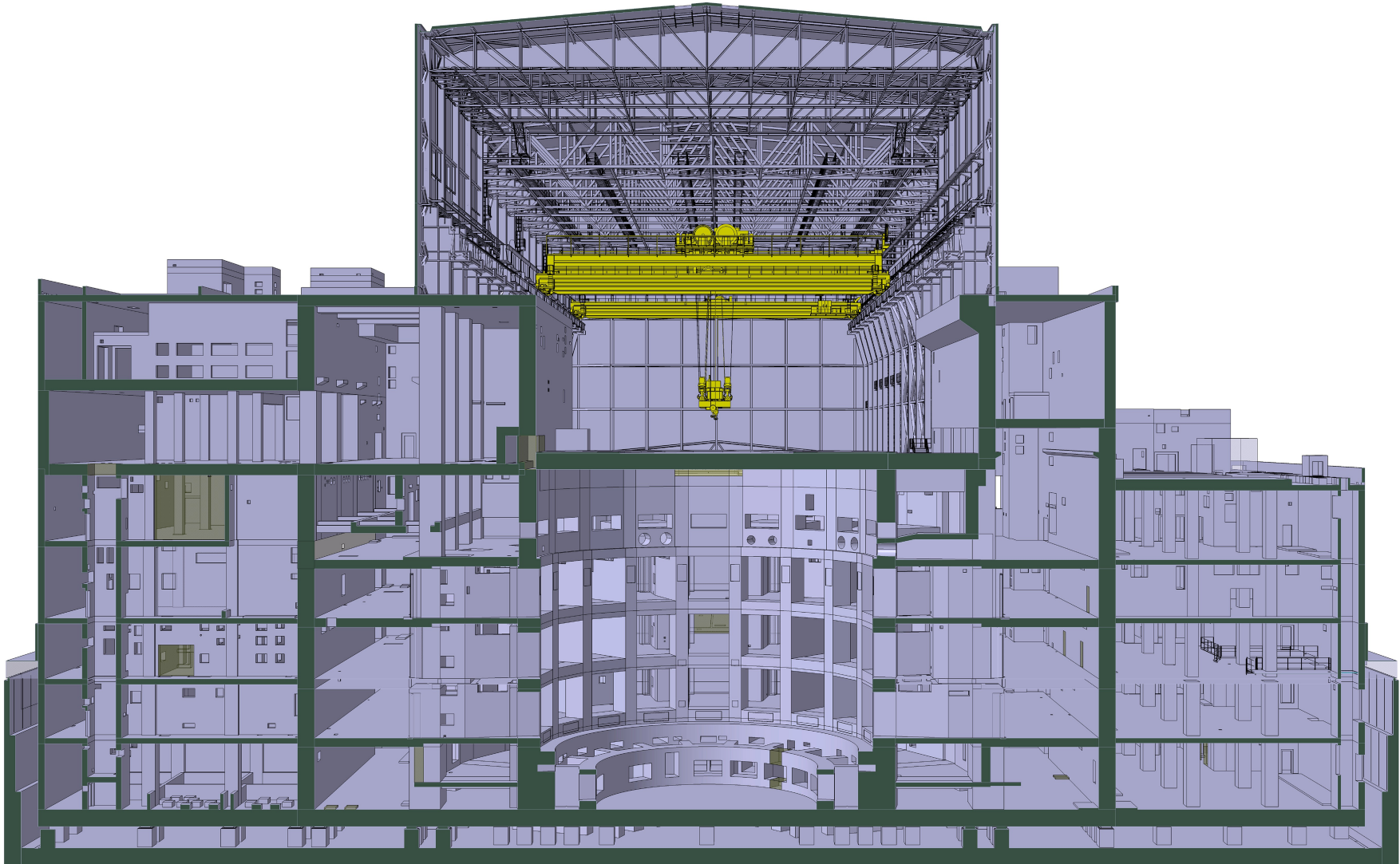


Outline Research Plan Structure

(Staged Approach Durations: 120 Months [10 Years] from FP to DT)



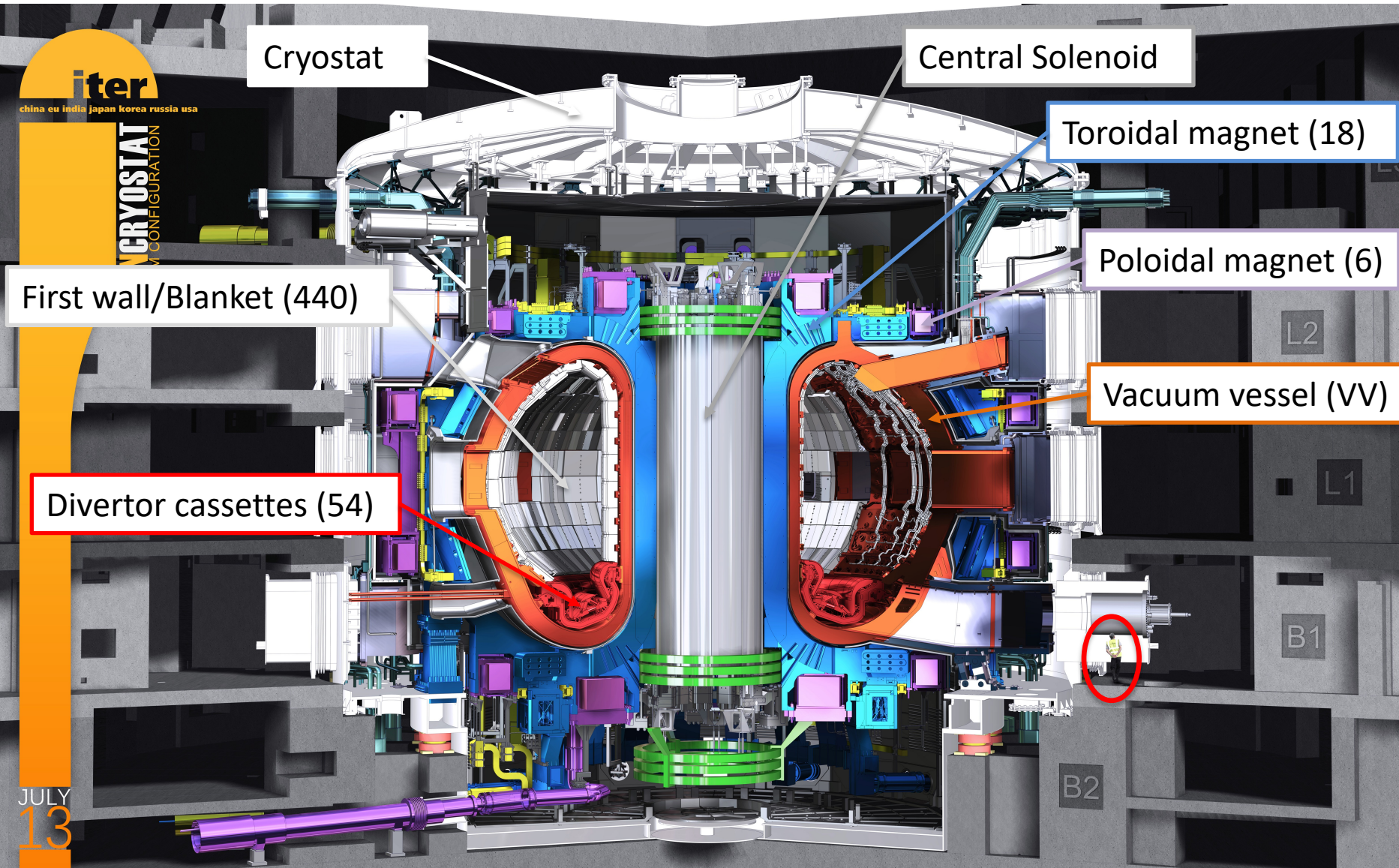
ITER Tokamak building



ITER Tokamak building



ITER Tokamak major components



iter
china eu india japan korea russia usa

CRYOSTAT
CONFIGURATION

First wall/Blanket (440)

Divertor cassettes (54)

Cryostat

Central Solenoid

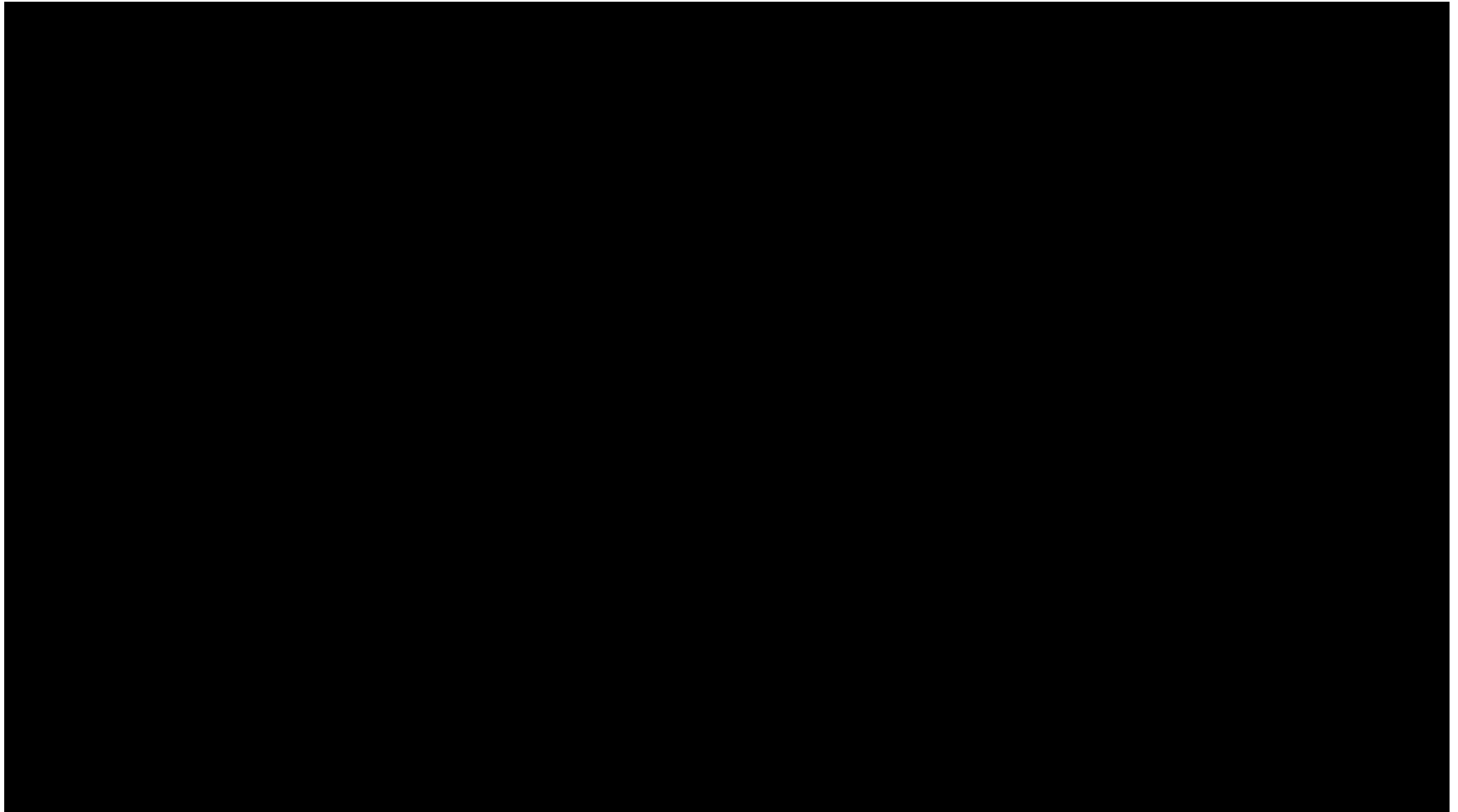
Toroidal magnet (18)

Poloidal magnet (6)

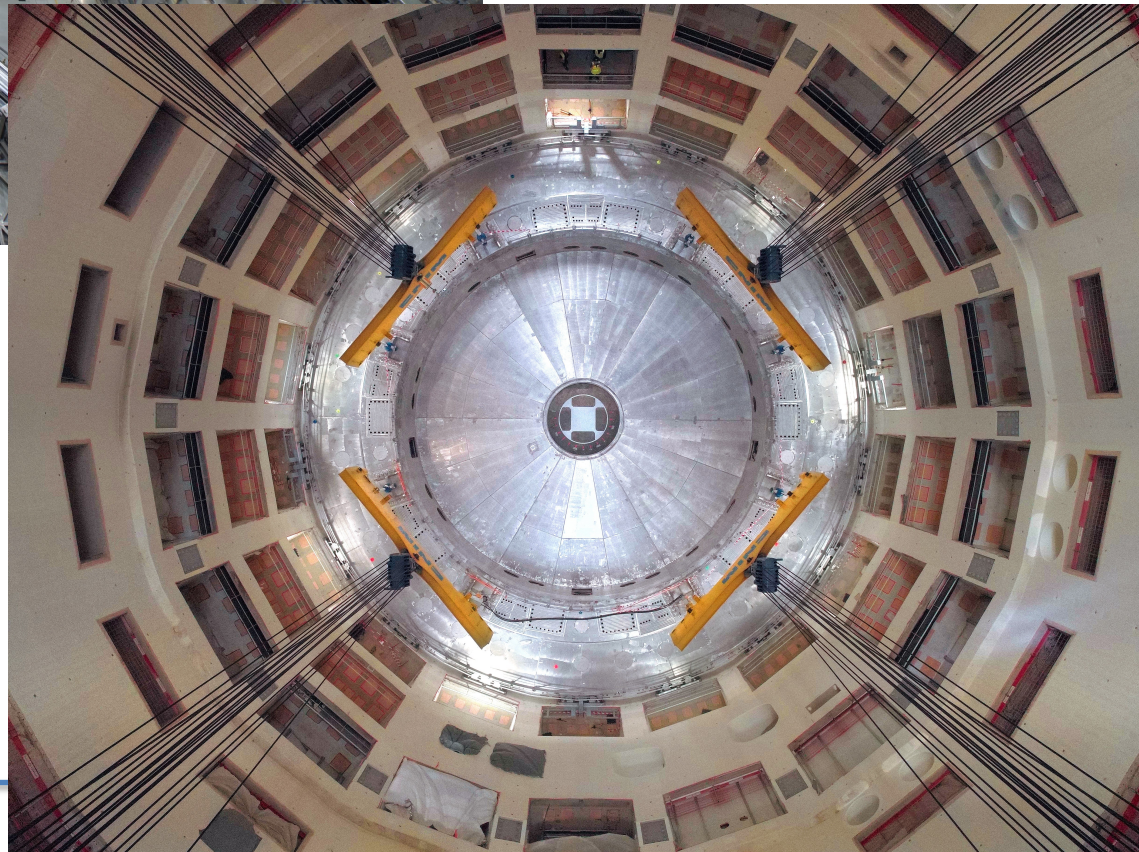
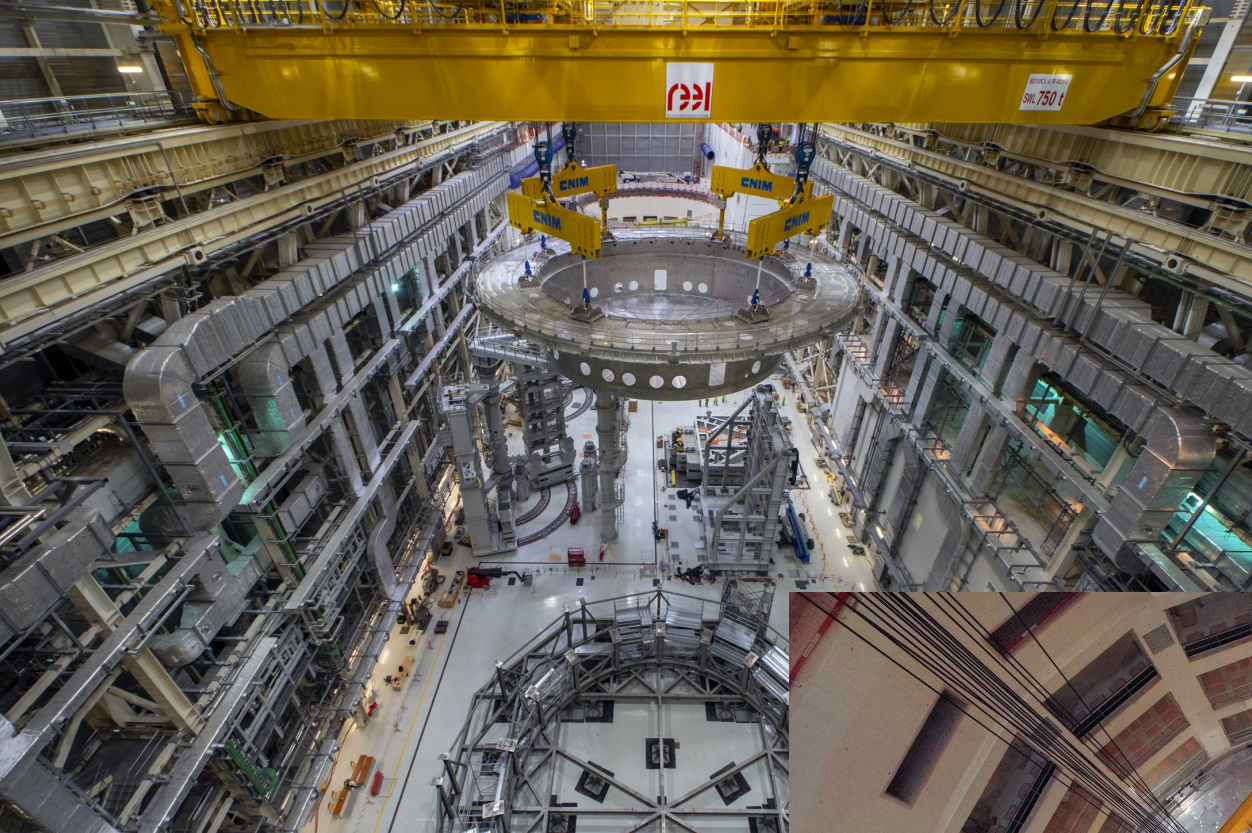
Vacuum vessel (VV)

JULY
13

ITER fly through







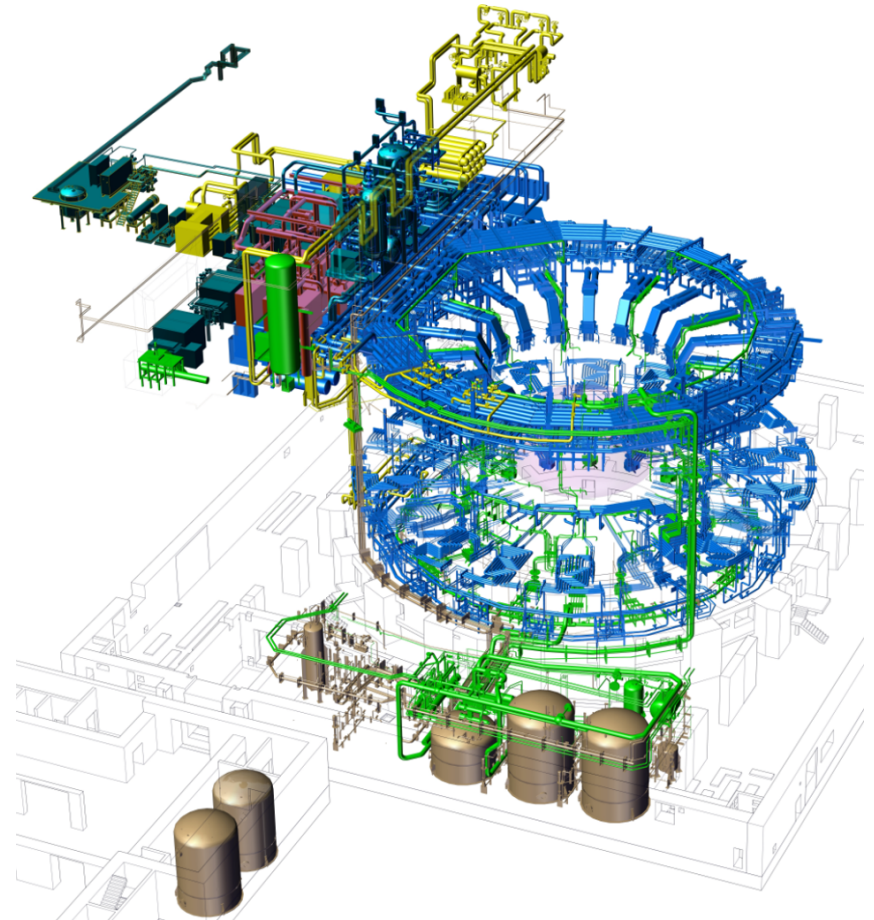


- Let's take a closer look now at the Tokamak Cooling Water System



TCWS Tokamak Cooling Water System

- Cools the plasma facing components, VV and NBI
- Transports the heat out of the Tokamak and to the CCWS
- Provide “baking” for VV and in-vessel components



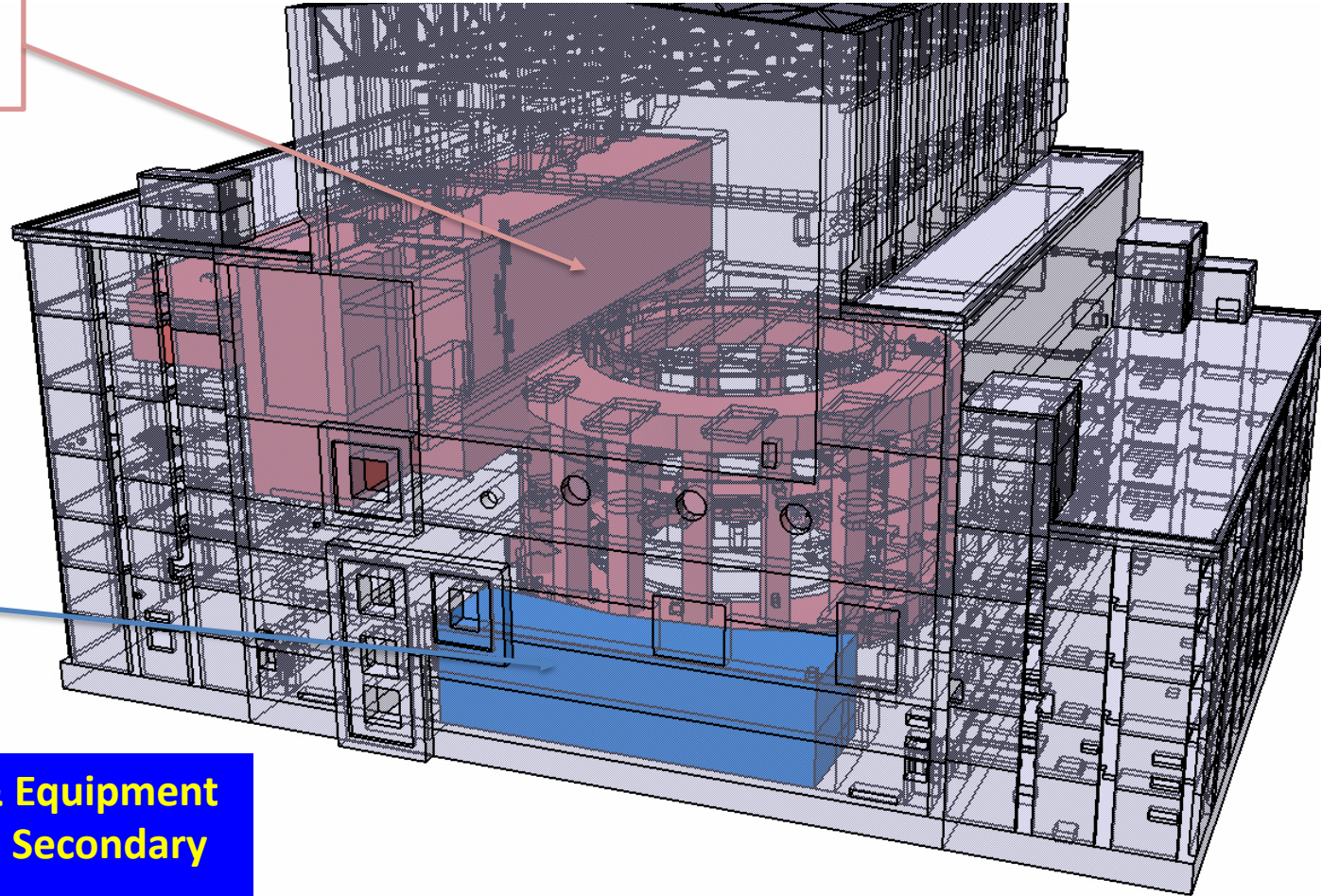
- Remove heat from TCWS client systems
- Transfer heat from client systems to CCWS
- Control coolant pressure, temperature and flow within required limits (CHF margin !)
- Provide baking for VV and in-vessel components
- Measure heat removed from VV, FW/BK, DIV, NBI
- Control the chemistry of the cooling water provided to the client systems (limit corrosion)
- Provide the capability to drain, dry and refill the TCWS and client systems for maintenance, leak detection and leak localization

- Provide primary **Confinement** for radioactive products
 - activated corrosion products (ACP), tritium, ^{16}N , ^{17}N
- Provide **Decay Heat Removal** capability in case of loss of power
- Provide **Safety Draining** of plasma chamber (water contains highly radioactive dust)
- Provide **Safety Signals** from TCWS to the Fast Plasma Shutdown System

TCWS Vault & Drain Tank Room

TCWS Vault
1 bar overpressure

Drain Tank Room
1 bar overpressure



**Entire TCWS Piping & Equipment
Are Placed Inside the Secondary
Confinement.**

TCWS – 7 subsystems



- TCWS has 3 PHTS and 4 supporting systems
- PHTS Primary Heat Transport System
 - IBED PHTS (Integrated Blanket Elm coil and Divertor)
 - VV PHTS
 - NBI PHTS
- Supporting systems
 - DRS DRaining System
 - DYS DrYing System
 - CVBD Chemical and Volume control for IBED PHTS
 - CVNB Chemical and Volume control for NBI PHTS

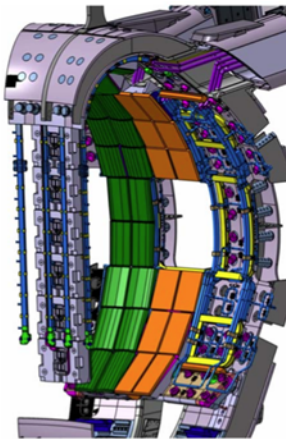
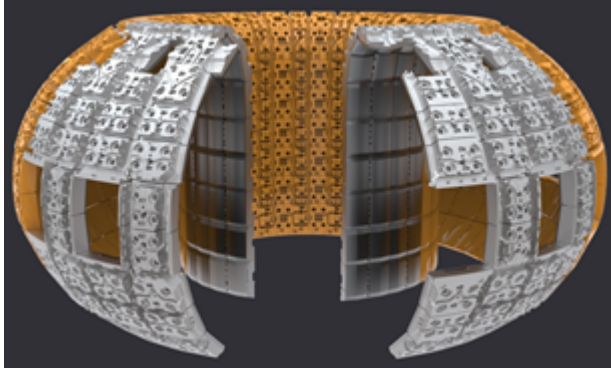
PHTS Plasma Operating Conditions



Main Design Parameters of Three PHTSs for Plasma Operations

Primary Heat Transfer Systems	Heat Removal (MW)	Flow Rate (kg/s)	Temperature (°C)	Pressure (MPa)	Water Volume (m ³)
IBED PHTS	880	4,770	70 – 126	4.0	464
NBI PHTS	85 (125)	714 (1042)	38 – 60	2.2	129
VV PHTS	32	950	100 – 110	0.8	401

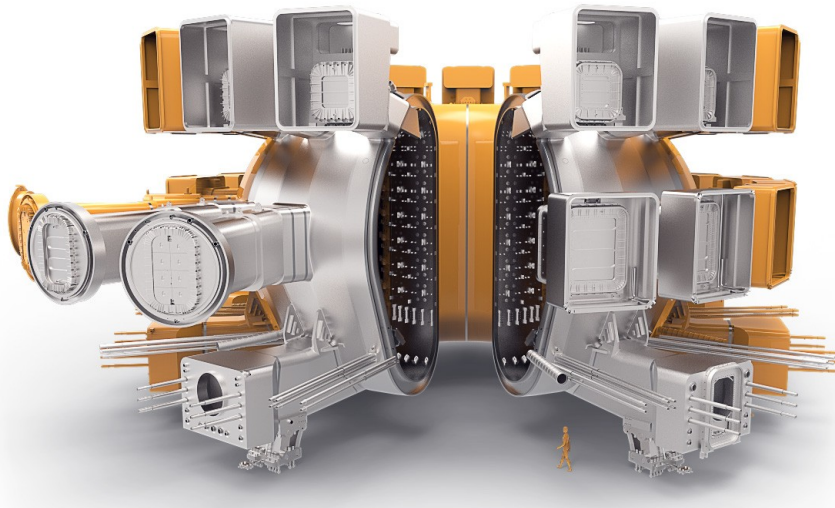
IBED PHTS Heat Input



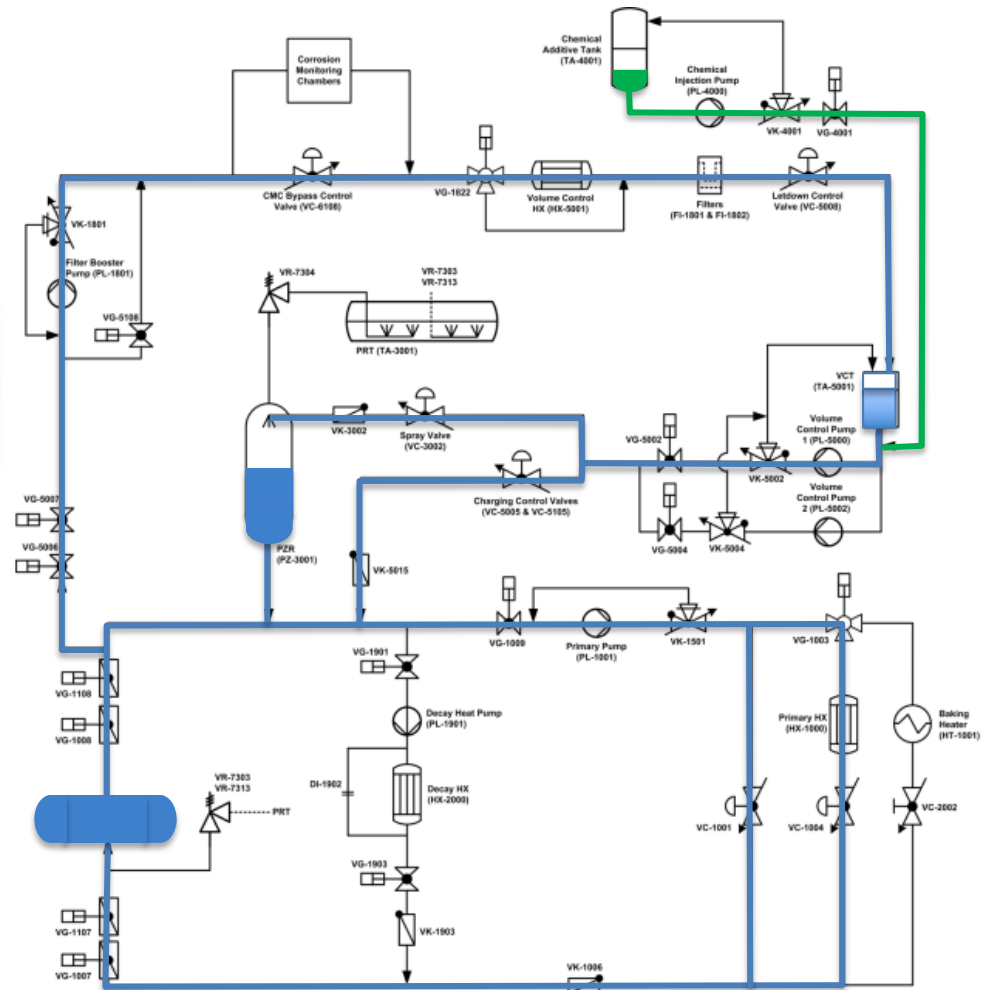
- Cools all the plasma facing components
 - 440 blankets, 639 MW
 - 54 DIV cassettes, 154 MW
 - 37 in-port components, 54 MW
 - 29 in-vessel magnetic coils, 12 MW
 - 8 circulation pumps 20 MW
- Total 880 MW

- Together with the client system a closed loop
- Pressurized with (steam or gas) pressurizer
- Heat exchanger(s) to CCWS
- Circulation pump(s)
- Expansion tank (Volume Control Tank)
- Electrical heater for baking
- Network of distribution piping
- Control, isolation and check valves

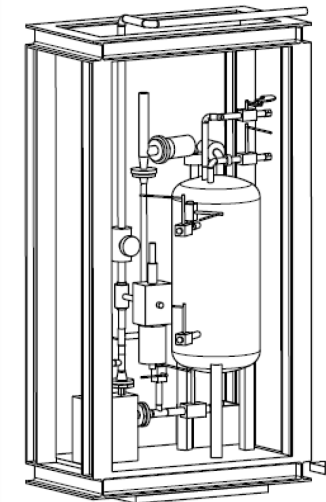
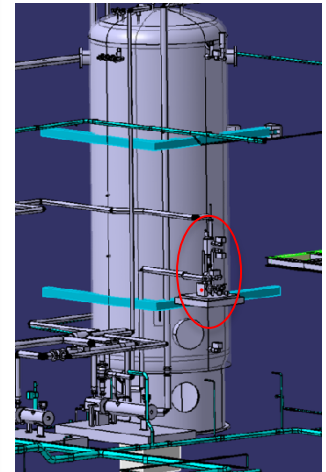
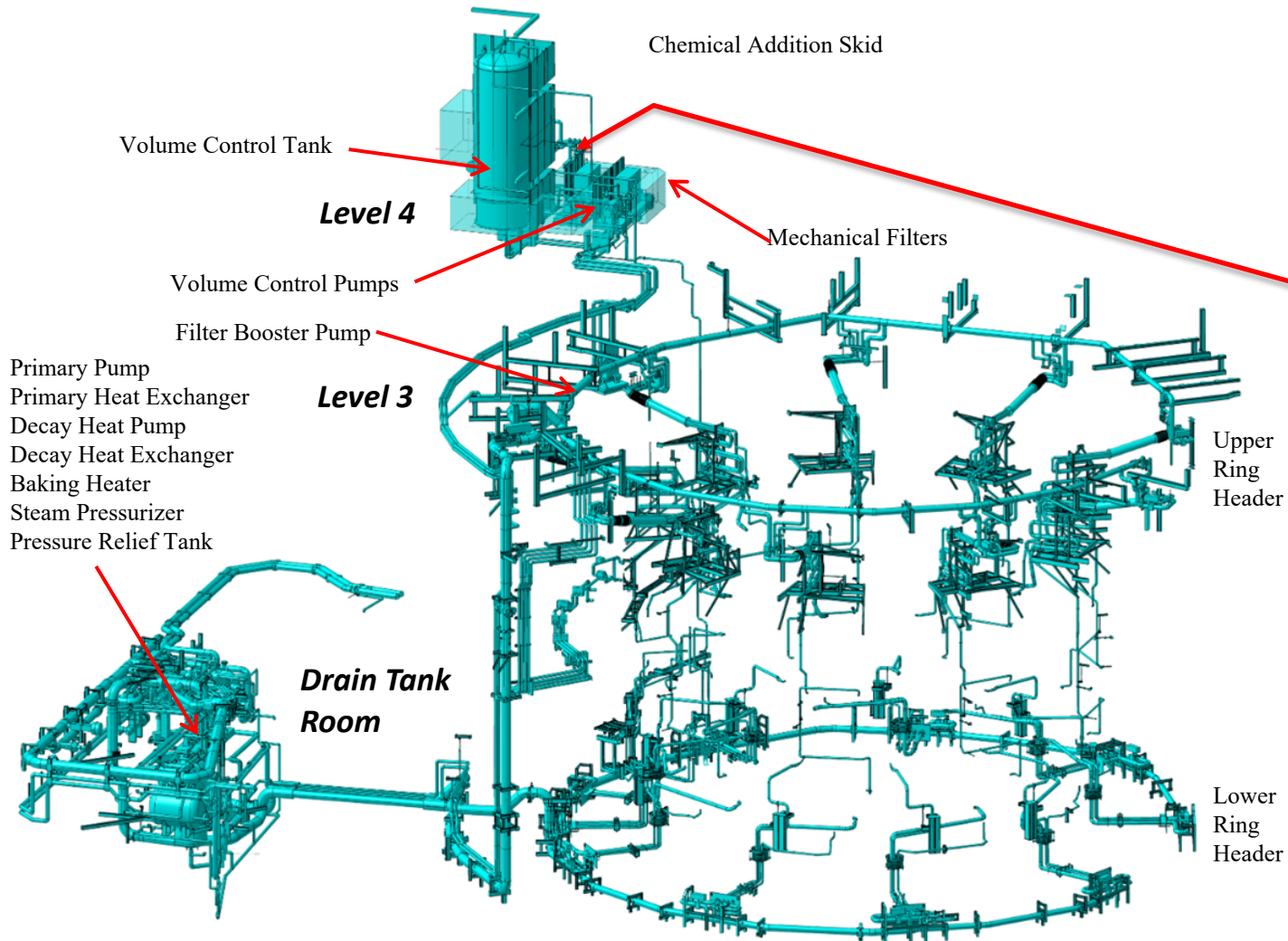
VV PHTS Process Flow Diagram



Removes 32 MW of heat from the VV



VV PHTS Layout



PHTS Baking Operating Conditions

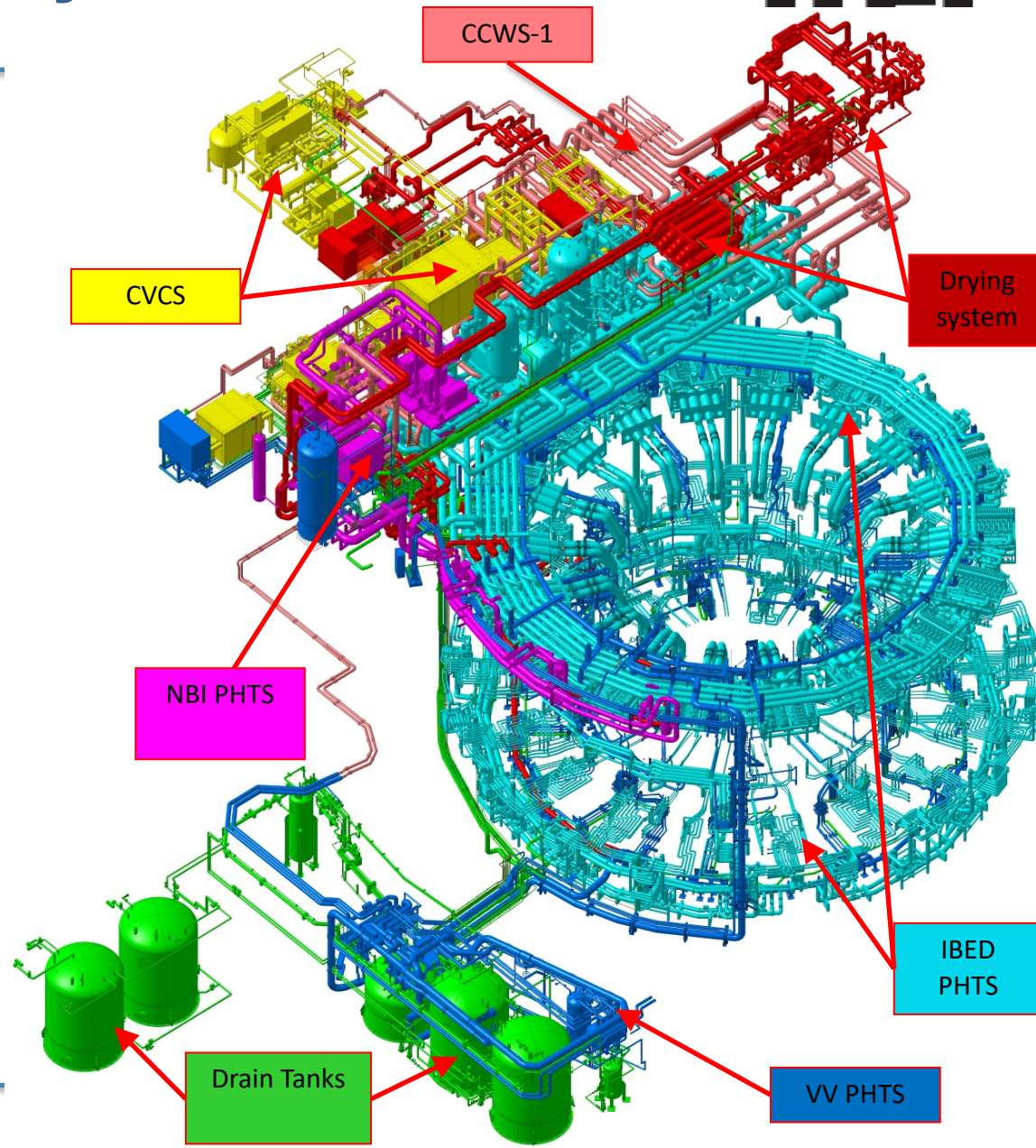


Main Design Parameters during Baking

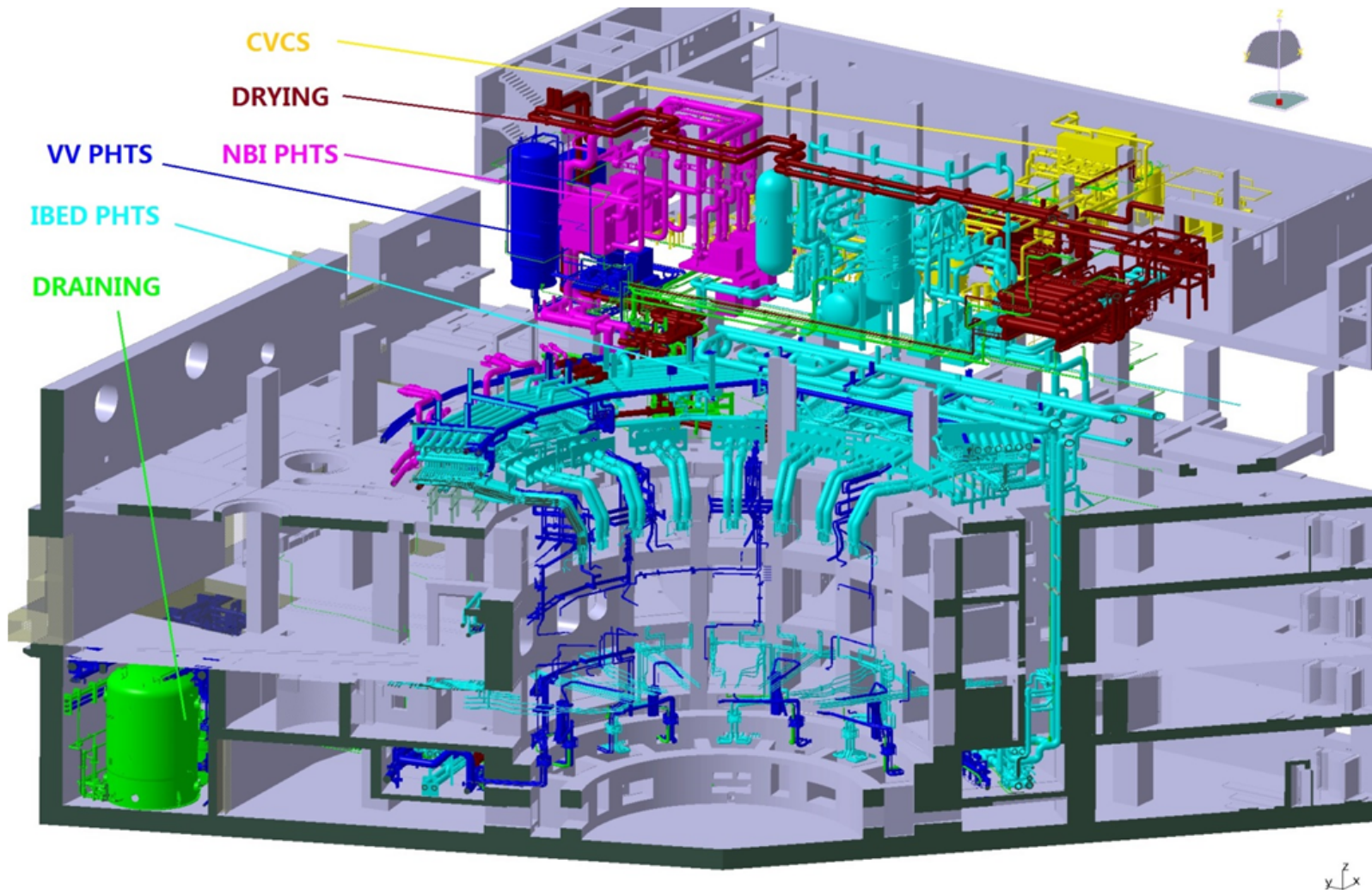
Primary Heat Transfer Systems	Flow Rate (kg/s)	Temperature (°C)	Pressure (MPa)
IBED PHTS	480	240	4.4
DIV gas baking	22 nitrogen	350	3.0
VV PHTS	500	195	2.1

The VV inner wall and all in-vessel components need to be “**baked**” from time to time at high temperature to remove impurities from their surface that can otherwise prevent the high purity of the vacuum needed for the plasma.

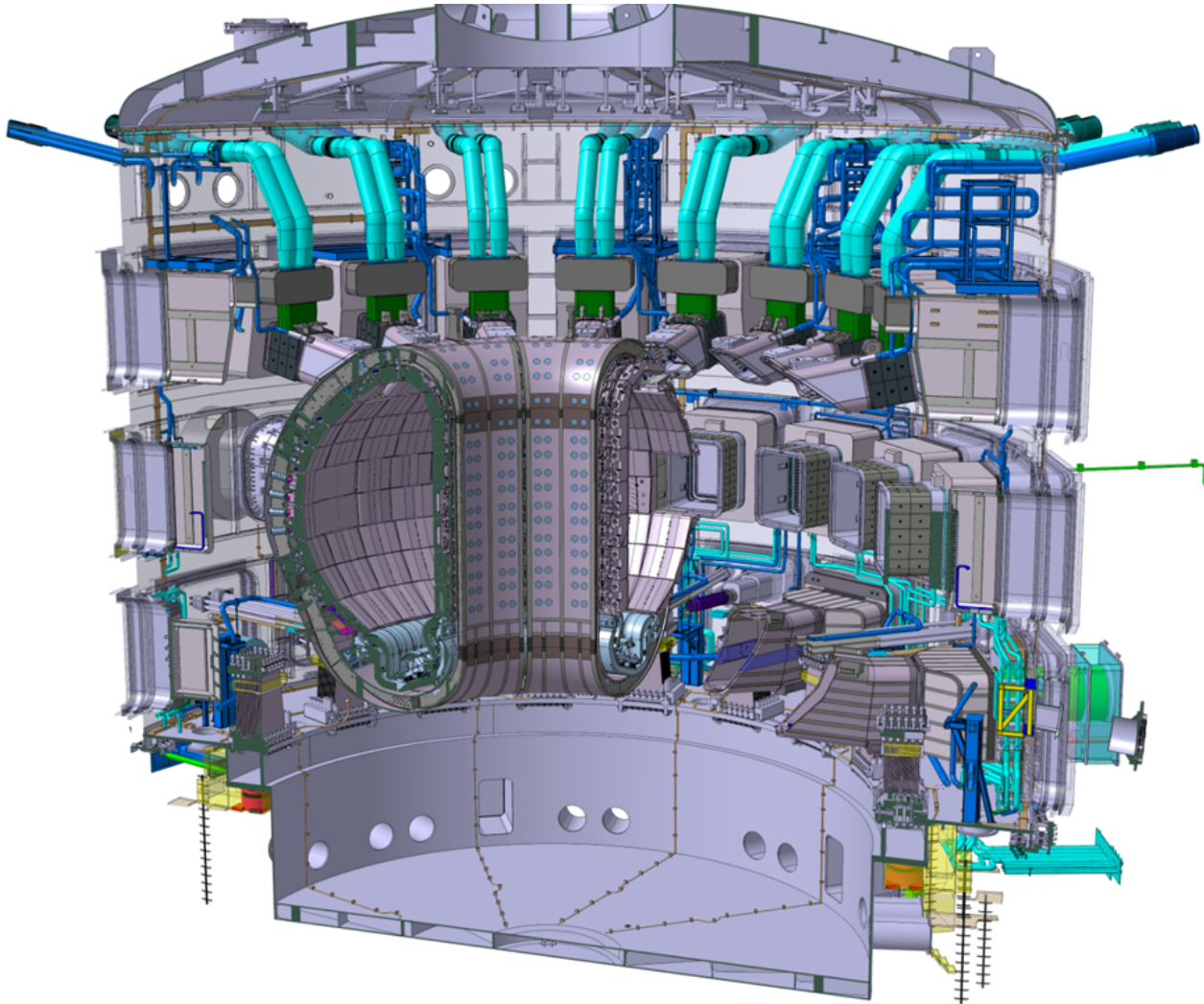
TCWS General Layout



TCWS in building



TCWS in cryostat



TCWS in numbers



- 1000 MW of heat removal capacity
- 36 km of stainless-steel pipes Ø 25 to 500 mm
- about 3000 valves
- 40.000 hp of pumping power
- 1.000.000 liter of cooling water
- operating pressure up to 50 bar
- operating temperature up to 240°C water / 400°C gas

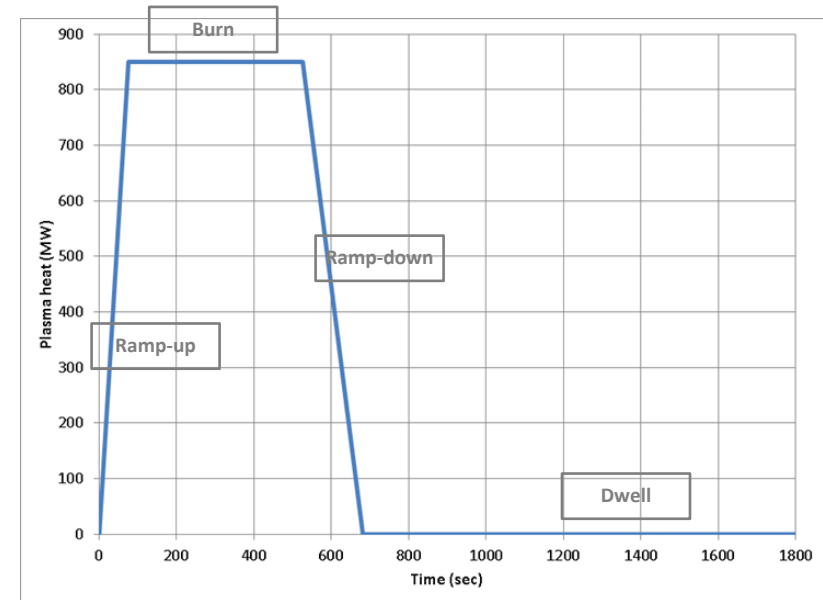
Some unique challenges



- Pulsed operation/non uniform heat distribution
- ^{16}N and ^{17}N isotopes
- Magnetic field
- Qualification
- Drying of the client systems

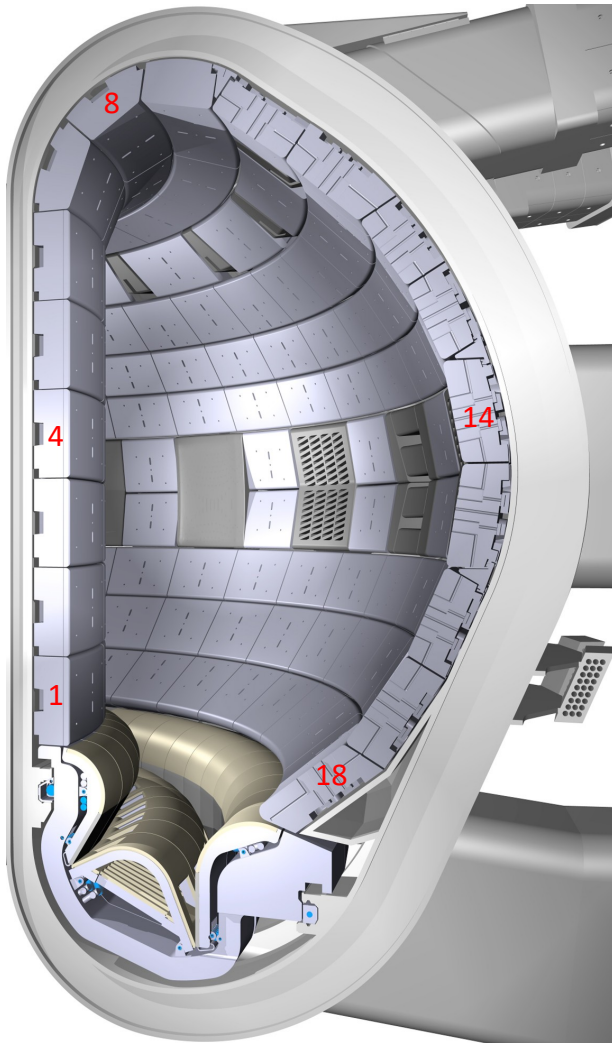
Pulsed operation

- Heat input is pulsed
- Design condition for the TCWS is 30000 inductive pulses

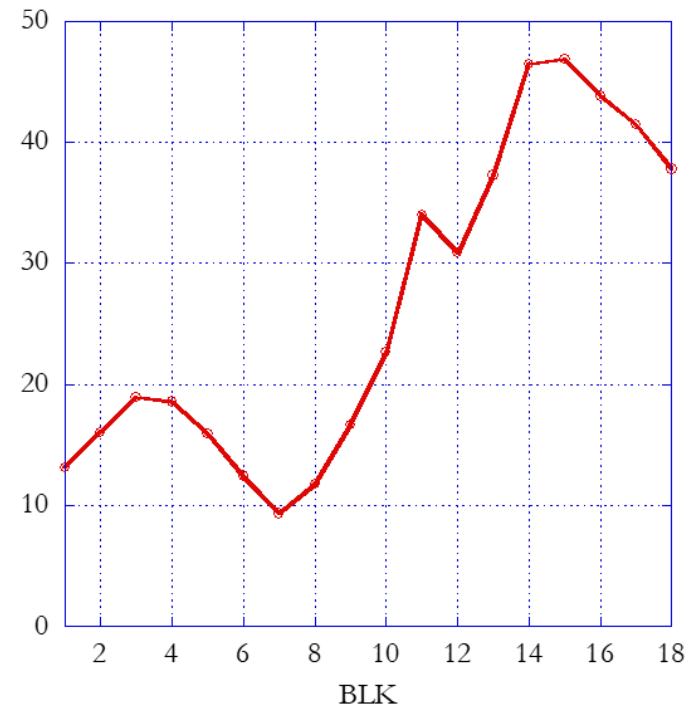


Parameter	Inductive Operation	Hybrid Operation	Non-Inductive Operation
Fusion Power (MW)	500	400	356
Burntime (s)	450	1000	3000
Repetition time (s)	1800	4000	12000

Toroidal heat distribution



Nuclear heat, MW



Each of the 440 blankets and 54 divertors needs a correctly tuned flow

First wall Critical heat Flux Margins



Modules	Module Type	Total Number of Circuits	Mass Flow Rate in One Circuit	Local Pressure	Local Velocity	Local Temperature	ACHF	Nuclear Contribution	Peak Heat Flux	Initial CHF Margin after 1 st Step	Final CHF Margin
			(kg/s)	(MPa)	(m/s)	(°C)	(MW/m ²)	(MW/m ²)	(MW/m ²)		
1	NHF	16	0.268	3.325	1.47	143.90	4.449	0.074	2.07	2.429	2.145
2	NHF	16	0.305	3.325	1.68	144.14	4.729	0.118	2.12	2.531	2.233
3	EHF	20	0.384	3.325	1.80	150.87	6.810	0.120	4.82	1.197	1.413
4	EHF	20	0.383	3.325	1.80	150.93	6.804	0.120	4.82	1.182	1.412
5	EHF	20	0.369	3.325	1.73	148.20	6.781	0.092	4.79	1.115	1.415
6	NHF	16	0.258	3.325	1.42	145.94	4.330	0.074	2.07	2.365	2.088
7	EHF	16	0.350	3.325	1.65	145.00	6.731	0.056	4.76	1.301	1.415
8	EHF	14	0.424	3.325	1.99	139.74	7.592	0.071	4.77	1.802	1.591
9	EHF	14	0.549	3.325	2.58	130.82	9.071	0.080	4.78	2.142	1.898
10S	NHF	16	0.370	3.325	2.03	138.09	5.352	0.114	2.11	2.865	2.531
11	NHF	18	0.279	3.325	1.53	149.39	4.405	0.149	2.15	2.329	2.050
12	NHF	16	0.279	3.325	1.53	159.37	4.184	0.172	2.17	2.200	1.926
13	NHF	14	0.412	3.325	2.26	137.17	5.669	0.190	2.19	2.683	2.589
13 (dogleg)	NHF	14	0.412								
14S (9°)	EHF	20	0.396	3.325	1.86	152.38	6.856	0.154	4.85	1.229	1.413
14S (dogleg)	EHF	20	0.396	3.325	1.86	152.38	6.856	0.154	4.85	1.229	1.413
14C (11°)	EHF	20	0.419	3.325	1.97	156.94	6.870	0.154	4.85	1.403	1.415
15S (9°)	EHF	20	0.396	3.325	1.86	152.36	6.855	0.156	4.86	1.238	1.412
15 (dogleg)	EHF	20	0.396	3.325	1.86	152.36	6.855	0.156	4.86	1.238	1.412
15C (11°)	EHF	20	0.418	3.325	1.97	156.99	6.862	0.142	4.84	1.417	1.417
16	EHF	20	0.397	3.325	1.87	152.94	6.845	0.151	4.85	1.272	1.411
16 (dogleg)	EHF	20	0.397	3.325	1.87	152.94	6.845	0.151	4.85	1.272	1.411
17	EHF	20	0.381	3.325	1.79	150.10	6.817	0.132	4.83	1.283	1.411
18	NHF	20	0.288	3.325	1.58	143.87	4.605	0.141	2.14	2.367	2.151

^{16}N and ^{17}N isotopes



- $^{16}\text{O}(\text{n},\text{p})^{16}\text{N}$ (E_{th} 10.5 MeV)
 - $^{16}\text{N}(\beta^-)^{16}\text{O}$ half life $T_{1/2}$ 7.13 sec
 - emits hard gamma rays
6.13 MeV(68.6%) 7.13 MeV(5%)
- $^{17}\text{O}(\text{n},\text{p})^{17}\text{N}$ (E_{th} 8.4 MeV)
 - $^{17}\text{N}(\beta^-, \text{n})^{16}\text{O}$ half life $T_{1/2}$ 4.17 sec
 - emits high energy neutrons
0.39 MeV(37.7%) 1.16 MeV(49.8%) 1.69 MeV (6.9%)
 - ^{17}O natural abundance 0.04%

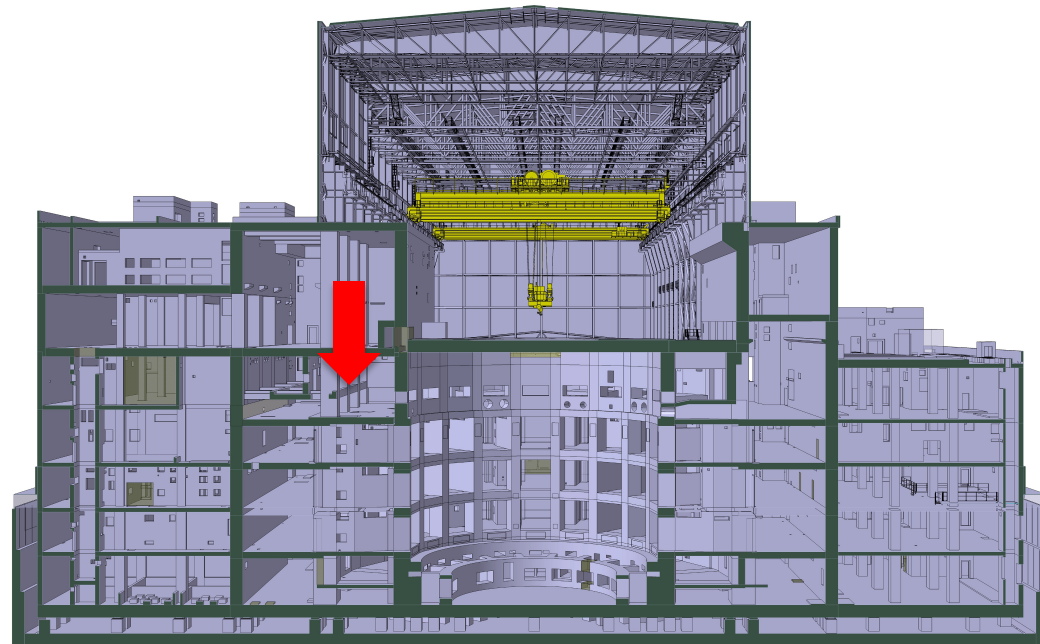
^{16}N and ^{17}N isotopes



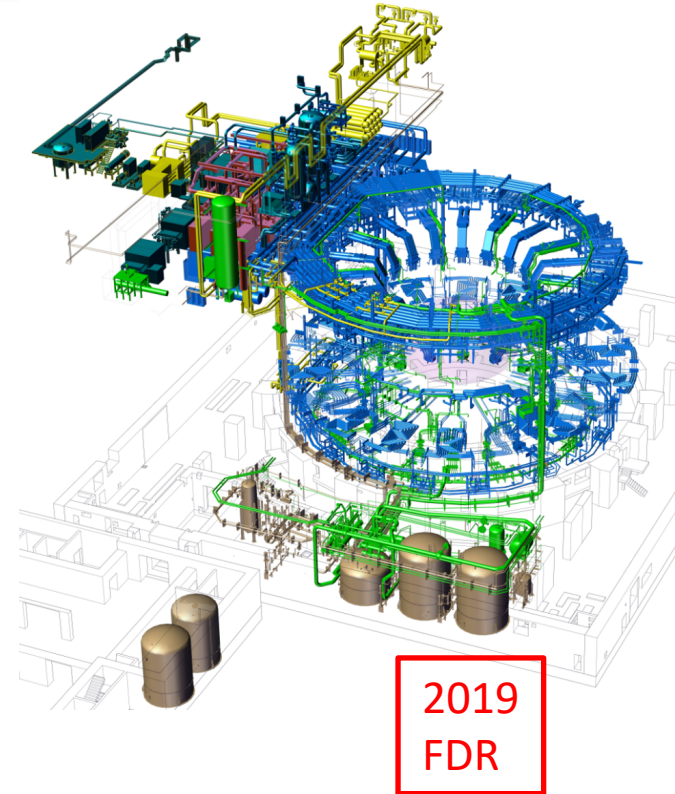
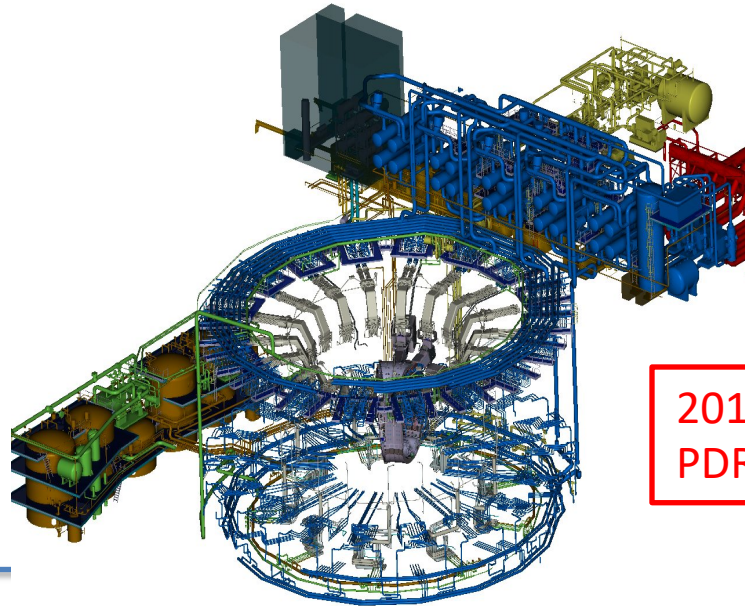
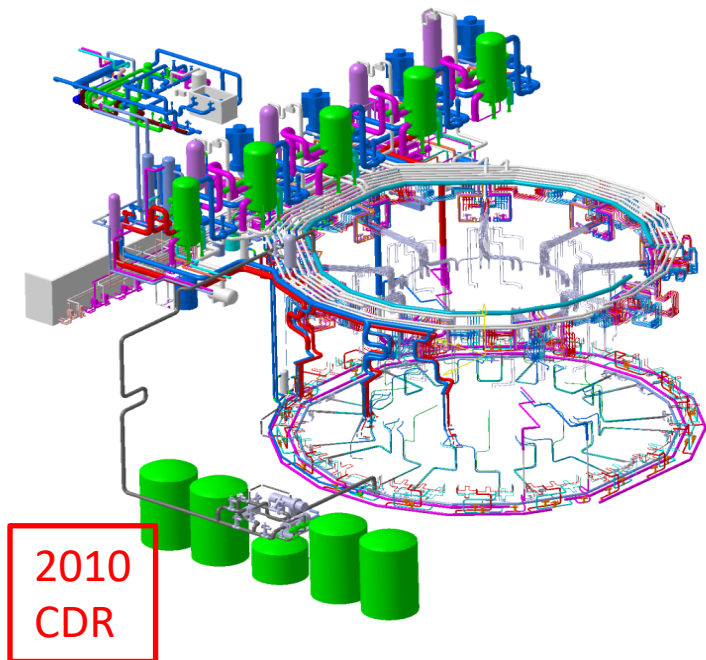
- Water gets activated as it cools the plasma facing walls
- Short half life, but very high coolant flow. Circulation time short enough for the isotopes to be transported by the coolant flow out of the Tokamak pit and into the rest of the building
- High radiation dose in building during plasma burn
- Concentration of ^{17}N about 10000 times less than ^{16}N , but produces neutrons, activates the materials of the TCWS, creates shutdown dose

^{16}N and ^{17}N isotopes

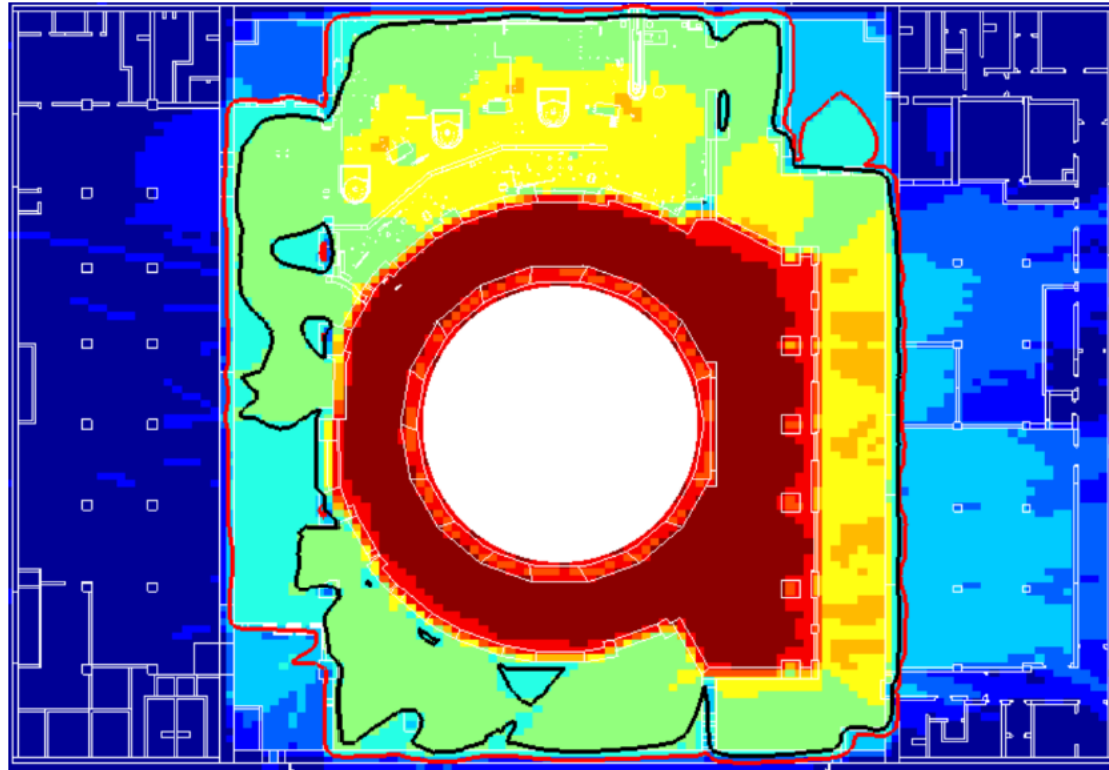
- 2014 new evaluation of radioactive dose in building due to ^{16}N and ^{17}N
- Building walls not sufficient to shield the radiation from TCWS located on 4th floor
- Required complete redesign of TCWS to move most of IBED PHTS equipment and piping to 3rd level and deeper in the building
- Required addition of borated heavy concrete shielding walls in the building



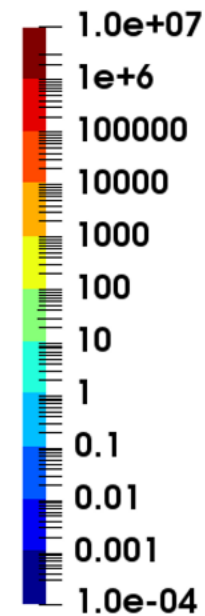
^{16}N and ^{17}N isotopes



^{16}N and ^{17}N isotopes



Dose in Si
(Gy)



Black:
10 Gy

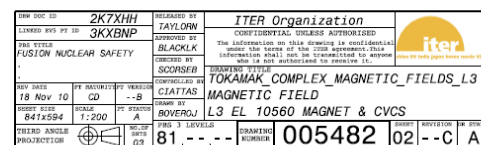
Red:
1 Gy

Integrated dose on L3 level for ^{16}N and ^{17}N

^{16}N and ^{17}N isotopes



- Side effects of the high radiation
- No electronics in the TCWS vault
 - Cubicles with the electronics moved to shielded areas, resulting in long cable lengths (up to 300 m)
 - No smart sensors, no smart valves, passive instruments to monitor the cooling system
- Materials get activated by high energy neutrons
 - Created shutdown dose, hampers maintenance
 - Request stainless steel with very low concentration of Co, Nb and Ta to limit long term radioactivity



Magnetic field

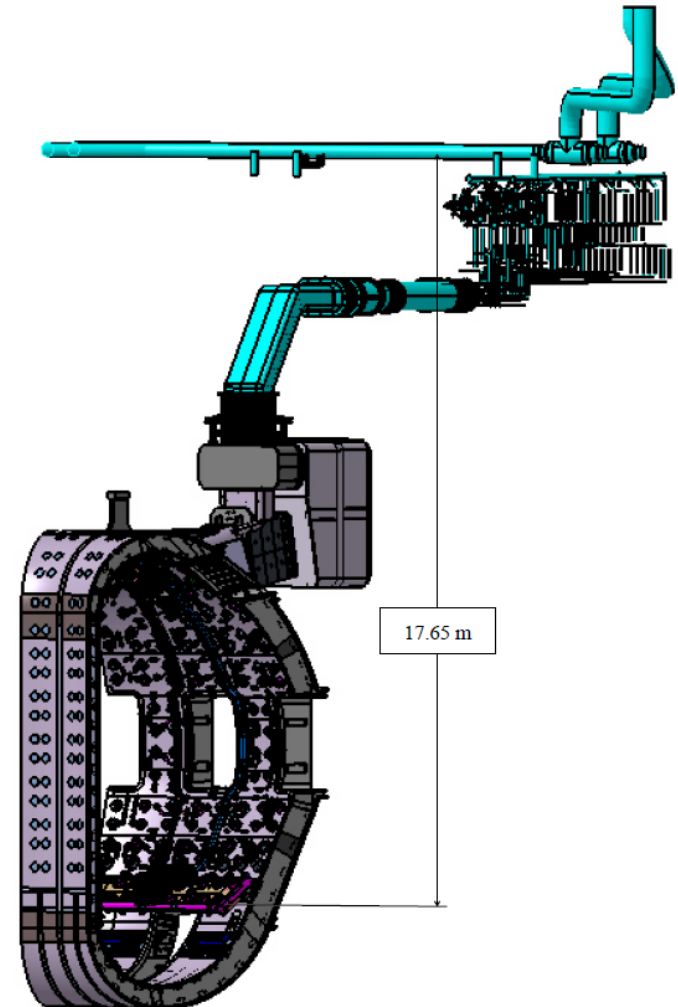


- Magnetic field value 10-100 mT in area where TCWS is located
- Piping and equipment in austenitic stainless steel to limit magnetic forces
- All equipment grounded
- Magnetic qualification required primarily for smaller items such as solenoids, sensors, small motors, fans, oil pumps

- All equipment inside the TCWS vault must be qualified for
 - Radiation (gamma + neutron)
 - Magnetic field
 - Seismic event
 - Accidental room conditions (1 bar, 130 °C)

Drying system

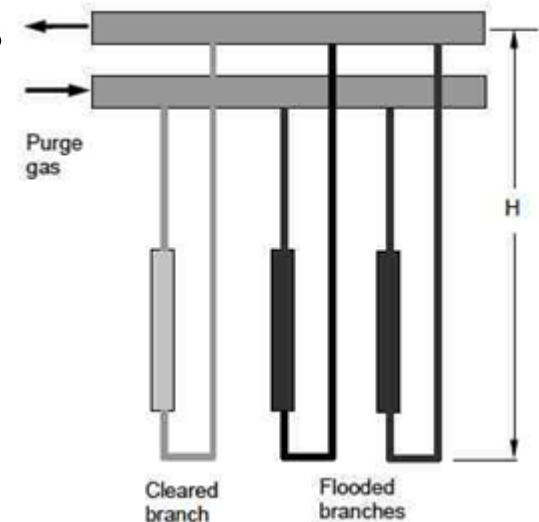
- Most client systems cannot be gravity drained
- Remove the water by forced gas flow



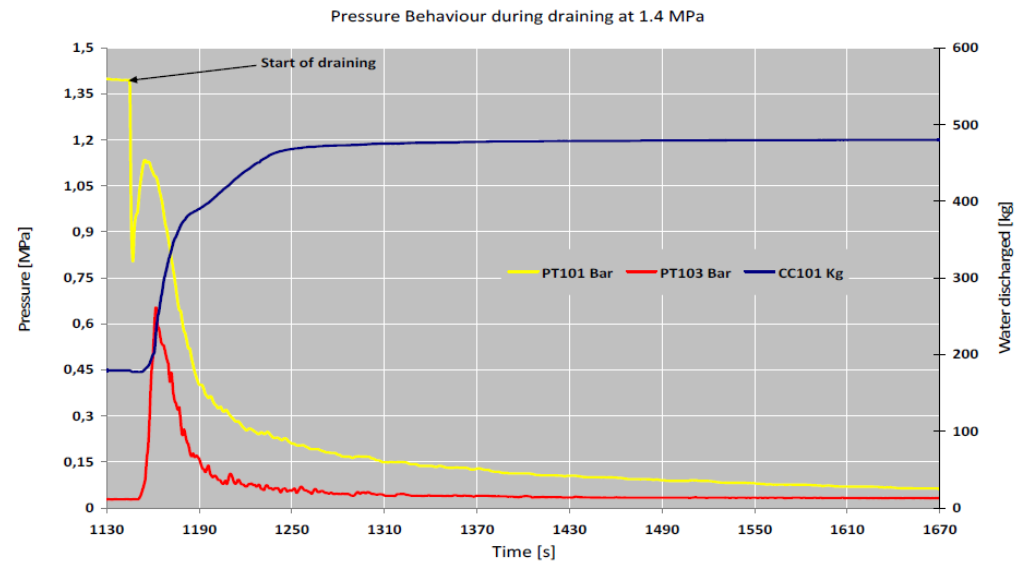
- Two step process
 - Blowout:
 - Push out most of the water with high flow of gas
 - Dryout:
 - When cooling water passages are cleared of water, heat up the systems with hot gas
 - Provoke boiling of the remaining water by lowering the pressure
 - Cool down again to ambient temperature

Drying System – Blowout

- Three criteria must be fulfilled for a successful blowout:
 - Build up sufficient pressure to overcome the manometric head and push down the water column to the lowest level
 - Overcome the CCFL (Counter-Current Flow Limitation) in the upward oriented channels and pipes (high density, high velocity)
 - Overcome flow bypass in parallel channels
- Need for high power compressor
2500 hp



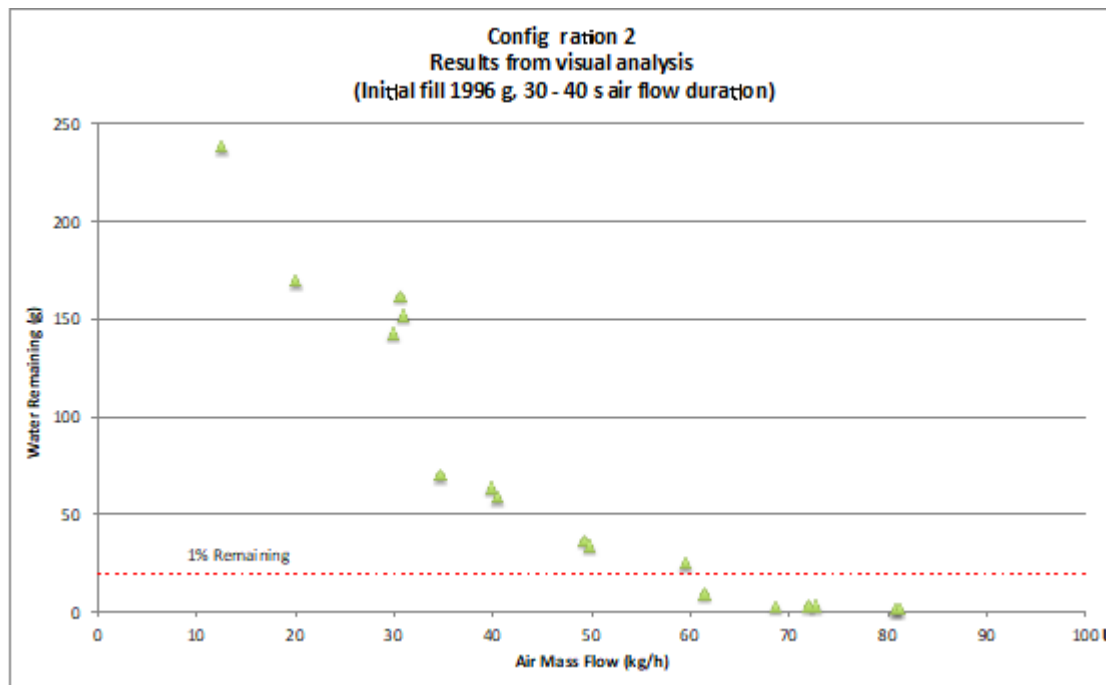
Experiments on DIV blowout



Blowout experiments performed on Divertor cassette prototype at ENEA, Brasimone, Italy

Drying System – Blowout

- For the FW/BLK, experiments performed at ORNL on mockups of specific geometries



Drying System – Dryout

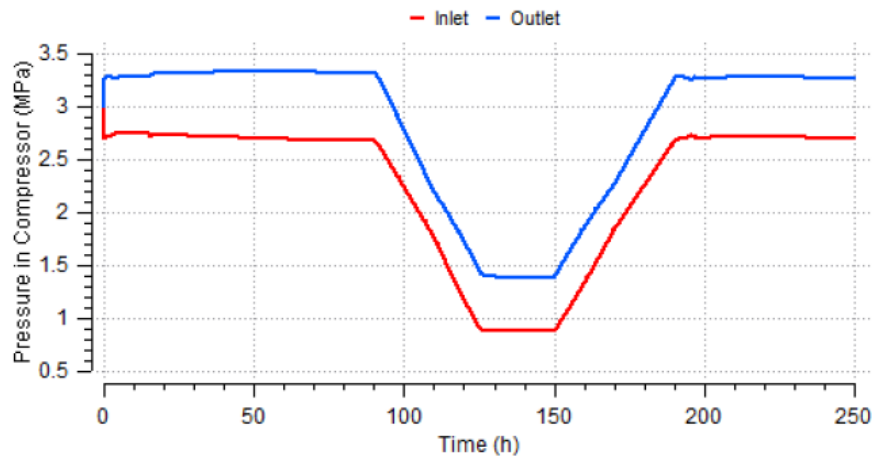


Figure 5-190 –Case7_IBEDDRY: Pressures in the Compressor

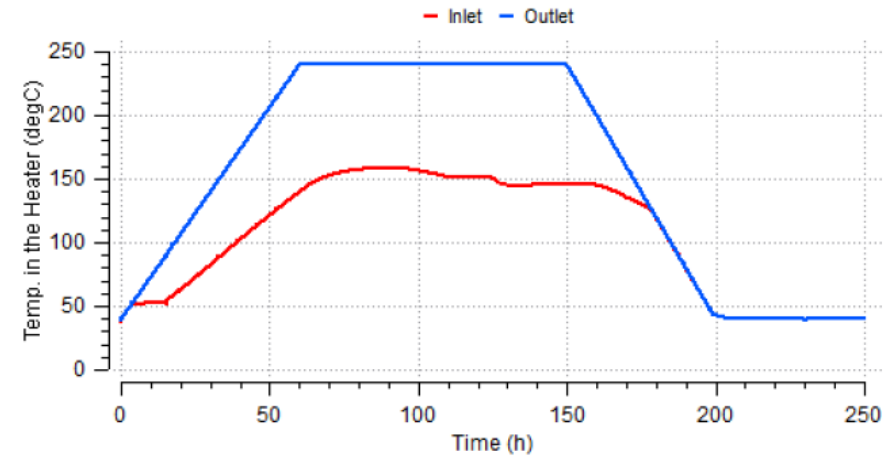


Figure 5-203 – Case7_IBEDDRY: Temperatures in the Heater

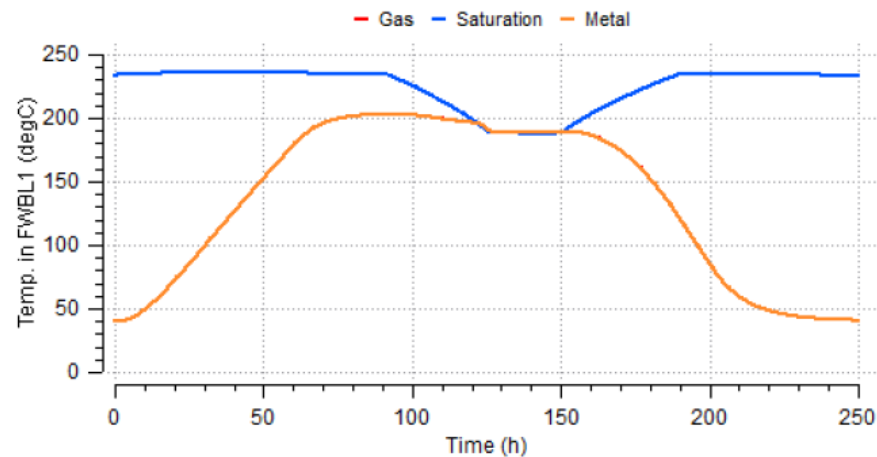


Figure 5-218 – Case7_IBEDDRY: Temperatures in the FWBLK1 client

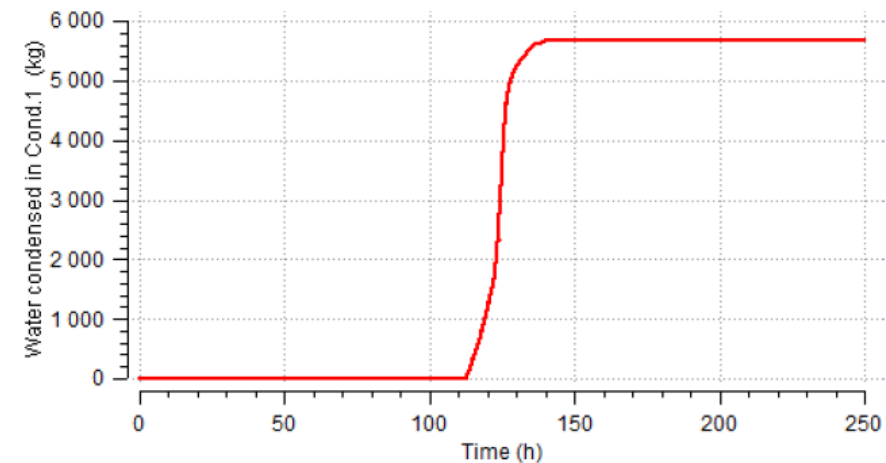


Figure 5-209 – Case7_IBEDDRY: Mass of water condensed in Condenser1

Manufacturing and installation



- Some cool pictures of the manufacturing and installation of the TCWS components

Arrival of 3 drain tanks at ITER



Drain Tank installation in DTR

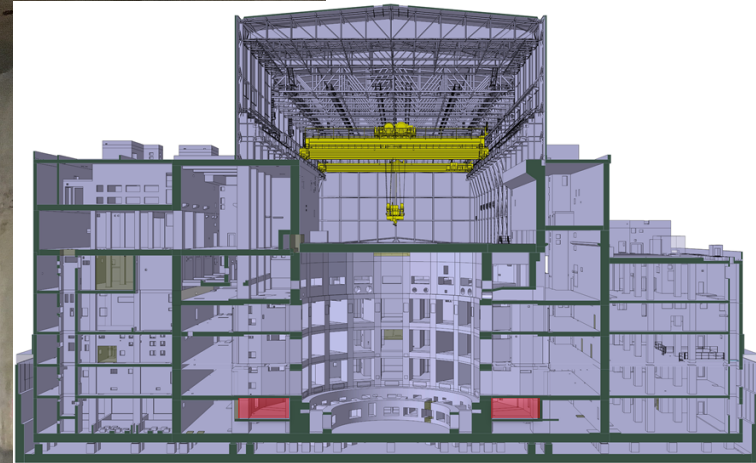


Embedded Plates

- No drilling in the concrete floor, walls and ceiling
- All equipment must be anchored to prepositioned Embedded Plates attached to the rebar



Lower Pipe Chase still empty



VV PHTS Volume Control Tank



Delivery of pipes to the warehouse



Acknowledgement



- US ITER TCWS team, currently 7 people (20 past 10 years) team leader Hughes, Duke
- IO TCWS team, currently 30 people, team leader Lioce, Donato
- And many more people over the past 25 years at Tractebel Engineering, Ansaldo Nucleare, Areva Federal Services, Empresarios Agrupados, ORNL
- Many manufacturers around the world building equipment and components

