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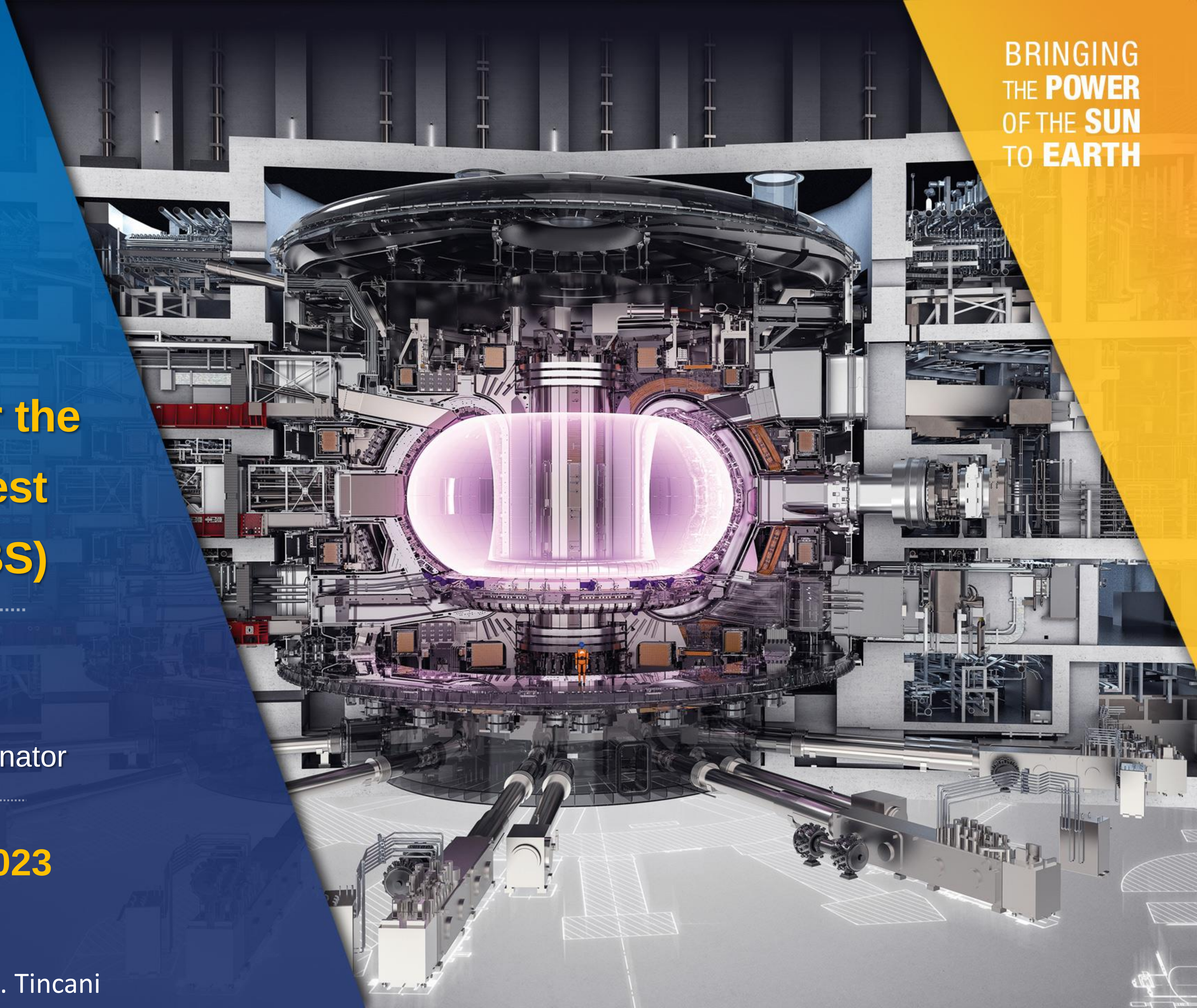
BRINGING THE POWER OF THE SUN TO EARTH



ISFNT-15

The Lead Lithium Loop for the European Water-Cooled Test Blanket System (WCLL-TBS)

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EU TBM Team

WCLL Ancillary Systems Technical Coordinator

14th September 2023

Special thanks to I. Ricapito, A. Aiello & A. Tincani

0.- Outline

1.- Brief Introduction to the Test Blanket Systems

2.- Specificities of the Water-Cooled Lithium Lead (WCLL) TBS

3.- The Lead-Lithium (PbLi) Loop for the ITER TBS

4.- Main Challenges and Achievements of the PbLi loop in ITER

5.- Open Issues & Conclusions

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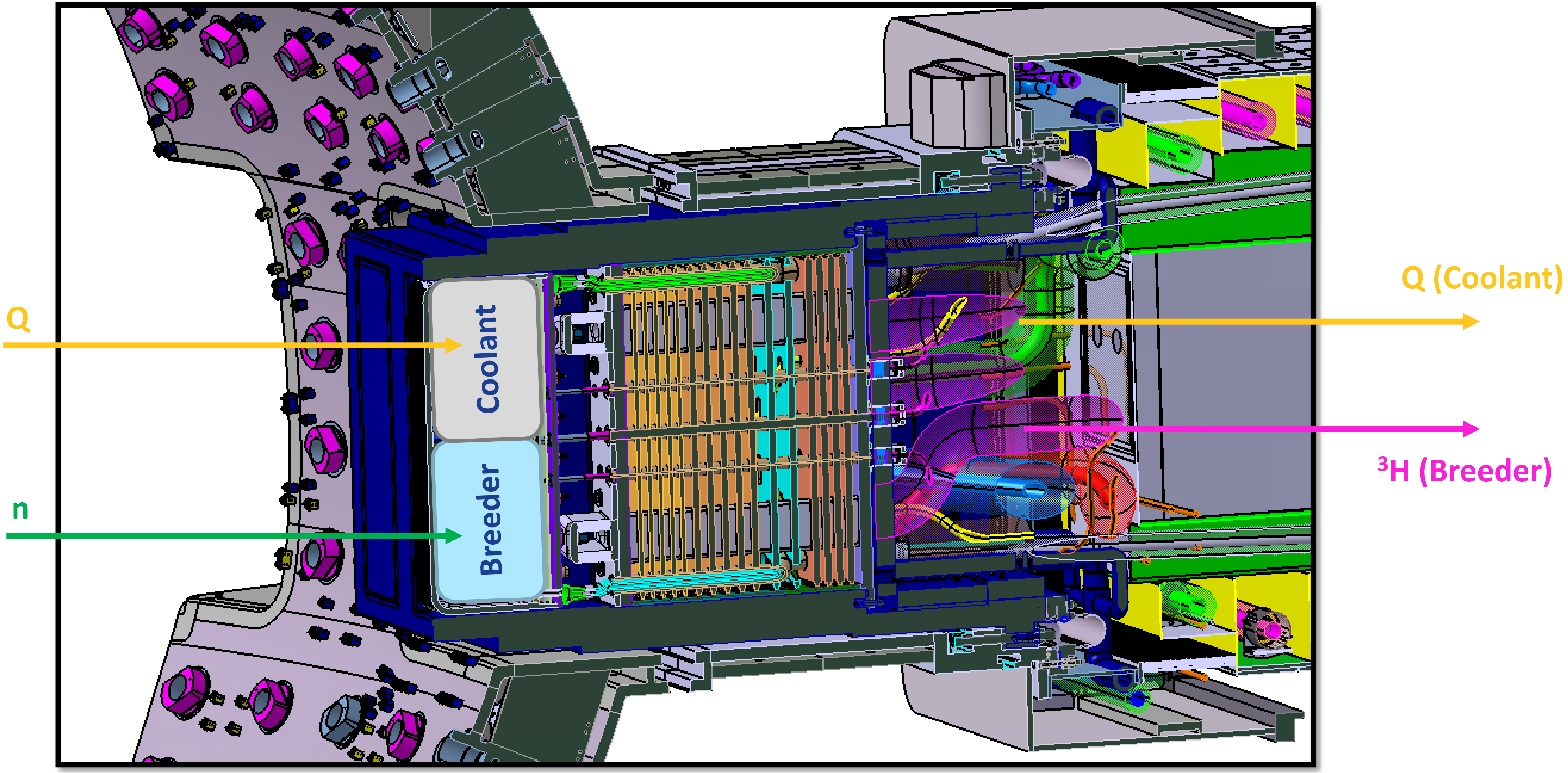

1.- Brief Introduction to the Test Blanket Systems

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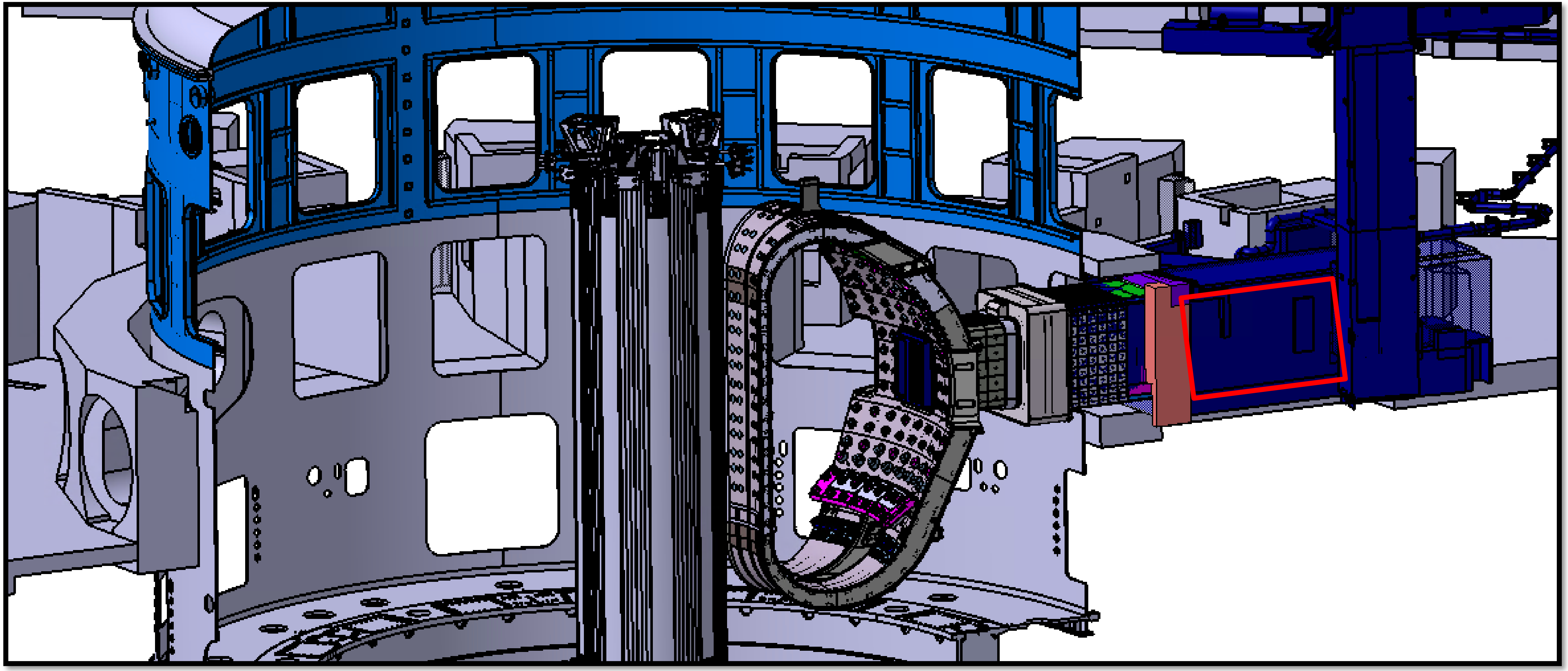

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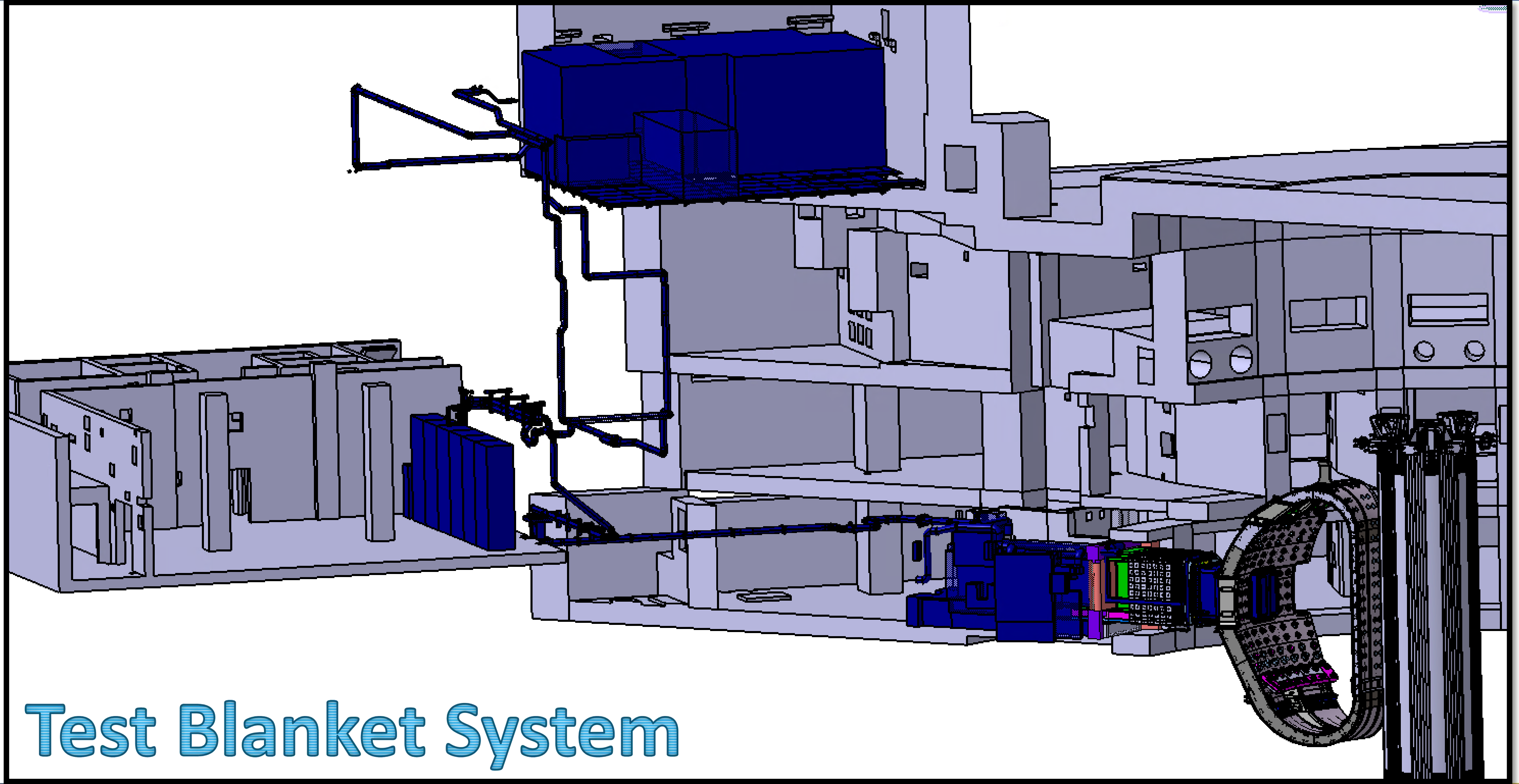

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2.- Specificities of the Water-Cooled Lithium Lead (WCLL) TBS

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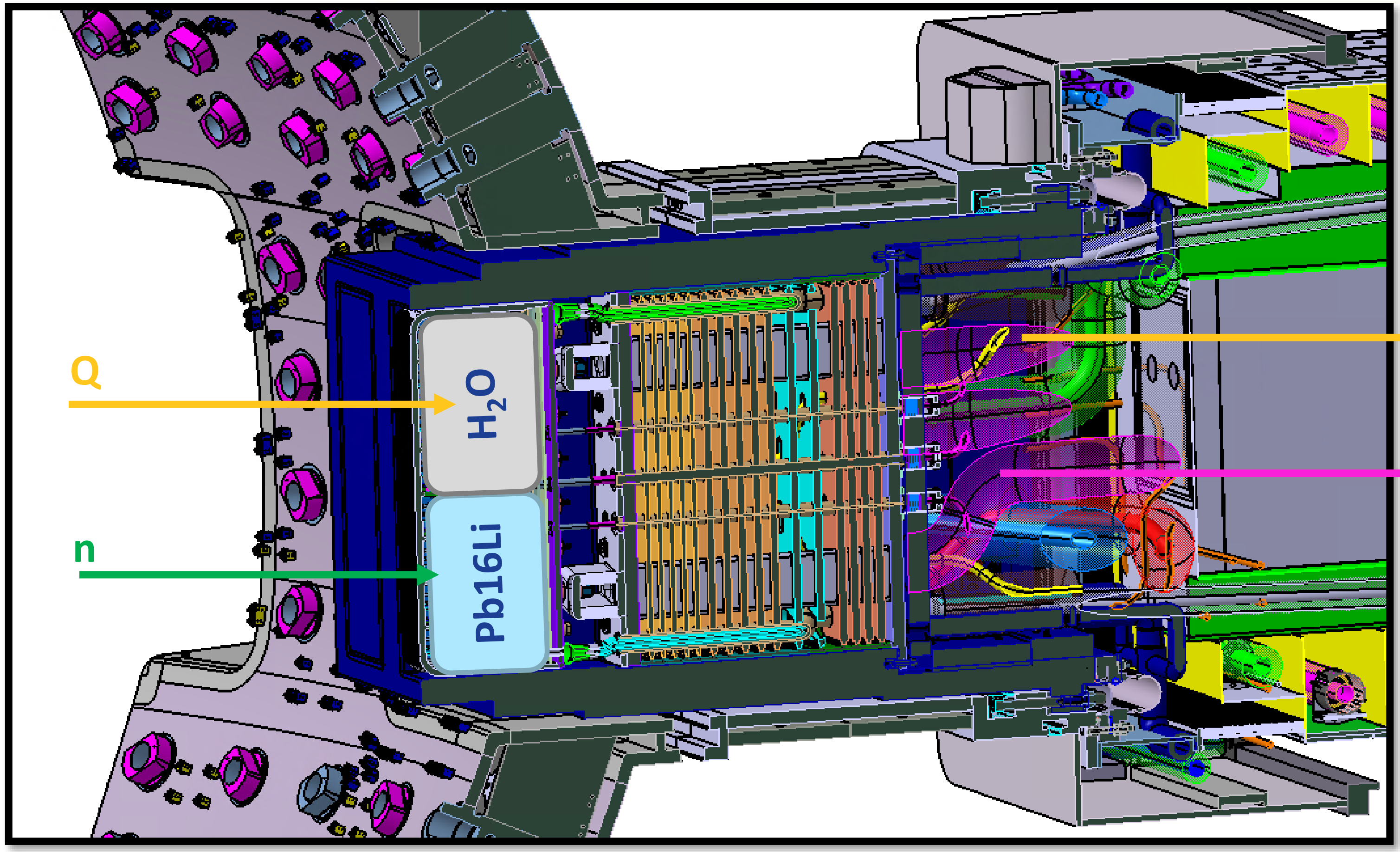

The coolant is pressurized water at 15.5 MPa, 295 - 328 °C and 3.74 kg/s

The breeder is molten Pb16Li that is circulated to promote external (to the TBM) tritium extraction. PbLi is circulated by **the PbLi loop** at 0.16 MPa, 295 - 322 °C and 0.65 kg/s

2.- Specificities of the Water-Cooled Lithium Lead (WCLL) TBS

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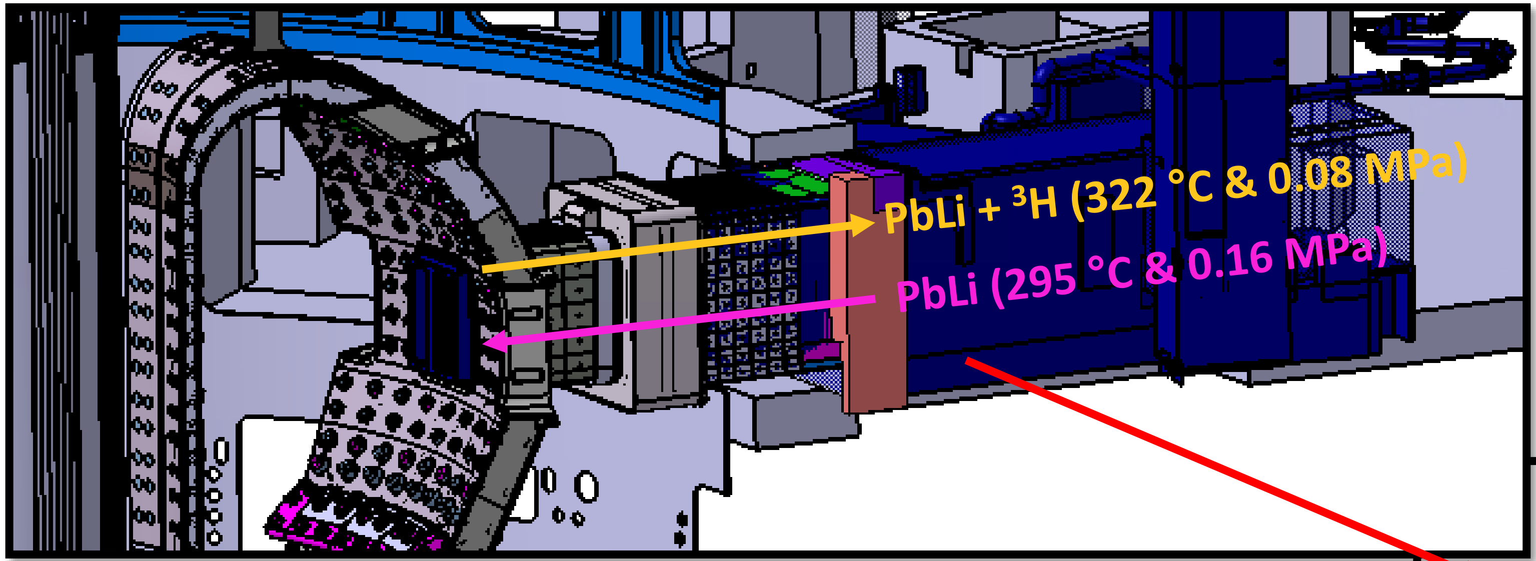
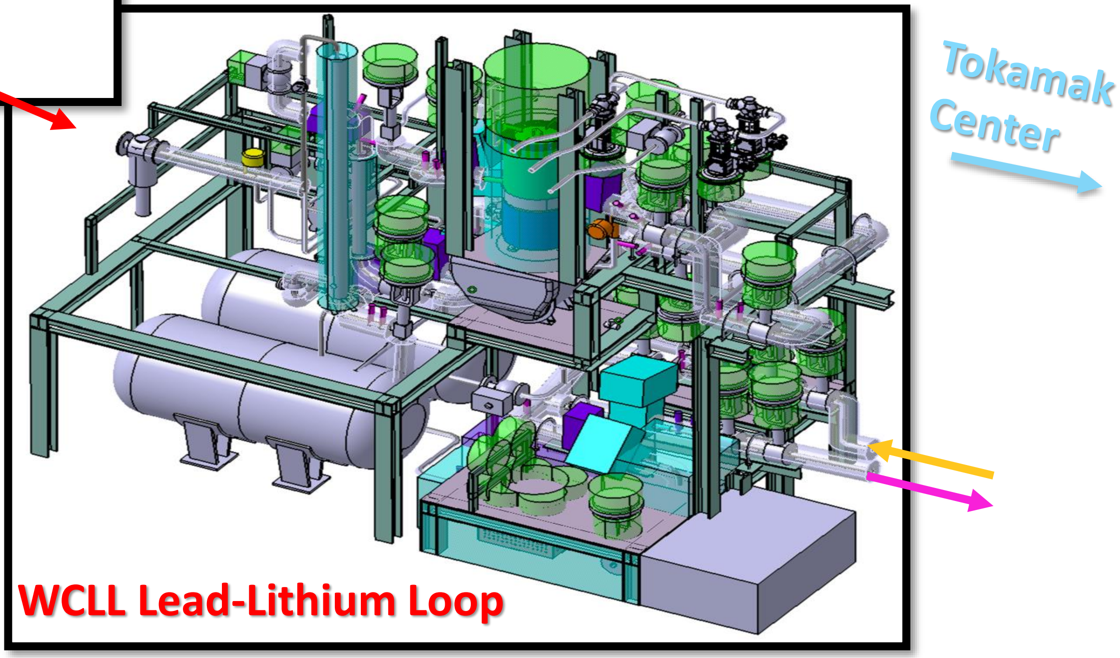


The molten PbLi is returned to the TBM with a reduced 3H concentration and at a regulated temperature of 295 °C.

The molten PbLi is circulated externally to the TBM mainly:

- to extract dissolved tritium (TEU);
- to eliminate impurities (Cold Trap);



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3.- The Lead-Lithium (PbLi) Loop for the ITER TBS

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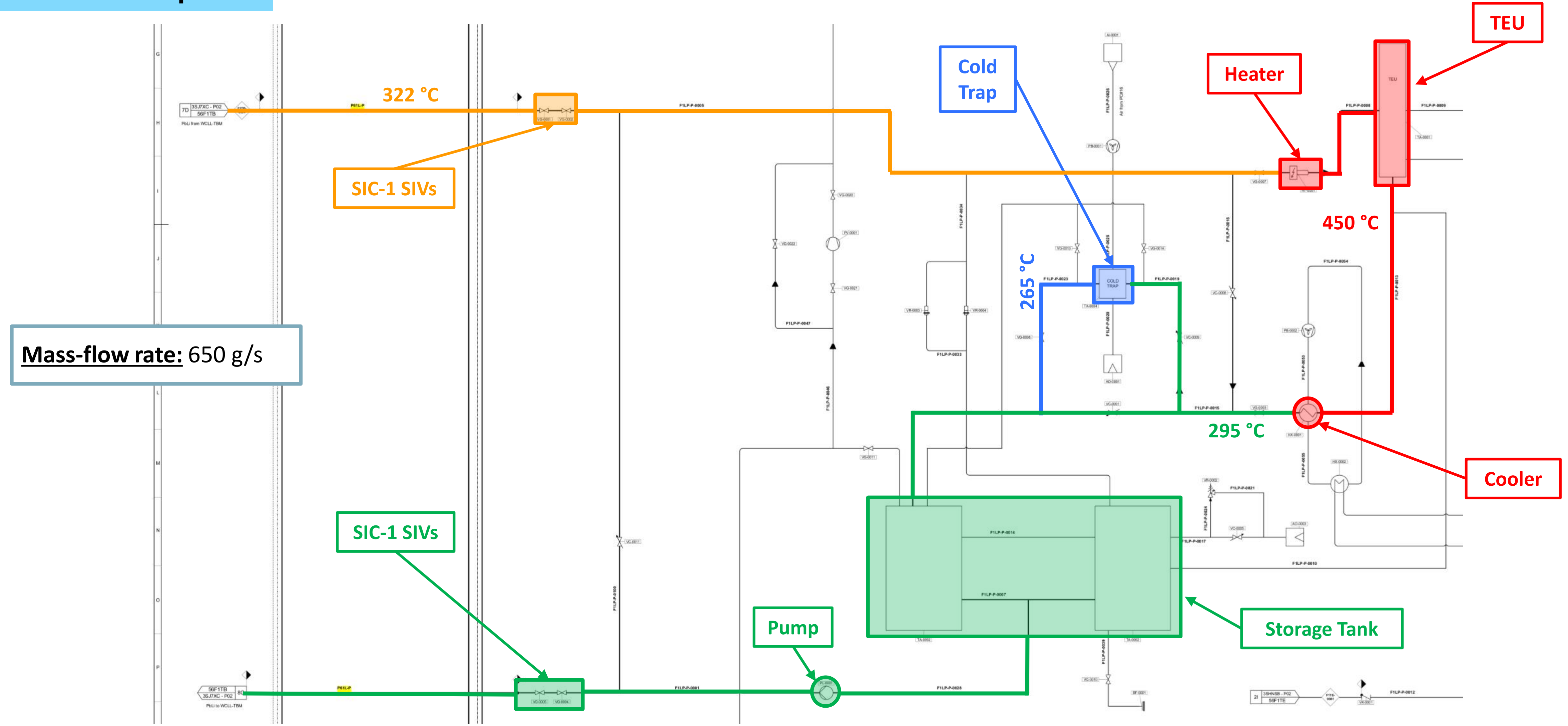
Main Functions of the System

- To provide, circulate and maintain PbLi eutectic alloy at operating conditions suitable for the WCLL-TBM correct operation
- To move tritium from TBM to promote external tritium extraction
- To remove impurities from the PbLi alloy
- To provide confinement for PbLi, helium and radioactive products
- To ensure the implementation of the safety functions

3.- The Lead-Lithium (PbLi) Loop for the ITER TBS

General Description



3.- The Lead-Lithium (PbLi) Loop for the ITER TBS

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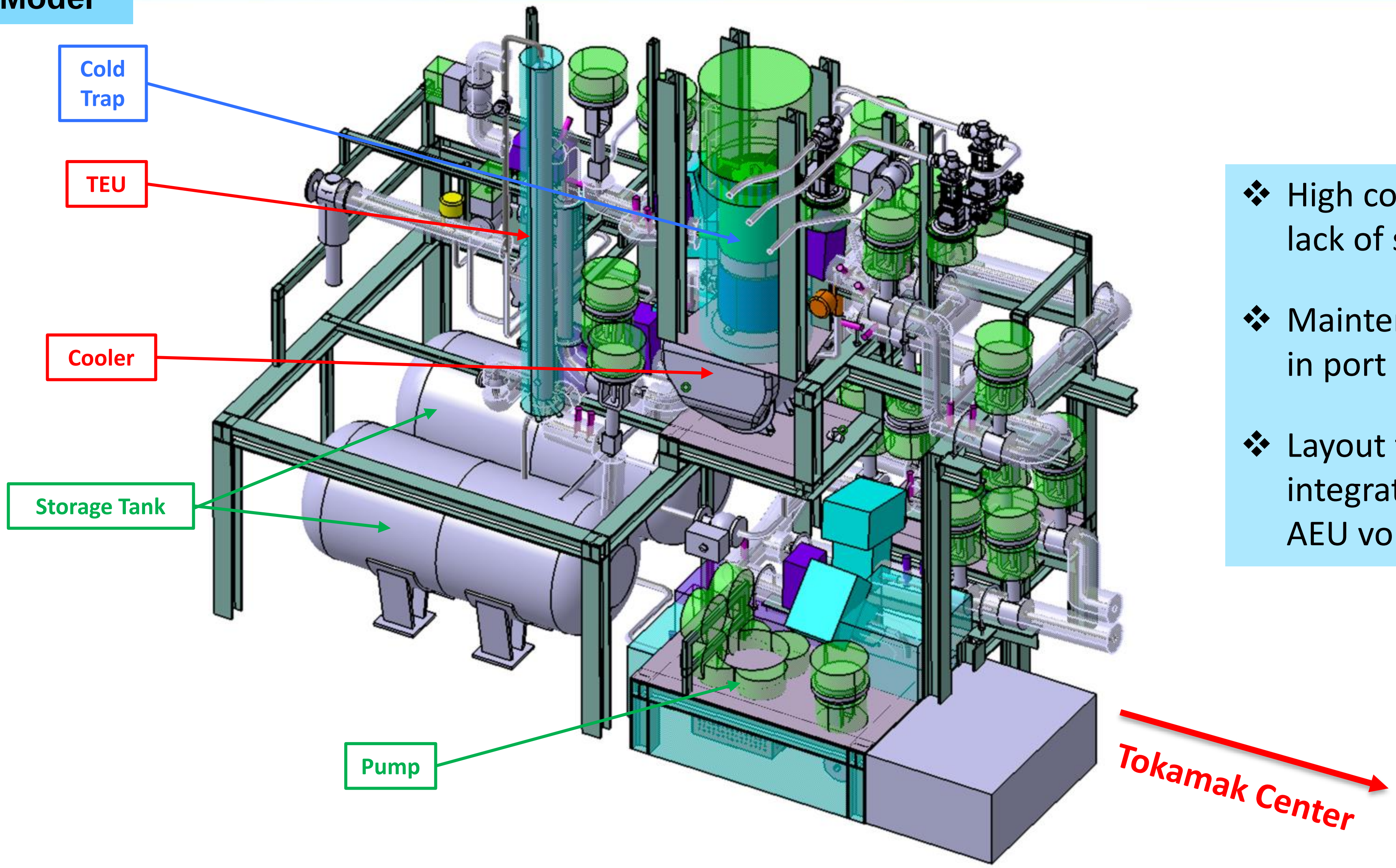
CAD Model



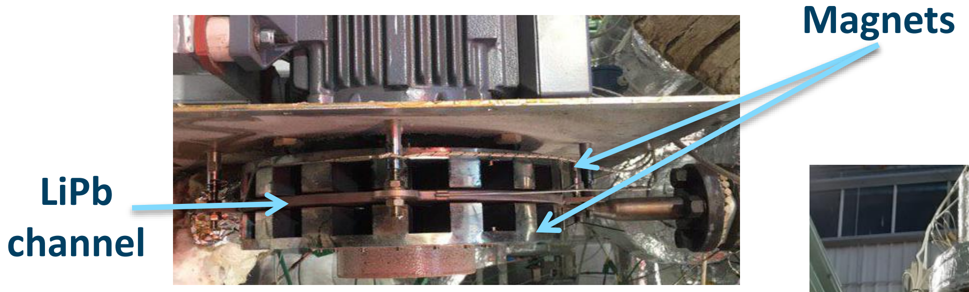
- High component density due to lack of space
- Maintenance not easy when AEU in port
- Layout to be reviewed for integration purposes with new AEU volume

3.- The Lead-Lithium (PbLi) Loop for the ITER TBS

Main Components: Function and Technology

Pump

- **Permanent magnets pump**;
- Advantage to avoid contact between moving parts and PbLi;
- Components subject to maintenance are external to the PbLi flow;
- Residual volume in the loop during operation is strongly reduced.



Tritium Extraction Unit (TEU)

- **Gas-Liquid Contactor** in packed columns configuration
- More stable & Mature than other concepts (i.e. PAV)
- Extraction performance (≈40 %) is stable along time but depends on flow parameters
- Low maintenance unit

Cold Trap

TEU

Cold Trap (CT)

- **Finned cylindrical steel labyrinth**
- No moving parts inside but subject to the formation of plugs due to low temperature (265 °C)
- The external fan increasing the air-flow through the fins is a concern with regards reliability
- The maintenance (i.e. replacement) of this unit is very complex

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4.- Main Challenges and Achievements of the PbLi loop in ITER

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This Section is divided in three main blocks:

1.- Dose rate in PC #16 exceeding limits (PbLi as main contributor)

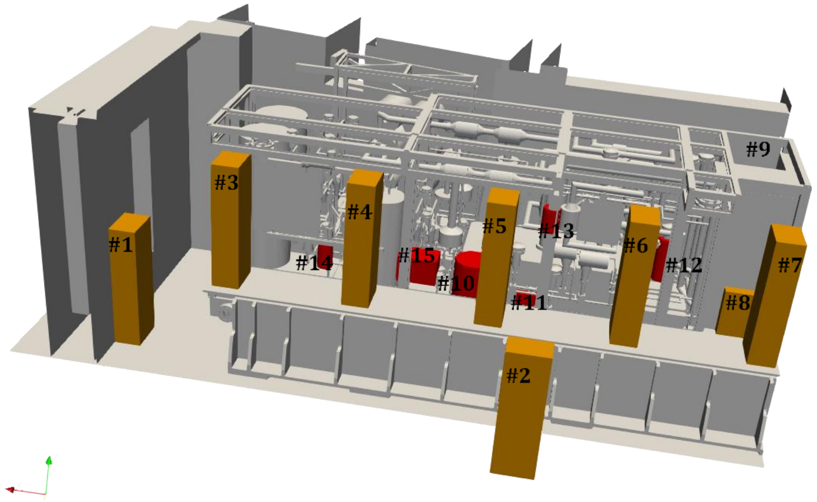
2.- Integration in ITER and space constraints

3.- Specific Research & Development needs

For these three points the next slides will present the challenges / issues, the achievement and the next steps

Dose rate in PC #16 | Challenges 1/2

Cat. I Chit at CDR



AEU tallies – PC #16

Without taking into account the PbLi residual layer contribution, the limit of 10 µSv/h is met almost in all tallies

	Total biological dose rate after 1 day in PC (µSv/h)				
AEU-PC tally	**Activated Components**	**PbLi layer in pipes**	**PbLi in storage tank and cold trap**	**ACP**	**Total**
1 - PC entrance door	0.1	21.0	0.2	0.0	21.3
2 – Lateral stairs	0.9	555.6	1.9	0.2	558.5
3 – AEU platform Pos1	0.2	77.5	0.7	0.1	78.5
4 – AEU platform Pos2	0.4	306.7	1.6	0.4	309.0
5 – AEU platform Pos3	0.7	1419.2	6.4	0.4	1 426.8
6 – AEU platform Pos4	1.2	3197.1	1.5	0.5	3 200.4
7 – AEU platform Pos5	1.1	1305.9	0.4	0.5	1 307.9
8 – Back BP right side	5.2	1864.0	1.1	0.6	1 870.9
9 – Back BP left side	4.6	1481.0	1.6	1.0	1 488.3
10 – Cold trap	0.1	454.5	264.4	0.4	719.4
11 – Flow meter	0.9	5441.6	11.5	0.1	5 454.2
12 – Valves	1.2	2693.0	0.5	1.8	2 696.5
13 – PbLi pump	0.1	1191.2	0.4	1.5	1193.2
14 – Back Valves	0.3	50.3	0.5	0.4	51.8
15 – Vacuum pump in PC	0.3	238.1	13.8	0.6	252.9

Dose rate limit after 24 h: 10 µSv/h

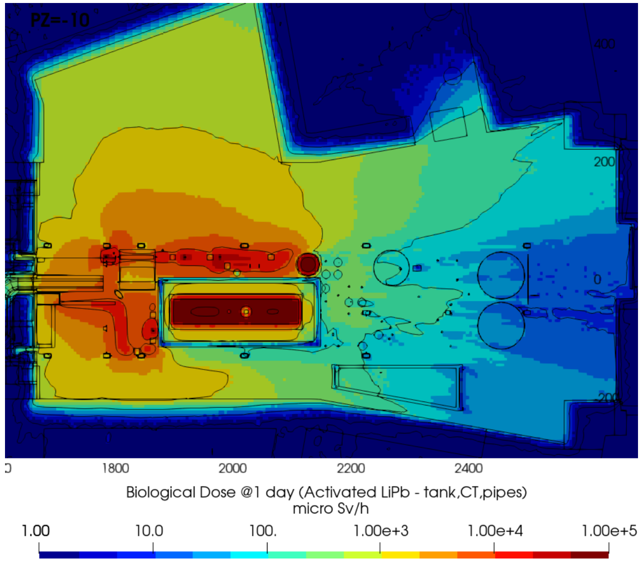
Dose rate in PC #16 | Challenges 2/2

Cat. I Chit at CDR

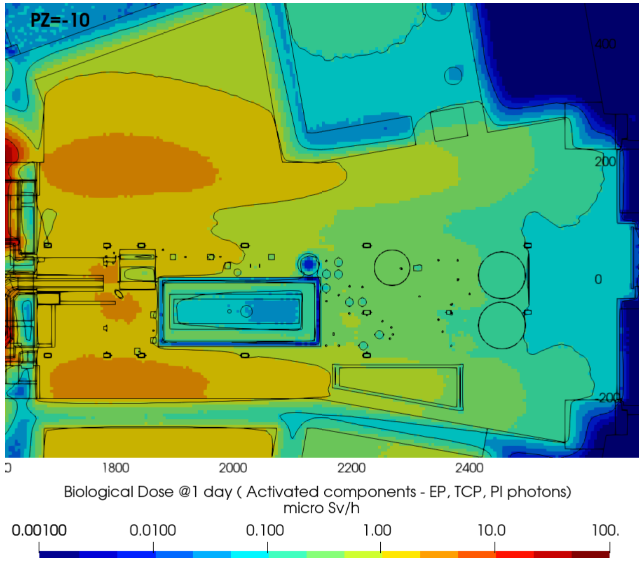
Dose rate limit after 24 h: 10 µSv/h

Total biological dose rate source contribution maps @ 1 day

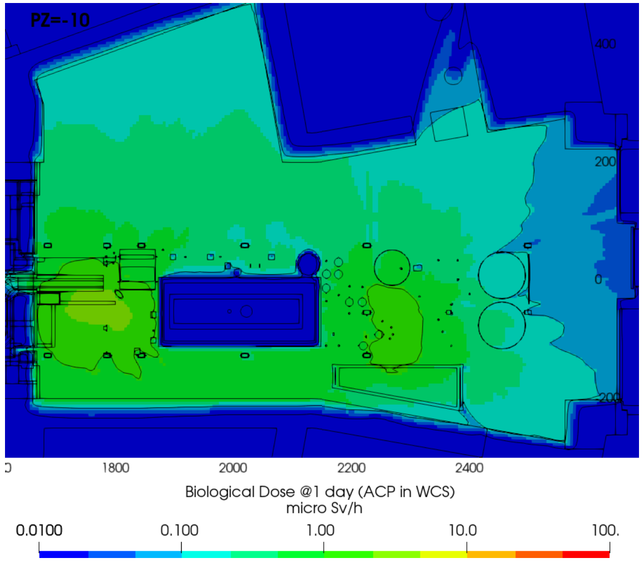
PZ -10cm



PbLi (total)



Act. Components



ACP in WCS

⚠ *Note PbLi scale different from Act. Comp. and ACP maps*

Dose rate in AEU side of the PC **is mainly due to residual PbLi layer** inside the pipes.

4.- Main Challenges and Achievements of the PbLi loop in ITER

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Dose rate in PC #16 | Achievements

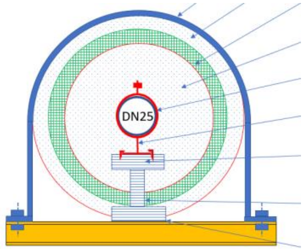
The main reason for exceeding dose rate limit was the assumed layer of activated PbLi that remained inside the loop after drainage. The 1 mm thickness of PbLi layer considered during the CDR resulted to be an over-conservative assumption.

- Examining the data from experimental PbLi loops operated in Europe, thicknesses for the residual layer of about 50 µm have been found. This has been confirmed by parametric CFD analysis providing results in the same range (as low as ≈10 µm).
- to achieve this residual layer thickness the PbLi loop shall:
    i. implement a slope of at least 3 %;
    ii. maintain a temperature of at least 295°C during drainage;
    iii. be drained during at least 24 hours;
- in addition, local nuclear shielding shall be put in place. Preliminary values for the shielding are 10 mm of lead or 55 mm of steel);
- A preliminary check on the 3D model has confirmed the feasibility to implement the changes having an impact on the PbLi loop layout (i.e. slope and shielding);

With all the above changes implemented, the resulting dose rate is lower than the limit of 10 µSv/h

After the achievements some margins have been taken to avoid future issues, the next steps for updating the PbLi loop design are as follows (ongoing tasks):

- **A PbLi residual layer of 100 µm has been assumed to be a conservative but realistic value. This means that use of lead shielding instead of steel provides significant improvement in terms of used space. At the same time the lead shielding shall be encapsulated to avoid issues due to lead low melting temperature. The piping layout has been defined as follows and needs to be fully implemented;**



- **The value of the pipe slope has been conservatively set as 5% with a minimum of 3% in some areas if needed. The new thickness of shielding and the pipe slope have been preliminary implemented in a 3D model but it needs to be finalized and improved:**
- **A new nuclear analysis is being developed so:**
  - i. **the results in terms of dose rate reduction can be confirmed within the limits;**
  - ii. **a parametric analysis is performed to improve shielding thicknesses;**
  - iii. **the precise new layout of the PbLi loop is taken into account (i.e. slope);**

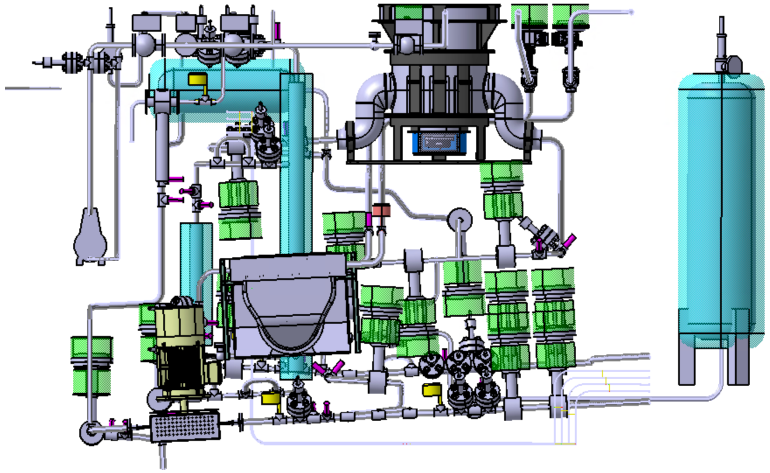


Image courtesy of NIER Ingegneria

4.- Main Challenges and Achievements of the PbLi loop in ITER

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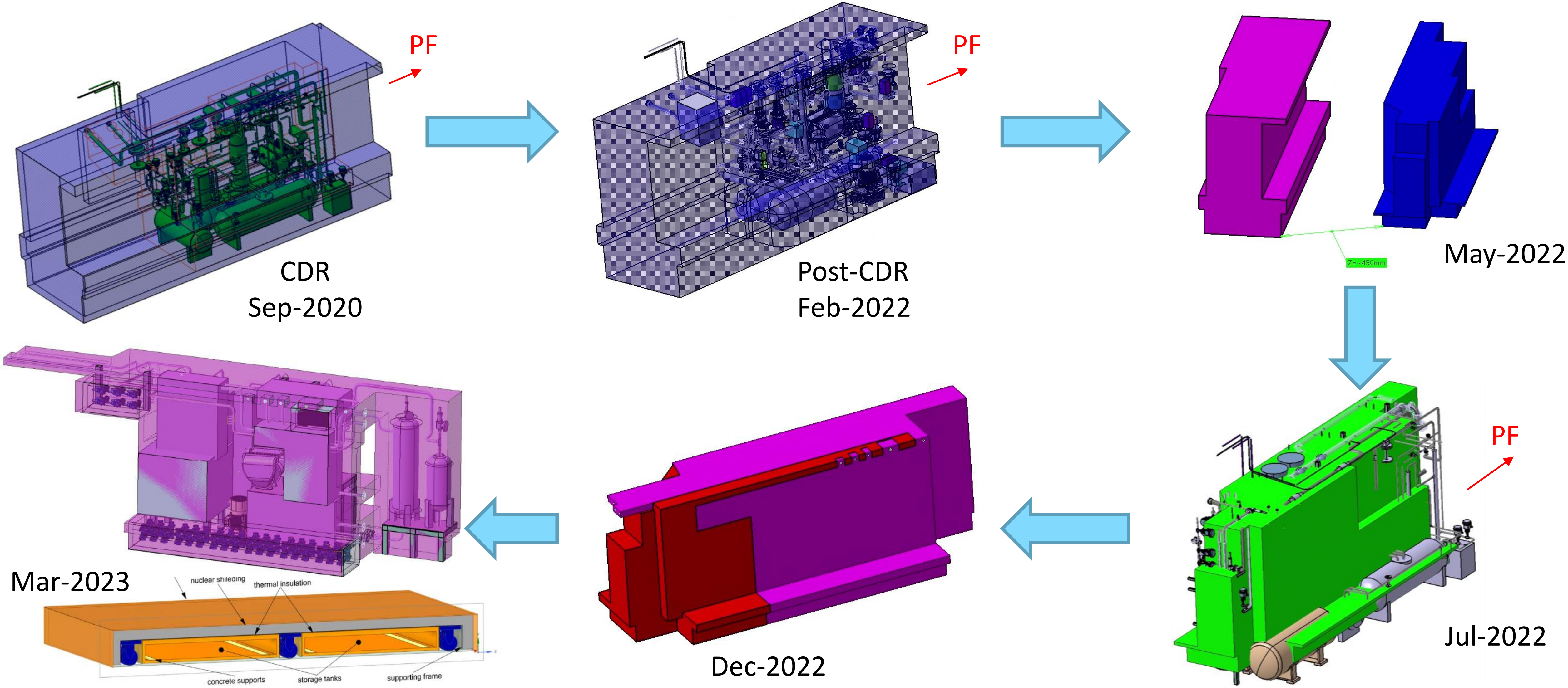
Integration in ITER | **Challenges**

- Integration has many different aspects that shall be taken into account:
  - We are going to install a Test Blanket System in an INB (“*Instalation Nucleaire de Base*”) -> Regulations
  - ITER is not a dedicated facility -> TBSs co-exist with many other systems
  - TBSs are not essential for the operation of the machine -> need to accommodate last minute changes
  - TBSs are experimental devices -> unique and complex sub-systems (i.e. PbLi loop is unique in ITER)
  - Different design responsibles for different parts of the sub-systems
- These particularities make needed to:
  - Deploy the different sub-systems among different locations in the tokamak complex -> 3 different rooms
  - Have interfaces with many other PBS (e.g. services) -> WCLL-TBS interfaces with up to 27 different PBSs
  - Accommodate the systems into the available space

4.- Main Challenges and Achievements of the PbLi loop in ITER

Integration in ITER | **Physical Integration**



In order to synchronize the different stakeholders and to solve the integration issues in PC for PDR:

- First action on simplifying the systems as much as possible
  - Three stakeholders have been requested to **simplify and remove** components -> gain space
  - The main idea behind is to **ensure feasibility** of having two TBSs in one port
- Second action to create a Work-Plan up to PDR for integrated activities
  - It is clear that some activities require an integrated analysis (e.g. heat release)
  - These analyses shall be executed by one of the three entities but feed by the other two
  - Since PDR is approaching fast a detailed work-plan is needed so the three parties can organize their resources

4.- Main Challenges and Achievements of the PbLi loop in ITER

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Research & Development | **Ongoing Tasks**

- Gas-Liquid Contactor (TEU) characterization for WCLL-TBS: first set of experiments and data analysis;
- Tritium Sensors in PbLi (permeation and potentiometric sensors);
- Selection and qualification of Thermal-Hydraulic sensors in PbLi (pressure, mass flow rate, level);
- Coupling of Relap5 and Simmer to perform analysis at system level;
- Development of the DEMO PbLi code for the TBM Project
- Execution of tests on WCLL-TBM PMU in IELLLO and data elaboration

R&D Activities developed in partnership with EUROfusion

➤ Development of the DEMO PbLi code for the TBM Project

- It is expected to have in the end a unique code capable to simulate the lead lithium loop, from a TH point of view, in normal and accidental conditions, coupling the different involved phenomena.
- Integration in Relap5 of:
  - updated PbLi fluid libraries
  - the phenomena of transport for non-mixable species
  - Magneto-Hydro-Dynamic (MHD) effects

4.- Main Challenges and Achievements of the PbLi loop in ITER

Research & Development | **Some Details 2/2**

➢ Execution of tests in IELLLO (Integrated European Lead Lithium LOop) and data elaboration to feed the design with:

- the real thickness of residual PbLi in pipes after drainage;
- the maximum length of pipe that in case of heating cable failure will have no consequences on PbLi circulation;
- the thermal behavior of pipes crossing the shield and connecting the pipe forest to TBM manifolds.

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- Integration issues, preliminary job done but it is needed to take into account maintenance;
- The design of the cold trap has been update in order to: 1.- solve some local issues revealed by the TM analyses; 2.- allow the maintenance of the fan (only active part) without dismounting the shielding (i.e. ORE reduction);
- The changes needed to accommodate the removal of the storage tank (substituted by a small circulation tank) need to be studied more in detail. For instance, the process of filling-up the PbLi loop require the pressurization of the drainage tank since the permanent-magnets pump is not able to suck the PbLi from the tank underneath;
- From an R&D point of view also activities need to be finished so all the missing information regarding optimization (e.g. TEU) and instrumentation (e.g. T sensors) can be gathered;
- The operating conditions of the PbLi loop might also need to be adapted in the next future following ITER operating conditions.

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Back-Up Slides

3.- The Lead-Lithium (PbLi) Loop for the ITER TBS

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Operating Parameters

ITER Plant Global Operational States				
	POS	TCS	STM	LTM
PbLi Loop	**NOS** PbLi loop inlet pressure 0.165 MPa PbLi loop outlet pressure 0.078 MPa PbLi loop inlet temperature 322 °C PbLi loop outlet temperature 295 °C PbLi loop flow rate 0.65 kg/s **HSOS** PbLi loop inlet pressure 0.165 MPa PbLi loop outlet pressure 0.078 MPa PbLi loop inlet temperature 295°C PbLi loop outlet temperature 295 °C PbLi loop flow rate 0.65 kg/s	**HSOS** PbLi loop inlet pressure 0.165 MPa PbLi loop outlet pressure 0.078 MPa PbLi loop inlet temperature 295 °C PbLi loop outlet temperature 295 °C PbLi loop flow rate 0.65 kg/s **CSOS** PbLi loop inlet pressure 0.165 MPa PbLi loop outlet pressure 0.078 MPa PbLi loop inlet temperature 270°C PbLi loop outlet temperature 270°C PbLi loop flow rate 0.30 kg/s **TOS** PbLi loop inlet pressure 0.165 MPa PbLi loop outlet pressure 0.078 MPa PbLi loop inlet temperature 325 °C PbLi loop outlet temperature 325 °C PbLi loop flow rate 0.65 kg/s **RFOS** PbLi loop inlet pressure 0.165 MPa PbLi loop outlet pressure 0.078 MPa PbLi loop inlet temperature 295°C PbLi loop outlet temperature 295°C PbLi loop flow rate 0.30 kg/s	**CSOS** PbLi loop inlet pressure 0.165 MPa PbLi loop outlet pressure 0.078 MPa PbLi loop inlet temperature 270°C PbLi loop outlet temperature 270°C PbLi loop flow rate 0.30 kg/s **TOS** PbLi loop inlet pressure 0.165 MPa PbLi loop outlet pressure 0.078 MPa PbLi loop inlet temperature 325°C PbLi loop outlet temperature 325°C PbLi loop flow rate 0.65 kg/s **RFOS** PbLi loop inlet pressure 0.165 MPa PbLi loop outlet pressure 0.078 MPa PbLi loop inlet temperature 295°C PbLi loop outlet temperature 295°C PbLi loop flow rate 0.30 kg/s	**CSOS** PbLi loop inlet pressure 0.165 MPa PbLi loop outlet pressure 0.078 MPa PbLi loop inlet temperature 270 °C PbLi loop outlet temperature 270 °C PbLi loop flow rate 0.30 kg/s IDLE PbLi is drained into the storage recirculation tank. However, the loop is ready for start-up procedure. MS Loop is under maintenance with all the process fluids evacuated and stored. The loop is not ready to be restarted.

For each ITER Global Operational State the TBS have a set of own Operational States defined:

- NOS: Normal Operation State
- HSOS: Hot Stand-by Operation State
- CSOS: Cold Stand-by Operation State
- TOS: Tritium Outgassing State
- RFOS: Reduced Flow Operation State

3.- The Lead-Lithium (PbLi) Loop for the ITER TBS

Components Classification

Component Description	Fluid category	Safety Function	Safety Class	Location	Seismic Class	Quality Class	Tritium Class	Category PE/NPE	Design Temperature (°C)	Design Pressure (MPa)
Storage Tank	Liquid (PbLi), ESP group 1, Gas (Helium), ESP group 2	Confinement	SIC-2	11-L1-C16	SC1(SF)	QC1	TC 2A	IV / N2	350	10.9
Pump	Liquid (PbLi), ESP group 1	Confinement	SIC-2	11-L1-C16	SC1(S)	QC1	TC 2A	II / N2	350	10.9
Cold trap	Liquid (PbLi), ESP group 1	Confinement	SIC-2	11-L1-C16	SC1(SF)	QC1	TC 2A	II / N2	350	10.9
TEU	Liquid (PbLi), ESP group 1	Confinement	SIC-2	11-L1-C16	SC1(SF)	QC1	TC 2A	II / N2	500	10.9
Heat Exchanger (Cooler)	Liquid (PbLi), ESP group 1	Confinement	SIC-2	11-L1-C16	SC1(S)	QC1	TC 2A	II / N2	500	10.9
Heater	Liquid (PbLi), ESP group 1	Confinement	SIC-2	11-L1-C16	SC1(S)	QC1	TC 2A	SEP/N2	500	10.9
Relief tank	Gas (water), ESP group 2, Liquid (PbLi), ESP group 1	Confinement	SIC-2	11-L1-C16	SC1(S)	QC1	TC 2A	IV / N2	500	10.9
Safety Isolation Valves	Liquid (PbLi), ESP group 1	Confinement	SIC-1	11-L1-C16	SC1(SF)	QC1	TC 2A	IV / N2	500	10.9

The maximum classification for the PbLi loop is PED Category IV and ESPN Level N2 -> Maximum in ITER

4.- Main Challenges and Achievements of the PbLi loop in ITER

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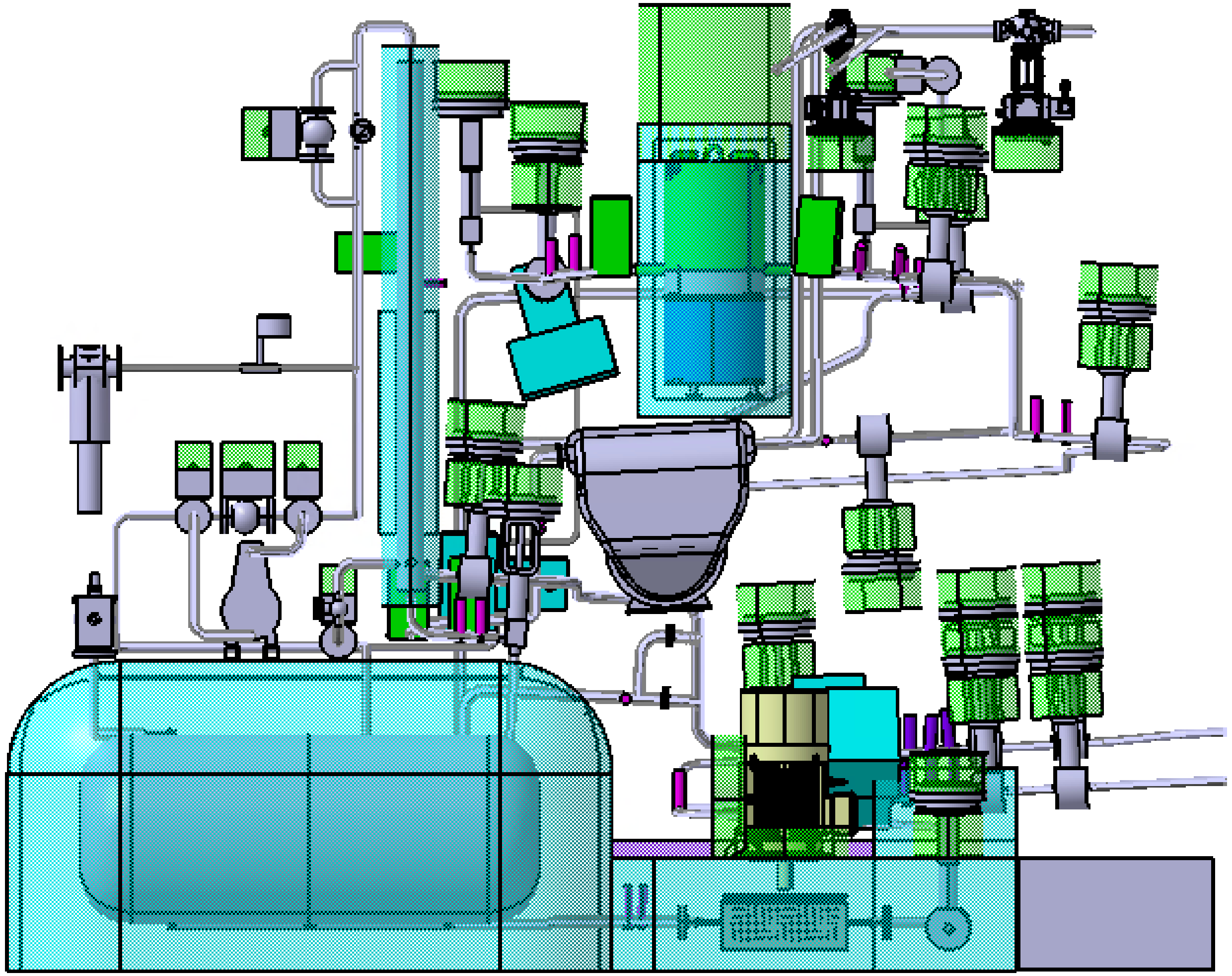
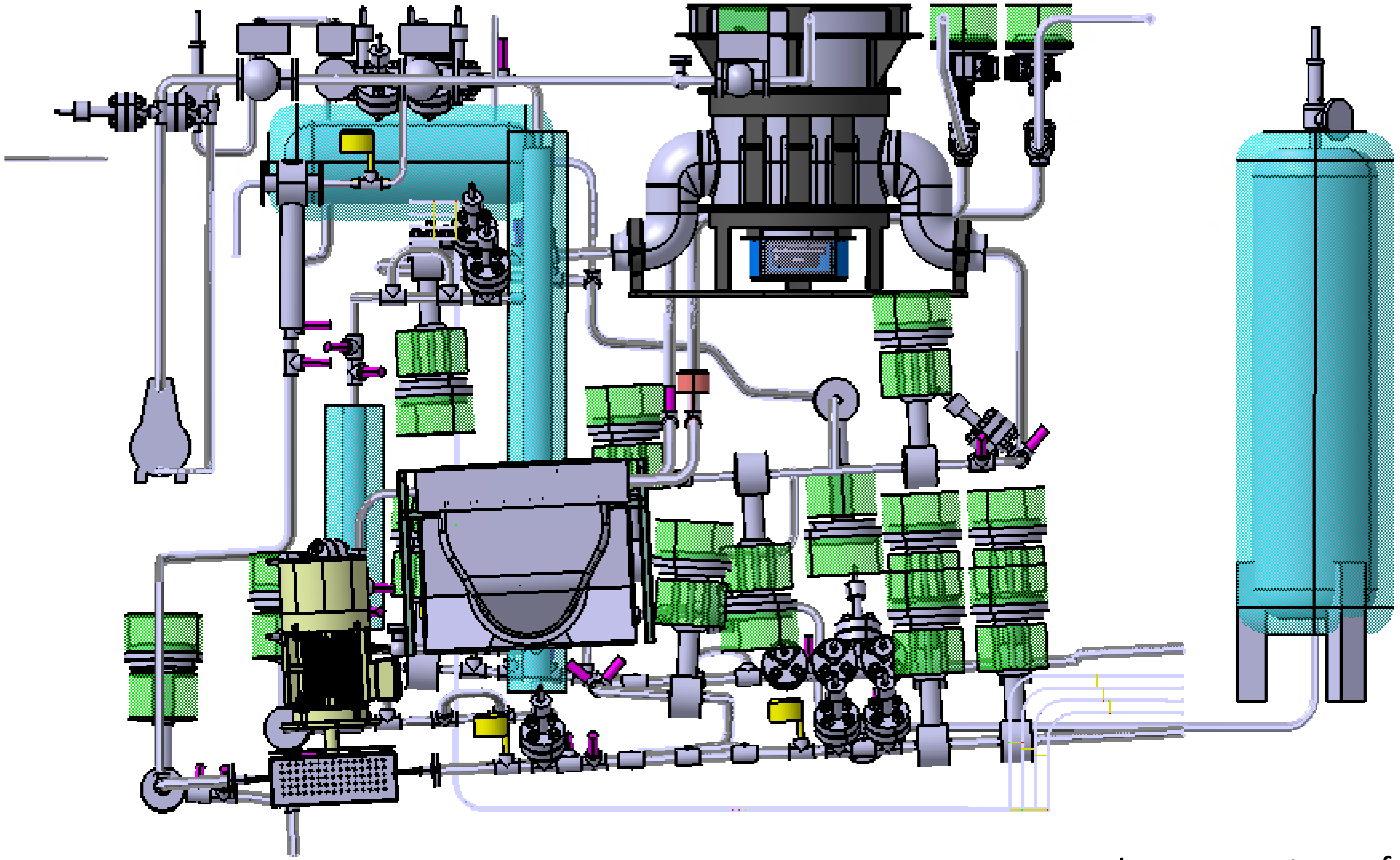
Dose rate in PC #16



Pipe insulation and shielding removed for visual purposes

4.- Main Challenges and Achievements of the PbLi loop in ITER

Dose rate in PC #16



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