8th IAEA DEMO
Programme Workshop
September 1st 2022

EUROfusion

(DEMO) "Thermal Power Management in View of Coolant Choice and the Balance of Plant (BOP)"

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Acknowledgement to WPBOP Team

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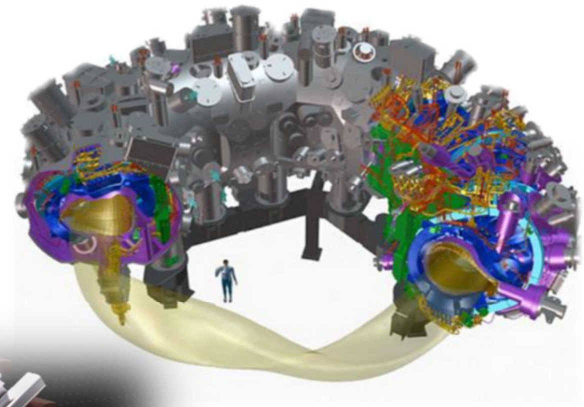
The views and opinions expressed herein do not necessarily reflect those of the European Commission.

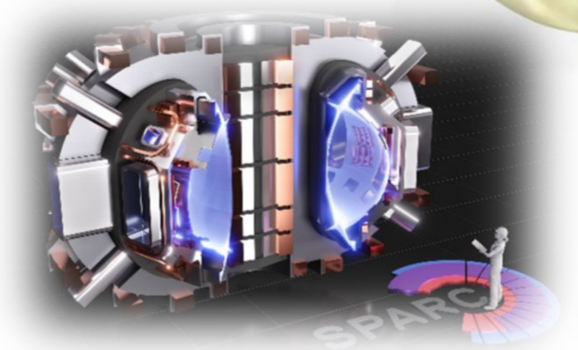
EUROfusion

Close to devices and experiments to demonstrate fusion feasibility by means of a variety of concepts:

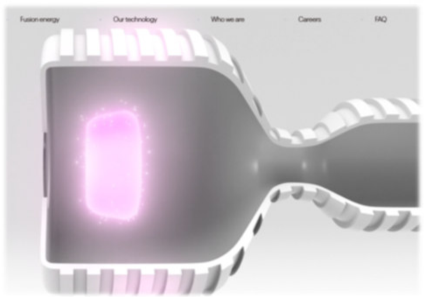
- ✓ Laser driven Inertial Fusion (USA): high frequent pulsed to achieve power output
- ✓ Stellarator / Heliotron:
  W7-X: HELIAS Power plant study:
  concept in work to increase flexibility



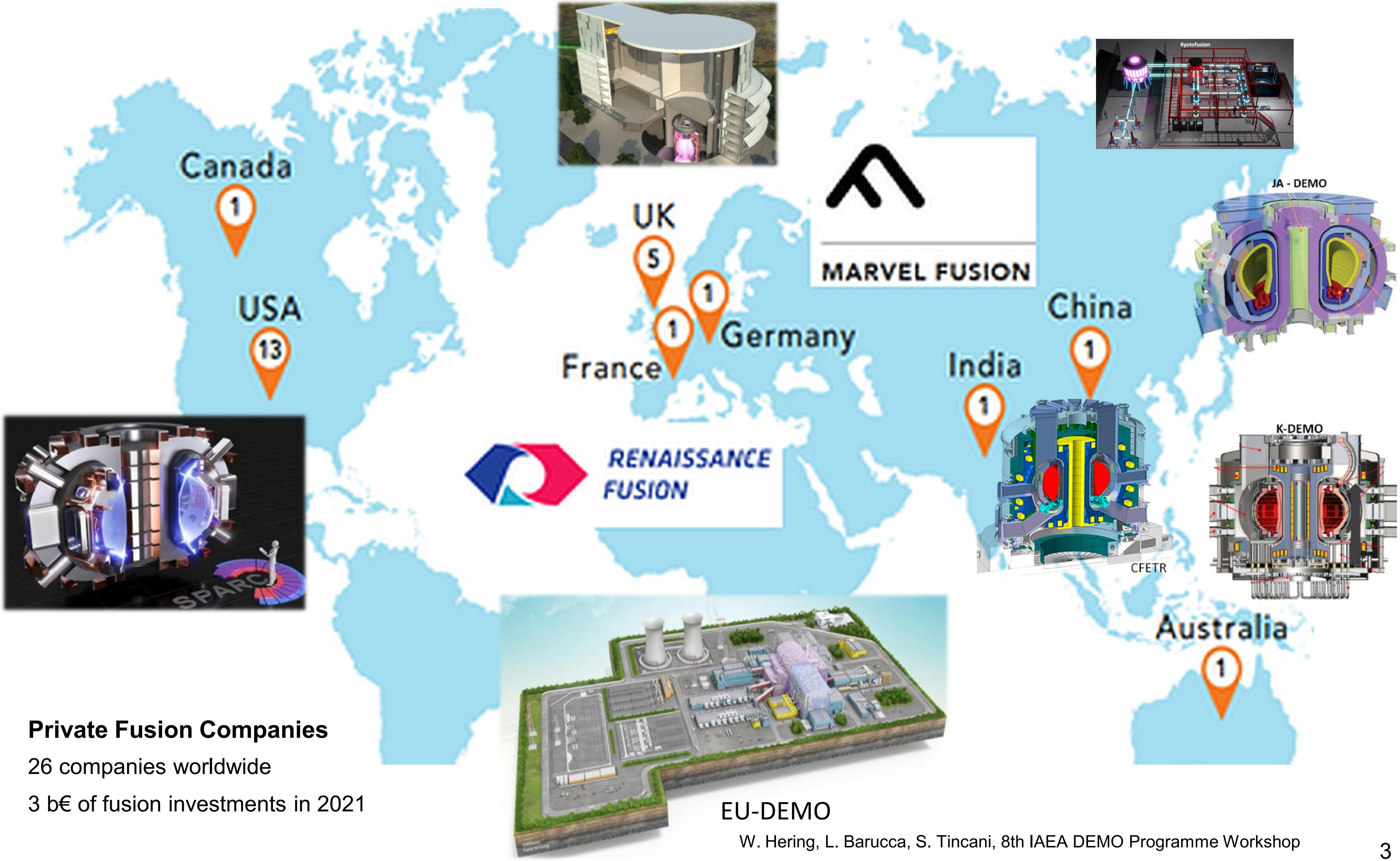
- ✓ Magnetic Mirror Concepts (SPARC)
  (USA, LLNL): pulsed



- ✓ Field reverse configurations
- ✓ Plasma Pinch // Z Pinch



How FUSION to become JOKER in energy POKER ?



Private Fusion Companies

26 companies worldwide

3 b€ of fusion investments in 2021

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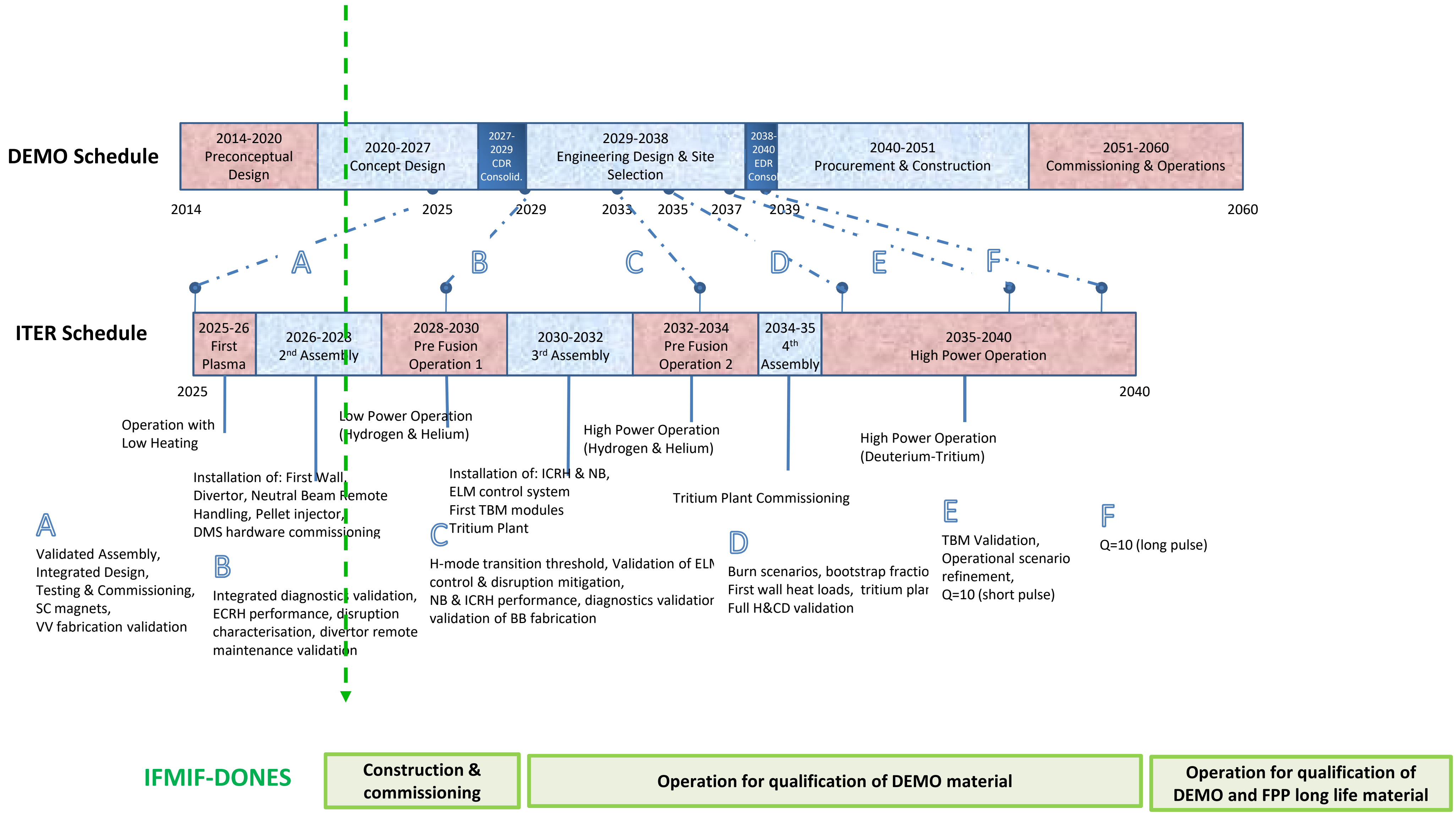
OUTLINE

- Fusion Power Plants Concepts for future Energy Systems
- Present status of EU DEMO:
  - Fusion Roadmap
  - Objectives

- Solutions for EU-DEMO Balance of Plant (BOP)
  Selected Designs during pCDP:
  - WCLL: Water Cooled Lithium Lead Direct coupled (WCLL BOP DCD)
  - HCPB: Helium Cooled Pebble Bed Indirect coupled (HCPB BOP ICD)
  - Common solutions
- Open points and perspectives
- BOP Comparison of fusion DEMOs
- Conclusion

The EU DEMO Plant: the Fusion Roadmap



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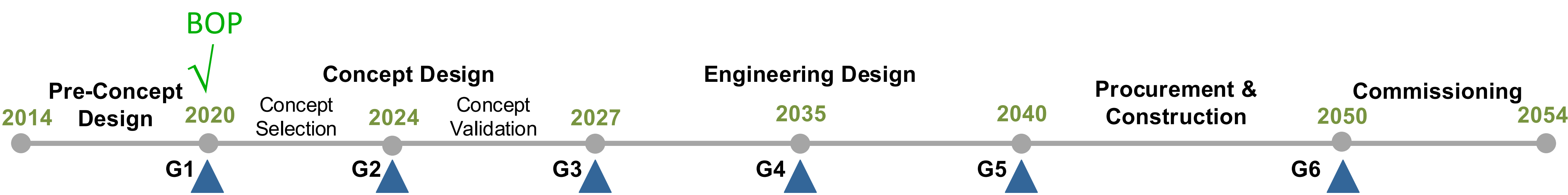
The EU DEMO Plant: Objectives

- start of operation around the middle of thîs century,
- the feasibility of operation with a closed-tritium fuel cycle,
- maintenance systems capable of achieving adequate plant availability,
- production of few hundred MWs of net electricity, → the design of DEMO requires BOP orientation
- to be a facilitating machine between ITER and a commercial Fusion Power Plant (FPP).

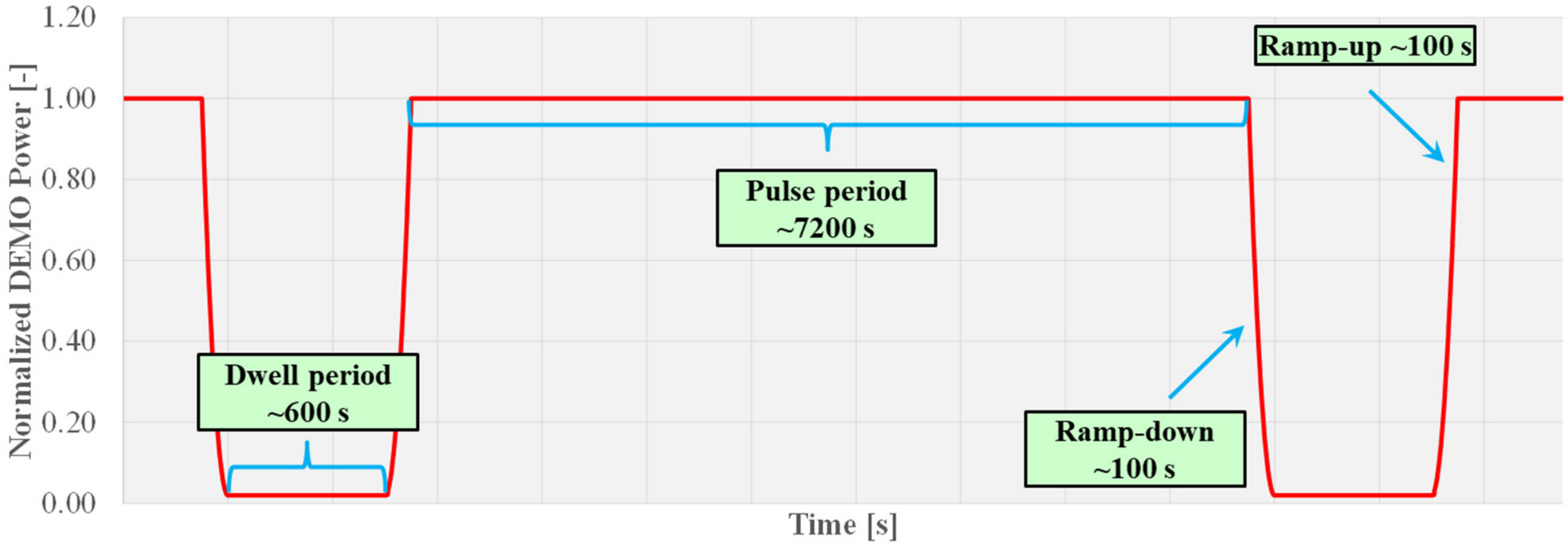


Introduction to EU-DEMO Balance of Plant (BOP)

- The EU-DEMO BOP system includes: i) the **Heat Transfer Systems** that remove the thermal power generated in the In-Vessel components and transfer it to the Power Conversion System and ii) the **PCS** itself which converts this fusion power in electricity.

- During the EU-DEMO Pre-Concept Phase, several BOP architectures (Indirect/Direct) for both blanket concepts have being investigated leading to **two reference design** to be further developed in Conceptual Design Phase: Water Cooled Lithium Lead Direct Coupling Design and Helium Cooled Pebble Bed Indirect Coupling Design.

- The main objective of activity has been to provide BOP solutions able to accommodate the impact of the ***challenging profile*** of the power source (i.e the plasma power pulsation) allowing safe, reliable and efficient BOP operations.



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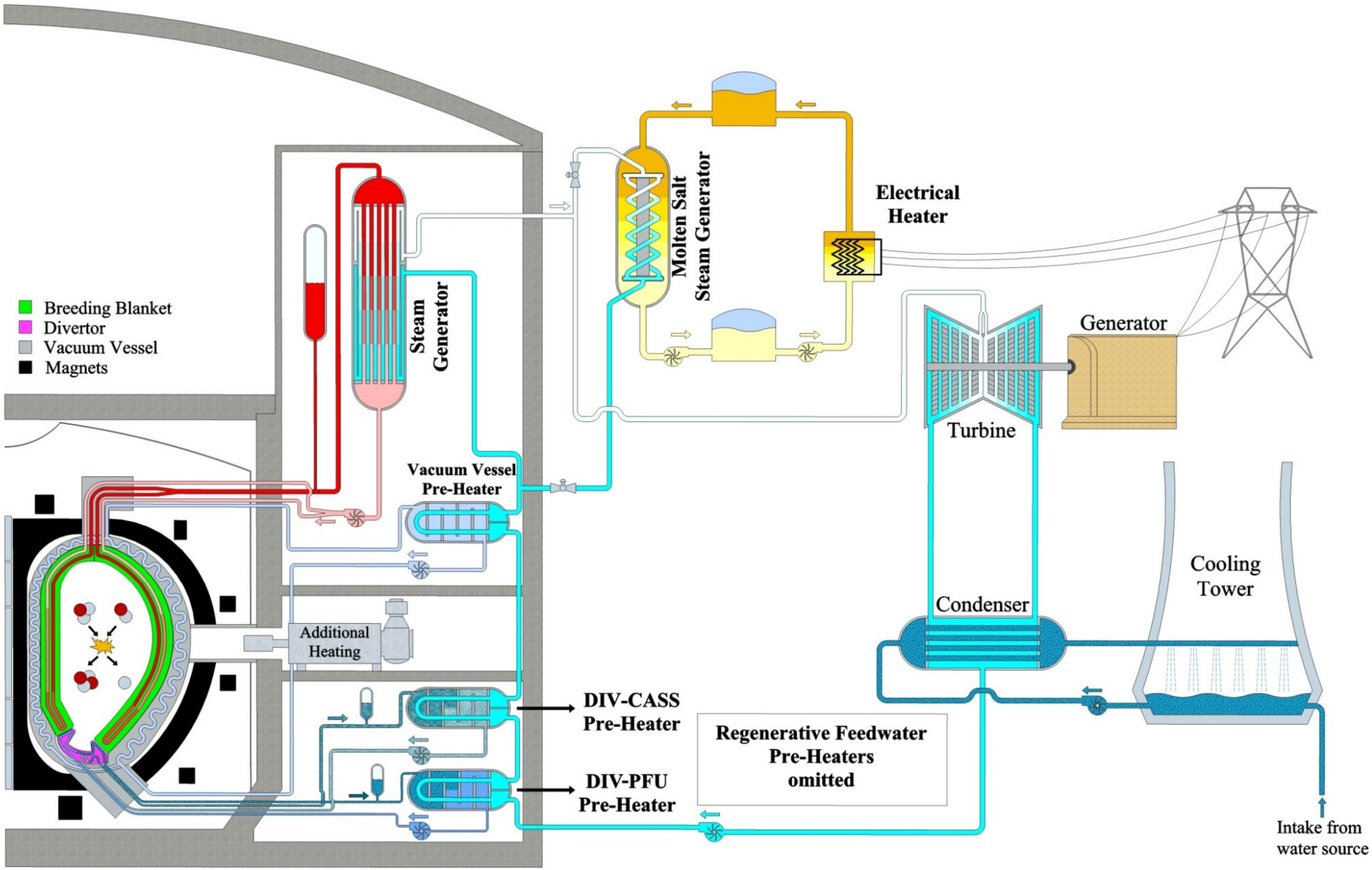
Introduction to EU-DEMO BOP: WCLL BOP Direct Coupled Design

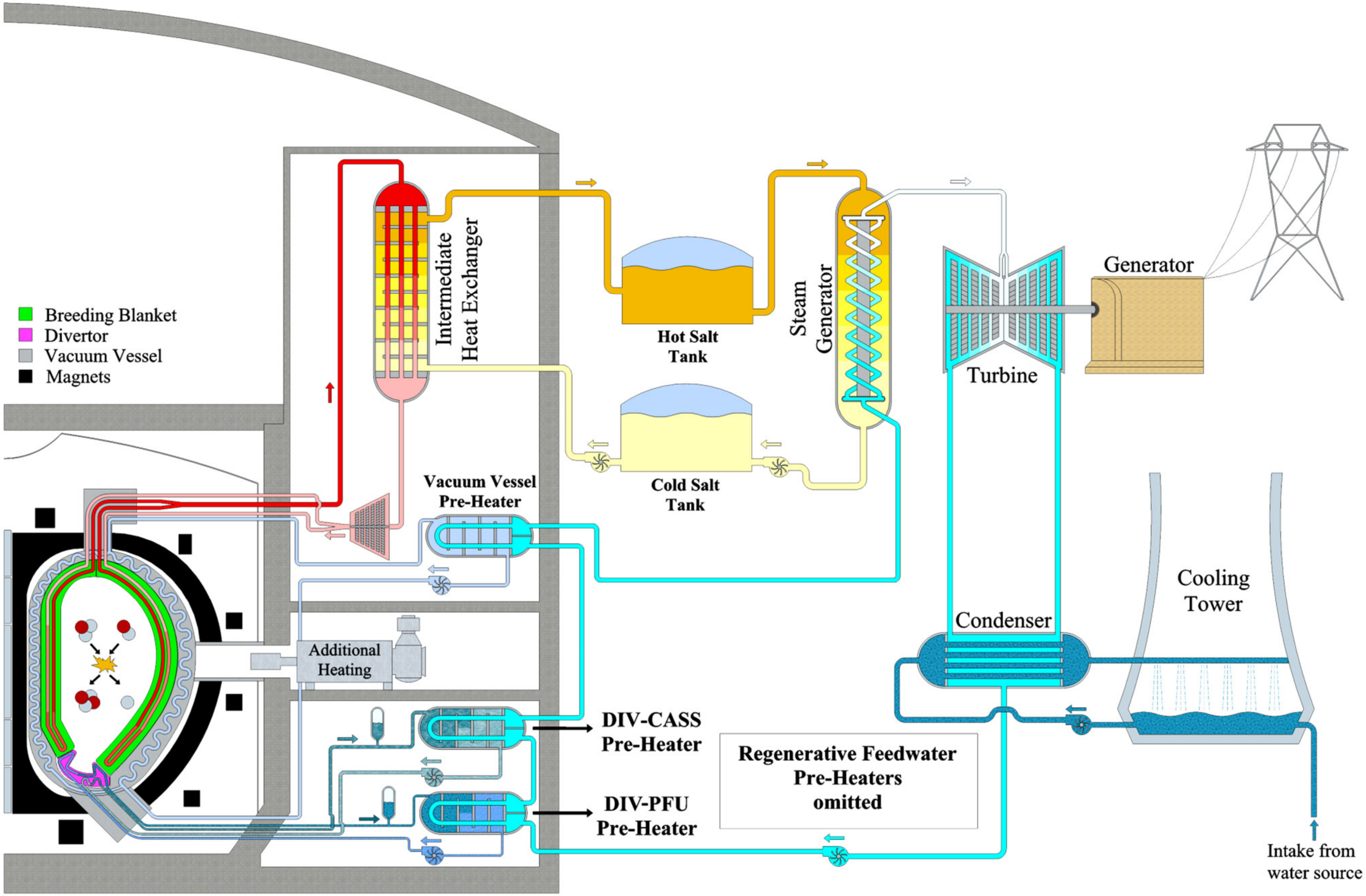
- **All PHTSs HXs/SGs integrated in PCS; High-T, High-P coolants for efficient energy conversion**
- **A small Energy Storage System (ESS) stores energy to supply around 10% steam to steam turbine during Dwell**



L. Barucca: FED169 (2021) 112504

Introduction to EU-DEMO BOP: HCPB BOP Indirect Coupled Design

- **BB PHTS thermally connected to Intermediate Heat Transport System +ESS that stores energy**
- **High-T, High-P coolants for efficient energy conversion**
- **IHTS thermally connected to PCS for continuous power transfer; DIV and VV PHTS HXs integrated in PCS**



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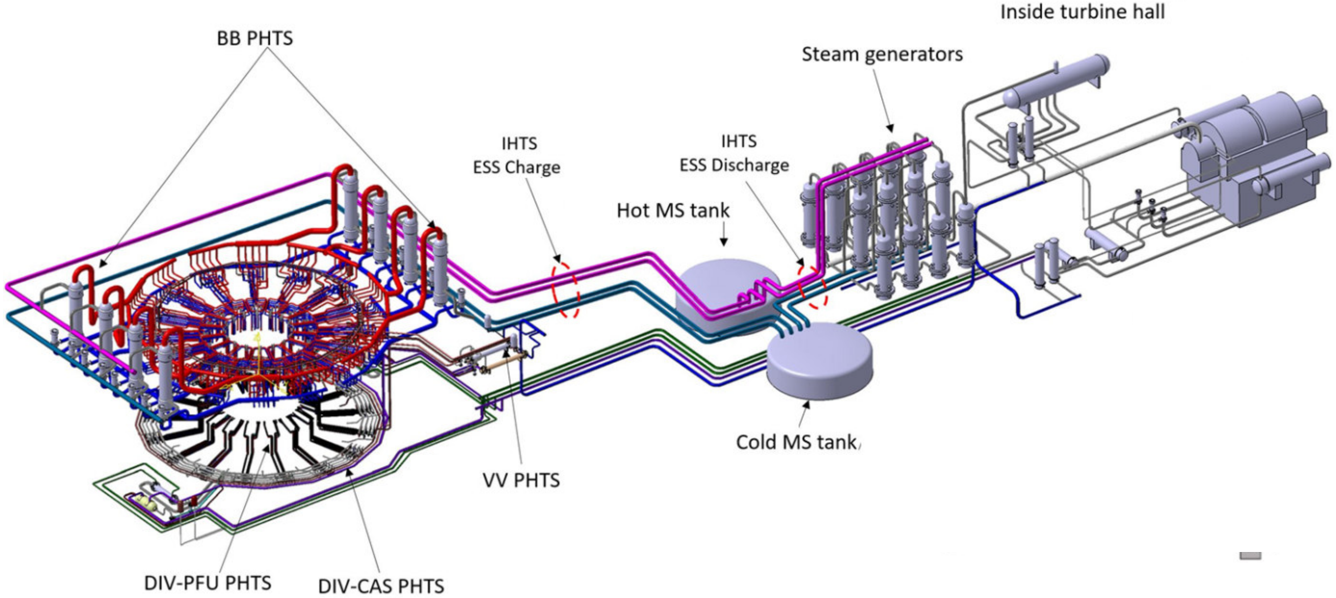
Introduction to EU-DEMO BOP: The reference concept designs

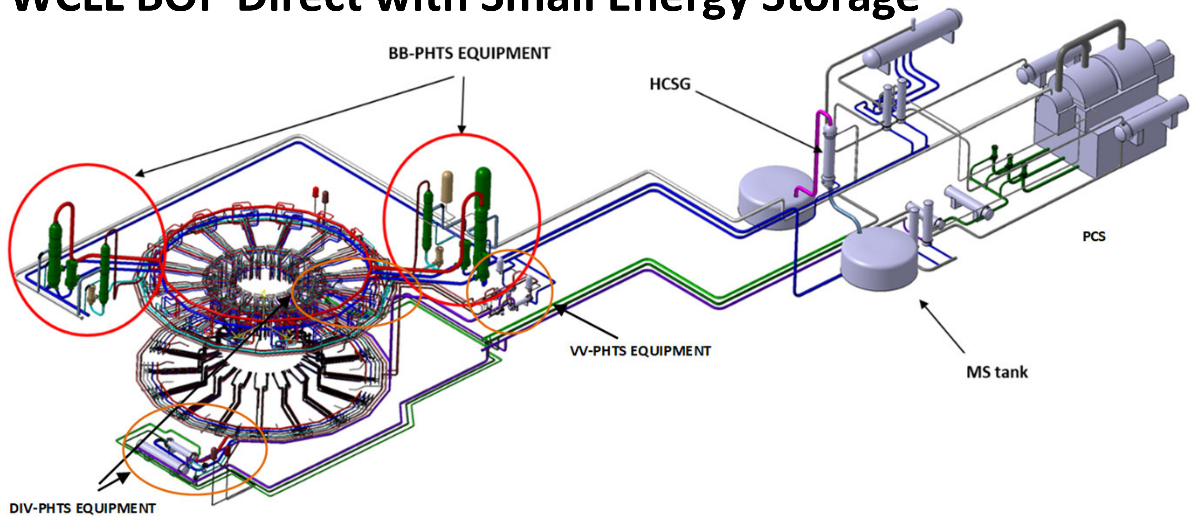
HCPB BOP Indirect



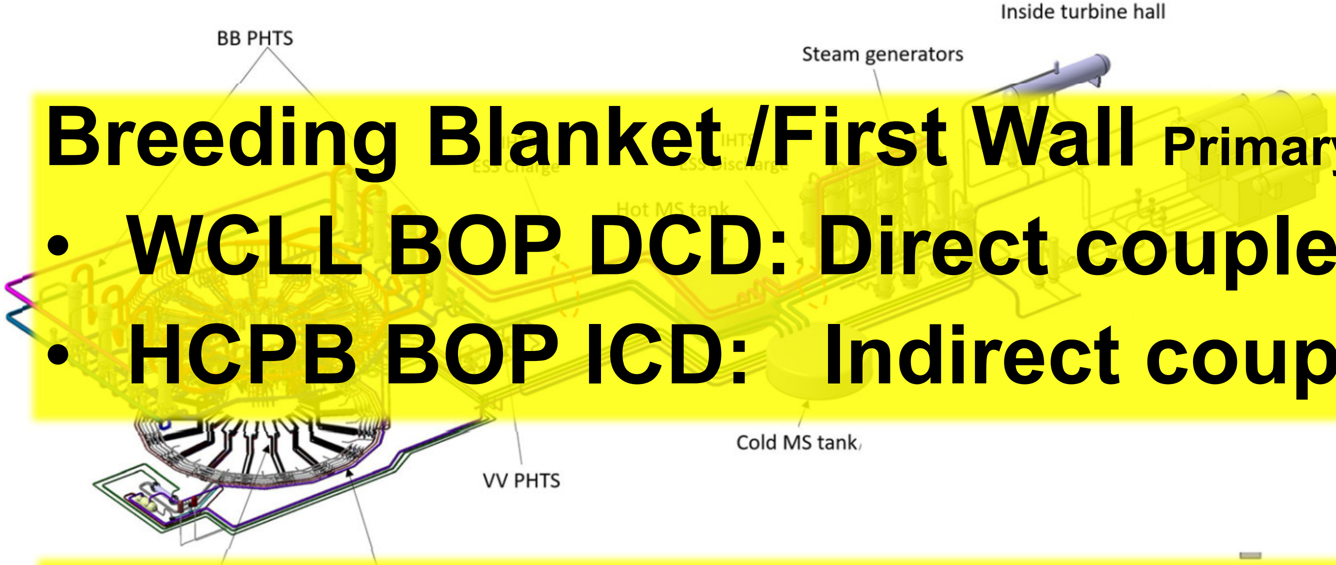
- ✓ T/H sizing of BOP components according to safety and operational requirements as well as integration constraints.
- ✓ Preliminary mechanical design of main relevant Primary Heat Transfer System components and thermo-mechanical verification.
- ✓ BOP Pulse-dwell transient analysis.
- ✓ BOP Cost assessment.
- ✓ BOP preliminary RAMI.

WCLL BOP Direct with Small Energy Storage

- ✓ Architecture simplification directly inter-facing PHTS to PCS.
- ✓ Provisions for PCS operation at low load in dwell.
- ✓ T/H components sizing and mechanical design of PHTS ones.
- ✓ BOP transient analysis and thermo-mechanical verification of BOP components of the pulsed operation.
- ✓ BOP Cost assessment.
- ✓ BOP preliminary RAMI.



HCPB BOP Indirect



- ✓ T/H sizing of BOP components according to safety and operational requirements as well as integration constraints.
- ✓ Preliminary mechanical design of Intermediate Primary Heat Transfer System components and thermo-mechanical verification.
- ✓ BOP Pulse-dwell transient analysis.
- ✓ BOP Cost assessment.
- ✓ BOP preliminary RAMI.

Breeding Blanket /First Wall Primary Heat Transport System

- **WCLL BOP DCD: Direct coupled Design**
- **HCPB BOP ICD: Indirect coupled Design**

WCLL BOP Direct with Small Energy Storage

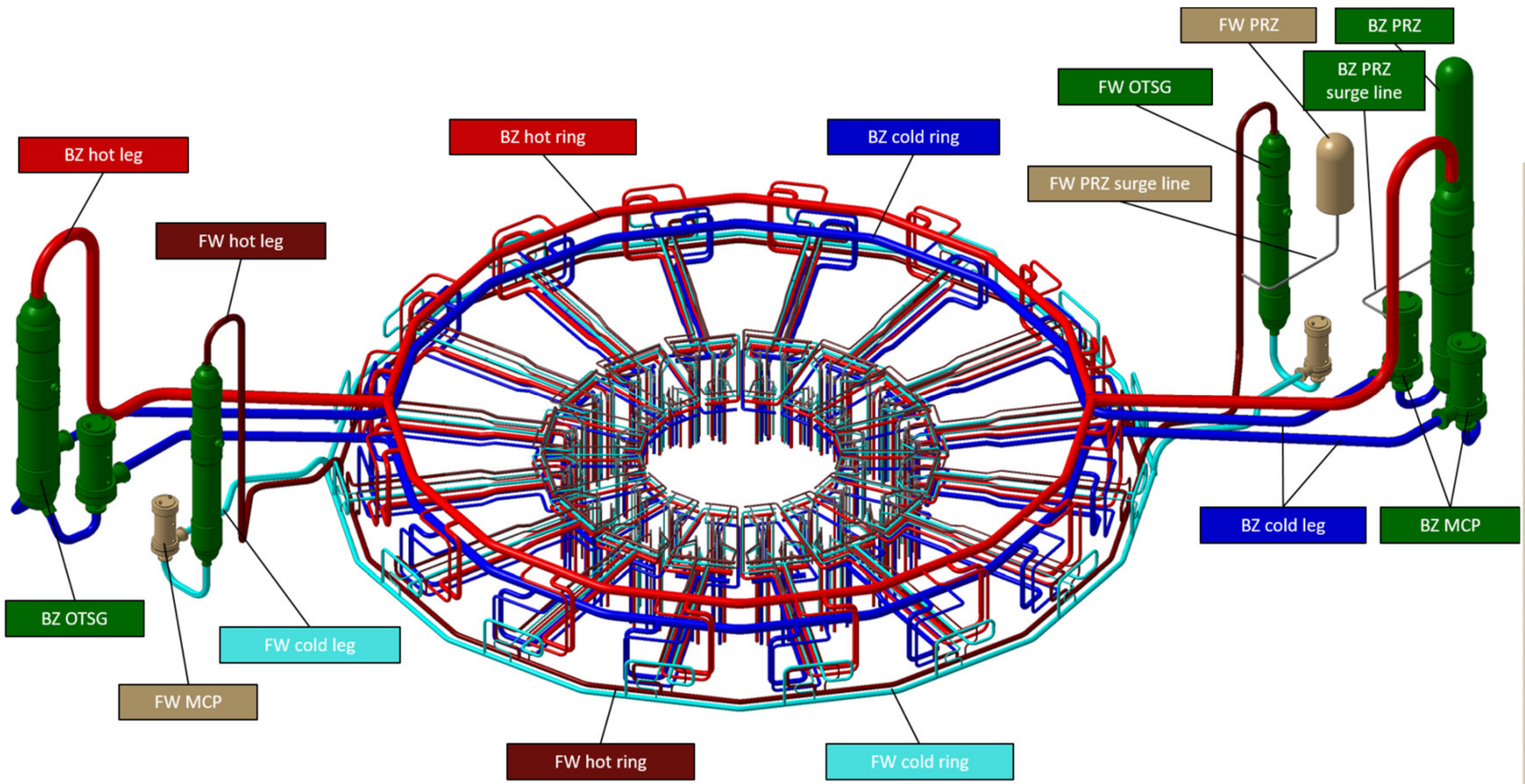
- ✓ Architecture simplification directly interfacing PHTS to PCS
- ✓ Provisions for PCS operation at low load in dwell
- ✓ T/H components sizing and mechanical design of PHTS ones.
- ✓ BOP transient analysis and thermo-mechanical verification of BOP components of the pulsed operation.
- ✓ BOP Cost assessment.
- ✓ BOP preliminary RAMI.

Common solution for secondary or "low temperature" Primary Heat Transport Systems:

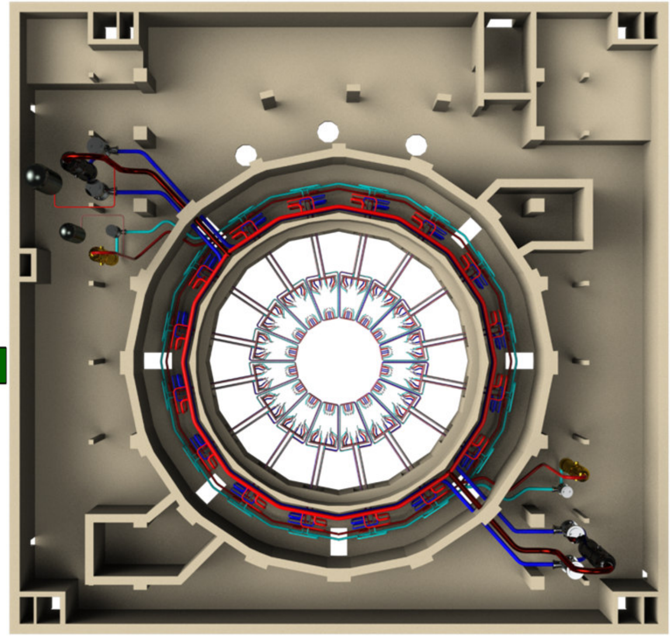
- **DIV-CAS: Divertor Cassettes**
- **DIV-PFU: Plasma Facing Units**
- **VV: Vacuum vessel cooling system (FP8)**
  … discarded during DEMO CDP

L. Barucca, FED179 (112291):113096

WCLL BOP DCD: The BB Primary Heat Transport System



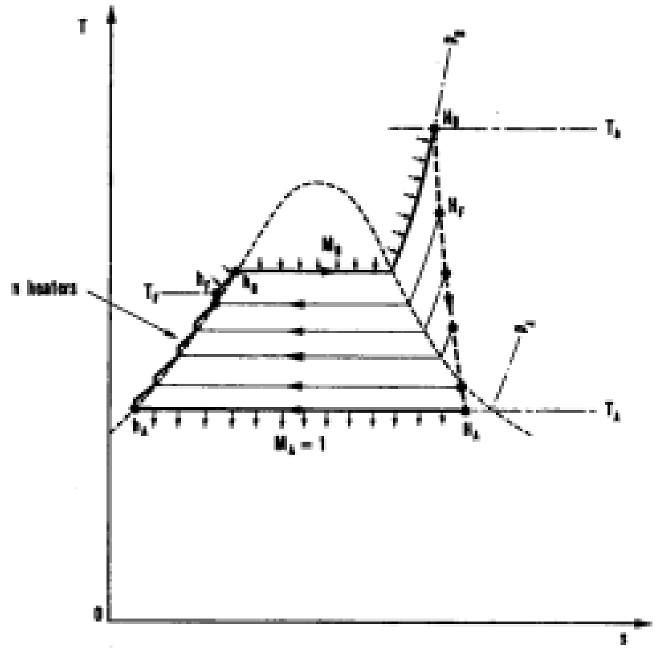
BB PHTS Integration in Tokamak Building

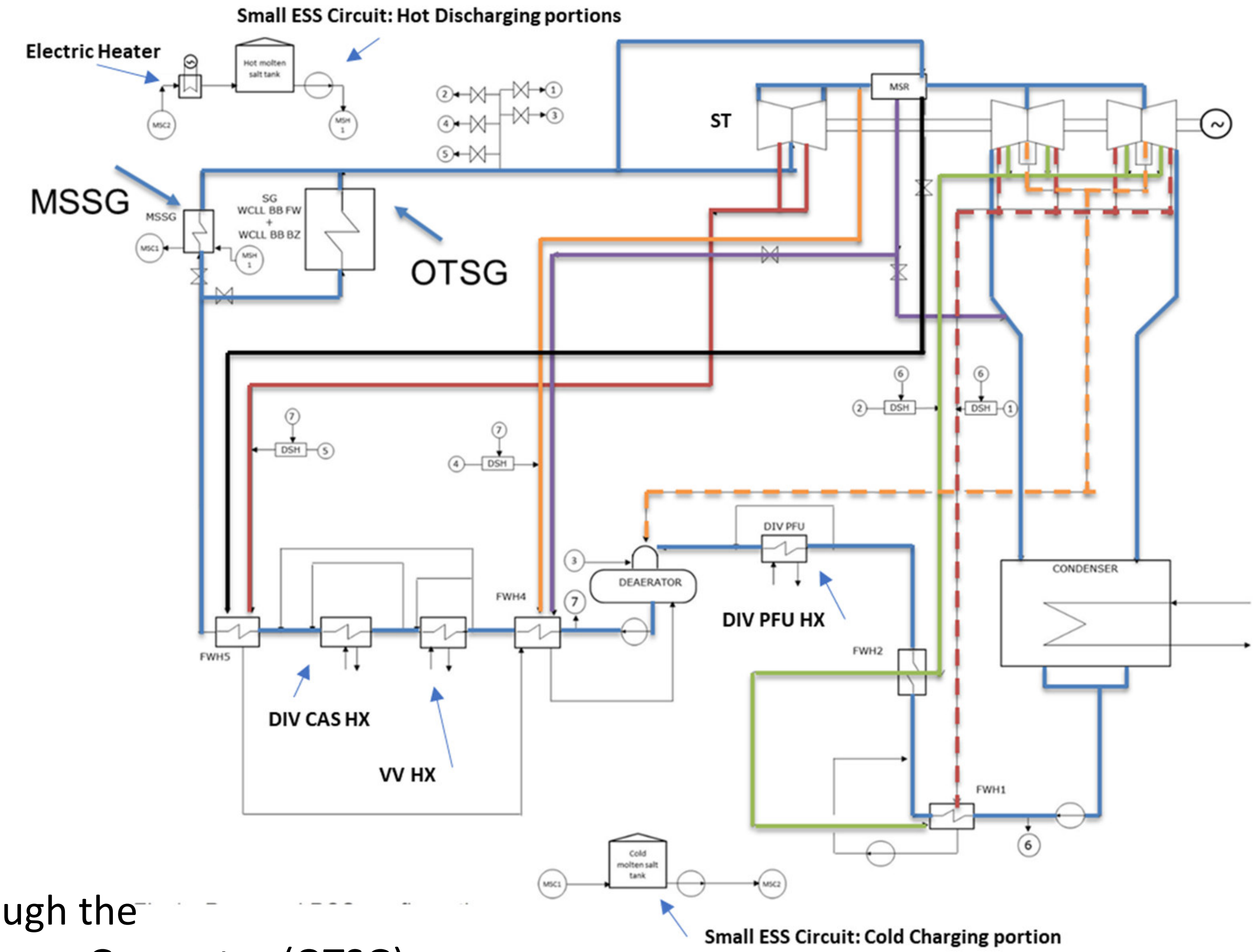


WCLL – FW PHTS main data	
Thermal power [MW]	440
Total water volume [m³]	159
Total piping length (In+Ex-VV) [m]	≈3700
Cooling loops [-]	2
Tin/out, °C	295/328

WCLL - BZ PHTS main data	
Thermal power [MW]	1483
Total water volume [m³]	563
Total piping length (In+Ex-VV) [m]	≈3200
Cooling loops [-]	2
Tin/out, °C	295/328

WCLL BOP DCD: The “pulsed” PCS Goal, performance & efficiency





Main Design Goals:

- ✓ Direct coupling BB PHTS and PCS through the water-water/steam Once Through Steam Generator (OTSG).
- ✓ Minimization of thermal and mechanical loads of PCS components due to pulsed operation ⍰ additional steam generation in dwell ⍰ small Energy Storage System (ESS) plus electrical heater
- ✓ Turbo-Generator always synchronized to grid.
- ✓ Integration of DIV, VV PHTS HXs in feedwater train to increase performances.
- ✓ Rankine with one stage reheater

EU-DEMO WCLL BOP DCD: power output and performance (P/D)

Steam	WCLL	
	Pulse	Dwell
Operative pressure [bara]	70,5	67
Operative temperature [°C]	299,2	299,8
Turbine inlet temperature [°C]	298	198

Steam

Average pulse-dwell BOP net Efficiency	WCLL
Average	**31,3 %**

Efficiency

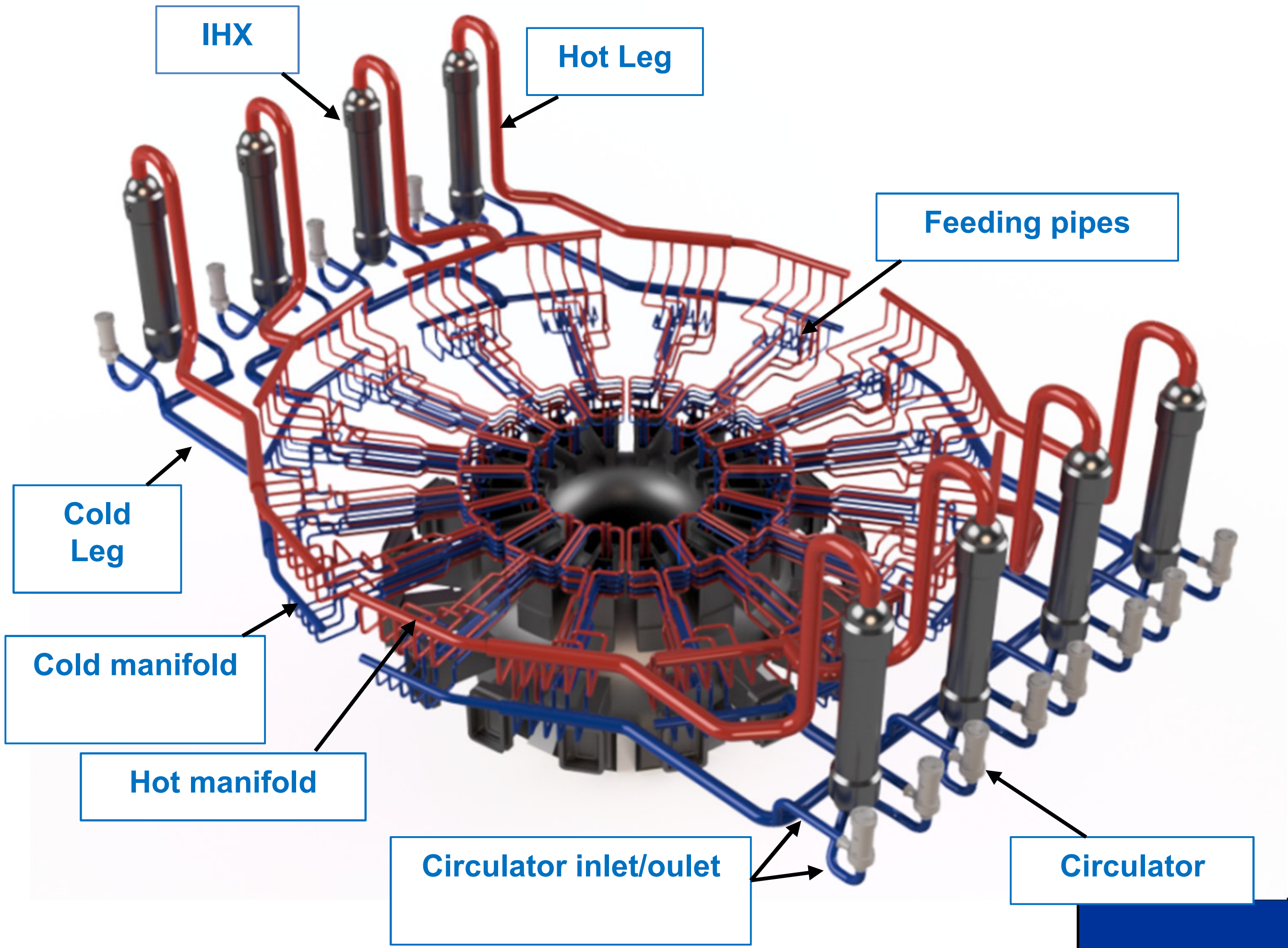
Power [gross]	WCLL
During Pulse [gross/net]	791,6 / 701,8 MW
During Dwell [gross/net]	62,4 / 10,4 MW
Avalilable Thermal Power	2260 MW

Power

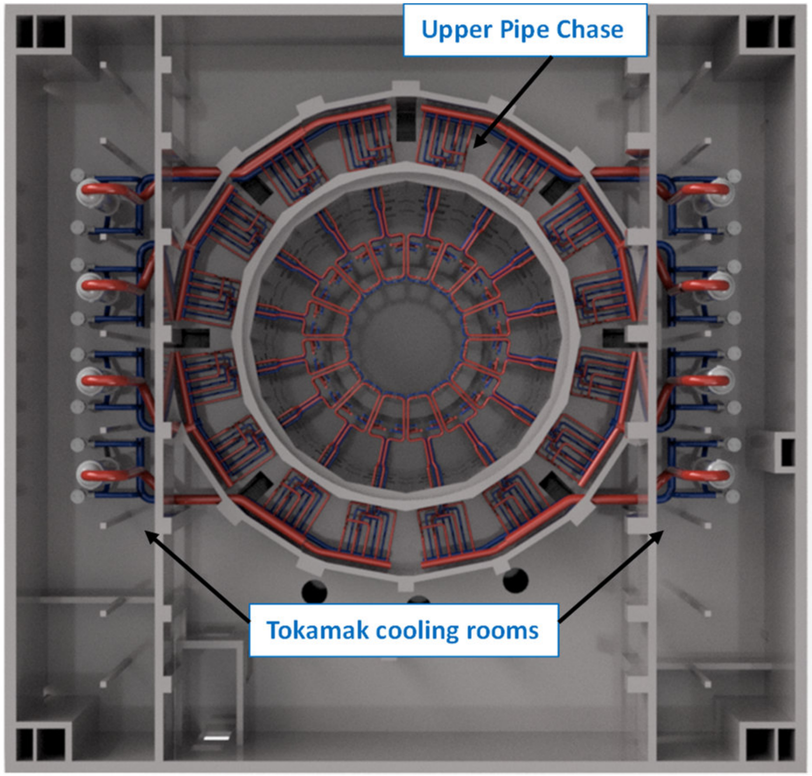
BOP Loads	WCLL
Electrical consumption during Pulse	85,65 MW
Electrical consumption during Dwell	36,3 MW

Only PHTSs + PCS+ ESS loads

HCPB BOP ICD: The Breeding Blanket Primary Heat Transport System



HCPB PHTS Integration in Tokamak Building



HCPB - BB PHTS main data	
Thermal power [MW]	2029.1
Total helium volume [m^3]	1735
Total piping length (In+Ex-VV) [m]	6300
Cooling loops [-]	8

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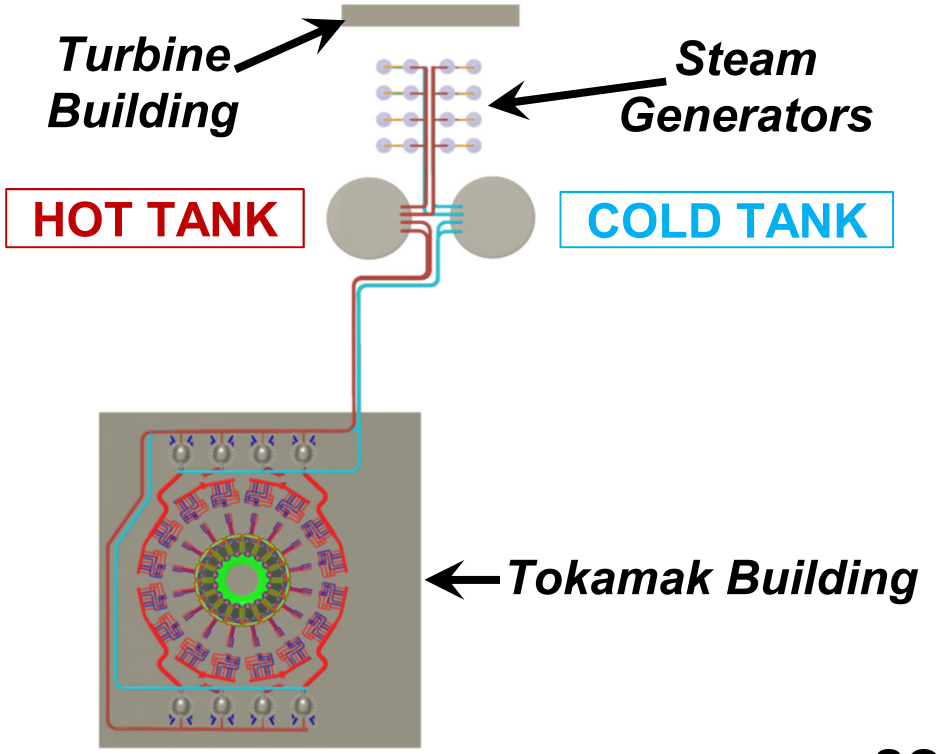
EU-DEMO HCPB BOP ICD: Intermediate Heat transfer System (IHTS)



IHTS+ESS main data	
Heat Transfer Fluid [-]	HITEC
Thermal Storage Capacity [MWh]	426
T_{cold} / T_{hot} tanks [°C]	270/465
Piping length [m]	1500
Piping volume [m^3]	1000
Tanks nominal volume [m^3]	2 x 3000

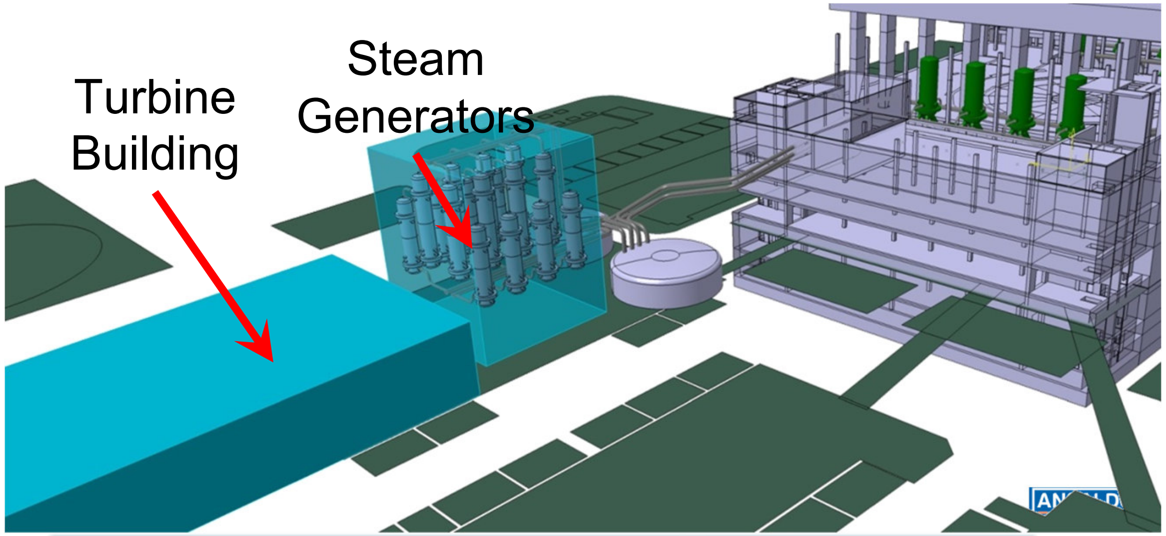
SOLANA (Arizona) Concentrated Solar Plant

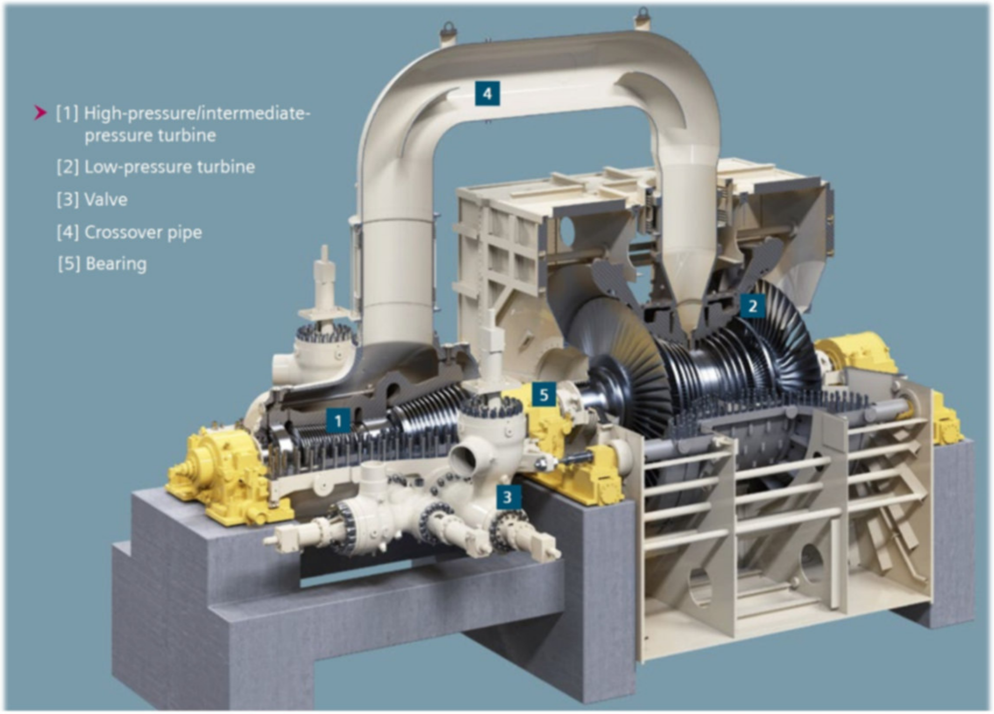
- 280 MW_e
- 4470 MWh
- 12 tanks (6 hot/cold)
- 135000 tons of salt
- Tank size 37 x 10

EU-DEMO HCPB BOP ICD: industrial support for PCS

The main components of the PCS have been developed based on experiences with molten salt used in commercial Concentrating Solar Power plants and supported by industrial experiences and specifications:

- ICD: **Kraftanlagen Heidelberg** and **Siemens** delivering adapted PCS
- Modular concept of SG of **SIEMENS** due to size and weight limitation on transportation routes to CSP sites.





www.siemens.com/steamturbines

EU-DEMO HCPB BOP ICD: power output and performance (P/D)

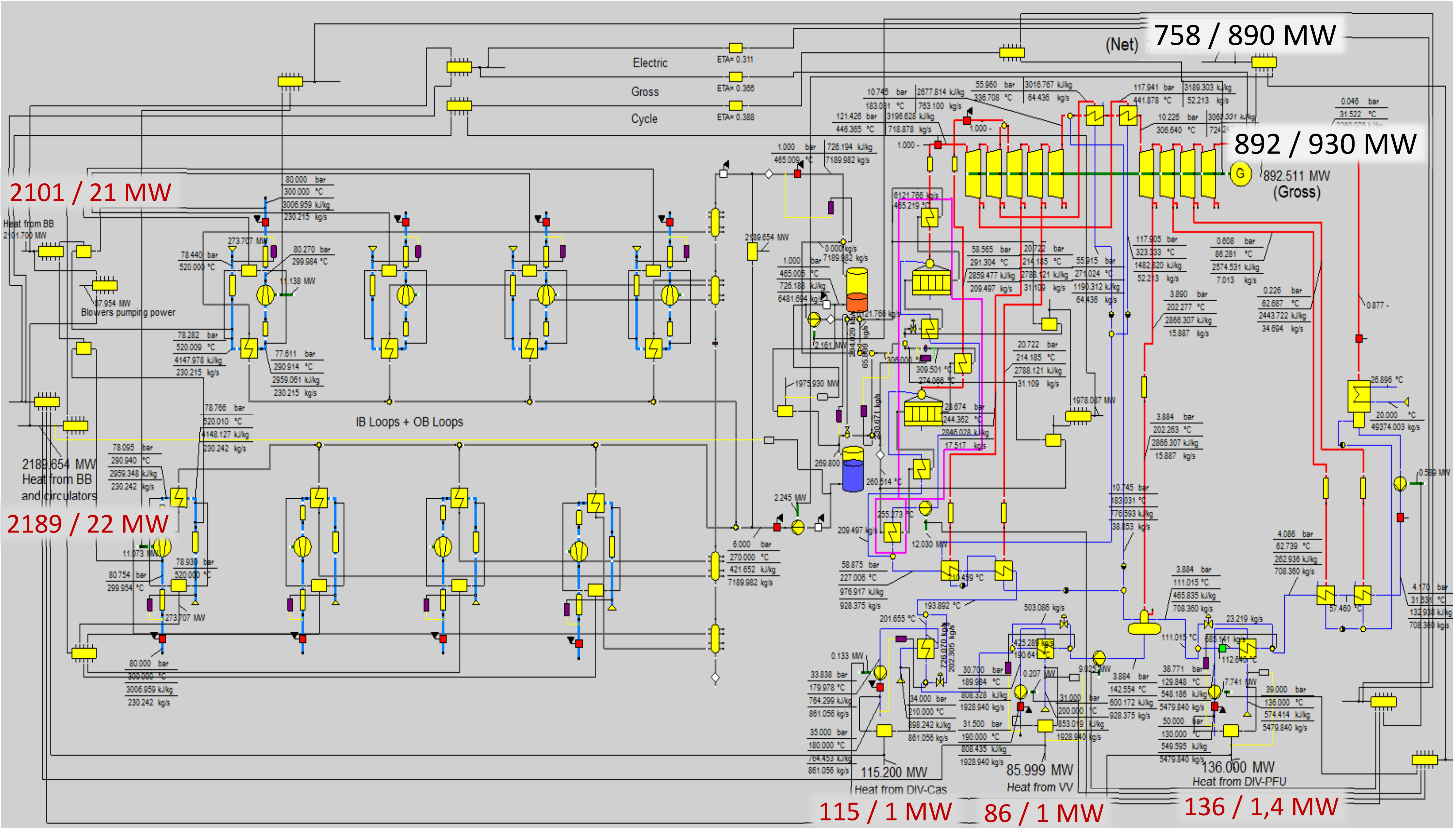


Figure and Data from: https://www.mdpi.com/1996-1073/14/23/7894

EU-DEMO HCPB BOP ICD: PCS power output and performance (P/D)

Steam	HCPB	
	Pulse	Dwell
Operative pressure HP/LP [bara]	122.4 / 56.0	123.2 / 56.0
Operative temperature HP/LP [°C]	446 / 291	446 / 291
Turbine inlet temperature HP/LP [°C]	446 / 288	446 / 287.8

Steam

Power [gross]	HCPB
During Pulse [gross/net]	933.9 / 792.4
During Dwell [gross/net]	830.7 / 789.5
Available Thermal Power	2580

Power

Average pulse-dwell BOP net Efficiency	HCPB
Average	34.1 %

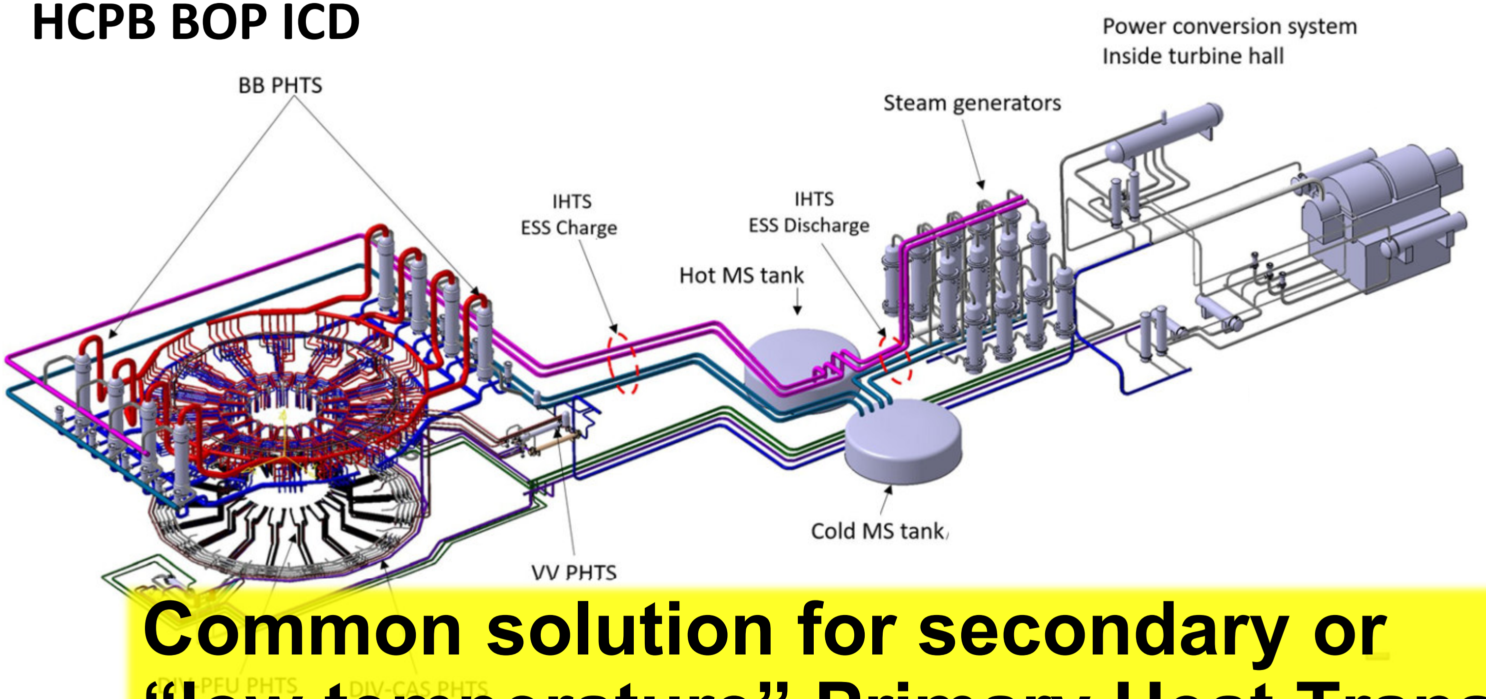
Efficiency

Primary Pumps/Compressor	HCPB
Electrical consumption during Pulse	40.9 / 88.7
Electrical consumption during Dwell	39.7 / 1.2

Including BB PHTS He circulator plus IHTS+PCS loads

Introduction to EU-DEMO BOP: The reference concept designs

HCPB BOP ICD



- ✓ T/H sizing of BOP components according to safety and operational requirements as well as integration constraints.
- ✓ BOP 3D CAD model development.
- ✓ Preliminary mechanical design of main relevant Primary Heat Transfer System components and thermomechanical verification.
- ✓ BOP Pulse-dwell transient analysis.

Common solution for secondary or “low temperature” Primary Heat Transport Systems:

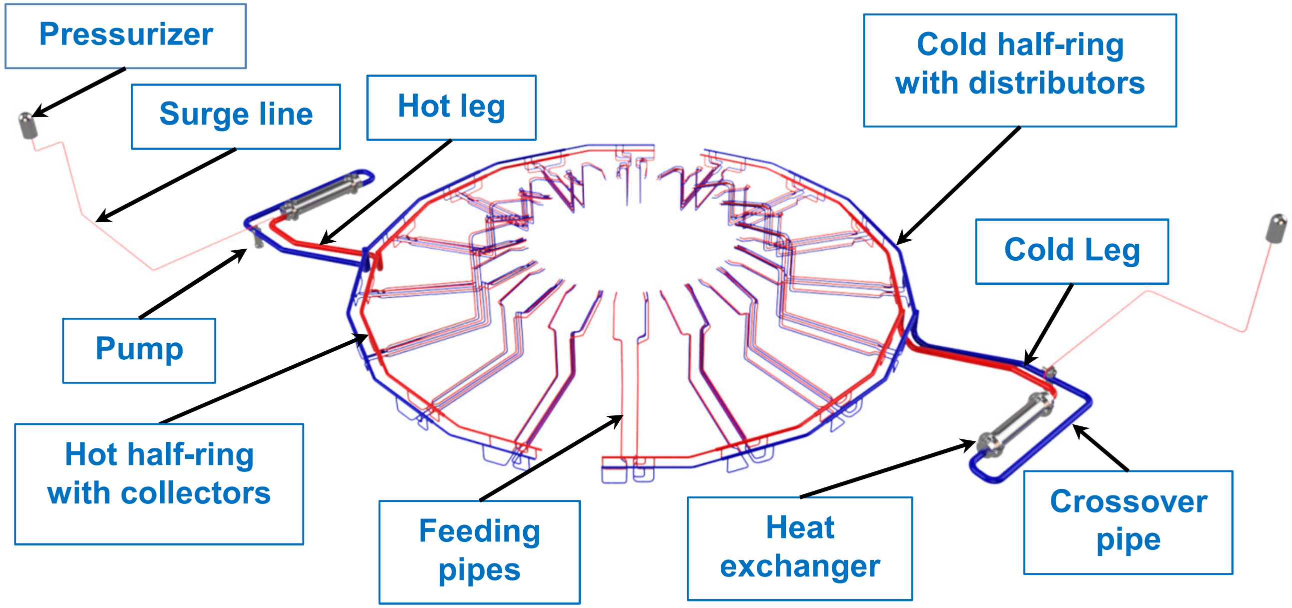
- **DIV-CAS: Divertor Cassettes**
- **DIV-PFU: Plasma Facing Units**
- **VV: Vacuum vessel cooling system (FP8)**

… discarded during DEMO CDP

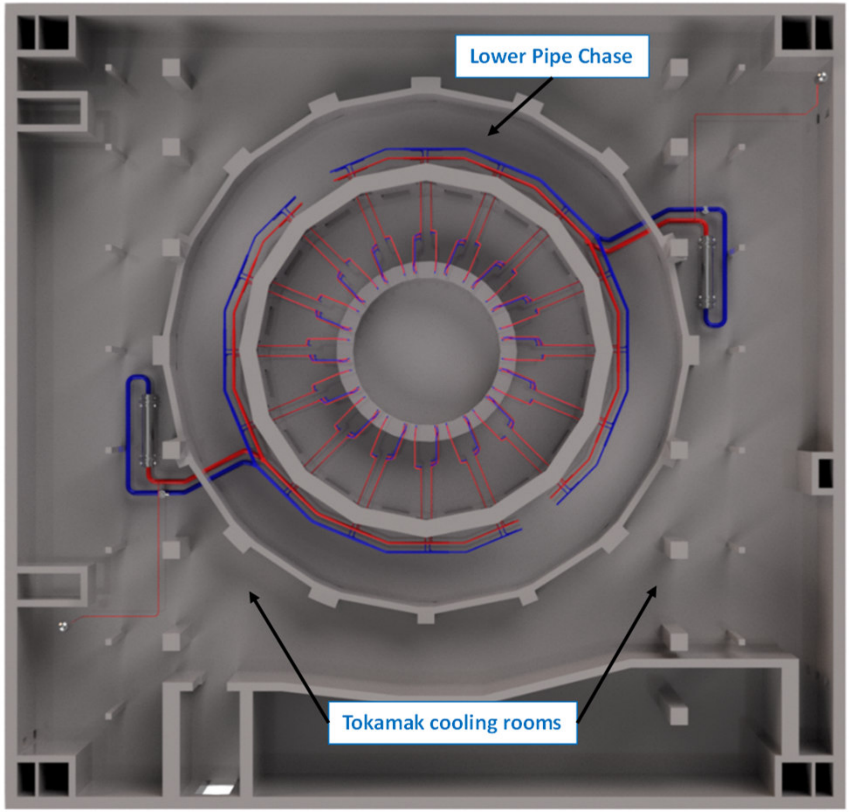
- ✓ Architecture simplification through direct thermal coupling of PHTS to ...
- ✓ Provisions for PCS operation at low power in dwell.
- ✓ T/H components sizing and mechanical design of PHTS ones.
- ✓ BOP 3D CAD model development.
- ✓ BOP transient analysis and thermo-mechanical verification of BOP components of the pulsed operation.

EU-DEMO BOP Design: DIVERTOR: CASsettes and PFU Plasma Facing Units

DIV PFU/DIV CAS Layout arrangement



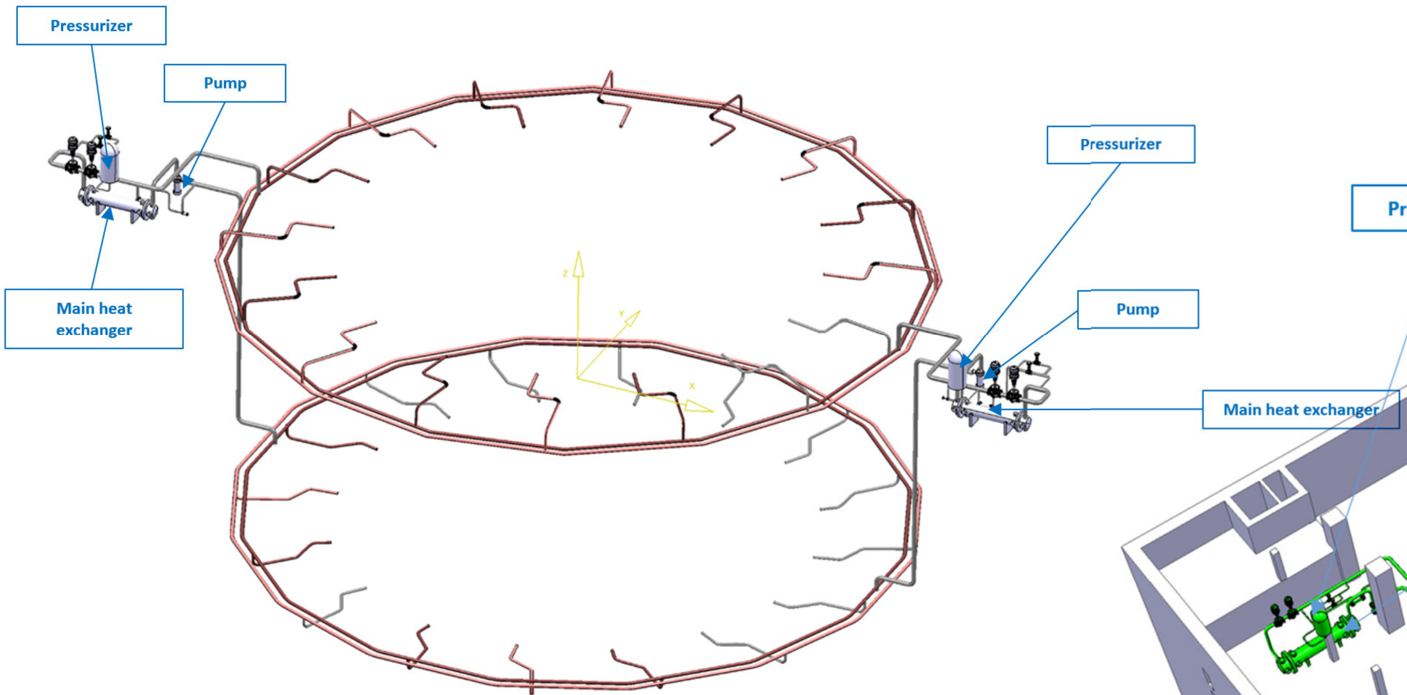
DIV PFU PHTS Integration in Tokamak Building



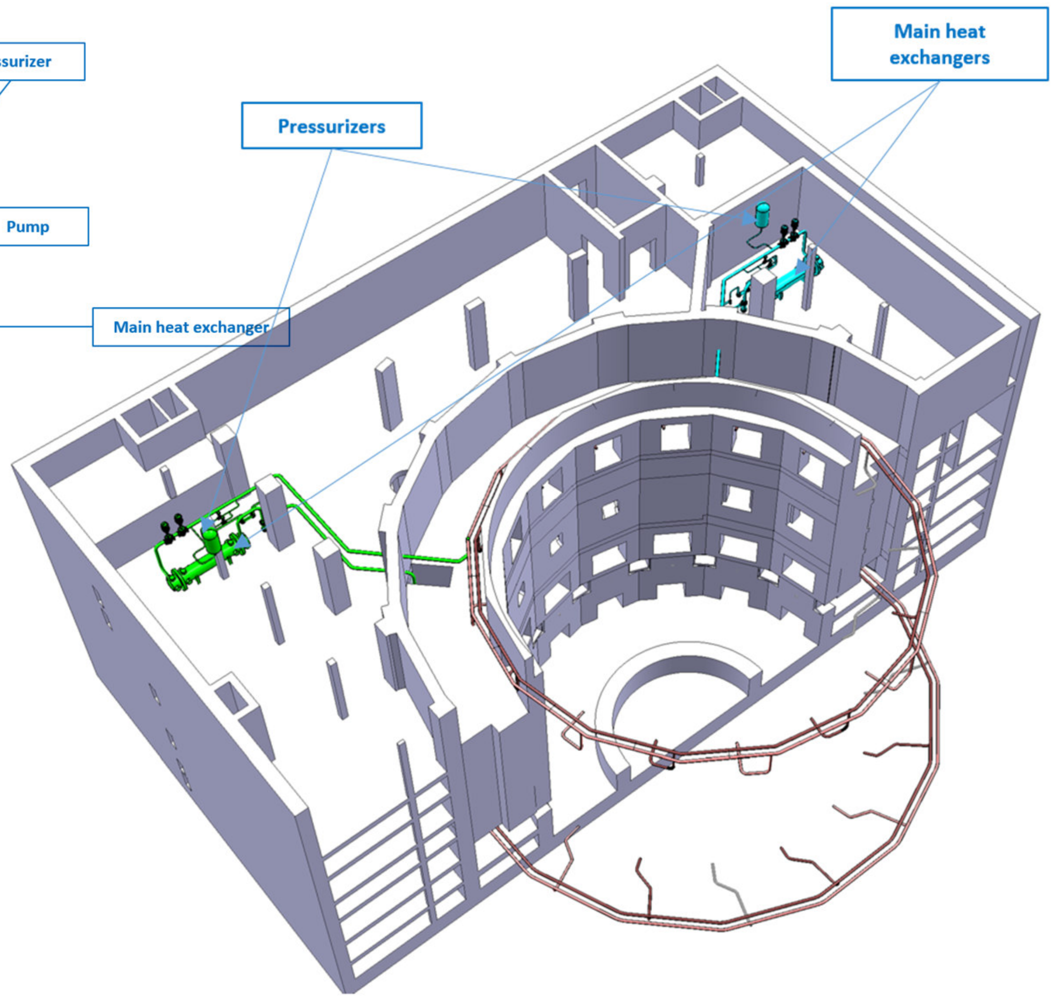
DIV PFC PHTS main data	
Thermal power [MW]	136.0
Total water volume [m³]	114.4
Total piping length (In+Ex-VV) [m]	2545
Cooling loops [-]	2
Tin,out [°C]	130/136

DIV CAS PHTS main data	
Thermal power [MW]	115.2
Total water volume [m³]	130.2
Total piping length (In+Ex-VV) [m]	2787.0
Cooling loops [-]	2
Tin,out [°C]	180/210

EU-DEMO BOP Design: The Primary Heat Transport System of Vacuum Vessel



Isometric view of the VV-PHTS 3D layout



Safety oriented VV PHTS Integration in Tokamak Building

VV PHTS main data	
Thermal power [MW]	86.0
Total water volume [m^3]	598.7
Total piping length (Ex-VV) [m]	2474.8
Cooling loops [-]	2
Tin,out [°C]	190/200

EU-DEMO BOP: Robustness?

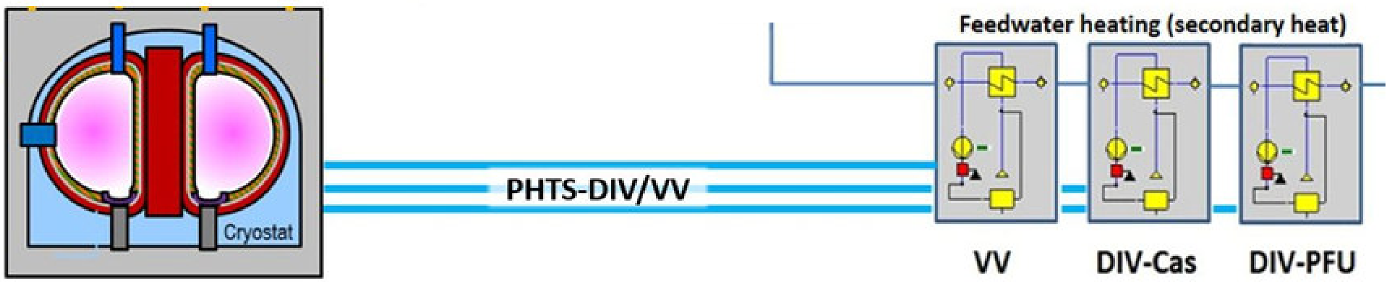
Robustness of BOP if primary and/or secondary power inputs change during CDP???
Here examples changed from 2018 (FP8) to 2021 (FP9) energy map:

1. FW/BB power may change slightly app. 5%
2. DIV total power output increased by ~100%
3. VV temperature dropped to ~40°C ⍰ not longer usable

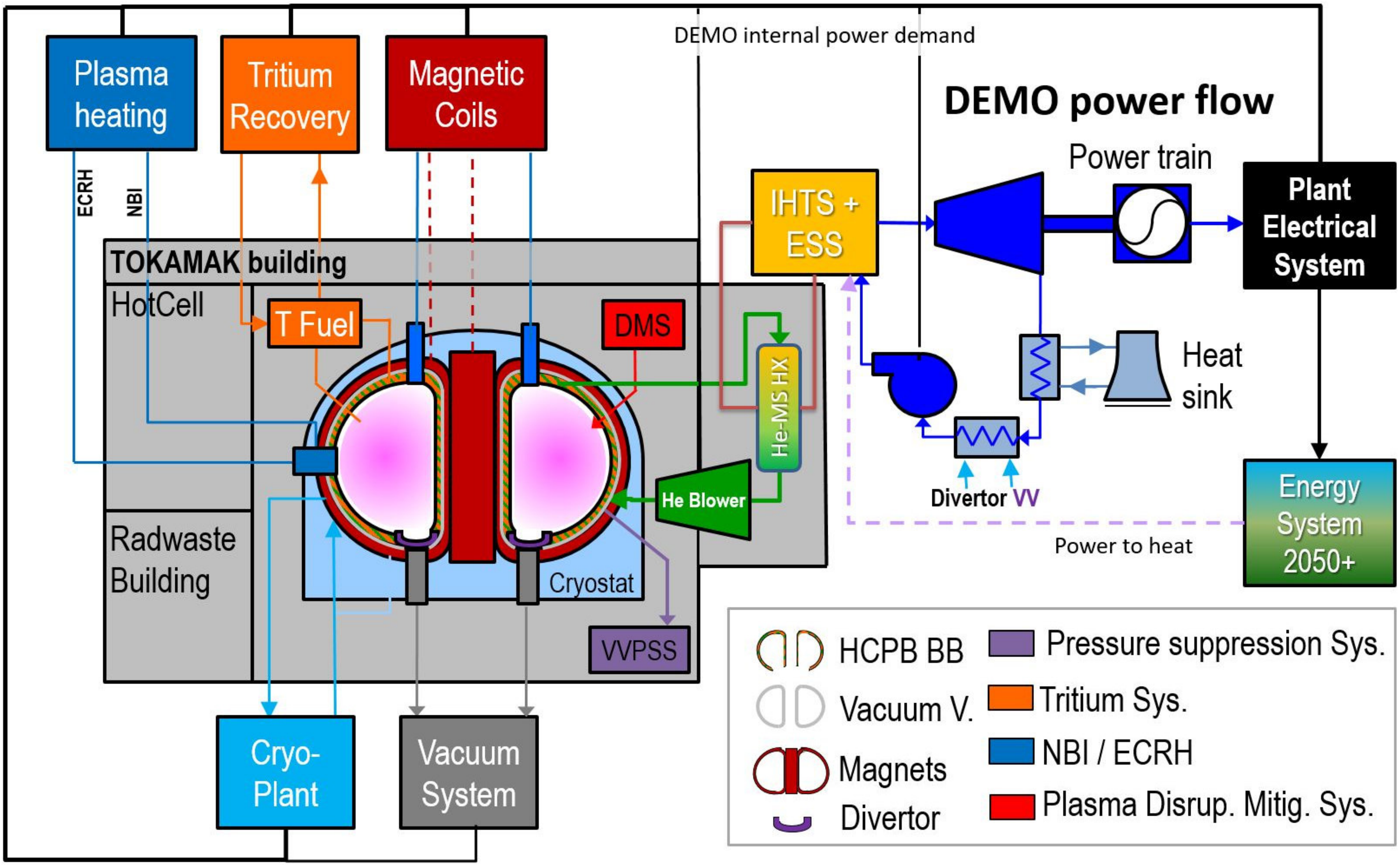
Condensed:

1) Former VV power removed in both BOP the feedwater train is simplified, power loss compensated by steam (open: costs to Component Cooling System)
(*E. Bubelis: Sensitivity analysis on FP8 HCPB BOP ICD of new VV cooling temperature)*

2) Feedwater train shows some limitations and has to be optimized to accommodate future power variations, especially with respect to available capabilities during dwell.
(Further Ebsilon analyses under way by E. Bubelis at KIT)



EU-DEMO BOP: overview of the main plant loads



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EU-DEMO BOP: preliminary plant steady loads and impact on efficiency

DEMO PBS	HCPB ICD Estimated PF	HCPB ICD Indirect Flat-Top [MW]	HCPB ICD Indirect Dwell time [MW]	WCLL DCD Estimated PF	WCLL DCD Direct Flat-Top [MW]	WCLL DCD Direct Dwell time [MW]
Breeding Blanket PHTS	0,9	99,66	25,81	0,9	21,09	21,09
Tritium, Fuelling, Vacuum	0,85	12,4	12,4	0,85	12,4	12,4
Tritium Extraction and Removal	0,85	3	3	0,85	3	3
Plasma Diagnostic & Control System	0,9	9,68	9,68	0,9	9,68	9,68
Vacuum Vessel (VV) PHTS	0,9	5,43	5,43	0,9	5,43	5,43
VV Pressure Suppression System	1	2,3	2,3	0,85	4,6	4,6
Divertor & Limiter PHTS	0,85	10,86	2,17	0,85	9,29	9,29
Remote Maintenance System	0,85	5	5	0,85	5	5
Assembly	0,9	4,6	4,6	0,9	4,6	4,6
Radwaste Treatment and Storage	0,9	3	3	0,9	3	3
BoP Power Conversion System	0,9	26,7	26,7	0,9	63,8	30,41
Cryoplant & Cryodistribution	0,85	101,81	101,81	0,85	101,81	101,81
Auxiliaries of Power Supply Systems	0,9	39	39	0,9	39	39
Buildings	0,9	57,93	57,93	0,9	57,93	57,93
Plant auxiliaries	0,85	90,95	90,95	0,85	90,95	90,95
Summ of internal steady demand	**0,887**	**472,32**	**389,78**	**0,877**	**431,58**	**398,19**
Power output of PCS		~830	~930		~890	~40

W. Hering, https://www.mdpi.com/1996-1073/14/23/7894 Narvisi, www.mdpi.com/2071-1050/14/10/5779

E. Bubelis, EFDA_D_2P5HSH

[1] HCPB: Helium Cooled Pebble Bed, one of the two Breeding Blanket concept to be developed in the CD phase
[2] WCLL: Water-Cooled Lithium-Lead, another Breeding Blanket concept to be developed in the CD phase

EU-DEMO BoP: Summary

During pCDP for both BB versions (WCLL and HCPB) several variants have been developed and optimized focused to account for different objectives:

1. **WCLL: compact direct coupled BOP based on PWR technology**
2. **HCPB: Indirect coupled (IHTS) with sensible energy storage based on proven CSP technology**

1) **Feasibility** proved and new built infrastructures initiated to close open issues:
   - STEAM: WCLL Once Through Steam Generator (OTSG) functional feasibility
     Demonstration of low load/ high load and transition (P2D, D2P) operation.
     Turbine low load-very low load operation feasibility demonstration by Industry.
   - HCPB: HELOKA-US test of MS and He components, operability of IHTS,
     dynamic behavior and damping of dwell/pulse transitions
2) **Robustness:**
   IHTS enhances robustness against power changes caused by optimizations in CDP.
3) **Efficiency:** integration of "cold" sources may decrease a little bit the efficiency, but delivers more gross power to feed important plant steady state loads.
4) **Adaptability:**
   IHTS/ESS can be adapated to different pulse/dwell regimes by modifying ESS size
   ESS can be simplified following CSP developments (2-Tank single tank)

5) Applicable for other FUSION concepts?

EU-DEMO BOP: New build Infrastructures

WCLL: STEAM

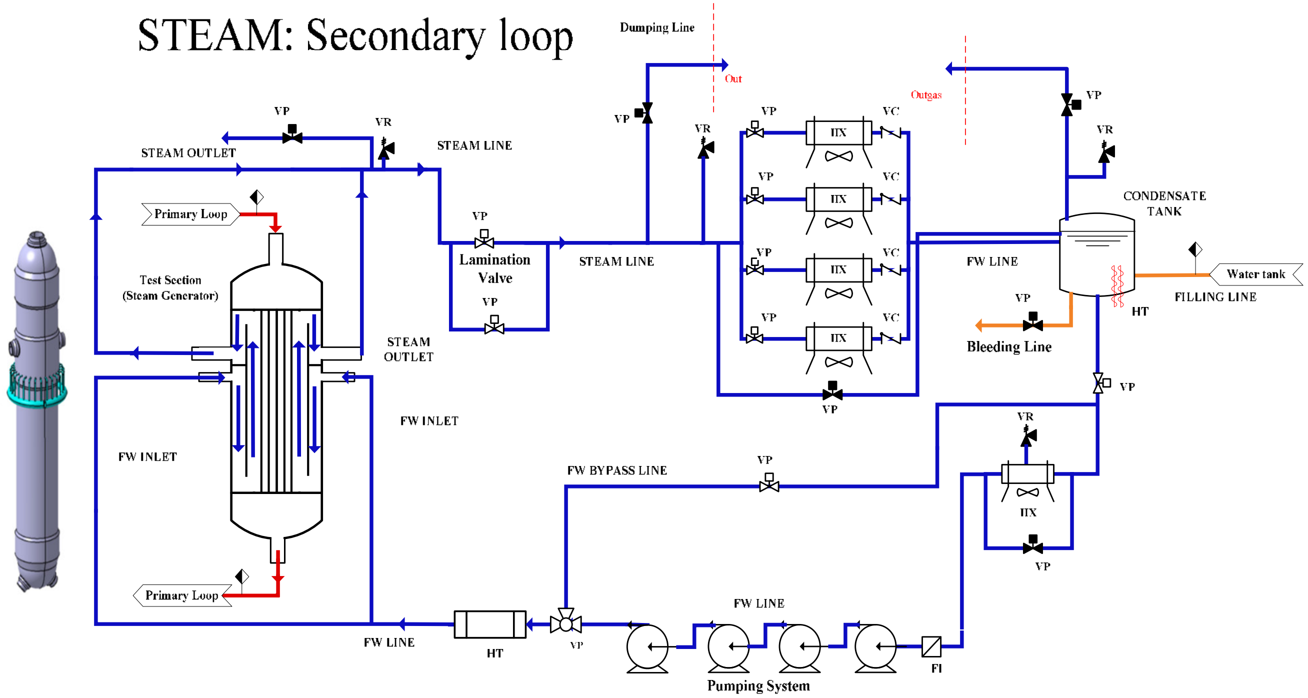
Scaling of OTSG:

Power/volume: ~1:200

Height/HT-Area: ~1:1

3 Phases:

1. Dwell: low load
2. Pulse: high load
3. Transitions: D2P and P2D



HCPB: HELOKA-US

Scaling:

Power/volume: 1:1000

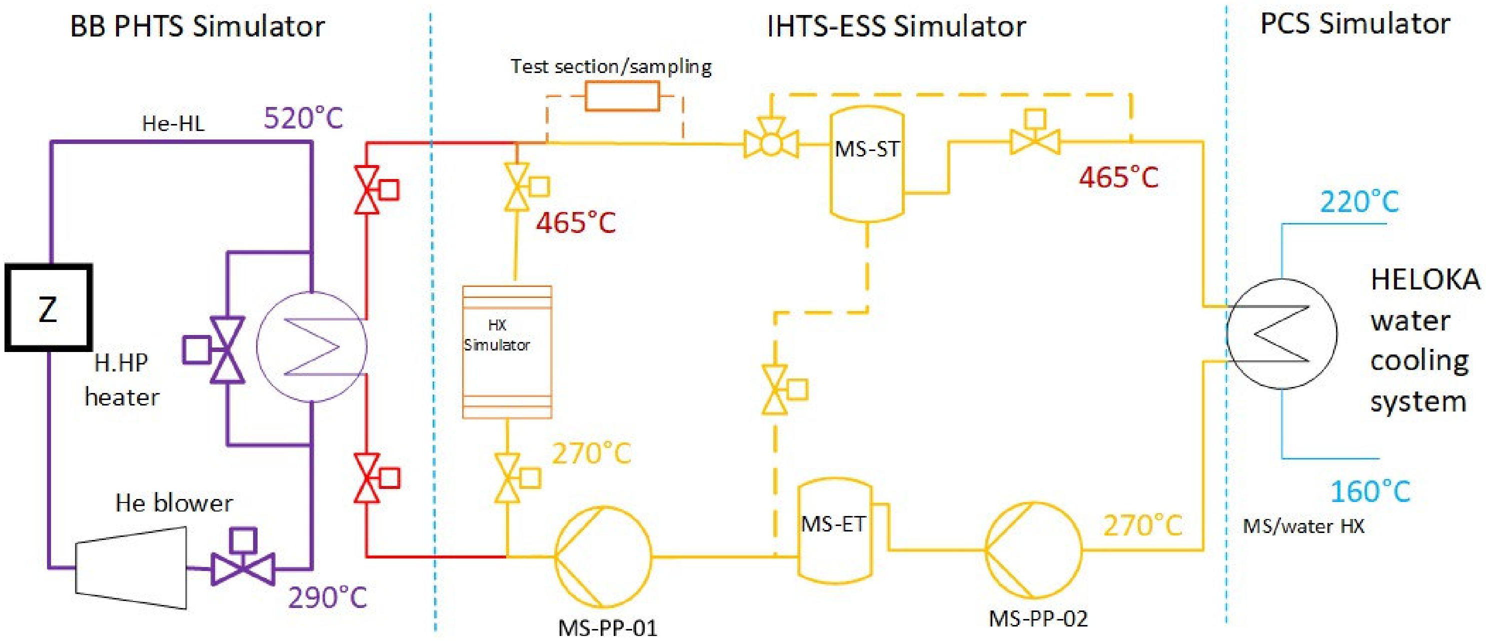
Height of IHTS: 1:10

3 Phases:

1a. el. HX Simulator

1b. He-Hitec - HX

2. DEMO specific blower

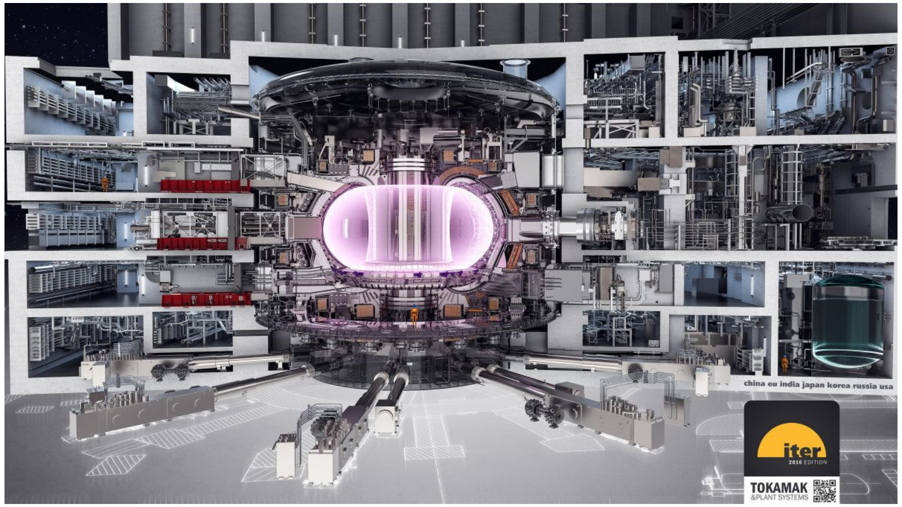


W. Hering, L. Barucca, S. Tincani, 8th IAEA DEMO Programme Workshop

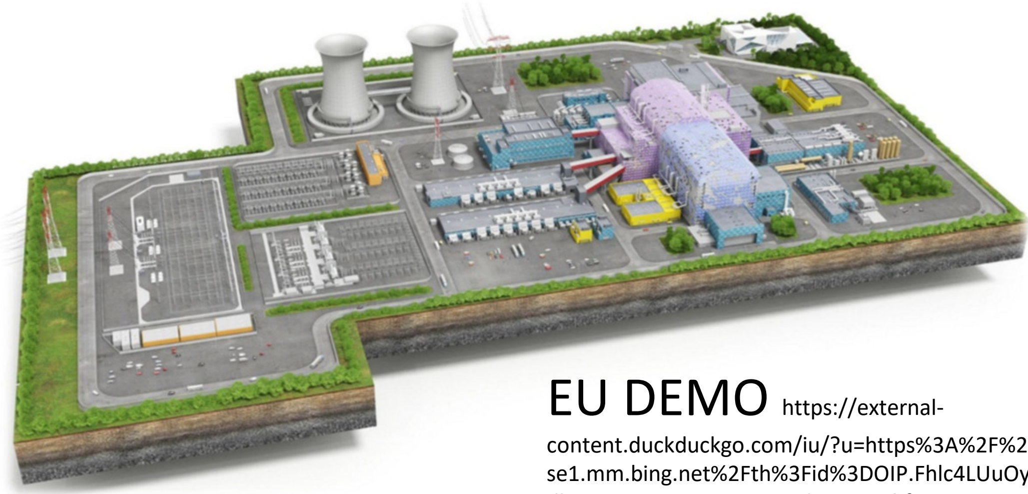
Fusion Power Plants Concepts for future Energy Systems

Some concepts expected to demonstrate the fusion electricity to grid ~2050:

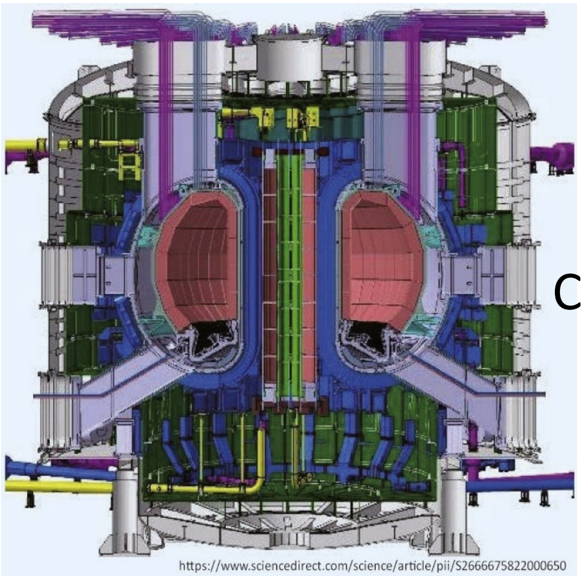
from ITER → EU DEMO /CFETR/ JA DEMO /STEP: pulsed



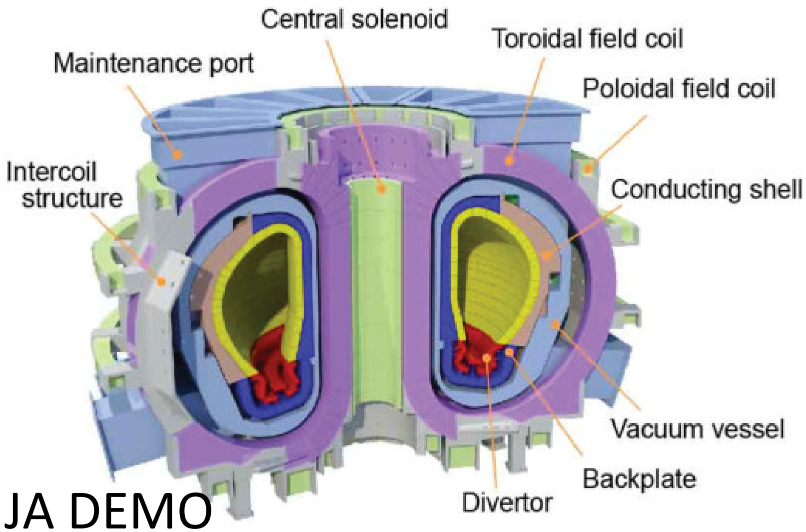
ITER https://global.techradar.com/it-it/news/fusione-nucleare-iter-passa-alla-fase-3



EU DEMO https://external-content.duckduckgo.com/iu/?u=https%3A%2F%2Ftse1.mm.bing.net%2Fth%3Fid%3DOIP.Fhlc4LUuOyKdl-FcWwyDTwHaDo%26pid%3DApi&f=1

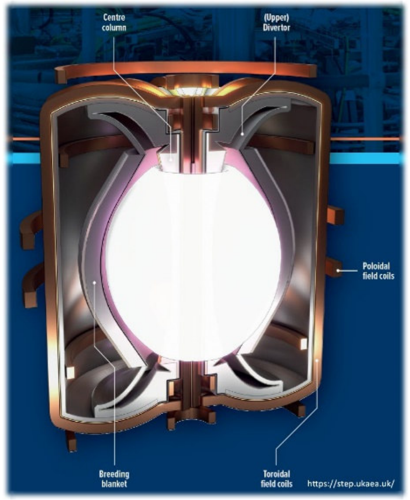


CFETR



JA DEMO

https://doi.org/10.1080/15361055.2019.1600931



STEP

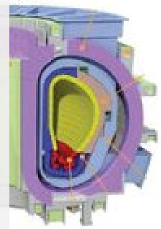
Worldwide steps to fusion power demonstration

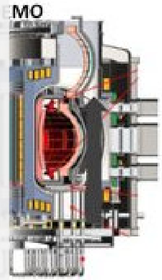
Name	Acronym	Country	Status	Fusion Power (GWth)	Pulsation [s]	BB Primary Heat Transport Sysem (PHTS) Coolant;Tin-Tout; Pressure	IHTS/ESS - (YES/No)	Use of 2nd heat sources (DIV, VV)	PCS type	PCS coolant cycle	Planned Operation
EU DEMO	DEMO (HCPB)	EU	CDP	2	7200	**Helium**; 8 MPa; 300°C-520°C	YES	yes	Rankine dual cycle	H2O	2050-
EU DEMO	DEMO (WCLL)	EU	CDP	2	7200	H20; 15,5MPa;295°C-328°C	No	yes	Rankine	H2O	2050-
China Fusion Engineering Test Reactor	CFETR(HCCB)	China	pCDP	0,2 - 1	7200	Helium; HCCB 8 MPa; 300°C-500°C	YES	yes	Bryton	S-CO2	2030s
China Fusion Engineering Test Reactor	CFETR (WCCB)	China	pCDP	0,2 - 1	long pulse? 28850	H2O; WCCB 285°C-325°C;15,5MPa	No	yes	Rankine	H2O	2030s
Japanese DEMO	JA DEMO	Japan	CDP	~1,5	steady state	H2O; WCCB 290-325; 15,5 MPa	t.b.d.	no	Rankine	H2O	2050
Korean DEMO	K-DEMO	Korea	CDP	2,2-3	3000s	H2O; WCCB 290°C-330°C, 15 MPa	t.b.d.	t,b.d	Rankine	H2O	2050
Spherical Tokamak for Energy Production	STEP	UK	CDP	~1,5	yes	H2O	forseen	t.b.d.	Rankine	H2O	2040
Indian DEMO fusion reactor		India	pCDP	1,2 - 1,7	both	Helium; HCLL and HCSB	Yes	yes	Rankine & Brayton	H2O, sCO2	>2050
DEMO hybrid fusion reactor	DEMO-FNS	Russia	?	0,2	Tritiom production incl. Transmutation. No electricity power						> 2045
Steady State Super-conducting Tokamak-2	SST-2	India			No electricity power output intended						>2035
Fusion Nuclear Science Facility	FNSF	USA			No electricity power output intended						2050
SPARC	SPARC	USA		0,14	No electricity power output intended						

Summary & Conclusion

YES: FUSION can become JOKER in energy poker

1. Worldwide efforts significantly ramped up
2. Various plans B to leading TOKAMAK in different stages to FPP as shown
3. Since 10 years requirements change due to:
   1. Energy crisis incl. avalanche of VRES
   2. Climate crisis and
   3. Water shortage
4. My vision:
   FUSION necessary for electricity and grid services plus: process heat, H_2 production and desalination





Priv
26 companies worldwide
3 b€ of fusion investments in 2021

EU-DEMO