Karlsruhe Institute of Technology

EUROfusion

Industry Supported Improved Design of DEMO BoP for HCPB BB Concept with Energy Storage System (ID #O3C.5)

E. Bubelis, W. Hering, S. Perez-Martin (KIT)

Institute for Neutron Physics and Reactor Technology

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

Outline

- Eurofusion at KIT
- Heat sources data for DEMO BoP
- DEMO HCPB BB with FW cooled in series with BZ & Plant configuration with IHTS/ESS
- Preliminary sizing of components and cost estimates
- Conclusions
- Acknowledgments

Eurofusion at KIT

- The KIT fusion work is well integrated within the German Helmholtz Programme Nuclear Fusion and within the European Fusion Programme (EUROfusion).
- Within EUROfusion, KIT is contributing to 18 out of 36 Work Packages, mostly within the Power Plant Physics and Technology (PPPT) section.
- In the framework of the EUROfusion PPPT, the Working Package Breeding Blanket (WPBB) aims at investigating 4 different Breeding Blanket (BB) concepts for a EU Demonstration Fusion Reactor (DEMO).
- One of these concepts is the Helium Cooled Pebble Bed (HCPB) BB, which is based on the use of pebbles of lithiated ternary compounds and Be or beryllides as tritium breeder and multiplier materials, respectively, EUROFER97 as structural steel and He as coolant.
- KIT experts are working on the design of DEMO BoP for the HCPB BB option.
- The task of Balance of Plant (BoP) for DEMO is to utilize heat from different internal sources, such as Breeding Blanket (BB), Divertor (DIV) and Vacuum Vessel (VV) and to convert it into electricity in an optimum way so as to fulfill the objective of demonstrating fusion electricity generation in a Demonstration Fusion Power Reactor (DEMO) around the middle of the century.

Heat sources data for DEMO BoP

Karlsruhe Institute of Technology

			HTF	Operation		Reference	Heating										
System			Fluid	time	type	Fusion Power, MW	Energy demand Thermal per IB segment, MW					Energy demand Thermal per OB segment, MW					Energy demand Thermal, MW
BB	HCPB						RP IB FW	NH IB FW	HF IB FW	IB FW	IB BZ	RP OB FW	NH OB FW	HF OB FW	OB FW	OB BZ	Total IB + OB
Objective(s)	TBR =	1.205	Helium	Pulse	stationary	2037	2.8	2.0	0.9	5.7	10.6	3.9	3.2	1.7	8.8	19.2	2101.7
t from breeder bla	HF BZ =	0.08		Dwell	stationary					0.057	0.106				0.088	0.192	21.017
										IB FW	IB BZ				OB FW	OB BZ	Total IB + OB
			Purge Gas	Pulse	stationary												
				Dwell	stationary												

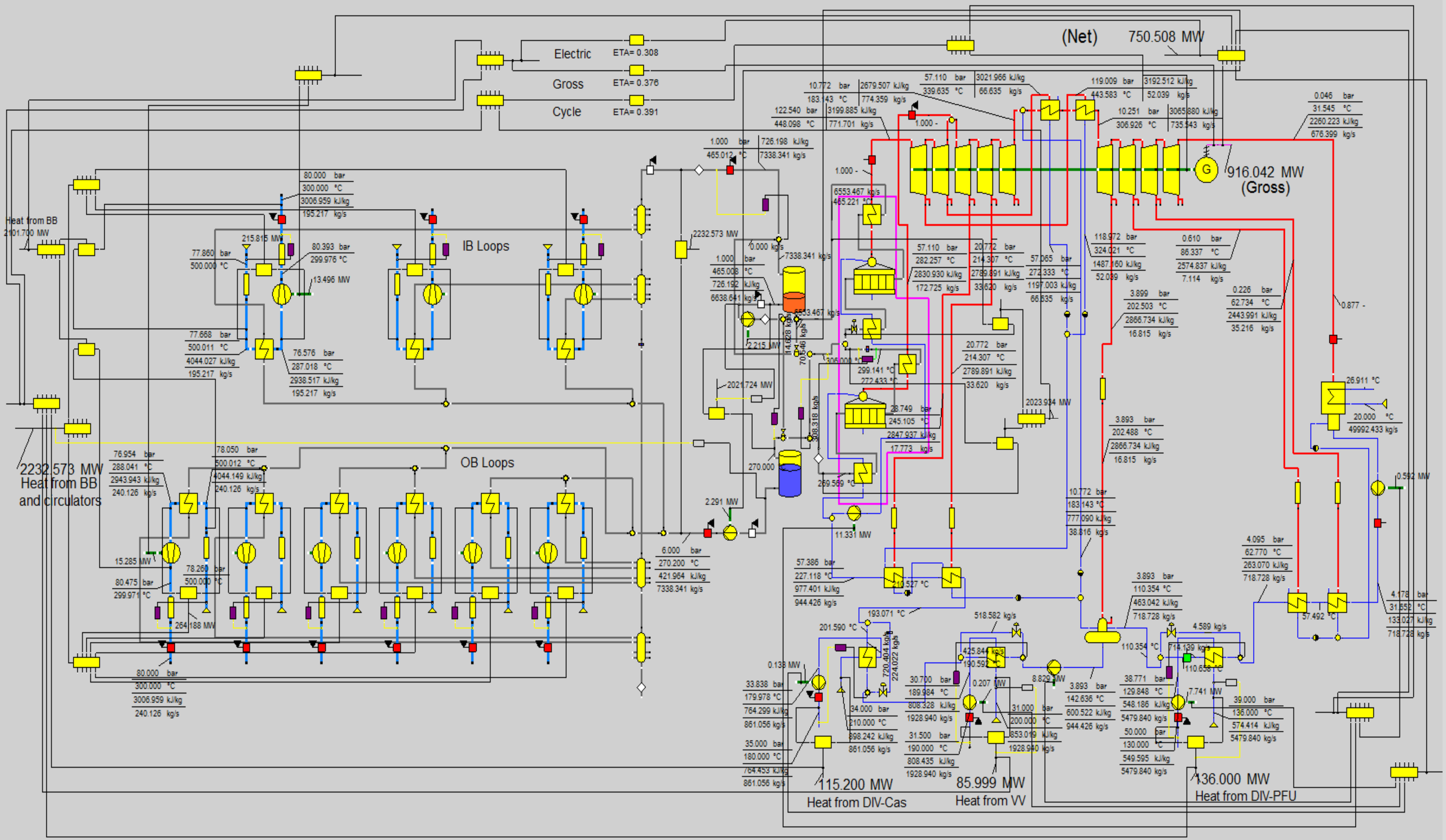
			HTF	Operation		Coolant temperatures				Coolant pressure	Segment Pressure drop				Coolant pressure				Mass flow rate				
System			Fluid	time	type	Tin, °C		Tout, °C		p_inlet, MPa	Δp, MPa				p_outlet, MPa				G per segment, kg/s				G, kg/s
BB	HCPB					IB FW	IB BZ	OB FW	OB BZ		IB FW	IB BZ	OB FW	OB BZ	IB FW	IB BZ	OB FW	OB BZ	IB FW	IB BZ	OB FW	OB BZ	Total
Objective(s)	TBR =	1.205	Helium	Pulse	stationary	300		500		8	0.214		0.174		7.786		7.826		16.4		26.8		2038.6
t from breeder bla	HF BZ =	0.08		Dwell	stationary					8													
						IB FW	IB BZ	OB FW	OB BZ		IB FW	IB BZ	OB FW	OB BZ	IB FW	IB BZ	OB FW	OB BZ	IB FW	IB BZ	OB FW	OB BZ	Total
			Purge Gas	Pulse	stationary	450		450		0.2	0.0039		0.0065		0.1961		0.1935		0.165		0.331		0.497
				Dwell	stationary					0.2													

			HTF	Operation	Operation	Heating	Coolant temperatures		Coolant pressure		Segment Pressure drop	Mass flow rate
System	Objective(s)		Fluid	time Pulse/Dwell	type	Energy demand Thermal [MW]	Tin [°C]	Tout [°C]	p_in [MPa]	p_out [MPa]	Δp [MPa]	G [kg/s]
DIV	Heat from Divertor	PFU	water	Pulse	stationary	136	130	136.0	5	3.9	1.1	5326
		Option 2		Dwell	stationary	1.42	133	133	5	3.9		5326
		Cassette	water	Pulse	stationary	115.2	180	210	3.5	3.4	0.1	861
				Dwell	stationary	1.07	195	195	3.5	3.4		861

			HTF	Operation	Operation	Reference	Nuclear Heating	Coolant temperatures		Coolant pressures		Segment Pressure drop		Mass flow rate
System	Objective(s)		Fluid	time Pulse/Dwell	type	Fusion Power, MW	Energy demand Thermal, MW	Tin, °C	Tout, °C	p_in, MPa	p_out, MPa	Δp, MPa		G, kg/s
VV	Heat from vacuum vessel		water	Pulse	stationary		86	190	200	3.15	3.1			1928
				Dwell	stationary		1	195	195	3.15	3.1			1928

DEMO HCPB BB with FW cooled in series with BZ & Plant configuration with IHTS/ESS (~91% – pulse time – 2h)

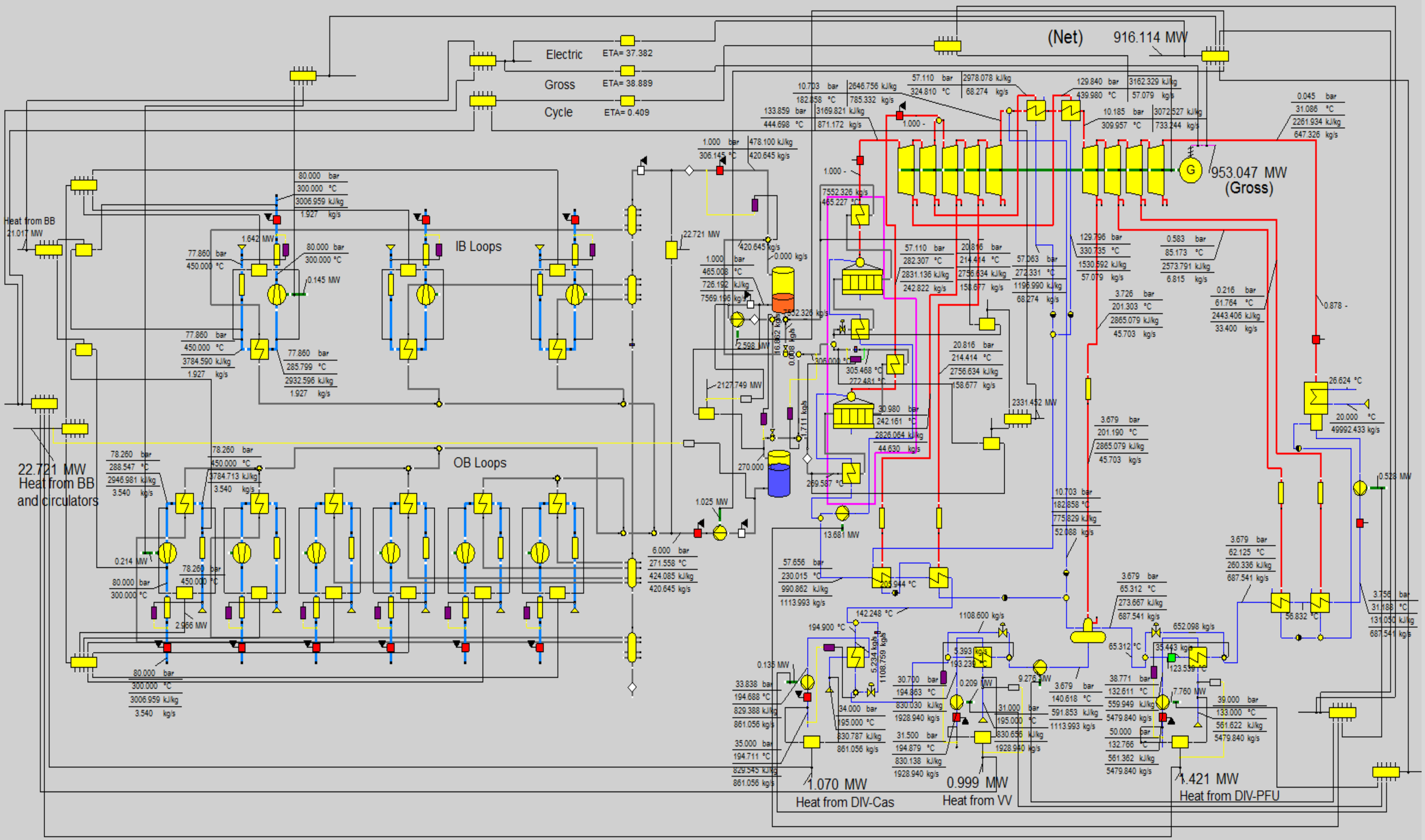
Karlsruhe Institute of Technology



Institute for Neutron Physics and Reactor Technology (INR)

DEMO HCPB BB with FW cooled in series with BZ & Plant configuration with IHTS/ESS (~103% – dwell time – 10min)

Karlsruhe Institute of Technology

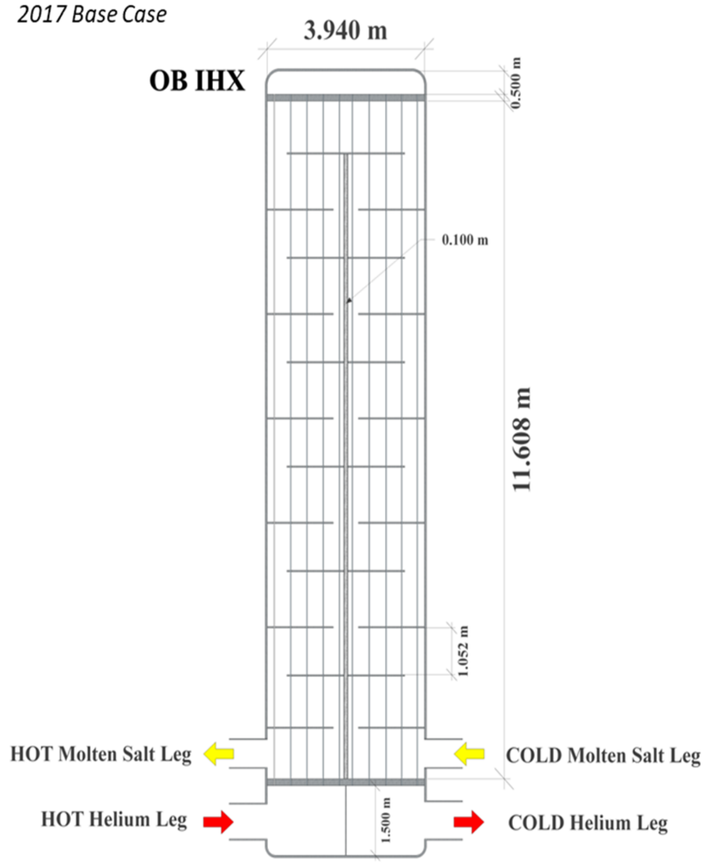


INR Institute for Neutron Physics and Reactor Technology (INR)

DEMO HCPB BB with FW cooled in series with BZ & Plant configuration with IHTS/ESS – PHTS components

Karlsruhe Institute of Technology

HCPB Tube&shell IHX main data – *2017 Base Case*		
Parameter	**INBOARD**	**OUTBOARD**
Thermal Power [MW]	208.05	265.80
T_{in}/T_{out} Helium [°C]	500/287.66	500/289.31
T_{in}/T_{out} Molten Salt [°C]	270/465	270/465
Tubes active length (per pass) [m]	12.19	11.61
Tube number (per pass) [-]	5801	7426
Shell diameter [m]	3.50	3.94
Ext. heat transfer surface [m^2]	8464.46	10316.49
Helium Volume [m^3]	49.48	61.32
Tube external diameter [mm]	19.05	19.05
Helium pressure drop [bar]	0.88	0.85
Molten Salt pressure drop [bar]	1.05	1.03



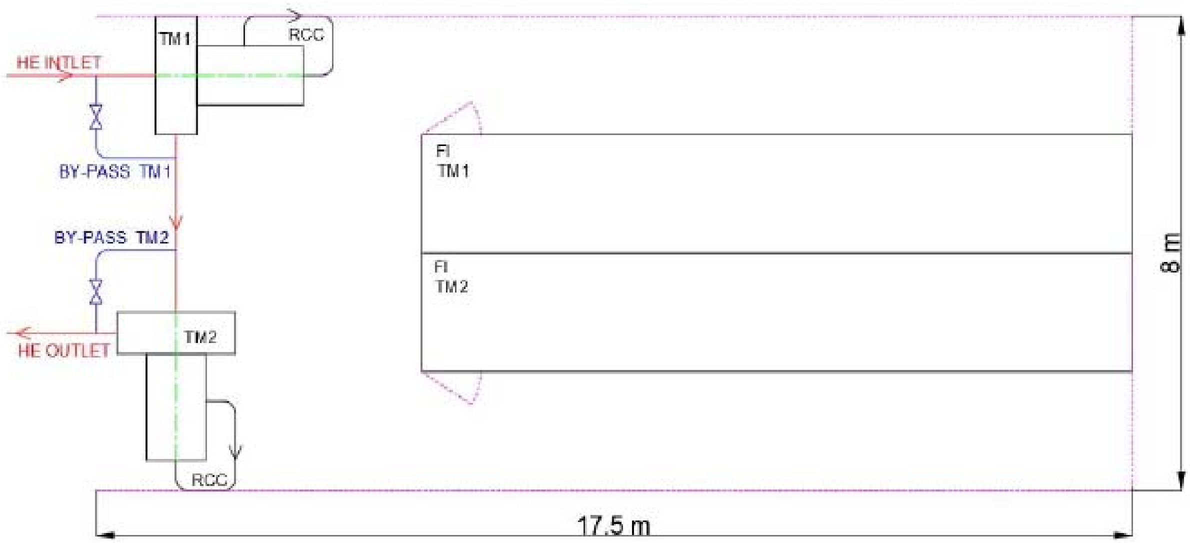
Simulations by I. Moscato (UNIPA)

3 PHTS IB HXs and 6 PHTS OB HXs are foreseen to be used in the current DEMO BoP conceptual design for HCPB BB option (18 sectors). *Ref: 2MGE9F*

DEMO HCPB BB with FW cooled in series with BZ & Plant configuration with IHTS/ESS – PHTS components

Karlsruhe Institute of Technology

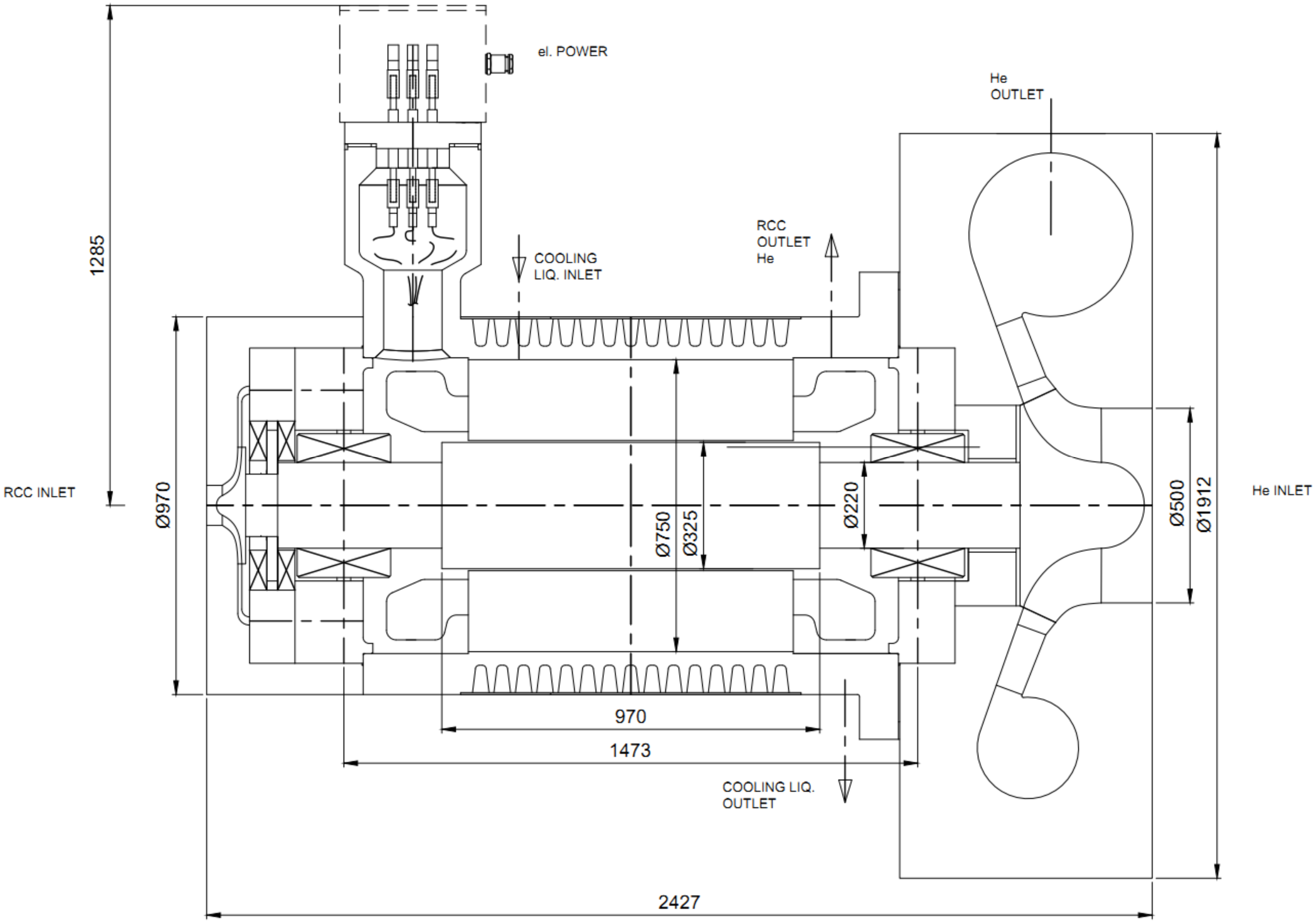
Each He blower (circulator) shown in the DEMO BoP conceptual design for HCPB BB option (18 sectors), in reality will be represented by two He compressors of 8MW power each, connected serially with each other.



Proposal by ATEKO

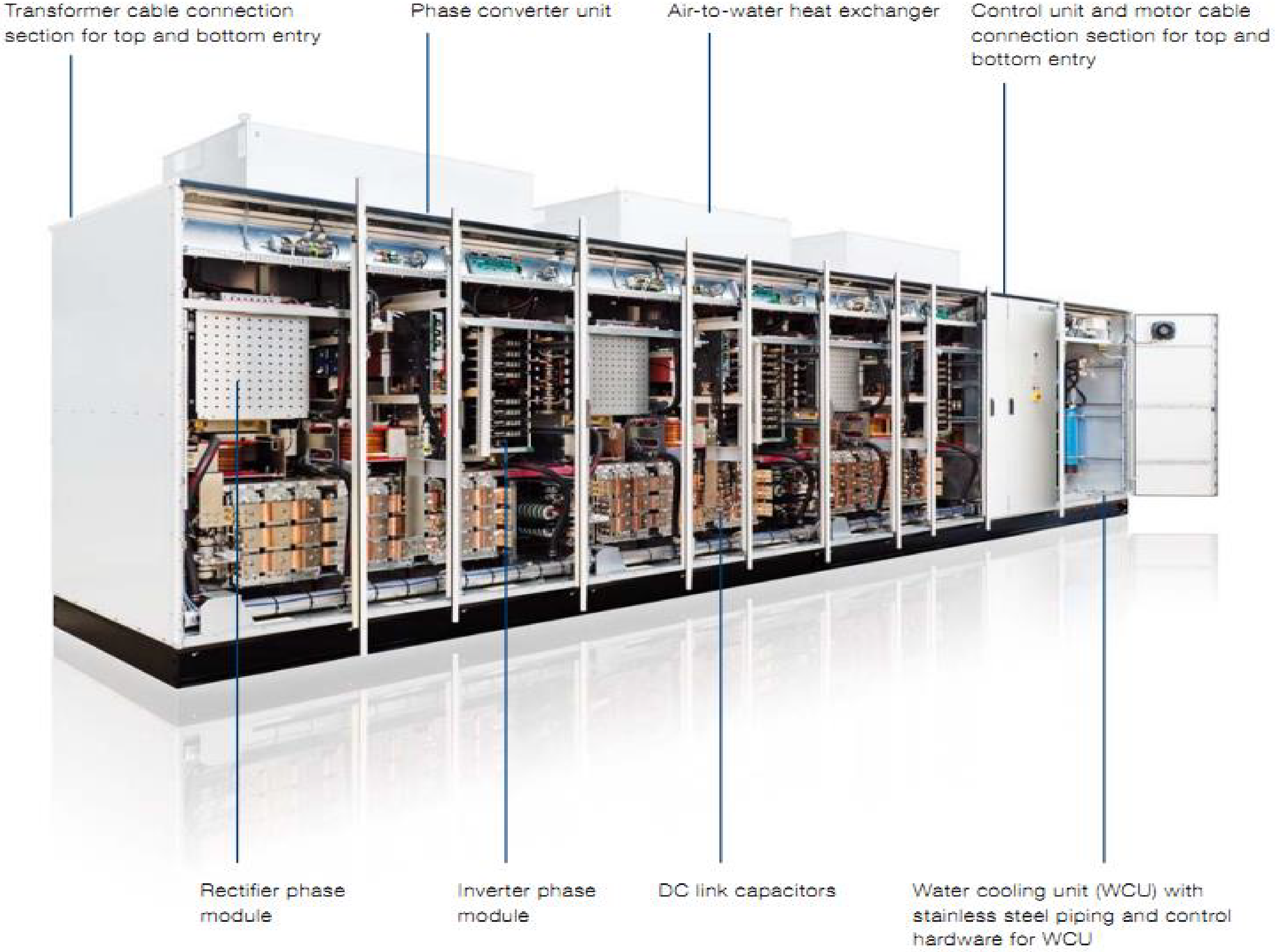
The reserved place for 2 He blowers with the respective frequency inverters should be 17.5 m long and 8 m wide, also occupying 3 m space in the height.
Each TM weights 14 tons and costs 16M Euro; each FI (ACS 5000) weights ~9 tons and costs ~ 1M Euro.

DEMO HCPB BB with FW cooled in series with BZ & Plant configuration with IHTS/ESS – PHTS components



Helium TM

DEMO HCPB BB with FW cooled in series with BZ & Plant configuration with IHTS/ESS – PHTS components



FI (circulator invertor)

ABB ACS 5000

DEMO HCPB BB with FW cooled in series with BZ & Plant configuration with IHTS/ESS – PHTS components

TH Design		
PHTS (Primary)	Tube Side	
PCS (Secondary)	Shell Side	
Tube material	Austenic steel SA-688 TP304	Austenic steel SA-688 TP304
Tube dimensional data (normalized)	1 1/4 in BWG 18	1 1/4 in BWG 18
Outer diameter (mm)	31,75	31,75
Thickness (mm)	1,2446	1,2446
Tube pitch size (mm)	39,6875	39,6875
Baffle spacing (m)	1,2	1,2
Pitch-Tube layout	Square	Square
Number of tube passes	1	1
Number of shell passes	1	1
Number of tubes	1091	1200
Heat transfer area (m2)	705,75	718,53
Length (m)	6,49	6
Shell diameter (m)	1,56	1,64

DIV-PFU HX design

TH Design		
PHTS (Primary)	Tube Side	
PCS (Secondary)	Shell Side	
Tube material	SA 213 TP 304	SA 213 TP 304
Tube dimensional data (normalized)	1/2 in BWG 17	1/2 in BWG 17
Outer diameter (mm)	15,875	15,875
Thickness (mm)	1,4732	1,4732
Tube pitch size (mm)	27,78125	27,78125
Baffle spacing (m)	1,2	1,2
Pitch-Tube layout	square	square
Number of tube passes	2	2
Number of shell passes	2	2
Number of tubes	2511	2762
Heat transfer area (m2)	3023,72	3096,52
Length (m)	12,07	11,24
Shell diameter (m)	2,34	2,46

DIV-Cas HX design

M. J. Montes Pita (UNED) group performed HXs simulations and have defined HXs characteristics and design. Pumps preliminary design parameters were also defined. *Ref: 2MSJRU*

DEMO HCPB BB with FW cooled in series with BZ & Plant configuration with IHTS/ESS – PHTS components

Karlsruhe Institute of Technology

VV PHTS HX design

#	HEX Tubes dimensions	Unit	Value
1	Material	--	INCONEL 600
2	Internal diameter	*m*	0.014096
3	Thickness	*m*	0.00089
4	External diameter	*m*	0.015876
5	Tube internal flow area	m^2	1.56E-4
6	Relative wall roughness	--	2.838E-4

#	HEX features	Unit	Value
1	Tubes number	--	1459
2	Total tubes flow area	m^2	0.2277
3	Diameter shell	*m*	0.867
4	Shell flow area	m^2	0.301
5	Tube thermal length	*m*	5.7296
6	HEX surface	m^2	416.939
7	PHTS water velocity	*m/s*	4.89
8	PCS water velocity	*m/s*	1.185
9	HEX tubes DP	*kPa*	2.19E+2
10	HEX shell DP	*kPa*	25.9

VV PHTS coolant pump parameters

#	Description	*Unit*	Value
1	Total pressure drops per loop	*kPa*	106.75
2	Pump efficiency	--	0.78
3	Max. pressure drops in VV	*kPa*	50
4	Total pumping power per system	*kW*	1227.77
5	Total El. Motor Power per system	*kW*	1574.06

A. Del Nevo (ENEA) group performed HX simulations and have defined HX characteristics and design. Pumps preliminary design parameters were also defined. *Ref: 2MV6DV*

DEMO HCPB BB with FW cooled in series with BZ & Plant configuration with IHTS/ESS – IHTS/ESS components

Two-tank thermal storage system was proposed by Kraftanlagen Heidelberg (KAH) from the available information of Concentrated Solar Power (CSP) plants as follows:

Thermal Storage System	
Heat transfer fluid	Molten Hitec salt
Total mass of Hitec XL salt per tank	5040000 kg
Tank nominal volume per tank	3000 m^3
Tank heat storage capacity	426 MWh_t
Size per tank	Diameter: 23.8 m; Height: 6.8 m
Footprint of thermal storage system	Approx. 2550 m^2

Currently there is no commercial offer for a thermal storage system available.

Costs for such a Thermal Storage system were estimated to be ~12.66M Euro, plus the costs for the HITEC salt, which are in the order of ~3.92M Euro.

DEMO HCPB BB with FW cooled in series with BZ & Plant configuration with IHTS/ESS – PCS components

Karlsruhe Institute of Technology

Turbogenerator specification was provided by Siemens Power and Gas Division.

Turbogenerator (PCS ST)	
Live steam pressure	130 bar(abs)
Live steam flow rate	842 kg/s
Live steam temperature	447 °C
Max. PCS Output	≈ 1009 *MW*
Turbogenerator weight	Approx. 1285000 kg
Turbine manufacturer	Siemens
Turbine type	SST5-6000: I50 / 6x12.5m²
No. of turbine stages	1 IP turbine stage; 3 LP turbine stages
Turbine rated speed	3000 rpm
Electrical generator manufacturer	Siemens
Electrical generator type	SGen5-3000W
Electrical generator rating	965 MVA
Condenser cooling water quantity	35184 kg/s
Condenser cooling water inlet temperature	20 °C
Condenser cooling water outlet temperature	29.5 °C
Turbogenerator space reservation	L=52m;H=24m;W=19m

The DEMO BoP turbogenerator consists of the steam turbine (PCS ST) together with a condenser, including condensate drain, two steam re-heaters and the electrical generator.

DEMO HCPB BB with FW cooled in series with BZ & Plant configuration with IHTS/ESS – PCS components

Deaerator specification was provided by our industrial partner KAH.

Spray Type Deaerator	
Operation pressure	4.25 bar(abs)
Feed water outlet mass flow	1069 kg/s
Max. PCS Output	$\approx 1009\ MW$
Deaerator gross volume	415 m³
Deaerator size	Diameter: 4 m; Length: 35 m
Total weight	Approx. 152000 kg
Performance	Approx. 7 ppb (oxygen)
Space reservation	L=40m;H=6m;W=5m

Reference deaerator design, Company Stork B.V.

DEMO HCPB BB with FW cooled in series with BZ & Plant configuration with IHTS/ESS – PCS components

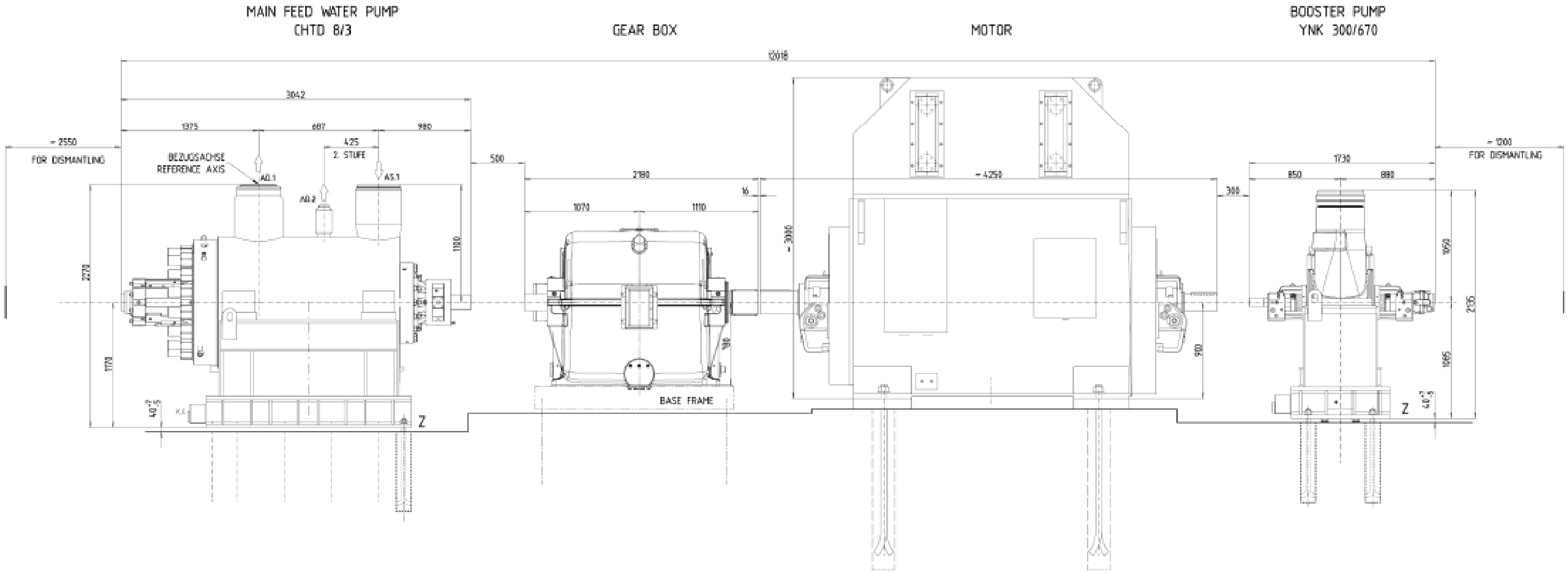
PCS Pump 1 (Main FW pump) specification was provided by our industrial partner KAH.

Feed Water Pump Aggregate (PCS pump 1)	
Pump manufacturer	KSB
Pump drive type	Electrical drive
Main pump type	CHTD 8/3
Booster pump type	YNK 350-620
Gear box power rating	13 MW
Motor rating	14 MW
Space reservation	L=16m;H=3m;W=3.4m

Each feedwater pump aggregate consists of one booster pump, gearbox, electrical motor and main pump connected in series.

PCS Pump 2 specification should be very close to the specification of PCS Pump 1.

DEMO HCPB BB with FW cooled in series with BZ & Plant configuration with IHTS/ESS – PCS components

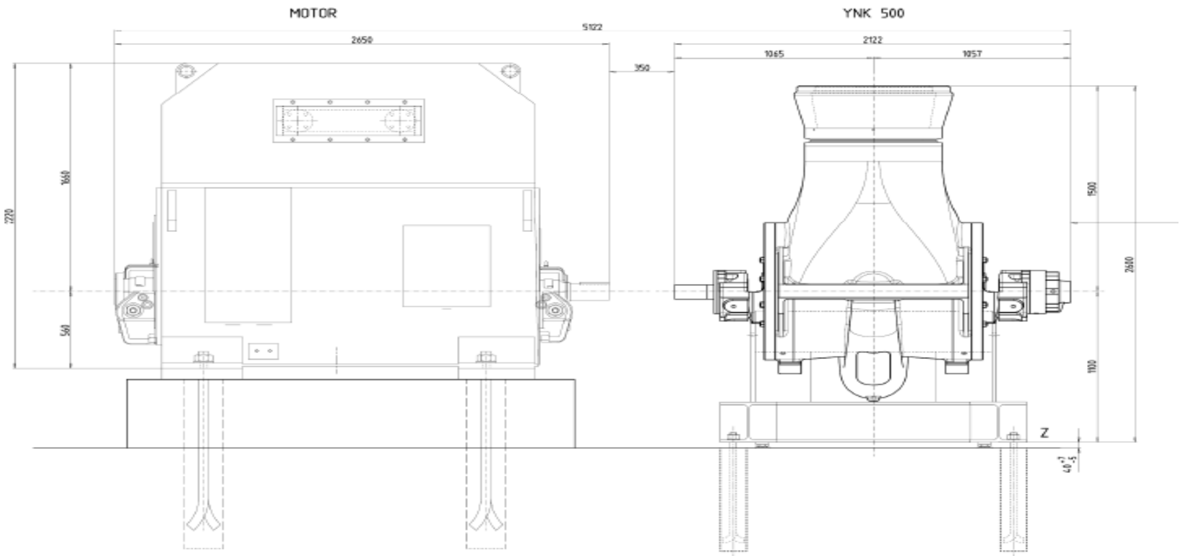


Main feedwater pump aggregate (Pump manufacturer KSB).

DEMO HCPB BB with FW cooled in series with BZ & Plant configuration with IHTS/ESS – PCS components

PCS FW Pump (condensate extraction pump) specification was provided by our industrial partner KAH.

PCS circulation Pump (PCS FW pump)	
Pump manufacturer	KSB
Pump drive type	Electrical drive
Pump type	YNK 500/800
Motor rating	2 MW
Space reservation	L=7m;H=3m;W=2.9m



DEMO HCPB BB with FW cooled in series with BZ & Plant configuration with IHTS/ESS

Space requirements and costs (1/2):

DEMO BOP Component	Design dimensions, m			Space reservation, m			Weight, t	Costs*, M Euro
	Length	Width/Diam	Height	Length	Width/Diam	Height		
PHTS IB HX	12.2	3.5						2.4
PHTS OB HX	11.7	4						3
PHTS IB He blower + FI				17.5 (x2)	8 (x2)	3 (x2)	23	17
PHTS OB He blower + FI				17.5 (x2)	8 (x2)	3 (x2)	23	17
PCS DIV1 HX	6.5	1.7						0.4
PCS DIV1 Pump								
PCS DIV2 HX	12.1	2.5						2.8
PCS DIV2 Pump								
PCS VV HX	10.8	1.5						0.7
PCS VV Pump								
IHTS Hot Tank		23.8	6.8	71.4	35.7	8	-	16.6
IHTS Cold Tank		23.8	6.8					
IHTS Pump 1								
IHTS Pump 2								
PCS FW1 HX	14.4	2.5						1.1
PCS FW2 HX	4	1.7						0.2
PCS FW3 HX	9.8	2		21	3.5	4	43.9	2.1
PCS FW4 HX	8.3	3.2						3.1

DEMO HCPB BB with FW cooled in series with BZ & Plant configuration with IHTS/ESS

Karlsruhe Institute of Technology

Space requirements and costs (2/2):

DEMO BOP Component	Design dimensions, m			Space reservation, m			Weight, t	Costs*, M Euro
	Length	Width/Diam	Height	Length	Width/Diam	Height		
PCS SG1 PH	14.8	1.5						0.9
PCS SG1	11.7	3.6						9.0
PCS SG1 SH	3.9	1.4						0.4
PCS SG2 PH	25.8	2.9						6.9
PCS SG2	8.9	3.5						7.1
PCS SG2 SH	23.1	2.4						6.5
DRAIN				52	19	24	1285	90.7
PCS SR1 HX								
PCS SR2 HX								
PCS ST								
PCS GENERATOR								
PCS CONDENSER	23	8.8						
PCS Pump 1				16	3.4	3	-	7.6
PCS Pump 2				16	3.4	3	-	
PCS FW Pump				7	2.9	3	-	
DEAERATOR	35	4		40	5	6	152	10.4

* Costs for pipework, valves, I&C, relay station, cooling towers, machine hall building and auxiliaries are not considered

Conclusions

- A short overview of the current (as of February 2018) DEMO BoP design, for HCPB BB option (18 sectors design), being developed and improved at KIT was presented.

- The development process of the DEMO BoP model was supported by our industrial partners: Siemens Power and Gas Division and Kraftanlagen Heidelberg (KAH).

- Presented were key components of the PCS, including preliminary sizing and cost estimates.

- However, the industrial components for IHTS/ESS and PHTS are still to be specified. Currently foreseen IHTS/ESS and PHTS component designs are based primarily on the design calculations performed by the project partners (UNIPA, UNED & ENEA).

Acknowledgments

This work has been carried out within the framework of the EUROfusion Consortium (WPBOP) and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No. 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.