The European Concepts of First Generation Fusion Power Plants

Overview & Identified Issues

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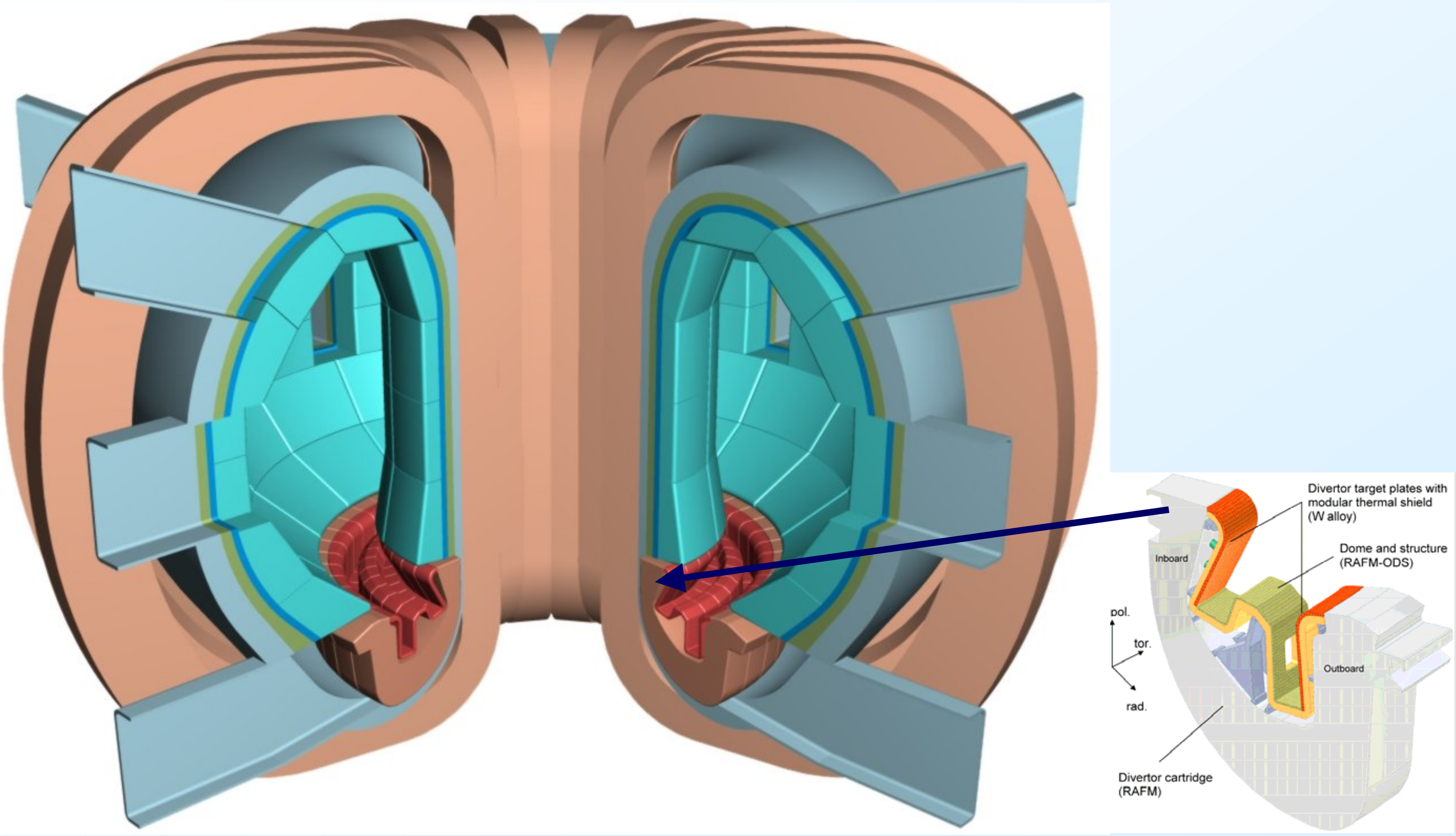
- PPCS
- Model A
- Model B
- Model AB
- Plant layout
- Maintenance
- Assessment
- Conclusions

Power Plant Conceptual Study (stage 3)

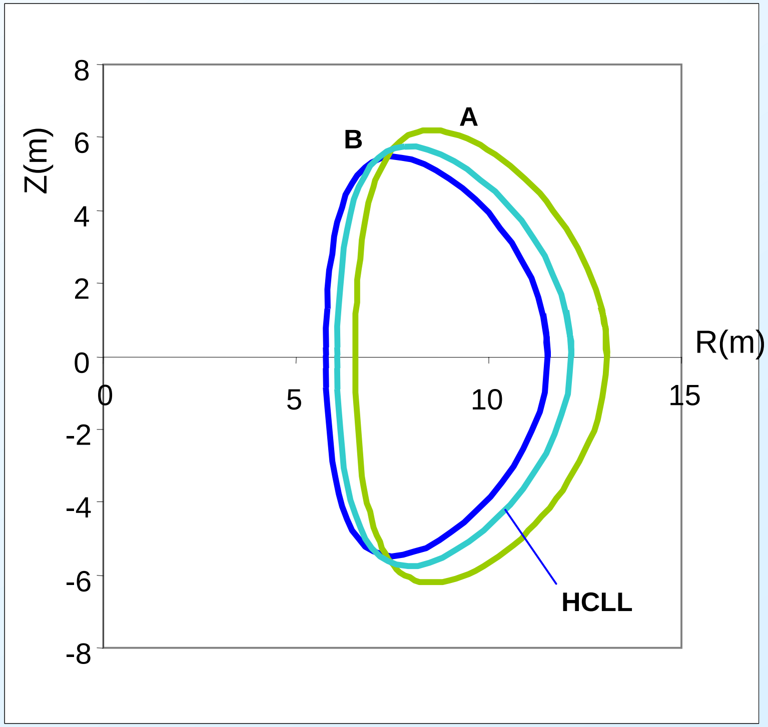
- **Demonstration of:**
  - Credibility of fusion power plant design
  - Safety and environmental advantages of fusions power
  - Economic viability of fusion power
- **Set of requirements issued by industry and utilities**
  - Safety
  - Operational aspects
  - Economic aspects
- **Three “near term” models were based on limited extrapolations on both physics and technology**
- **Economic safety and environmental analyses of these models were made**

Fusion reactor



Key parameters

- 1500 MW_e
- Fusion power is determined by efficiency, energy multiplication and current drive power
- Given the fusion power, plasma size mainly driven by divertor considerations

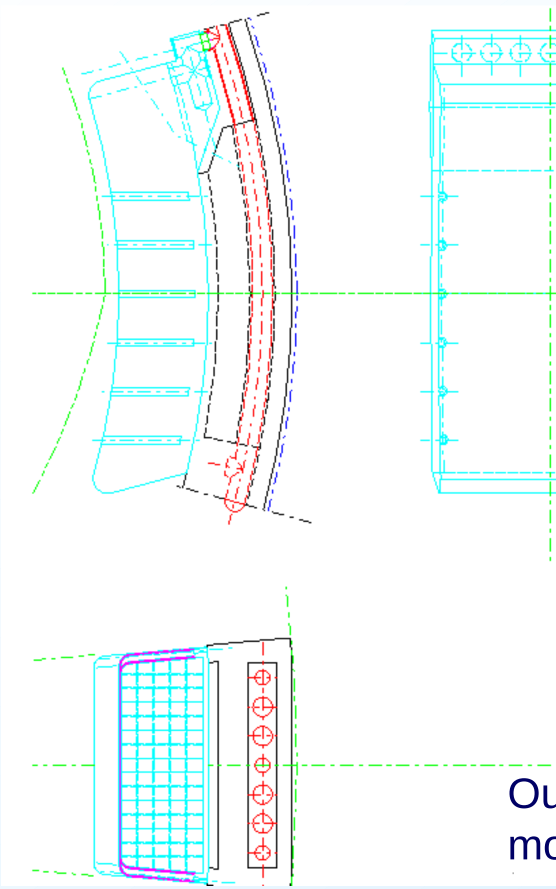


Plants main features

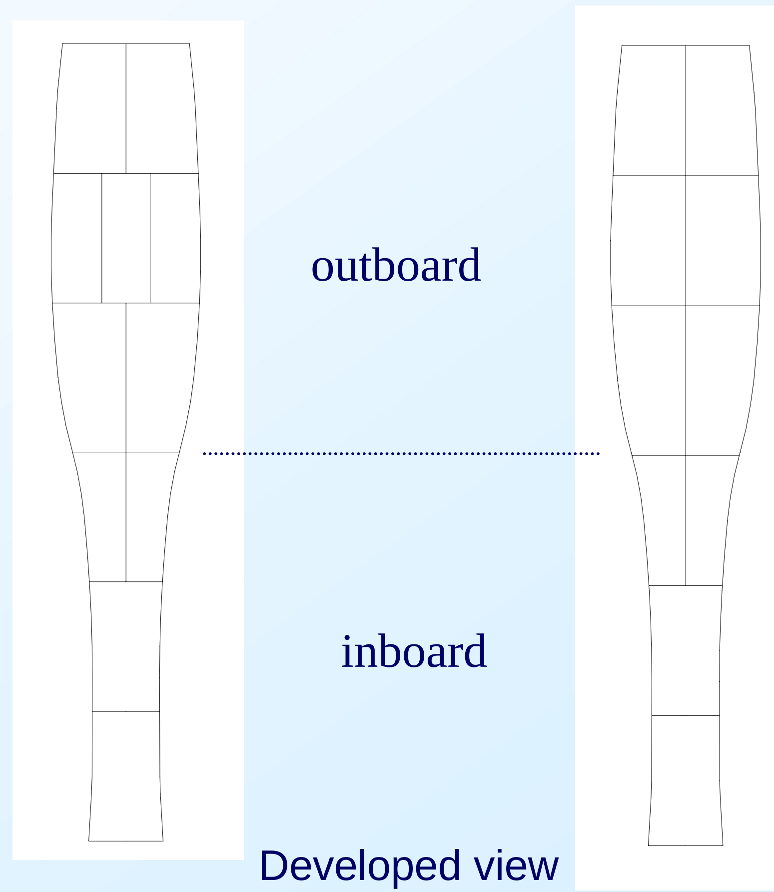
		Model A	Model B	Model AB
	Net Electric Power (GW)	1.55	1.33	1.50
	Fusion Power (GW)	5.00	3.60	4.29
	Blanket Gain	1.18	1.39	1.18
	Plant Efficiency	0.31	0.37	0.35
	Bootstrap Fraction	0.45	0.43	0.43
	P_{add} (MW)	246	270	257
	DV Peak load ($MW.m^{-2}$)	15	10	10
	Average neutron wall load	2.2	2.0	1.8
	Major Radius (m)	9.55	8.6	9.56
Blanket	Structural material	Eurofer	Eurofer	Eurofer
Blanket	Coolant	Water	Helium	Helium
Blanket	Breeder	LiPb	Li4SiO4	LiPb
Blanket	TBR	1.06	1.12	1.13
DV	Structural material	CuCrZr	W alloy	W alloy
DV	Armour material	W alloy	W alloy	W alloy
DV	Coolant	Water	Helium	Helium
	Conversion Cycle	Rankine	Rankine	Rankine

WCLL Blanket Concept (model A)

Eurofer as structural material, water as coolant, LiPb as breeder and neutron multiplier

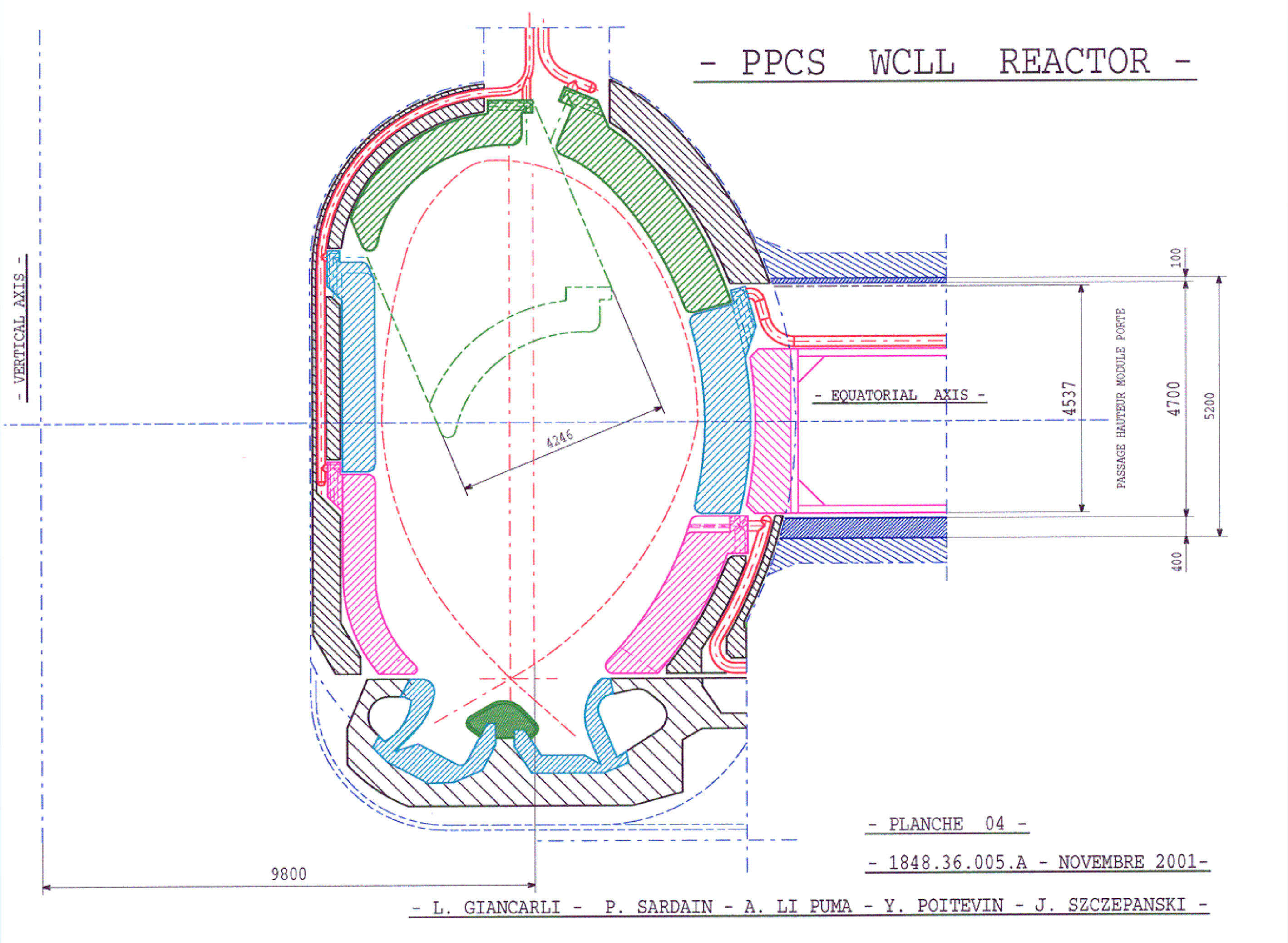


Outboard module

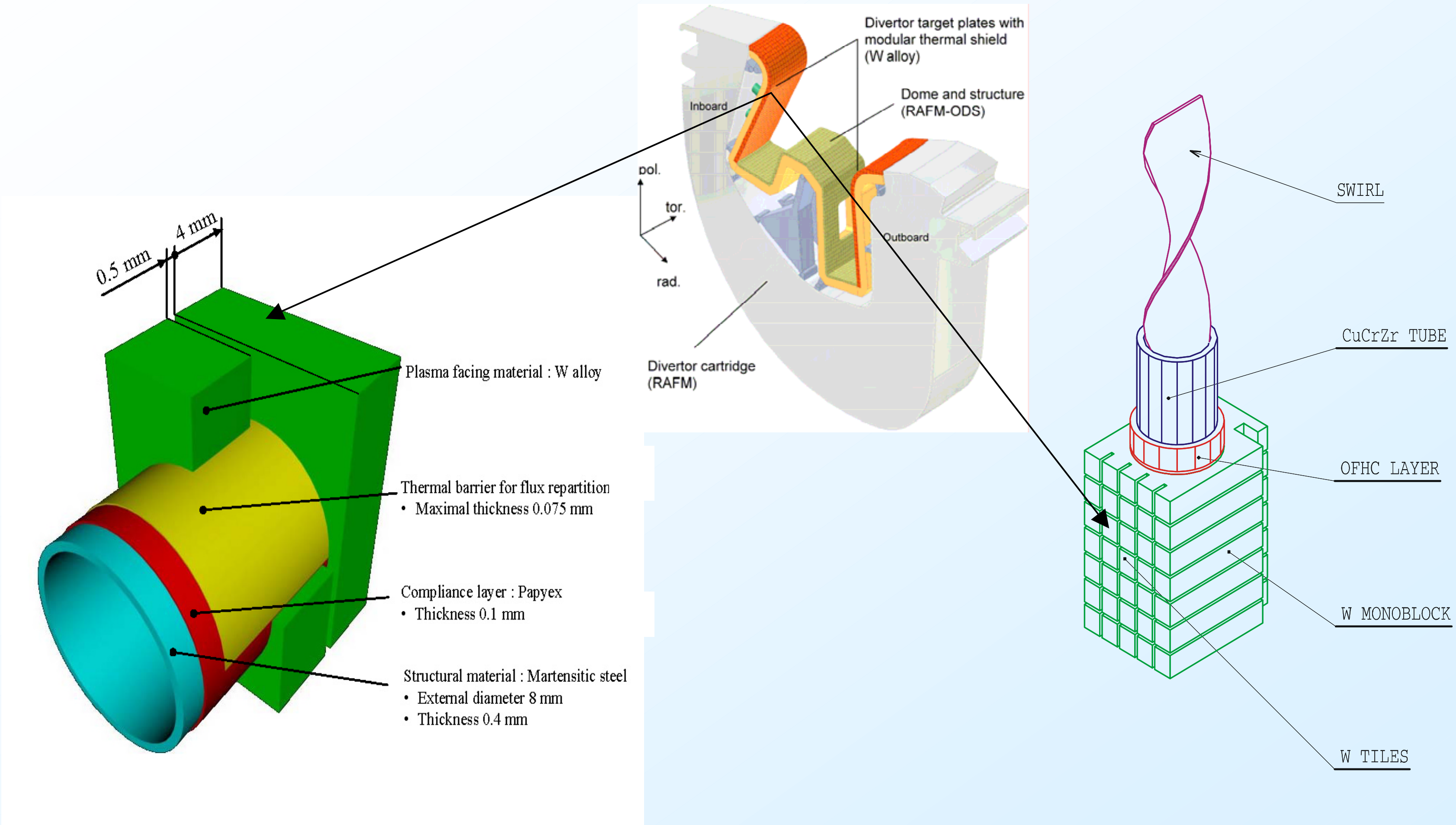


Developed view
Of a 20° sector

Model A: Segmentation



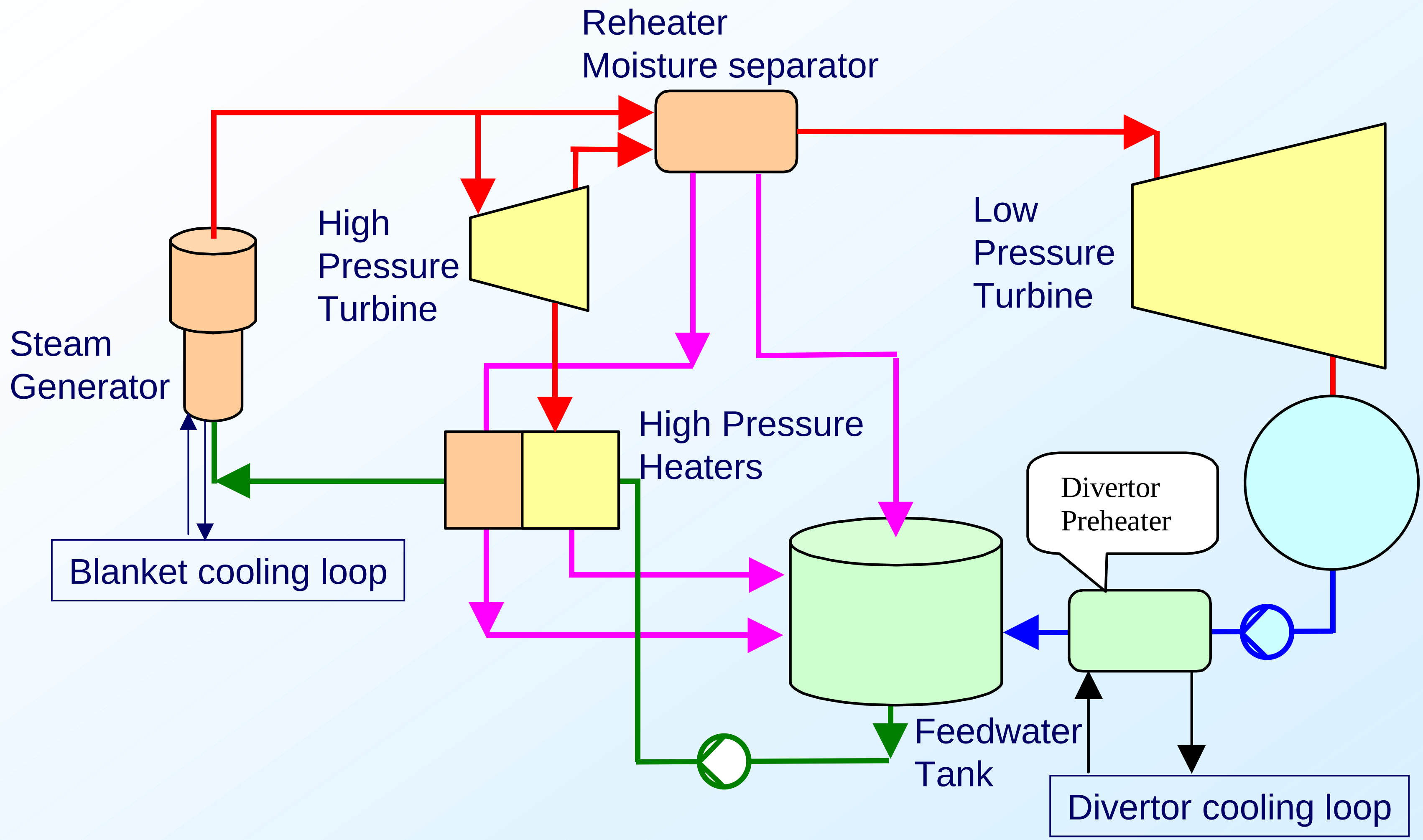
Model A: Water-cooled Divertor



High temperature Dv

Low temperature Dv

Power conversion (model A)

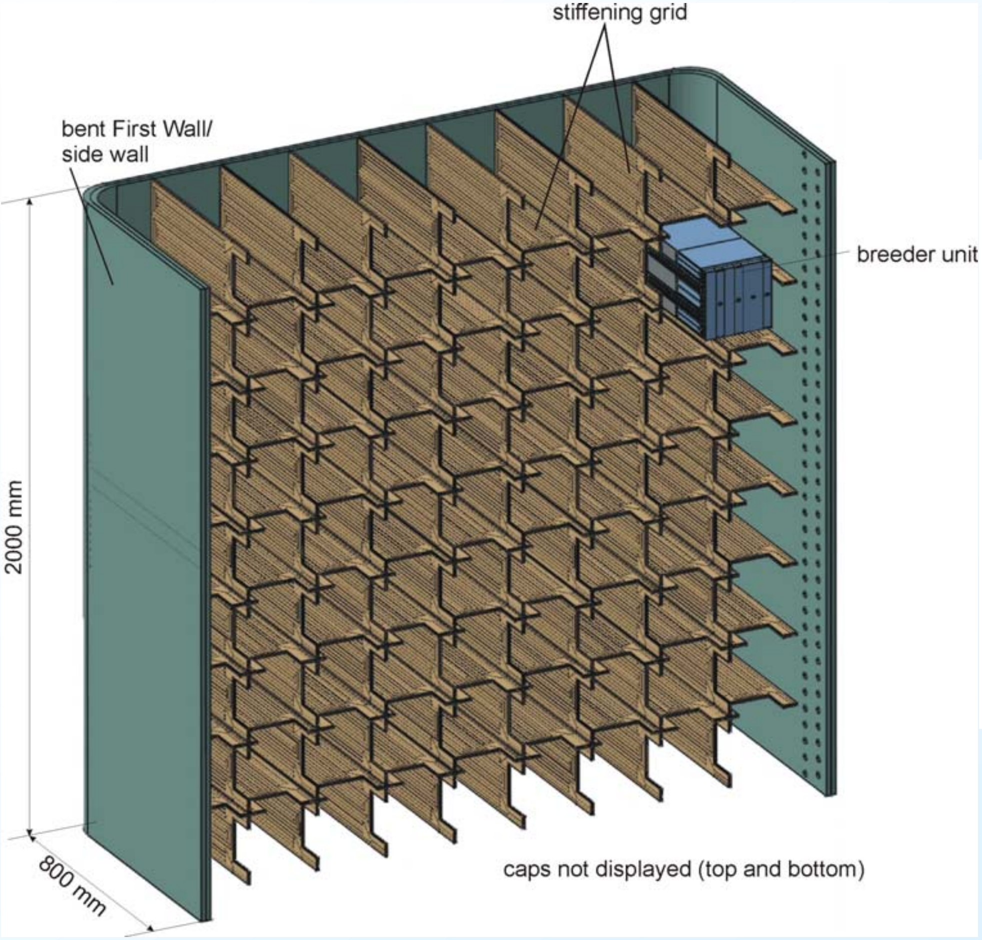


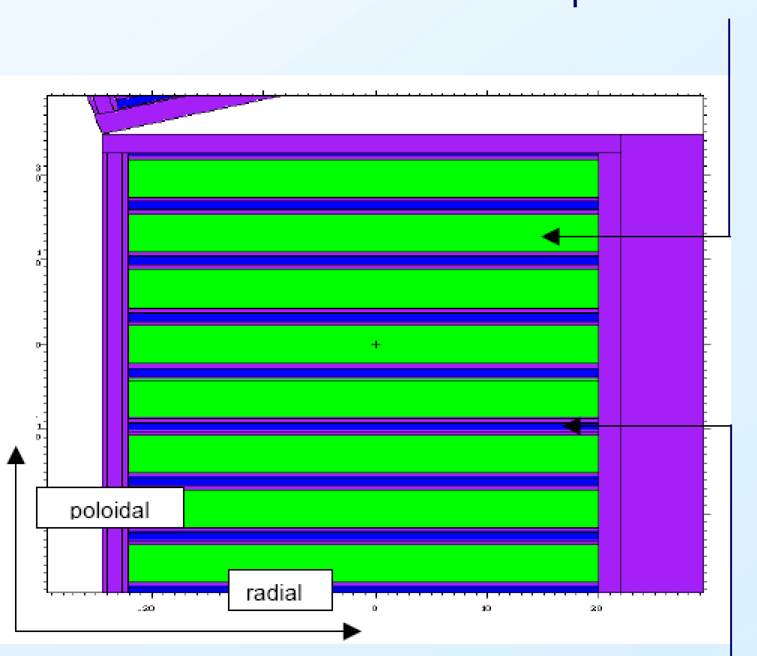
Model A: R&D needs

- Development of a HHF water-cooled divertor concept operating at the same coolant temperature as the blanket cooling loop ➔ higher efficiency
- Optimization of the attachment system
- Materials

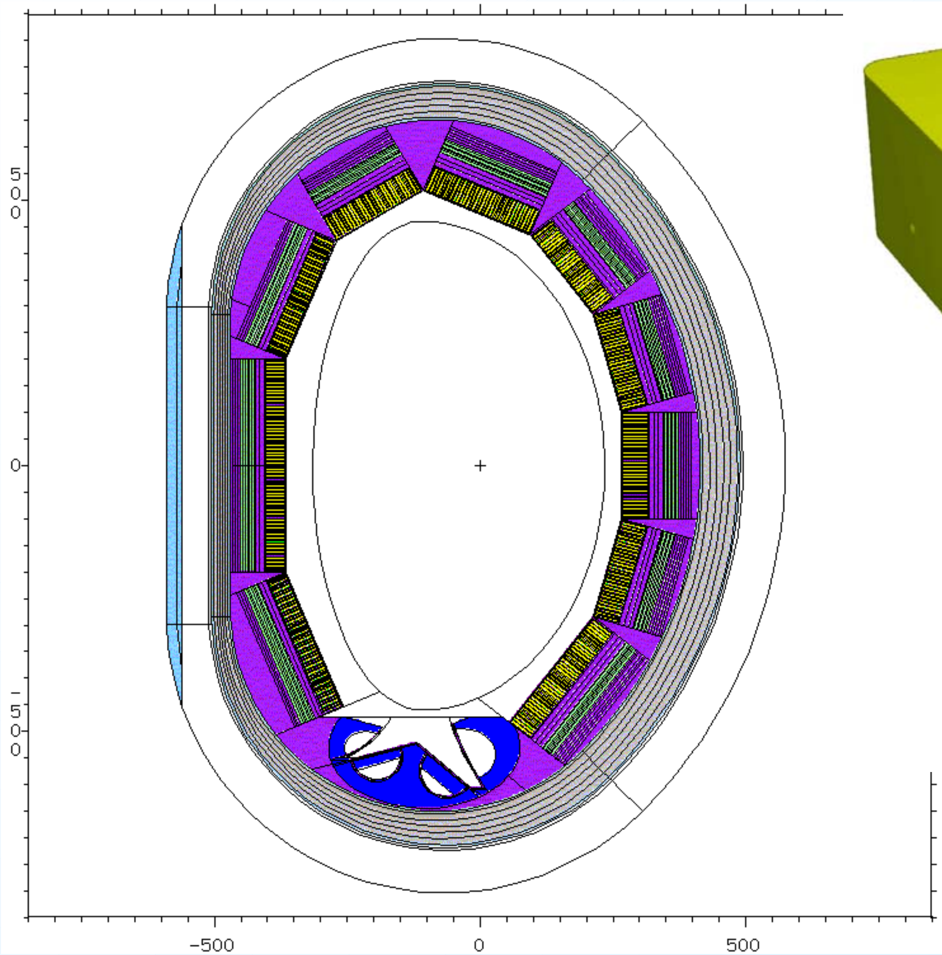
HCPB blanket concept (model B)

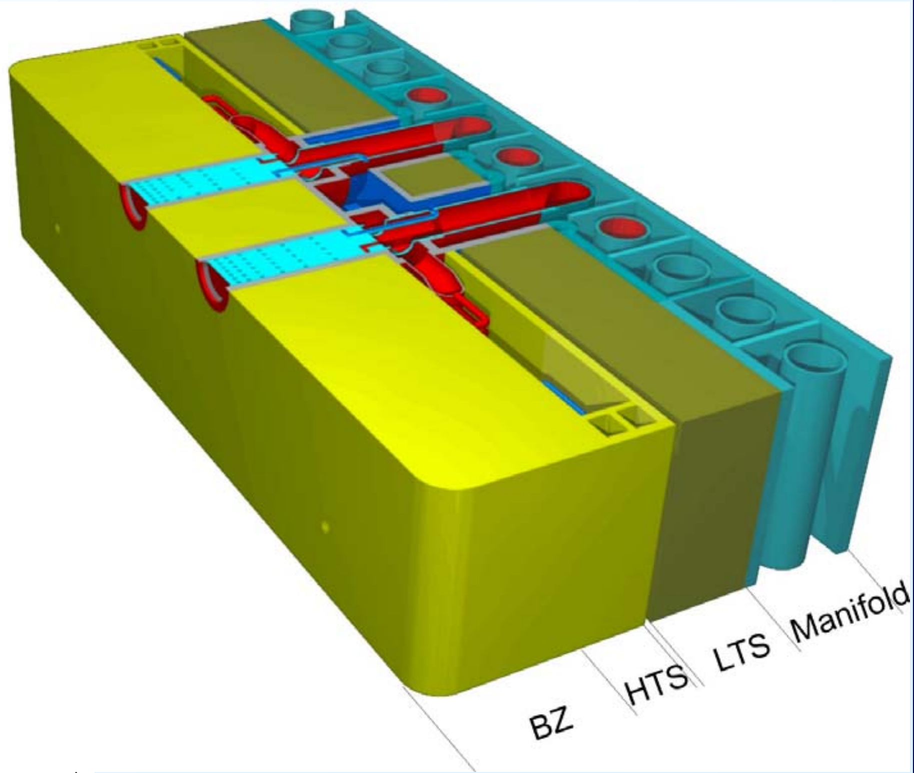
Eurofer as structural material, He as coolant, Li4SiO4 as breeder, Be as neutron multiplier





Model B: Segmentation

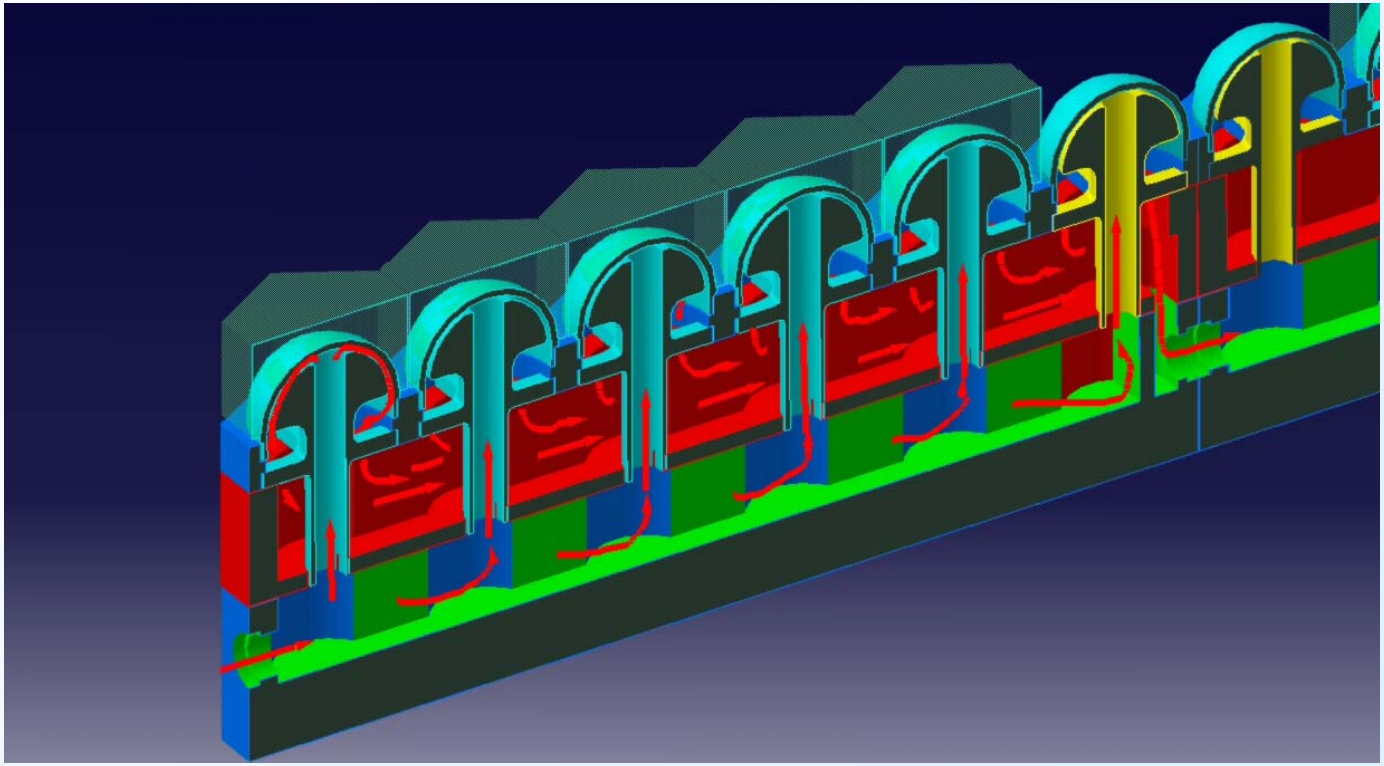


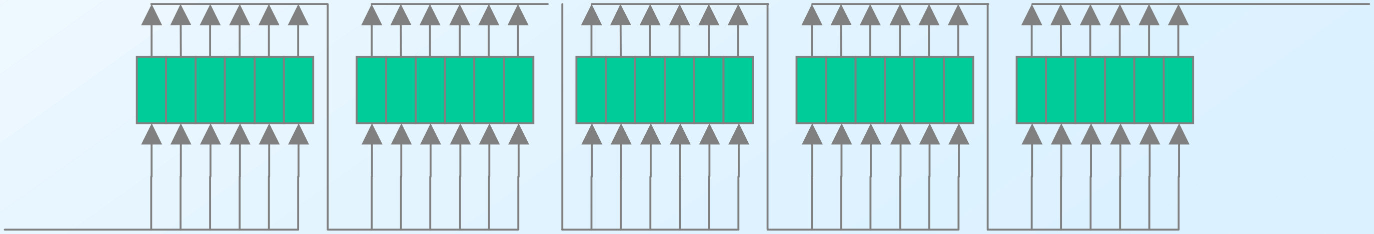


Design Requirements of He-cooled DV

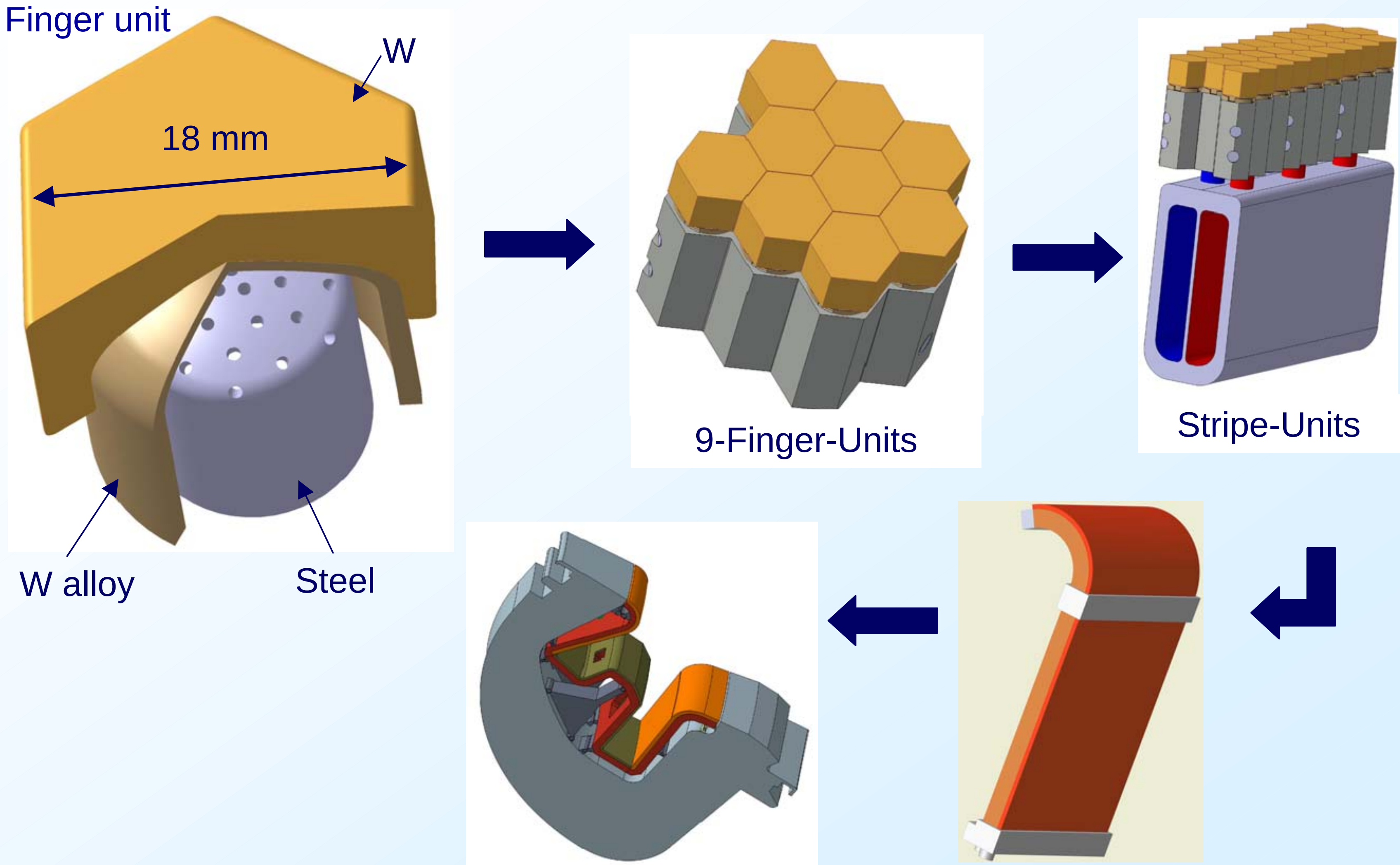
- **To achieve peak heat load of at least 10 MW/m²**
- **Modular design to reduce the thermal stresses**
- **Divertor operation temperature window due to DBTT and RCT of tungsten to be considered**
- **Short heat conduction paths from plasma-facing to cooling surface**
- **High heat transfer coefficients with as small a flow rate and small pumping power as possible**
- **To survive ca. 100 – 1000 thermal cycles between operating and room temperatures**

HETS Concept

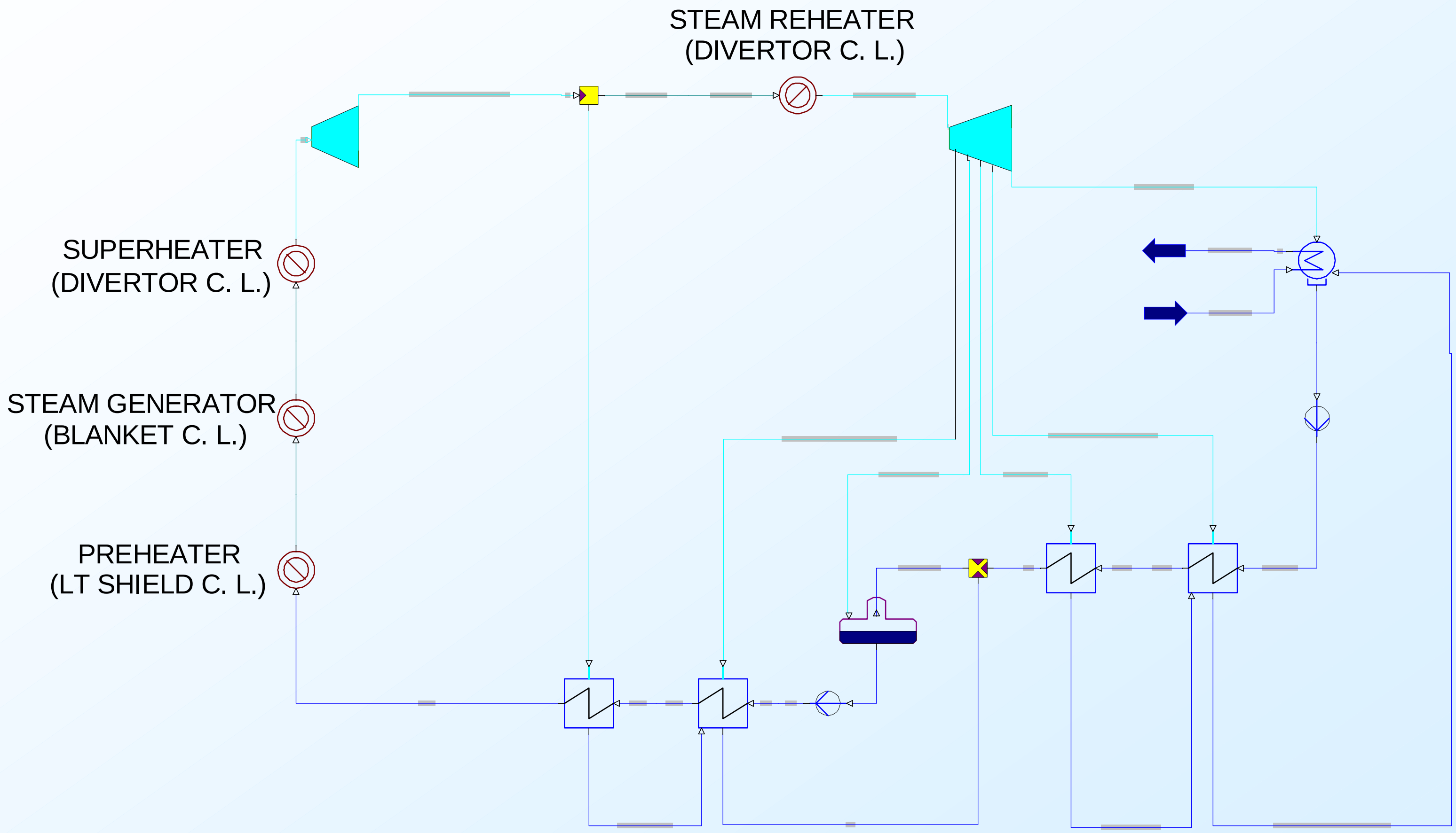




HEMJ Concept



Power conversion (model B)

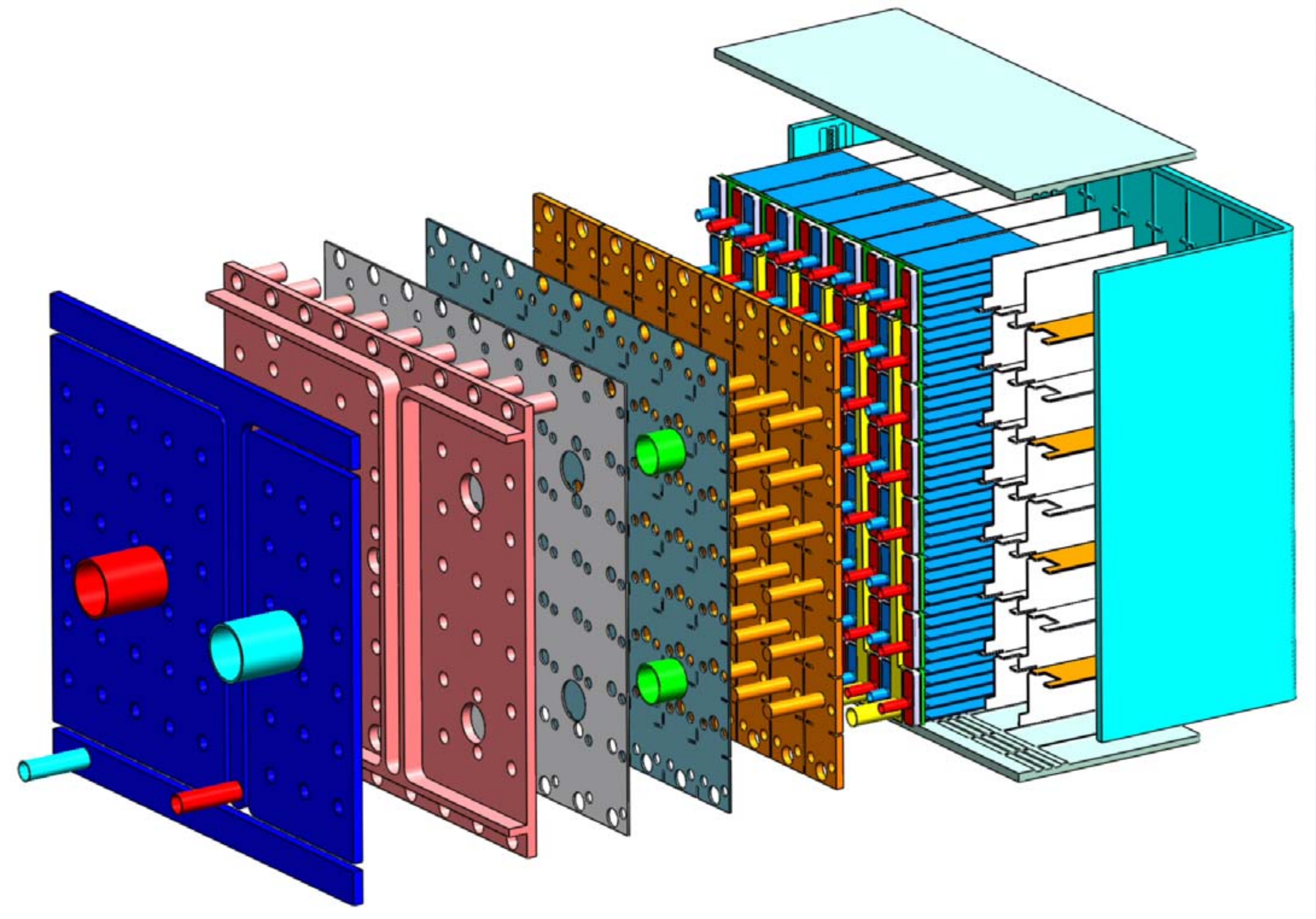


Model B: R&D needs

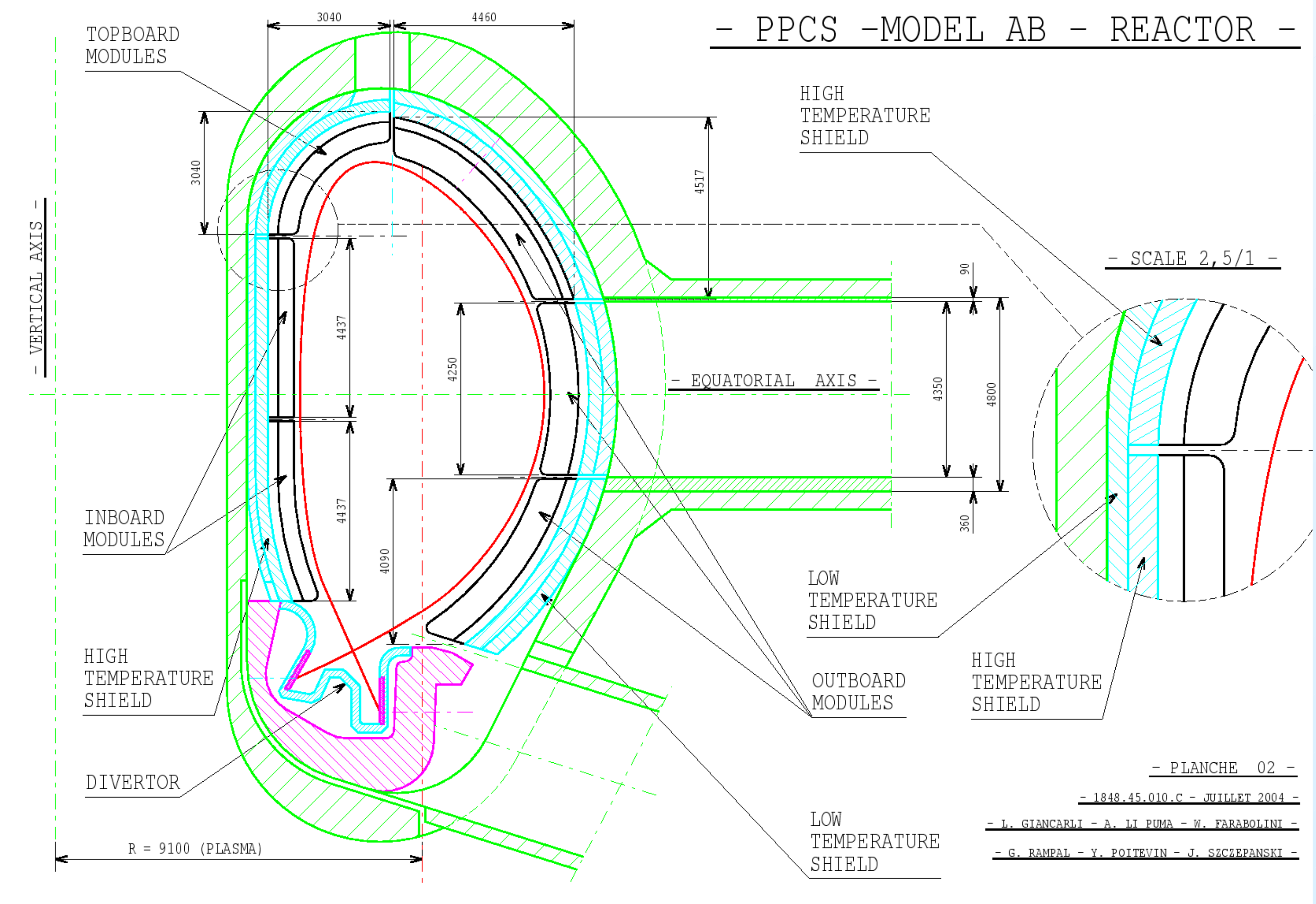
- **Development of a HHF Helium-cooled divertor**
- **Design update of the HCPB blanket with the aim of supporting blanket box pressurisation to the full coolant pressure**
- **Open questions related to technology**
  - **blanket fabrication issues**
  - **the thermo-mechanical behaviour of the used pebble beds**
  - **Tritium retention in irradiated Beryllium**
  - **Beryllium material grade/alloy to use**
- **Materials**

HCLL blanket concept (model AB)

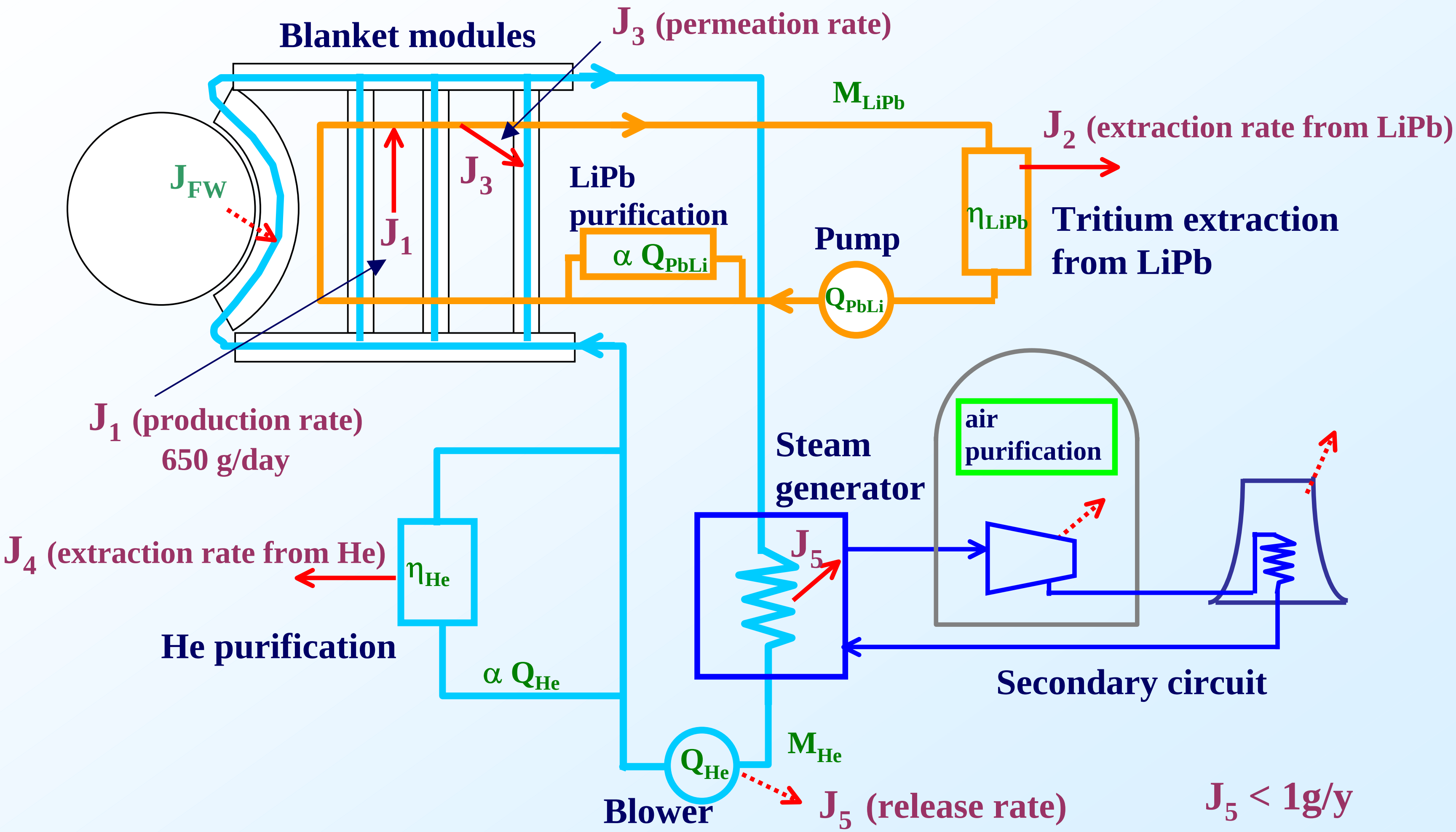
Eurofer as structural material, helium as coolant, LiPb as breeder and neutron multiplier



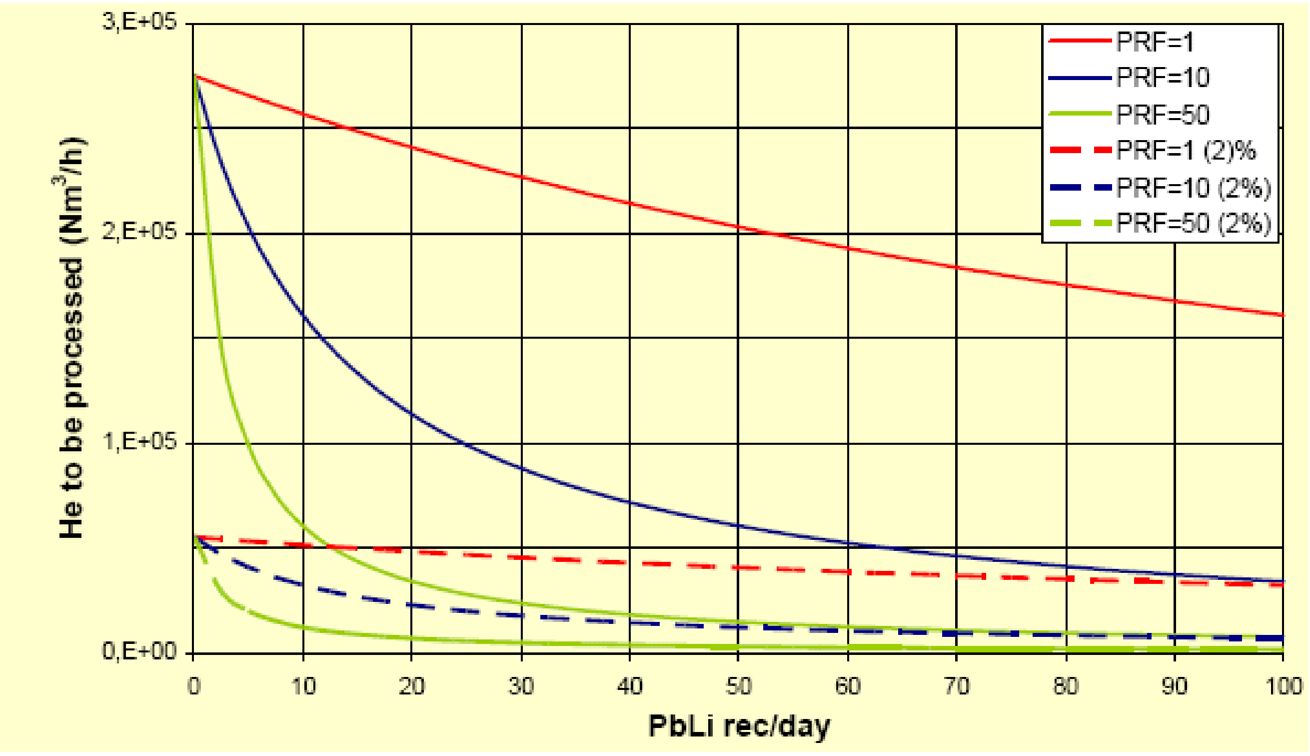
Model AB: segmentation



Model AB: tritium control



Model AB: tritium control



Data

Q_{He}= 4070 kg/s = 8.6E7 Nm^3/h

Q_{PbLi}= 0.068 m^3/h (10 rec./day)

Assumptions

η_{LiPb}= 0.8

K_{SG} = 0

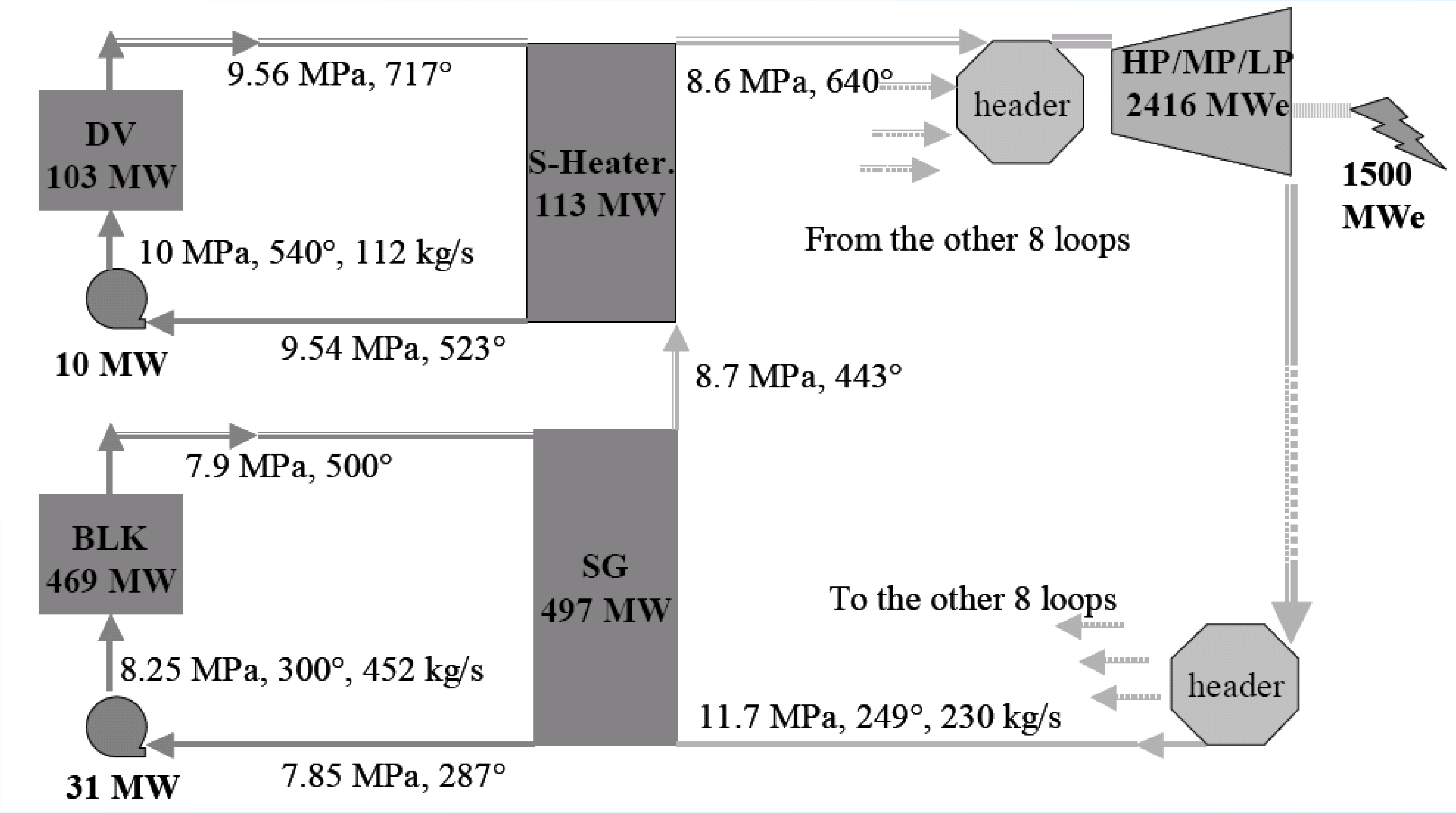
L_{SG}= 10% (2%) of total He inventory

Model AB: Power repartition and primary system

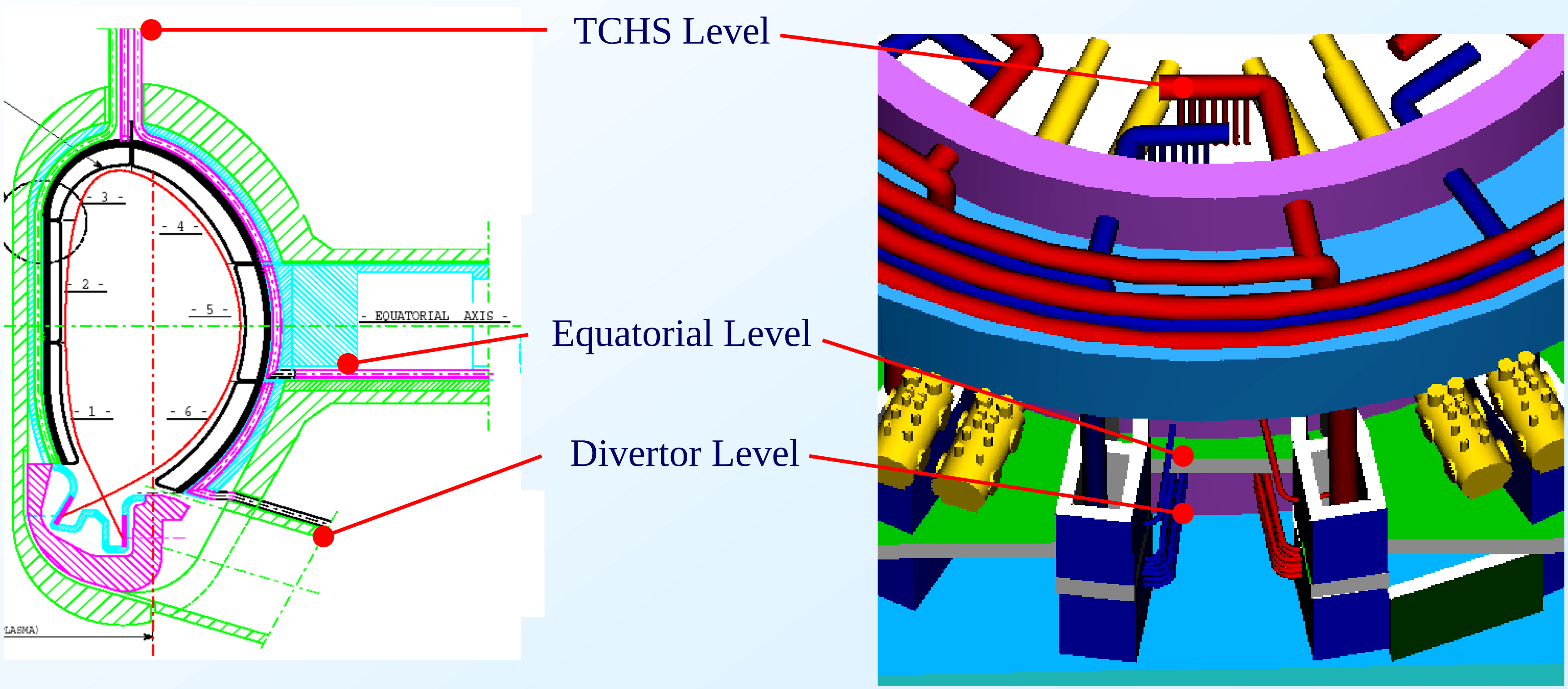
Blanket (+HTS) (MW)	**4478**
Divertor (MW)	**983**

Number of loops (blanket)	**9**
Number of loops (divertor)	**9**
Inlet/Outlet temperature (blanket) (°C)	**300/500**
Inlet/Outlet temperature (divertor) (°C)	**540/720**
Operating pressure (blanket) (MPa)	**8**
Operating Pressure (divertor) (MPa)	**10**
Heat Sink (blanket)	**Steam Generator**
Heat Sink (divertor)	**Superheater**

Model AB: BLK and DV cooling loops



Model AB: main connections of the cooling system



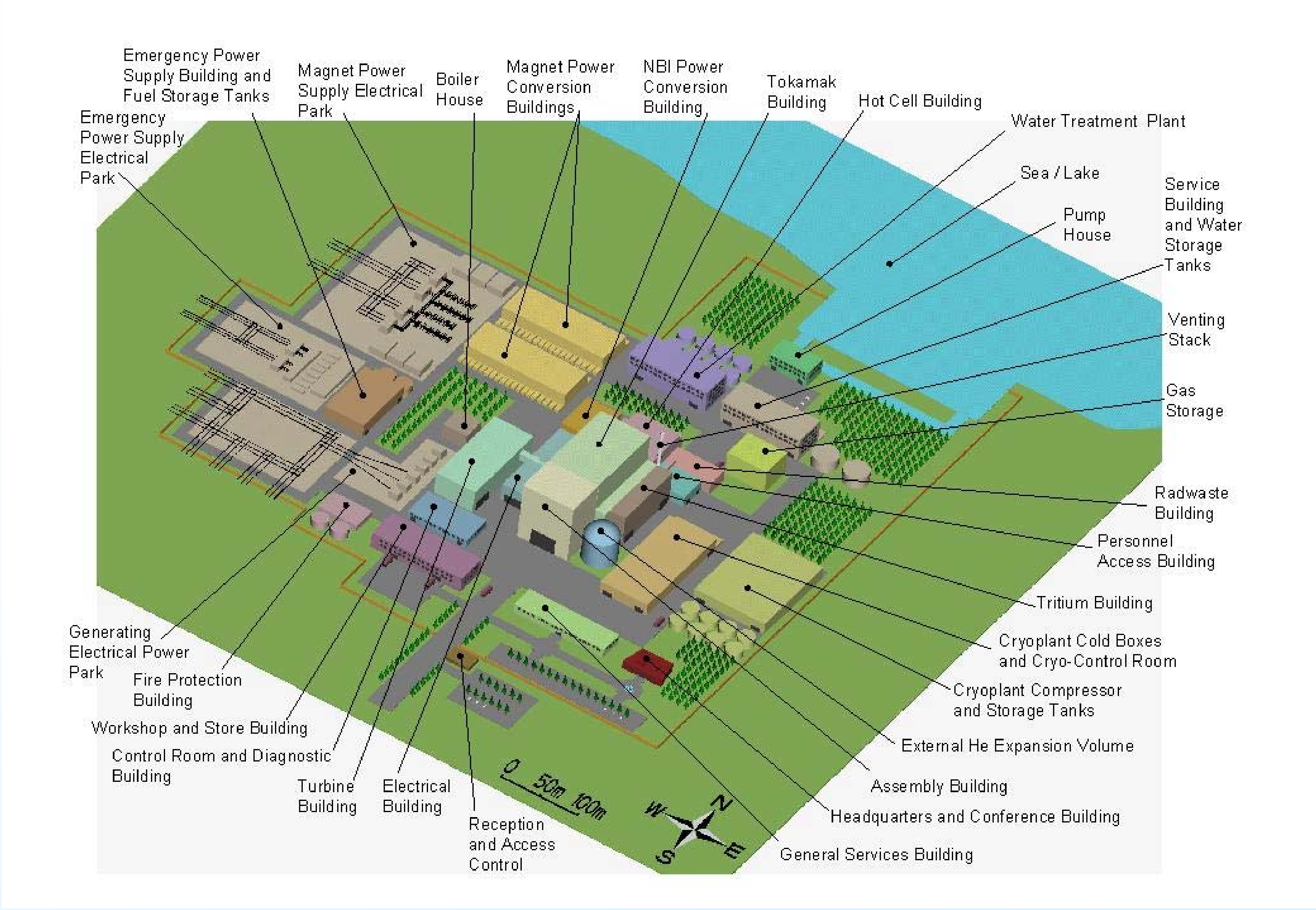
Model AB: R&D needs

- **Development of a HHF Helium-cooled divertor**

- **Open questions related to technology**
  - **blanket fabrication issues**

- **Materials**

Plant general layout

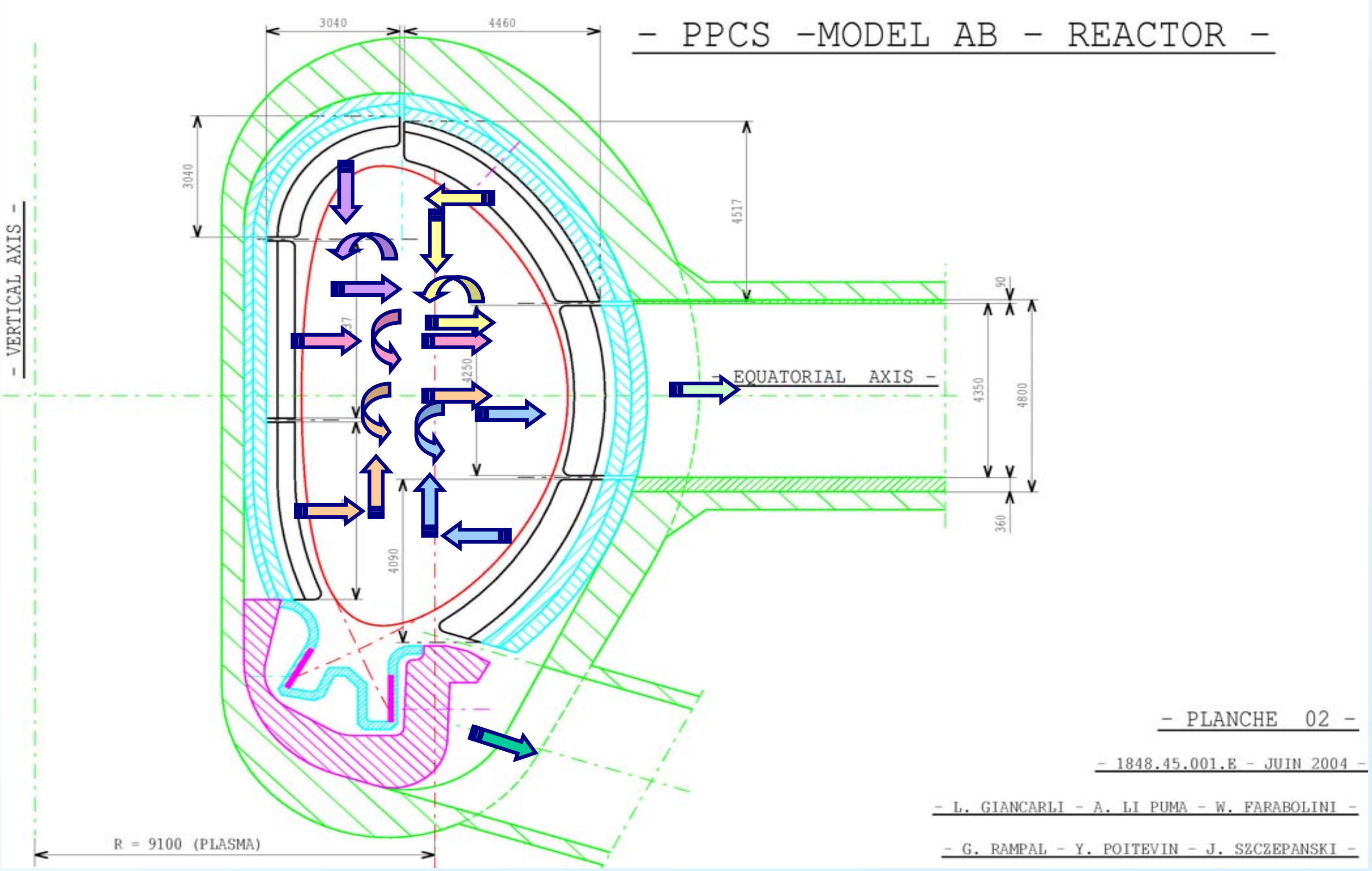


Maintenance scheme

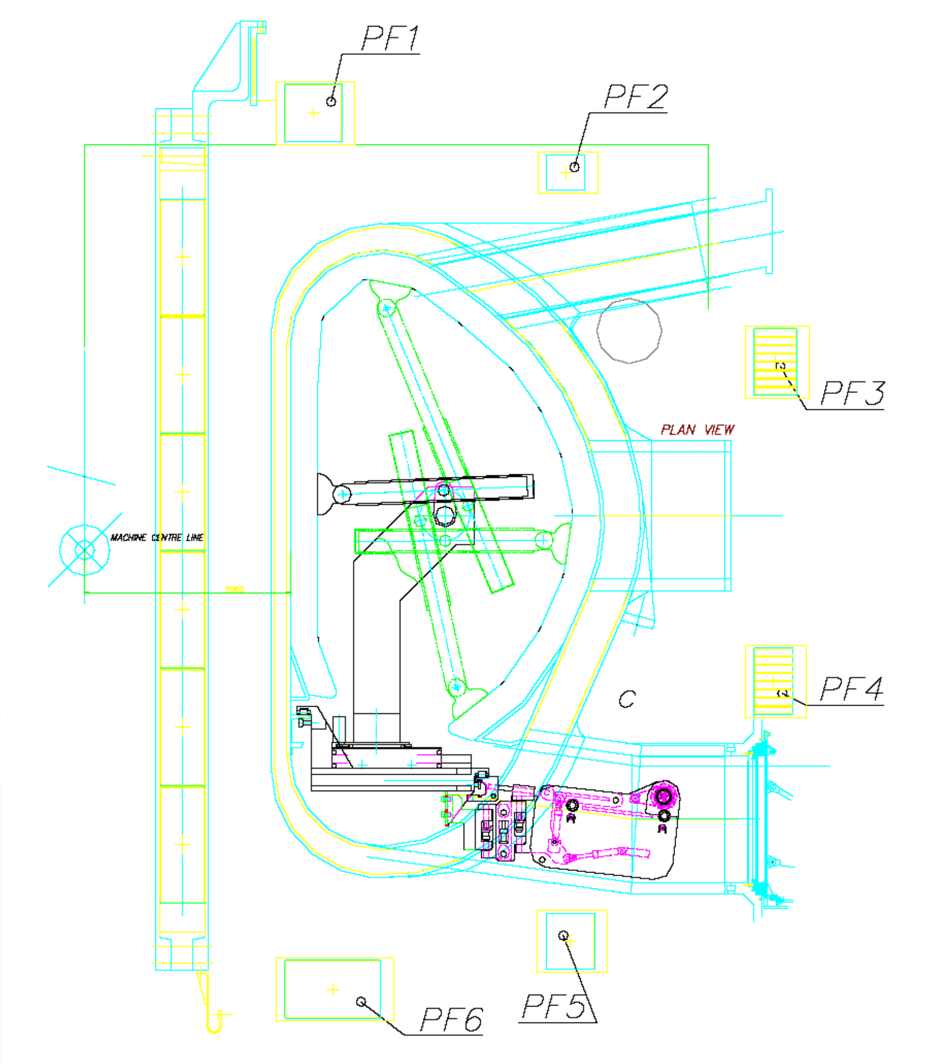
- **Large sectors**
  - Minimize the number of items to be replaced
  - Availability: 76.5 % - 81.2 % (12 days to replace one sector)

- **Segmentation**
  - A too large number of modules (like in ITER: 420) would not allow to reach the availability target
  - For the PPCS, the “large modules” maintenance concept has been considered

Handling Sequence



Handling device for large modules

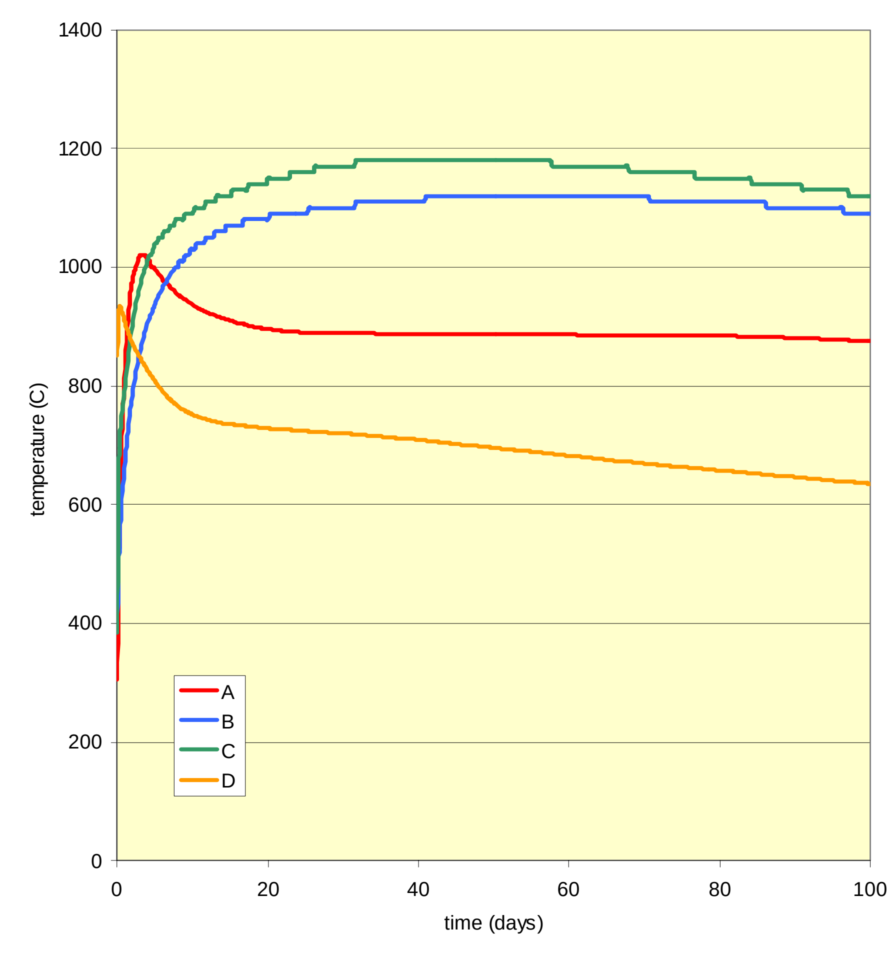


Bounding accident

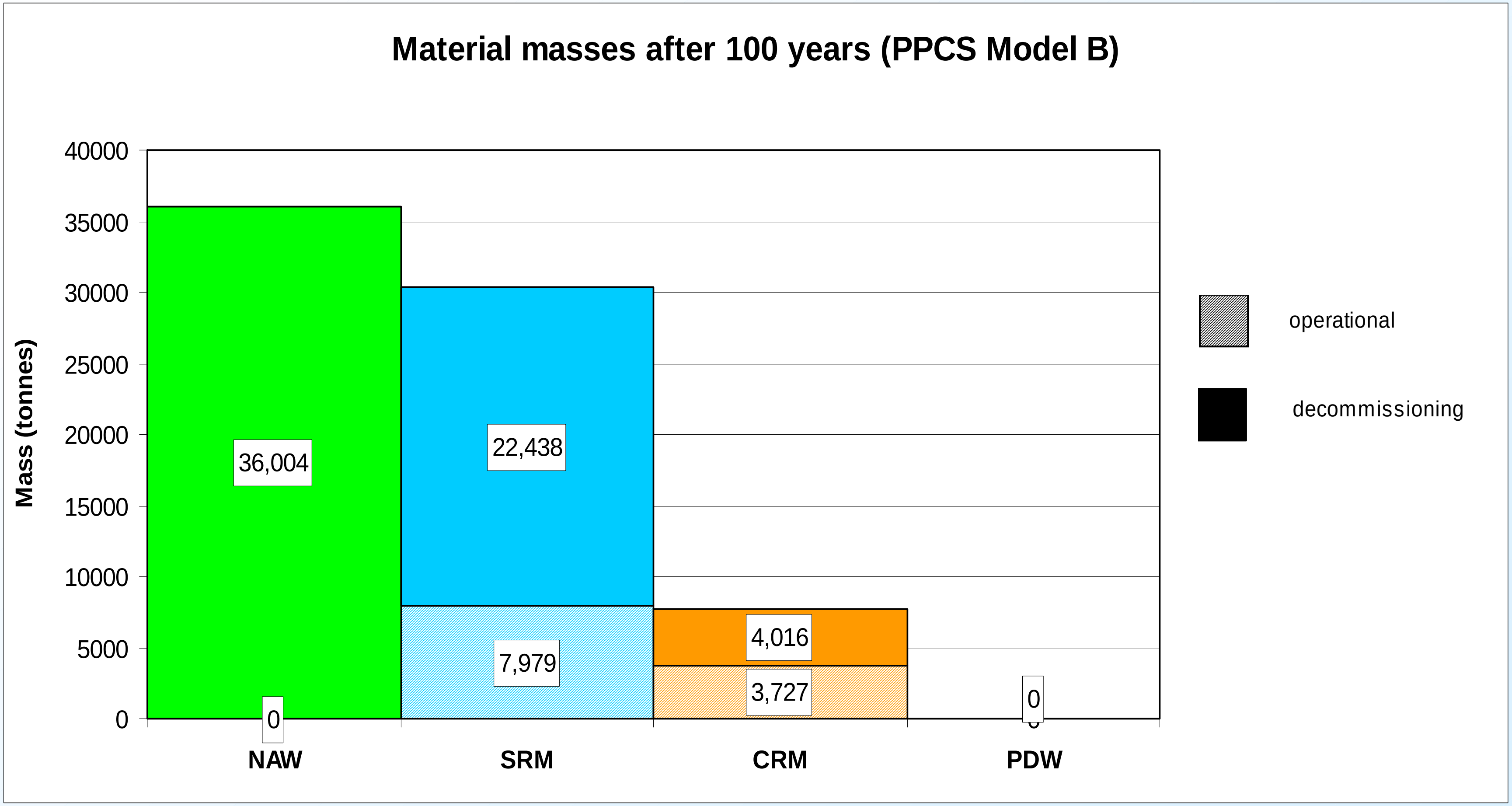
- Complete loss of coolant
- No active cooling or safety system

↓

- No melting of the structures



Wastes

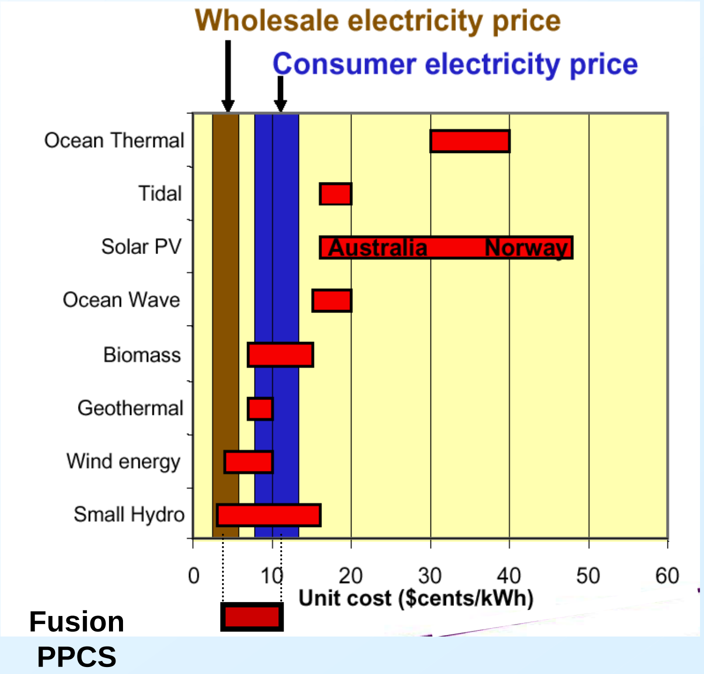

Material masses after 100 years (PPCS Model B)
Mass (tonnes)
40000
35000
30000
25000
20000
15000
10000
5000
0
36,004
0
22,438
7,979
4,016
3,727
0
NAW
SRM
CRM
PDW
operational
decommissioning

Internal costs

- **The cost of electricity mainly depends on the plasma parameters, the heat conversion cycle and the availability**

$$\text{coe} \propto \left(\frac{1}{A}\right)^{0.6} \frac{1}{\eta_{th}^{0.5}} \frac{1}{P_e^{0.4} \beta_N^{0.4} N^{0.3}}$$

A: availability
η_{th}: plant efficiency
P_e: net electric power
β_N: normalised plasma pressure
N: normalised Greenwald density



External costs

- **About 0.08 Eurocents/kWh**
- **For comparison**
  - **Wind: 0.05 Eurocents/kWh**
  - **Methane: 1-2 Eurocents/kWh**
  - **Oil power station: 5-8 Eurocents/kWh**

Conclusions (1)

- **All models meet the overall objectives of the PPCS (design, safety, economics)**
  - **Plasma performance only marginally better than the design basis of ITER is sufficient for economic viability of fusion reactors**
  - **Conceptual design of a helium-cooled divertor capable of tolerating a peak heat load of 10 MW/m^2**
  - **Definition of a maintenance concept capable of delivering high availability (75%)**
  - **A first commercial fusion power plant - accessible by a “fast track” route of fusion development - will be economically acceptable, with major safety and environmental advantages**

Conclusions (2)

- **R&D needed**
  - **Materials**
    - **Limitation of the concepts are mainly due to materials**
      - **Temperature window of materials, which impacts the temperature level of the coolant and thus the efficiency of the conversion system**
      - **Consequences of irradiation (materials swelling and embrittlement), which impacts the lifetime of the component and thus the availability of the reactor**
    - **Validation of Eurofer**
    - **Use of ODS**
      - **Temperature**
      - **Welding**
    - **Tungsten as structural material**
    - **SiC/SiC**

Conclusions (3)

- **R&D needed**
  - **He cooled divertor**
    - **Integration and technology issues**
  - **Attachment system and access to collectors**
    - **Implementation of the flexible part of the attachment**
    - **Piping layout through the ports**
  - **Maintenance**
    - **De-connection and re-connection to the manifolds: He pipes re-weldability**

Conclusions (4)

- **R&D needed**
  - **Tritium control system limiting tritium release**
    - **Strong reduction of the permeation in SG**
      - **Double walls pipes**
      - **Permeation barriers**
      - **Transformation of T_2 into HTO**
    - **Reduce uncertainties on the Sievert's constant**
    - **High permeation reduction factor in the blankets**

Conclusions (5)

- **R&D needed**
  - **Increase efficiency of He-cooled concepts**
    - **Possibility to improve the gross efficiency using other types of conversion cycles**
      - **Indirect Brayton cycle using supercritical CO_2 as working fluid: expected gross efficiency of about 49% at 550 ºC primary outlet temperature**
      - **Supercritical Rankine cycle: the turbine technology can be assumed mature**
    - **Improve the net efficiency by reducing the recirculating power**
      - **Reduce the pressure drops**
      - **Use of HTS magnets**