EU PPCS Models C & D Conceptual Design

Presented by

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PPCS Design Studies – Strategy definition [D. Maisonnier]

2 models with "limited" extrapolations

- Model A: WCLL (water cooled lithium lead) *[P. Sardain]*
- Model B: HCPB (helium cooled pebble bed) *[S. Hermsmeyer]*
- Divertor coolant = blanket coolant
- Normalised gross electric power output of 1.5 GWe

2 more "advanced" models

- **Model C: DC (dual coolant: helium and lithium lead)** *[P. Norajitra]*
- **Model D: SC (self cooled: lithium lead)** *[L. Giancarli]*
- **Divertor coolant = blanket coolant (C: He, D: PbLi)**
- **Normalised gross electric power output of 1.5 GWe**

Materials basis

Model	Divertor	Blanket structure	Blanket other
A	W/Cu/water	RAFM	LiPb/water
B	W/He	RAFM	Li_4SiO_4/Be/He
C	W/ODS/He	ODS / RAFM	LiPb/SiC/He
D	W/SiC/LiPb (He opt.)	SiC	LiPb

Model C reactor (DC blanket) – Main parameters

Basic Parameters	
Unit Size [GW_e]	1.5
Major Radius [m]	7.5
Aspect Ratio	3.0
Plasma Current [MA]	19.0
TF on axis [T]	6.0
Number of TF coils	16
TF on TF Coil Conductor [T]	13.6
Elongation (X-point, 95% flux)	2.1, 1.9
Triangularity (X-point, 95% flux)	0.7, 0.47
Q	34

Physics Parameters	
H_H (IPB98y2)	1.3
n/n_G	1.5
β_N(thermal, total)	3.7, 4.0
Bootstrap fraction	0.63
Safety factor q(95)	4.5
Z_{eff}	2.2
Average Electron Temp. [keV]	16
Temperature peaking factor	1.5
Density peaking factor	0.5

Engineering Parameters	
Fusion Power [GW] (after iteration)	3.45
Source peaking factor	2.5
Heating Power [MW]	112
Average neutron wall load [MW/m^2]	2.25
FW Surface Heat Flux [MW/m^2]	0.5
Max. Divertor Heat Load [MW/m^2]	10

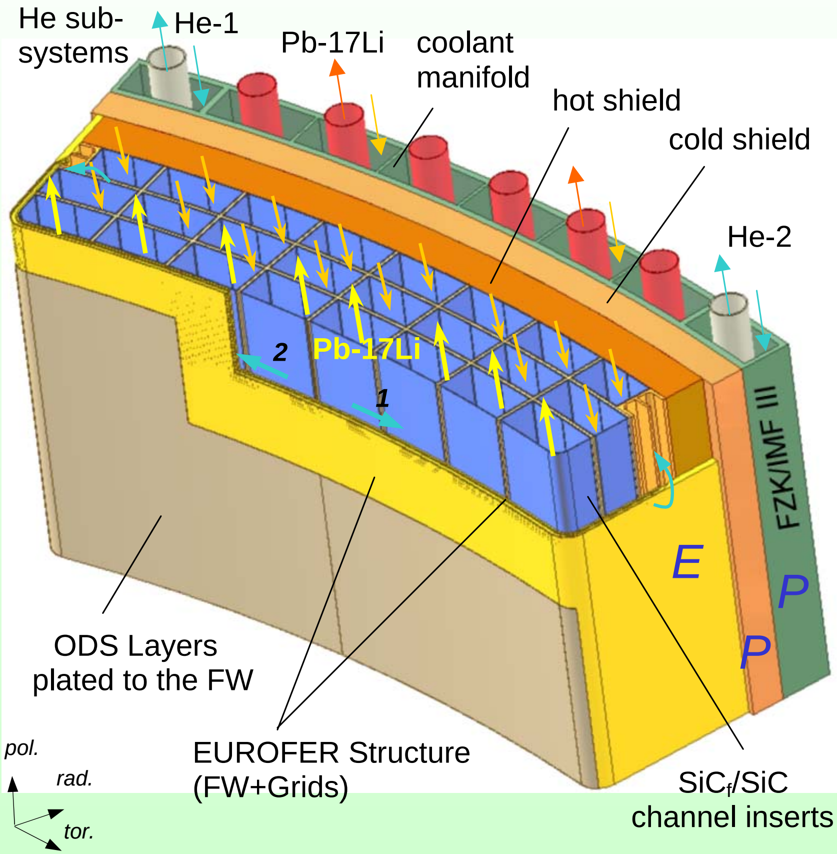
PPCS – Model C&D: General design requirements

- 1.5 GWe electric power output
- Small reactor dimension (minimization of the plant costs)
- High efficiency (low cost of electricity)
- High reliability and availability
- Easy blanket replacement
- Reduction of wastes quantities

PPCS – Model C&D: Response for detail design

- **Small radial blanket thickness, however must be ensured:**
- **TBR > 1 and sufficient n-shielding**
- **As high an coolant outlet temperature as possible, however:**
- **No excess of the permissible structure temperature, (C): 550°C for EUROFER) as well as the corrosion temperature PbLi/Steel (approx. 500°C)**
- **Thermohydrualics and MHD appropriate design with small pressure losses**
- **Homogeneous structure temperature distribution**
- **Simple construction, as much as possible permanent parts**

Model C: Main design features



DC outboard blanket (cut-out at torus centre)

Structure

- Modular blanket design (permanent *'P'* and exchangeable *'E'* parts)
- The basis blanket structure is made of EUROFER
- 2-3 mm ODS layer is plated onto the plasma facing FW surface, utilising high temperature strength of ODS (and getting rid of ODS welding problems)

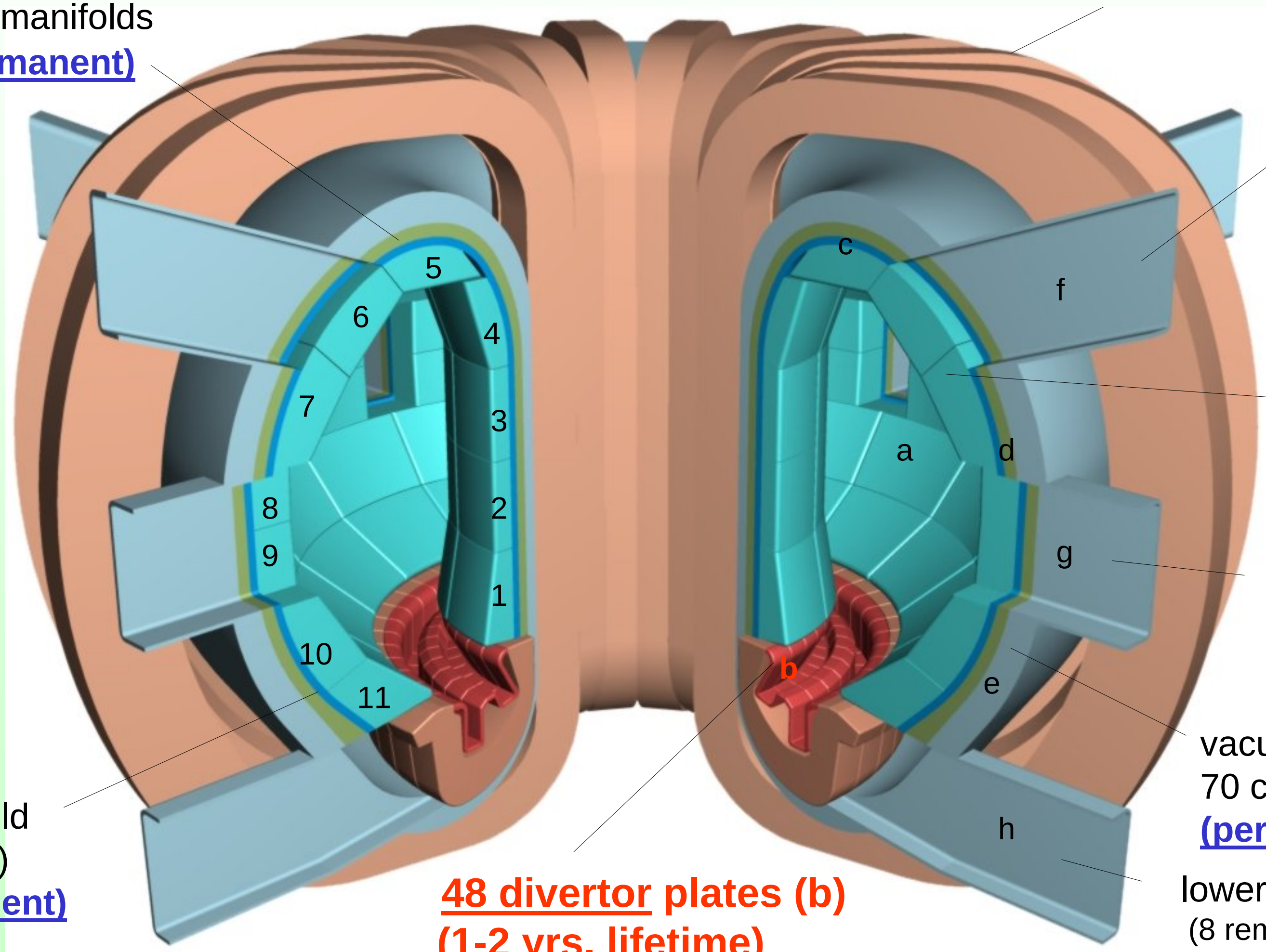
Flow channel inserts (FCI)

- SiC$_f$/SiC FCI for electrical (MHD reduction) and thermal insulation (high Pb17Li exit temperature, e.g. 700°C for higher thermal efficiency), no structural functions

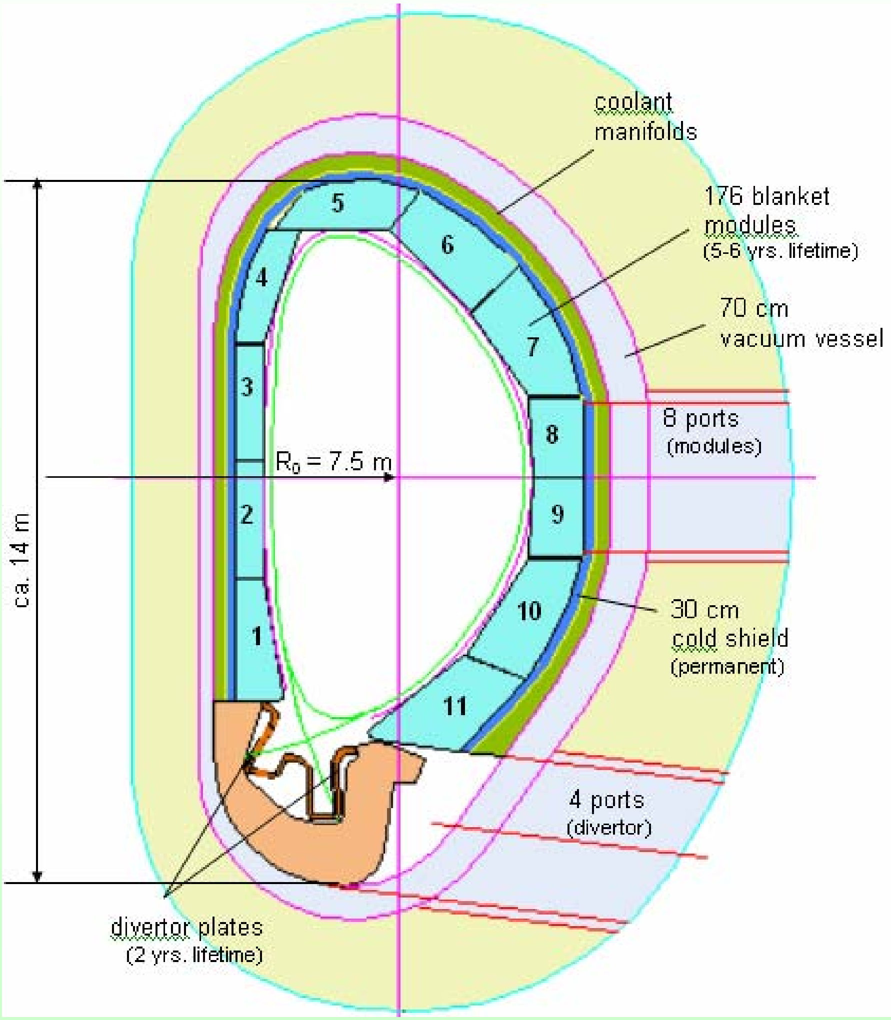
Dual-Coolants He/PbLi

- FW and steel grids are cooled by 8 MPa He
- Self-cooled Pb17Li acting as breeder and coolant

Model C: Modular design with permanent and exchangeable parts



Model C - The radial build [D. Ward]

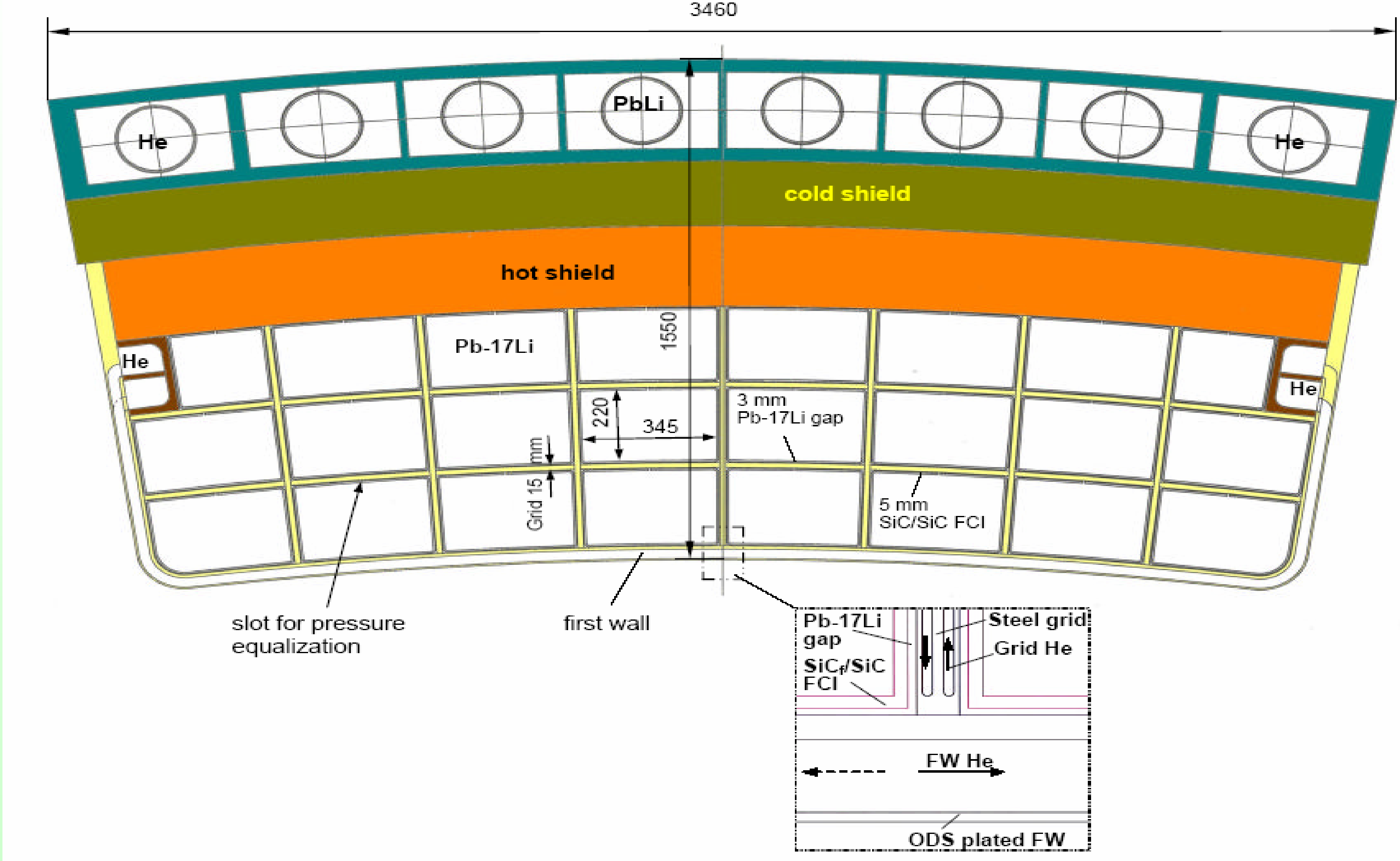


<u>Iterative approach betw. design and system code</u>

In-/Outb. blanket thickness (incl. shield): 1.1 / 1.6 (m)

Component	**Radial build (m)**
TF coil	1.84 - 3.34
Vessel and gap	3.34 - 3.76
Shield / blanket / first wall	3.76 - 4.86
Plasma	5.01 - 10.03
Shield / blanket / first wall	10.18 - 11.78
Vessel + gap	11.78 - 12.93
TF coil	12.93 - 15.65

Model C : DC Blanket Equatorial Cross-section



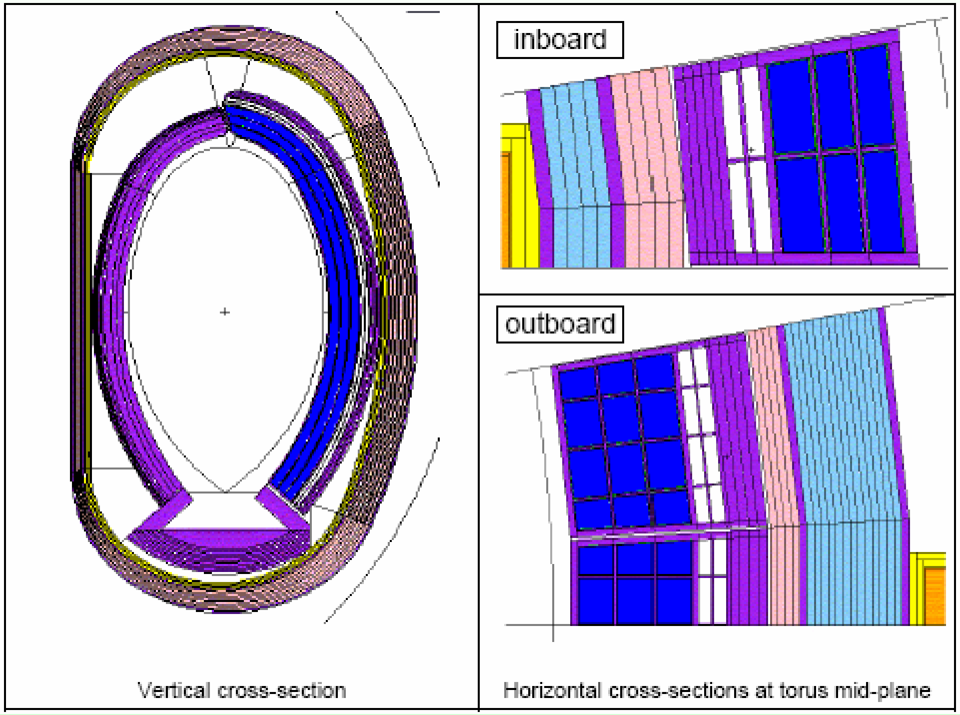
Model C - Size, weight, power, and required mass flow rates of the modules

Module No.	Group	Module size (mm)			Module weight (kg)		Power (MW)	Mass flow rate (kg/s)	
		Radial	Toroidal	Poloidal	Emptied	Full		He	Pb-17Li
1	IB	747	1656	2400	3430	15523	10.39	5.6	168.0
2	IB	545	1660	2300	3287	14876	11.56	6.1	187.0
3	IB	545	1660	2300	3287	14876	11.28	6.1	182.4
4	IB	741	1723	2339	3343	15128	11.16	6.0	180.4
5	IB	959	2423	2300	10254	45721	8.89	4.8	143.8
6	OB	1301	3110	2276	12619	57667	18.88	10.1	305.5
7	OB	1341	3548	2004	12499	57749	22.28	12.0	360.2
8	OB	1035	2965	1573	8361	38043	19.56	10.5	316.4
9	OB	1035	2965	1573	8361	38043	19.57	10.5	316.7
10	OB	1340	3639	2200	14037	64987	23.66	12.7	382.7
11	OB	1408	3049	2320	12639	57657	20.93	11.2	338.6

(IB = inboard, OB = outboard); Total number of module = 11 x 16 = 176

Model C : DC Blanket Neutronic Model and Results

TBR = 1.15 *[U. Fischer]*
(90% ^{6}Li, inb/outb breeder zone thk: 50.5/85.5 cm)



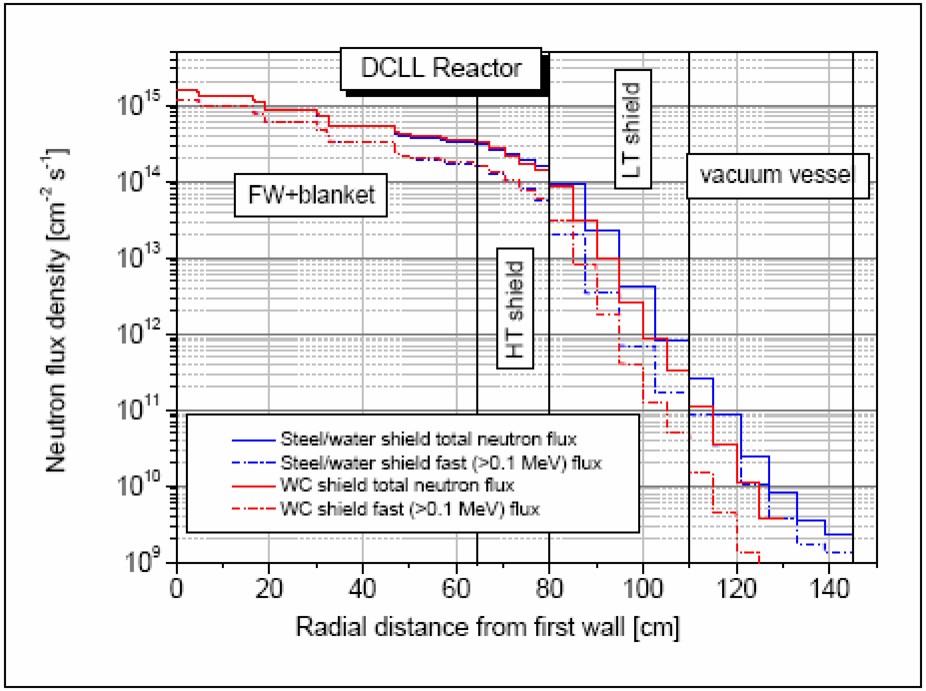
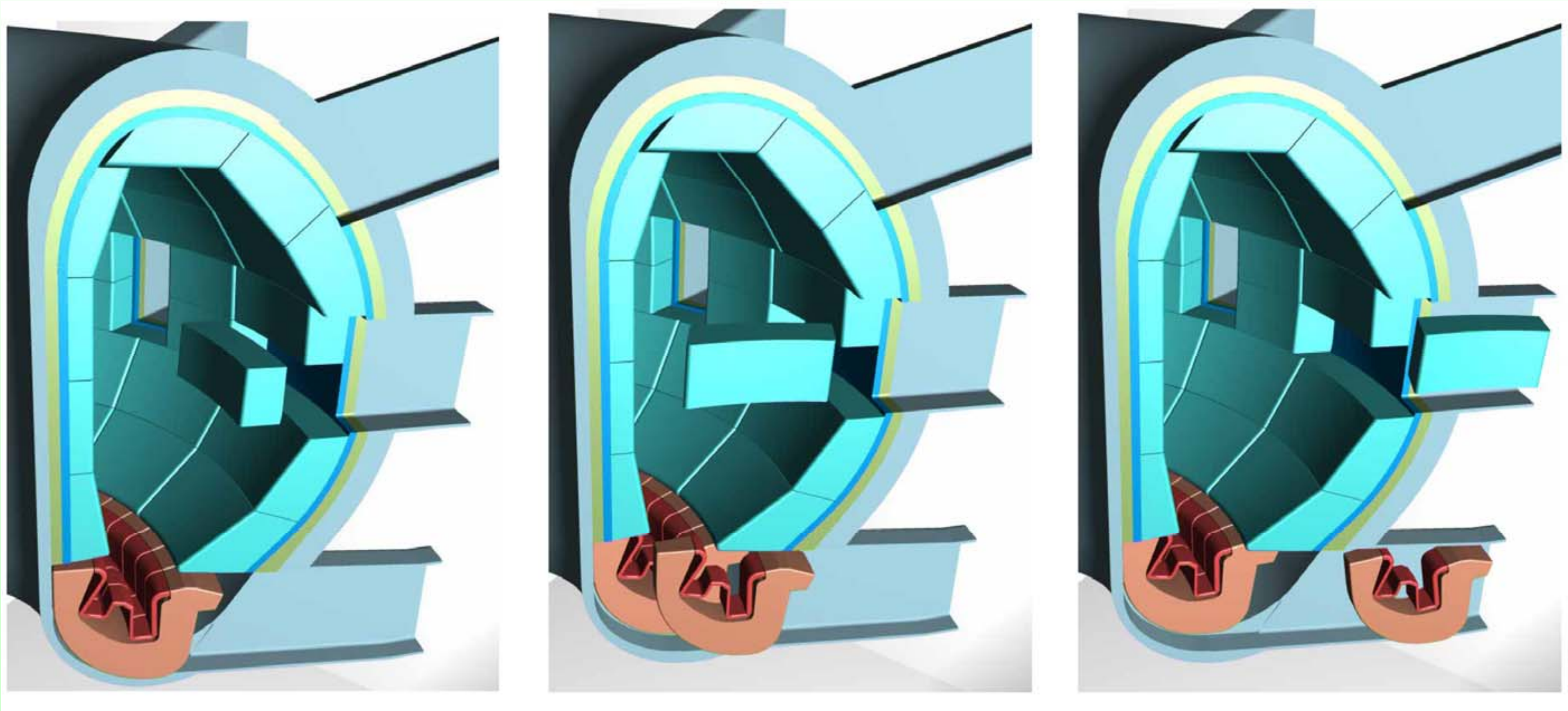
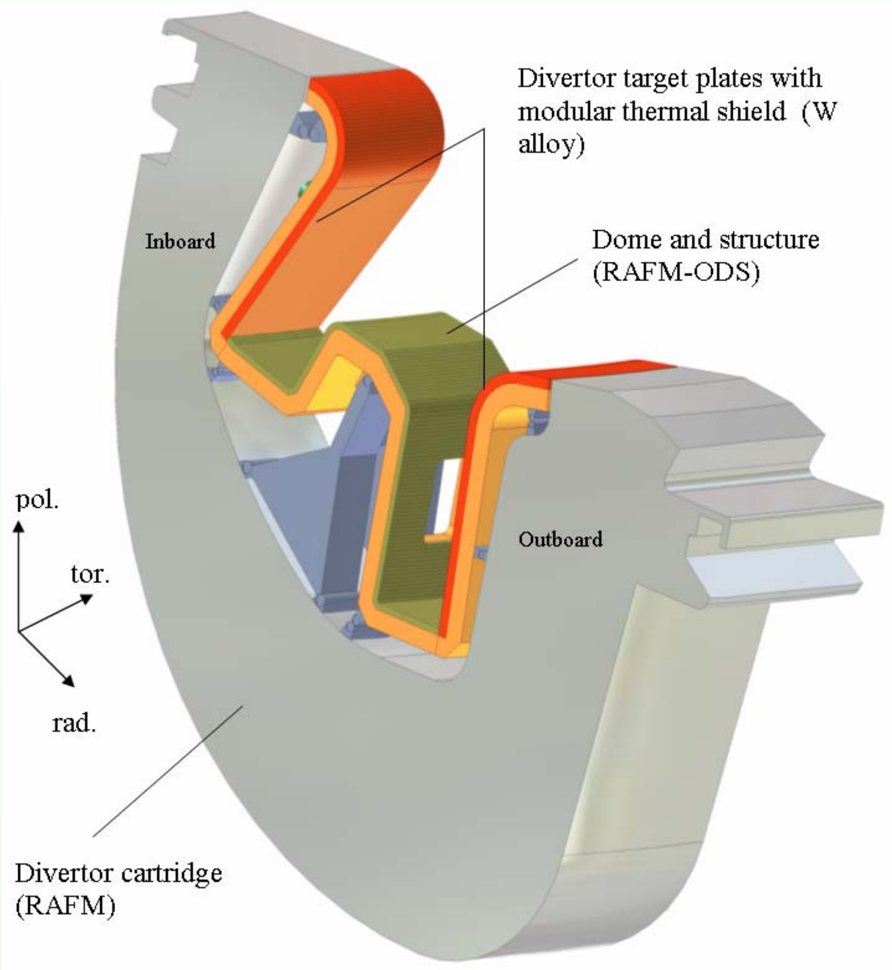


Fig. 4.3-2: Neutron flux profiles as calculated for the inboard mid-plane of the reactor.

Replacement path of blanket modules and divertor cassettes



Model C: Integration of He-cooled divertor



- ✓ 10 MW/m^2 (PPCS)
- ✓ W tile as thermal shield (5 mm thick)
- ✓ W-1%La_2O_3 cooling finger (thimble)
- ✓ RAFM (HT) ODS Eurofer structure
- ✓ T_{He}, inl/outl = 700/800 °C (target plate)
  (in this study advanced HT ODS was assumed)

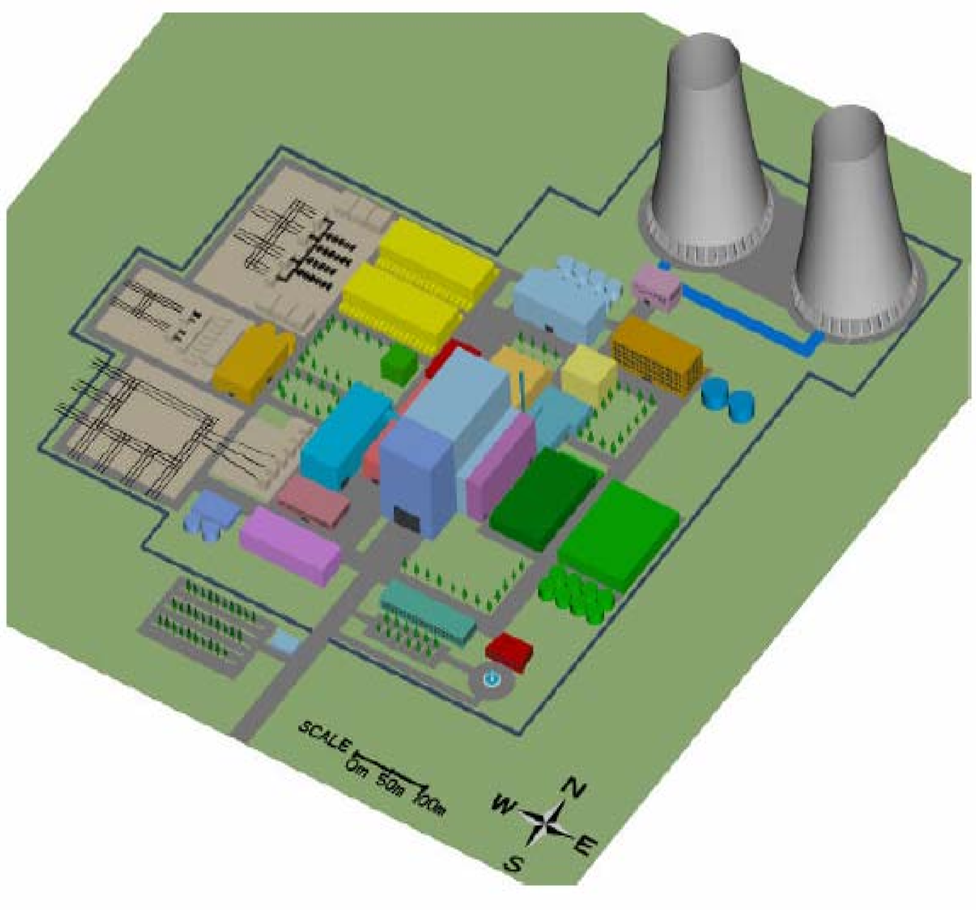
→ *presentation by L. Boccaccini*

Model C: Dual Coolant Systems

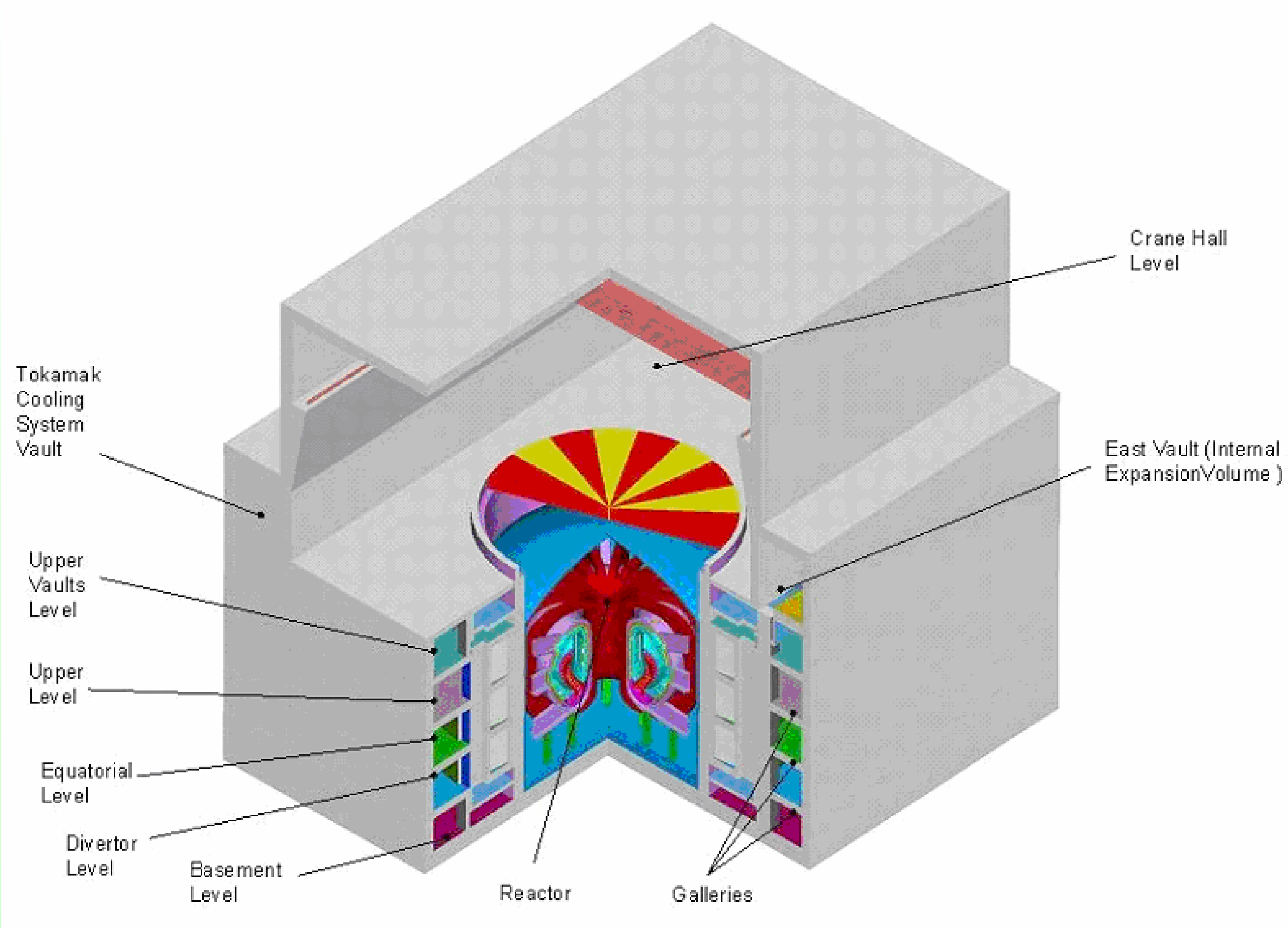
Blanket & Divertor Circuits Characteristics (4 parallel Brayton cycles – He turbine)

	Blanket	Divertor
Coolant:		
Helium:		
- Inlet temperature [°C]	300	700 (target)
- Outlet temperature [°C]	480	800 (target)
- Pressure [MPa]	8	10 (target)
- Mass flow rate [kg/s]	1528	473 (bulk) 477 (target)
- Pumping power, η = 0.8 [MW]	30	3.4
Pb-17Li:		
- Inlet temperature [°C]	480	
- Outlet temperature [°C]	700	
- Mass flow rate [kg/s]	46053	
- Pumping power, η = 0.8 [MW]	5	
Secondary helium:		
- Inlet temperature [°C]	285	
- Outlet temperature [°C]	700	
- Pressure [MPa]	15	
Thermal efficiency (power conv. system) Net efficiency (blanket/divertor cycle)	0.44 0.43	

Power Plant Layout



Model C – Tokamak building



Model C reactor – Main key issues and R&D needs

- SiC/SiC related issues: Flow Channel Inserts design (out of the main body) and fabrication, irradiation effects, compatibility with high v, high T LiPb
- MHD: modeling and computations of 3D inertial flow in expansion
- ODS: fabrication of ODS plated FW, irradiation effects
- Tritium recovery and LiPb purification: identification/demonstration of acceptable techniques
- Heat exchanger technology (for LiPb): to be defined
- Blanket system design: some integration aspects not solved or not addressed (because of lack of time)
- Divertor: He-cooled W-structures (see following presentation)

Model D reactor (SCLL blanket) – Main parameters

Basic Parameters	
Unit Size [GW_e]	1.5
Major Radius [m]	6.1
Aspect Ratio	3.0
Plasma Current [MA]	14.1
TF on axis [T]	5.6
Number of TF coils	16
TF on TF Coil Conductor [T]	13.4
Elongation (X-point, 95% flux)	2.1, 1.9
Triangularity (X-point, 95% flux)	0.7, 0.47
Q	35

Physics Parameters	
H_H (IPB98y2)	1.2
n/n_G	1.5
β_N(thermal, total)	3.7, 4.5
Bootstrap fraction	0.76
Safety factor q(95)	4.5
Z_{eff}	1.6
Average Electron Temp. [keV]	12
Temperature peaking factor	1.5
Density peaking factor	0.5

Engineering Parameters	
Fusion Power [GW] (after iteration)	2.53
Source peaking factor	2.5
Heating Power [MW]	71
Average neutron wall load [MW/m^2]	2.4
FW Surface Heat Flux [MW/m^2]	0.5
Max. Divertor Heat Load [MW/m^2]	5

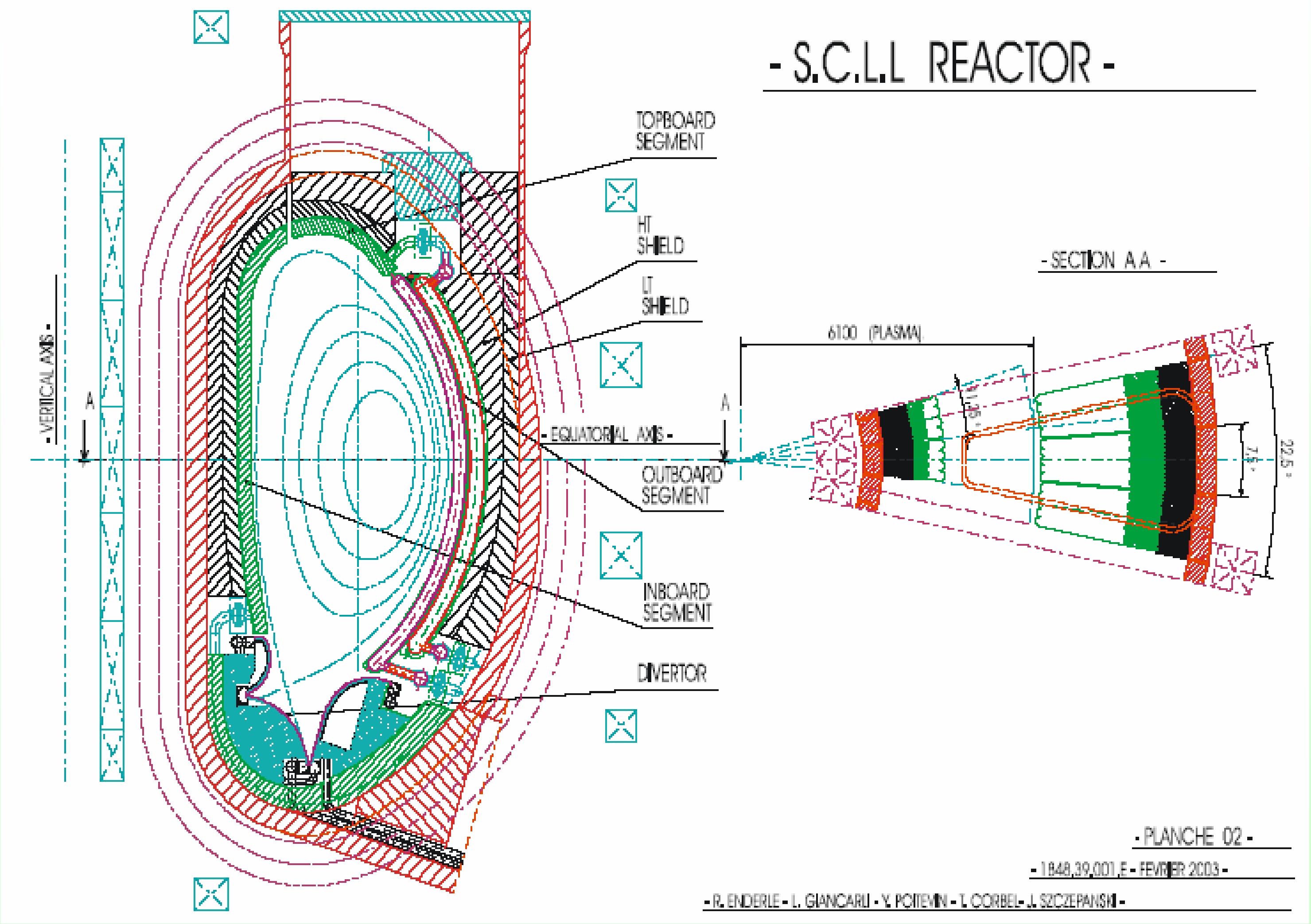
Model D reactor – Major design choices

- Structural Material: SiC/SiC for both Blanket and Divertor (low act., high T)
- Blanket working principle: co-axial Pb-17Li flow to maximize outlet T
- Divertor working principle: use of independent Pb-17Li coolant circuit, to minimize pressure/avoid structural W (NB: He-cooled divertor needs different optimization)
- Pb-17Li external circuits location: horizontal deployment, to minimize pressure
- Blanket remote maintenance procedure: segment geometry, maintained through vertical ports after Pb-17Li draining
- Divertor remote maintenance procedure: as in ITER
- Potential reduction of waste quantities: separation of outboard blanket in two zones in order to minimize radioactive waste (depending on lifetime evaluations)
- Magnet system: possibility of high T superconductors (77 K)
- Plasma heating system: acknowledge of need but not evaluated
- Advanced conversion systems: potential for H-production

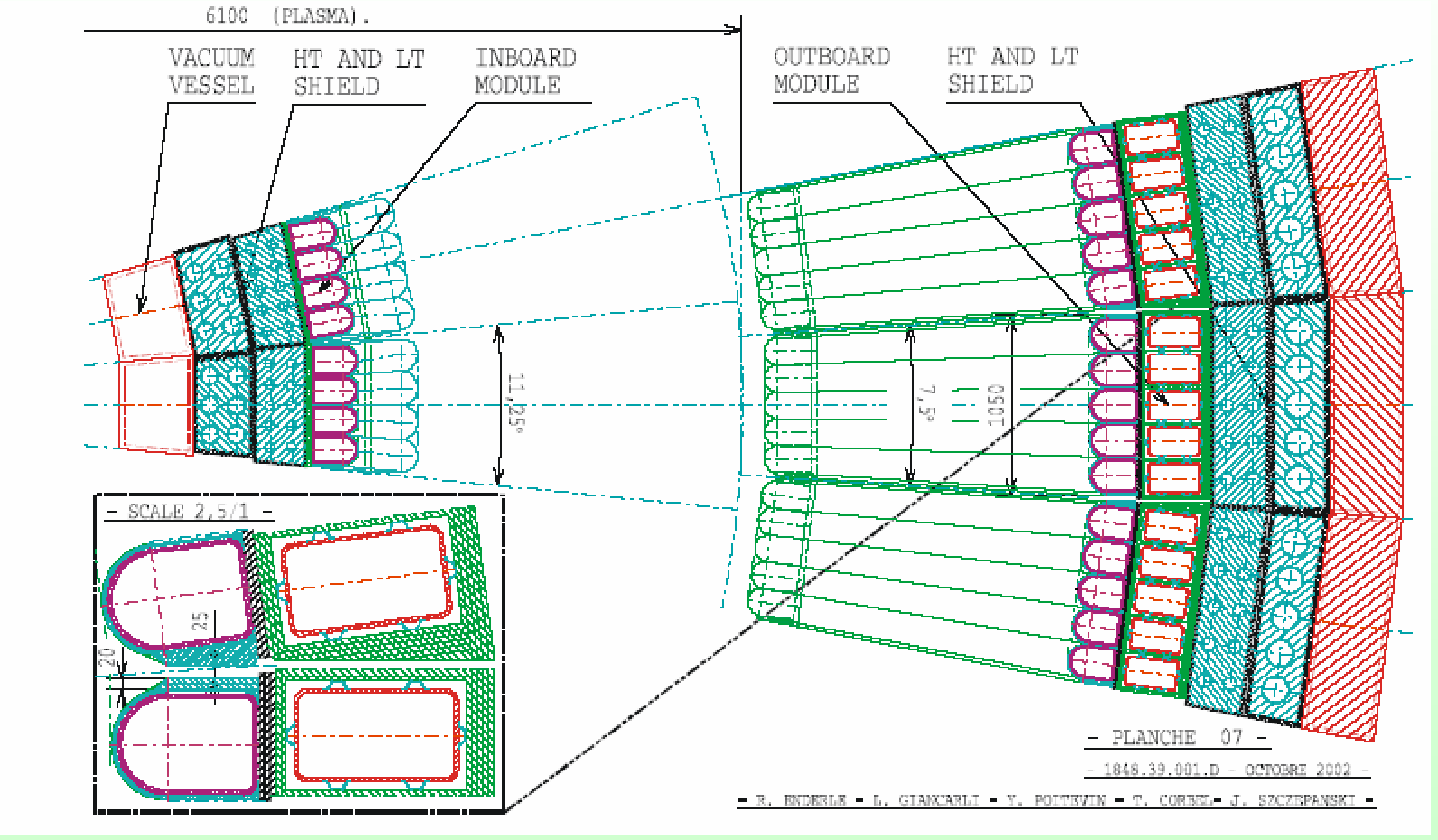
Assumed SiC/SiC Properties

Key SiC_f/SiC Properties and Parameters *	Assumed values [1] in the design analyses	Typical measured value
Density	˜ 3000 kg/m^3	˜ 2500 kg/m^3
Porosity	˜ 5%	˜ 10%
Young's Modulus	200-300 GPa	˜ 200 GPa
Poisson's ratio	0.16-0.18	0.18
Thermal Expansion Coefficient	˜ 4 x 10^{-6}/°C	4 x 10^{-6}/°C
Specific heat	190 J/kg-K	190 J/kg-K
Thermal Conductivity in Plane (1000°C)	˜ 20 W/m-K (EOL)	˜ 15 W/m-K (BOL)
Thermal Conductivity through Thickness (1000°C)	˜ 20 W/m-K (EOL)	˜ 7.5 W/m-K (BOL)
Electrical Conductivity	˜ 500 /Ωm (under irradiation, EOL value)	˜ 500 /Ωm (before irradiation)
Tensile Strength Trans-laminar Shear Strength Inter-laminar Shear Strength	300 MPa - -	300 MPa 200 MPa 44 MPa
Maximum allowable tensile Stress	Not used*	Unknown*
Max. Allowable Temperature (Irradiation Swelling basis)	˜ 1000 °C	˜ 1000 °C
Maximum Allowable Interface Temperature with breeder	˜ 1000°C (flowing)	˜ 800°C (static)
Min. Allowable Temperature (Thermal conductivity basis)	˜ 600 °C	˜ 600 °C
Cost	= $400/kg	˜ 10 times larger

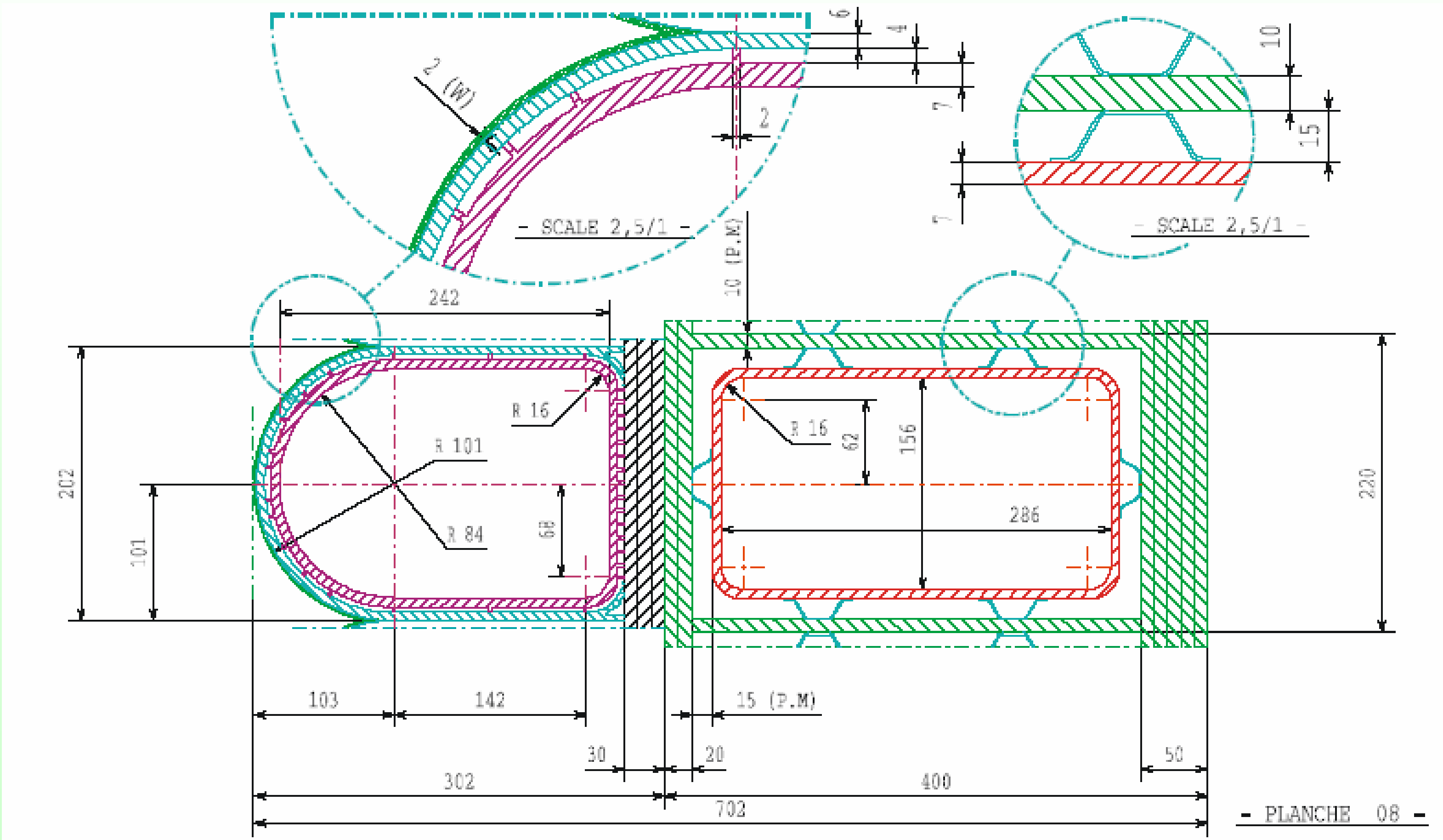
Model D : SCLL Blanket Scheme (poloidal cross-section)



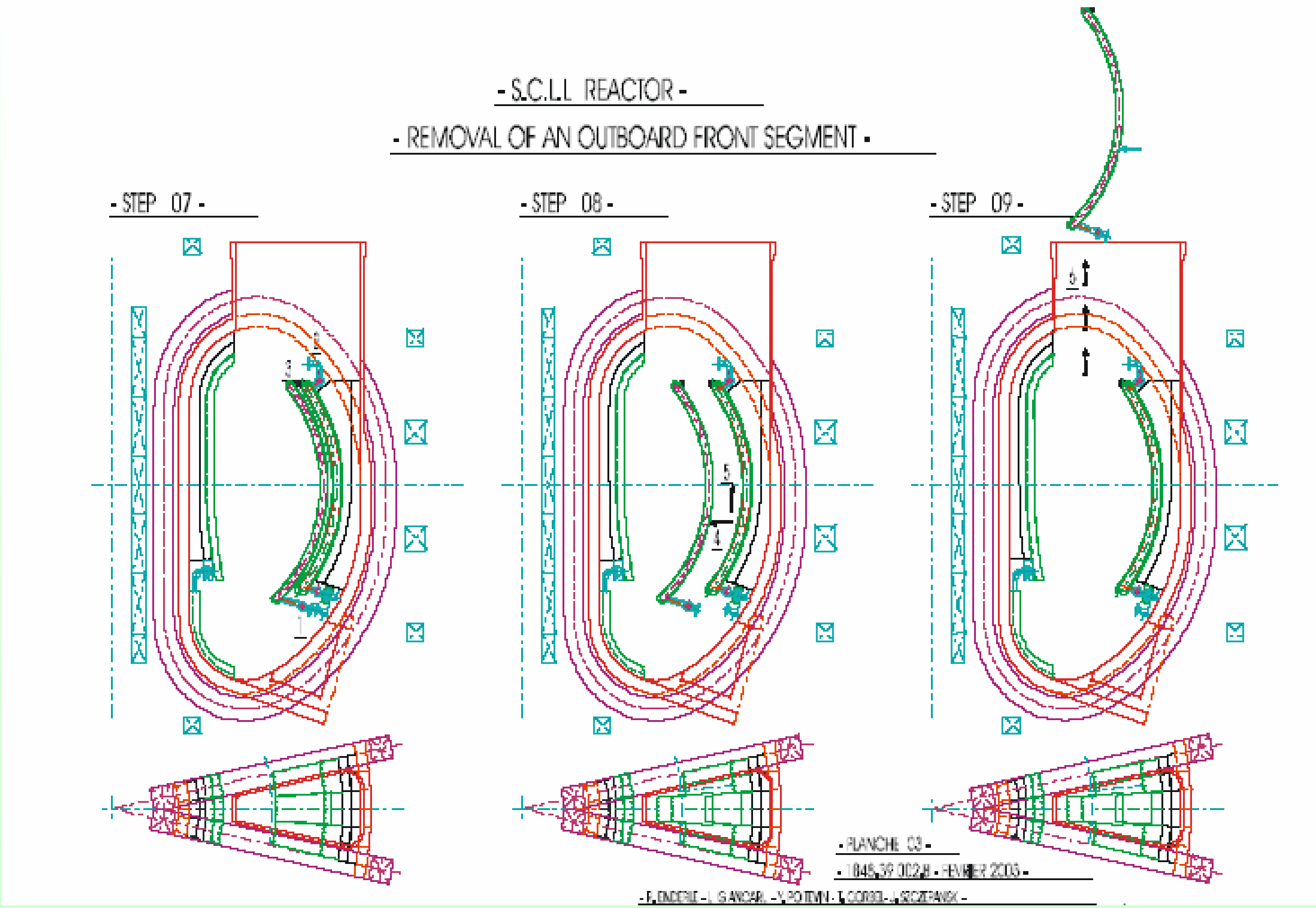
Model D : SCLL Blanket Scheme *(horizontal cross-section)*



Model D : SCLL Blanket Scheme *(outboard segment eq. cut)*



Model D : SCLL Blanket Replacement Procedure



Self-Cooled Lithium-Lead blanket & divertor (SCLL)

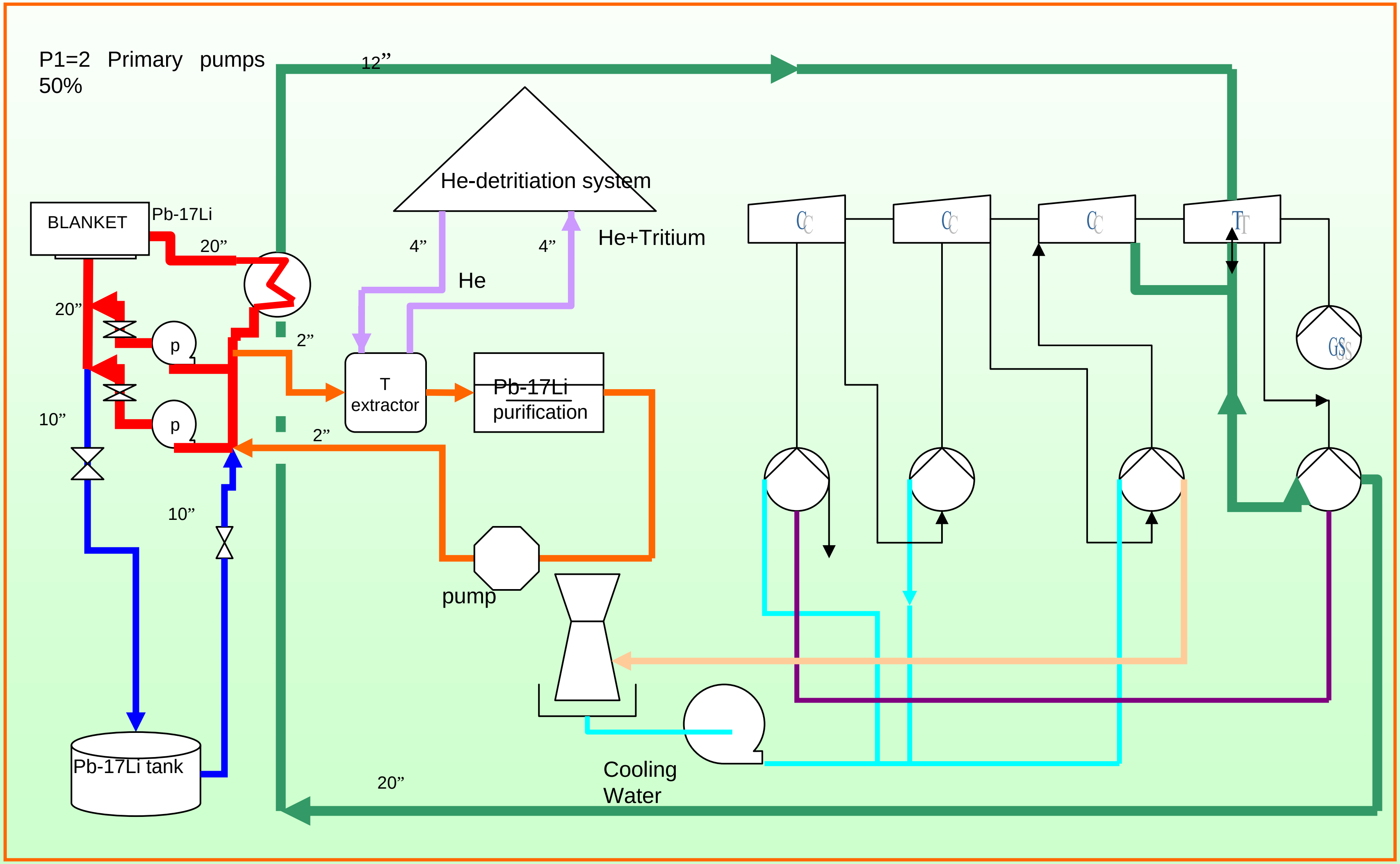
➔ general characteristics

- segment : SiC_f/SiC box acting as Pb-17Li container, 2 mm W protection
- use of 3D (industrial) SiC_f/SiC 3D , extensive use of brasing
- Pb-17Li: $T_{inlet/outlet}$ 700°C/1100°C *(div: 600/990°C)*, max. speed ~4.5 m/s
- dimensions outboard (front) segments: 5 modules h=8m, w=0.3m, thk=0.3m
- High T Shield: Pb-17Li-cooled WC, SiC_f/SiC structures (energy recovered)
- Low T Shield: He-cooled WC with B-steel structures (as for VV)

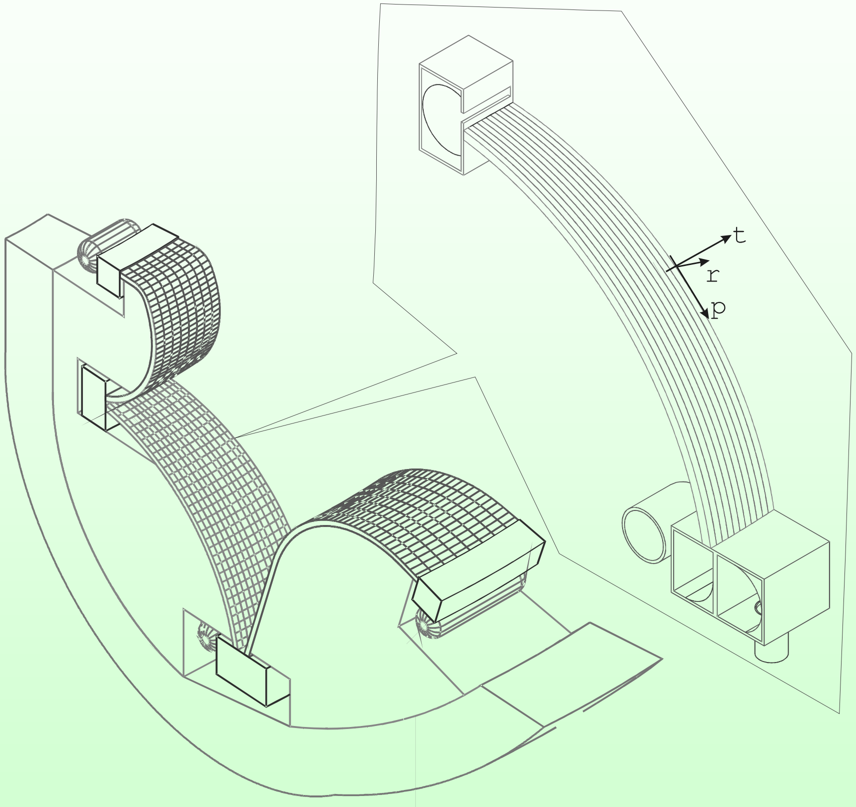
➔ *main performances*

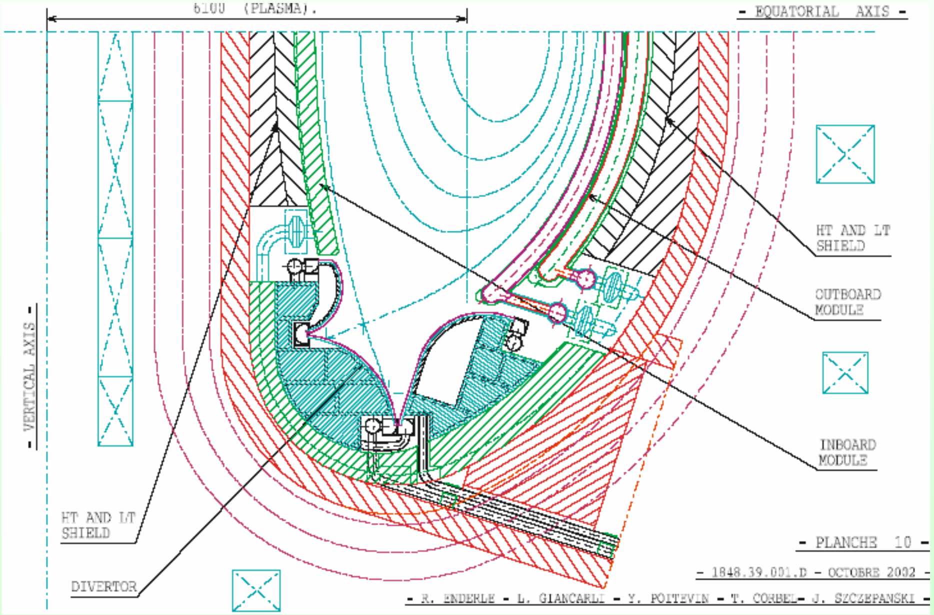
- *Neutronics : TBR = 1.12 (0.98 blankets, 0.125 divertor, 0.015 HT shield)*
- *Thermal results : T_{max} ~1100°C (if λ =20 W/mK, thk. FW 6 mm)*
- *Acceptable stresses (see criteria details) for Hydr. pressure = 0.8 MPa*
- *Acceptable MHD pressure drops*
- *1 independent cooling circuit for divertor, 4 for blanket, ε = 61 % (P_{el}/P_{fus})*
- *T-extraction performed on the cold leg (Pb-17Li renewal ~1100 times/day)*

Model D : SCLL T-extraction and PbLi purification systems

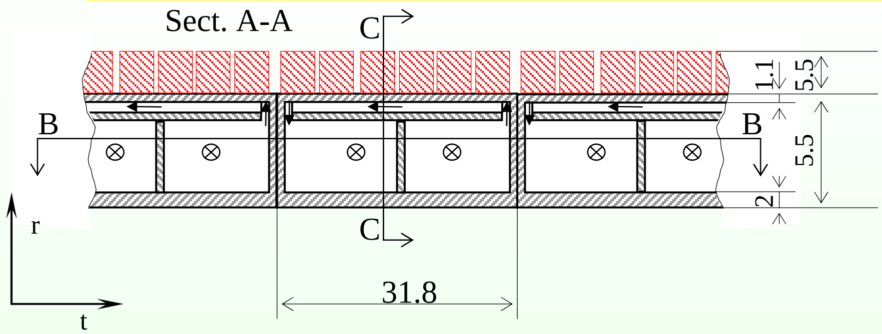


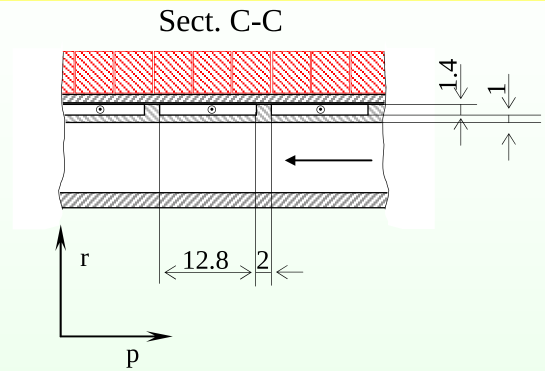
Model D : SCLL Divertor (general views)

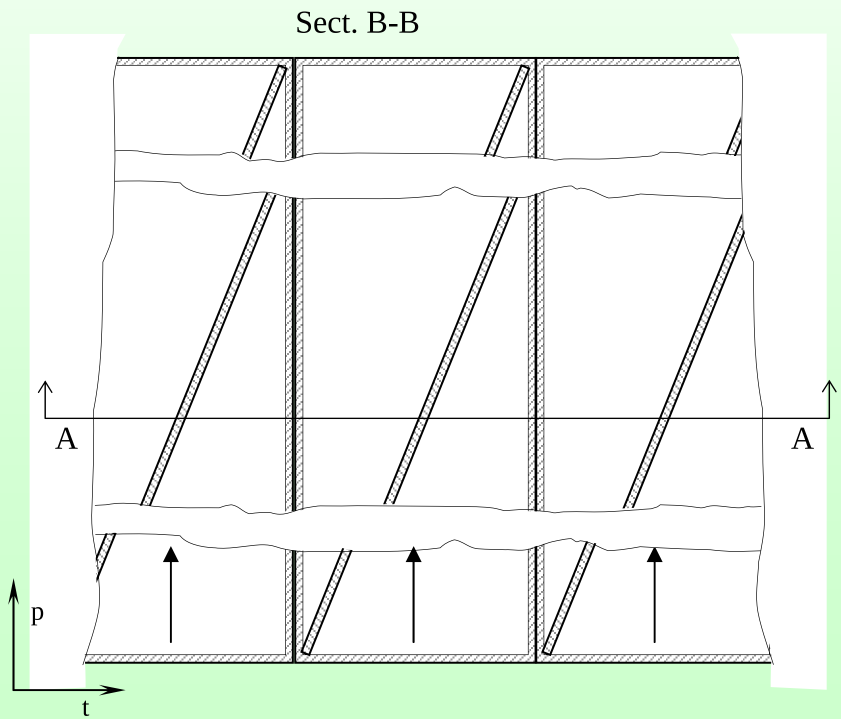




Model D : SCLL Divertor (details)







Model D reactor – Main key issues and R&D needs

- SiC/SiC related issues: structural functions, assumed extrapolated properties for design, several aspects can be critical
  ➔ *properties under irradiation (i.e., thermal conductivity, burn-up, lifetime)*
  ➔ *fabrication (brazing, weaving, pipe connections)*
  ➔ *properties reliability, behavioral modeling, compatibility with high v & T LiPb*
- MHD: modeling and computations of 3D inertial flow in expansion
- Tritium recovery and LiPb purification: identification/demonstration of acceptable techniques for high flow rates (>1000 LiPb recirculations per day)
- Heat exchanger technology: to be defined, SiC/SiC structures probably needed
- External circuits: SiC/SiC structures probably needed, basic components not available
- Blanket system design: several integration aspects not solved or not addressed (because of lack of time)
- Divertor: LiPb-cooled SiC/SiC structures, fabrication to be defined, impact of irradiation (not taken into account) very critical