EU DEMO: Staged Design Approach

Gianfranco Federici, the PPPT PMU and Project Teams
Power Plant Physics and Technology

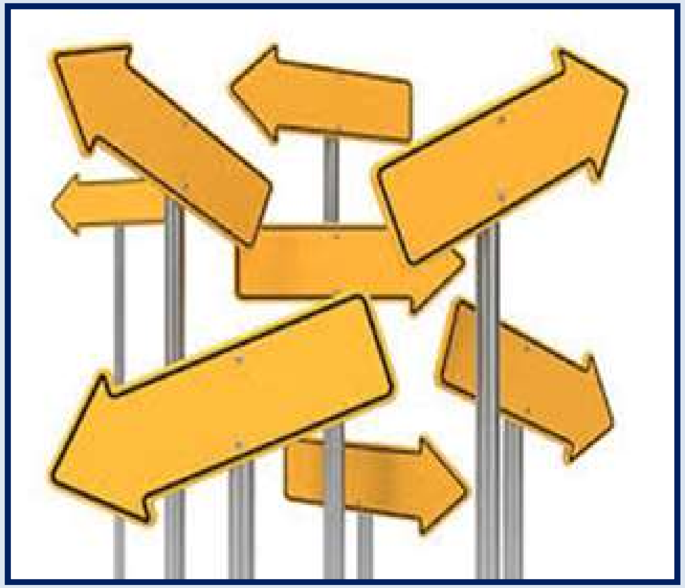
POWER PLANT PHYSICS & TECHNOLOGY DEPARTMENT

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.

Preamble

- Still divergence of opinions around the world on how to bridge the gaps to FPP
- EU Path to FE is based on a DEMOnstration Power Plant to follow ITER and operate > 2050
- However, there are outstanding issues common to any next major facility after ITER, whether a CTF, a Pilot Plant, a DEMO, or else:

→Work which we are doing in Europe can be (in large part) transferred to other 'architectures'.



Main design challenges

- Knowledge gaps in key reactor technologies (R&D)
- Design dealing with uncertainties (physics/ technology)
- High degree of complexity/system interdependencies
- Integration of design drivers across different systems

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→**Work which we are doing in Europe can be (in large part) transferred to other 'architectures'.**

- A lot of discussions about making **fusion smaller, cheaper, and faster**, but there is **no magic bullet to solve the integrated design problems**. Every time you squeeze somewhere, you make problems worse elsewhere….
- By postponing integration, assuming that it restricts innovation and inhibits an attractive DEMO plant, one risks to develop design solutions that cannot be integrated in practice.

Outline

- DEMO in the EU roadmap
- Lesson learnt
- Key design integration issues
- Highlights of technology achievements
- Industry/ International collaborations
- Outlook

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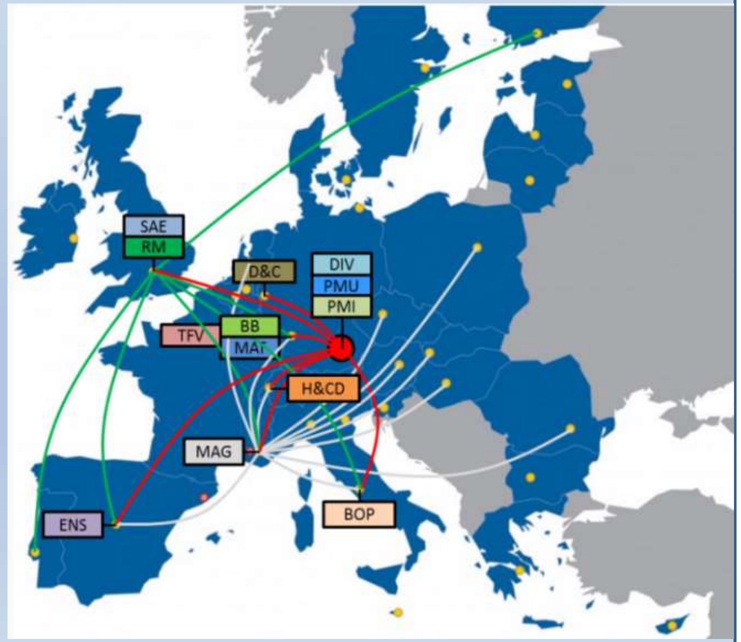


Acknowledgements

The PPPT PMU Team:
C. Bachmann, C. Baylard, S. Ciattaglia, F. Cismondi, E. Diegele, T. Franke, C. Gliss, T. Haertl, J. Holden (IPP), G. Keech, R. Kembleton, F. Maviglia, B. Meszaros, M. Siccinio, C. Vorpahl, H. Walden, H. Ebert (Framatome).

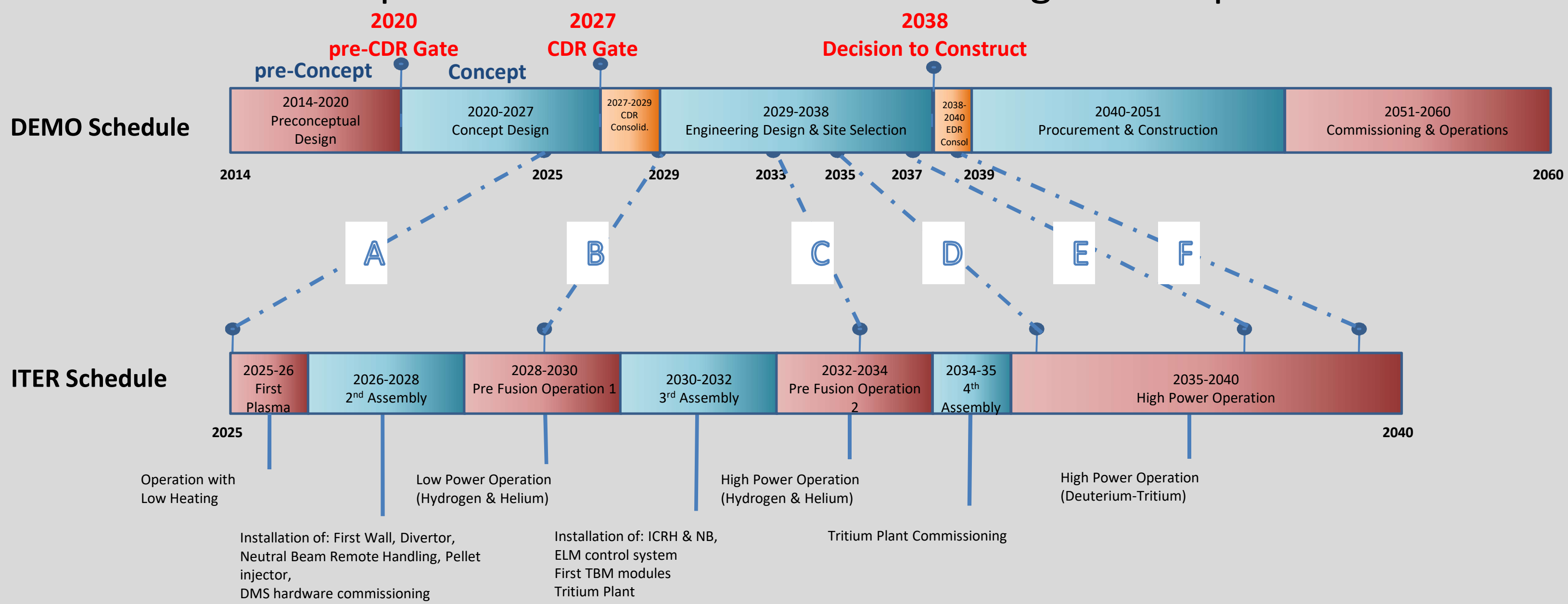
The PPPT Project Leaders:
L. Boccaccini (KIT), G. Pintsuk (FZJ), C. Day (KIT), W. Biel (FZJ), J-H. You (IPP), N. Taylor (CCFE), T. Loving (CCFE), V. Corato (ENEA), A. Ibarra (CIEMAT), M.Q. Tran (CRPP), L. Barucca (Ansaldo Nucleare), C. Bustreo (Consorzio RFX).

DEMO in the EU Roadmap

ITER is the crucial machine on which the validation of the DEMO physics and part of the technology basis depends

The DEMO staged-design approach relies on a progressive flow of validation input from ITER prior to start of DEMO construction

ITER developments of relevance to DEMO design - examples



A

Validated Assembly, Integrated Design, Testing & Commissioning, SC magnets, VV fabrication validation

B

Integrated diagnostics validation, ECRH performance, Disruption characterisation, Divertor remote maintenance validation

C

H-mode transition threshold, Validation of ELM control & disruption mitigation, NB & ICRH performance, Diagnostics validation, Validation of TBM fabrication

D

Burn scenarios, Bootstrap fraction, Full plasma control incl. He and impurities , First wall heat loads,, Exhaust at high power Tritium plant validation, H&CD and fuelling validation

E

TBM Validation, Operational scenario refinement, Q=10 (short pulse)

F

Long pulse) burning plasma

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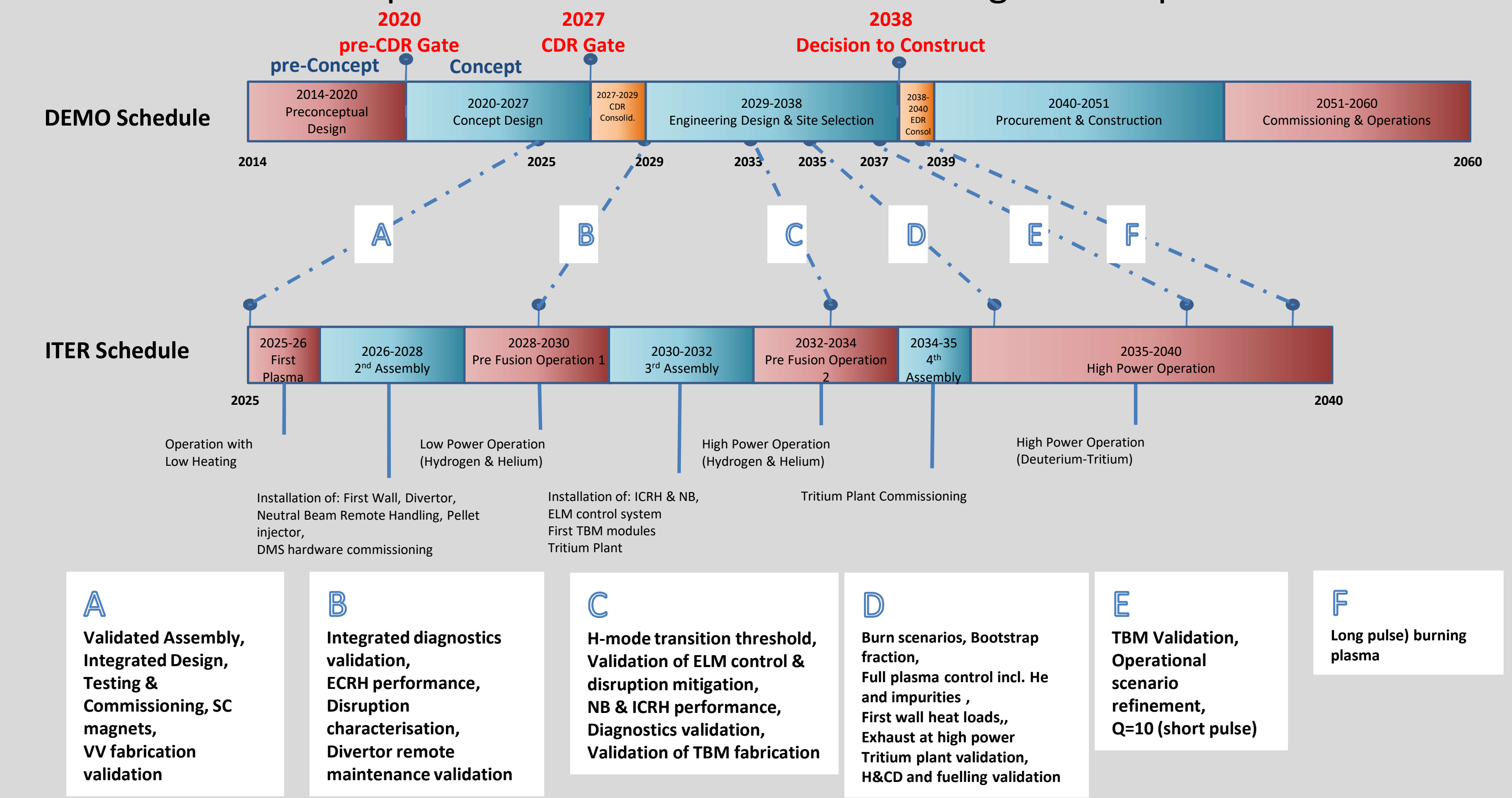


Key messages – pre-Concept Design Phase

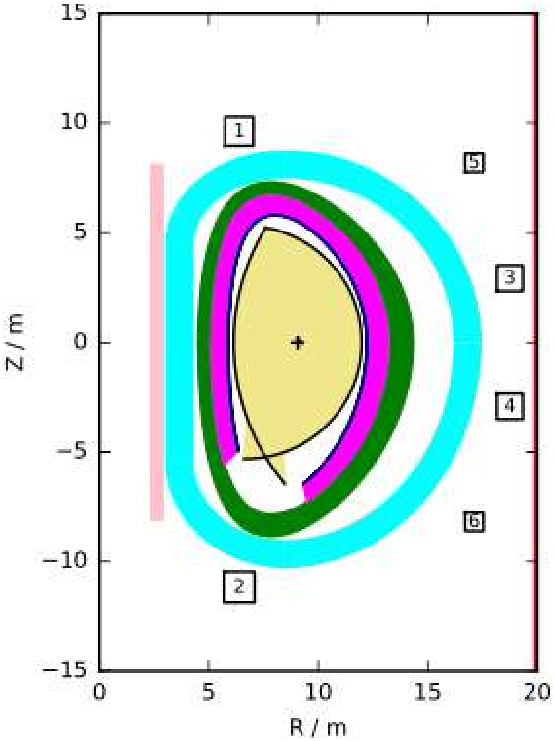
- At present, the **DEMO design has not been formally selected** and detailed operational requirements are still being developed.
- **Definition of DEMO HLRs** following interaction with **external stakeholder group** composed of experts from industry, utilities, grids, safety, licensing, etc.
- Frequent exchanges with **Gen IV fission and ITER to learn from their experience.**
- A **more systems-oriented approach** brought clarity to a # of critical design issues.
- **Early attention given to industrial feasibility, costs, nuclear safety and licensing**.
- **Staged design approach with formal Gate Reviews** (pre-CDR Gate 2020).
- Design readiness evaluation, together with a **technology maturation and down selection strategy** by embedding industry experience from the very beginning.
- **New strategy for the DEMO breeding blanket →** impact on the EU TBM Program: replace one of the two He-cooled (i.e., HCLL) with a water-cooled concept (WCLL).

DEMO design points under study*

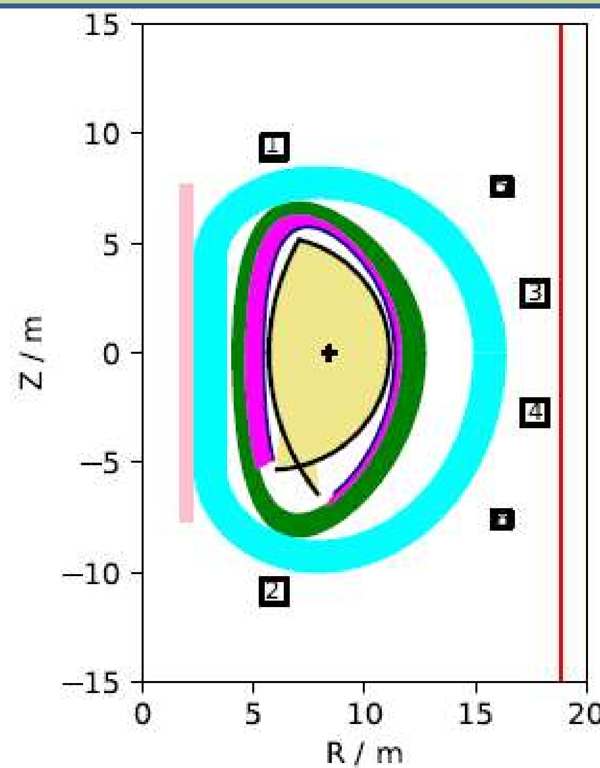
M. Siccinio et al. FIP/P7-1
H. Lux et al., FIP/P7-2

DEMO 1	Parameters	flexi-DEMO Lop(ind)	flexi-DEMO Hop(ss)
9, 2.9	R_0, a (m, m)	8.4, 2.71	8.4, 2.71
3.1	A	3.1	3.1
5.9	B_T,(T)	5.8	5.8
18, 3.6	Ip (MA), q	16.63, 4	14.17, 4.7
1.6, 0.33	k_{95} / δ_{95}	1.69, 0.33	1.69, 0.33
12.6	$\langle T_e \rangle$ (keV)	12.1	15.1
0.73	$\langle n_{e,vol} \rangle$ ($10^{20}m^{-3}$)	0.88	0.75
2.2	Z_{eff}	2.23	2.86
1.1	H	1.13	1.48
2	t_{burn} (hrs)	1	St. State
37	f_{bs} (%)	0.47	0.66
50	P_{aux} (MW)	>100	>100
161	P_{div} (MW)	165	194
120	P_{LH} (MW)	123	109
2014	P_{fus} (MW)	2000	2000
500	$P_{e,net}$ (MW)	395	399
1.0	Av_{NWL}(MW/m^2)	1.15	1.15

DEMO 1



flexi-DEMO



DEMO 1: a "**conservative baseline design**" i.e. a DEMO concept deliverable in the short to medium term, based on the expected performance of ITER with reasonable improvements in science and technology; i.e., a large, modest power density, long-pulse inductively supported plasma in a conventional plasma scenario.

*** Both machines assume Nb_3Sn superconductor. Physics performance, divertor heat loads, H&CD power are higher for flexi-DEMO. *H*-factors and energy confinement times are radiation corrected**

A flexi-DEMO: an "**optimistic design**", that operates in inductively driven pulsed regime, with the possibility to be upgraded to a longer-pulse or steady-state machine with a greater reliance on auxiliary current drive. This option requires confidence in physics extrapolation and highly-reliable and efficient H&CD systems.

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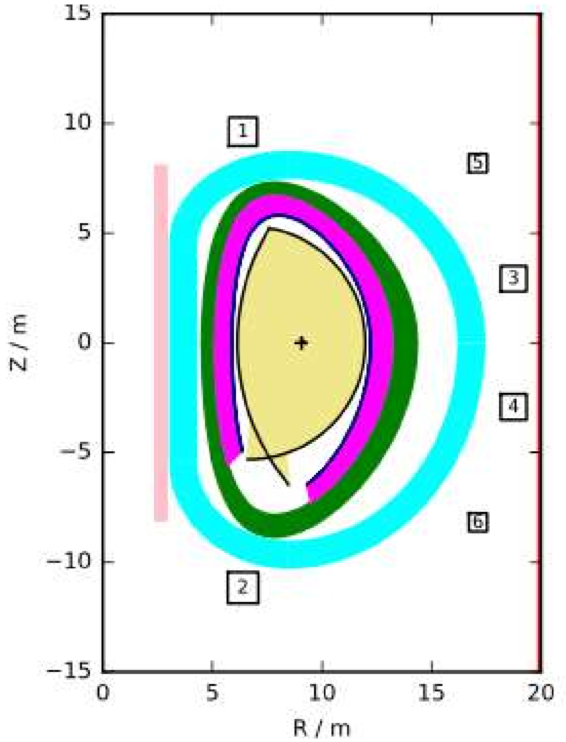

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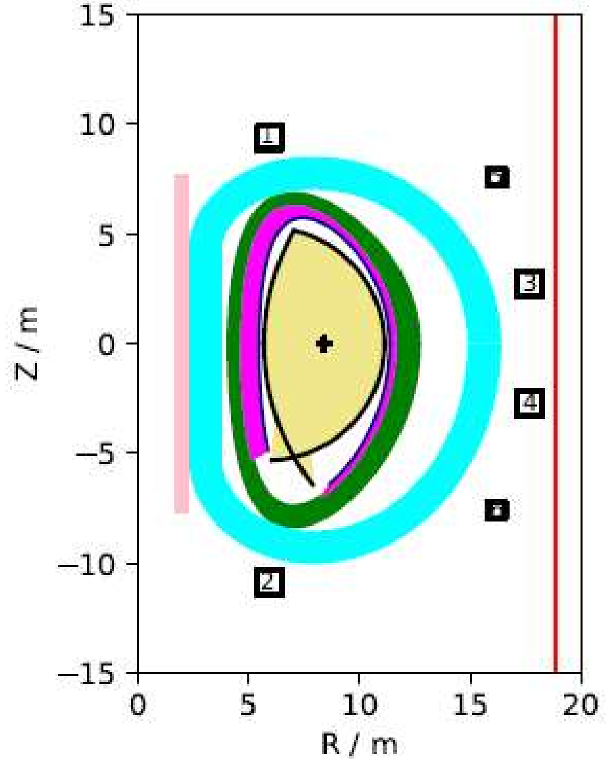

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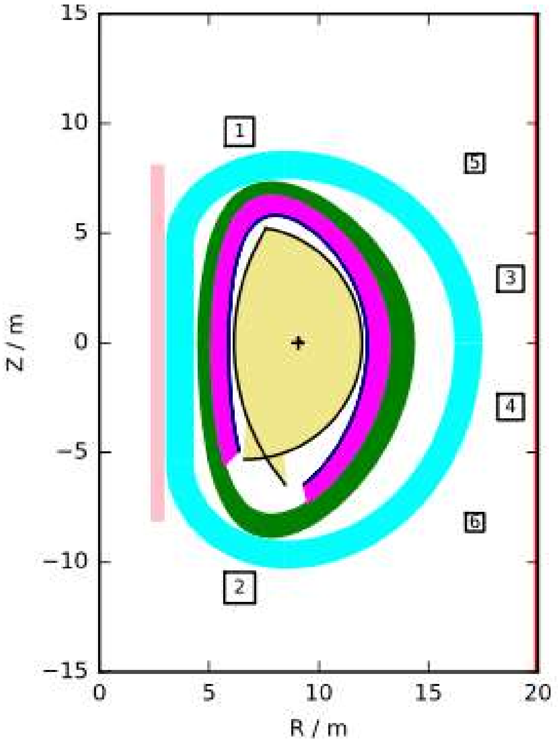

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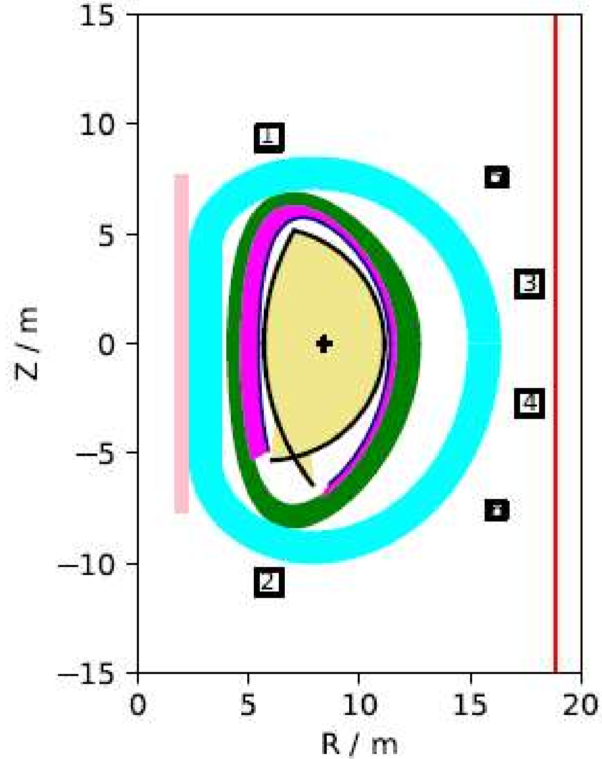

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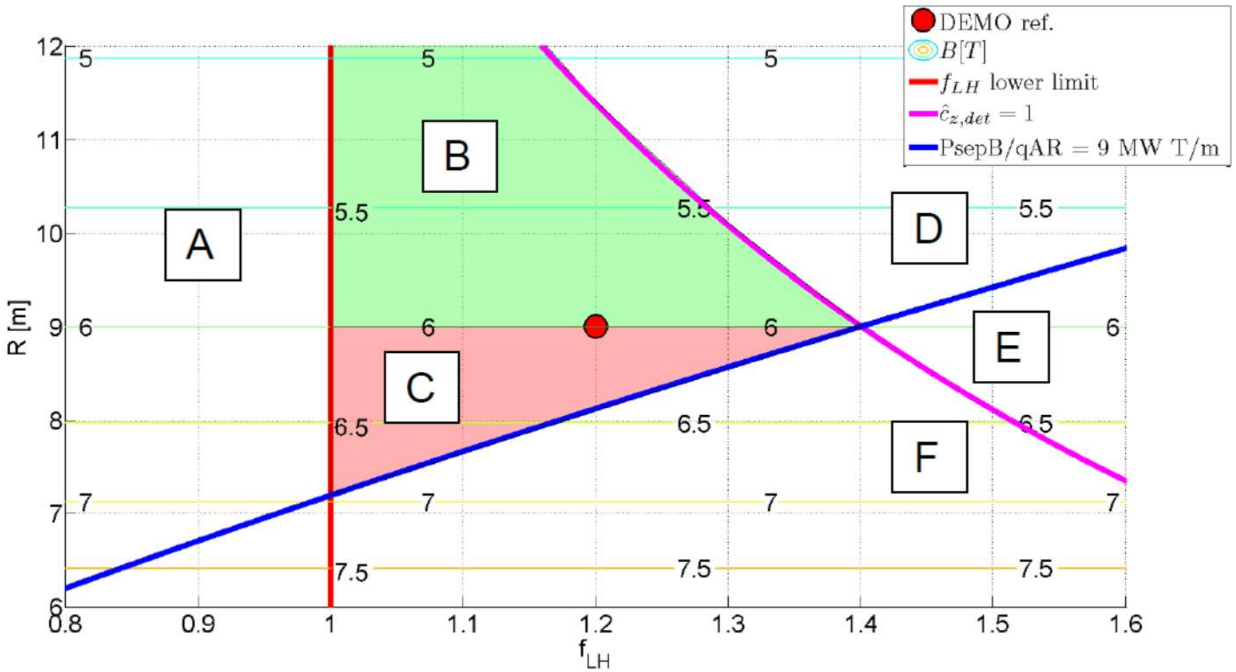
Divertor remains an important DEMO-size driver



[M. Siccinio et al., submitted to NF]

- **A**: ***unfeasible***, below L-H threshold
- **B**: ***feasible***
- **C**: ***feasible***, *if more compact magnetic technology were available*
- **D**: ***unfeasible***, too high imp. conc. for detachment
- **E**: ***unfeasible***, too high heat flux @ re-attachment and too high imp. conc. for detachment
- **F**: ***unfeasible***, too high heat flux @ re-attachment

- For a given fusion power level, the ***size of a reactor is limited in terms of R*** by the impurity concentration to reach detachment *[M. Reinke, NF 2017]* ***and in terms of B*** by the heat flux by re-attachment
- More in general, a compact, ***high field magnet technology*** would have ***limited impact on the machine size***

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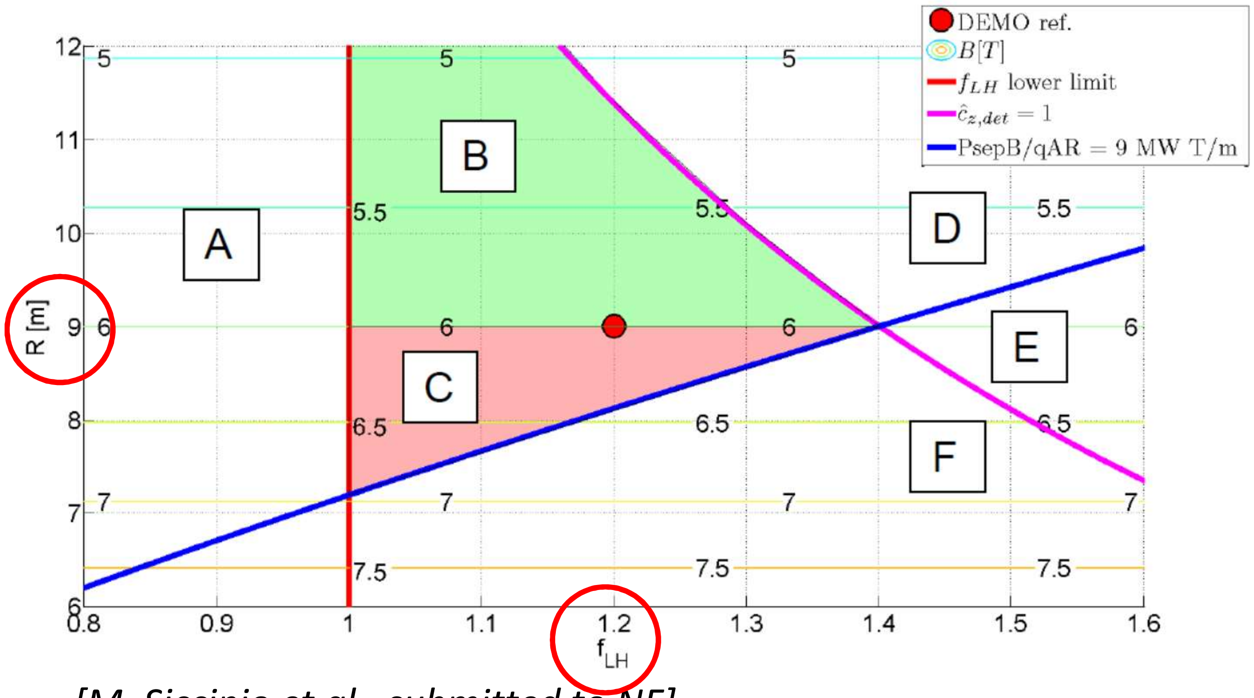

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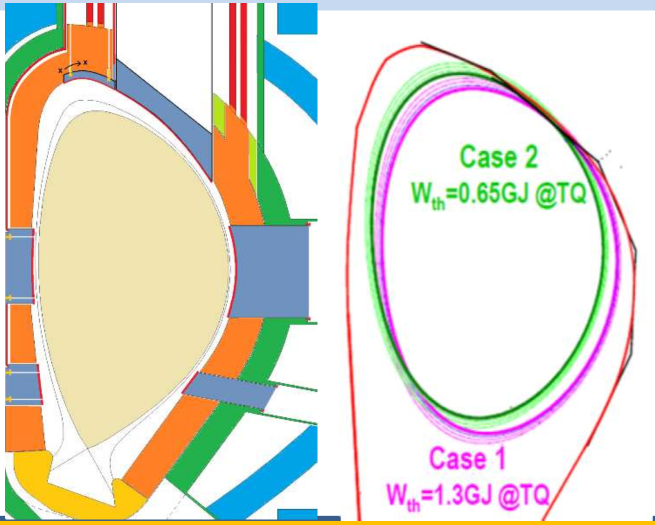
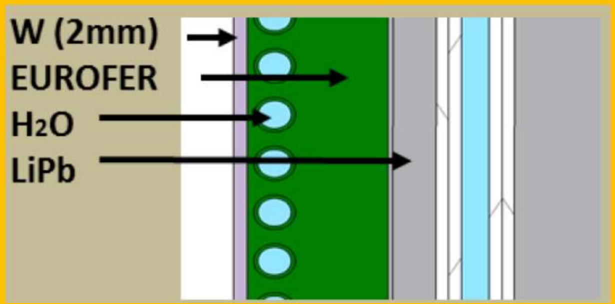
Key lessons learnt during the DEMO pre-CD phase

1) Still large plasma physics uncertainties that impact the design - Off-normal transients are a major design driver. DEMO requires dedicated protections in some areas



K. Keogh et al.
Fus. Eng. Des.

Schematic DEMO first wall



F. Maviglia, Fus. Eng. Des. 2018

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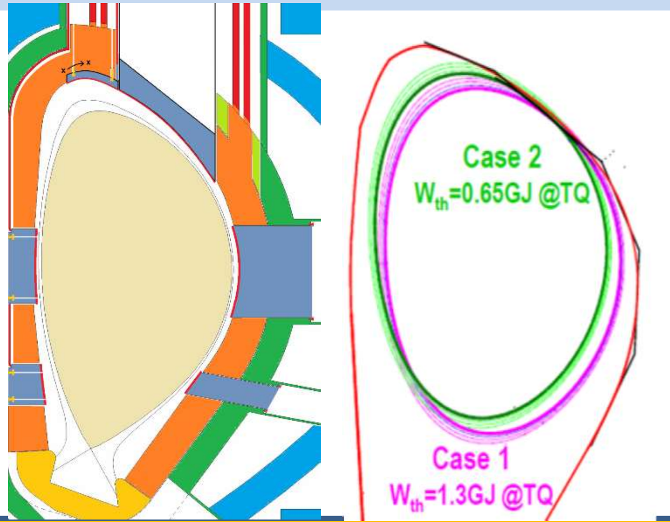

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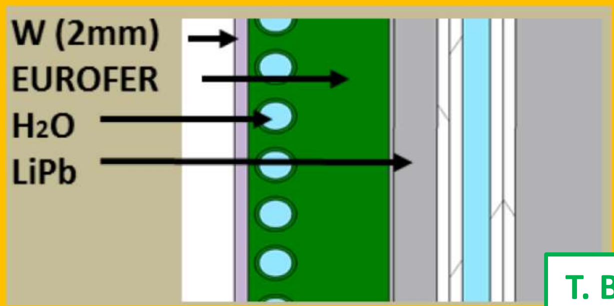

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T. Barret
FIP/2-2

2) Integration of multiple design drivers across different systems – Blanket vertical maintenance and coolant (LiPb) pipe routing

O. Crofts et al.
FIP/P7-33

Blanket Vertical Maintenance: Several poloidal segmentations and pipe routings investigated – tools developed

2017 Welding Tool Proof of Principle Detailed Design

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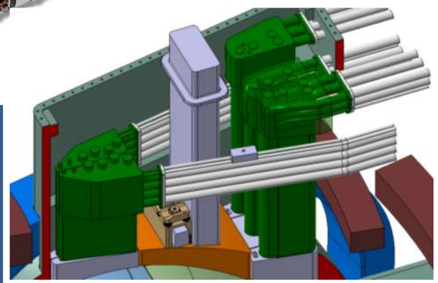

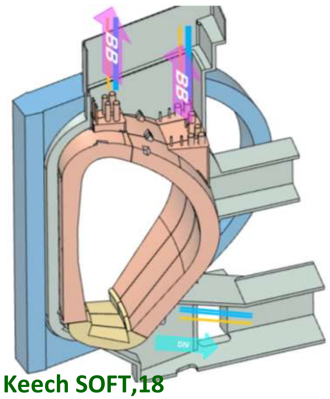

G. Keech SOFT,18

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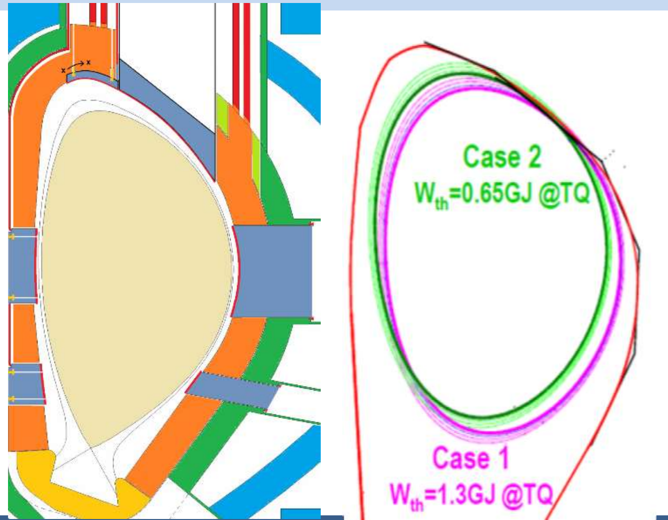

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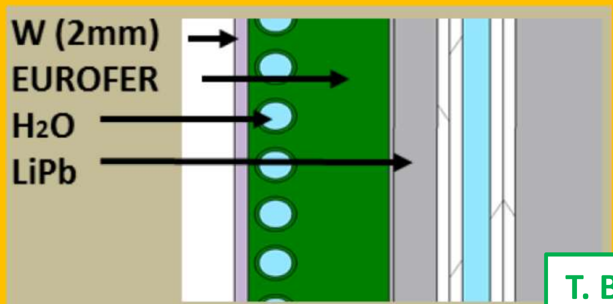

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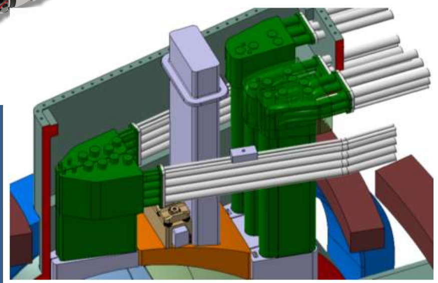

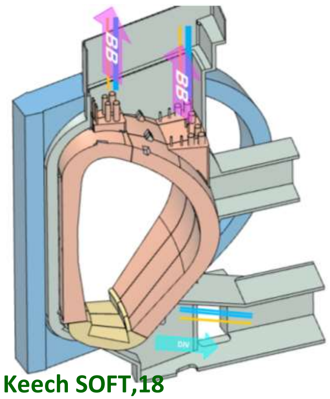

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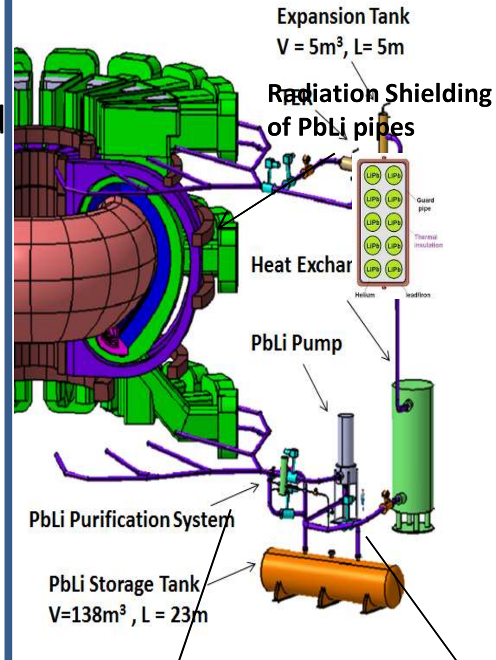

M. Utili et al. SOFT, Giardini Naxos

Removal of activation products

Gas saturator + cold trap

Key lessons learnt during the DEMO pre-CD phase

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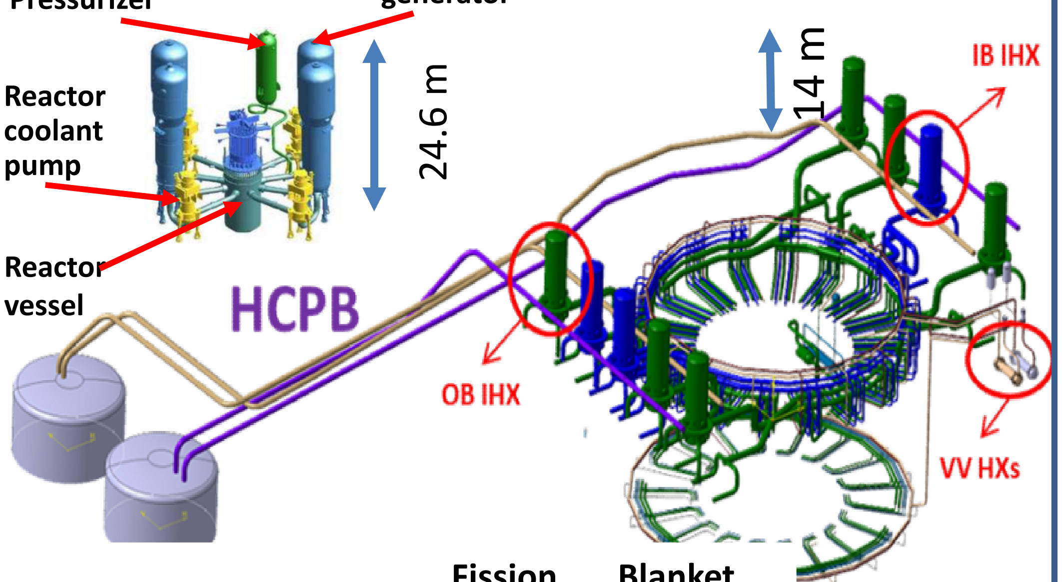
3) Many systems interdependencies and interfaces with key nuclear systems: PHTS

Significant differences: pipe lengths, coolant inventory, HeX surfaces, tritium.



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Coolant loops		4	9
Overall pipe length,	km	0.12	4
Coolant inv/loop	m^3	460	1940
Pipe diam	m	0.780	1.197
Volume ESS	m^3	0	6000
IHEX	m^2	-	87290

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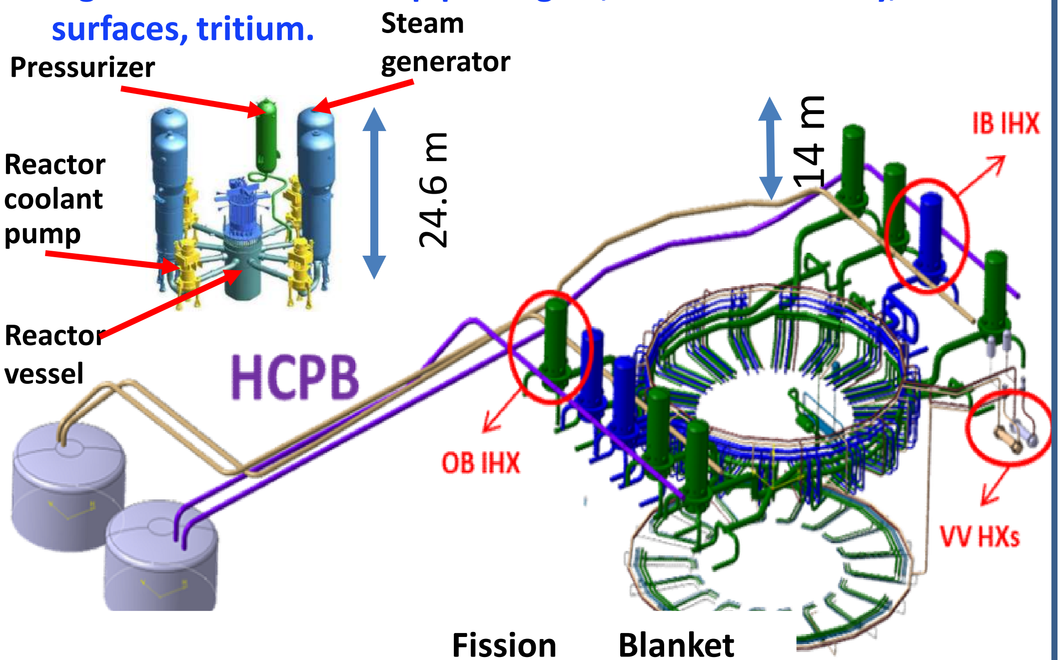

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4) Global new nuclear build - Lack of parallel development in areas of advanced BoP of nuclear systems and high temp. structural materials from fission industry

- ~450 reactors in 30 countries, providing some 14% of world's electricity
- ~60 new NPs under constr., in 4 countries
- Of those, majority in China, India, Russia.

EPR Flamanville

- Extensive regulatory oversight after Fukushima is responsible for significant cost increase of many of nuclear installations under construction (including ITER).
- Consolidation of design of Vendors.
- GEN IV development on gas systems has been halted and is difficult to predict significant developments in the near and medium term.

Key Design Integration Issues (KDIIs)

THE HATEFUL 8

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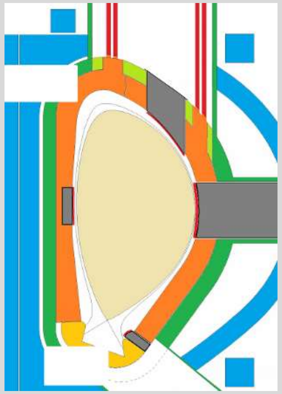
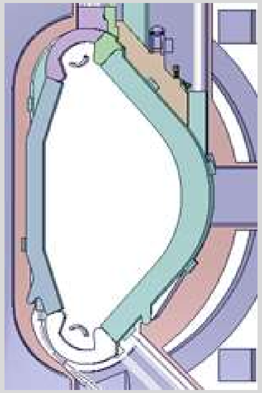
H1 - Wall protection from transients:
Design option with top limiters and DN divertor



SN with top and eq. limiters



DN

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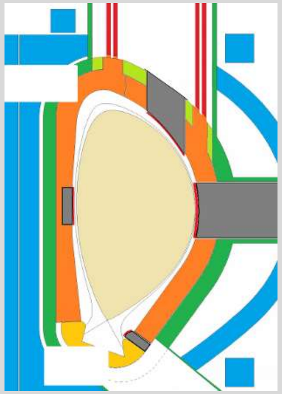

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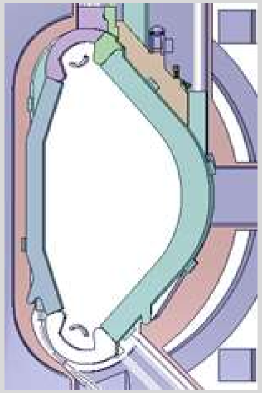
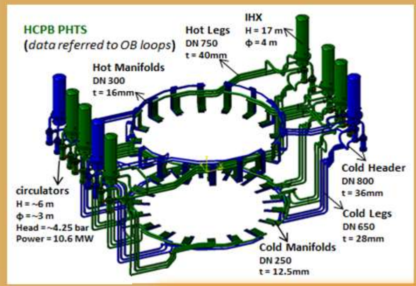


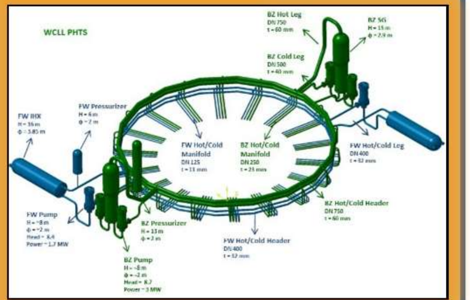
DN

H2 - Blanket PHTS and BoP: He and H_2O



Helium
300-500C, 80 bar

Water
292°C-328°C
150bar



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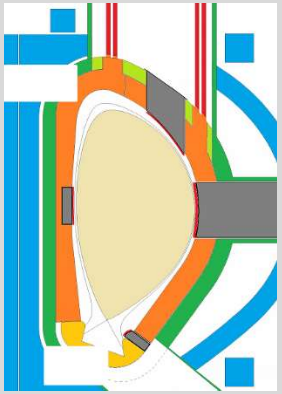
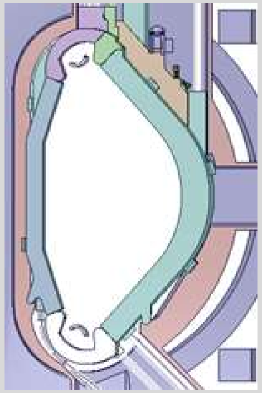
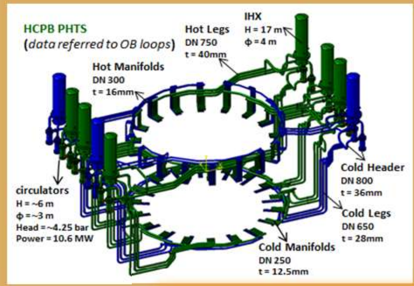


SN with top and eq. limiters



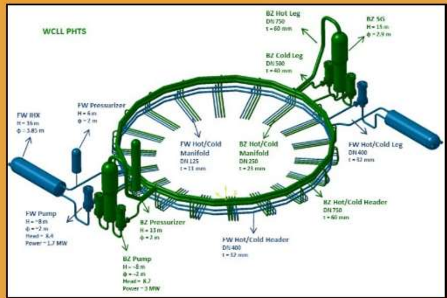
DN

H2 - Blanket PHTS and BoP: He and H_2O

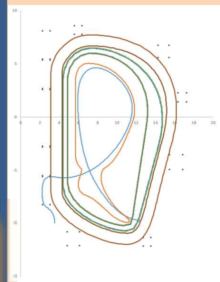


Helium
300-500C, 80 bar

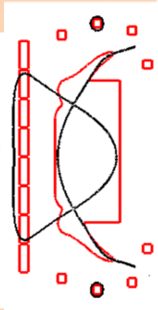
Water
292°C-328°C
150bar



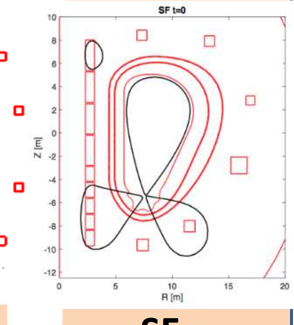
H3- Advanced divertors: engineering and design Integration risks



SX



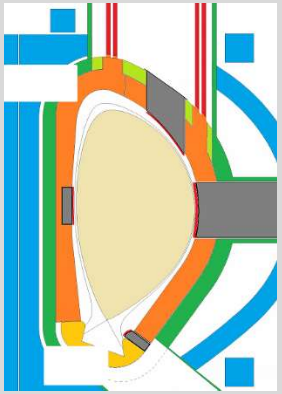
DN-SX



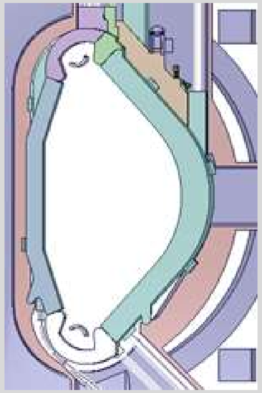
SF

Key Design Integration Issues (KDIIs)

H1 - Wall protection from transients:
Design option with top limiters and DN divertor



SN with top and eq. limiters



DN

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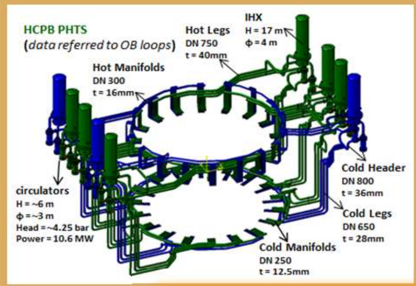

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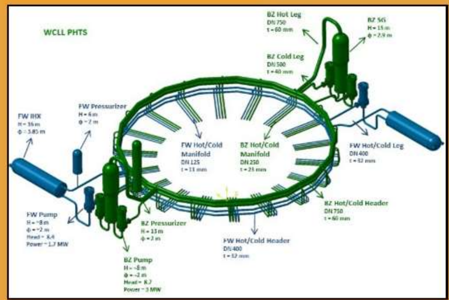

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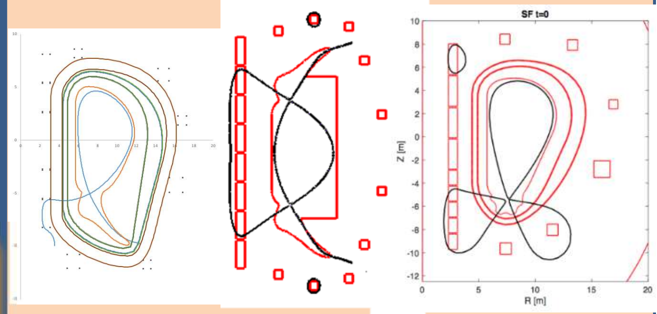
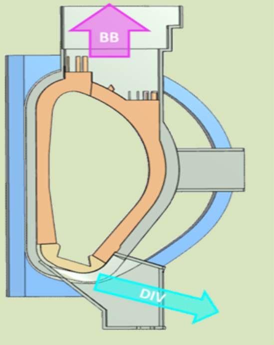
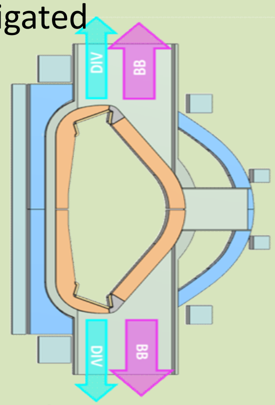


SX **DN-SX** **SF**

H4 - Blanket Vertical Maintenance:
Several poloidal segmentations and pipe routings investigated



1.) Full Blanket Segment Single Null



2.) Equatorial Split Blanket Double Null

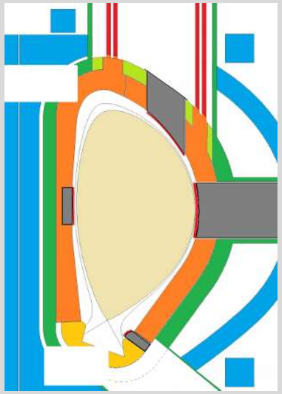
G. Keech, SOFT 2018

Key Design Integration Issues (KDIIs)

THE HATEFUL 8

H1 - Wall protection from transients:

Design option with top limiters and DN divertor



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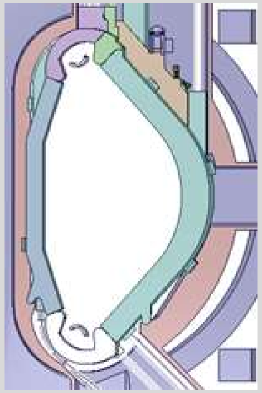

DN

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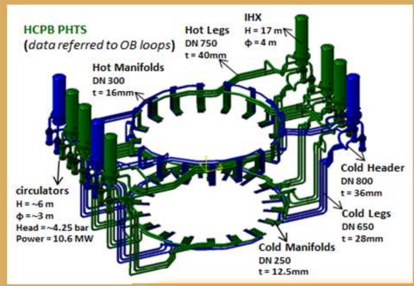

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300-500C, 80 bar

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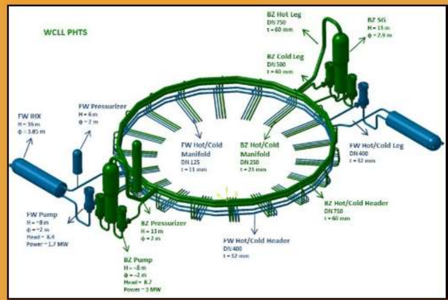

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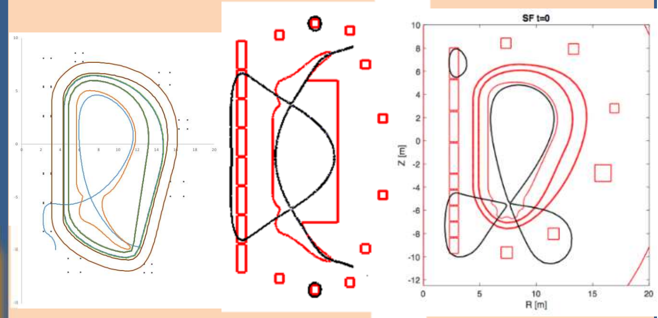
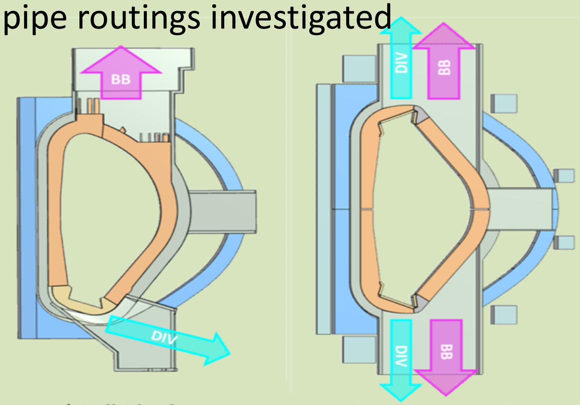


SX DN-SX SF

H4 - Blanket Vertical Maintenance:

Several poloidal segmentations and pipe routings investigated



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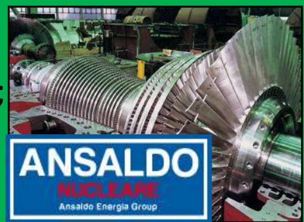
G. Keech, SOFT 2018

H5 - PCS options, i.e., direct or indirect

Two options: 1) indirect with ESS; 2) direct or very small ESS



Key Design Integration Issues (KDIIs)

THE HATEFUL 8

H1 - Wall protection from transients:
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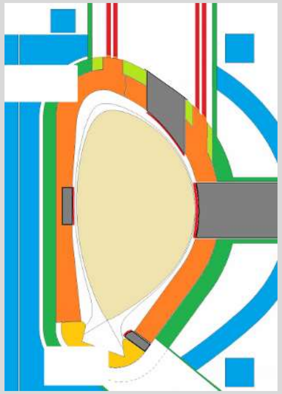

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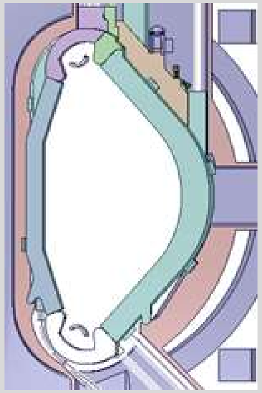

DN

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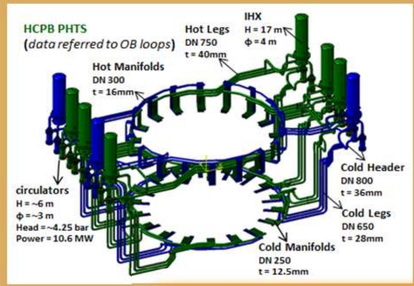

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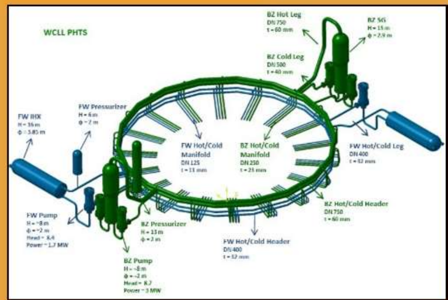

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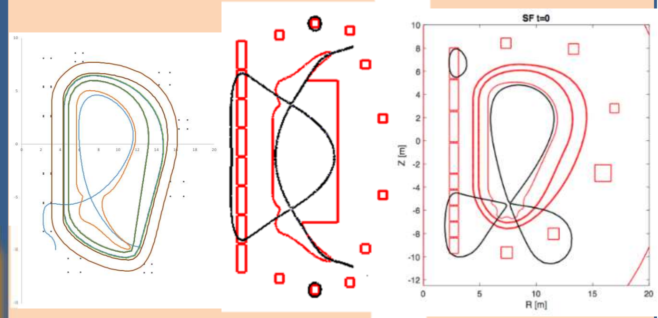
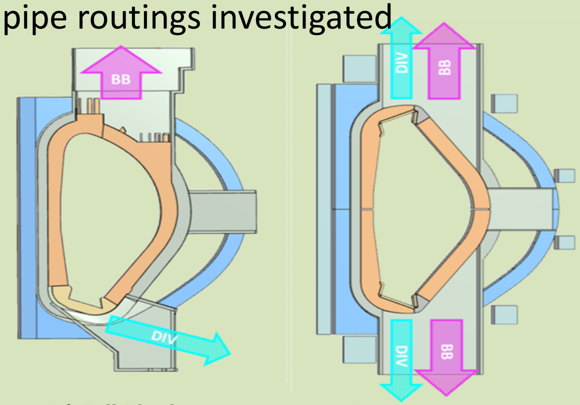


SX **DN-SX** **SF**

H6 - Design nuclear building concepts incl. ex-vessel RM

H4 - Blanket Vertical Maintenance:
Several poloidal segmentations and pipe routings investigated



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G. Keech, SOFT 2018

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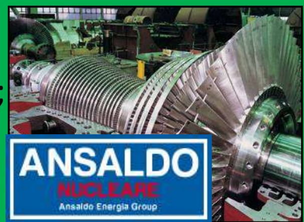
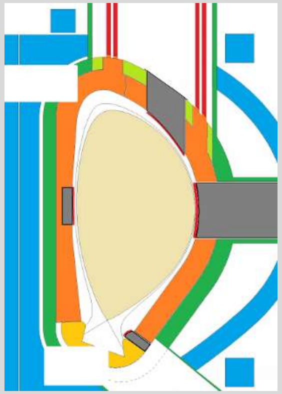
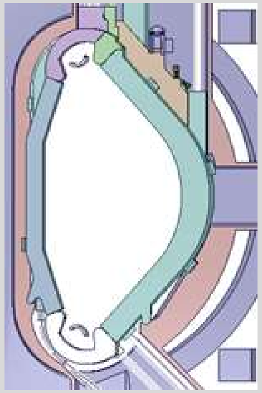


Key Design Integration Issues (KDIIs)

THE HATEFUL 8

H1 - Wall protection from transients: Design option with top limiters and DN divertor





SN with top and eq. limiters **DN**

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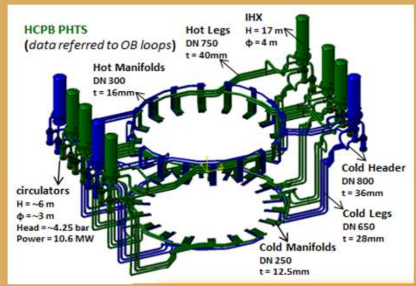

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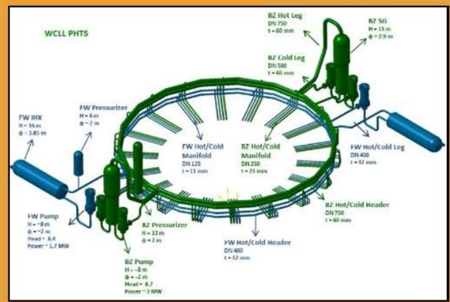

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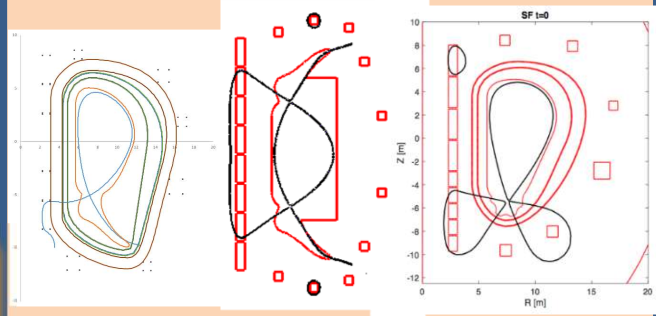

SX **DN-SX** **SF**

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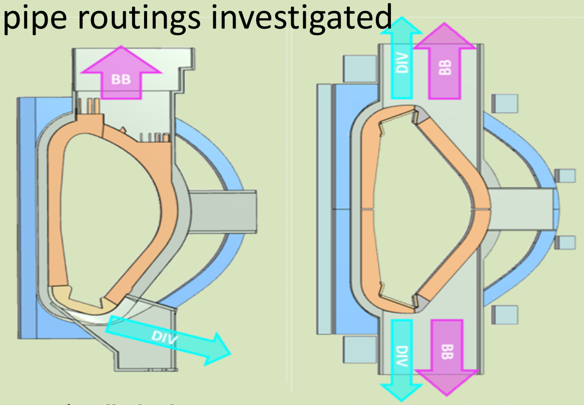

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G. Keech, SOFT 2018

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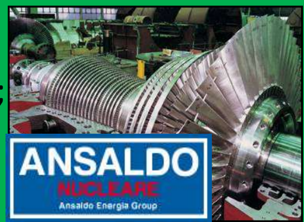
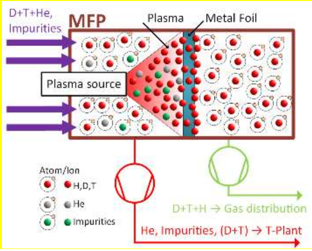
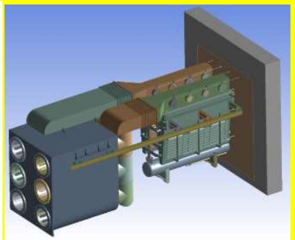


H7 - Feasibility of tritium cycle concept with direct recirculation



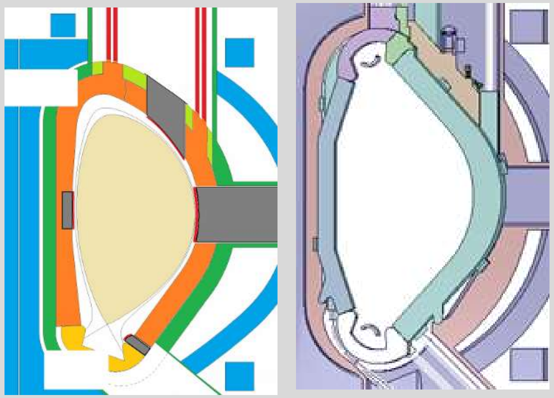


Key Design Integration Issues (KDIIs)

THE HATEFUL 8

H1 - Wall protection from transients:

Design option with top limiters and DN divertor



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DN

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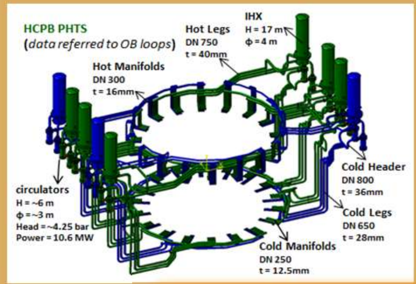

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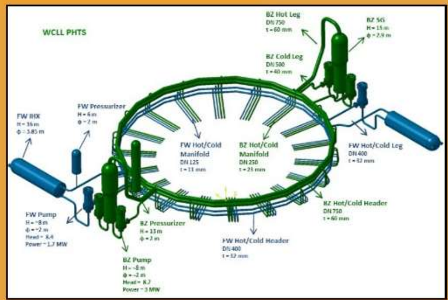

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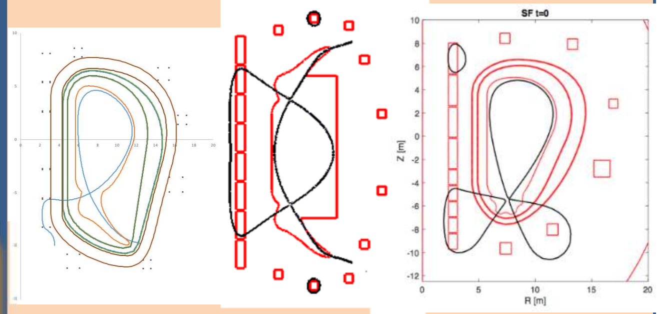

SX DN-SX SF

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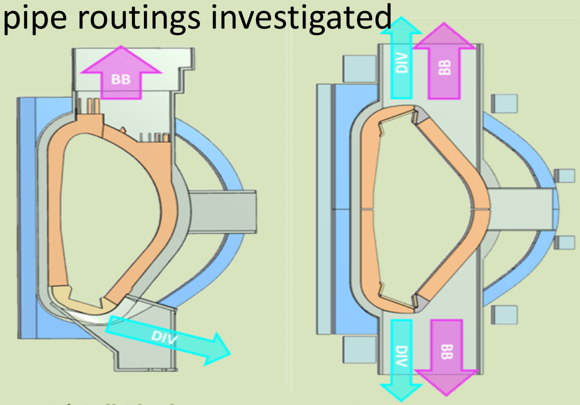

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G. Keech, SOFT 2018

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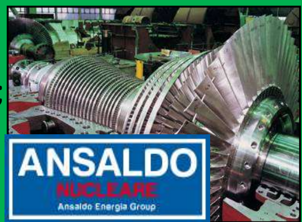
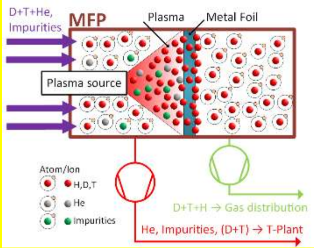


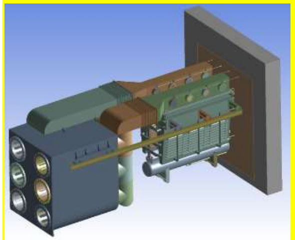
ANSALDO NUCLEARE Ansaldo Energia Group

H6 - Design nuclear building concepts incl. ex-vessel RM

framatome

H7 - Feasibility of tritium cycle concept with direct recirculation





H8 - Plasma operating scenario and supporting HCD and Diagnostic systems

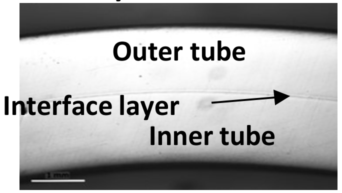
Divertor: Inter-ELMs loads
- ✓Divertor detachment
- ✓Loss of detachment

ELMs
- ✓Active control
- ✓ELM-free scenarios and their consequences

Highlights Technology Achievements

DEMO Blanket Manufacturing

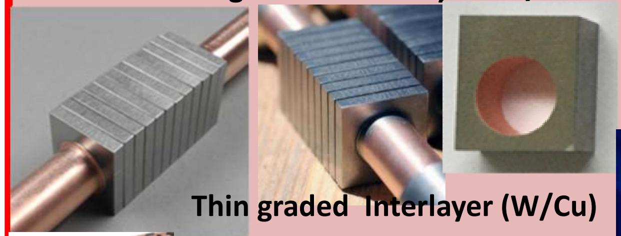
Fabrication of DWT (Double Wall Tube)



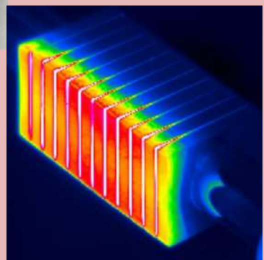
L. Forest et al., SOFT2018

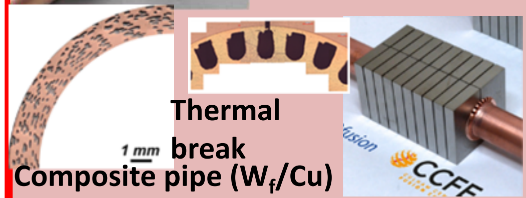
Technology R&D for HHF PFCs

- Study improvements of ITER technology
- Mock-up fabrication
- HHF testing reached 100 cycles up to 20 MW/m^2



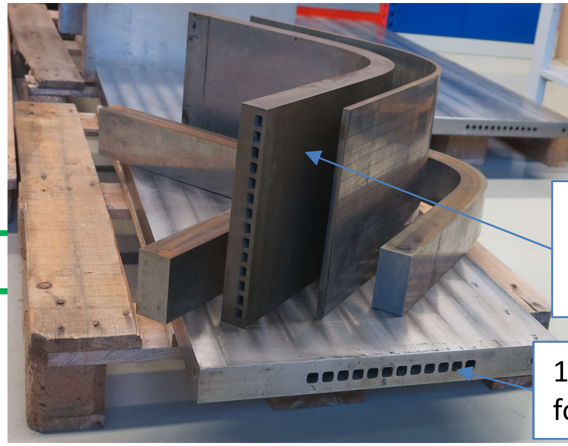
100th cycle





Electrical Discharge Machining / Forming / Machining

H. Neuberger (SOFT 2018)
C. Koehly (SOFT 2018)



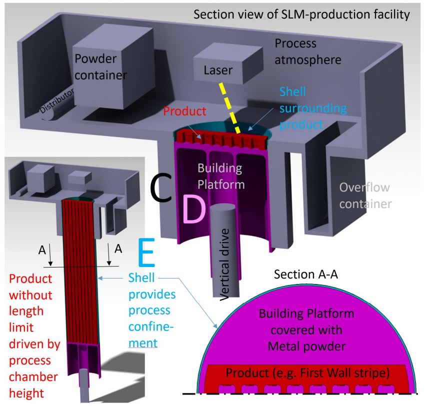
900 mm / 14 channels / 90 ° bend / externally machined by wire cutting

1600 mm / 12 channels / forming 2 x 90 ° in 2019

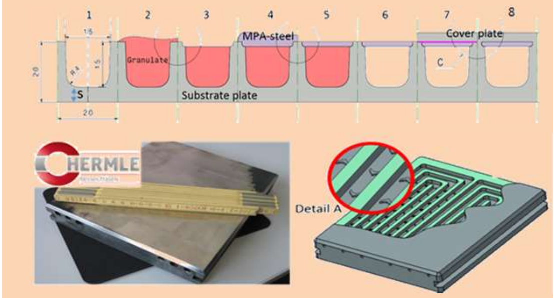
Innovative routines based on Additive Manufacturing

Selective Laser Melting

Concept for continuous production by SLM e.g. for fabrication of First Wall panels or Divertor components



Metal Powder Application & machining



HCPB SLM parts, examples

Knowledge exchange with ITER

Valuable lessons learnt and technical insights directly informing DEMO tasks

- ✓ Ad-hoc technical meetings with ITER Design Integration Teams.
- ✓ Training of some Engineering Grants in part in ITER IO.
- ✓ ITER IO (and F4E) experts attend DEMO design reviews.

Main topics include:

- Tokamak building design
- Plant layout
- Systems engineering
- Neutron shielding concept
- Port plug port integration and RH
- In-cryostat maintenance
- Thermal shield design
- Design of magnet feeders
- VV cooling Loop
- Diagnostics integration

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Industrial Involvement

- **Project / Program Management**
- **Plant Architect Engineering: Systems Engineering and Design Integration**
- **Cost, risk, safety and RAMI analysis**
- **Evaluation of design alternatives**
- **Plant engineering tools, modelling and simulation**
- **TRL MRL, assessment, etc.**
- **Design for robustness and manufacture of critical components/systems;**
- **design simplification/ low fabrication costs**

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Architect engineering studies support
Evaluation and selection of design alternatives

Fusion Industry Innovation Forum FIIF

AIRBUS **System Engineering Training**

ANSALDO NUCLEARE, Kraftanlagen Gruppe, SIEMENS

Design studies BOP/PCS Fortum

MAN **Design simplification and robustness of critical components such as vacuum vessel; reduced fabrication costs**

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International Collaborations

- **Japan (Broader Approach) IFERC**
  - ✓ joint DEMO Design Activities (DDA) to address most critical DEMO design issues
- **China:**
  - ✓ DEMO/ CFETR joint technical meetings
  - ✓ Breeding blanket R&D
  - ✓ HTS design
  - ✓ Remote Handling
- **UCLA (LiPb flows) + Design criteria**
  - ✓ upgrade and use of existing MaPLE facility, WCLL, DCLL.
- **Fission Reactor Irradiation Experiment HFIR (ORNL)**
  - ✓ Collaborations to use non-EU MTRs for high fluence irrad.

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- **Cost, risk, safety and RAMI analysis**
- **Evaluation of design alternatives**
- **Plant engineering tools, modelling and simulation**
- **TRL MRL, assessment, etc.**
- **Design for robustness and manufacture of critical components/systems;**
- **design simplification/ low fabrication costs**

framatome

Architect engineering studies support
Evaluation and selection of design alternatives

Fusion Industry Innovation Forum FIIF

AIRBUS **System Engineering Training**

ANSALDO NUCLEARE, Kraftanlagen Gruppe, SIEMENS

Design studies BOP/PCS Fortum

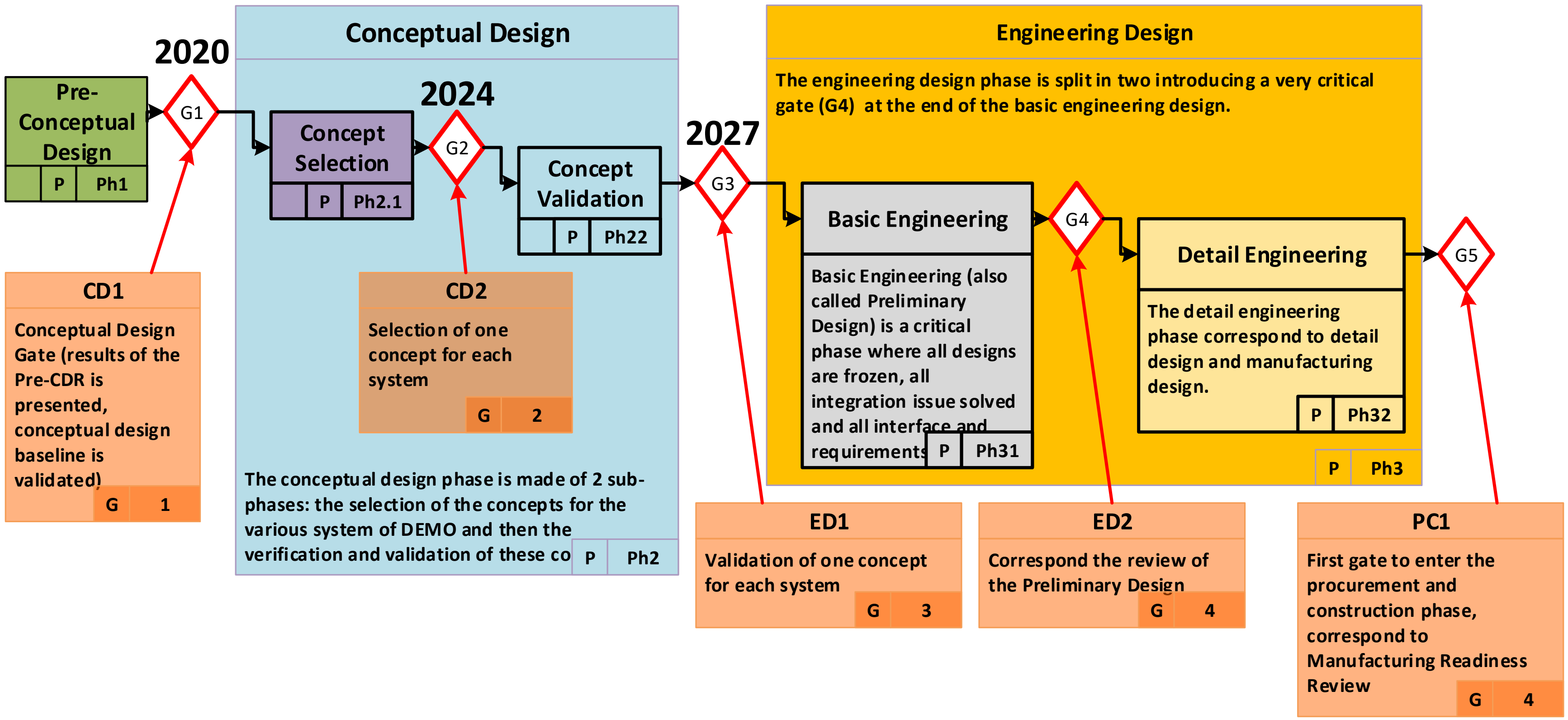
MAN **Design simplification and robustness of critical components such as vacuum vessel; reduced fabrication costs**

International Collaborations

- **Japan (Broader Approach) IFERC**
  - ✓ joint DEMO Design Activities (DDA) to address most critical DEMO design issues
- **China:**
  - ✓ DEMO/ CFETR joint technical meetings
  - ✓ Breeding blanket R&D
  - ✓ HTS design
  - ✓ Remote Handling
- **UCLA (LiPb flows) + Design criteria**
  - ✓ upgrade and use of existing MaPLE facility, WCLL, DCLL.
- **Fission Reactor Irradiation Experiment HFIR (ORNL)**
  - ✓ Collaborations to use non-EU MTRs for high fluence irrad.

Delaying the undertaking of DEMO Engineering Design too far beyond the end of construction of ITER will risk dissipating and losing this experience and interest of Industry

Outlook



Strong emphasis on study of systems integration aspects and a structured and traceable assessment methodology where design options/technologies are evaluated and down-selected through the implementation of Gate Reviews


Thank you!