EU DEMO Design and R&D Activities: Progress and Updates

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Power Plant Physics and Technology

Special thanks for preparing this talk go to H. Zohm, R. Kembleton, M. Siccinio

EUROfusion
POWER PLANT PHYSICS &
TECHNOLOGY DEPARTMENT

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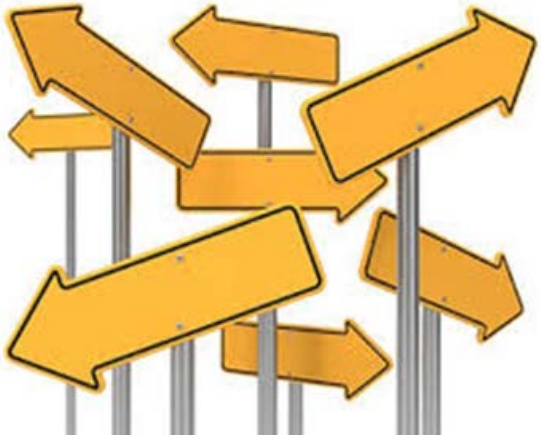
Preamble



- **EU Path to FE is based on a DEMOnstration Power Plant to follow ITER**
- **Still divergence of opinions around the world on how to bridge the gaps to FPP**
- **However, there are outstanding issues common to any next major facility after ITER, whether a CTF, a Pilot Plant, a DEMO, or else:**
  - ✓ *Power exhaust (divertor)*
  - ✓ *Operating plasma scenario ⇒ CD requirements,*
  - ✓ *T-breeding, cooling and extraction of heat from breeding blanket*
  - ✓ *Maintenance scheme ⇒ plant architecture*
  - ✓ *Structural and PFC materials*

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

Previous Meetings with International Fusion Community

International Workshop on Magnetic Fusion Energy (MFE) Roadmapping in the ITER Era; 7–10 September 2011, Princeton, NJ, USA

- **Perspectives on DEMO and the roadmap to DEMO**
- **Magnetic configurations and operating modes (***Tokamals and Stellarators)*
- **Physics-technology integration and optimization**
  - *System performance models*
  - *Steady-state heating and current drive (H and CD)*
  - *Diagnostics and integrated control*
  - *High density operation and fuel cycle*
  - *Plasma power exhaust scenarios*
- **Technology: basis, gaps, risks and facility needs**
  - *Plasma power exhaust technology*
  - *Materials*
  - *RAMI of core components*
- **Major facilities on the path to DEMO**
  - *ITER and existing facilities*
  - *DEMO divertor test bed*
  - *14 MeV neutron irradiation facilities*
  - *Next-step fusion nuclear facility*

G.H. Neilson, G. Federici, J. Li, D. Maisonnier and R. Wolf, *Summary of the International Workshop on Magnetic Fusion Energy (MFE) Roadmapping in the ITER Era*; 7–10 September 2011, Princeton, NJ, USA, **Nucl. Fusion 52 (2012) 047001 (11pp).**

Outline

- ***The context:*** **DEMO in the EU Roadmap**
  - ❖ Technical mission and scope
  - ❖ Timeline considerations
- ***The approach:*** **DEMO-staged Design Approach**
  - ❖ Organisation of DEMO design and R&D activities
  - ❖ Staged design approach and Technical targets
  - ❖ Key messages
- ***The ideas:*** **Design Choices under Considerations**
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Technical Mission and Scope

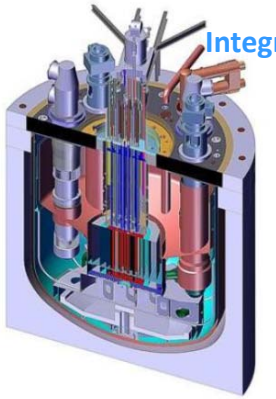
Mission Requirements

EU DEMO Mission Requirements agreed with DEMO External Stakeholders (e.g., industry, utilities, grids, safety, licensing, funding bodies)

- DEMO Net electricity (~500 MWe)
- Makes its own fuel (TBR > 1)
- Reliable operation
- Reasonable availability
- Allow extrapolation to a FPP

Meetings with GENIV Fission projects to gain insight into Project execution strategies

ASTRID: SFR Prototype GEN-IV



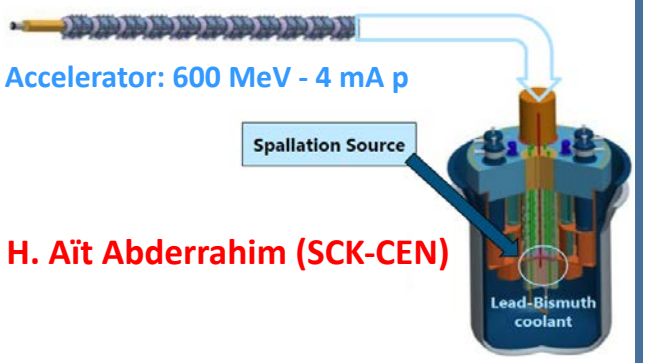
Integrated Technology Demostrator 600 MWe

F. Gauche (CEA)

MYRRHA: ADS

65 to 100 MW_{th}

Flexible irradiation facility

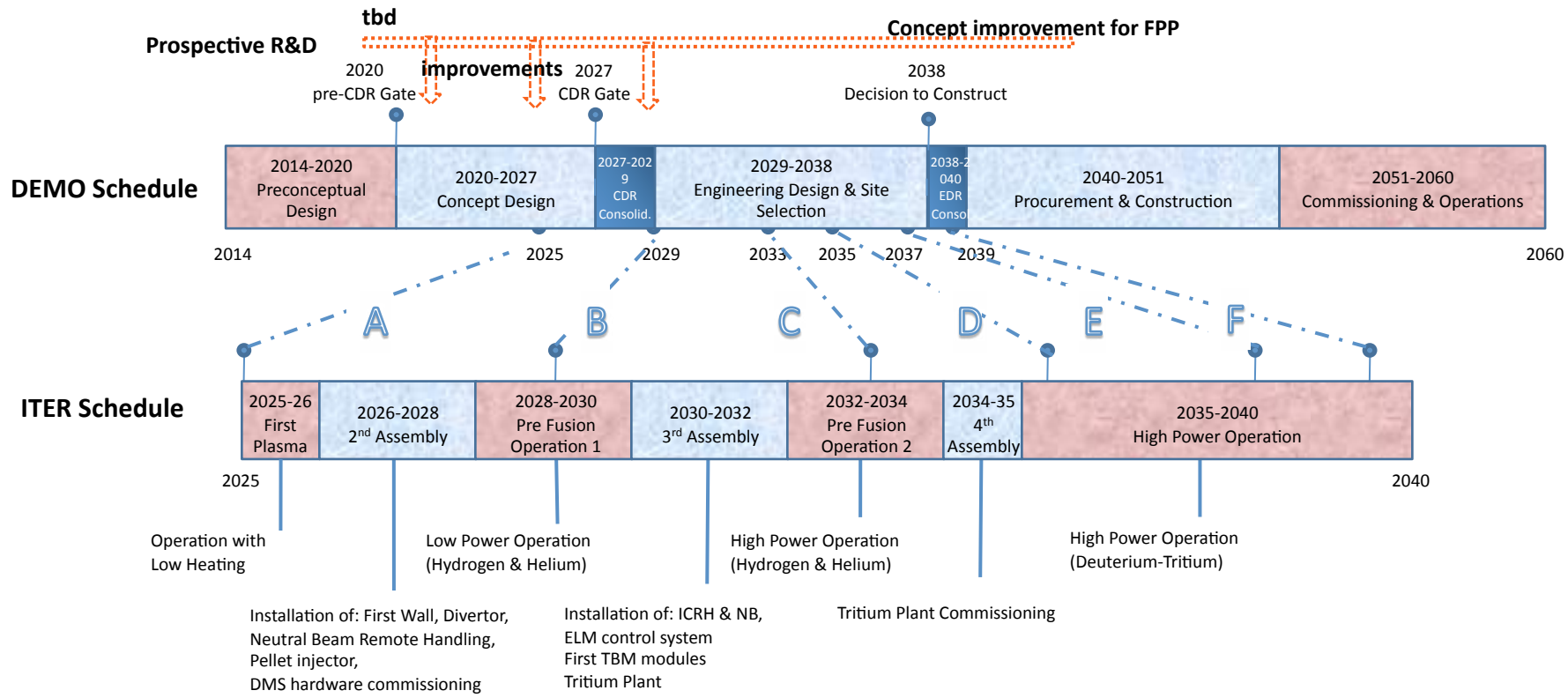


H. Aït Abderrahim (SCK-CEN)

- Fission projects follow pattern of evolution in each successive plant, ASTRID drawing from SuperPhenix, MYRRHA maturing from extensive test bed development.
- **Design should drive R&D** and not other way around.
- **Fusion** is a nuclear technology and as such **will be assessed with full nuclear scrutiny by a regulator**.
- **Traceable design process** with rigorous **SE approach**.
- Emphasis should be on **maintaining proven design features** (e.g., use **mature technology**) to **minimize risks**.
- **Safety, reliability and maintainability** should be **key drivers**: allow for design margins as well as redundancy within systems to ensure more fault tolerant design.
- Gen IV has leveraged **impressive industry support**.

Timeline Considerations: Important Role of ITER

The driver is to be ready for DEMO construction when ITER succeeds, and some of the design decisions are driven by this 'urgency'. With much longer timescales and resources, improvements for more attractive designs are conceivable. In the future, two branches of the PPPT (1) DEMO Design Project; 2) Prospective R&D. Only 1 is discussed here.



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 BB fabrication

D
Burn scenarios,
bootstrap fraction,
First wall heat loads,
tritium plant validation,
Full H&CD validation

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

F
Q=10 (long pulse)

PPPT – Knowledge Exchange With ITER

A huge wealth of valuable lessons learnt and technical insights are gained that are directly informing DEMO tasks

- Ad-hoc technical exchange meetings between PPPT and ITER Design Integration Teams.
- Engineering Grants spend some training in ITER IO.
- ITER IO (and F4E) experts invited to attend DEMO Work Packages design reviews.

Main topics covered include:

- Tokamak building design
- Plant layout
- Systems Engineering
- Neutron shielding concept
- In-cryostat maintenance
- Port plug port integration and maintenance
- Project Management
- Thermal Shield Design
- Cryostat Bellows Design
- Design of magnet feeders
- VV Cooling Loop
- Diagnostics integration

Delaying the undertaking of DEMO Engineering Design to far beyond the Design and Construction of ITER will risk dissipating and losing this wealth of Experience.

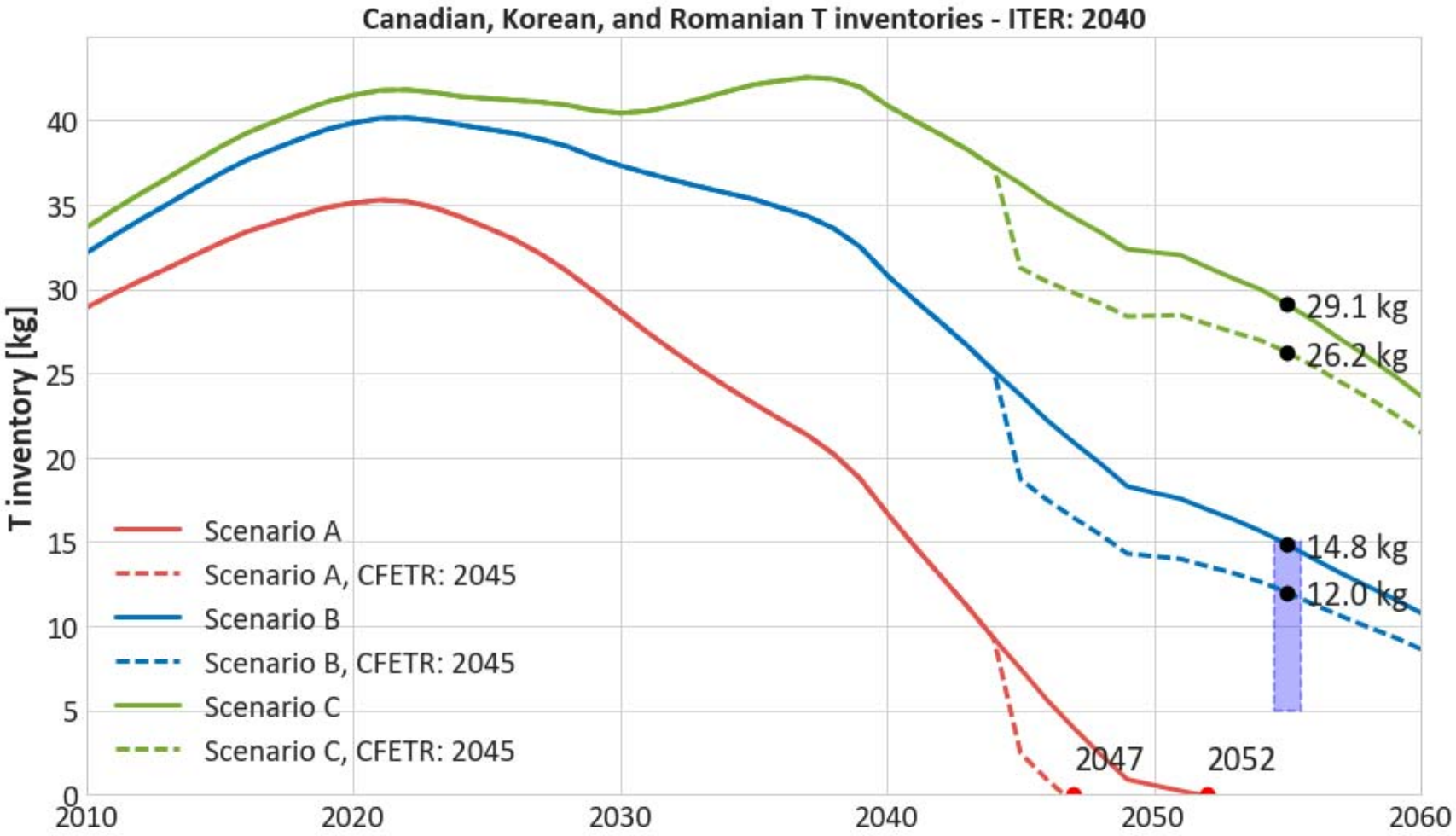
External Constraints: Framing the Program When?

Fusion Design and Engineering expertise is scarce and keeps getting scarcer

- Over the next few decades, not many nuclear reactors being built:
  - 60 new fission plants being constructed today, majority in China, India, Russia. Unfavorable future prospects in many Countries. Consolidation of vendors.
  - Only a handful of nuclear fusion reactors will exist and operate in the next 30 years: ITER and probably the Chinese Fusion Engineering Test Reactor (CFETR).
- An entire generation of engineers will have brought ITER to fruition, and if the DEMO EDA starts too long after ITER is delivered this highly skilled and experienced workforce will be lost to other industries. **Brain Drain and loss of lessons learned!**
- A large gap from the end of construction and assembly of ITER to the Engineering Phase of DEMO would lead to the **loss of industrial interest and expertise that is critical to DEMO**.

Over time, fusion becomes increasingly sensitive to factors outside our control:

- **Politics:** to justify the continued use of public funds to develop nuclear fusion, there must be an **emphasis on a solution that allows fast deployment of fusion energy**.
- **`Tritium:** A central issue for fusion development. (1) The production of T is largely outside the control of the fusion community. (2) Many uncertainties regarding the future commercial and defence consumption of T. (3) **There *may* only be enough T for one DEMO that enter in operation < 2060 (see next slide).**



M. Kovari, M. Coleman, I. Cristescu and R. Smith 2018, *Tritium resources available for fusion reactors*, *Nucl. Fusion* **58** 026010

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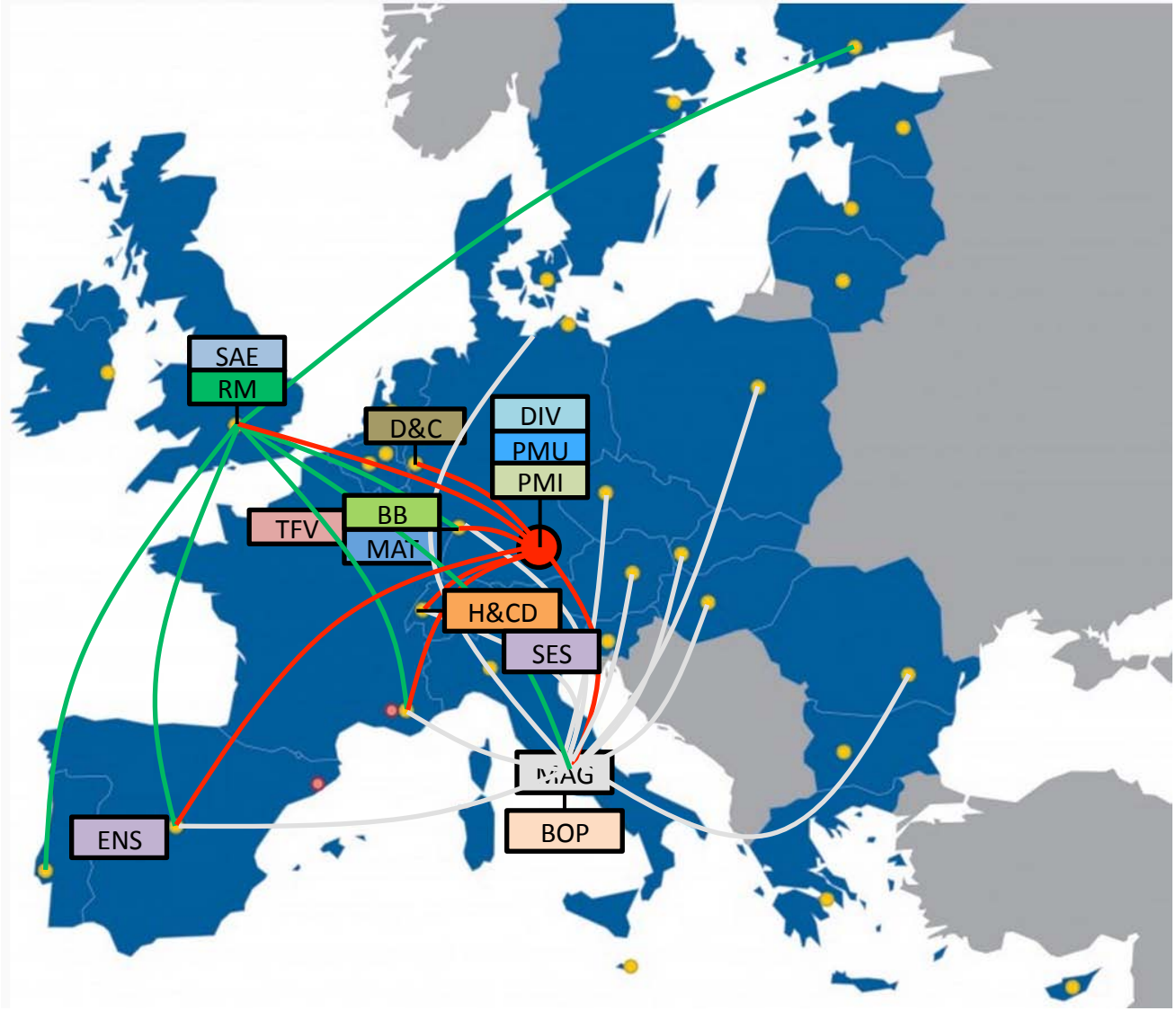
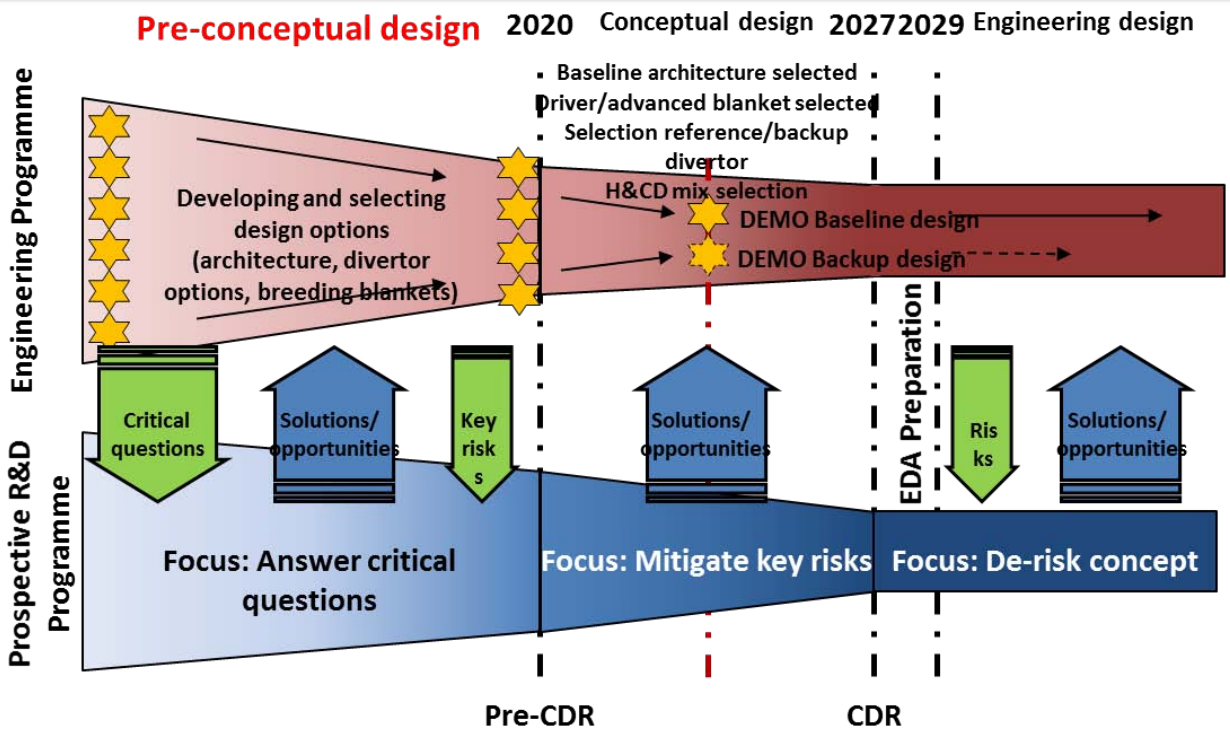
Organisation of Design and R&D Activities

A project-oriented structure with a **central Project Control and Design/ Physics Integration Unit** (LSI) and **(10-12) distributed Project Teams** aiming at the design and R&D of components.



A Staged Design Approach

A staged design approach that consists of three phases: (1) a pre-concept design phase to be concluded in 2020; (2) a concept design phase with a CDR in 2027; and (3) an engineering design to follow up.



Such work is essential

- **to develop an understanding of the importance and relative difficulties of various design integration and technological problems**
- **to provide the context for further design improvement and future R&D.**

EU Roadmap emphasizes, design based on

- **modest extrapolations from the ITER physics basis,**
- **robust design features, incorporating either proven technologies or innovations that can be validated through realistic R&D programs, to bound development risks, and**
- **safety features and design licensability integrating lessons learned from ITER licensing.**

Key Messages

- Contacts made with **Gen IV fission and ITER to learn from their experience.**
- **Definition of DEMO HLRs** following interaction with **external stakeholder group** composed of experts from industry, utilities, grids, safety, licensing, etc.
- A **philosophy of integrated design** established with a **traceable decision making process**.
- Sensitivities studies to **determine impact of uncertainties** of underlying physics and engineering/technology assumptions on machine parameters and design feautures.
- A **more systems-oriented approach** brought clarity to a number of critical design issues.
- Initiate **building of relationships with industry** and embedding **industry experience** in the design to ensure licensing, manufacturing and operational aspects.
- Ensure **early attention is given to industrial feasibility, costs, nuclear safety and licensing**.
- Main **design Integration Risks** that affect Plant architecture identified.
- **Evaluate multiple design options** for systems and/or technologies with high technical risk or novelty.
- **Design of a first DEMO plant layout** in collaboration with industry to identify major structures needed to contain the plant equipment; to identify needs for improvements.
- Preliminary **safety assessments**, including **assessments of radioactive waste**.

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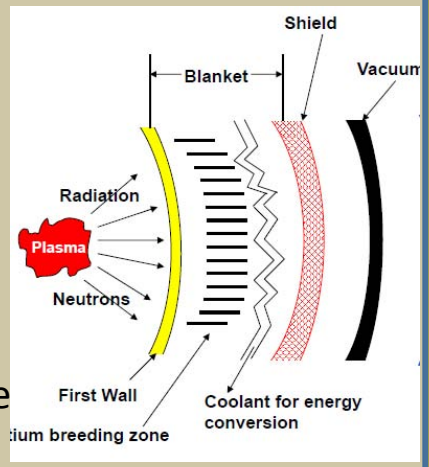
Recap of Major DEMO Design Issues

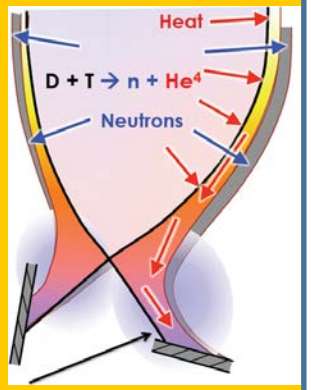
Tritium breeding blanket

- ✓ most novel part of DEMO
- ✓ TBR >1 marginally achievable with thin PFCs/few penetrations
- ✓ Feasibility concerns/ performance uncertainties with all concepts -> R&D
- ✓ Selection now is premature
- ✓ ITER TBM is important



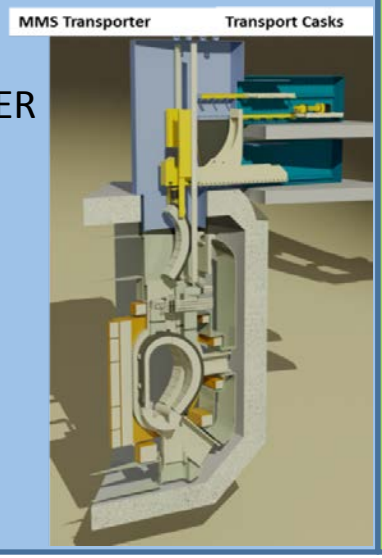
Divertor Power Exhaust

- Peak heat fluxes near technology limits (>10 MW/m^2)
- Use H_2O as coolant and Cu-alloy
- ITER solution may be marginal for DEMO



Remote Maintenance

- ✓ Significant differences with ITER RM approach for blanket
- ✓ RH schemes affects plant design and layout
- ✓ Large size Hot Cell required
- ✓ Service Joining Technology R&D is urgently needed.
- ✓ Minimise IVC work in the high radiation areas (2kGy/hr)



Materials

- ✓ Embrittlement of RAFM steels at low temp. and loss of mech strength at ~ high temp.
- ✓ Progressive blanket operation strategy (1st blanket 20 dpa; 2nd blanket 50 dpa)
- ✓ Need irradiated matl property data and structural design criteria.
- ✓ Urgent need of a dedicated fusion irradiation facility (IFMIF-DONES)

- Advanced solutions may be needed but integration is very challenging. A dedicated DTT is planned

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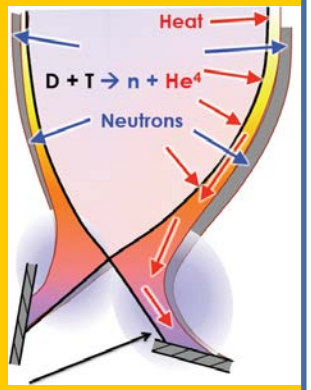

A lot of discussions about making fusion smaller, cheaper, and faster, but there is no magic bullet to solve the integrated design problems

Every time you squeeze somewhere, you make problems worse elsewhere…

EU-DEMO is current viewed to be the lowest risk option to meet all targets within given timescales (this does not mean it is low risk!)

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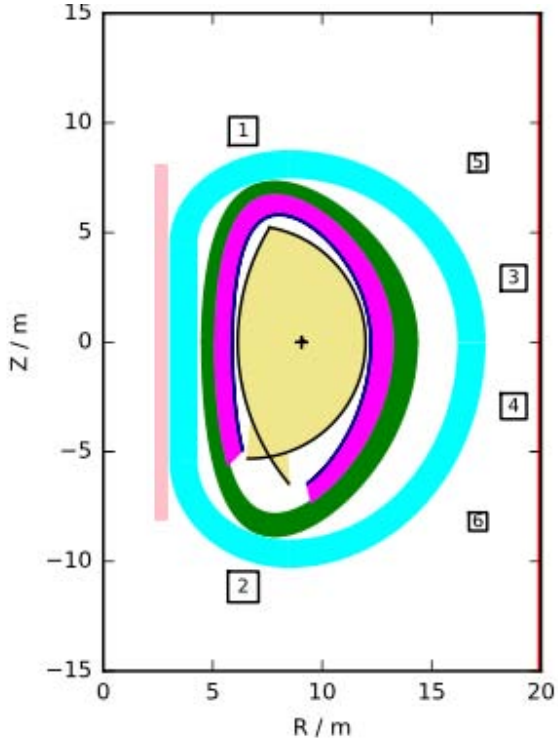
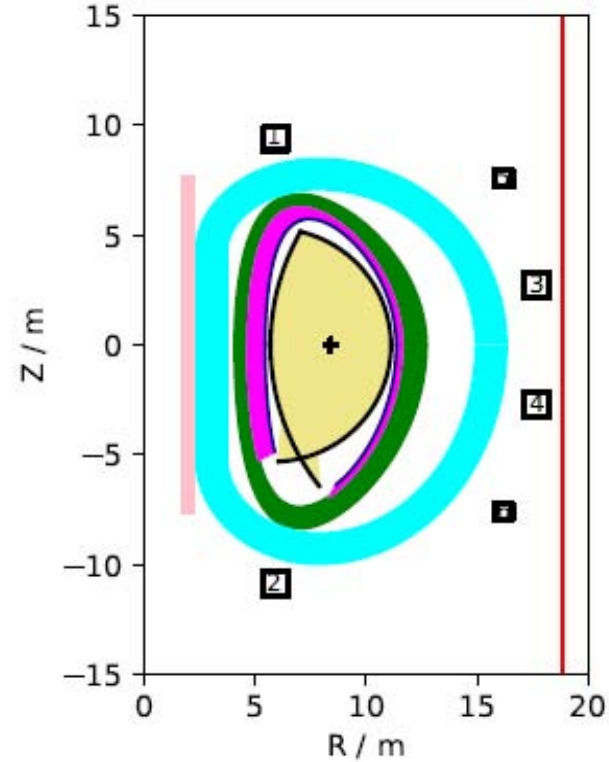
DEMO Design Options under Study*



DEMO 1	Parameters	flexi-DEMO
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/m²)	1.15	1.15



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 initially 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.

Size of DEMO

- EU-DEMO based on best currently available data (plus foreseen ITER results)

  → Conventional aspect ratio ~3; ITER-like divertor; standard operational regimes (H-mode); characterised materials

- TBR>1 requires breeding on inner wall of reactor

  → distance TF coil to plasma: thermal shield+VV+breeder+shield+FW+SoL~1.7m

  → B_{TF}<12.5T, B_0>5T : R_0>6.5m

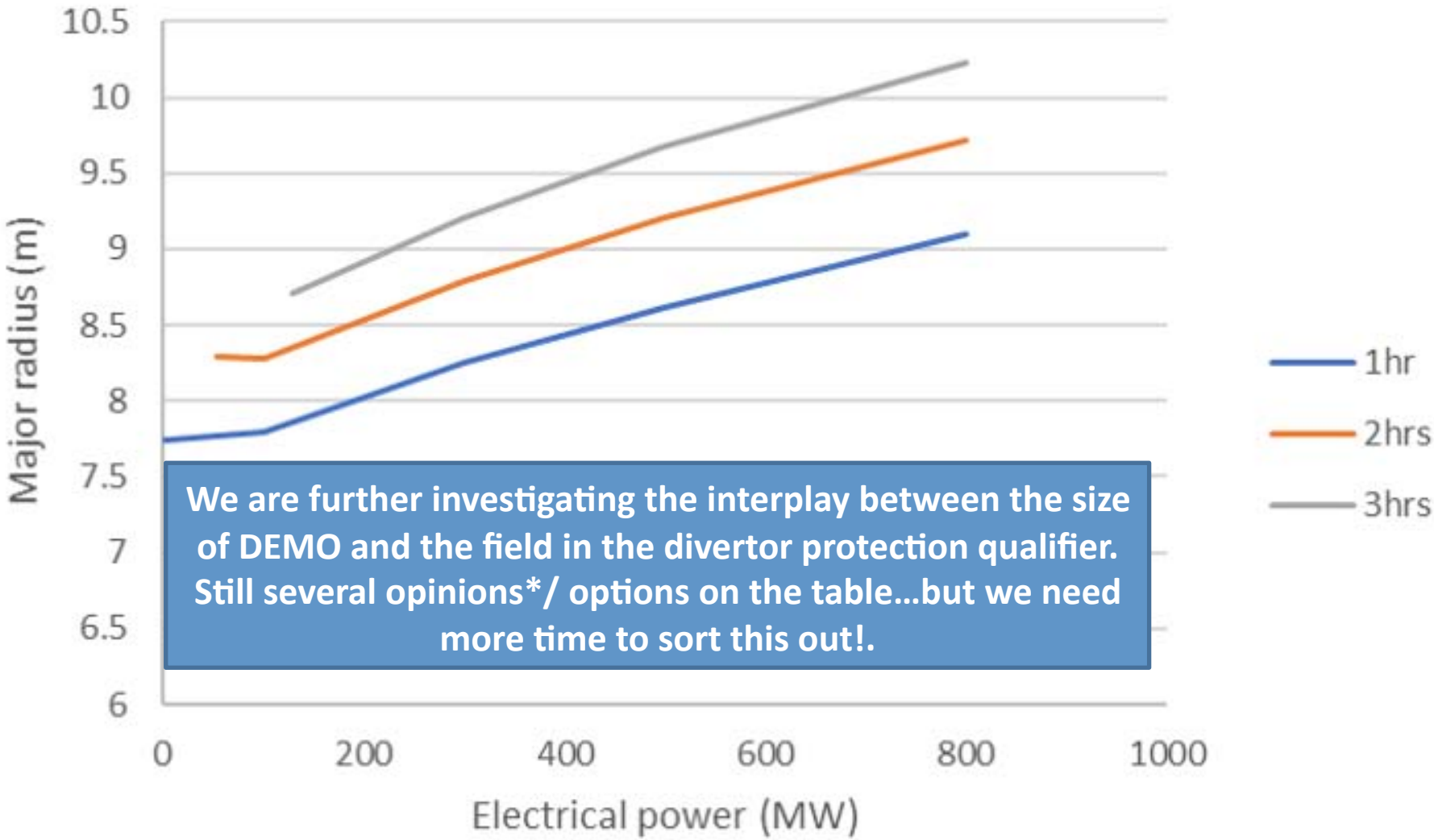
- Production of 100s MW electricity requires ~2000MW fusion power: 400MW alpha power (+ auxiliary power for control or current drive)

  → With conventional divertor and 90% radiation, R_0>7 m.

- Access for efficient RH → larger machine gives generally easier kinematics as thickness of breeder components does not change with machine size

- Long pulses require significant current drive (divertor issues) or large solenoid (larger machine)
- All these sizings based on very simple models: more detailed models plus some conservatism lead to EU-DEMO at ~9.0m

Size of DEMO (2)



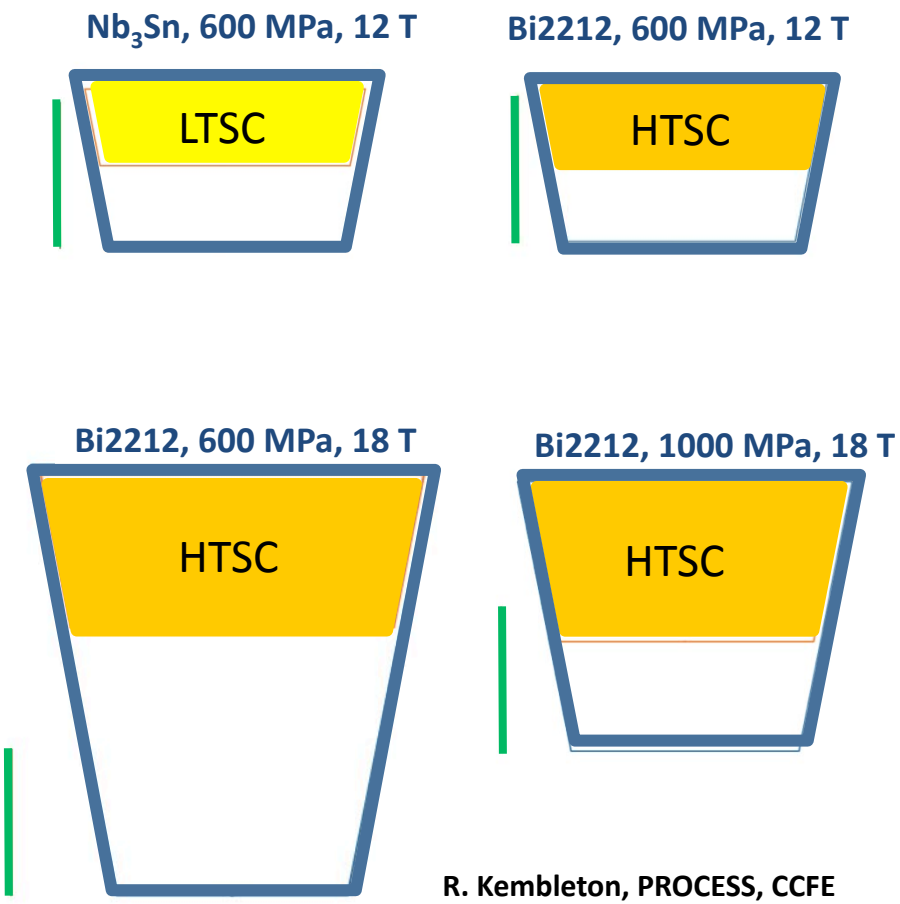
We are further investigating the interplay between the size of DEMO and the field in the divertor protection qualifier. Still several opinions*/ options on the table…but we need more time to sort this out!.

***Divertor protection qualifier**

- **P_{sep}/R, one finds Psep/R ~ B*R, thus increasing B or R has the same effect;**
- **PB/qAR, one finds PB/qAR ~ B^2 R, thus this seems to suggest an unfavourable scaling with B**
- **Critical impurity concentration cz ~B^0.88 R^1.33, thus scaling more favourably with B than with R [Reinke, NF 2017]**

EU DEMO doesn't (currently) use high B TF coils

- Any increase in B inherently leads to higher stresses ($\sigma \propto B^2$)
  - ➔ TF coil nose grows to accommodate field, offsetting gains in R_0
- To really see benefit of high B_t in the machine size (R_0), we would need higher strength cryogenic steels



R. Kembleton, PROCESS, CCFE

"ITER-like" DEMO magnets with LTS and HTS

(Green line = 1m)

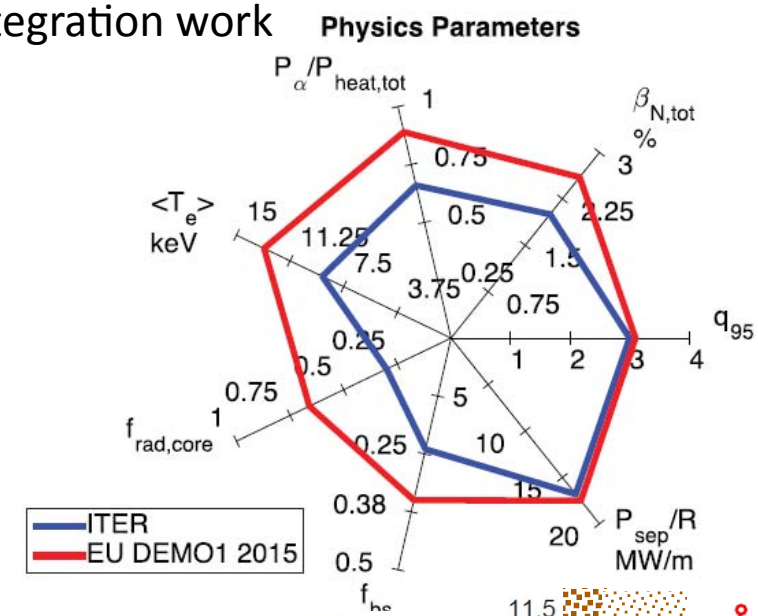
High-field magnets (18T) with HTS: current structural materials and high-strength materials

The development of HTS coils is not a useless endeavour; there are many aspects of HTS conductors which are very promising. In the EU R&D is ongoing (see following slides)

A Pulsed DEMO as a Proxy for Design Integration Work

A 'proxy' for relevant design integration work

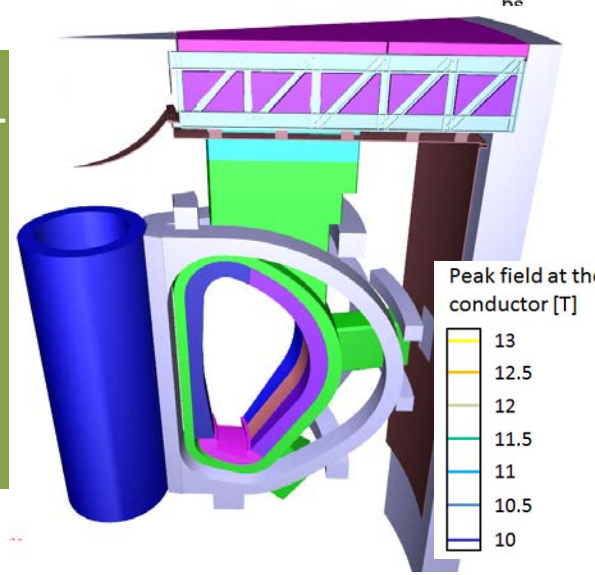
Physics:
- Single null
- Conventional H-mode
- H=1.1 (radiation corrected)
- Based on ITER performance (Q=10)
- P_{sep}/R_0=17 MW/m (fully detached)
- Pulsed (2 hours)
- "Conservative", i.e. established physics basis.

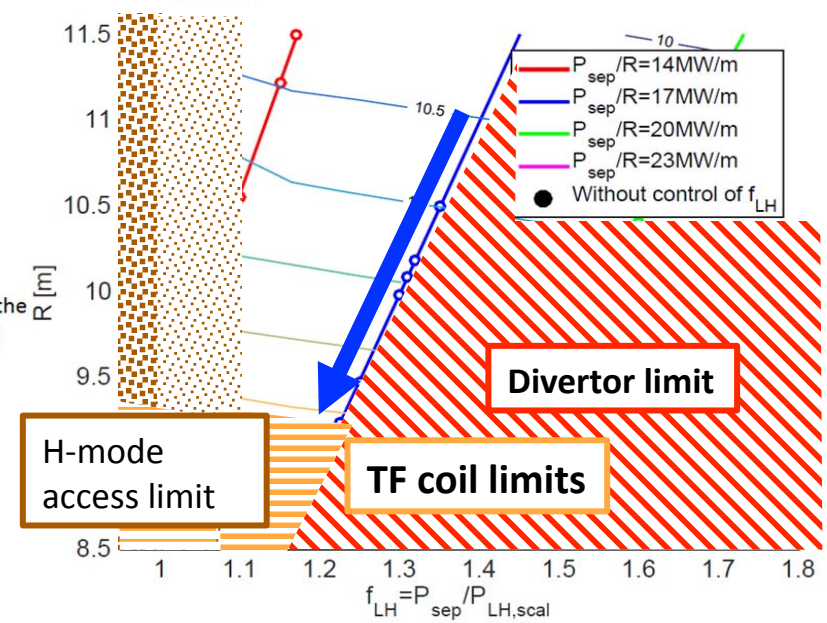


	DEMO1
R_o	~9 m
A	3.1
k_{95}	1.65
B_T	5 T
β_N	2.6
H	1.1

$P_{el,net}$ = 500 MW
τ_{pulse} = 2 hr
A = 3.1

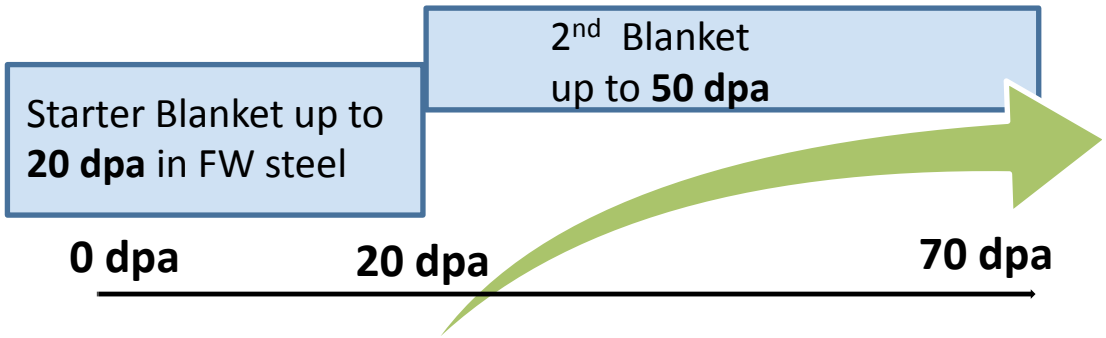
Engineering:
- 16 LTSC TF Coils, Nb_3Sn, ~12 T
- Vertical Maintenance
- EUROFER IVCs
- Starter blanket (20 dpa) + Second blanket (50 dpa) (~6-7 FPY total)
- TBR > 1.1
- Availability target 30%



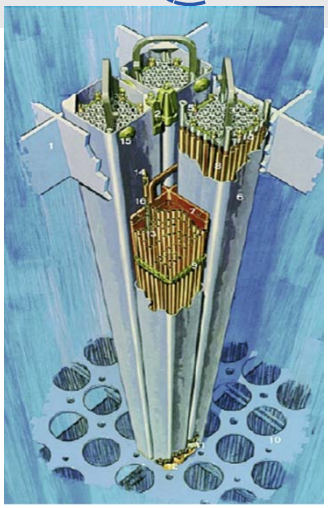


DEMO Breeding Blanket/ Rationale Progressive Approach

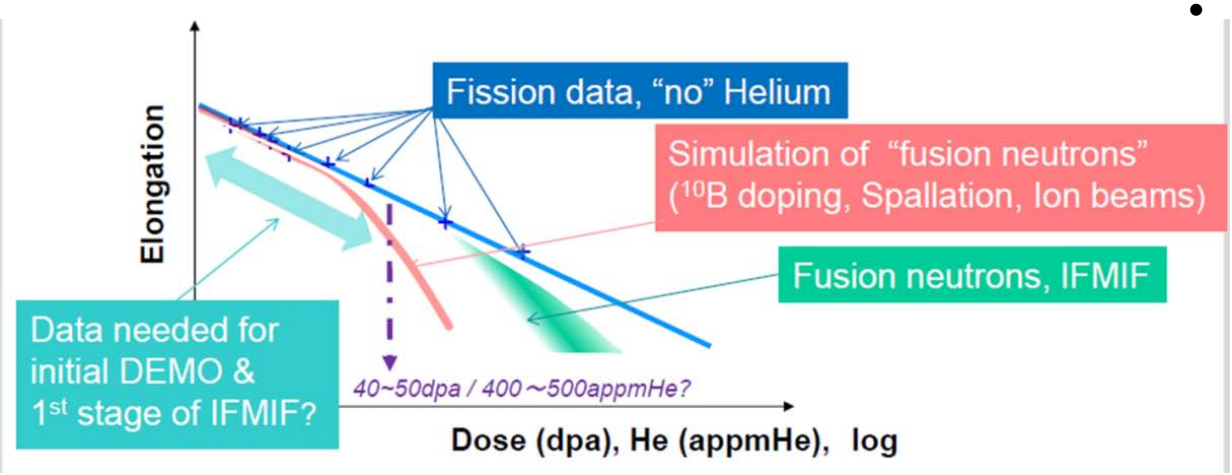
Discussed and endorsed by the Assessment of the EU R&D Programme on DEMO Structural and High-Heat Flux Mtls EFDA_2MJ5EU, D. Stork, S, Zinkle et al.



D. Stork, et al., (2014) Materials R&D for a timely DEMO: Key findings and recommendations of the EU Roadmap Mat. Ass. Group, Fus. Eng. Des. 89 (2014) 1586–1594 .



- **Progressive Approach to Licensing approval** for operation up to moderate damage could be obtained for the "starter" blanket, while high-dose engineering data is being generated.

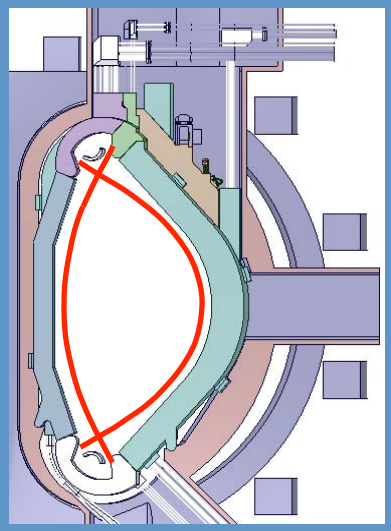


- This type of approach has been used for the fuel cladding in fission reactors for many years (e.g., for the MAGNOX in the UK) as a demonstration of the lifetime extension method against increasing technical knowledge of a plant design.

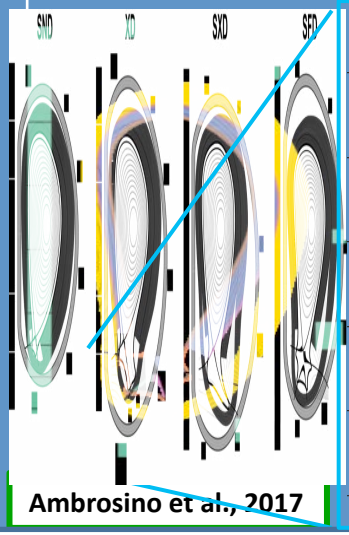
Alternative DEMO Divertor Configurations

Engineering investigation are underway , involving WPDTT1, to evaluate the engineering shortcxomings, related to Remote Maintenance, Design Integration, Nuclear Shielding, Coils layout and forces, etc.

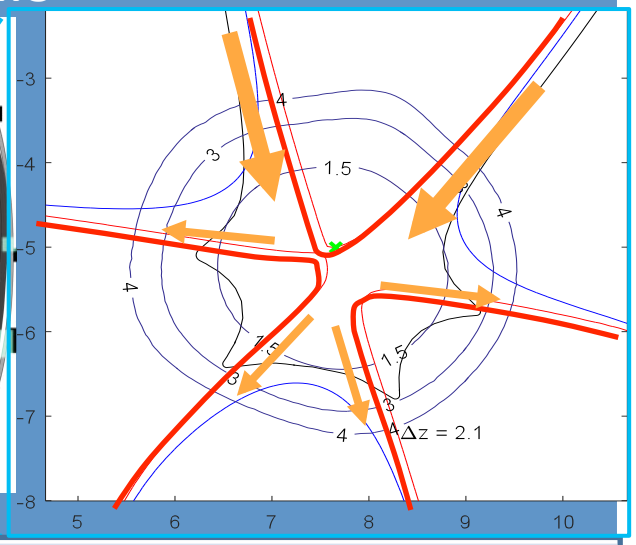
Double Null DEMO



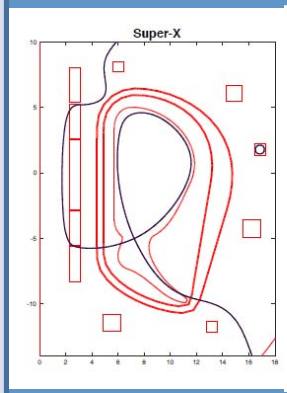
Snowflake-DEMO

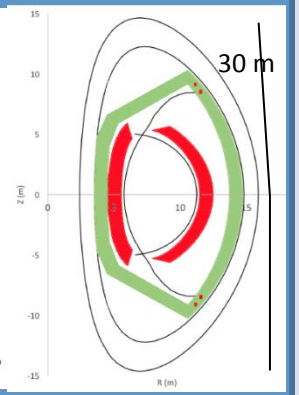


Ambrosino et al., 2017



Super-X-DEMO





Physics

Conventional divertors

- Stability of detachment
- ELMs and Disruptions
- Sweeping/ Wobbling

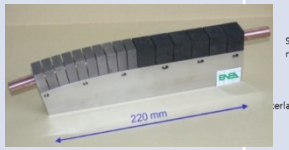
Advanced divertors

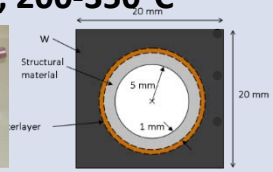
- Snowflakes
- Super-X
- Liquid Metals

TRL

Technology

- Water cooled design
- Armour: Tungsten
- Structural: Cu-alloys
- EOL <10 dpa, 200-350°C





- Limited effort on He-cooling and on LM

Engineering assessments to evaluate issues

- Remote maintenance
- Forces on the PF coils
- Nuclear shielding
- Design integration

Outline

- ***The context:*** **DEMO in the EU Roadmap**
  - ❖ Technical mission and scope
  - ❖ Timeline considerations
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  - ❖ Organisation of DEMO design and R&D activities
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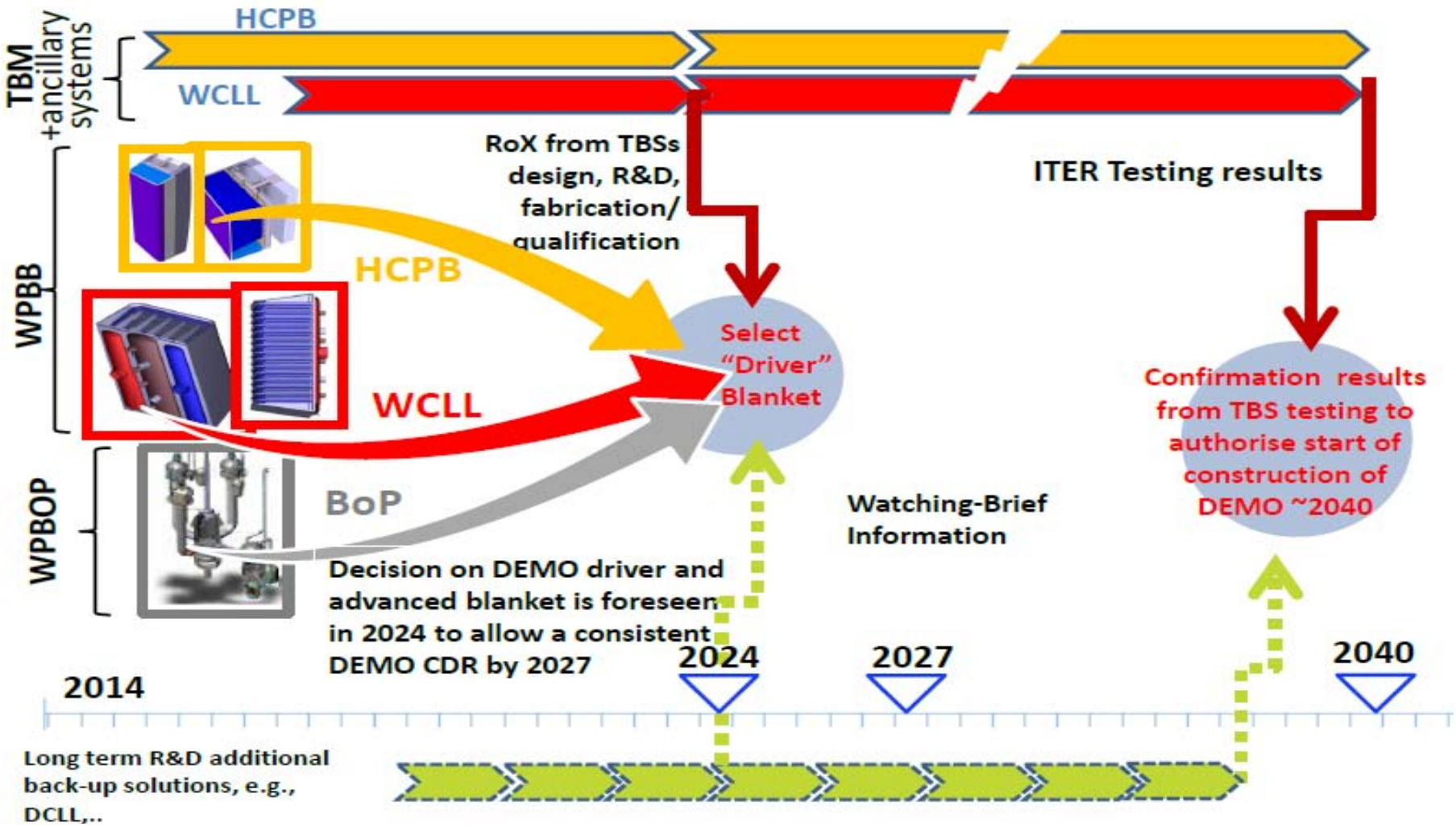
  - ❖ Examples of main achievements
  - ❖ Industry and International collaborations
- **Looking forward/ Summary**

DEMO Breeding Blanket/ Strategy to select Driver

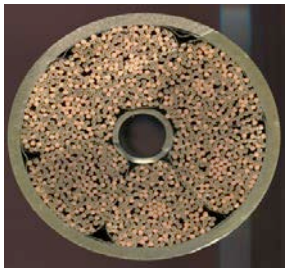
Results of a recent assessment to streamline the European Fusion Programme on the Breeding Blanket. Implementation of the recommendations still pending management approval



Examples of Technology Achievements (1)

The ITER technology of Nb_3Sn magnets forms the basis for DEMO, but more advanced cables are being developed to **reduce performance degradation under cyclic operation** and **cost**.

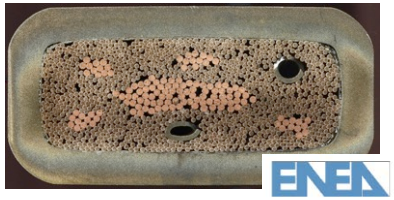
ITER TF



- Degradation with e-m cycles
- **ΔT_{marg} > 1.3K @** 68kA,12T
- Total strain ε_{eff}=-0.70%

DEMO TF conductors

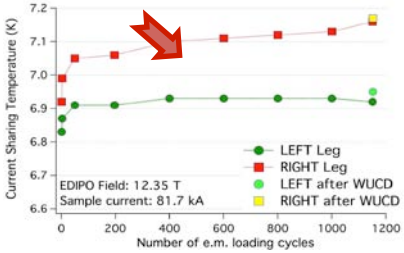
Nb_3Sn Wind & React



ΔT_{marg} >2K @ 82kA,13T

ε_{eff} ≅-0.55%

NO degradation with e-m cycles

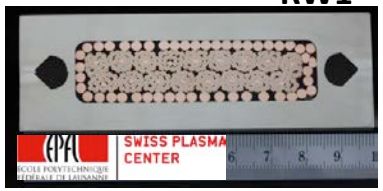


ε_{eff} ∈[-0.55, -0.35]%

- **Higher I_c**
- **Less superconducting strands**

Nb_3Sn React & Wind

RW1



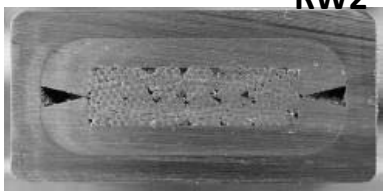
ΔT_{marg} >2.0 K

Low degradation w. e-m cycles

Low AC losses

ε_{eff} ≅-0.35%

RW2



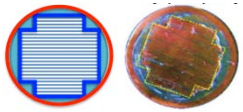
ΔT_{marg} >1.5 K

Moderate degradation w. e-m cycles

ε_{eff} ≅-0.40%

Very low AC losses

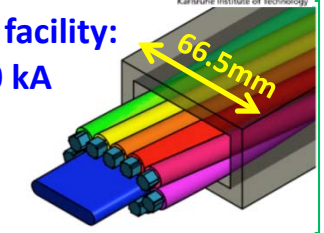
HTSC conductors



9.3 mm HTS Cross Conductor as strand

Measured at FBI facility:
I_c(4.2K, 12T) > 10 kA

Design of HTS CroCo Cable



I_c(4.5 K, 13 T)=50kA ΔT_{marg}=12 K.

Prize at SOFT 2016

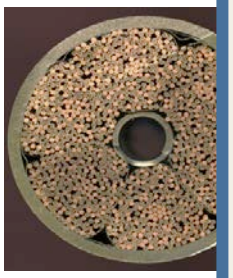
60 kA cable for large magnets demonstrated @ 4.2 K and 12 T
Based on REBCO tapes

V. Corato, Fus. Eng. Des. 2018 (sub ISFNT 13)

Examples of Technology Achievements (1)

The ITER tech … anced cables are being dev … and **cost**.

ITER TF

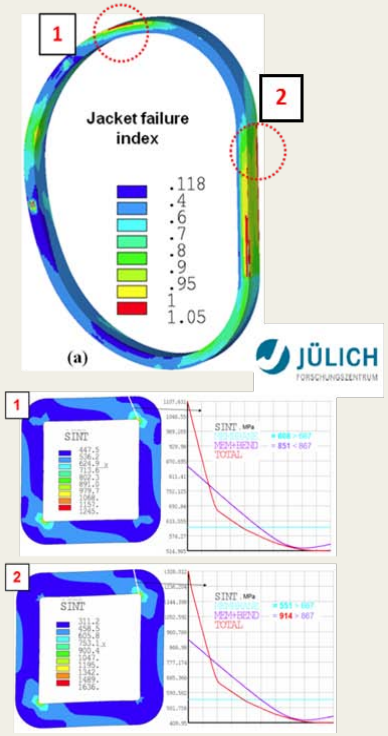


•Degradatio … e-m cycles

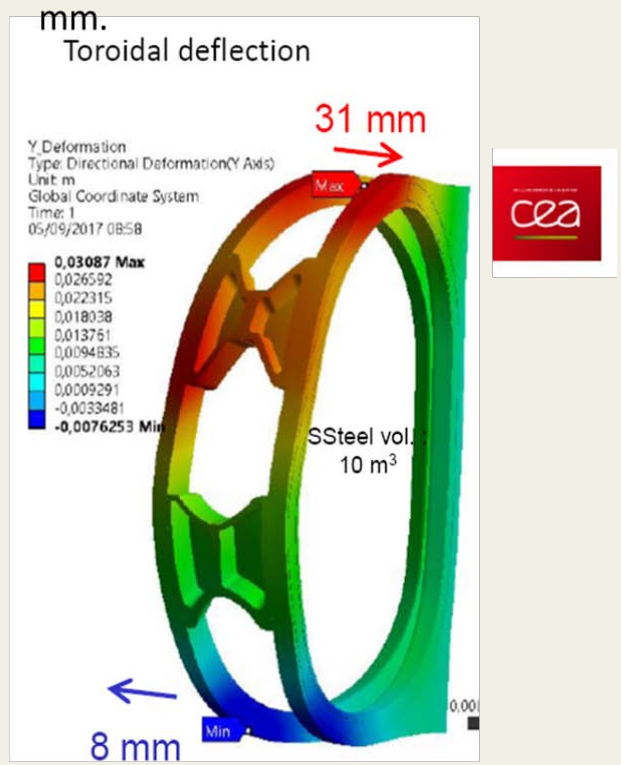
•ΔT_{marg} > 1.… 68kA,12T

• Total strain ε_{eff}=-0.70%

Mechanical critical locations in all **TF** WPs have been studied. Limits are only exceeded in the corners of the jacket.



Optimization of TF Outer Intercoil Structures. Wall thickness is about 150-200 mm.



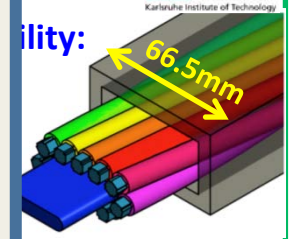
uctors

mm HTS

ss Conductor

strand

ility:



ΔT_{marg}=12 K.

FT 2016

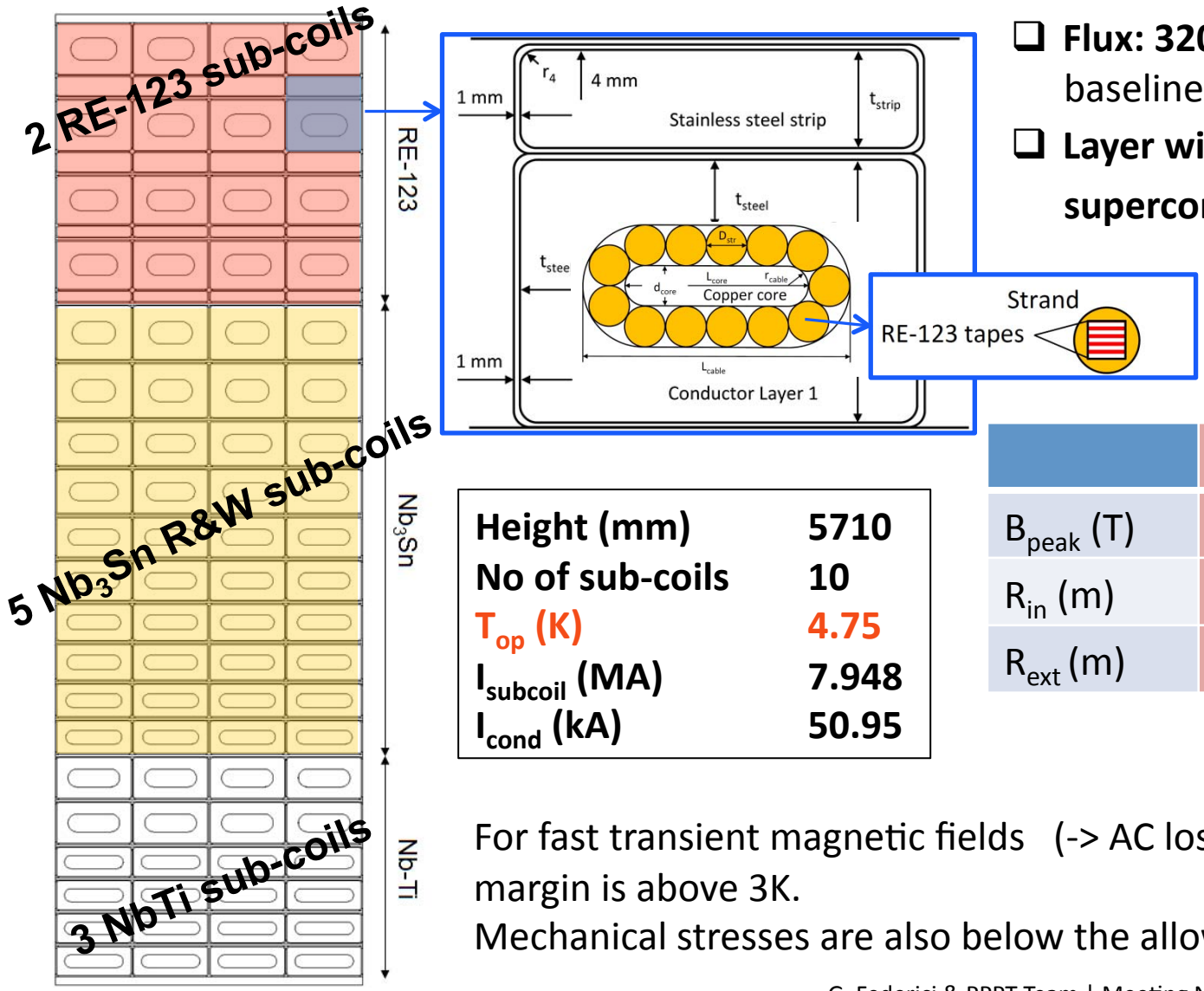
S PLASMA
ER

r large magnets
l @ 4.2 K and 12 T
CO tapes

V. Corato, Fus. Eng. Des. 2018 (sub ISFNT 13)

Hybrid CS coil for DEMO

5 modules CS (with a central double module): **CS1** is shown as example



- **Flux: 320 Vs**, as defined by the baseline 2015.
- **Layer winding with grading on superconductor and jacket**

Height (mm)	**5710**
No of sub-coils	**10**
T_{op} (K)	**4.75**
$I_{subcoil}$ (MA)	**7.948**
I_{cond} (kA)	**50.95**

Possible reduction of the CS size

	Hybrid CS	Nb_3Sn CS
B_{peak} (T)	17.5	13.7
R_{in} (m)	1.9	2.4
R_{ext} (m)	2.8	3.2

Baseline 2015

For fast transient magnetic fields (-> AC losses) the temperature margin is above 3K.
Mechanical stresses are also below the allowed values.

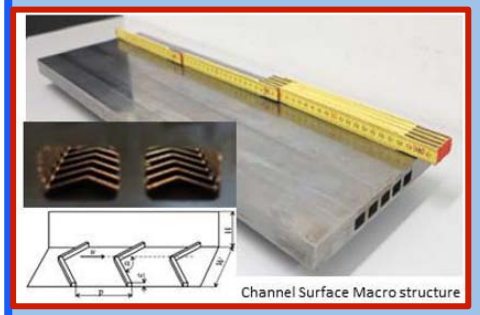
Examples of Technology Achievements (2)

WPBB – Blanket Fabrication Technologies

WCLL: manufacturing of EUROFER tubes P

Preliminary procedure to deposit interface layer (to stop/deflect crack propagation at tubes interface) on inner tube and to assemble both tubes (HIP welding process).

WCLL (EUROFER tubes)



Spark erosion and bending (FW)

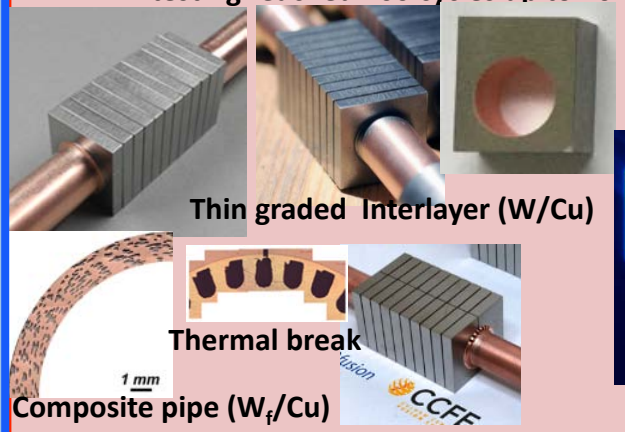
HCPB: Fuel Pin and Cooling Plate

Laser Beam Melting

HIP and EB processes (FW / cooling plates on FW)

WPDIV - Technology R&D for HHF PFCs

- Study improvements of ITER technology
- Mock-up fabrication
- HHF testing reached 100 cycles up to 20 MW/m²

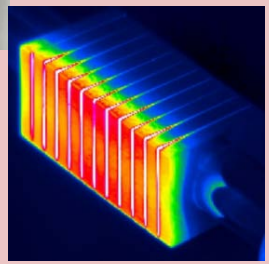


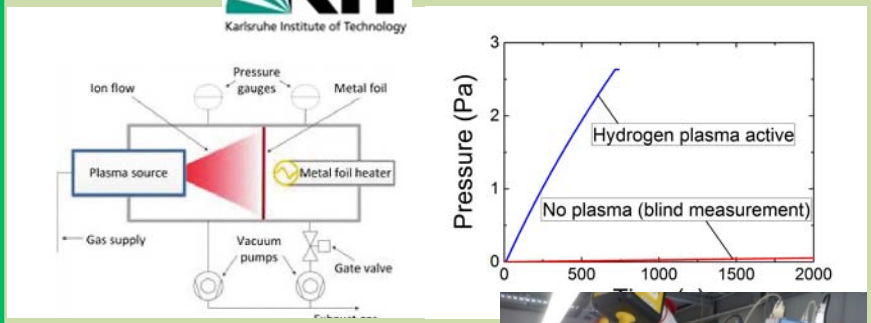
Thin graded Interlayer (W/Cu)

Thermal break

Composite pipe (W_f/Cu)

100th cycle



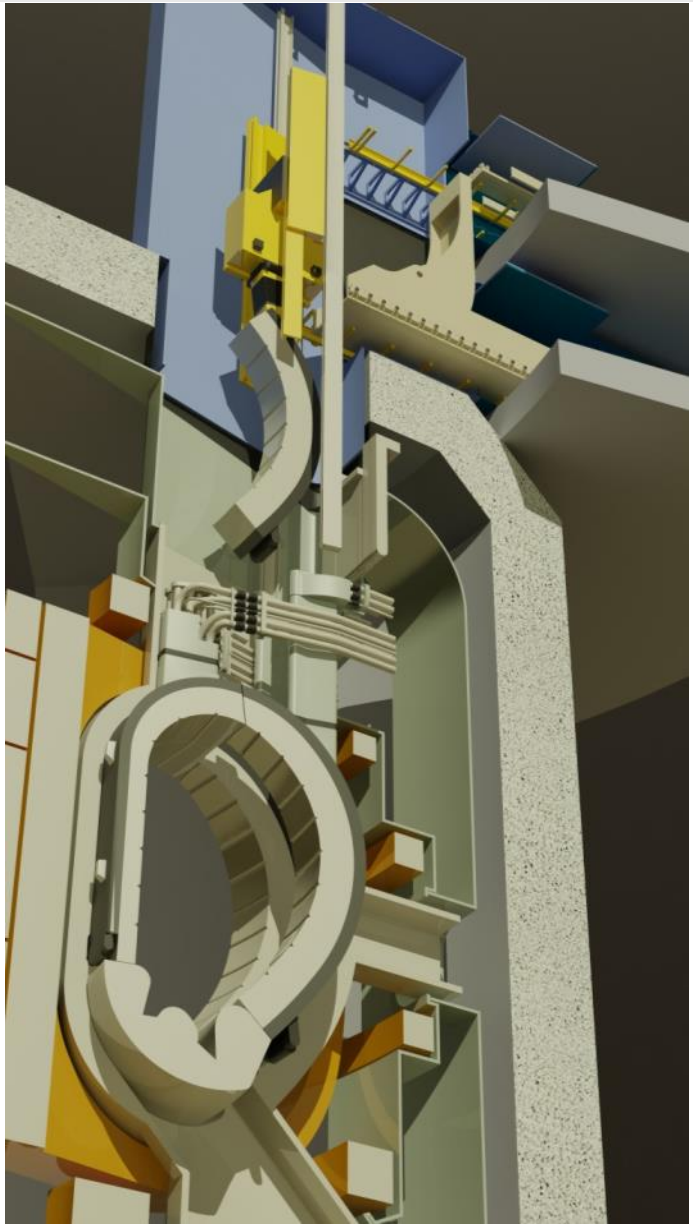


Demonstration of superpermeability for immediate separation of the exhaust gas in metal foil pumps.

Examples of Technology Achievements (3)

Early attention must given to Remote maintenance

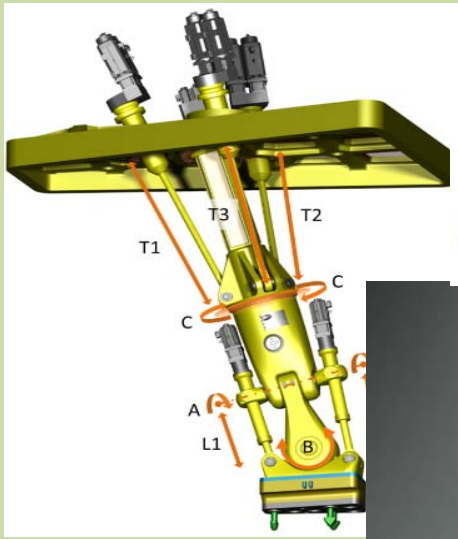
- The remote maintenance strategy is important for the reactor architecture as a whole. Approach in EU
  - ✓ Develop strategy in parallel with the component design
  - ✓ Investigate technology limits
  - ✓ Relevant for a range of reactor designs
  - ✓ Achieve a viable power plant design
- Concentrate work in areas with highest risk to the feasibility of the strategy:
  - Precision placement of large in-vessel components
  - Pipe joining technology
- Remote maintenance is a **Design Defining Driver** for a fusion power plant and must be substantiated early.



Examples of Technology Achievements (3)

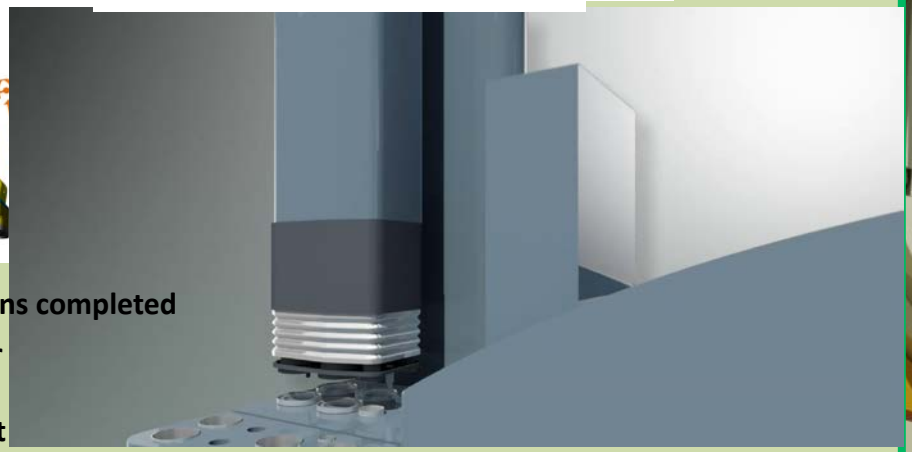
- **Precision control of large heavy components that deform significantly under static/dynamic loads**
- **In-vessel work in the high radiation areas (2kGy/hr) must be minimised and ideally avoided**
- **Concept designs and tests for proof-of-principle cutting and welding tools developed**

In-bore weld achieved



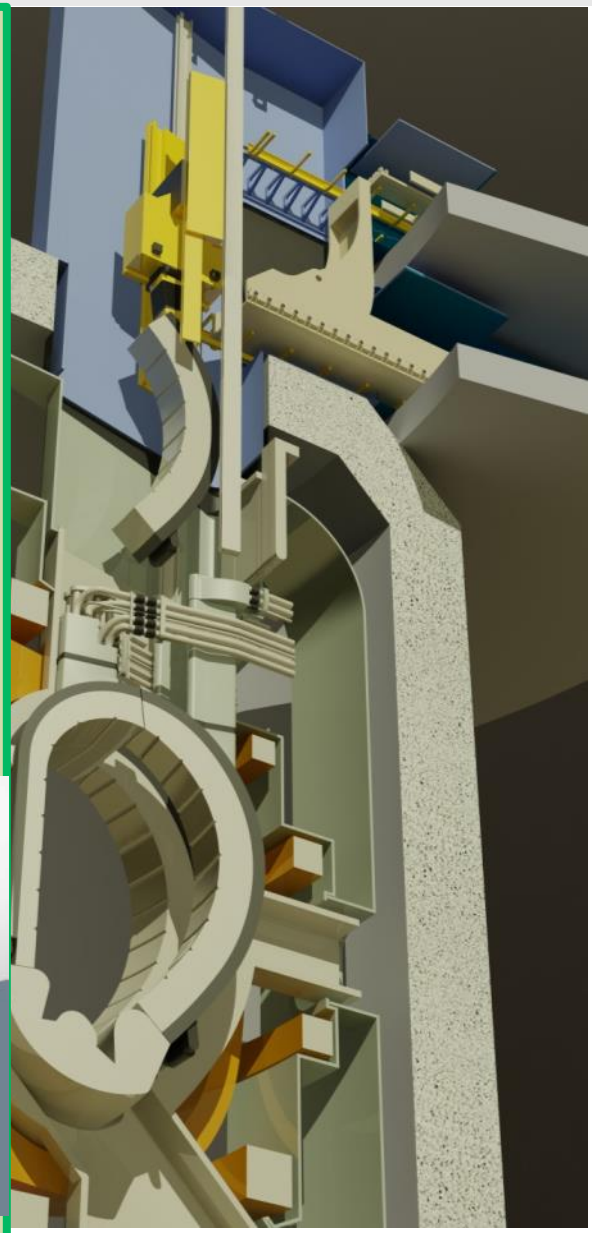
Keelan Keogh et al. (CCFE) to appear in Fus. Eng. Des.

2017 Welding Tool Proof of Principle Detailed Design



Proof of principle tool designs completed

- **Fit-up tolerance and filler material methods**
- **Post weld heat treatment**
- **Control of weld profile with dual lasers**



Areas of Industrial Involvement

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

AIRBUS

- System Engineering Training
- Advisory role on Central Integration Project Team
- FIIF

ANSALDO NUCLEARE
Ansaldo Energia Group

Kraftanlagen Gruppe

Fortum

SIEMENS

- Design studies BOP/ PCS
- Design amelioration of turbines for pulsed loads
- FIIF

EUROfusion

FIIF Fusion Industry Innovation Forum

Fusion Industry Innovation Forum

- Atmostat
- Empresarios Agrupado
- Cosylab
- Assystem
- Saarstahl, Germany
- CSM S.p.A., Rome, Italy
- Plansee
- GRS GmbH

- Architect engineering studies support
- Evaluation and selection of design alternatives

AREVA

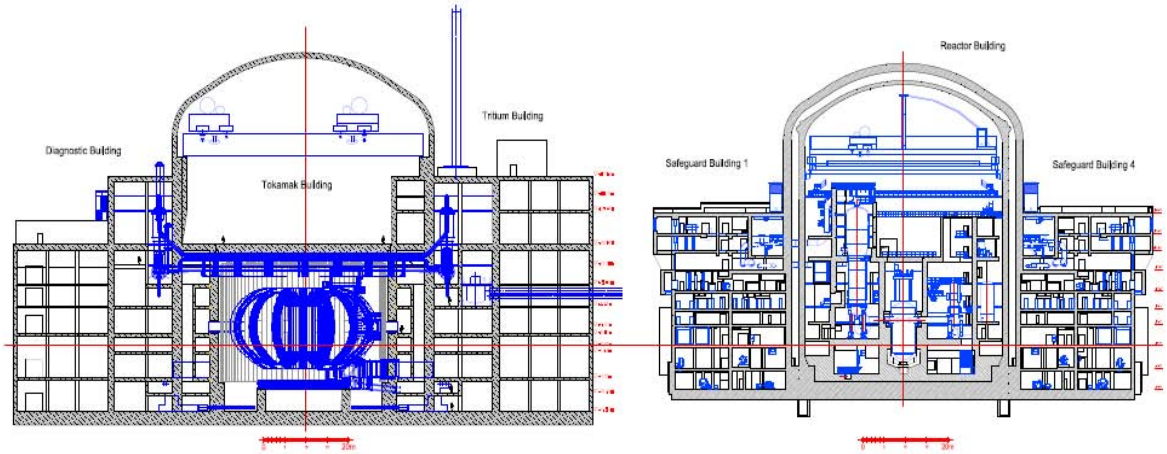
MAN

Design for simplification and robustness of critical components such as vacuum vessel; reduce fabrication costs

Highlights Industry Activities 2017: *Preliminary DEMO Plant Design*

Initial integration studies with the support of a "nuclear architect " to:

- identify the major structures needed to contain plant equipment;
- develop a technically feasible, operable, and maintainable plant design;
- provide a starting point for safety analyses and further design improvements;
- identify areas with significant technical uncertainties;
- early substantiation of maintenance concepts to limit risk of redesign.



- The plant layout must include the maintenance infrastructure from the outset
- Understanding of: maintenance strategy; standardised handling; transfer corridors

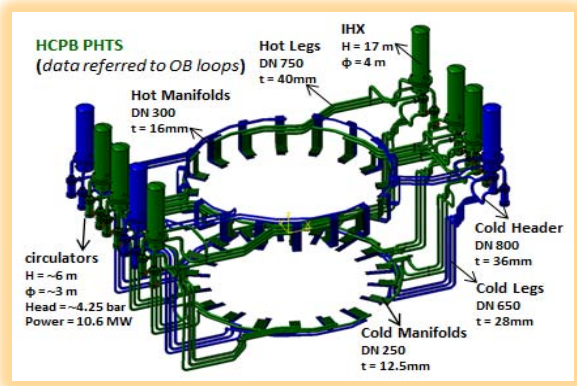
C. Gliss (PMU), W. Korn (AREVA): to appear in Fus. Eng. Des.

Highlights Industry Activities 2017: *DEMO BoP Design*

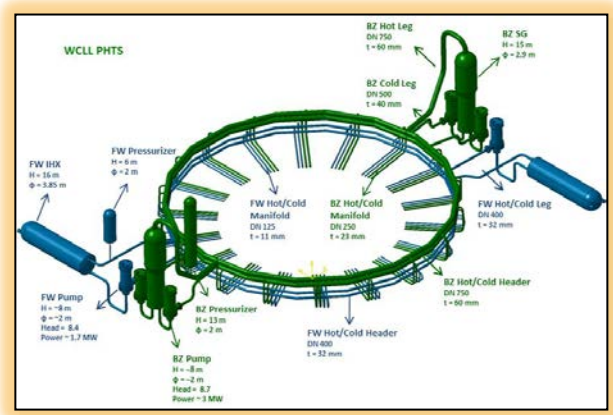
Preliminary design of BoP for two coolant options for the breeding blanket: He and water

and

Characterization of Technology – TRL



He: 300-500C, 80 bar



water: 292°C-328°C, 150bar

- Assess dimensions of main components (e.g. HEX, circulators/pumps, pipes, headers, tanks)
- Establish layout requirements and implications on other systems
- Understand commercial availability of components and R&D needs
- Identify technical feasibility issues

Divertor and limiters (Water: 130°C-150°C)
VV (Water: 190°C-200°C)

L. Barucca, S. Ciattaglia, M. Chantant, A. Del Nevo, W. Hering, Status of EU DEMO Heat Transport and Power Conversion Systems, Int. Symp. on Fus. Nucl. Techn. (ISFNT), Sept. 2017, Kyoto, Japan, to appear Fus. Eng. Des.

Ongoing International Collaborations

- **Japan (Broader Approach) IFERC**
  - joint DEMO Design Activities (DDA) to address most critical DEMO design issues investigate feasible DEMO design concepts
- **China as of 2016**
  - **DEMO/ CFETR joint design task forces**
    - Technical exchange meetings: CFETR and EU-DEMO
    - Systems codes studies
    - Divertor configuration and performance, incl. alternative divertor geometries and potential implementation in CFETR / EU-DEMO / DTT
  - **Breeding blanket R&D cooperation:**
- **UCLA (LiPb flows) + Structural Codes**
  - upgrade and use of existing MaPLE facility for combined magneto-hydrodynamic (MHD) thermofluids and fluid-materials interaction experiments
- **Fission Reactor Irradiation Experiment**
  - Collaborations to use non-EU MTRs for high fluence irrad. to close gaps in EUROFER and Cu data base and work towards common MPH and design rule development

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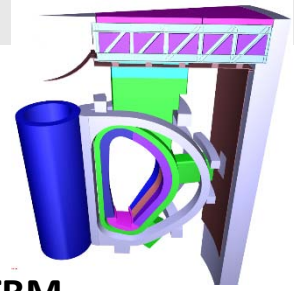
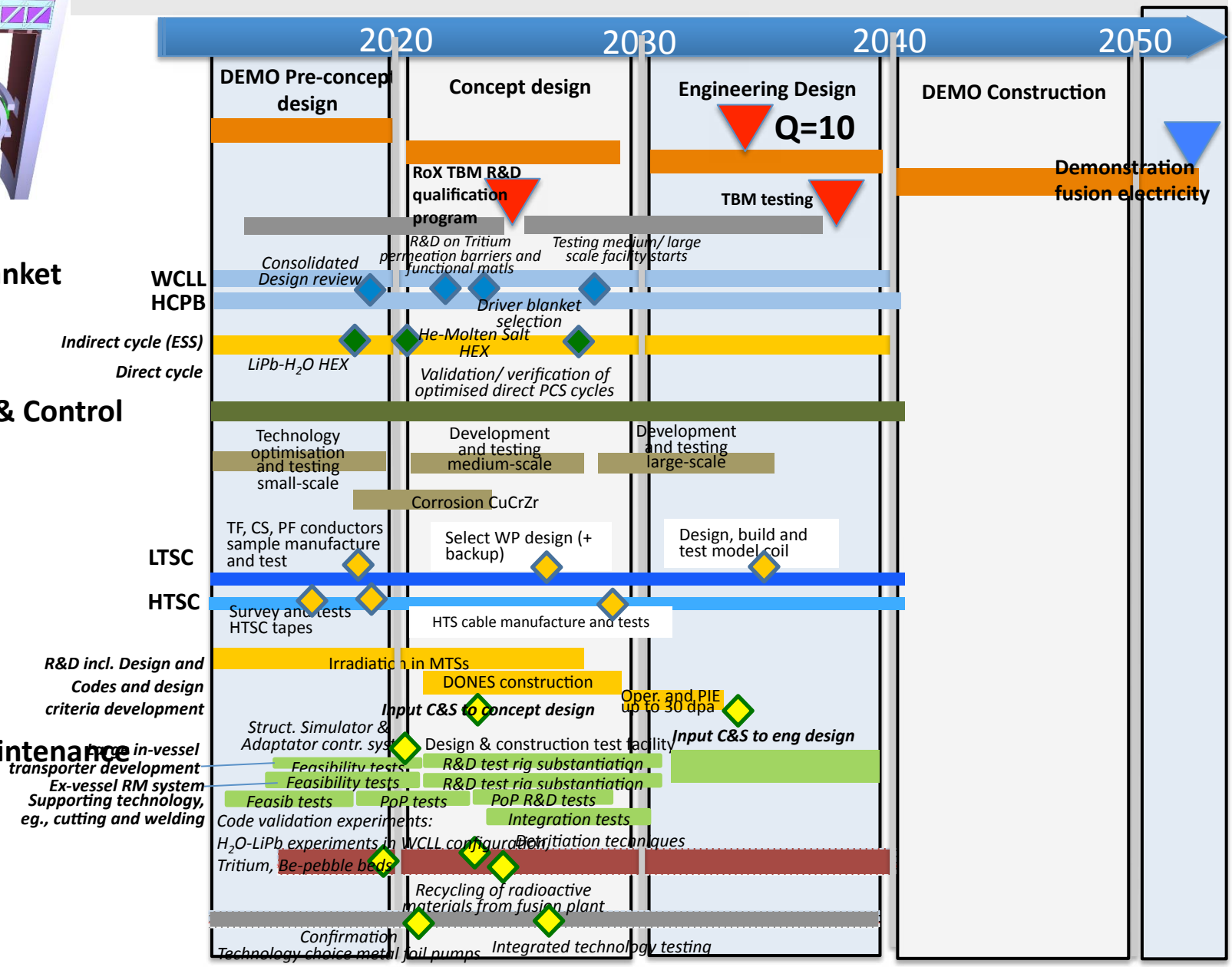
DEMO Technology R&D Needs *(in a nutshell)*



1. TBM
2. Breeding Blanket
3. BoP
4. Diagnostics & Control
5. Divertor
6. H&CD
7. Magnets
8. Materials
9. Remote Maintenance
10. Safety
11. Tritium



Neutron Irradiation Campaigns – *launched 2016/17*

Material	Reactor	Conditions	Material Properties
Engineering data			
EUROFER97	HFIR	20 dpa (Fe), 200-550°C	Fracture & Fatigue
CuCrZr	LVR-15 [Cz]	5 dpa (Cu), 100-300°C	Tensile, toughness, LCF
Tungsten	BR2	1 dpa (W), 400-1200°C	Toughness
Screening & Modelling			
Advanced steels	HFIR	2.5 dpa, 300°C	Fracture ->DBTT
W alloys	BR2	1 dpa (W), 600-1200°C	Thermo-shock via HHF
W alloys	BR2	1 dpa (W) 600-1100°C	Bending, Fracture->DBTT
Cu alloys	BR2	1 dpa (W), 150-450°C	Tensile
Functional materials	BRR [H]	0.1 -1 dpa, 250°C	Optical and dielectric properties
W model alloys	BR2	1 dpa (W), 600-1200°C	Hardness / strength / DBTT

PIE -DBTT

Main systems of IFMIF/DONES

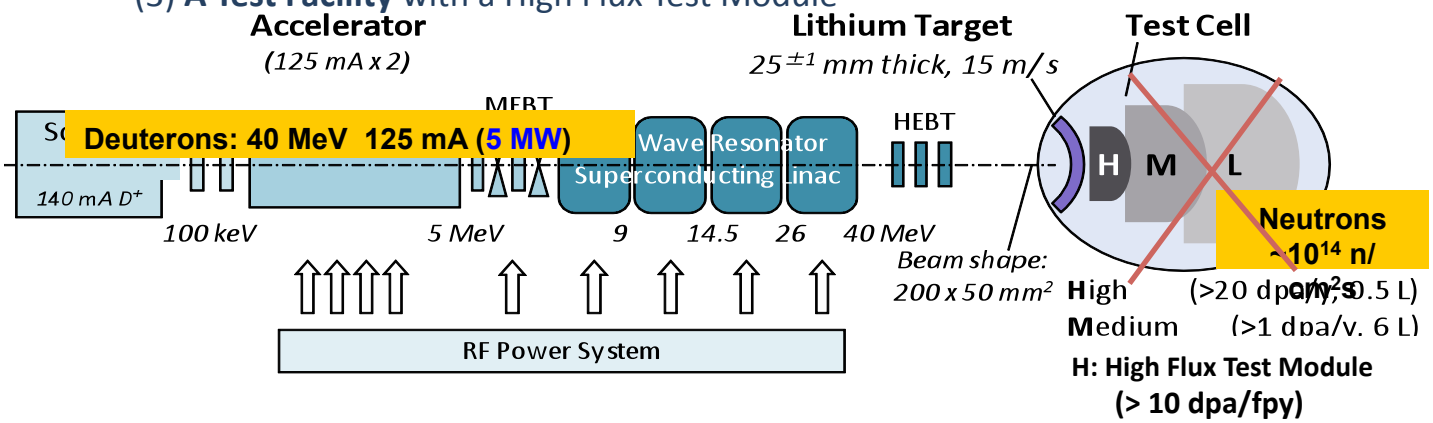
DONES design is derived from the IFMIF concept: one accelerator instead of two, only High Flux Test Module

The **DONES facility** is designed to produce a fusion relevant neutron spectrum by Li(d,xn) nuclear reactions and consists of three key systems:

(1) **A 40 MeV Deuteron Accelerator** system using Linear Accelerator technology;

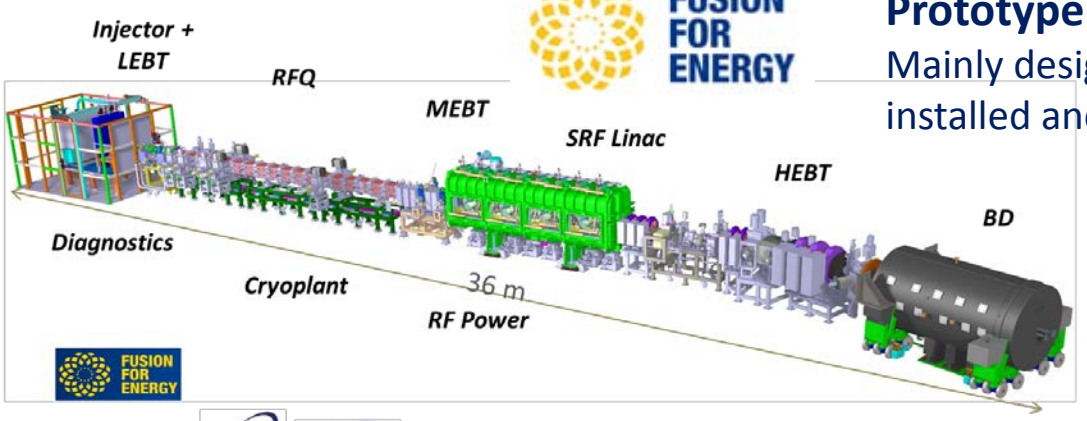
(2) **A Lithium Target system** providing intense high energy neutron beam

(3) **A Test Facility** with a High Flux Test Module



Heat extraction using high velocity liquid Li

Accelerator Validation: LIPAc



FUSION FOR ENERGY

Prototype accelerator: D, 9 MeV, 125 mA

Mainly designed and manufactured in Europe, installed and commissioned in Rokkasho

Conclusions

- The **demonstration of production of electricity** around the middle of this century in DEMO is a **primary objective of the fusion program in Europe**. **Strong emphasis on:**

  - **Credible extrapolations from the ITER** physics and technology basis **to minimize development risks.**
  - An **holistic design approach** to develop a coherent integrated DEMO concept design that meets the requirements.
  - **Emphasis on design integration risks** and **engineering/operational challenges** arising from power conversion aspects and technology feasibility, safety licensability and RH.
  - **Targeted technology R&D** that responds to **critical design feasibility, performance and integration risks.**
  - Gate Reviews planned to effectively assess Design Maturity/ System Design Readiness help evaluate and down-select multiple design options.

  - **This approach represents an important change in the EU fusion laboratory culture**
  - **Involvement of industry and exploitation of international collaborations on a number of critical areas is desirable.**

Acknowledgements

The PPPT PMU Team:
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The EU Fusion Laboratories involved:

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- Revised DEMO Design and Development Plan (As part of update of the EU Roadmap to Fusion Electricity) 2N2FJB
- DEMO Stakeholder Requirements Document 2MGNEW
- DEMO Plant Requirements Document 2MG7RD
- Plant Break-down Structure 2MJ6WB
- DEMO Physics Design Guideline 2MPJUR
- General Safety Principles (draft) 2LJVZ7
- DEMO Plant Safety Requirements Document (PSRD) First Draft 2MKFDY

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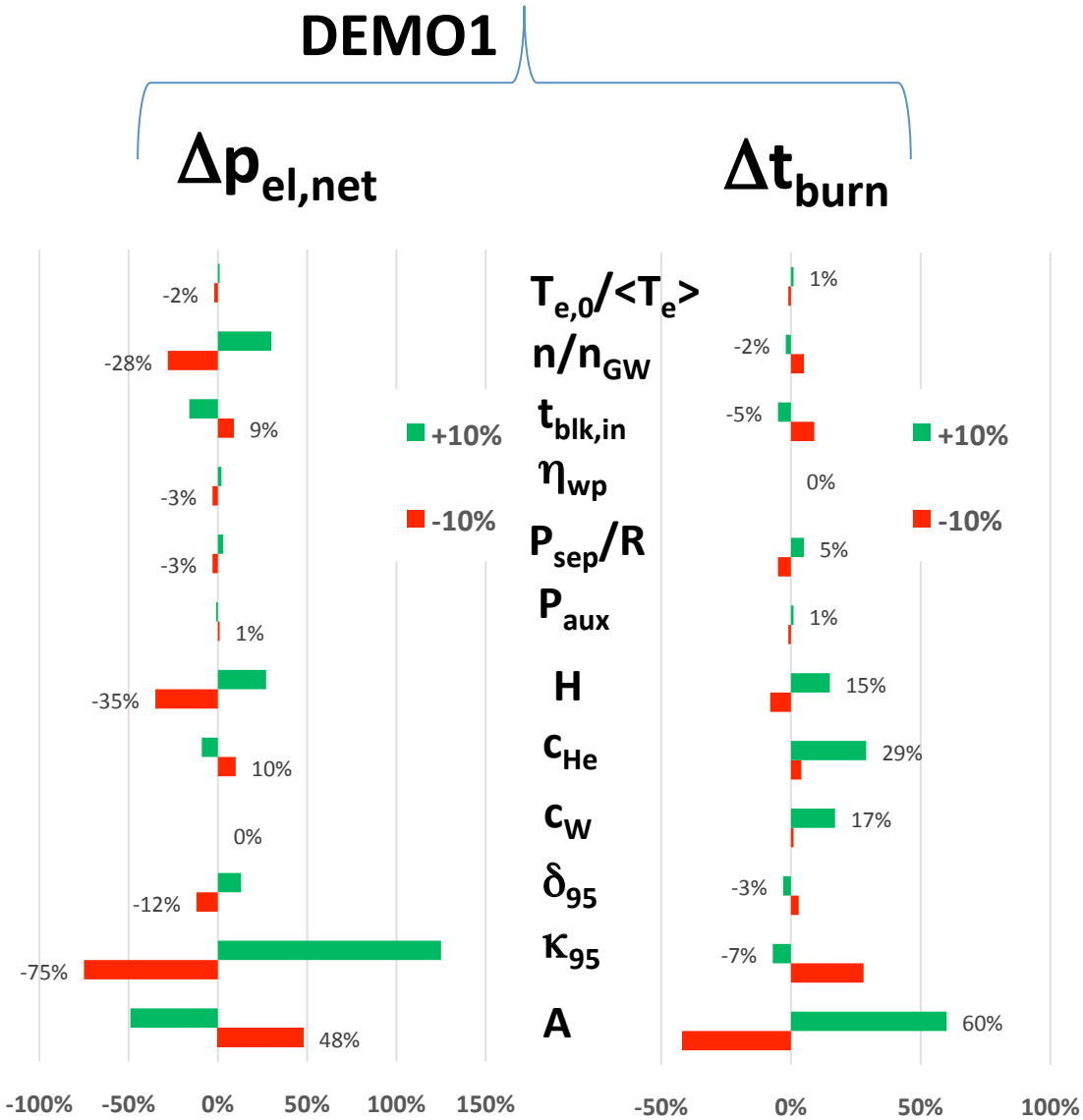
- **Born 28.5.1960**
- **Degree in Nucleal Engineering,** Polytechnic Milan 1985
- **Ph.D. UCLA 1989** (Fusion Eng. /Applied Plasma Physics)
- **Post-Doc Fellowship** EU Commission, Fusion 1990-92
- **NET Team**, 1992-93
- **ITER Team**, 1994-2006: Divertor and plasma interfaces
- **EFDA Garching**, 2006-2007: Field Coordinator VV/IVCs
- **F4E Barcelona** – Advisor of Chief Engineer (2008 – 2010)
- **F4E Garching, EUROfusion**: PPPT Dept. Head (2011–today)

Backup Slides

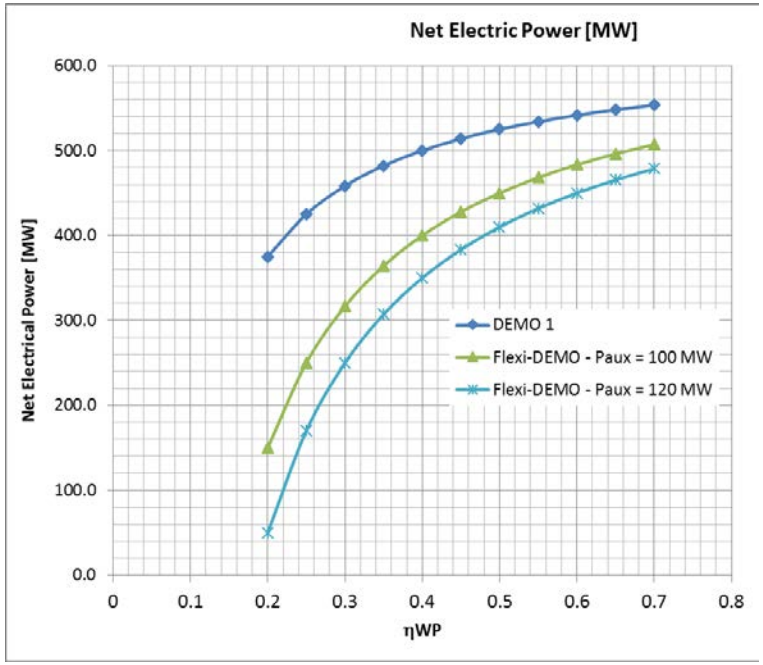
Sensitivity to Physics Uncertainties



R. Wenninger, et al., (2017) The physics and technology basis entering European system code studies for DEMO, Nucl. Fus. 57 016011.

Flexi-DEMO

The Flexi-DEMO option requires confidence in physics extrapolation and highly-reliable and efficient current-drive systems.



Mattia Siccinio, IPP

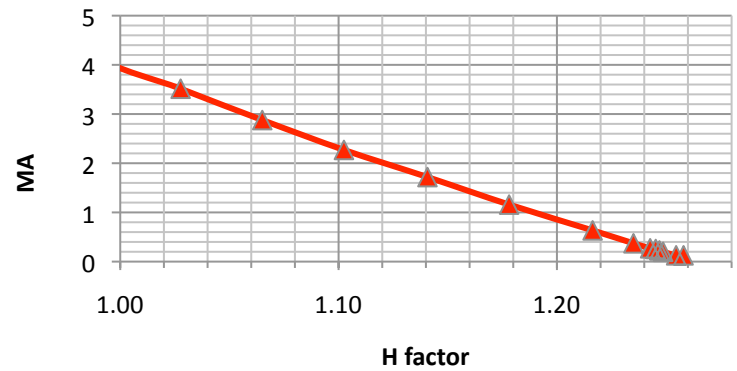
DEMO Design Options under Study: Flexi-DEMO

DEMO with a **focus on the extrapolability of the plasma scenario** to a FPP

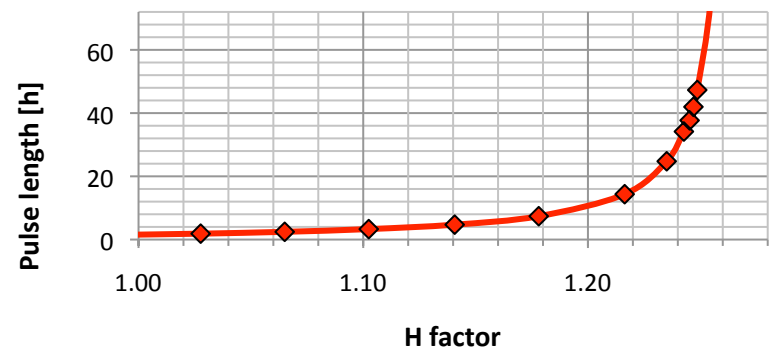
- Hybrid-type scenario; machine optimised for steady-state operation at H = 1.25
- **"Stepladder"** approach (Zohm, 2010):
  - $P_{fus} \propto B^7 \propto R^7$ (design parameters)
  - $P_{CD} \propto P_{fus}{}^{1/7}$
  - Limits for divertor and mode access
- **Target an attractive (but realistic) steady-state FPP plasma scenario** (e.g. f_{rec}<20%, i.e. 1000 MWe net)
- Scale down to a steady-state DEMO (few 100 MWe net) with higher f_{rec}.
- For H-factor < 1.25:
  - Pulsed operation
- Feasibility of **engineering integration and operational flexibility to be assessed**

F. Träuble, E. Fable, H. Zohm

Flexi DEMO Ohm. Curr. [MA]



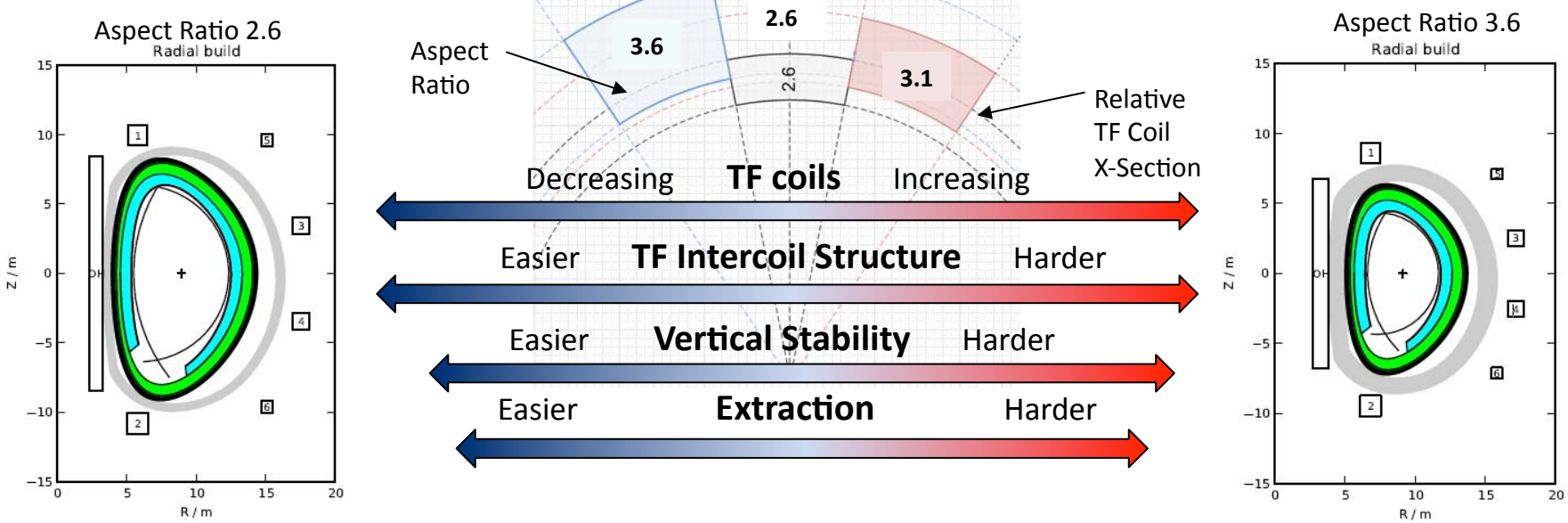
Flexi-DEMO Pulse length [h]



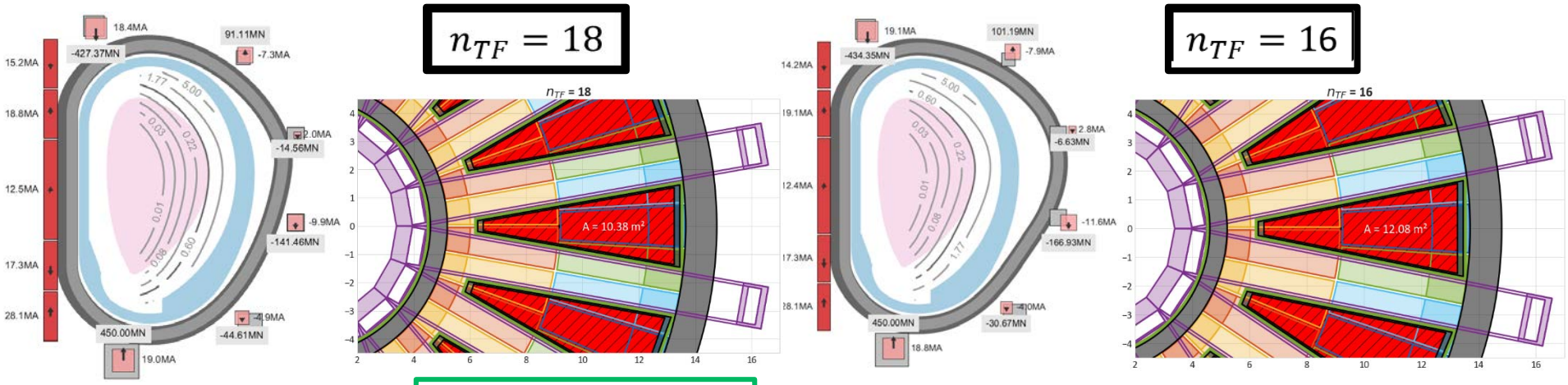
H. Zohm et al., A stepladder approach to a tokamak fusion power plant. Nucl. Fus. 57, 086002 (2017).

Examples of Engineering Trade-off Studies/1

1) Trade-Off Studies: Aspect Ratio – R/a



1) Trade-Off Studies: # of TF coils



S. McIntosh, 2017

Examples of Engineering Trade-off Studies/2

3) Trade-Off Studies: TBR

Blanket size (radial thickness):
Inb: ~80 cm / Out: ~130 cm

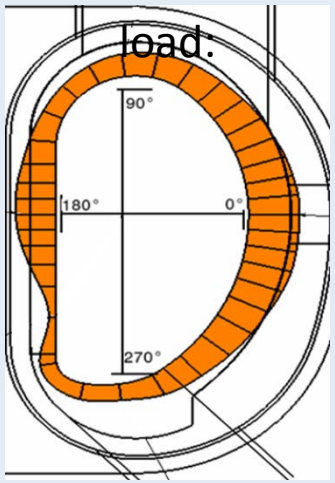
→Requirement: TBR ≥ 1.05

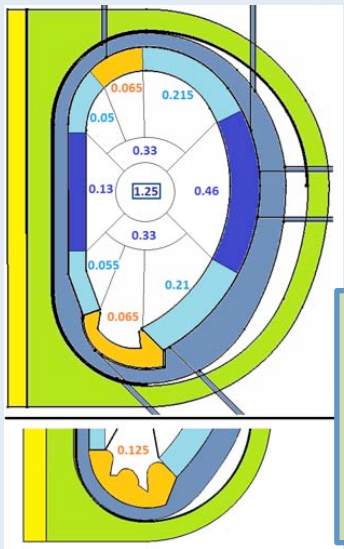
(after integration of diagn/ H&CD)

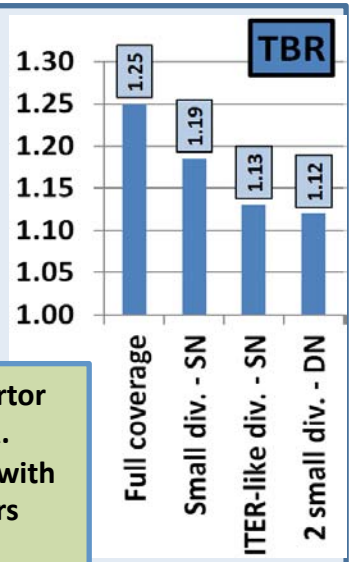
→Configuration: About 85% of the plasma must be covered by the breeding blanket.

→Integration issue: Space for divertor, limiters, and auxiliary systems is limited.

Neutron wall load.



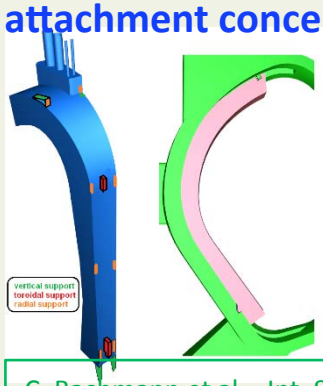


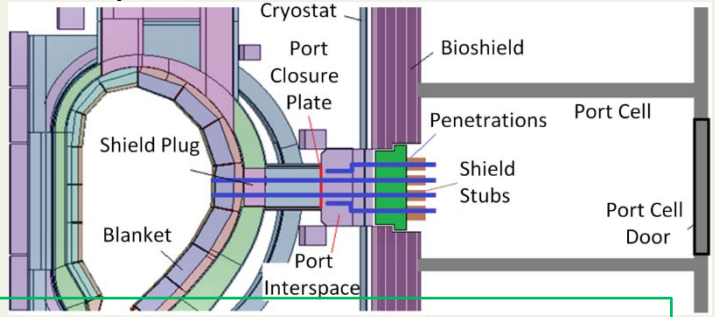


Reduction of divertor size improves TBR. DN configuration with two small divertors seems possible regarding TBR.

Blanket mechanical attachment concept

Design of n-shielding structures necessary to meet limits of tokamak components and the requirements for manual and remote maintenance.

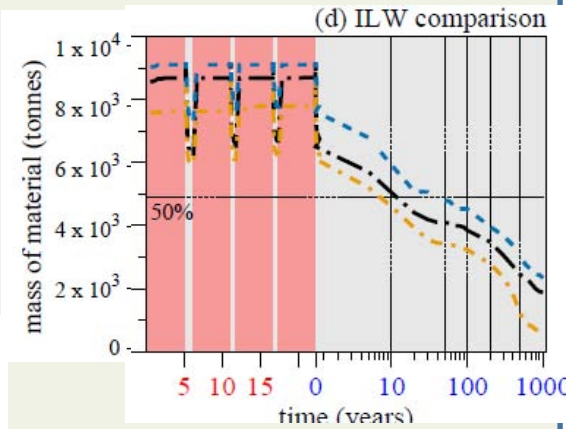




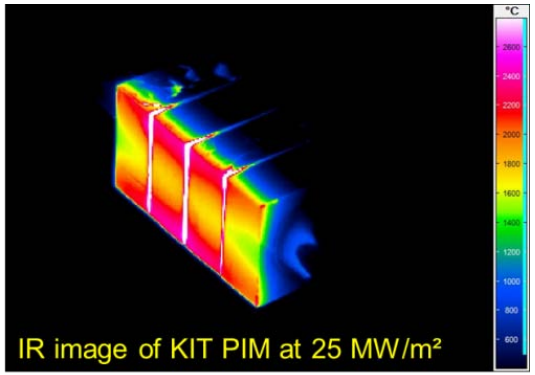
C. Bachmann et al.,, Int. Symp. on Fusion Nuclear technology (ISFNT), Sept. 2017, Kyoto, Japan, to be published.

Waste mass from the Vacuum Vessel (VV) for three DEMO BB designs

M. Gilbert, CCFE (ISFNT13 – 2017)



Examples of Technology Achievements (4)

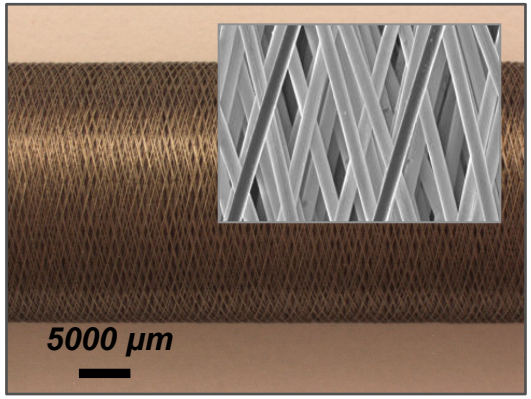


Tungsten

- **Successful HHF-test of mock-ups with PIM-W and of mock-ups with an W/Cu-FGM at 20 MW/m²**

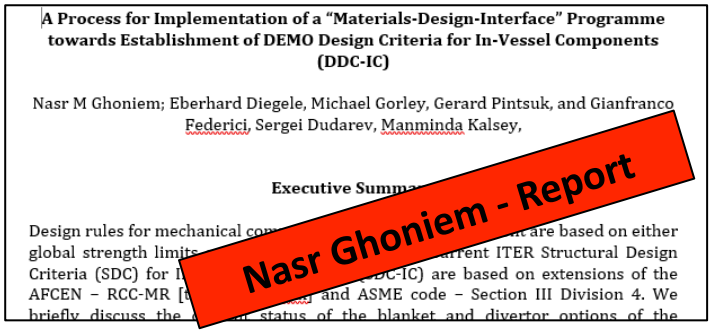
Demo-Design-Criteria [DDC]

DDC: International experts (Nasr Ghoniem) developed plans for progressing the "Material-Design-Interface



Tungsten/Copper mock-ups

- **Fabrication of W-particle, W-fiber and W-foil reinforced Cu/ CuCrZr pipes and implementation into mock-ups**


A Process for Implementation of a "Materials-Design-Interface" Programme towards Establishment of DEMO Design Criteria for In-Vessel Components (DDC-IC)

Nasr M Ghoniem; Eberhard Diegele, Michael Gorley, Gerard Pintsuk, and Gianfranco Federici, Sergei Dudarev, Manminda Kalsey,

Executive Summa

Design rules for mechanical co … are based on either global strength limits … rrent ITER Structural Design Criteria (SDC) for I … DC-IC) are based on extensions of the AFCEN – RCC-MR [… and ASME code – Section III Division 4. We briefly discuss the … status of the blanket and divertor options of the

Nasr Ghoniem - Report

ODS-Steels -> towards industrial scale

- **Fabrication of 14%Cr ferritic ODS (~50-100 kg) by conventional MA route at industrial scale involving several EU companies → thin) plates were successfully produced by hot and cold rolling**

Examples of Technology Achievements (5)

Safety and Environment

Setting safety objectives and requirements
- Top-level safety objectives
- Plant-level Safety Requirements
  - ➢ set with design teams involvement to ensure requirements are realistic and clearly understood by those responsible for implementation in design

Accident Identification
- Functional Failure Modes and Effects Analysis (FFMEA) completed for all key systems
- Done at functional level due to lack of design detail at this stage

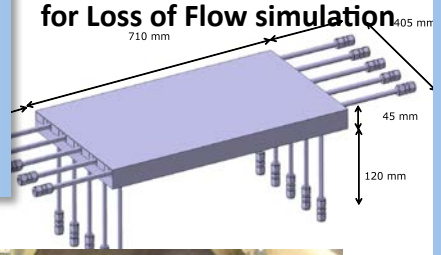
Identified initiators grouped into **21 Postulated Initiating Events (PIEs)**

Accident Analyses
- Modelling of accident event scenarios (e.g. Loss of Coolant, using MELCOR code)
- Focus on postulated events with possible impact on design choices
- Studies to estimate source terms (e.g. in-vessel tritium and dust inventory)

Safety Classification
- Definition of SIC classes
- Classification at top (system) level
- Classification at more detailed levels in progress

Model and code validation
- Experiments under way to provide data for safety code and model validation

First Wall Mock-up experiment at KIT for Loss of Flow simulation



Cold Crucible experiments at CV Rez, Prague

Environmental Releases (effluent)
- Identification of all systems that could be source of tritium release in normal operation
- Identification of potential release pathways
- Seek to minimise inventories and restrict pathways

Occupational Radiation Exposure
- Identification of potentially largest contributors to ORE
- Seek ways to minimise exposure / use Remote Handling

Radioactive Waste Management

Studies of key aspects to minimise active material requiring disposal as waste.

Detritiation
- Comprehensive survey of possible techniques
- Ranking and identification of most promising candidates
- R&D started on selected techniques

Recycling
- Studies of feasibility of recycling active material
- Studies (by industry) of technologies required in recycling process (e.g. large-scale melting)
- Best Available Technique (BAT) study

Work Programme to 2020
- Complete ongoing studies and analyses
- Produce provisional version of DEMO Generic Site Safety Report (GSSR)