# DEMO design activities in Europe

## Status and Prospects

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*FuseNet PhD event*
*EPFL, Lausanne*
*23 August 2023*

This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.

# Outline

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## 1. **The new context**

- ✓ Change of fusion landscape
- ✓ Need to reinforce the EU Roadmap
- ✓ Lesson learned from ITER and gaps

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## 2. **DEMO-related design activities**

- ✓ Re-baselining DEMO after G1
- ✓ Impact of high field coils: design and R&D
- ✓ Development needs of key core technologies

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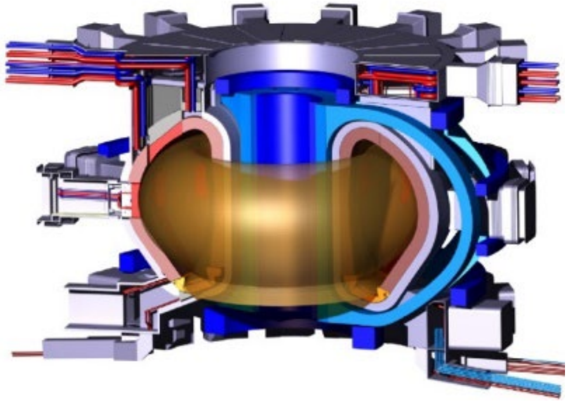
## 3. **Non-technical risks and bottlenecks**

- ✓ Licencing uncertainties
- ✓ Shortage of engineering skills
- ✓ Involvement of industry



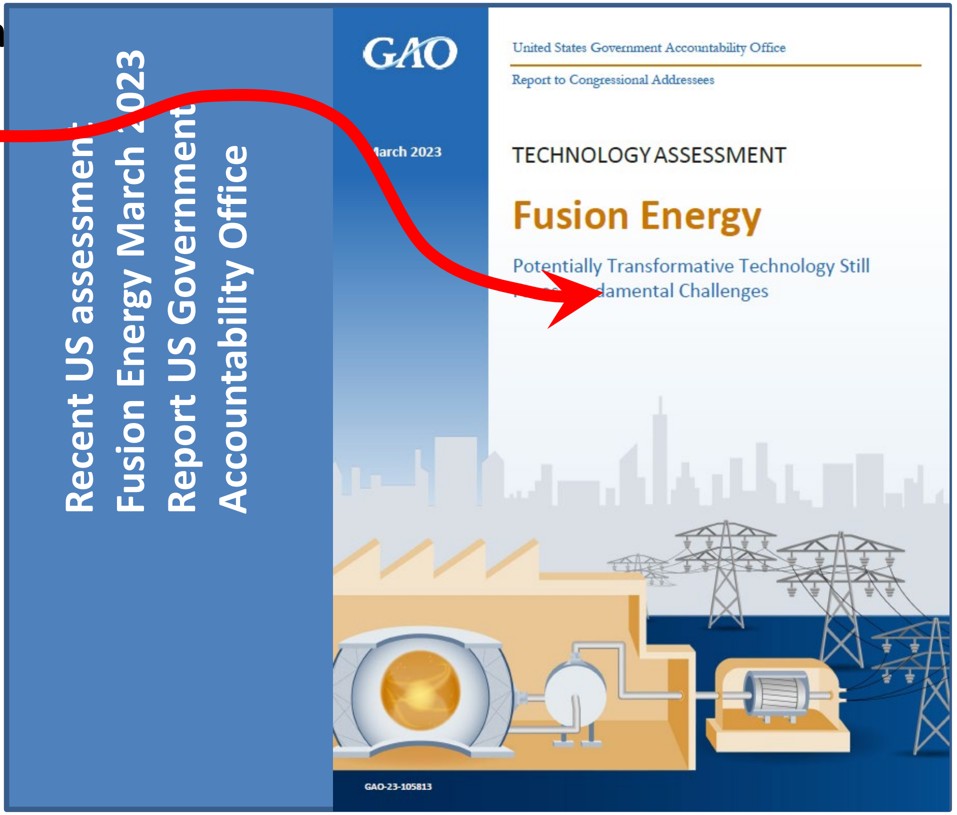
**Relevant recent publications:**

a. G. Federici - **Testing Needs for the Development and Qualification of a Breeding Blanket for DEMO**, submitted to Nuclear Fusion
b. J. Elbez-Uzan et al. - **Recommendations for the Future Regulation of Fusion Power Plants**, submitted to Nuclear Fusion
c. G. Federici et al. - **Relationship between magnetic field and tokamak size – A system engineering perspective and implications to fusion development**, to be submitted to Nuclear Fusion
d. C. Bachmann - **Relevance of a high magnetic field to the design of the EU DEMO**, submitted to Fusion Design and Engineering

New Context

# Fusion landscape is changing fast

- ✓ Increased perception, by governments and public, of the urgency to address clean baseload electricity and energy security
- ✓ A rapid transition is necessary to reduce dependence on fossil fuels
- ✓ Unprecedented rate of formation of so-called fusion energy startups (private investments)
- ✓ Overly ambitious claims (through a barrage of press releases) of com
- ✓ ITER is facing further delays
- ✓ **Technology Readiness of essential enabling technologies (breeding blanket, T fuel cycle, Divertor, Materials, RH) is low**
- ✓ **Europe is updating its roadmap**
  - ○ Maintain leadership and technological competitiveness, and increase appeal to younger generations
  - ○ Bolster and accelerate technology gaps activities exploring routes for earlier deployment
  - ○ Stronger involvement of industry in public-private partnerships
  - ○ Address regulatory uncertainties



Recent US assessment:
Fusion Energy March 2023
Report US Government
Accountability Office

GAO
United States Government Accountability Office
Report to Congressional Addressees

arch 2023

TECHNOLOGY ASSESSMENT

**Fusion Energy**

Potentially Transformative Technology Still
damental Challenges

GAO-23-105813

# Gain insights from ITER

- DEMO benefits largely from the experience gained from ITER
- **ITER remains the crucial machine for the validation of the DEMO physics and part of the technology**

- RoX from ITER emphasises the importance of safety and licensing, design integration, quality, shielding, fabricability, costs, RH
- These play an important role in the design of DEMO

**Ad-hoc technical meetings with ITER**

**Contribute to training young engineer grantees**

**IO (and F4E) experts are invited to attend DEMO reviews**

- There are still major technology gaps beyond ITER
- Low TRLs of DEMO enabling technologies for systems (i.e., breeding blanket, materials, RH) even after ITER
- The role of ITER in de-risking DEMO in the area of breeding blanket is questionable and risk mitigation options are studied

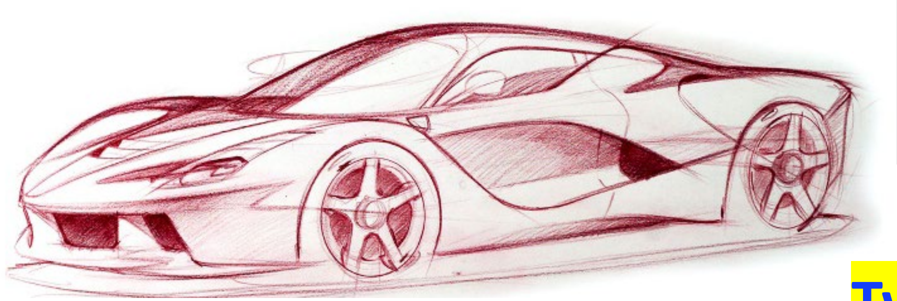
## TRL Now

**Water BoP (TRL 7-8)**
**Divertor RH (TRL 6)**
**ECH 170 GHz (TRL 6)**
**Magnets $Nb_3Sn$ LTSC (TRL 6)**
**Divertor (TRL 4)**
**He BoP (TRL 4-5)**
**NB (1MeV) (TRL 3)**
**Blanket RH (TRL 3)**
**Blanket (TRL 2-3)**

## TRL after ITER

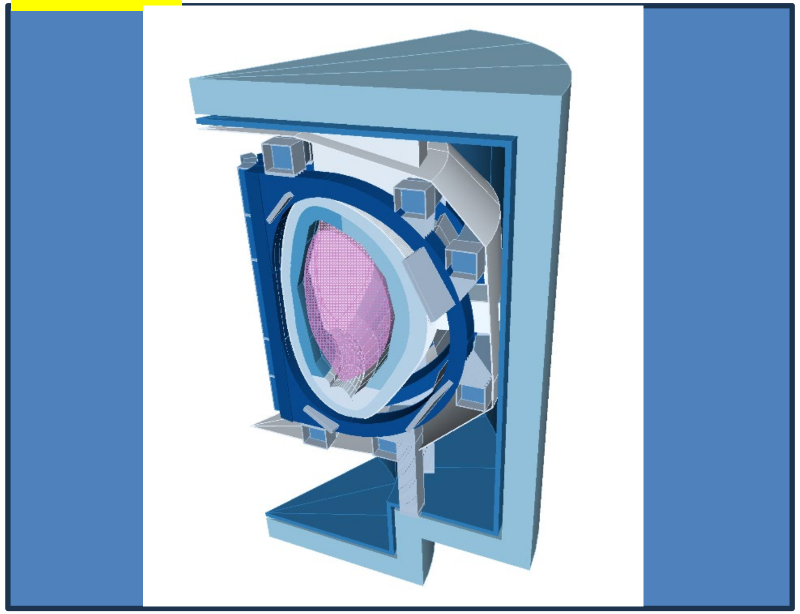
**Magnets $Nb_3Sn$ LTSC**
**Buildings**
**Vacuum Vessel**
**Cryopumps**
**Divertor and div RH (TRL 7-8)**
**ECH 170 GHz (TRL 6-7)**
**NB (1MeV)**
**DEMO Blanket RH**
**DEMO Blanket – TBM (TRL 4-5)**

# Main design activities



## Two concepts with different missions are being explored

## DEMO

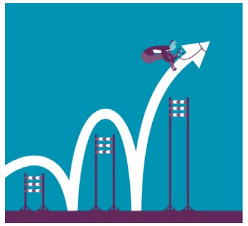


**MISSION / OBJECTIVES**

- ✓ Electricity production
- ✓ Tritium self-sufficiency (TBR>1)
- ✓ Reasonable plant availability towards the end of operation

$P_{fus}$=2 GW, $P_{el}$=0.5 GW
Pulse duration=2 hr
R= 8m, a = 3 m
$B_o$=5.9 T, $B_{leg}$=13 T
$I_p$=20 MA
NWL= 1 MW/$m^2$,
Fluence = 20+(50) dpa

Advancing the DEMO concept design by addressing all the technical issues emerged during the Gate Review G1



- ✓ Breeding blanket / remote maintainability
- ✓ Plasma scenario, plasma exhaust, and first wall protection
- ✓ Confinement/ contamination strategy and nuclear buildings

## Plasma-based VNS (not new!)

**Tentative**

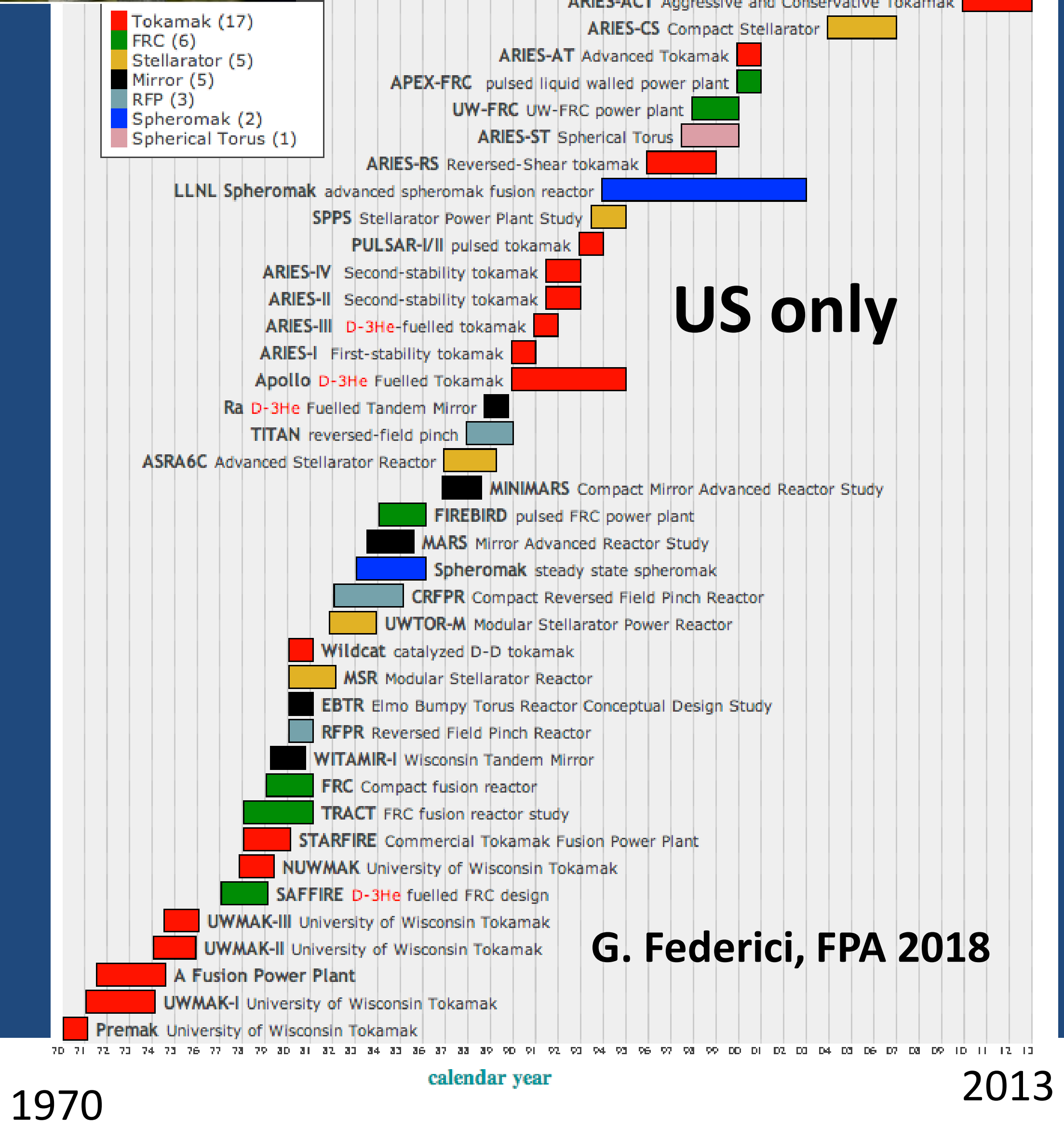
$P_{fus}$=50 MW
$P_{el}$=0.0 GW
steady state
NWL= 0.5 MW/$m^2$
N-Fluence=tbd

**Feasibility Study**
**Just started!**

**MISSION / OBJECTIVES**

- ✓ **Reduce DEMO risks by qualifying essential technologies in advance**
- ✓ **Demonstrate breeding, quantify failure modes**
- ✓ **Eliminate the need for high-fluence in DEMO**
- ✓ **DEMO no longer a 'qualification' device, becomes a real demonstrator (FOAK FPP)**
- ✓ **Enable faster deployment of FPP**

# Lesson of the past: many MFE power plant studies:

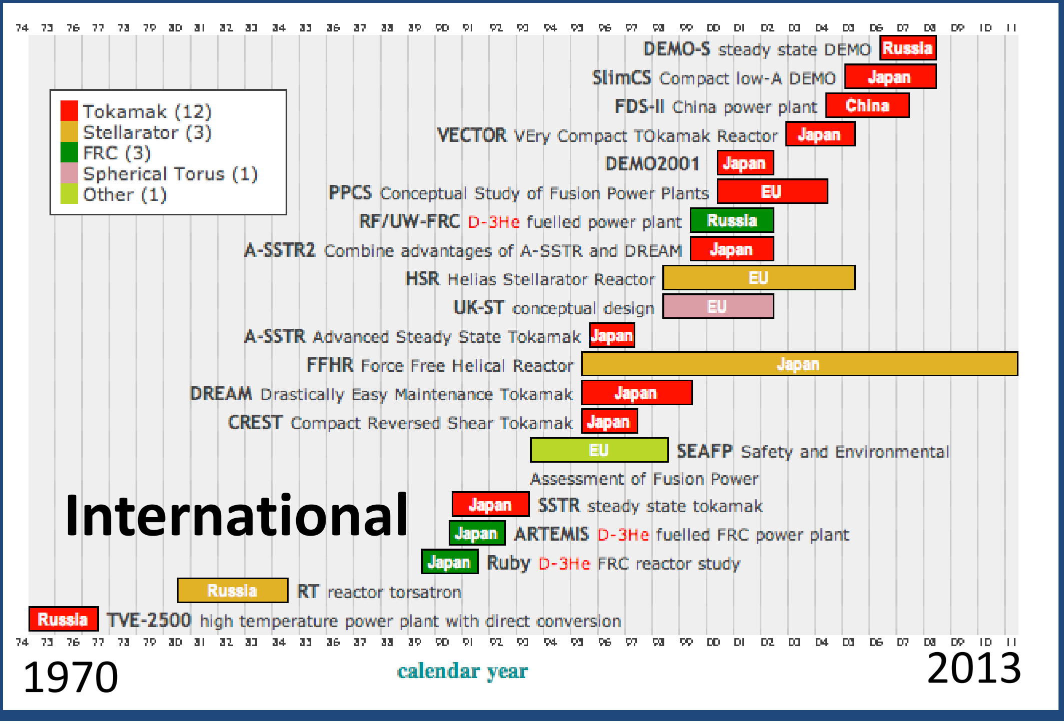


**G. Federici, FPA 2018**

## Caveats

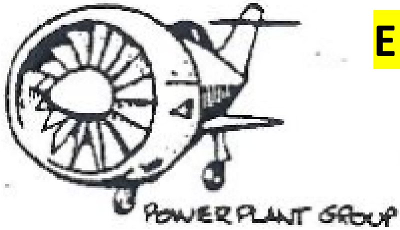
### A wealth of interesting information, <u>but</u>:

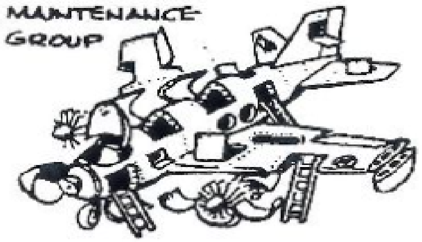
- Very favourable physics and technology assumptions, unrealistic
- Divertor problem underestimated or ignored
- Lack of thorough nuclear design integration considerations

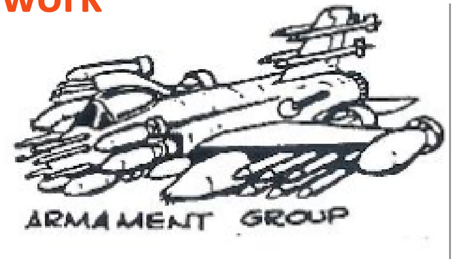


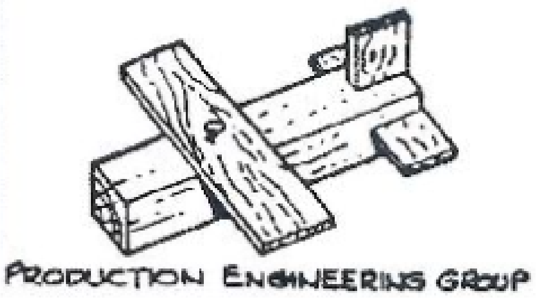
# Search for the optimum design

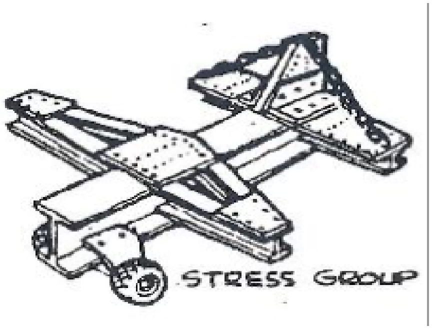
If everyone is let to go on his own way you end up having something that does not work











***Dream Airplanes** by C.W. Miller. Optimal airplane design from the perspective of engineers of different specialties 2010. Reston, VA: American Institute of Aeronautics and Astronautics.

G. Federici "FPA 40th Annual Meeting, Washington DC, USA, Dec. 3-4 2019.

## EUROFUSION system-oriented design approach

- A lot of discussions about making fusion smaller, cheaper, and faster, **but there is no magic bullet to solve the integrated design problems.**
- **What makes a design sound:**
  - ✓ Realistic physics and technology assumptions
  - ✓ A sound operating scenario and a consistent strategy for the power exhaust to be validated by ITER
  - ✓ Robust design with margins considering all the loads and the constraints often coming from system interdependencies
  - ✓ Early attention to nuclear design integration and safety/licensing
  - ✓ Sufficiently mature technologies for all the systems

## Lesson learnt from DEMO pre-concept design

Still large plasma physics uncertainties that impact the design

Integration of multiple design drivers across different systems

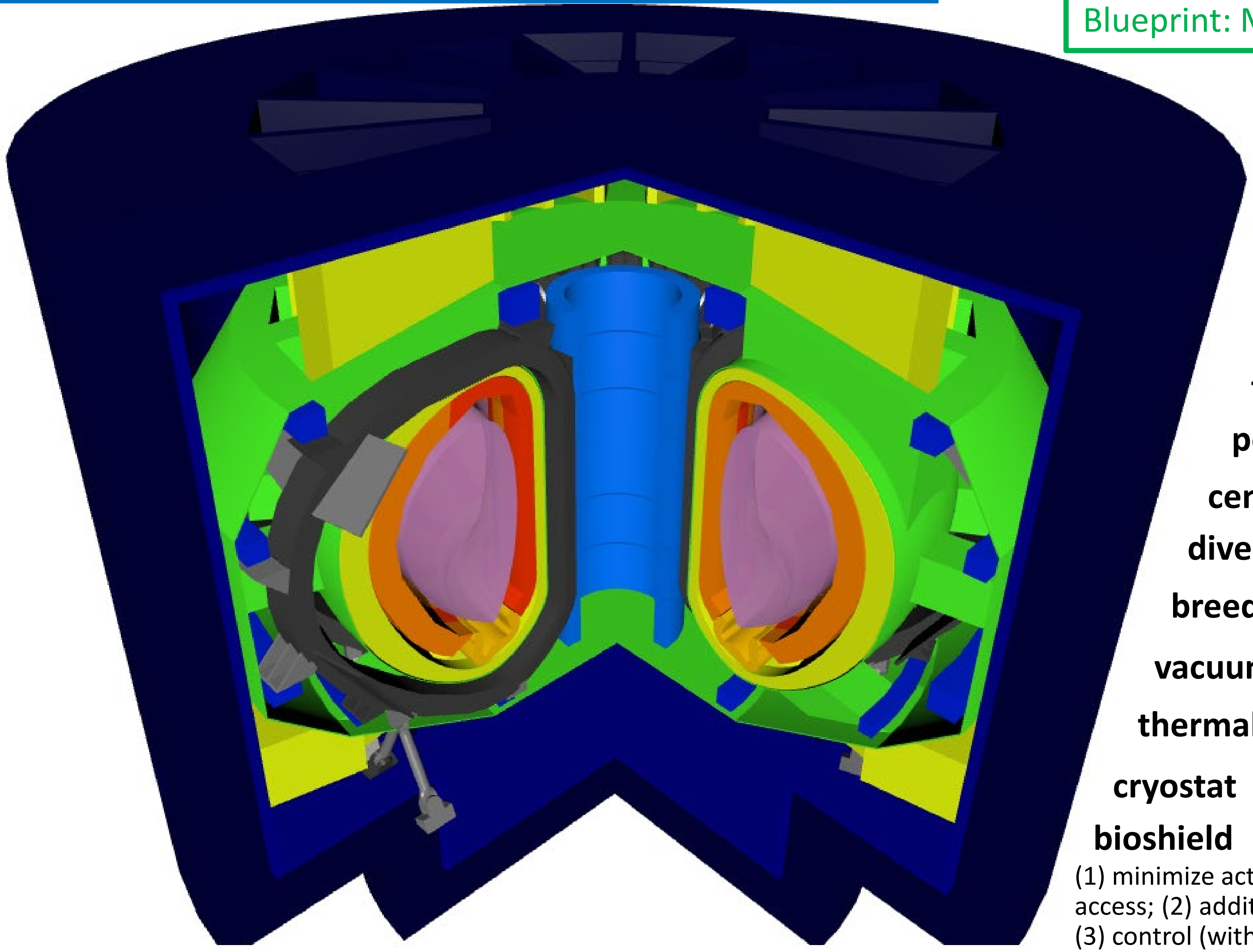
**Many systems interdependencies with key nuclear systems:**

**Low technology readiness of essential enabling technologies**

https://www.sciencedirect.com/journal/fusion-engineering-and-design/special-issue/10RRZQ6LW4H

# DEMO fusion reactor build

Blueprint: Matti Coleman (CCFE)



**plasma**

**toroidal field coils**

**poloidal field coils**

**central solenoid**

**divertor**

**breeding blanket**

**vacuum vessel**

**thermal shield**

**cryostat**

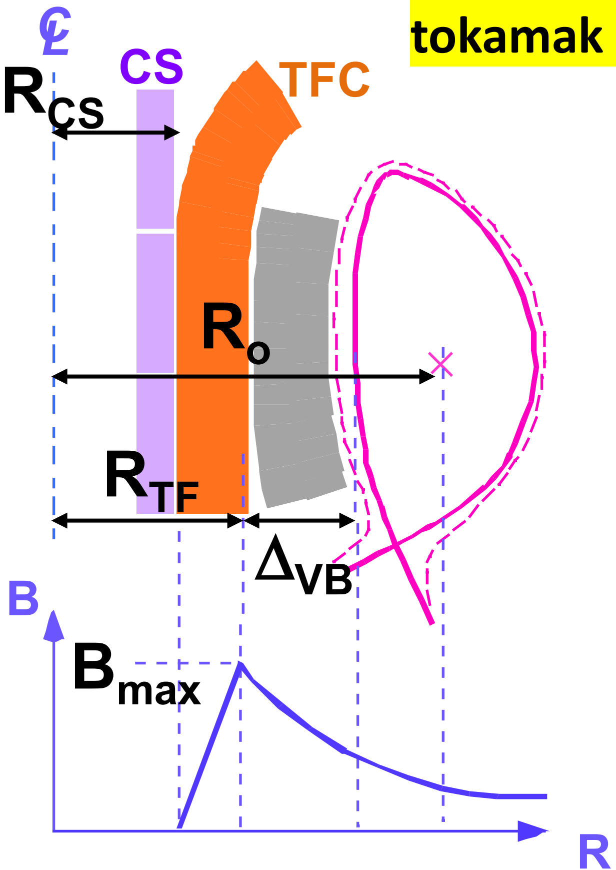
**bioshield**

(1) minimize activation and permit human access; (2) additional confinement barrier. (3) control (with HVAC) contamination spread; (4) shielding during remote handling cask transport. (5) it can be seismically isolated.

**Limited Spaces AVALIABLE**

# What defines the size of a DEMO tokamak?

**Inboard space utilization is a crucial design aspect in tokamak design: trade-off plasma/shielding/magnets**



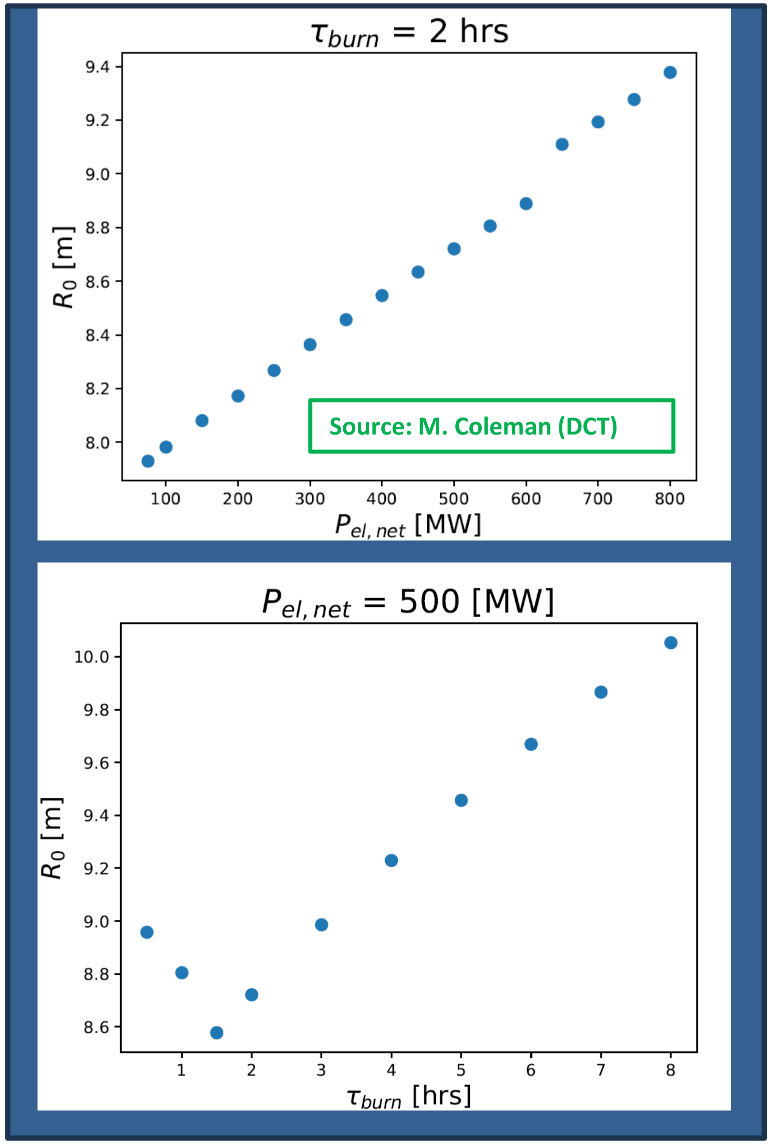
**Key constraints/ engineering drivers**

Central Solenoid: (pulsed machine – become constraining at low aspect ratio)

TF coil radial build (see next slide)

Shield/ breeding blanket (1.3-1.4 m inboard)

Plasma: divertor heat load at reattachment

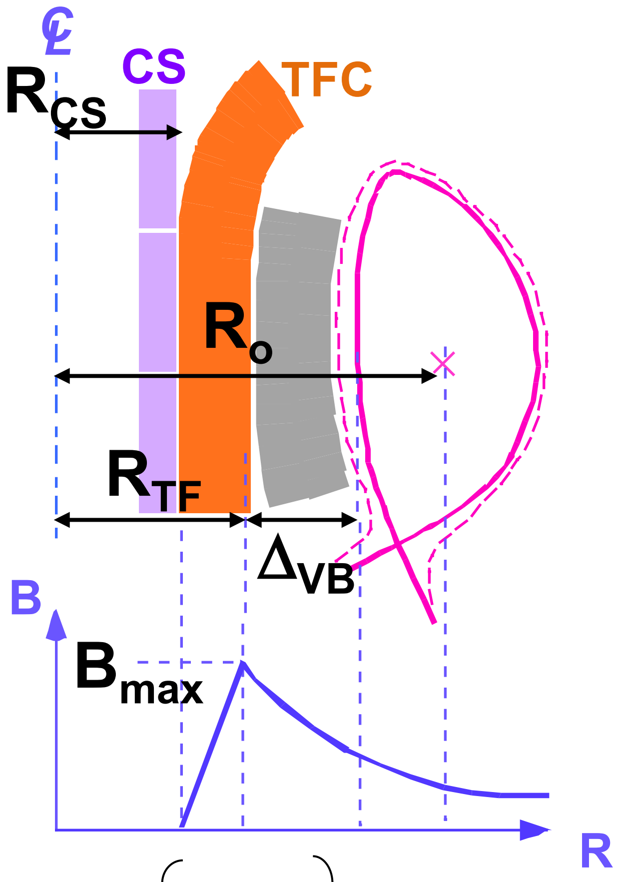


Source: M. Coleman (DCT)

Study to analyze **sensitivity of machine size** to **plant electrical output**, **pulse duration**

- Reducing electricity output does not bring significant size reduction
- The CS size increases as a function of the pulse duration but also at very low pulses because of fatigue considerations

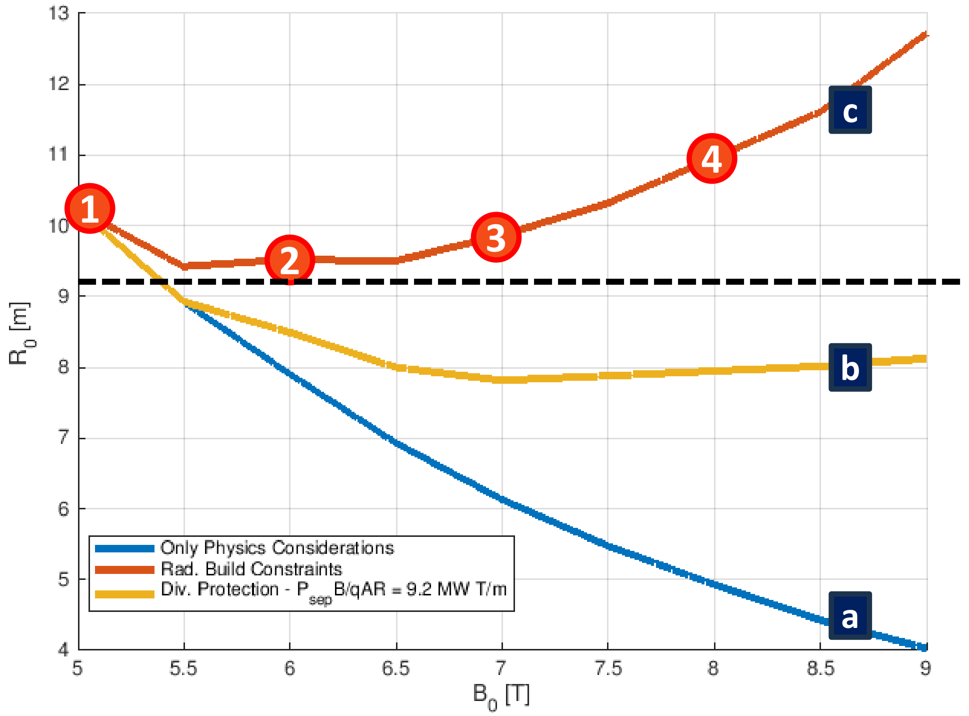
# Impact of high field coils on machine size



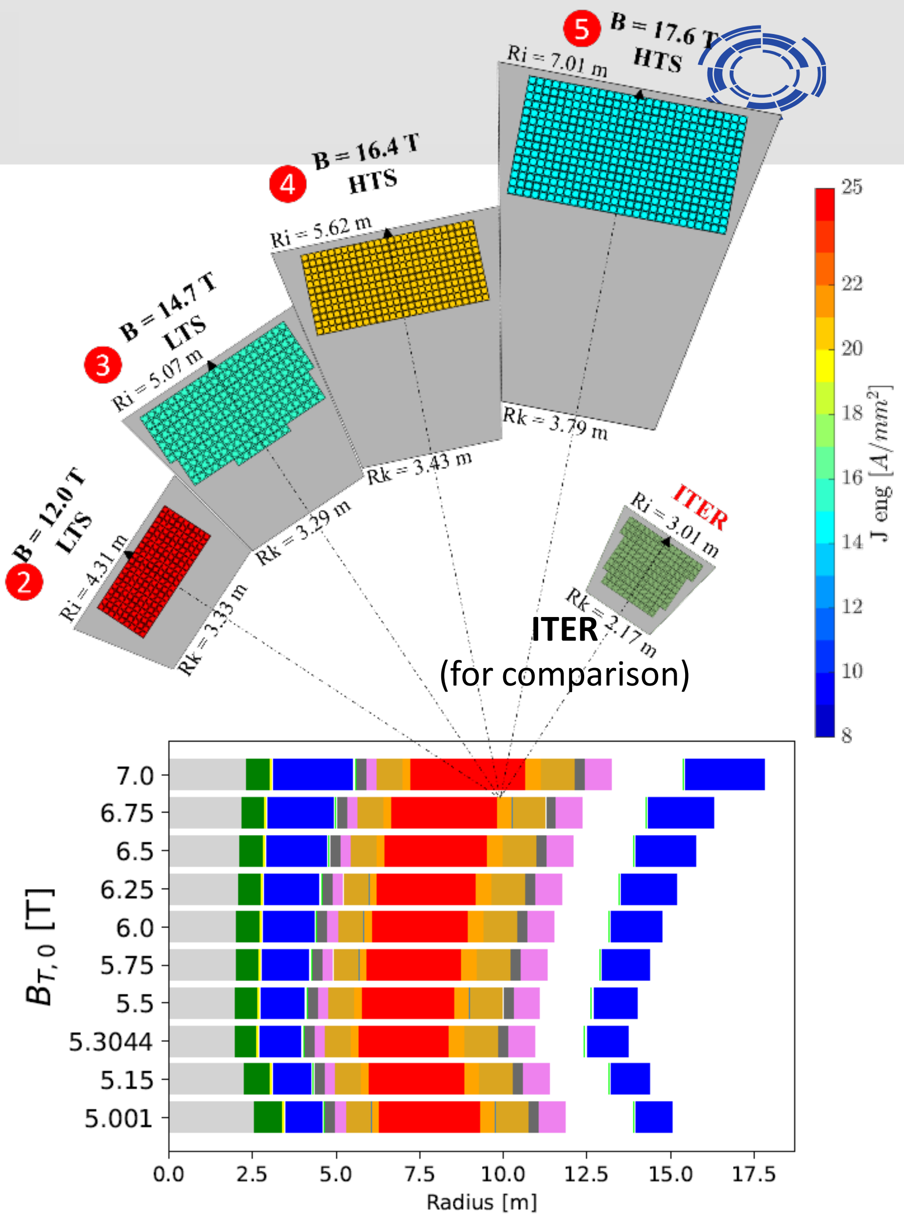
$\Delta_{VB}$ { Breed BLK, n-shield, VV, TH-Shield }

*Rule of thumb* 1.3-1.4 m

**$P_{fus}$=2000 MW, pulse = 2 hrs, A=3.1**



M. Siccinio, C. Bachmann. L. Giannini



Source: PROCESS M. Coleman

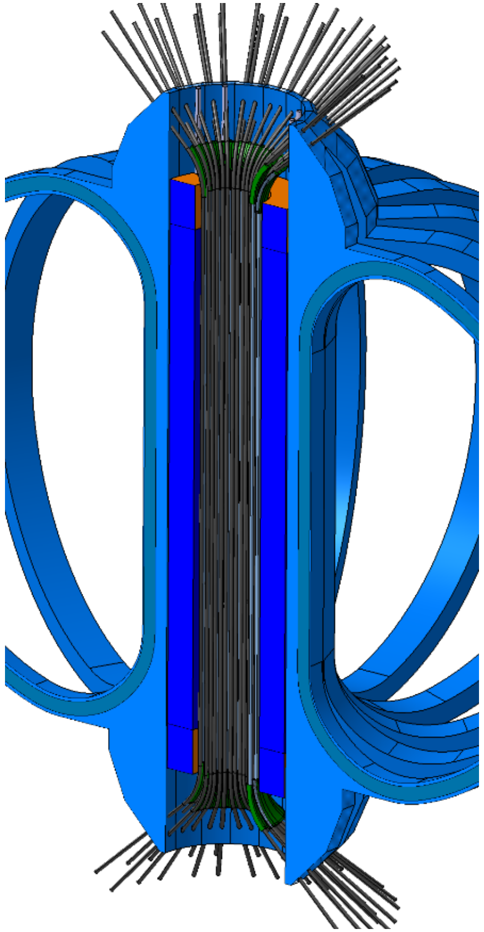
→**for higher B-field**, large structures are required to resist radial/vertical forces TF inner leg. Alternative mechanical concepts are very challenging or do not bring significant improvements

# Alternative mechanical concepts for DEMO are either unfeasible or do not bring much improvements

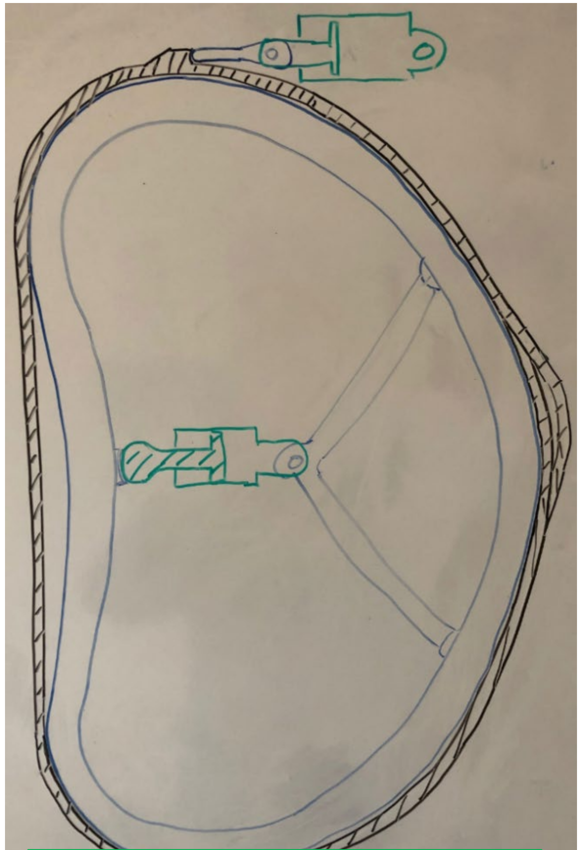
Source: C. Bachmann

## Concepts of TF vertical pre-compression

Steel cables @ 1200 MPa tension generate vertical + radial pre-compression



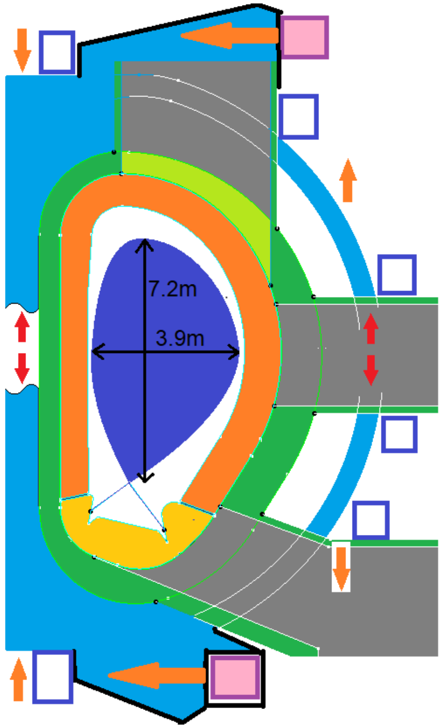
Steel cable wound around TF coil in assembly hall to generate overall pre-compression of coil



C. Bachmann - Relevance of a high magnetic field to the design of the EU DEMO, submitted to Fusion Design and Engineering

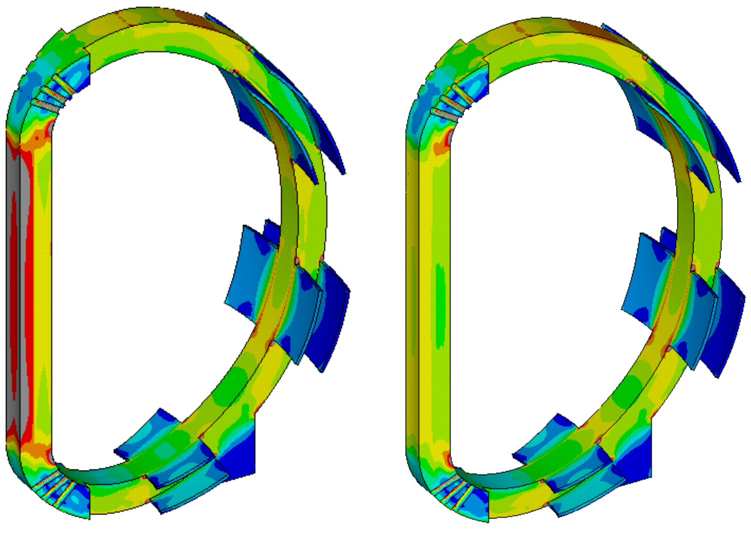
C-clamp principle [P. Titus, FNSF, TOFE-2020]:

- Large pre-compression rings cause a vertical pre-compression of the TF
- Transfer of vertical loads to the outboard side



**Bucked + wedged concept:**

- Release TF inboard leg from EM forces through transfer of radial force to CS
- Reduce stress cycle on CS conductor
- This relies on wedged inboard legs: only possible if an assembly gap of ~3mm ± 1mm between CS and TF can be ensured which is very unlikely!



Assembly gap = 5mm

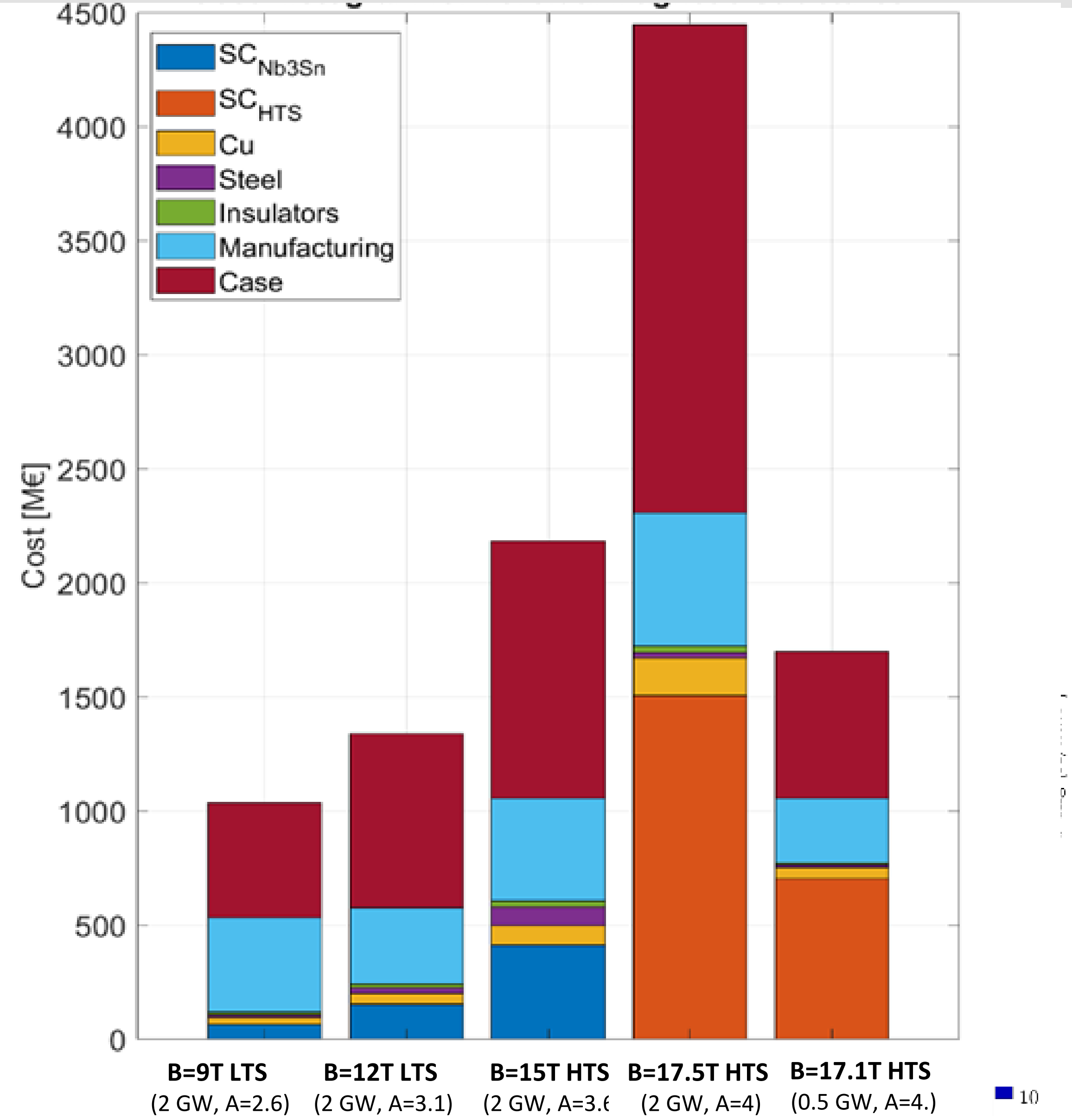
Assembly gap = 1mm

# Industrial coil feasibility and cost issues

## Benefits from coil designs that minimises TF structures

- With high-field one needs massive structures
- There is a practical limit to the max. thickness of the TF nose based on manufacturability (given by size of forgings)
- There is also a limit to weldability of segments and weld deformation, which becomes hard to control in large and thick structures. Mock-ups are required
- For DEMO-class machines, the cost of the structures alone (just the coil case) is a significant fraction of overall cost of TF coils
- In ITER, the material procurement and manufacture of the TF coil cases was the main driver of the schedule of TF coil deliveries (even with an intense three-supplier approach)
- A DEMO industrial study concluded a minimum of 12 years for structure production, assuming two suppliers in parallel

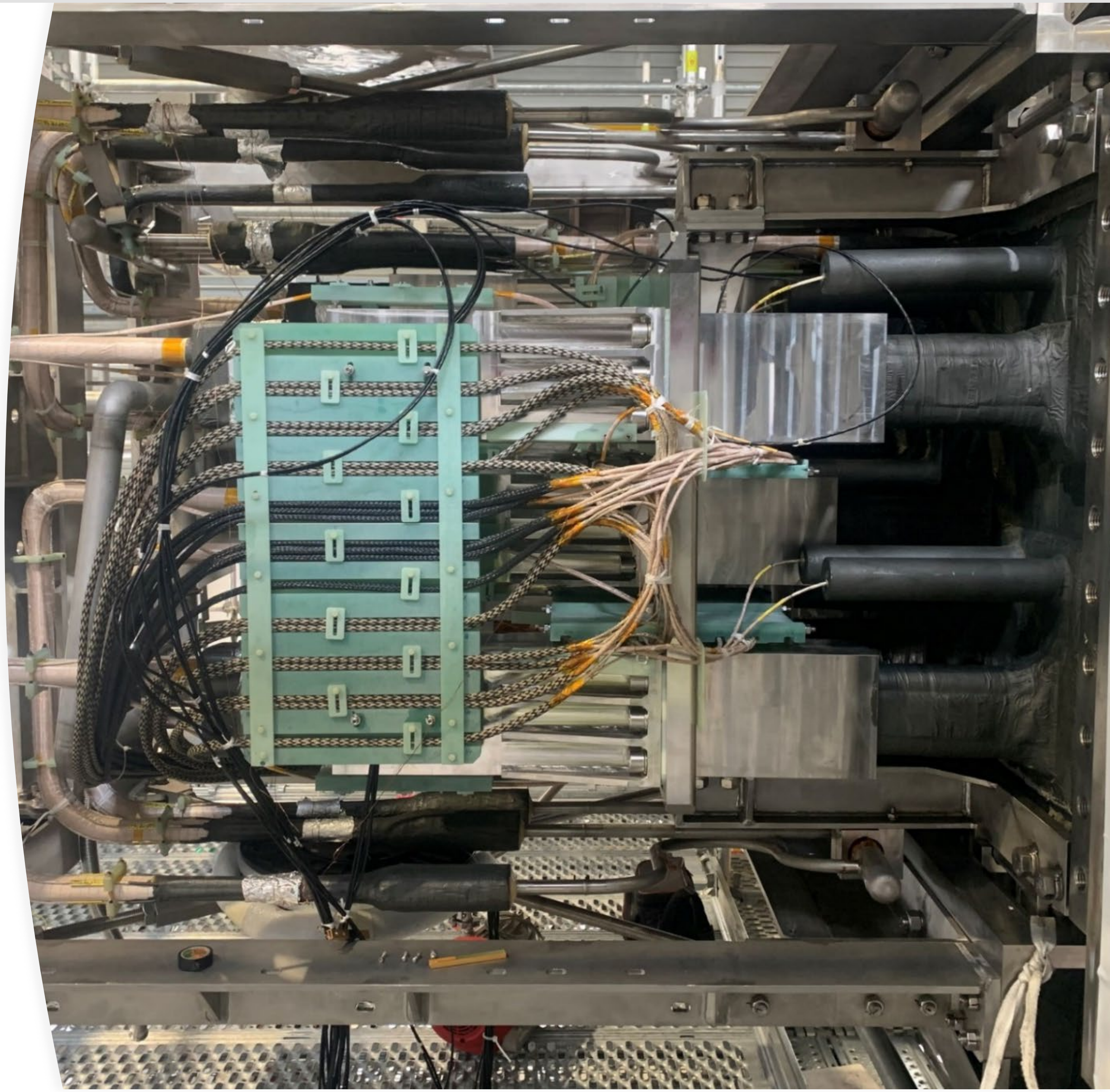
Source: L. Giannini, M. Siccinio, M. Lungaroni



# Magnet with HTS conductors

## STRATEGY RECOMMENDATIONS

- HTS offer the promise of operating at both higher magnetic fields and higher current density ( for Non-Insulated coils)
  - Potential to increase flux in **CS coil** of a tokamak
  - Quench protection of NI coils for large-scale magnets is an area in which development and qualification is still needed (maturity level)
- However, even if we do not operate at high field and start within conventional insulated coils, HTS can still offer benefits:
  - **Simplification** of the magnet cooling scheme thanks to increased temperature margin (indirect conduction cooling)
  - This in turn can greatly simplify coil construction and **minimize High-Voltage risks** at the terminals by decoupling coolant and current-carrying functions of the conductor



ITER TF coil terminals
Leads, wires, and pipes with electrical breaks, all penetrating the ground plane

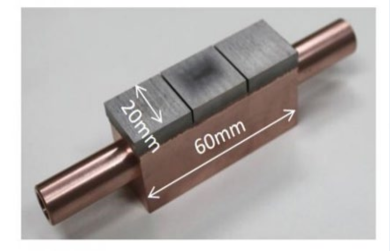
**Time-consuming**

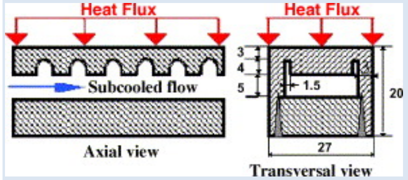
**Tasks**

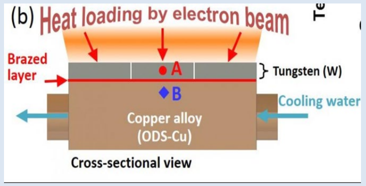
# Performance and reliability of critical core technologies
# → long lead times for R&D needed: (15-25 yrs)

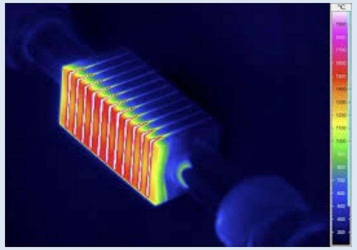
## Divertor targets

- ✓ Impressive advances thanks to ITER R&D (1990's-2000's)
- ✓ Fabrication of many (**> 100**) types of small- and medium-scale mock-ups (e.g., different tube, mtls, geometries, armors and geometries, fabrication methods, joints types)
- ✓ Qualification/industrialization of key processes High heat flux testing campaigns: investigating degradation after repetitive thermal loads in HHF tests stands (Gladis, Judith, US, RF, Ja EBs etc.







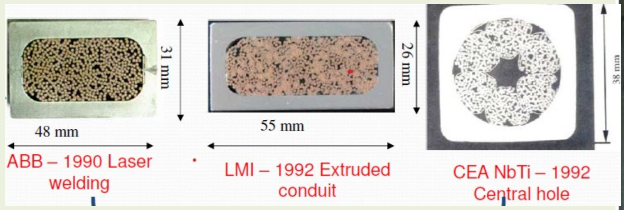


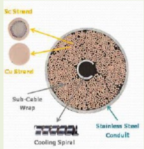
## Superconductor samples

- ✓ Development and testing of many types of conductors (mtls., void fraction, twist pitch etc.) inc. HTS. Tests in Sultan and Edipo (EPFL-PSI as of 1992)
- ✓ Qualification and industrialization of key components and technologies
- ✓ Model coil fabrication and testing e.g., FENIX (MFTF-B choke coil in Nb3Sn ITER TF and CS 2000's)

**DPC Nb3Sn cable in conduit 1985**

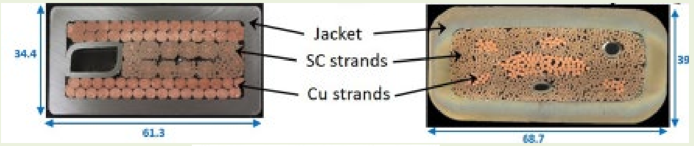
**CICC 1991**





**ITER TF 1993**

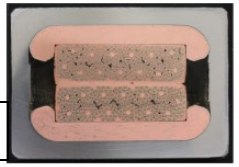
**ITER CS**

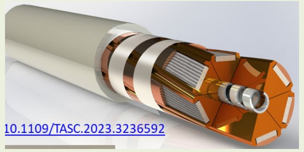


**DEMO**

**Sultan**

**LTS joint**



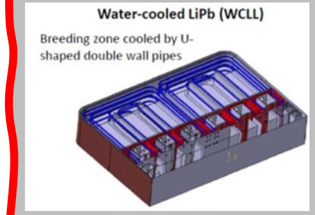


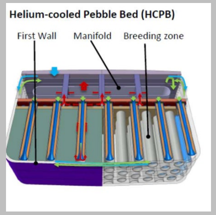
10.1109/TASC.2023.3236592

**HTS**

## Breeding blanket

Most novel and complex system





- ✓ Heat transfer across breeder/RAFM plates and coolant pipes
- ✓ High temp./pres. coolants→ strong influence on reactor design
- ✓ T generation and extraction in Li-based solid/ liquid breeders
- ✓ n-irradiation damage→ structural material properties
- ✓ Power and particles on first wall

No breeding blanket has ever been built or tested under relevant integrated conditions.

- Still large uncertainties/ feasibility concerns → very low TRL
- Strong impact on machine availability

**There is a technology gap in this area that needs to be urgently addressed**

# Regulatory uncertainties

## 12 recommendations

**EUROfusion established an expert group in April 2022 to identify key recommendations when developing a regulatory framework tailored to fusion safety.** Outcome is being published in Nuclear Fusion

### R1 - GOAL SETTING REGULATION

A regulatory approach should be adopted whenever possible for FPP design, construction, commissioning, operation, and decommissioning, to allow the operator to apply a proportionate approach to reflect the FFP hazard potential.

### R2 - CRITERIA FOR EMERGENCY REFERENCE LEVELS IN REGULATIONS

A design objective for FPPs should be that no accident within the design basis should result in the release of radioactive materials that would require offsite emergency countermeasures or further restrictions of the civilian population outside the plant.

### R3 - ENVIRONMENTAL CRITERIA FOR LARGER PUBLIC ACCEPTANCE

To encourage public acceptance of FFPs, transparency, education, and information of the public with respect to tritium discharges is necessary.

### R4 - RADIOACTIVE WASTE PRODUCTION

Seek international agreement on the need for uniformity of waste acceptance, storage and disposal criteria and understanding of fusion specificities. Minimization of radioactive waste shall be of primary consideration…….

### R5 - REGULATION OF FPP PRESSURIZED SYSTEMS

Specific European regulations on pressurized equipment shall be written for FPP or adapted from the existing set of the European Directives to consider fusion specificities.

### R6 - INTERNATIONAL DATABASE

Internationally verified and validated analysis codes should be developed to ease the acceptability of simulation by local authorities. A list of topics for which international databases are needed to consider the specificity of FPPs shall be assessed, and operating modes as well as to fusion material nuclides effects and complex maintenance activities.

### R7 - FUSION CODES AND STANDARDS

C&S, developed for fission facilities, are used by designers, regulators, and operators of nuclear plants. These codes and standards (e.g., ISO, IEC) should consider fusion specificities. A list should be established, topic by topic, to identify the nuclear and/or industrial codes and standards that are applicable, non-applicable, to be newly created.

### R8 - GRADED APPROACH TO SAFETY DEMONSTRATION

This graded approach applies as follows:

- no systematic application of the single failure criterion when the consequences of accident scenarios are low,
- acceptance of potential common mode failures when consequences of acc. scenarios are low,
- no systematic combination of loads when the consequences of accident scenarios are low,
- adaptation of design extension conditions to FPPs

### R9 - DETERMINISTIC AND PROBABILISTIC APPROACHES

Safety demonstration shall be based on an initial deterministic approach (using conservative assumptions), with appropriate lines of defence that are proportionate to the hazard potential. This approach should be complemented by the application of a probabilistic approach…

### R10 - CONSENSUS ON A REGULATORY FRAMEWORK FOR FUSION POWER PLANTS

Engage IAEA and members states to seek international agreement on what constitutes the basis of an appropriate legal and safety regulatory framework for FPPs that should be delivered by the national regulator.

### R11 - IMPLEMENTING A LEGAL AND REGULATORY FRAMEWORK FOR FPPs

A new regulatory framework for future Fusion Power Plants should be consistent with the IAEA Fundamental Safety Principles and, preferably, technology neutral.

### R12 - PRESCRIPTIVE REGULATORY FRAMEWORKS

For countries using a prescriptive approach to regulation, any regulatory requirements and regulations relating to the safety of Fusion Power Plants should be based on a graded approach and be proportionate to the hazard potential of a Fusion Power Plant

# Workforce development is a critical bottleneck

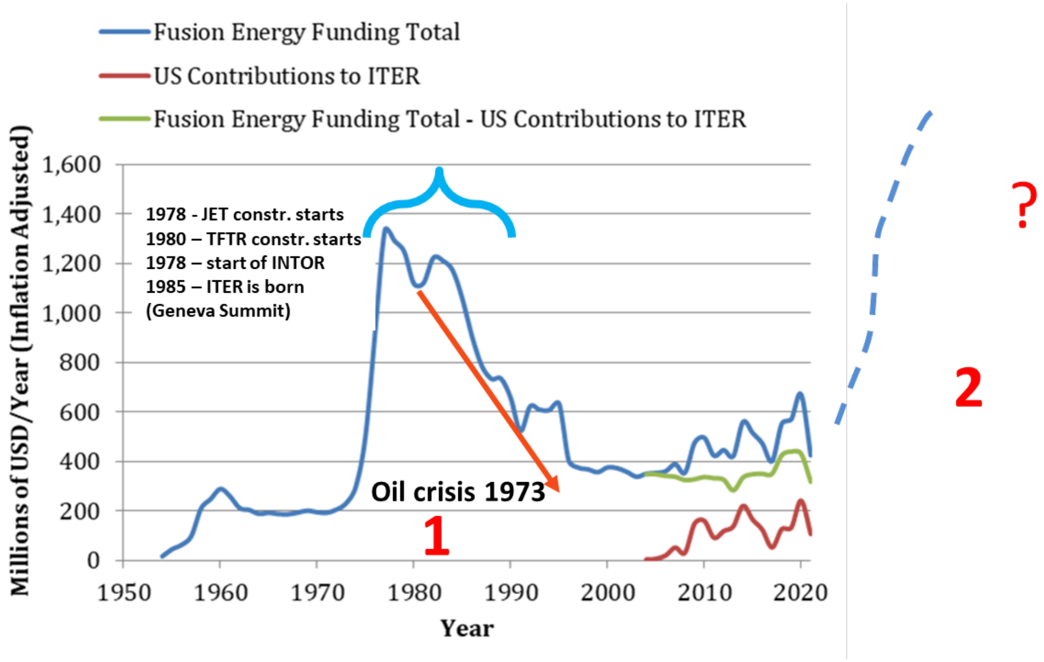
- The fusion programme is internationally picking up momentum
- A first generation of fusion pioneers has left or is leaving the field
- Acute shortage of engineering skills in fusion.
- We need to draw significantly more people into the fusion
- Education and training of fusion engineers (with a nuclear culture) must play an important role in our programme
- In Europe we are training > 200 PhD (mainly physics) per year and 20 young engineers per year.
- University Programs, and Fusion Laboratories (with their facilities) are absolutely vital to develop and train this type of skill

# Risks & opportunities

- ITER remains  a cornerstone project for Europe
- We’re advancing the DEMO conceptual design by addressing G1
- High-B DEMO magnets, do not lead to a reduction in size, as large structures are needed to withstand the enormous forces
- Large technology gaps remain (i.e., breeding blanket) and more aggressive technology R&D programme is needed
- We explore options to de-risk the breeding blanket, incl. plasma-based VNS in parallel with ITER and the DEMO design process.
- Need to address misalignments in public and private efforts and ramp-up PPPs
- Keep the interest of industry, private investors and governments high in the short to medium term
- Address lack of skills and prepare a new generation

## Recurrent Fusion Hypes

A recurrent and genuine wish to accelerate fusion deployment to reduce dependence on fossil sources and minimise energy crises risk.



1978 - JET constr. starts
1980 – TFTR constr. starts
1978 – start of INTOR
1985 – ITER is born
(Geneva Summit)

Oil crisis 1973

### Risks and opportunities

- (+) Unprecedented rate of formation of so-called fusion energy startups.
- **(-)** Overly ambitious claims (through barrages of press releases) of commercial electricity production by 2030
- **(-)** Scientific credibility and ability to deliver remain questionable/ Lack of credible design documentation.
- (+) Foster involvement and integration of private sector/ industry in the public-private initiative to accelerate fusion
- (+) address human resources and supply chain weaknesses arising from isolated projects (RoX-ITER)

# Thank You!

**FAIRNESS**

Transparency
Collaboration
Loyalty

**OPENNESS**

Open doors
Open hearts
Open minds
Open ears

**COMMITMENT**

Ownership
Critical thinking
Determination
Respect

**DIVERSITY**

Cooperation
Equal opportunities
Inclusion