EUROfusion

Prospects for future fusion reactor developments in Europe

Gianfranco Federici, Hartmut Zohm

43rd FPA Annual Meeting and Symposium: The Road Ahead
December 7-8, 2022 Grand Hyatt Washington

EUROfusion
FUSION TECHNOLOGY DEPARTMENT

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.

EU is launching an update of its Fusion Roadmap

Ambrogio Fasoli - Chair of the General Assembly – presentation Eurofusion Bureau - 22.11.2022

- Fusion landscape is changing fast, driven by evolving boundary conditions (climate change, energy crisis), an increased perception of urgency for clean baseload electricity, and private investments
- To keep European leadership position, maintain technological competitiveness, and increase appeal to younger generations, we must strengthen and accelerate our activities to make fusion a reality earlier than aimed at in the present Roadmap
- Elements to be considered for the revision of our approach:

  - ✓ Further ITER delays and technological RoX from ITER
  - ✓ Remaining large technology gaps and technological risks of DEMO need to be addressed somehow
  - ✓ Optimise parallelisation of activities, e.g. blanket testing, T-breeding, materials testing, divertors, plasma scenarios,… Increase use of numerical simulations
  - ✓ Ramp-up in public-private partnerships
  - ✓ Balance the needs to accelerate and to remain realistic and pragmatic
  - ✓ Explore higher risk – higher potential solutions shorter deployment times.

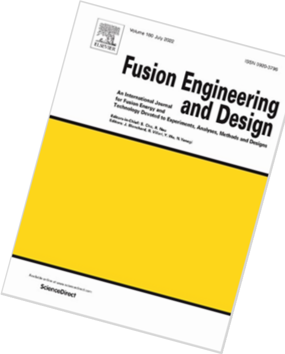
The present EU-DEMO ‘baseline’

G1 - Baseline	
R [m]	9.00
A	3.1
B_0 [T]	5.86
q_{95}	3.89
δ_{95}	0.33
κ_{95}	1.65
I_p [MA]	17.75
P_{fus} [MW]	2000
P_{sep} [MW]	170.4
P_{LH} [MW]	120.8
H_{98}	0.98
β_N [% mT/MA]	2.5
Fusion Gain Q	>40
$P_{sep}B/q_{95}AR$ [MW T /m]	9.2
Pulse length [sec]	7200
NWL (MW/m^2)	~1
n-fluence: 20 dpa 1st BB/ 50 dpa 2nd BB	70 dpa
* Also a test facility for advanced blankets due to the absence of another qualification route	DEMO TBMs

Nuclear performance

DEMO investigations have identified a # of critical elements in integrating physics and engineering and needed technology R&D is underway.

A special issue on the DEMO Pre-Concept Design Phase activities has been completed for the **Fusion Engineering & Design** (FED) scientific journal. All articles can be accessed via this link: https://www.sciencedirect.com/journal/fusion-engineering-and-design/special-issue/10RRZQ6LW4H.

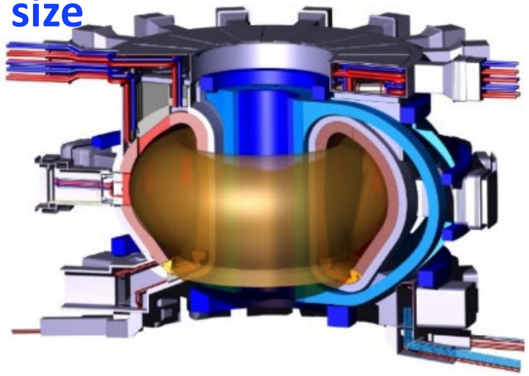


Goal: *“simple” DEMO. FPP must be based on robust solutions.*

Can we do better?

Two (coupled) aspects are presently being analyzed to explore opportunities for design simplification and size reduction:

- use higher field (HTS)
- change of aspect ratio

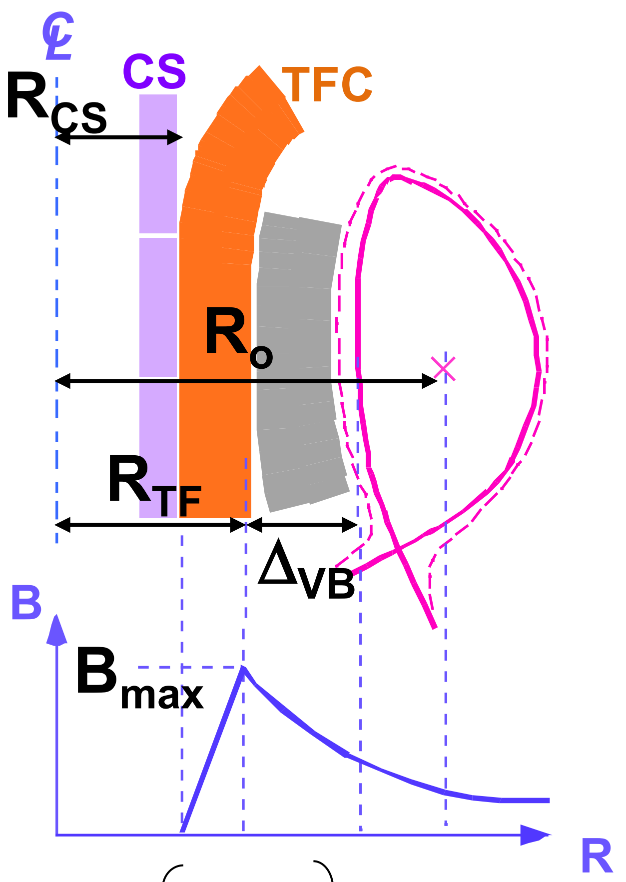


Design Space Exploration – Impact of Engineering Constraints on Machine Size

Engineering constraints:
- Divertor power handling limits
- Stress and forces in the magnets

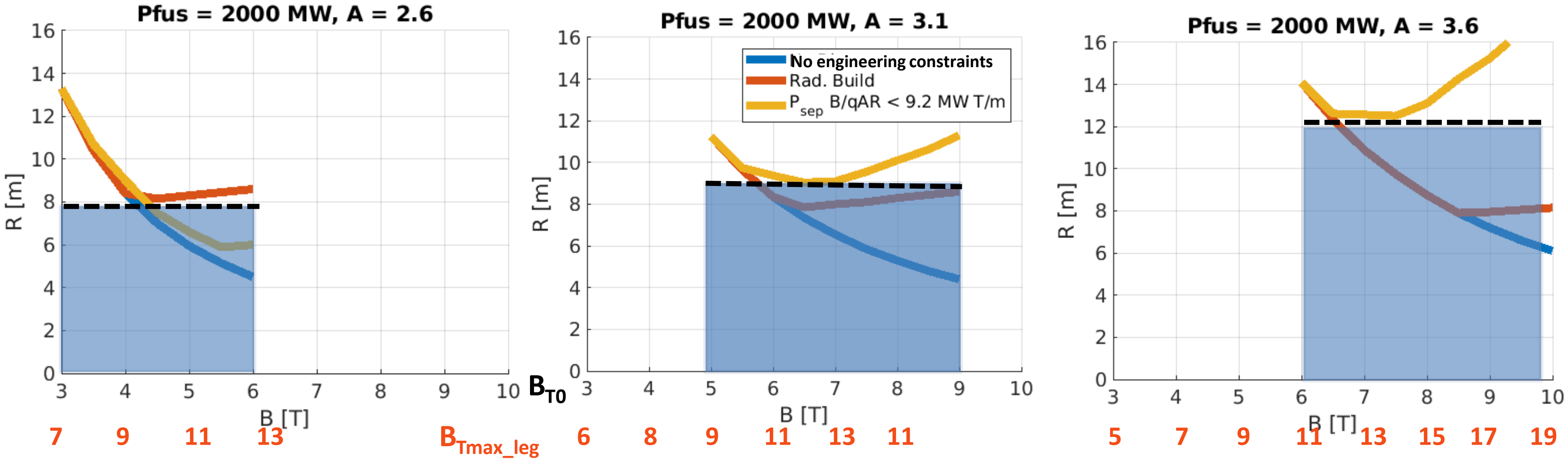
Mattia Siccinio,
Christian Bachmann

TF Inner Leg Space Allocation



Δ_{VB} { Breed BLK, n-shield, VV, TH-Shield }

Rule of thumb 1.3-1.4 m



Keeping reference assumptions (2 GW, 2 hrs, 70 dpa, wedged support), limited impact on machine size

- **for higher B-field**, large structures required to resist radial/vertical forces TF inner leg Alternative mechanical concepts are either unfeasible or do not bring the required amelioration. **See appendix slides**
- note that at lower A, both exhaust challenge and (TF) coil engineering are relaxed

DEMO is the key step to a FPP of the EU R&D program

ITER DT — ITER new DT — DEMO Construction — DEMO new construction

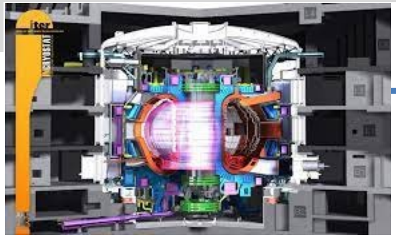
ITER:

1. Plasma
- Confinement
- Divertor
- Disruption control
- Current drive

2. System integration

3. Plasma support technologies
- Magnets
- Heating
- Technologies

ITER



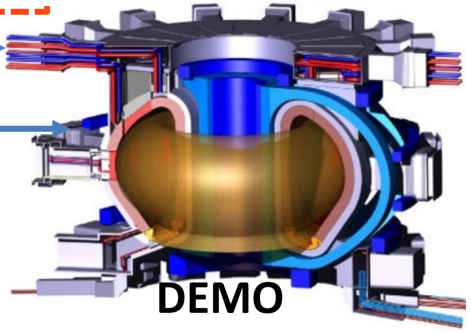
2035 DT

+n yrs (?) DT

ITER

2040 -2050

(construction)



DEMO

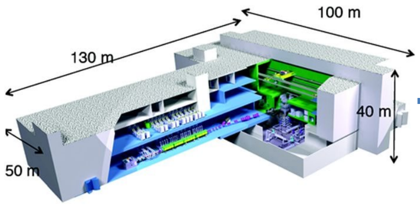
+n yrs

DEMO

EU DEMO mission requirements
- DEMO Net electricity (~500 MWe)
- Makes its own fuel (TBR>1)
- Reasonable plant availability
- Allow physics / technology extrapolation to a FPP
- Operation up to 70 dpa (~7 FPY)
- Test facility for advanced BB concepts

Gone with FTQP

DONES ["Point" Neutron Source]
Small volume (<0.01 m^3), high availability facility to address lifetime neutron radiation effects in small limited volume (and limited time)



2030

FTQP /VNS

~2030 construction

FTQP (VNS)
To reduce risk technology DEMO Mission
To complement ITER as a dedicated fusion facility to test, develop and qualify FNT components and materials required for DEMO operation (e.g., BB, RH, matls), reliability growth.

Weaknesses of this approach
- Rely on ITER operation
- Large knowledge gaps and risks for DEMO untested technologies
- Need for DEMO high fluence (operating DEMO 2 GW is very costly)

DEMO as a nuclear qualification facility or real demonstrator?

- The present strategy foresees a DEMO with high n-fluence, long operation (~7 FPY @ 1MW/m^2) and as a blanket test (qualification) facility
- A **change of strategy is advocated** that re-introduces a nuclear plasma device that serves as a 14 MeV n-source (VNS) for a **Fusion Technology Qualification Platform (FTQP)** to be run in parallel to ITER operation and DEMO design process:
    - focus on testing/ development of FNT components and material combinations
    - complement ITER (which is focused on burning plasma physics)
    - complement DONES (which is focused on large dpa in small material samples)
    - not a plasma physics experiment, plasma should be robust (boring), we have exciting plasma experiments in the programme: existing (W7-X, tokamaks) and coming (DTT, JT60-SA , ITER)
    - started exploration of a small toroidal device dominated by beam target fusion (NBI)

Benefits (FTQP)

- **Reduce DEMO technological risk by qualifying essential technologies in advance** (breeding, MTBF, reliability).
- Eliminate the need for high-fluence in DEMO (operating DEMO 2 GW to high fluence is very costly)
- **DEMO no longer a 'qualification' device**, becomes **a real demonstrator** (first-of-a-kind FPP)
- Forcing function to concept engineering developments (nuclear performance, reliability growth, RH)
- Provides additional experience in design, construction and licensing of nuclear a fusion device
- Keep industry, private Investors and governments' interest high

Key Takeaways

Technology and nuclear design challenges for harnessing fusion power remain paramount

Many venturous claims by fusion start-ups promising smaller and cheaper fusion power devices to be deployed quickly

The truth is that… a successful fusion reactor concept depends on:

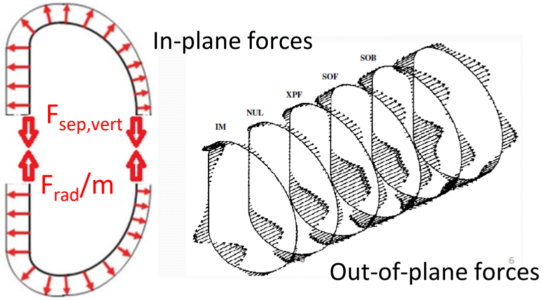
- Well defined fusion plant requirements
- A sound plasma operating scenario and a robust power exhaust strategy (both to be confirmed by ITER DT operation!!)
- A robust design (with sufficient margins) and a solution for all the key design integration issues
- Mature technology solutions for all reactor systems to be validated and qualified by a focussed R&D

- We are considering alternative development routes that provide opportunities for reduced technology risks and fast deployment times. This includes for example a dedicated fusion technology facility to test, develop and qualify FNT components required for DEMO. **Not a new idea!!**
- Complements DONES (which is focused on large dpa in very small samples)
- Seek ways to leverage industry and other private entities involvement.

- Started exploration of a small toroidal device (tokamak or stellarator) driven by NBI

- Additional slides

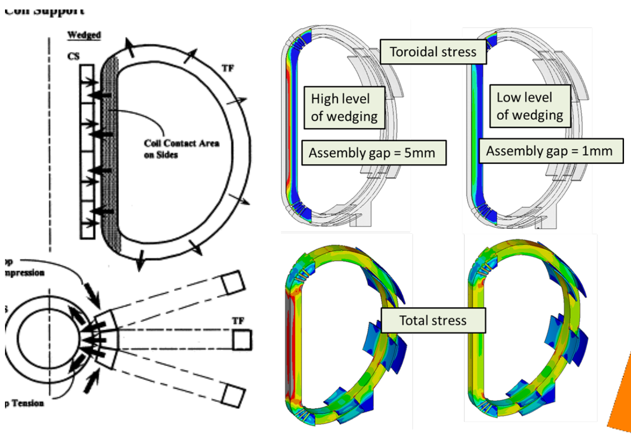
Alternative mechanical concepts for the TF inboard leg => not much help!



	$F_{sep,vert}$	F_{rad}/m
ITER TF	~100 MN	~50 MN
DEMO, A = 2.6, B=10T	~100 MN	~43 MN
DEMO, A = 3.1, B=12T	~275 MN	~90 MN
DEMO, A = 4.5, B=20T	~600 MN	~250 MN

Bucked + wedged concept

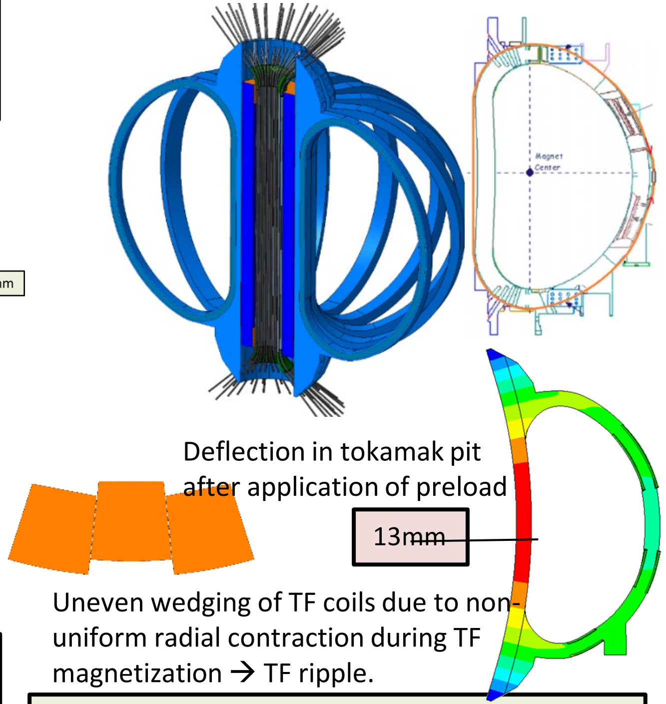
- Release TF inboard leg from EM forces.
- Transfer of radial force from TF to CS.
- Reduce stress cycle on CS conductor.
- By ensuring an assembly gap of ~3mm between CS and TF retain a level of toroidal compression sufficiently high to transfer out-of-plane forces by friction.



Findings:
- Even without any bucking and maximum wedging the friction between TF coils might be insufficient to allow the transfer of out-of-plane forces by friction.
- Very high sensitivity on the precision of the assembly gap.

Concepts of TF vertical pre-compression

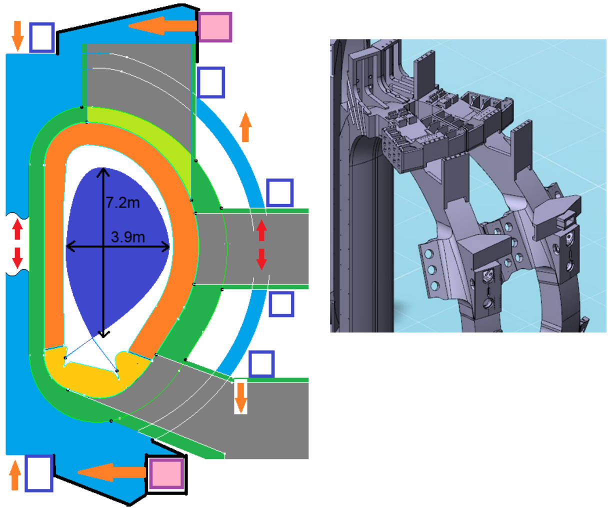
Steel cables routed through the CS bore ore wound around TF coil in assembly hall to generate overall pre-compression of coil radial pre-compression



Uneven wedging of TF coils due to non-uniform radial contraction during TF magnetization → TF ripple.

Findings
- Pre-compression of coil will cause deflection of straight inboard leg and challenge wedged concept.
- Pre-compression force (10-20%) insufficient to justify the added complexity.

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 outboard side.



Sizing of pre-compression rings:
- Vertical separation force on single inboard leg very large. For example, B=16T would require about 4 times large pre-compression rings as compared to ITER (30MN)

The inter-coil (IC) structures
- IC need to be radially disconnected from the TF coils, otherwise they will react the pre-compression → different design concept required transferring shear only.

Deflection of inboard leg – 1st result: by >8 mm