Overview of Design and R&D Activities towards a European DEMO

Tony Donné, Gianfranco Federici

on behalf of EUROfusion PPPT Department

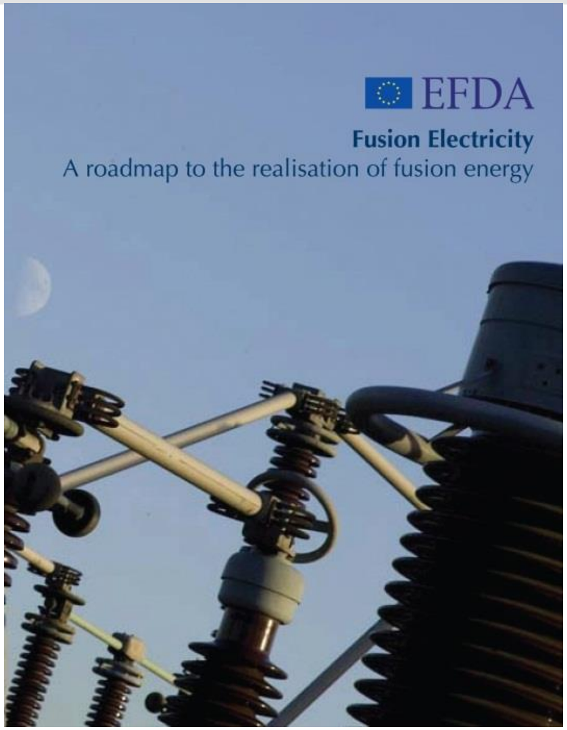
POWER PLANT PHYSICS &
TECHNOLOGY DEPARTMENT

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

Background

EU Fusion Roadmap to Fusion Electricity (Update)

- An ambitious roadmap implemented by a Consortium of 29 Fusion Labs (EUROfusion)
- Distribution of resources based on priorities and on the quality of deliverables
- Support to facilities based on the joint exploitation
- Focus around 8 Programmatic Missions
- Assumption in the original Roadmap:
  - ITER first plasma in early 2020's, with start of DT by 2027.



EFDA

Fusion Electricity

A roadmap to the realisation of fusion energy

Eight Programmatic Mission

1. *Plasma Operation*
2. *Heat Exhaust*
3. ***Neutron resistant Materials***
4. ***Tritium-self sufficiency***
5. ***Safety***
6. ***Integrated DEMO Design***
7. ***Competitive Cost of Electricity***
8. *Stellarator*

DEMO

Justification/rationale for updating DEMO part:

❖ Delay of ITER construction of at least 5 years : Q=10 probably achieved around mid 2030's

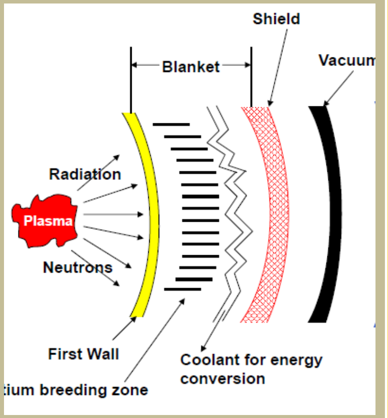
❖ General recommendation from the DEMO Stake Holders group to explore design variants longer than previously planned

Outstanding Technical Challenges with Gaps beyond ITER

For any further fusion step, safety, T-breeding, power exhaust, RH, component lifetime and plant availability, are important design drivers and CANNOT be compromised

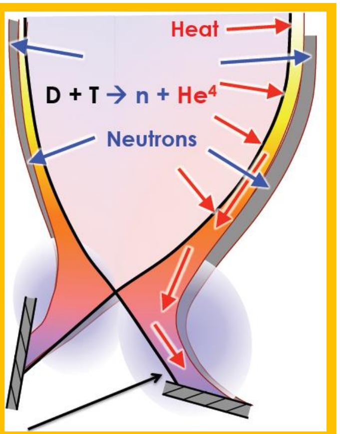
Tritium breeding blanket

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



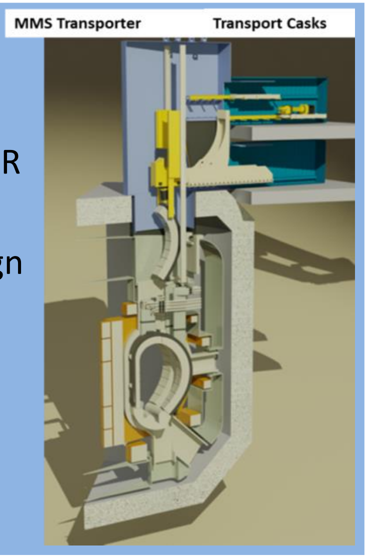
Power Exhaust

- Peak heat fluxes near technological limits (>10 MW/m^2)
- ITER solution may be marginal for DEMO
- Advanced divertor solutions may be needed but integration is very challenging
- Plans to upgrade MSTs and/or build a dedicated DTT



Remote Maintenance

- Strong impact on IVC design
- 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.



Structural and HHF Materials

- Progressive blanket operation strategy (1st blanket 20 dpa; 2nd blanket 50 dpa)
- Embrittlement of RAFM steels and Cu-alloys at low temp. and loss of strength at ~ high temp.
- Need of structural design criteria and design codes
- N-irradiation in fission reactors selection
- Design and development of an Early Neutron Source (IFMIF-DONES)

Organisation of Design and R&D Activities

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

L. Boccaccini-KIT WPBB

M. Grattarola-Ansaldo WPBOP

W. Biel-FZJ WPDC

J..H. You-IPP WPDIV

M.Q. Tran-CRPP WPDHCD

L. Zani-CEA WPMAT

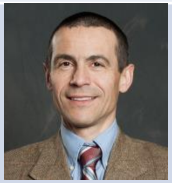
M. Rieth-KIT WPMAT

A. Loving-CCFE WPRM

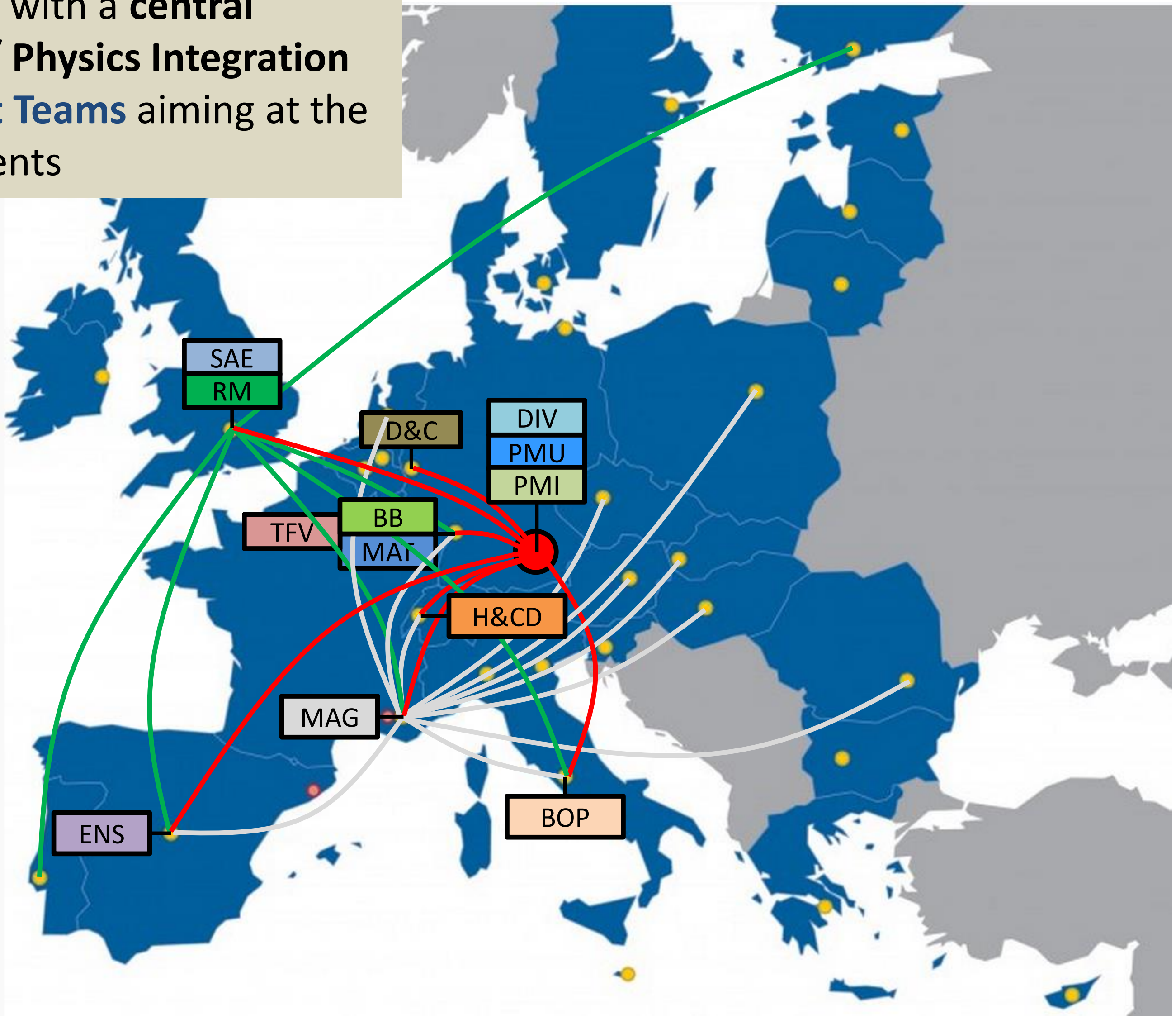
N. Taylor-CCFE WPSAE

C. Day-KIT WPTFV

A. Ibarra-CIEMAT WPENS



G. Federici WPPMI



Constraints

ITER's successful operation is a prerequisite for completion of DEMO design

- DEMO can only be built once the validity of its scenario is verified and confirmed by machine performance and operation in ITER
  - e.g. confinement, density, pedestal, self-heating for alpha-particle, divertor control, disruption control, …
- Lesson learned from initial operation includes engineering feasibility/ component performance /infant mortality of plasma support systems (magnets, fuelling, H&CD, divertor).

Availability of tritium supply

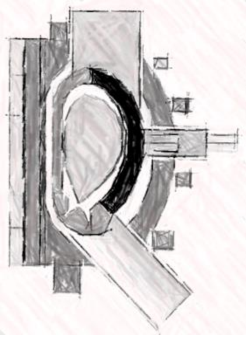
- DEMO must breed T from day 1 and use significant amount of T (5-10 kg) for start-up.
- Current realistic forecast of civilian T supplies points to very limited quantities of T available after ITER operation.
- Operation of an intermediate device like CFETR would further stretch the problem.

Political constraints

- To justify use of public funds pressure is towards fast deployment of fusion electricity.
- Postponing the presently targeted delivery date by more than a decade bears the risk of loss of public and political interest in fusion as a solution for future energy needs.

Revised Time Plan and Scope DEMO work

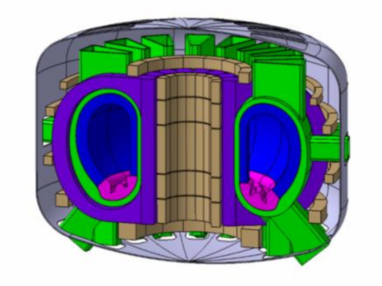
Scope



Preparatory Phase

EFDA PPPT
2011-2013

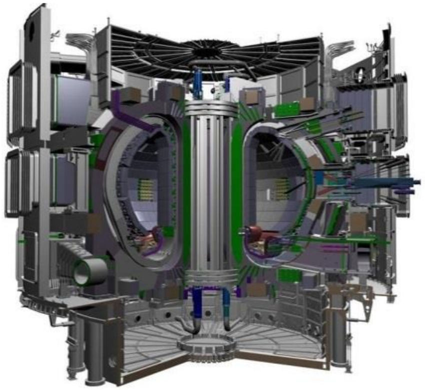
- Identify DEMO pre-requisites
- Identify main design and technical challenges (physics/ technology)
- Preliminary assessment technical solutions
- Prioritization of R&D to be included in the Roadmap



Pre-Conceptual Design

EUROFusion
PPPT
2014-2020

- Definition and analysis of initial requirements
- Preliminary design concept definition and trade-off analysis
- Identify main physics basis development needs,
- Determine the critical technology development requirements (by including more industry)
- Conduct technology and material R&D
- Concept evaluation and screening/selection of promising options



Conceptual Design

EUROFusion
PPPT
2021-2024

- **Continue DEMO technology and material validation R&D and physics R&D**
- **Detailed concept definition and final trade-off analyses:**
  - ○ Divertor configuration selection and first wall protection strategy (SN/ DN)
  - ○ Breeding blanket concept and coolant selection
  - ○ Plasma operating scenario selection
  - ○ H&CD mix selection

2025-2027

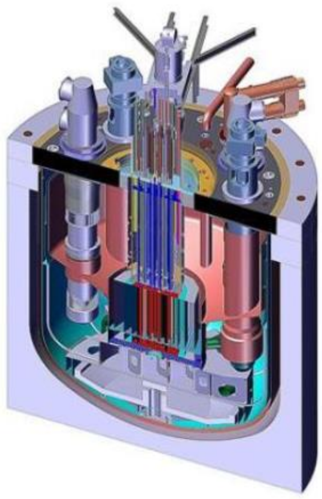
- **Finalisation of plant concept design and reviews**

Concept design approach

Lessons learned from Gen-IV as part of SHG Engagement

Meetings held with GEN-IV Fission projects to gain insight into Project Execution strategies

ASTRID :SFR Prototype GEN-IV



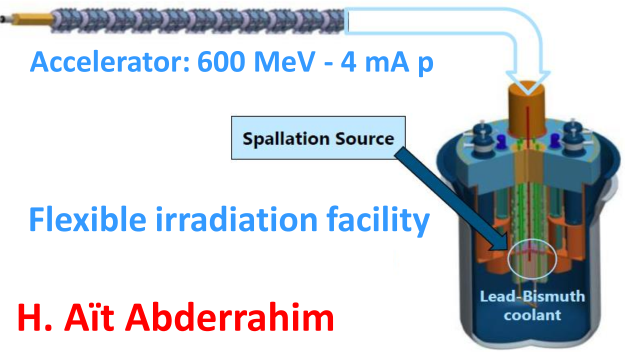
Integrated Technology Demostrator 600 MWe

F. Gauche (CEA)

MYRRHA: Acceleration Driven System

Reactor: Subcritical/ critical modes – 65 to 100 MW_{th}

Accelerator: 600 MeV - 4 mA p



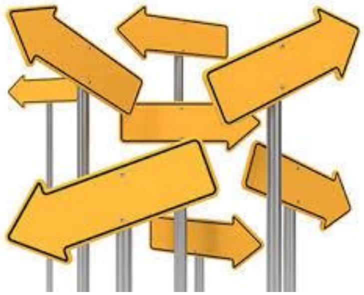
Flexible irradiation facility

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.

1st Stake Holders Group (SHG) Meeting, 18/03/15
Engage experts (e.g., industry, utilities, grids, safety, licensing) to establish realistic HLRs for DEMO plant to embark on coherent conceptual design approach -> Main outcomes: Safety, Performance and Economic viability missions.

Design Integration / Systems Engineering Approach



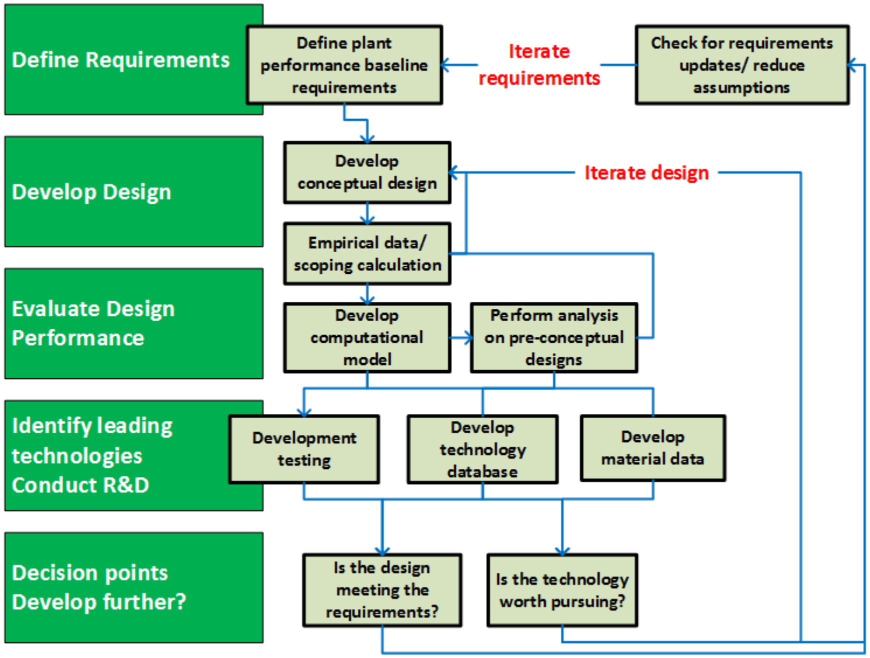
- Since 2014 a traceable design process with SE approach was started to explore available DEMO design/ operation space to understand implications on technology requirements

Main Challenges

- Integration of design drivers across different projects
- Design dealing with uncertainties (physics and technology)
- High degree of system integration/ complexity/ system interdependencies
- Trade-off studies with multi-criteria optimisations, including engineering assessments.

Ensuring that R&D is focussed on resolving critical uncertainties in a timely manner and that learning from R&D is used to responsively adapt the technology strategy is crucial.

Basic Process Flow for Conceptual Design Work



Define Requirements

Define plant performance baseline requirements

Iterate requirements

Check for requirements updates/ reduce assumptions

Develop Design

Develop conceptual design

Iterate design

Empirical data/ scoping calculation

Evaluate Design Performance

Develop computational model

Perform analysis on pre-conceptual designs

Identify leading technologies Conduct R&D

Development testing

Develop technology database

Develop material data

Decision points Develop further?

Is the design meeting the requirements?

Is the technology worth pursuing?

Concept Design Approach

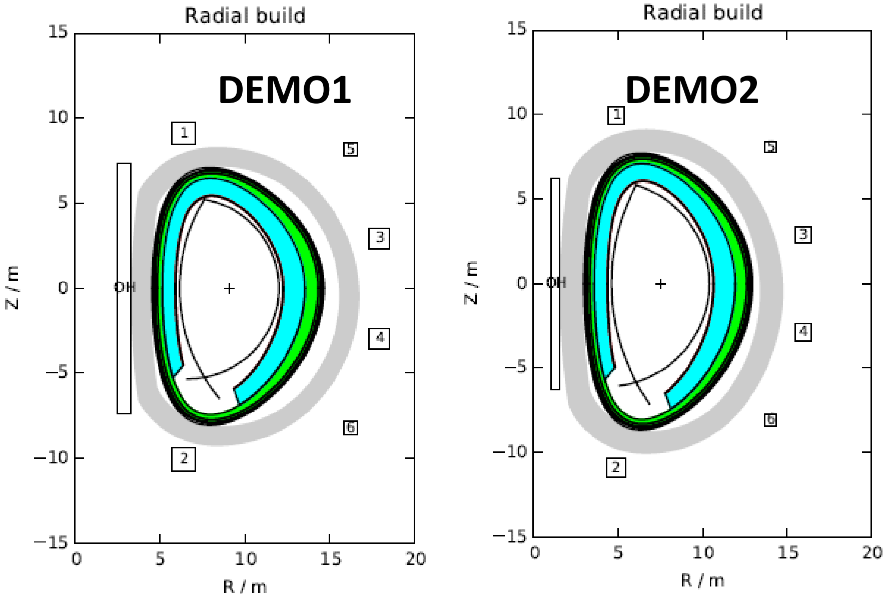
Preliminary DEMO Design Choices under Evaluation

Design features (near-term DEMO):

- 2000 MWth~500 Mwe
- Pulses > 2 hrs
- SN water cooled divertor
- PFC armour: W
- LTSC magnets Nb_3Sn (grading)
- B_{max} conductor ~12 T (depends on A)
- RAFM (EUROFER) as blanket structure
- VV made of AISI 316
- Blanket vertical RH / divertor cassettes
- Lifetime: starter blanket: 20 dpa (200 appm He); 2nd blanket 50 dpa; divertor: 5 dpa (Cu)

Open Choices:

- Operating scenario
- Breeding blanket design concept selection
- Primary Blanket Coolant/ BoP
- Protection strategy first wall (e.g., limiters)
- Divertor configurations (SN, DN, advanced)
- Number of coils

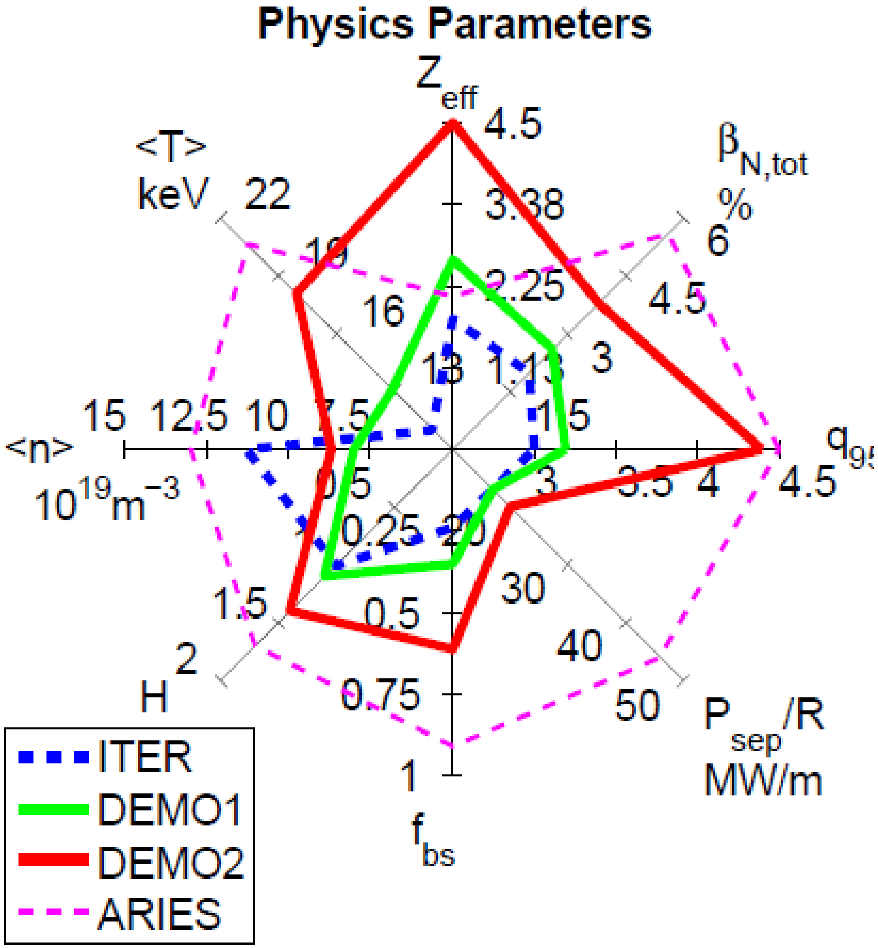


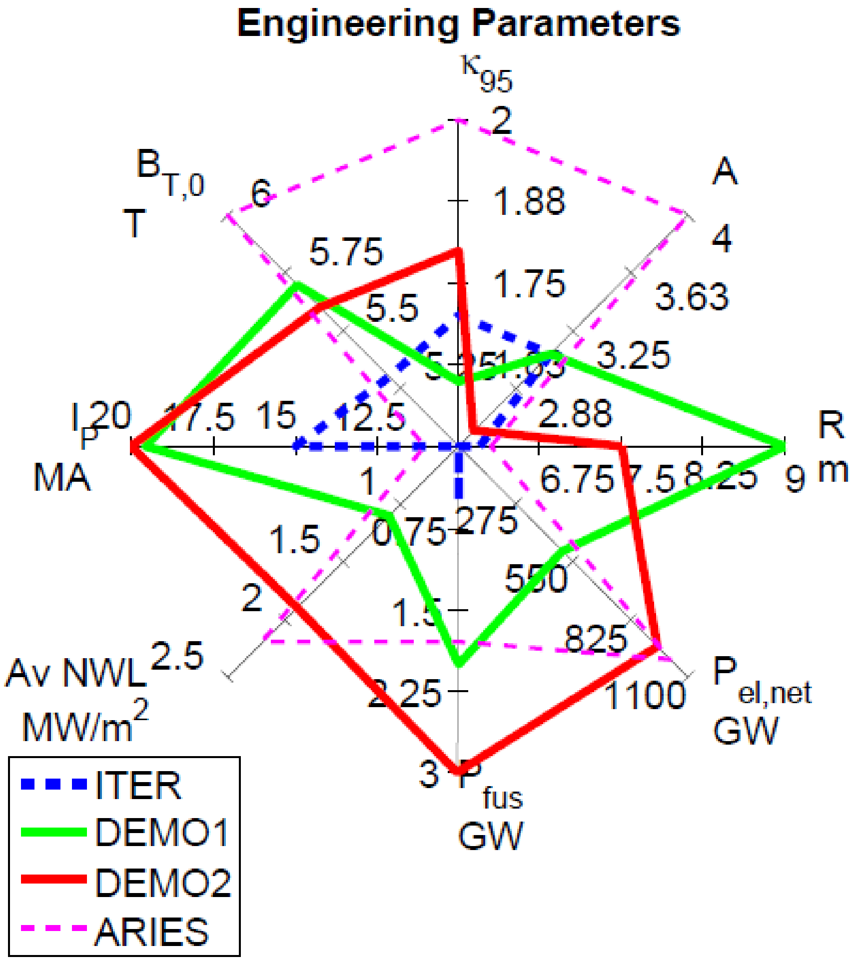
Under revision

	ITER	DEMO1 (2015) A=3.1	DEMO2 (2015) A=2.6
R_0 / a (m)	6.2 / 2.0	9.1 / 2.9	7.5 / 2.9
K_{95} / δ_{95}	1.7 / 0.33	1.6 / 0.33	1.8 / 0.33
A (m^2)/ Vol (m^3)	683 / 831	1428 / 2502	1253 / 2217
H non-rad-corr / β_N (%)	1.0 / 2.0	1.0 / 2.6	1.2 / 3.8
P_{sep} (MW)	104	154	150
P_F (MW) / P_{NET} (MW)	500 / 0	2037 / 500	3255 / 953
I_p (MA) / f_{bs}	15 / 0.24	20 / 0.35	22 / 0.61
B at R_0 (T)	5.3	5.7	5.6
$B_{max,conductor}$ (T)	11.8	12.3	15.6
BB i/b / o/b (m)	0.45 / 0.45	1.1 / 2.1	1.0 / 1.9
Av NWL MW/m^2	0.5	1.1	1.9

DEMO Physics Basis / Operating Point

- **Readiness of underlying physics assumptions makes the difference.**
- **The systems code PROCESS is being used to underpin EU DEMO design studies, and another code (SYCOMORE), is under development.**





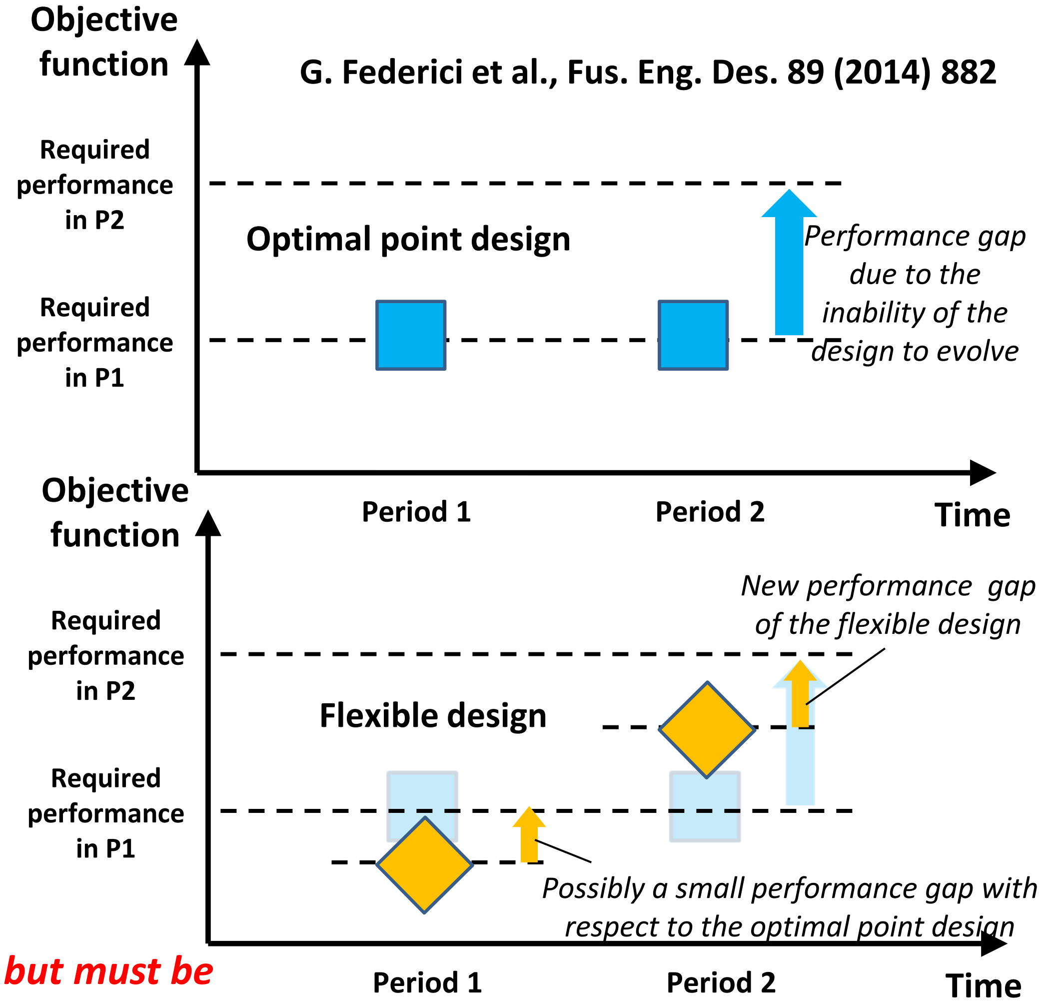
‘Optimal’ point design vs. ‘Flexible ’ design

Prospects of design staging or operation phasing

- Further develop the plasma physics, materials science, and technology while gaining experience from operating such a device and also extending its nuclear capability step by step e.g. upgrade of blanket, divertor, materials, H&CD, etc.

- Traditionally, system optimisation has sought to identify an **‘optimal’ point design** by fixing a set of requirements and technological constraints at the start of the design => *This could result in overly constrained system unable to incorporate potential upgrades.*

- However, if improvements in technology are expected over the operational lifetime of the plant, **flexible design** provisions should be embedded in the initial design of the system to allow the system performance to evolve with time.



G. Federici et al., Fus. Eng. Des. 89 (2014) 882

Design staging is not a one-off modification but must be carefully thought out, planned and continuously managed

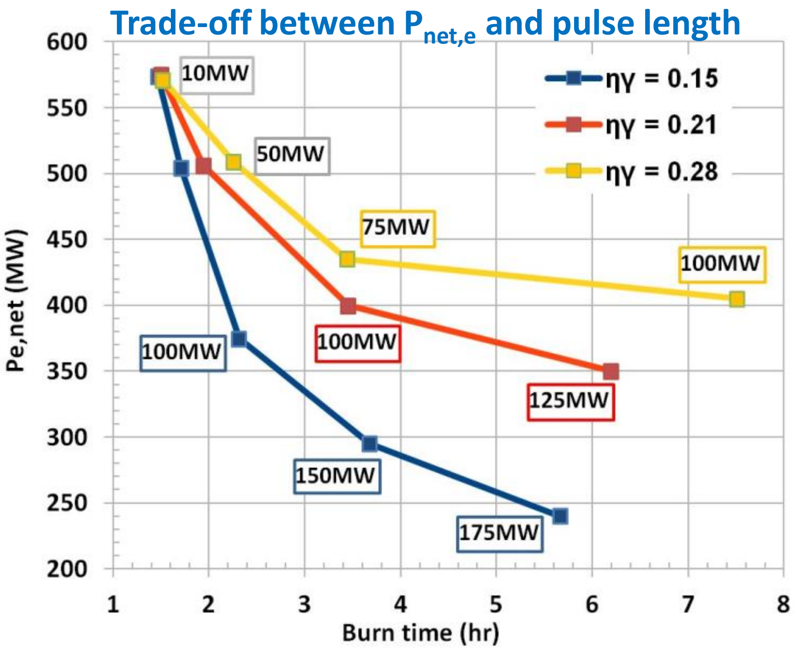
Design flexible nuclear fusion systems is very difficult

- **Staged approach and upgrades successfully followed in existing devices**
- **But for a nuclear fusion reactor (like DEMO and also ITER) flexibility is much more limited**

❖ A tokamak is a very complex system with multiple interfaces
❖ Machine geometry will be fixed (B, I, etc.)
❖ Magnetic / divertor configuration will be fixed ($R_{0,}$ a, radial build, etc.)
❖ Dimensional / mechanical / hydraulic Interfaces cannot be altered
❖ Limited access by RH to core components through constricted ports
❖ Activation of internal components / contamination
❖ Changes are limited to ancillary systems e.g. fixed coolants and operating conditions

Limited potential upgrade paths, e.g.,:

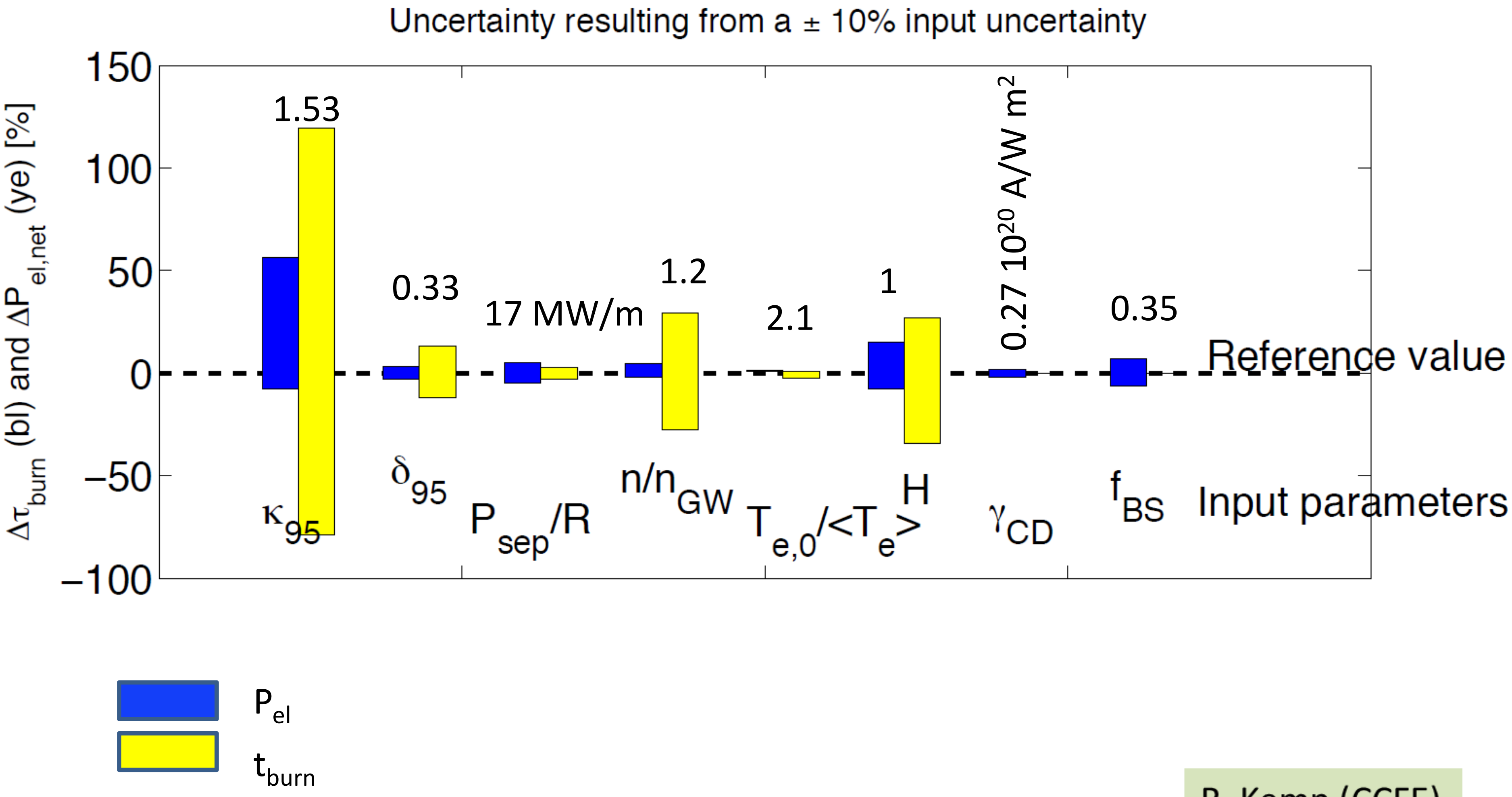
- **Utilize a "starter" blanket with a higher fluence blanket upgrade from material advances**
- **Extension of inductive pulse by auxiliary H&CD (if η_{CD} can be improved, see graph)**
- **Improved plasma control with better diagnostics**


Trade-off between $P_{net,e}$ and pulse length

G. Federici et al., Fus. Eng. Des. 89 (2014) 882

Results of Selected Studies

Point Designs “Robustness” / Uncertainties of Physics Assumptions



R. Kemp (CCFE)

Results of selected studies

TBR Sensitivity Analysis

Blanket design:
- Breeder/multiplier materials are within a box and covered by a FW.
- Box is reinforced by stiffening grids

→ n-absorption by steel

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

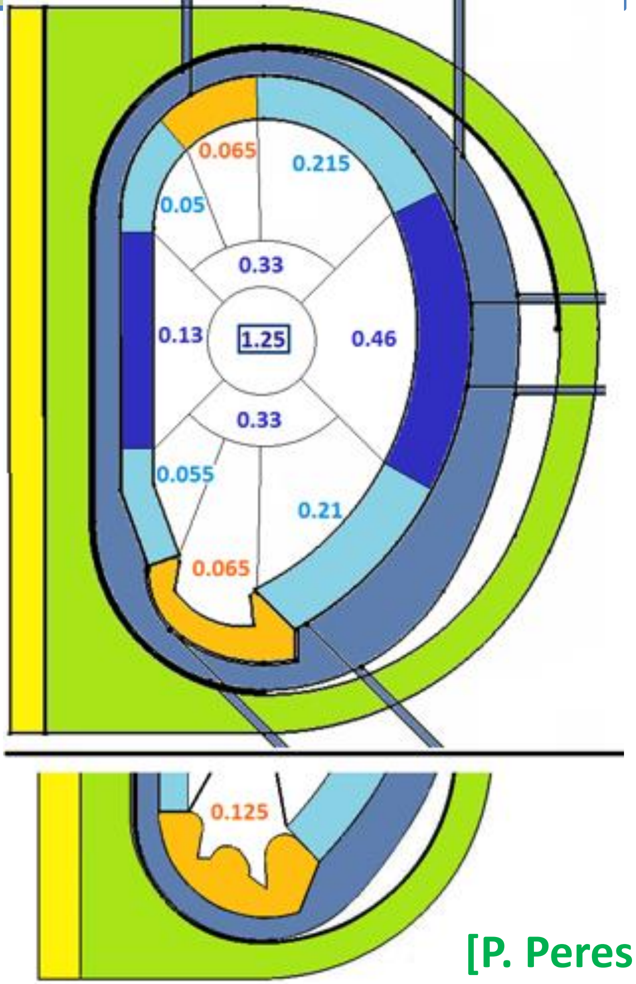
→ Requirement: TBR ≥ 1.05

(after integration of diagn/ H&CD)

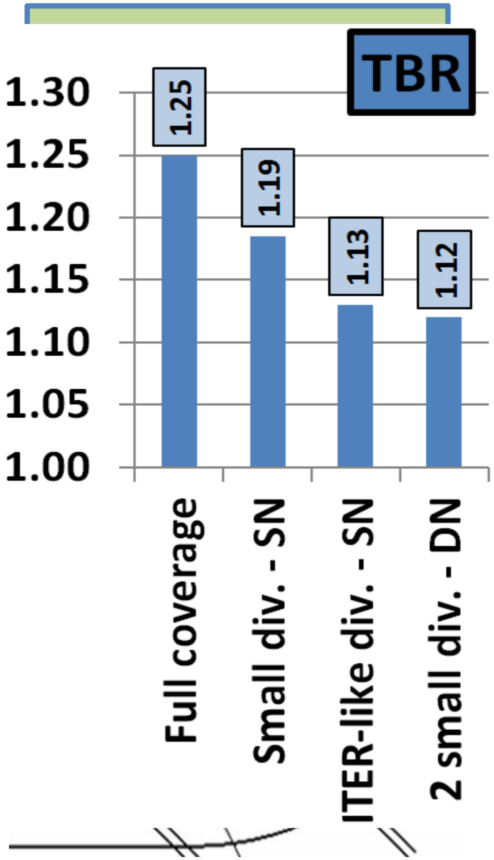
→ Configuration: About 85% of the plasma must be covered by the breeding blanket.

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

Potential Tritium breeding contributions:



Total TBR:



[P. Pereslavtsev, ISFNT12]

- Significant improvement of TBR due to reduction of divertor size.
- DN configuration with two small divertors seems possible regarding TBR.

International Collaborations/ Involvement of Industry

- **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**
    - Systems codes, comparing/ benchmarking EU and CN codes
    - Divertor configuration and performance, in particular alternative divertor geometries and their potential implementation in CFETR / EU-DEMO / DTT
  - **Breeding blanket research cooperation**
    - To be defined in 2016 with visit to laboratories and discussion of scope
- **UCLA (DCLL)**
  - upgrade and use existing MaPLE facility for combined magneto-hydrodynamic (MHD) thermofluids and fluid-materials interaction experiments
- **Fission Reactor Irradiation Experiment**
  - Collaborations to use materials test reactors outside of Europe for high fluence irradiation experiments to close gaps in the EUROFER data base
- **Increased involvement of industry** to ensure early attention is given to industrial feasibility, costs, nuclear safety and licensing aspects, important in design of a reactor.

Conclusions

- The demonstration of electricity production ~2050 in a DEMO Fusion Power Plant is one of the priorities for the EU fusion program
- ITER is the key facility in this strategy and the DEMO design/R&D will benefit largely from the experience gained with ITER construction
- There are outstanding gaps requiring a vigorous integrated design and technology R&D (e.g., breeding blanket, divertor, Remote Handling, materials)
- Main difficulty with designing is dealing with uncertainty. DEMO reactor design suffers from high degree of complexity/ system Interdependencies
- Keep reasonable flexibility at the beginning. Trade-off studies with multi-criteria optimisations, including engineering assessments are underway and planned.
- We are developing an update of the fusion roadmap to determine possible adaptations to minimise the impact of ITER delay on the demonstration of fusion electricity around the middle of the century.