The Strategy for the (Pre-)Conceptual Design of a European DEMO
(Revision of the EU Fusion Roadmap for DEMO)

Matti Coleman¹,²
G. Federici¹, R. Wenninger¹, R. Brown¹,², A. Loving², R. Kembleton², R. Ellis²

¹EUROfusion Power Plant Physics and Technology (PPPT) Department
²United Kingdom Atomic Energy Authority (UKAEA)

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.
Outline

• Revision of the Roadmap and the DEMO design strategy (efforts ongoing)
• Approach to DEMO design
  • Description of the EU-DEMO baseline
  • Systems engineering approach
  • DN DEMO
  • Other architectures
  • Why we don’t have high $B_t$
• Comparisons and decisions: a framework
• Risks, opportunities, and the prioritisation of R&D
• Conclusions
EU Roadmap to Fusion Electricity

- An ambitious roadmap implemented by a Consortium of Fusion Labs (EUROfusion) and F4E
- Distribution of resources based on priorities and on the quality of deliverables
- Support to facilities based on the joint exploitation
- Focus around 8 Missions

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

Emphasis on:
- Central role of ITER
- DEMO as a single step to commercial FPPs
- Demonstrating production of electricity and tritium self-sufficiency by 2050

Rev. 1.0: Romanelli, 2012
The revision of the EU Roadmap

The re-working of the **DEMO Design Implementation Strategy** triggered by:

- **Anticipated ITER delay**: consequences for DEMO, but PPPT PMU has explored possible adaptations of the development strategy in order to minimise the impacts of the ITER delay on the mission to realise Fusion electricity by the early 2050’s.

- **Recommendations to explore a wider design space**:
  - Investigate the attractiveness of alternative plant concepts in order to more fully explore the design space
  - Improve our confidence that we can eventually move towards an attractive design

- **Use the time to improve our answers to questions which ITER will not be answering for us, including**:
  - **Tritium fuel cycle** (self-sufficiency)
  - **Power exhaust** (survival)
  - **Remote maintenance** (availability)
  - **Structural and HHF materials** (lifetime, availability)

- Recognising all the while that if ITER doesn’t work, we won’t build DEMO
Framing the Programme

The following are important considerations that frame the revised DEMO Plan:

- **External constraints:** political constraints, and validation of ITER operational scenario(s) must be considered.

- **The position of DEMO in relation to ITER and a FPP:** depends on the remaining gaps to a commercial plant after the exploitation of ITER, and the time scale for fusion deployment and development risks that can be accepted.

- **Roadmap timeline and budget:** It will be an important task of the pre-conceptual design activities to assess an achievable design point consistent with the Roadmap timeline and allocated budget.

- **Harnessing ITER Competence:** 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.

- **Capitalising on ITER Industry Experience:** A large gap from the end of the 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 realisation.
EU Fusion Roadmap to Fusion Electricity (v2.0)

(Still under discussion, dates indicative)

- Remove or reduce risks to ITER's goals (M1+M2)
- Plasma and technology to maximise ITER input to DEMO-stage devices (M1+M2, M4-7)

ITER
- Construction
- Commissioning
- H, He, D ops, DT ops
- TBM programme, DEMO plasma scenarios, long pulse

Q = 10
Q = 5 long pulse

EU-DEMO
- Baseline plasma + exhaust scenario (M1+M2)
- Tritium, safety, reliability and technology (M1-5)

Consistent Concept
- ITER DT results into DEMO design (M1+M2+M3+M6)
- ITER enhanced performance and technology for DEMO exploitation (M1,M2,M4,M6)

Comence Construction
- Commence construction
- Site Selection & Construction
- Commissioning

Science & Technology Basis for first FPPs

Materials
- Pre-CDA
- CDA
- EDA
- MTR
- IFMIF-DONES

Consistent Concept
- Materials data, final design criteria (M3)
- Improve plasma, components, systems (M1-7)

W7X, Helias reactor: Pre-CDA, CDA, EDA for a stellarator DEMO/FPP (M8)

2016 2020 2027 2030 2040 2050

Matti Coleman | 4th IAEA DEMO Programme Workshop | Karlsruhe | November 18th 2016 | Page 6
EU DEMO Power Plant Stakeholder Requirements

Or: What does our DEMO have to do?

A group of Stakeholders was formed (comprising members from industry, utilities/grid operators, safety, and licencing), to establish realistic high level requirements for DEMO.

Stakeholders’ DEMO Mission Statement:
“The DEMO power plant has to be a representative fusion power station in terms of predictable power production, fuel cycle self-sufficiency and plant performance thereby allowing an extrapolable assessment of the economic viability, safe operation as well as environmental sustainability for future commercial FPPs.”

DEMO has to:
• Produce net electricity (300-500 MWe), safely and reliably
• Be tritium self-sufficient and start up another reactor
• Have a representative (extrapolable) performance:
  • Lifetime
  • Cost
  • Availability
  • Net efficiency
  • Waste
EU Approach to DEMO Design

Development of multiple architectures in parallel to satisfy PRD

- Recognition that we do not know what the ideal DEMO looks like
- **Baseline**: best guess and a realistic representation of what DEMO could look like – and a useful tool!
The baseline is a set of working assumptions, enabling more realistic and comprehensive investigations to take place.

- Highlights issues/flashpoints with many design configurations
- Lays the framework for a collaborative DEMO design and analysis loop, which is vital to the study of any reactor configuration
- Brings a distributed team together and triggers discussions of alternatives

The baseline is a set of working assumptions, enabling more realistic and comprehensive investigations to take place.

- Highlights issues/flashpoints with many design configurations
- Lays the framework for a collaborative DEMO design and analysis loop, which is vital to the study of any reactor configuration
- Brings a distributed team together and triggers discussions of alternatives
Description of the EU-DEMO baseline - i

Or: Why ours looks the way it does.

**Physics:**
- Single null
- Conventional H-mode
- H=1.1 (radiation corrected)
- Based on ITER performance (Q=10)
- \( P_{sep}/R_0 = 17 \text{ MW/m (fully detached)} \)
- Pulsed (2 hours, 50 MW steady-state HCD)
- “Conservative” a.k.a. established physics basis

**Engineering:**
- Vertical Maintenance (MMS)
- EUROFER IVCs
- Starter blanket (20 dpa) + Second blanket (50 dpa) (~6-7 FPY total) – 4 concepts in parallel
- TBR > 1.1
- Availability target 30%
- Etc.

Still many outstanding points for which no clear solution has yet been identified (e.g. ELMs, disruptions, FW, etc.)

---

<table>
<thead>
<tr>
<th>Legend</th>
<th>DEMO1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Opt. target</td>
<td>( R_0 (\text{min.}) )</td>
</tr>
<tr>
<td>Input</td>
<td>( A )</td>
</tr>
<tr>
<td>Output</td>
<td>( P_{fus} )</td>
</tr>
<tr>
<td></td>
<td>( P_{el,net} )</td>
</tr>
<tr>
<td></td>
<td>( t_{pulse} )</td>
</tr>
<tr>
<td></td>
<td>( \kappa_{95} )</td>
</tr>
<tr>
<td></td>
<td>( \delta_{95} )</td>
</tr>
<tr>
<td></td>
<td>( B_{T,0} )</td>
</tr>
<tr>
<td></td>
<td>( I_P )</td>
</tr>
<tr>
<td></td>
<td>( P_{sep}/R )</td>
</tr>
<tr>
<td></td>
<td>( n_{TF} )</td>
</tr>
<tr>
<td></td>
<td>H-factor</td>
</tr>
<tr>
<td></td>
<td>( f_{GW} )</td>
</tr>
<tr>
<td></td>
<td>Avg. NWL</td>
</tr>
</tbody>
</table>
Description of the EU-DEMO baseline - ii

- HCPB (ITER EU TBM)
- HCLL (ITER EU TBM)
- WCLL
- DCLL

Development of an innovative T fuel cycle
Many and varied interactions between systems, e.g.:

- More external current drive needed \(\Rightarrow\) more plasma facing surface area required \(\Rightarrow\) tritium breeding decreases
- Neutron shielding insufficient \(\Rightarrow\) Magnet performance decreases and cryogenic loads increase

Optimising individual systems does not lead to overall optima

The complexity of dependencies between systems increases significantly once we move to their physical embodiments...
The present EU DEMO baseline is **not** the only way to meet these top-level requirements.

**Alternatives are being considered** to address weaknesses in the present baseline:

- Double-null (DN) DEMO
- Flexi-DEMO
- ...

Note: none currently have “high” $B_t$!

Each system is allocated requirements and functions, and broken down into further sub-systems until a sub-system design can be “sub-contracted” to a Work Package with a formalised set of requirements (SRD).
EU-DEMO option: DN DEMO

Single null (SN) baseline has issues with power deposition in non-divertor areas which are difficult to protect.

A promising solution for dealing with the power exhaust problem:

- Potentially reduced peak divertor target plate loads (ss, transient)
- Reduced local peak FW power loading

But, there are downsides:

- TBR is more marginal
- More complex in-vessel physical architecture

A comprehensive comparison between single and double-null DEMOs is underway
EU-DEMO options

Other DEMO options are beginning to be defined:

• **“Flexi-DEMO” (AWP17)**
  • Focus on the extrapolability of the DEMO plasma scenario to a FPP
  • Target steady-state operation

• **Enhanced power handling DEMO**
  • Dependent on DTT recommendations, e.g. snowflake, X, super-X..

• **“DEMO2”**
  • Steady-state, more optimism

• **Long-pulse DEMO**
  • DEMO with a longer pulse, targeting a higher COE

Each of these alternatives is effectively **addressing one or more key weaknesses** in the present baseline.

Each of these will **make use of the baseline**; in many cases the information generated is relevant and the R&D/technology is applicable or transferable.
One of the most FAQs is: *why aren’t we developing a high B DEMO?*

**Some theory/facts:**
- \( P_{\text{ fus}} \propto \frac{B_t^4 \beta_N^2 \beta_{95}^2 R_0^3}{q_{95}^2 A^4} \propto B_t^4 \)
- HTS materials > LTS materials

**Some other facts:**
- 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
- In present design points, the SC is \(~5\%\) of the TFC area
- PROCESS code systems runs (with LTS TF coil models) show similar decreases in \( R_0 \) for:
  - Factor 5 increase in \( j_{\text{ crit}} \) at 4K
  - Factor 1.2 increase in \( \sigma_{\text{ allowable}} \)
Why our DEMO doesn’t (currently) need high B TF coils - ii

Some more facts:

• DEMO size is effectively driven by the divertor power handling capability, \( P_{\text{sep}} \), (currently assumed to be 17 MW/m)
• We need \( P_{\text{sep}} > f_{\text{LH}} \cdot P_{\text{LH}} \) to access \( H \)-mode:
  \[
  f_{\text{LH}} \approx 1.1 - 1.3
  \]

At present, the **EU DEMO baseline does not strongly require higher field TF coils**. To have a significant benefit, we would first need:

• **Higher strength steels** (casing and conductor)

And, either of:

• A significant reduction of the access power for the regime of operation which is being targeted requirements (e.g. \( f_{\text{LH}} = 0.8 \), or different scaling)
• An even better solution to the divertor problem (e.g. \( P_{\text{sep}}/R_0 = 20 \) MW/m)

**We are, however, looking at HTS coils.**
Framework for Plant Concept Assessment

- A conceptual fusion power plant is a large and complex system:
  - Numerous uncertainties and many options
  - Not well-suited to traditional engineering decision-taking approaches
  - Need to ground our technical opinions in a universal currency (€ ?, risk?)
- A **Plant Concept Assessment** approach
  - Enable **objective** and **traceable** comparison of plant concepts
  - **Capturing stakeholder objectives** and programme delivery considerations.
- Process of DEMO plant concept selection should as *closely as possible* follow established concept selection processes from **nuclear fission** and other highly regulated fields.

**INPRO Methodology**

**NASA Risk-Informed Decision Making Handbook**

**Collaboration with Industry to:**
- **Part I** – To support the definition of the framework (2016)
- **Part II** – To assist in the definition of criteria (2016)
- **Part III** – Assessment of plant technology options (2017/18)
Such a framework could also be used to evaluate the value of R&D activities.
PPPT is currently in the process of:

- Implementing a **Risk/Opportunity Management Strategy**
- Building a DEMO-wide **Risk Database**
  - Explicitly identify and measure risk
  - Traceability of the management of risks

Devolved risk management with **centralised review and weighting**
### RM example of Risk Management and R&D Prioritisation

#### Risk Identification

<table>
<thead>
<tr>
<th>Risk ID</th>
<th>Risk Label</th>
<th>Impact</th>
<th>Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>D_RM_4</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

#### Risk Assessment

<table>
<thead>
<tr>
<th>Risk</th>
<th>Likelihood</th>
<th>Impact</th>
<th>Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>D_RM_4</td>
<td>Very High</td>
<td>Very High</td>
<td>256</td>
</tr>
</tbody>
</table>

#### Risk Handling

- **RM_A1**: Design and develop a dynamic metrology system to provide real-time feedback on the blanket and divertor position.
- **RM_A2**: Design and develop an adaptive control system to adjust the installation of large components.
- **RM_A3**: Design and develop V/V operator interfaces to provide accurate positional feedback.

#### R&D Programme

- **RH test facility (building)**
- **Technology Development**
  - **Feasibility tests**
  - **R & D/test rig substantiation**
- **Blanket EE**
  - **Design PoP transporter**
  - **Mock-up design**
  - **Construction**
- **Control System**
  - **Design & Feasibility tests**
  - **Mock-up design**
  - **Construction**
- **Vertical Port**
  - **Feasibility tests**
  - **Mock-up design**
  - **Construction**
  - **Integrated mock-up & testing**
- **Radiation hardness R&D/testing**
- **PH1 Testing**
- **PH2 Testing**

#### Decisions:

1. **DEMO CDR Baseline**
2. **Blanket concept down**.
• Finite budgets mean prioritisation is vital:
  • The **expected value** of an R&D activity needs to be quantified from the plant perspective, e.g.:
    • 10% higher $\eta_{CD}$ is strong/important
    • 10% higher $j_{crit}$ is weaker/unimportant (at present)
  • The **expected cost** of an R&D activity needs to be quantified

• Finite schedules (and budgets) mean timely down-selection is key
  • Immature technologies with high development costs and timelines either need to be extremely valuable or indispensable
  • Mature technologies with low development costs inherently preferred in a finite budget scenario…

• Ultimately, **“tolerable” levels of risk** will need to be taken and **“suitable” opportunities** seized
  ➔ this process has not yet been defined! (tricky)
• The updated Roadmap shall eventually contain indications of:
  • **The key lines of R&D expected** to be carried out in support of the DEMO programme
  • Any **major facilities required** in the near to mid-term future
• Analysis of the risks will lead to a prioritisation of the R&D and proportional allocation of the budget
• The **DEMO design point should be achievable within the programme**:
  • Reliant upon developments achievable within the programme budget and timescales, i.e.:
    • Operational in the 2050s
    • Development costs within Programme budget
  • Important not to continuously hedge our bets…
Conclusions

- Aim to retain the ambition to demonstrate fusion electricity to the grid by the 2050’s
- Minimise the impact of the ITER delay as best we can by:
  - Exploring a wider design space in the search of a more attractive design
  - Further reducing the engineering/physics uncertainties the ITER will not
- The approach is generally conservative (lowest risk), and based upon being able to deliver by 2050.
- Investigating alternative architectures, in particular a double-null solution
- Ultimately make decisions using a comparison framework based on meeting the DEMO Stakeholder Requirements
- Look to set R&D priorities, guided by a relative understanding of the risks
Thank you for your attention

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.
Acknowledgements

Programme Manager:  T. Donné

PPPT PMU HoD:  G. Federici

The PPPT PMU Team:
R. Wenninger, F. Maviglia, C. Bachmann, R. Brown, B. Meszaros, T. Franke, S. Ciattaglia, E. Diegele, F. Cismondi, C. Gliss

PPPT Project leaders:
L. Boccaccini (KIT), M. Rieth (KIT), C. Day (KIT), W. Biel (FZJ), J-H. You (IPP), N. Taylor (CCFE), A. Loving (UKAEA), L. Zani (CEA)/V. Corato (ENEA), A. Ibarra (CIEMAT), M.Q. Tran (SPC), M. Grattarola (ENEA).

PPPT Work Programme Collaborators on this talk
(in particular):
F. Träuble (IPP), E. Fable (IPP), H. Zohm (IPP), V. Loschiavo (ENEA), R. Ambrosino (ENEA)

PPPT Expert Group:
H. Zohm (IPP), W. Morris (UKAEA), B. Saoutic (CEA), C. Waldon (UKAEA), P. Sonato (RFX), T. Mull (AREVA), K. Hesch (KIT), S. Chiocchio (ITER), P. Barbaschi (F4E).
References and Further Background

• Federici et al., 2014, Overview of EU DEMO design and R&D activities, Fusion Engineering and Design 89
• Federici et al., 2015, Overview of the design approach and prioritization of R&D activities towards an EU DEMO, Fusion Engineering and Design 109-111
• Bachmann et al., 2015, Initial DEMO tokamak design configuration studies, Fusion Engineering and Design 98-99
• Wenninger et al., 2015, Advances in the physics basis for the European DEMO design, Nuclear Fusion 55
• Zohm et al., 2010, On the minimum size of DEMO, Fusion Science and Technology 58
• Zohm et al., 2016, Where to locate DEMO in a one-step-to-an-FPP strategy, to be published
• NASA Risk-Informed Decision Making Handbook, NASA/SP-2010-576
Additional Slides
Or: Why ours looks the way it does.

**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, 50 MW steady-state HCD)
- “Conservative” a.k.a. established physics basis

**Engineering:**
- Vertical Maintenance (MMS)
- EUROFER IVCs
- Starter blanket (20 dpa) + Second blanket (50 dpa) (~6-7 FPY total) – 4 concepts in parallel
- TBR > 1.1
- Availability target 30%
- Etc.

**Still many outstanding points for which no clear solution has yet been identified (e.g. ELMs, disruptions, FW, etc.)**

**Legend**

<table>
<thead>
<tr>
<th>Opt. target</th>
<th>DEMO1</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_0$(min.)</td>
<td>9.1 m</td>
</tr>
<tr>
<td>$A$</td>
<td>3.1</td>
</tr>
<tr>
<td>$P_{fus}$</td>
<td>2037 MW</td>
</tr>
<tr>
<td>$P_{el,net}$</td>
<td>500 MW</td>
</tr>
<tr>
<td>$t_{pulse}$</td>
<td>2 h</td>
</tr>
<tr>
<td>$\kappa_{95}$</td>
<td>1.59</td>
</tr>
<tr>
<td>$\delta_{95}$</td>
<td>0.33</td>
</tr>
<tr>
<td>$B_{T,0}$</td>
<td>5.7 T</td>
</tr>
<tr>
<td>$I_P$</td>
<td>19.6 MA</td>
</tr>
<tr>
<td>$P_{sep}/R$</td>
<td>17 MW/m</td>
</tr>
<tr>
<td>$n_{TF}$</td>
<td>18</td>
</tr>
<tr>
<td>H-factor</td>
<td>1.1</td>
</tr>
<tr>
<td>$f_{GW}$</td>
<td>1.2</td>
</tr>
<tr>
<td>Avg. NWL</td>
<td>1.1 MW/m$^2$</td>
</tr>
</tbody>
</table>
Description of the EU-DEMO baseline - ii

Development of an innovative T fuel cycle

WPBB
WPTFV
WPRM
Outstanding Technical Challenges with Gaps beyond ITER

For any further fusion step, safety, T-breeding, power exhaust, RM, 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
- Selection now is premature
- ITER TBM is important

**Power Exhaust**
- Peak heat fluxes near technological limits (>10 MW/m²)
- ITER solution may be marginal for DEMO
- Advanced divertor solutions may be needed but integration is very challenging

**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 mechanical strength at ~ high temp.
- Need of structural design criteria and design codes
- Technical down selection and development of an Early Neutron Source (IFMIF-DONES)
EUROfusion is a consortium of the European fusion Research Units

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.