The Role of a Divertor Test Tokamak in the EU PEX Strategy

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Presented at DTT Workshop, Frascati, June 19, 2017

¹not involved in specific ENEA DTT discussions
Outline

1.) Recap of the original PEX strategy (AHG report May 2016)

2.) What’s new (June 2017)
   • Boundary conditions
   • Conventional divertors
   • Alternative divertors
   • Alternative materials

3.) Role of DTT
   • Original strategy
   • What if we built it now?

4.) Questions to ENEA and further work of the AHG
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Aim is exhaust solution for an FPP, so strategy should lead via a series of steps to a credible solution for the exhaust problem in an FPP.

Principal future steps are ITER and DEMO (= single step between ITER and FPP).

Two routes:
- Conventional: ITER solution, i.e. single null lower divertor using a solid target
- Alternative (risk mitigation): ‘advanced’ divertor configuration and/or liquid metal target
Safety analysis
Qualify materials and prototypes in fission test reactors
Establish machining and joining technologies
Integrated performance of DEMO component under plasma conditions (MSF)
Assess impact of safe PFC operation on high performance plasma scenario (MSF)
Identify and assess interfaces
Evaluate applicability of existing design codes
Determine operation conditions and materials requirements

Develop machining and joining technologies, develop reliable low cost manufacture
Demonstrate materials compatibility with plasma in MSF/JET
Demonstrate proof of principle

Development and qualification of ITER PFUs (F4E)

Proof of principle phase

End of H2020 programme
start JT-60SA operation
start MSF HHF/long pulse operation

Now

Demonstration phase

Efficient PFU operation scheme validated for ITER Material is part of relevant nuclear design code
Mockup fabrication demonstrated
Component compatibility with plasma proven under MSF conditions
Assess impact of safe PFC operation on high performance plasma scenario (MSF)

2020

start ITER operation
JT-60SA steady state (C)
JET DT complete
start DONES operation
start DEMO EDA (~2030)

2027

Fusion relevant irradiation (DONES)
Component fabrication on industrial level
Integrated test of mock-up (JT60-SA)
Demonstrate safe PFC operation in DEMO scenario in JT-60SA (W)
Assess combined loads using predictive models

Component fabrication on industrial level
material accredited in design codes
Component compatibility with plasma proven under DEMO relevant conditions (JT-60SA?)

Qualification phase

Real size component produced by industrial supplier

2035

ITER Q=10
JT-60SA steady state (W)
start DEMO construction (~2040)

≥ 2050

Preparation for DEMO (mass production, remote handling etc.)
Integrated test of component in DEMO for use in FPP

Qualification of component in DEMO relevant conditions (JT-60SA?)

Demonstrate safe PFC operation in DEMO scenario in JT-60SA (W)
Assess combined loads using predictive models
PEX: Conventional Divertors

Proof of principle phase

- Systematic study of seed impurities (MST&JET)
- Interpretation with SOLDIV codes (quantitative match)
- Development of ITER and DEMO compatible sensors for detachment
- Experimental characterisation of confinement at high $f_{\text{rad,core}}$
- Develop physics models for confinement at high $f_{\text{rad,core}}$

Demonstration phase

- Control detachment in MST&JET at high $P_{\text{sep}}$
- Demonstrate exhaust in Q=10 scenario in MST/JET(DT)
- Verify SOLDIV codes (incl. first principles transport elements)
- Develop high $f_{\text{rad}}$ steady state scenario in MST(W)&JT60-SA(C)
- Characterise first wall loads in high $f_{\text{rad,core}}$ scenario (MSF, JET, JT-60SA)
- Develop first principles model for confinement at high $f_{\text{rad,core}}$

Q=10 exhaust scheme ready for use in ITER

- Assess high $f_{\text{rad}}$ for ITER Q=5 (P$_{\text{aux}}$ upgrade), and DEMO
- Qualify detached divertor under ITER Q=10 conditions
- Verify full predictive SOLDIV code
- Demonstrate high $f_{\text{rad}}$ steady state scenario in JT60-SA(W)
- Verify first principles model for confinement at high $f_{\text{rad,core}}$

EDA

- Now
- 2020
- 2027
- 2035
- 2039
- ≥ 2050

End of H2020 programme
start JT-60SA operation
start MSF/long pulse operation
start ITER operation
JT-60SA steady state (C)
JET DT complete
ITER Q=10
JT-60SA steady state (W)

ITER steady state
start DEMO ops
start DEMO construction (~2040)

Qualification phase

- Qualify combination of high $P_{\text{sep}}$ and high $f_{\text{rad,core}}$ in DEMO
- Implement in DEMO
- Develop high $f_{\text{rad,core}}$ scenario demonstrated at intermediate $P_{\text{sep}}$
- Demonstrate high $f_{\text{rad,core}}$ scenario in JT-60SA(W)
- Verify coupled core-SOLDIV model
- Develop high $f_{\text{rad,core}}$ scenario demonstrated at low $f_{\text{rad,core}}$
- Verify coupled core-SOLDIV model
- End of H2020 programme
- start ITER operation
- start MSF/long pulse operation
- start ITER operation
PEX: Alternative Materials and Plasma Facing Units (PFUs)

**Proof of principle phase**
- Integrated concept, incl. liquid metal loop, plasma compatibility, etc. (on paper)
- Reactor relevant target design survives ≥ 10 MW/m² in steady state (linear device)
- Qualification of suitable material (Li, Sn, LiSn): T-retention and operational temperature window
- Assess in-principle feasibility of contender concepts at DEMO scale

**Demonstration phase**
- Compatibility with main and divertor plasma (e.g., different recycling conditions), ≥ 2025
- Develop theoretical description on a first principle model (both PFU and plasma impact)
- Demonstrate closed loop function and target performance in a realistic tokamak environment, ≥ 2025
- Advance the technical implementation on a DEMO to CDA level

**Assess readiness for use in DEMO (integrate on EDA level)**
- Assess qualification process for Alternative PFUs in DEMO

**Assess qualification process for Alternative PFUs in DEMO**
- Demonstrate integrated plasma operation in ‘DTT’ ≥ 2030
- Verify predictive model in ‘DTT’ ≥ 2030
- Technical integration in DEMO on CDA/EDA level (depending on readiness)

**Qualification phase**
- Decide on DEMO divertor concept using ITER info on conventional exhaust performance and scenario compatibility in ‘DTT’
- Include results from conventional materials program for structural materials

**Conventional materials development**
- Include results from conventional materials program for structural materials

**Parallel strand on vapour box development (outside EU)**

**Now ~ 2022**
- Results from PEX Upgrades
- integrated scenario on MSF level
- start of DEMO EDA (~2030)

**2027**
- integrated scenario on 'DTT' level
- start of DEMO construction (~2040)

**2035**
- Direct use on DEMO

**> 2050**
- Continue for FPP, not DEMO (concept improvement)
- New device (large)
- Large delay to DEMO
- Direct use on DEMO (large step, implies a delay of DEMO construction)
- Include in FPP, using models and DEMO to convince
PEX: Alternative Divertors

**Proof of principle phase**
- Identify theoretically and experimentally the mechanisms that can give advantages
- Demonstrate (some of) the expected advantages qualitatively in MSTs (using PEX upgrades?)
- Identify causes of impact (positive and negative) on core scenarios (e.g. pedestal, impurities)
- Assess in-principle feasibility of contender concepts at DEMO scale, incl RAMI & TBR and impact on DEMO design (involve PPP&T)

**Demonstration phase**
- Demonstrate benefits of advanced divertor quantitatively supported by first-principles models in existing devices
- Advance the technical implementation on a DEMO to CDA level
- Demonstrate path to integrate with relevant (improved?) core scenario using experiments and first-principles models
- Assess readiness for use in DEMO (integrate on EDA-level)
- Establish qualification process for the individual mechanisms, the integrated plasma and the integrated engineering design

**Qualification phase**
- Confirm first principles model of advanced divertor in 'DTT' (≥ 2030)
- Demonstrate compatibility with core scenario in 'DTT' (≥ 2030)
- Technical integration in DEMO on CDA/EDA level (depending on readiness)
- Decide on DEMO divertor concept using ITER info on conventional exhaust performance and scenario compatibility in 'DTT'

**Core scenario development**
- Impact on possible core scenarios choices (including expansion of options)
- Impact on possible core scenarios choices (including expansion of options)

**Now ~ 2022**
- results from PEX Upgrades

**2027**
- integrated scenario on MSF level

**2035**
- start of DEMO EDA (~2030)

**> 2050**
- start of DEMO construction (~2040)

**Integrate on DEMO**
- Include in FPP, using models and DEMO to convince
- New device (large)
- ITER upgrade
- Large delay to DEMO

**Integrate on DEMO**
Summary of strategy to close the gaps
(as presented at Lisbon GA, April 2016)

Conventional approach:
• If all goes according to plan, the presently planned set of devices (MSF's, JET, JT-60SA, DONES, ITER, DEMO) is sufficient to arrive at an FPP with conventional exhaust solution
• Qualifying the conventional divertor in ITER is key to this strategy

Alternative approach:
• A full development will need a ‘DTT’ at some point and a comprehensive modelling capability
• We find it too early to tell if the alternatives are promising enough to take this step now (assess rigorously in ~2022).
• The delay of DEMO and Fusion Electricity on the alternative path crucially depends on the ability to combine alternative exhaust with the core scenario developed along the conventional line.

MST = Medium Sized Tokamak (presently funded by EUROfusion WPMST1)
MSF = Medium Sized Facility
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Evolving boundary conditions

Several things have evolved since our strategy document was written
• ITER time line now officially confirmed, but roughly in line with our assumptions (first plasma in 2025, D-T in 2035)
• JET future (ITER compatibility, Brexit – also affecting MAST-U?) – not within scope of our group to speculate about it, but final D-T most likely earlier than originally assumed (‘completed by 2027’)
• might mean much less time for exhaust experiments in JET (this is a concern!)
• a number of PEX MST upgrades approved – important for 2022 assessment

This type of evolving boundary conditions does at present not lead to drastic changes in our strategy document (although missing JET might have strong impact on the conventional path).

Also, scientific and technological progress has been made in the PEX area (very active field) – this will be discussed in the next slides
Recent progress: conventional divertor

Heuristic Goldston/Eich scaling may change route to design DEMO and FPP
• Higher B, smaller R attractive ($\lambda_q$ decreases like $1/I_p$, but radiative losses at fixed $f_z$ and $n/n_{GW}$ increase like $I_p^2$)
• Note this needs advances in technology to further increase B

Will there be a deviation from heuristic Goldston/Eich scaling?
• What are the physics elements governing SOL transport and $\lambda_q$ and what is their relative importance in present experiments / ITER / DEMO?

Increasing separatrix density without deteriorating confinement has emerged as a very important issue for ITER and DEMO
• What is the physics behind it (shift of $n_e$-profile? Change of turbulence?)
• Can pedestal degradation be avoided/controlled?
Recent progress: conventional divertor

Do radiative scenarios in conventional divertors always involve dominant X-point radiation?
• Impact on confinement (good H-mode with cold X-point)?
• Impact on divertor performance (loss of compression and pumping)?

Conclusion for conventional divertors: need for first principles understanding even more pronounced. Experiments should be judged according to their ability to give input to and provide crucial tests to theory development.
Recent progress: alternative divertors

Work in DTT1 has shown the principal feasibility of integrating alternative solutions into present DEMO design
- SF and XD fit within present design, at increased cost (e.g. larger TF volume)
- SXD may need a more radical change in design philosophy (internal coils?)

Various benefits for long legged divertors have been predicted
- Toroidal flux expansion (to be studied in MAST-U with PEX Upgrades)
- Increased neutral interaction along tightly baffled divertor leg

TCV has shown enhanced X-point radiation in SF configuration, albeit with a C-wall and hence ‘intrinsic seeding’. A clear advantage over conventional has not yet been shown.
- TCV & AUG with PEX upgrades can address these questions until 2022

Conclusions for alternative divertors: the situation has not changed drastically w.r.t. to the previous analysis. It is still too early to select a concept now. PEX upgrades are a step into this direction (still to be assessed in detail).
Recent progress: alternative materials

The liquid metal (LM) area is still in a proof-of-principle phase.

- Capillary Porous System (CPS) has been identified as the most promising candidate.
- A CPS design has been tested up to 20 MW/m².
- However, a credible concept for a closed loop LM solution for DEMO is still missing (need realistic and quantitative estimates of evaporation, concentration, condensation, D-T uptake etc...).

A strategy to arrive at such a concept by 2019 (gate review) has now been discussed in the recent LM workshop in Prague.

- This would be a necessary step to arrive at a concept selection for planning implementation in a major tokamak with poloidal divertor after 2022.

In parallel, the impact on divertor physics has to be studied

- How will the recycling be changed and what does it mean for the divertor plasma solution (it may be very different from solid target solutions).

Conclusions for alternative materials: the situation has not changed drastically w.r.t. to the previous analysis. A credible concept is urgently needed. This was also highlighted by the PMU PEX Upgrade Strategy.
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The role of DTT in the original strategy

• In absence of the ‘ITER-step’ for the alternatives, there must be a (set of) facilities that qualify the envisaged solution for DEMO
• An early exploratory phase in which different concepts are tested is handled by the MSFs with PEX Upgrades
• This should lead to an understanding of the benefits and a theory based prediction of what would be best for DEMO and an FPP
• Once this solution has been chosen, we anticipate that there will be specific physics elements that cannot be verified in MSFs
• The role of DTT in the original strategy was to specifically resolve these questions / provide predictive capability to model them
What if we built DTT now?

Ideally, the DTT design would address the remaining questions for the alternative solution chosen after assessment of the different options

• Since the different options have not been characterised in MSFs so far and also, the theoretical understanding is limited, it is at present not clear to define which questions exactly the DTT step should address
• Hence, it is also not clear which parameter regime must be accessed in order to validate the specific physics elements

The role of DTT, if built now, changes from qualification of a chosen solution to being an exploratory device with a potential to qualify a solution.

The potential strongly depends on
• flexibility: what is the range of configurations that can be accommodated? It might be that we need a different DTT for some solutions!
• accessible plasma parameter range: where does DTT sit w.r.t. MSFs and DEMO?

These aspects constitute the bulk of our questions to the ENEA team
How to evaluate ‘usefulness’ of a DTT?

A first assessment can be found in the ‘blue book’ and in the PEX Assessment Group Report. They are all 0-D and there is not a single universally agreed set of similarity parameters.

- $P_{tot}/R$: ‘magnitude of exhaust problem’
- $P_{totB}/(ARq_{95})$: the same, but assuming Goldston/Eich scaling of $\lambda_q$
- Also: $P_{sep}/R$, $P_{sepB}/(ARq_{95})$ – ‘magnitude of SOL/divertor loading’

Source: PEX Assessment Group report

A first assessment can be found in the ‘blue book’ and in the PEX Assessment Group Report. They are all 0-D and there is not a single universally agreed set of similarity parameters.
How to evaluate ‘usefulness’ of a DTT?

Ideally, one would like to see detailed divertor modelling to assess what physics can be studied, e.g.
- expected divertor compression in the different configurations
- expected neutral pressure at the pumping entrance (He pumping!)
- expected gain in detachment window for the different configurations
- transfer of this solution to DEMO (same physics?)
- ...

Can we improve in finite time (e.g. moving from TECXY to SOLPS-ITER)?
What if we built DTT now?

An additional aspect is the contribution of DTT to the development of the conventional solution (if no promising alternative emerges by 2022, that would be the main purpose of ENEA DTT). This has not been considered by the PEX report since it was concluded the existing devices are sufficient.

• if JET terminates earlier/has less experimental time to address PEX questions, it cannot be the upper step of the stepladder in the 2020s.
• since ENEA DTT will operate at full parameters from ~ 2030 on, it will run in parallel to JT-60SA and ITER.
• The question is hence: what are the unique points that ENEA DTT can deliver in addition to the set of MSFs, JT-60SA and ITER

There is also benefit in having an ‘ITER satellite’ device, i.e. a machine that operates in parallel to ITER but with much higher flexibility and able to dedicate more experimental time to specific points. To assess the value of ENEA DTT in this respect, it must be compared mainly to JT-60SA.

This area is another focus of our questions to the ENEA team.

*Note: we assume a W-wall in JT-60SA from ~2027 on and a sizeable fraction of the programme on JT-60SA (e.g. 25% of the total) devoted to exhaust studies.*
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Questions for the ENEA Team

Questions to the proponents focus on three main areas:

Flexibility
• since it is not yet clear which alternative concepts to chose, flexibility to accommodate different solutions is a key for a machine to be built now
• Should include SF, SX, SXD, DN and options to install a closed loop liquid metal solution

Timing
• It is important to understand what will be available when, in order to judge the usefulness of the contribution for the present strategy.
• Note: assessment of time and resource plan not part of AHG charge.

Plasma parameters
• Which plasma parameters will be achievable in the different configurations and at what time (see above)?
• How do these compare to the existing set of devices and the upcoming ones (JT-60SA and ITER) as well as DEMO/FPP (what are the unique contributions)?
Further work of the AHG

This workshop will be an important input to understand the capabilities of the proposed ENEA DTT

- We thank the proponents already in advance for answering our numerous questions at short notice.
- The workshop should also help us understand what the right questions are, so there should also be broader scientific discussion

Next steps according to our charge:

- Assess flexibility of ENEA DTT to adapt in ~2022 to preferred solution
- Assess scientific and technical input to alternative materials and divertors in the sense of the post 2022 divertor test facility identified in the report.
- Assess extra input to conventional path for further risk mitigation for the conventional approach (if no promising alternative emerges by 2022, that would be the main purpose of ENEA DTT).

After these steps, the AHG will assess the general PMU PEX strategy as proposed in April 2017. The provisional deadline for the whole assessment is end of 2017 (December GA).