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Memo

Open issues in the new ITER baseline with a W wall for Q = 10 operation that require experimental assessment

Memo summarizing open issues related to W first wall to be addressed by experiments (and ITPA)

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Open issues in the new ITER baseline with a W wall for Q = 10 operation that require experimental assessment

ITER Science Division

This document describes a set of key issues that need to be assessed to refine the plasma scenarios associated with the ITER new baseline proposal, including a W first wall, to demonstrate Q = 10 operation in DT-1. This assessment includes the optimum use of the ancillary systems included in the new baseline to achieve this goal.

Addressing these issues requires new experiments in fusion facilities and/or analysis of existing experimental measurements together with plasma simulations to understand/reproduce them. Such experimental results will be used for direct empirical extrapolation to ITER and for validation of the models that are applied to predict ITER Q =10 plasmas.

1. Introduction

The ITER new baseline consider dividing the ITER Research Plan into three phases.

1.1. Augmented First Plasma

In this phase the ITER device will be equipped with:

- Inertially cooled in-vessel components for First Wall, including tungsten (W) protection limiters;
- Water cooled W divertor;
- 40 MW of ECH heating from the equatorial and upper launchers;
- 5 MW of ICH heating to demonstrate ICWC and to test ICH heating in a W environment;
- 4 pellet injectors for plasma fuelling and ELM control;
- Complete set of in-vessel coils and power supplies (Vertical Stability and ELM control);
- A large set of plasma diagnostics;
- A boronization system.

The main overall objective of this phase is to minimize/retire risks for later IRP phases with specific sub-objectives:

- To commission control and protection systems with plasma;
- To demonstrate disruption mitigation up to maximum current and field;
- To develop plasma scenarios to 15 MA/5.3 T in L-mode and to, at least, 5 MA/2.65 T in H-mode with deuterium plasmas.

1.2. DT-1

In this phase, the ITER device will be equipped with:

- Water cooled W first wall and divertor;
- 67 MW of ECH heating from two equatorial and upper launchers;
- From 5 to 20 MW MW of ICH heating (to be decided) for ICWC and for ICH heating in a W environment;
- 33 MW of neutral beam heating;
- 6 pellet injectors for plasma fuelling and ELM control;
- Complete set of in-vessel coils and power supplies (Vertical Stability and ELM control);
- An extensive set of plasma diagnostics for DT operation;

- A boronization system.

The main objective of this phase is to demonstrate routine Q = 10 operation with P_{fusion} = 500 MW with, at least 300 s burn, within a total neutron fluence of 3 10^{25} neutrons and with specific sub-objectives:

- To commission control and protection systems with plasma up to Q = 10;
- To demonstrate disruption mitigation up to Q = 10;
- To develop plasma scenarios in DT up to 15 MA/5.3 T in H-mode (or lower current levels if Q = 10 can be demonstrated at those levels);
- To address specific issues for the TBM development programme.

1.3. DT-2

In this phase, the ITER device will be equipped with:

- Water cooled W first wall and divertor;
- 67 MW of ECH heating from two equatorial and upper launchers;
- From 5 to 20 MW MW of ICH heating for ICWC and for ICH heating in a W environment;
- 33-50 MW with neutral beam heating;
- 6 pellet injectors for plasma fuelling and ELM control;
- Complete set of in-vessel coils and power supplies (Vertical Stability and ELM control);
- The complete set of plasma diagnostics for DT operation;
- A boronization system.

The main objectives of this phase are to demonstrate routine operation in all ITER reference high Q scenarios (Q = 10 inductive, Q = 5 long pulse and steady-state), to support the TBM development programme and to address fusion reactor issues up to the Project Specification fluence goal of 3 10^{27} neutrons.

2. Open key issues for the new baseline demonstration of Q = 10 in DT-1

A set of key open issues is described below with focus on the demonstration of Q = 10 operation in DT-1. Issues related to the development path towards Q = 10 as well as for the other ITER high Q reference scenarios will be described in a separate document since these are of lower priority.

2.1. Boronization

The new ITER baseline includes a boronization system to deposit thin (50-100 nm) layers by GDC with diborane in helium carrier gas. This requires ramping the toroidal field down and it should preferentially be done on an occasional basis. The main objective of the boronization system in ITER is to provide good vacuum conditions for plasma start-up. The coverage of the W surfaces exposed to plasma by boron is expected to last only 100's of seconds (few ITER plasma discharges) while layers in remote areas are expected to last 1000's of seconds.

The key open issues related to boronization in ITER are described below.

2.1.1. Need for boronization with high Z plasma facing components (PFCs)

Experiments have shown that start of plasma operation with high Z plasma facing components is possible but this pose some difficulties. Open issues are:

- What are the main drawbacks of starting operation with W PFCs and no-boronization?
- What could be the short-term and long-term consequences of such strategy in ITER (e.g. on plasma start-up/ramp-up, etc.)?

When boronization is applied:

- How long does the boronization effect last for W PFC coverage (reduction on W source by coverage)?
- How long does the boronization effect last for good vacuum conditions (oxygen level reduction)?
- Does the type of plasma operation ($<n_e>$, P_{inp}, etc.) impact the duration of boronization for reduction of W source and for oxygen level reduction?
- What is the reason for deterioration of vacuum conditions between boronizations?

2.1.2. Optimum application of boronization

ITER plans to apply boronization with diborane in a helium mix by GDC. The system is being designed to provide an, as far as possible, toroidally and poloidally uniform boron layer. Open issues are:

- How thick needs to be the boronized layer to have clear effects on vacuum?
- What is the impact on operation (W coverage/vacuum conditions) of a non-uniform layer?
- How to optimize glow (species, pressure, etc.) for maximum uniformity?
- What are the key design choices to provide such uniform layer (e.g. number of GCD anodes, injection points, etc.)?
- Can other systems to apply boron (e.g. powder dropper) be used in conjunction with GDC to optimize boronization ?

2.1.3. Formation of boron deposits and fuel retention

Boronized layers in ITER can be a significant source of dust and tritium retention. Therefore, it is important to quantify both impacts and to investigate possible approaches to re-activate the boron layers in-situ. Open issues are:

- Where does boron deposit following plasma operation?
- What is the content of hydrogen, oxygen, etc., in the boronized layers?
- Can oxygen be removed from boron layers in-situ (leaving boron) by GDC or ICWC (i.e. boron layer in-situ re-activation)?
- How much fuel can be removed from boron layers by baking, ICWC and GDC?
- What processes occur when boron layers, co-deposits and dust are exposed to air/humidity (oxidation, release of fuel, …) during vessel venting ?

2.2. Operation with W first wall plasma facing components in ITER for Q = 10 demonstration

ITER Q = 10 operation is based on a conventional high-density H-mode scenario with suppressed ELMs and radiative divertor operation by extrinsic impurity seeding to provide appropriate divertor heat and helium exhaust. According to modelling, this results in W concentrations in the core plasma of 1-2 10^{-5}, and thus acceptable core radiation levels, and Q = 10 fusion performance for the calculated W wall and divertor sources. Key physics processes behind modelling predictions are: a) the high edge separatrix densities, required for divertor exhaust, which provide W screening in the pedestal through neoclassical transport effects, b) the anomalous pedestal W transport associated with ELM suppression and a stationary pedestal pressure and c) the lack of core W accumulation due to the lack of a strong core particle source in ITER and the dominant electron heating of Q = 10 plasmas.

The specific open issues for this operational scenario are described below for a range of physics issues that impact it.

2.2.1. Limiter operation with W first wall PFCs

All ITER plasmas have a low plasma current limiter phase (typically up to ~ 3 MA) before becoming diverted and this can be impacted by W PFCs. Open issues are:

- How is the operational range for plasma limiter ramp-up modified/restricted when W PFCs are used, compared to low Z PFCs?
- Which schemes can be used to expand operational range of W limiter ramp-up (in addition to boronization of the limiter)?

2.2.2. W wall source in diverted operation

The W source from the wall is the result of sputtering by plasma ions (hydrogenic species and impurities) and charge-exchange neutrals in ITER. This sputtering can take place during stationary phases and during ELMs; in the latter the characteristics of plasma and neutrals that reach the wall are very different from those during stationary phases. Since Q = 10 operation requires suppressed (or negligibly small) ELMs, it is important to experimentally determine the main driving processes expected for W wall sputtering at play in ITER by comparison with other more routine plasma operating conditions (L-mode and Type I ELMy H-mode) in present experiments. Open issues on this topic are:

- Which are the processes that dominate production of W from the wall for L-mode plasmas at high and low $\langle n_e \rangle$?
- Which are the processes that dominate production of W from the wall for Type I ELMy H-modes at high and low $\langle n_e \rangle$ and with radiative divertor conditions by extrinsic impurity seeding?
- Which are the processes that dominate production of W from the wall for small/no-ELMs H-modes (including ELM suppressed plasmas by 3-D field application) at high/low $\langle n_e \rangle$ and with radiative divertor conditions by extrinsic impurity seeding?
- Does a W wall introduce additional requirements for ELM control to prevent core W contamination?
- Which other metallic impurity influxes are measured in the H-mode scenarios above besides those of W?
- What is the impact of ICH heating on the W wall source for the H-mode scenarios above?

2.2.3. Transport of W from the wall to the separatrix

The W produced at the wall has to reach the plasma separatrix to contaminate the core plasma. This is influenced by the location of the source and the SOL plasma that W ions need to transport through to reach the separatrix. ITER is expected to have a high density and high temperature SOL plasma and this can decrease the efficiency from W produced at the wall to reach the confined plasma. Open issues on this topic are:

- What is the impact of W wall source location on the separatrix W density (outer midplane separatrix-wall gap, inner midplane separatrix-wall gap inner gap, proximity of upper X-point to double-null, etc.)?
- What is the impact of SOL parameters (low and high n_e far-SOL) on the penetration of W from the wall to the separatrix?

2.2.4. Transport of W from the separatrix into the core plasma through the pedestal

The W ions reaching the separatrix are further transported into the core plasma through the pedestal. The physics of W transport through the pedestal is found to play an important role in the shielding of the core plasma from the W produced by the wall and divertor in ITER. Open issues on this topic are:

- How does W pedestal transport depend on edge plasma parameters (e.g. n_{sep}, n_{ped}, T_{sep}, T_{ped})?
- Can W transport in the pedestal be described by neoclassical transport for both diffusion and convection or is anomalous transport required in this description?
- What is the impact of small/no ELM H-mode pedestals (including ELM suppressed plasmas by 3-D field application) on W transport in the pedestal?
- Are there specific impacts on pedestal W transport, when 3-D field are applied for ELM suppression, in addition to the associated increased pedestal transport causing ELM suppression?

2.2.5. Transport of W in the core H-mode plasma

In addition to a global increase of the W level in the plasma by the additional source from the wall, W can accumulate in an uncontrolled way in the plasma central area and lead to the radiative collapse of the discharge. Previous modelling studies for ITER have shown that the likelihood of uncontrolled W accumulation in ITER stationary phases is very low because of the lack of an intense particle source from the neutral beams in ITER (1 MeV) and the dominant electron heating in Q = 10 plasmas. Accumulation during transients (in particular H-mode termination phases), on the other hand can happen but can be avoided by tuning of heating and fuelling schemes ramp-downs. This is consistent with present experimental evidence and modelling of existing experiments but a quantitatively validated prediction for ITER remains outstanding. Open issues on this topic are:

- What is the impact of the various features of the heating schemes on core W transport (electron/ion heating, associated particle source, rotation effects, etc.) in present experiments and can these be modeled quantitatively?
- Is W accumulation possible in ITER Q = 10 plasmas given their specific features (dominant electron heating, low rotation Mach number and low core particle source)?
- Which are the physics mechanisms behind the control of W transport in the core plasma by electron heating? Is W control achieved through a direct effect of turbulent transport on W or as an indirect effect through main plasma ion/electron profile modifications and can this be modelled accurately?

- What is the impact of W transport control by electron heating on energy confinement and can this minimized by adjusting the electron heating source (e.g. level, heat deposition profile)?

2.2.6. Global impact of W wall on H-mode plasmas and its minimization

Besides the specific physics questions above, it is also important to understand and document the global impact of a W wall on H-mode plasmas in existing experiments and the methods that are presently used to minimize it. This can be used to determine if such impact is relevant for ITER or not and to explore if the present impact minimization approaches can be used in ITER Q = 10 plasmas or not. It should be noted that extrapolation from present experiments to ITER may not be trivial for some of the issues and is likely to require extensive simulations to validate models against experiments and application to ITER to reach conclusions.

The quantification of the impact could be done by comparing plasma conditions in the same device with a high Z and a low Z wall or by comparing plasma operation near boronization (up to few days after it is applied while W wall plasma exposed surfaces are covered by boron) and well away from boronization (several weeks after when plasma exposed W wall surfaces are not boron covered). Issues that require documentation and understanding on this topic are described below: How does the W wall restrict the H-mode operational space in Type I H-modes (dominantly RF heated, if possible) compared to low Z wall (e.g. I_p, q_{95}, $\langle n_e \rangle$, P_{inp})

- Are these restrictions modified when comparing un-seeded Type I H-mode plasmas and similar plasmas with extrinsic impurity seeding and radiative divertor operation?
- Which schemes/operational strategies can be used to widen operational space of Type I ELMy H-modes (un-seeded and seeded) (e.g. wall clearance, proximity to double null, heating schemes mix, fuelling schemes, etc.)?
- How does the W wall restrict the H-mode operational space in small/no-ELMs H-modes (dominantly RF heated, if possible) compared to low Z wall (e.g. I_p, q_{95}, $\langle n_e \rangle$, P_{inp})?
- Are these restrictions modified when comparing un-seeded small/no-ELMs plasmas and similar plasmas with extrinsic impurity seeding and radiative divertor operation?
- Which schemes/operational strategies can be used to widen operational space of small/no-ELMs H-modes (un-seeded and seeded) (e.g. wall clearance, proximity to double null, heating schemes mix, fuelling schemes, etc.)?
- Which are the optimum operational strategies to achieve core W concentrations of 1-2 10^{-5} in H-mode plasmas with $H_{98} > 0.9$? Are this applicable to ITER Q = 10 operation ?
- Does the W wall impact the termination phase of H-mode plasma scenarios compared to a W divertor and a low Z wall and, if it does, which additional operational strategies are required for successful terminations?