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Operation Plan

ITER Research Plan (IRP) - Level 1 - ITER Research Plan

The ITER Research Plan defines the strategy to achieve the objectives defined in the Project Specification through the scientific and technical exploitation of the ITER tokamak device and its ancillary systems. This strategy requires the availability of tokamak and ancillary systems as established within the Staged Approach. This document is a high-level (Level-1) summary describing the overall timeline of the configuration of the ITER facility and the research activities foreseen for each phase to achieve the main plasma operational goals, including the plasma scenarios to be developed.

Approval Process			
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Co-signatories			
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Change Log			
ITER Research Plan (IRP) - Level 1 - ITER Research Plan (24QSG6)			
Version	***Latest Status***	***Issue Date***	***Description of Change***
v1.0	Signed	08 Aug 2019	
v1.1	Approved	22 Sep 2019	Revised version taking into account comments by the reviewers and by the DG.
v1.2	Signed	14 Oct 2020	Typos in Fig. 2 corrected (ICH removed from PFPO-1) and Mise en Service translated into English (French footnote). Few instances of incorrect spelling of FPO corrected in index and section headings)
v1.3	Approved	14 Oct 2020	Typos in Fig. 2 corrected (ICH removed from PFPO-1) and Mise en Service translated into English (French footnote). Few instances of incorrect spelling of FPO corrected in index and section headings).
v1.4	Approved	29 Apr 2021	Minor changes to align high level TBM program stages with ITER Council decisions
v2.0	Approved	07 Nov 2024	ITER Research Plan accounting largely for the so-called Scenario B changes (new staged approach SRO/DT1/DT2 and replacement of beryllium in the first wall armour by tungsten) as presented to STAC-30 in June 2024 and STAC-31 in October 2024 (IC/STAC-30/5.1. Updated ITER Research Plan - Level 1 (AXUP2U v1.4)) and baselined via PCR-001600 Baseline 2024 - Scenario B - Level 1 Documentation and PR Annexes (technical parent PCR)

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1 Purpose

The *ITER Research Plan* defines the strategy to achieve the objectives defined in the Project Specification [1] through the scientific and technical exploitation of the ITER tokamak device and its ancillary systems. This strategy requires the availability of tokamak and ancillary systems as established within the 2024 New Baseline (for a detailed configuration of tokamak and ancillary systems see [2]) and defined in the ITER Research Plan baseline documents down to Level 3. This document is a high-level (Level-1) summary describing the overall timeline of the configuration of the ITER facility and the research and development activities foreseen for each phase to achieve the main operational and technical goals, including the plasma scenarios to be developed, and to establish the scientific and technical basis for the realization of nuclear fusion as an energy source.

2 Applicable documents

[1] Project Specification (PS) (2DY7NG)

[2] PCR-XXX – Establishment of the 2024 New ITER Baseline

[3] ITER Physics Basis, Nucl. Fusion **39** (1999)

[4] Progress in the ITER Physics Basis, Nucl. Fusion 47 (2007)

[5] Project Requirements (PR) (27ZRW8)

[6] New ITER baseline licencing strategy (TBD)

[7] ITER Concept of Operations (S7T73E v2.0)

3 Introduction

The strategy of the ITER Research Plan is based on the scientific and technical knowledge developed in the ITER Members' fusion research communities over many years [3, 4]. The ITER Research Plan defines the research and development to be executed up to the achievement of the Project's fusion power goals, including the testing program of the Test Blanket Modules (TBMs) [Annex A], provided by several ITER Members for tritium breeding and operated under the responsibility of the ITER Organization, as well as the demonstration of ITER operation as a fully integrated fusion engineering system with the achievement of key technological goals for the demonstration of nuclear fusion as an energy source for mankind. These fusion power demonstration goals are specifically: the demonstration of 500 MW of fusion power with fusion power multiplication factor (Q) ≥ 10 for lengths of 300-500 s and of long pulse and steady-state non-inductive scenarios with Q ≥ 5 and burn lengths of 1000 s and 3000 s respectively, as defined in the Project Specifications [1] and Project Requirements [5]. The ITER Research Plan strategy has been developed consistent with the successive installation of tokamak components and ancillary systems up to the completion of the ITER baseline configuration [2], with a stepwise approach nuclear safety demonstration [6], including the progressive acquisition of knowledge and lessons learnt in each phase to prepare the next one.

The ITER Research Plan is divided into five major phases:

- **Integrated Commissioning I (IC-I)**: This phase concerns the integrated commissioning of all ITER tokamak and plant components/systems installed in the Pre-SRO assembly phase up to the demonstration of the capabilities required to produce a tokamak plasma, including the achievement of nominal currents in the superconducting coils, i.e. the demonstration of full magnetic field operation. The IC-I phase is foreseen to last 18 months.

- **Start or Research Operation (SRO):** This phase starts with the demonstration of the first tokamak plasma and concludes with the demonstration of tokamak operation up to the nominal design parameters of 15 MA / 5.3 T in a diverted plasma configuration, including the use of the electron cyclotron (ECH) and ion cyclotron (ICH) heating and current drive (H&CD) systems up to their nominal coupled power levels into the plasma and for durations of up to 50 s. Within the SRO phase an experimental campaign with deuterium plasmas at reduced current up to 7.5 MA and toroidal field (2.65 T) will take place to explore the operational space and control of H-mode plasmas in ITER. This will mark the Start of Nuclear Operation (SNO) in ITER; the neutron fluence in the deuterium experimental campaign will be limited to enable the installation of in-vessel components foreseen in the Post-SRO assembly phase, while respecting shutdown dose rate requirements for workers involved in these activities. The SRO phase is foreseen to last 27 months, including the demonstration of the first tokamak plasma in ITER. In this phase, the engineering evaluation of the ITER tokamak as an integrated system with as-built and as-assembled components/systems will be performed.
- **Integrated Commissioning II (IC-II)**: This phase concerns the integrated commissioning of all ITER tokamak and plant components/systems installed in the Post-SRO assembly phase and re-commissioning of those installed in Pre-SRO assembly up to the demonstration of the capabilities required to produce deuterium-tritium tokamak plasmas. The IC-II phase is foreseen to last 10 months.
- **First Deuterium-Tritium phase (DT-1):** In this phase, deuterium (D) – tritium (T) plasma scenarios will be developed to demonstrate the Project's goal of 500 MW of fusion power with multiplication factor (Q) $\geq$ 10 for lengths of, at least, 300 s and to demonstrate high-duty operation with fusion power levels of 250 MW for, at least, 300 s. Operations in this phase are divided into two-year cycles with 16 months of plasma operations, followed by 8 months of long-term maintenance, which include integrated commissioning activities before each campaign [7]. Research in this phase will address, among others, a wide range of burning plasma physics and scenario integration issues and will provide demonstrations of key technologies required for demonstration fusion reactors such as those related to heat flux handling components at an average neutron flux $\geq$ 0.5 MW/m^2 as per Project Specifications [1]. The neutron fluence in this phase will also be limited to enable the performance of maintenance activities in the corresponding long-term maintenance periods, while respecting shutdown dose rate requirements for workers as specified in the Project Requirements [5]; this fluence is evaluated to be of the order of ~1% of the ultimate Project fluence goal as per Project Specifications [1]. This phase will also provide key reference data to perform safety-related evaluations for D-T operation in ITER (e.g. radiation maps, T retention and removal, dust production, etc.), which will be used to refine the licencing requirements details in the second deuterium-tritium phase that will follow DT-1. The DT-1 phase is foreseen to last up to 10 years, i.e., it includes 5 experimental campaigns.
- **Second Deuterium-Tritium phase (DT-2):** In this phase, D-T plasma scenarios will be developed to demonstrate all the Project's fusion power production goals. These goals are specifically: the demonstration of 500 MW of fusion power with fusion power multiplication factor (Q) $\geq$ 10 for lengths of 300-500 s in high duty operation and of long pulse and steady-state scenarios with and Q $\geq$ 5 burn lengths of 1000 s and 3000 s respectively, as defined in the Project Specifications [1] and Project Requirements [5], which support the physics basis of scenarios considered for demonstration fusion reactors. In addition, research will be carried out to support the ITER Members' demonstration fusion reactor programmes including both scenario development issues (e.g. heat flux exhaust), design/operational issues (e.g. optimum H&CD mix)

and their TBM programmes, in principle, up to neutron fluences of at least 0.3 MWa/m^2 as per Project Specifications [1]. The activities to be performed in this phase will be defined in detail during DT-1 once high fusion power production in D-T plasmas has been produced in ITER and the licencing requirements for DT-2 have been defined. Operations in this phase are divided into two-year cycles with 16 months of plasma operations, followed by 8 months of long-term maintenance, which include integrated commissioning activities before each campaign [7]. Before the start of DT-2 specific integrated commissioning of the newly available or upgraded components or systems and recommissioning of the existing ones will take place. The DT-2 phase is foreseen to last up to 10 years, i.e., it includes 5 experimental campaigns.

The timeline of the ITER Research Plan is summarized in Fig. 1; note that assembly phases in the timeline of Fig. 1 are shown for information only since they are not part of the Research Plan. Table 1 summarizes key tokamak components and systems that will be available to execute the programme in each of the phases. The successful implementation and execution of the ITER Research Plan relies on close collaborations between the ITER Organization and the ITER Member's fusion research institutes in both the experimental and theory/modelling areas.

4 Phases of the ITER Research Plan

4.1 Integrated Commissioning I

The objective of this phase is to prepare the tokamak for plasma operation and to demonstrate that the integrated operation of the tokamak and ancillary systems, as installed in the Pre-SRO assembly phase, meet the performance requirements for plasma operation. This demonstration is required before plasma operation can be attempted. The IC-I phase starts with the closure of the cryostat. The activities in this phase involve commissioning of the core tokamak components (cryostat, vacuum vessel, superconducting coils, in-vessel coils, divertor, …), conditioning of in-vessel components, and commissioning of ancillary systems such as ICH, disruption mitigation system (DMS), glow discharge cleaning system (GDC), controls, safety and interlock systems for plasma operation, etc. This phase concludes with the commissioning of the superconducting magnets to full current demonstrating that they can support operation at 15 MA/5.3 T. The successful completion of this commissioning marks the culmination of IC-I and opens the way to the SRO phase.

The licensing process for ITER to start nuclear operation (Authorization for Operation of Nuclear Installation for deuterium plasmas or "Mise en Service" for deuterium plasmas), following the delivery of the required in-situ qualification and commissioning test results to the nuclear regulator, shall be completed during the integrated commissioning phase in advance of SRO operations. The IC-I phase is planned to last 18 months and proceeds directly to the SRO phase.

Key outcomes of the activities planned for IC-I include:

- Superconducting coil operation at nominal current levels and ramp rates, as required for the nominal 15 MA/5.3T scenario;
- Demonstration of high quality vacuum required for tokamak plasma operation;
- Commissioning of the controls, safety and interlock systems required for plasma operation;
- Elaboration of the first version of a safety-orientated knowledge acquisition programme based on the in-situ qualification and commissioning test results and the first safety report;
- Authorization for Operation of Nuclear Installation for deuterium plasmas ("Mise en Service" for deuterium plasmas).

4.2 Start of Research Operation Phase

The objective of this phase is to develop the operational basis for the plasma scenarios to be later employed for fusion power production in DT-1 and to commission with plasma key systems required to support them (e.g. PCS, DMS, etc.). This phase starts with the demonstration of the first tokamak plasma, which requires all tokamak, plant, and auxiliary systems to operate in an integrated way under the plasma control system (PCS) satisfying their respective requirements for plasma operation. In the following part of the SRO phase, tokamak operation up to the nominal plasma current and field of 15 MA / 5.3T will be demonstrated in low confinement mode (L-mode); high confinement mode (H-mode) scenarios will be explored up to 7.5 MA at 2.65 T, both in diverted plasma configurations. This requires commissioning of the available H&CD systems (ECH and ICH) up to their nominal plasma coupled power levels for durations of, at least, 50 s. Most plasmas will be performed in hydrogen (with helium as minority species for ICH) with a specific set of experiments carried out in deuterium plasmas (with hydrogen as minority species for ICH) to address the exploration of H-mode scenarios, which will mark the Start of Nuclear Operations in ITER. The use of hydrogen and deuterium plasmas allows the execution of the experimental programme with low production of neutrons and tritium by fusion reactions. The neutron fluence in the deuterium experimental campaign will be limited to enable the installation of in-vessel components foreseen in the Post-SRO assembly phase, while respecting shutdown dose rate requirements for workers involved in these activities.

The SRO phase is planned for 27 months of plasma operations including the demonstration of first plasma (FP). By the start of SRO many systems are in their baseline configuration while others are in a partial or temporary configuration to facilitate the achievement of SRO objectives with minimum operational risks, such as those associated with disruption loads and their mitigation. More details on key components and systems available for operation in each of the ITER Research Plan phases can be found in Table 1.

Integrated operation with a large number of tokamak components and ancillary systems in their final baseline configuration and with an inertially cooled tungsten (W) wall in SRO provides substantial minimization of the risks associated with physics uncertainties and plasma operational aspects for later operation in the DT-1 phase with deuterium-tritium plasmas. In particular, control and investment protection algorithms and systems (PCS, APS, CIS, …) as well as the DMS will be commissioned with plasma during this phase both in L-mode to the nominal 15 MA/5.3 T levels as well as in H-mode up to 7.5 MA/2.65T. In-vessel components will, thus, already be subject to the highest electromagnetic loads in SRO. This will allow the identification of possible design/manufacturing weaknesses leading to infant failures, which will be possible to solve by hands-on assisted corrective maintenance.

Together with this, the development of the basic building blocks of ITER plasma scenarios (plasma start-up, plasma current ramp-up, flat-top and ramp-down) for both L-mode and H-mode plasmas is the fundamental purpose of this phase. In this phase the schemes to provide and maintain good vacuum conditions foreseen for operation with all-tungsten plasma facing components (GDC and Boronization) and to maintain an acceptable tungsten core plasma concentration will be tested and optimized to minimize impact on machine operations.

Key outcomes of the activities planned in SRO:

- Demonstration of the capability of superconducting coils and the cryoplant to operate plasma scenarios up to 15 MA/5.3 T in diverted configuration;
- Routine operation with shape and vertical position control up to 15 MA/5.3 T in L-mode;
- Exploration of the H-mode operational space up to 7.5 MA/2.65 T in deuterium plasmas;

- Commissioning of diagnostic systems with plasma and demonstration of their successful integration into the Plasma Control, Interlock and Investment Protection Systems;
- First validation of ITER plasma scenario predictions in L-mode and H-mode (over the range accessible in SRO). This includes (among many key physics and scenario integration issues):
    - Confirmation of energy and particle confinement expectations for ITER (based on scaling laws and advanced turbulent transport modelling) in L-mode and H-mode,
    - Confirmation of the additional heating power requirements to access and sustain H-mode plasmas in ITER (presently based on scaling laws),
    - Assessment of the efficiency of gas fuelling versus pellet fuelling in L-mode and H-mode plasmas,
    - Demonstration of the requirements for ELM control in H-mode plasmas with low input torque and dominant electron heating (as required for Q = 10 operation),
    - Quantification of the impact of ELM control on H-mode confinement,
    - Determination of the scrape-off layer power e-folding length in ITER H-mode plasmas and of its scaling with plasma conditions,
    - Assessment of the compatibility of H-mode confinement with radiative divertor operation;
    - Quantification of the tungsten sources (divertor and first wall), of the tungsten transport from the edge to the core plasma and of their impact on L-mode and H-mode plasma scenarios;
- Commissioning of the installed H&CD (ECH and ICH) systems with plasma up to their nominal plasma coupled power levels (40 MW and 10 MW, respectively) for up to 50 s;
- Demonstration of the compatibility of ICH heating with acceptable core plasma tungsten concentrations in L-mode and H-mode plasmas, guiding the decision for an additional 10 MW coupled plasma power upgrade to be installed for DT-1;
- Identification and optimization of the correction of error fields due to machine assembly and intrinsic non-toroidally symmetric features of ITER's design;
- Demonstration of required divertor and first-wall protection and core impurity control methods, necessary for high-performance H-mode scenarios in DT-1, in deuterium H-mode plasmas up to 7.5 MA/2.65 T;
- Characterization of disruption loads, to validate safety-related assumptions, and of their effective mitigation by DMS up to 15 MA/5.3 T, including runaway loads;
- Demonstration and optimization of wall conditioning schemes (GDC, Boronization, ICWC, ECWC);
- Engineering evaluation of the ITER tokamak as an integrated system with as-built and as-assembled components/systems, including the development of an integrated plant simulator;
- First validation step of the radiation maps by measurements obtained during deuterium operation and testing of safety-related measurements/systems such as the plasma current monitor and the fusion power shutdown system;
- First assessment of fuel (deuterium) retention and removal efficiency, dust production and in-vessel material analysis (first wall samples);
- Elaboration of the first update of the safety-orientated knowledge acquisition programme with regards to plasma transients (disruptions, VDEs, runaways), safety-related diagnostics and systems, dust production, in-vessel fuel retention and corrosion products in the cooling systems.

The demonstration of these objectives is key to minimize risks and to ensure robust operation in DT-1 with D-T, when the facility will begin to operate under the full nuclear licensing rules and activation will make changes or repairs inside the tokamak much more expensive and time consuming.

4.3 Integrated Commissioning II

This phase follows the SRO experimental phase and the second phase of assembly (Post-SRO assembly) after SRO. During the Post-SRO assembly phase, additional diagnostics are installed, the ECH system is upgraded with an additional 20-27 MW of power coupled to the plasma, and the ICH heating power may be increased by an additional 10 MW of power coupled to the plasma, if tests at SRO are successful. The TBMs [Annex A], and two NBI (HNB-1 and HNB-2) systems are installed to operate using hydrogen in the ion sources, as foreseen in the Neutral Beam Test Facility (NBTF) Research Plan [Annex B]. Regarding in-vessel components, water-cooled W first wall panels will be installed and connected to the blanket shield modules. The capabilities of the diagnostic set will be expanded from those available in SRO, in particular, to measure fusion products. Prior to the start of the IC-II phase a calibration of the neutron diagnostics will be performed.

The objective of this phase is to re-commission the systems already available from IC-I and to commission the newly available systems together with additional control, interlock and safety systems required for them and for later operation in DT-1. Of particular importance in this phase is the integrated commissioning of TBMs, NBIs and of the Tritium Plant connected to the tokamak. By this phase, the Tritium Plant will have been commissioned stand-alone, which requires the reception of tritium on-site during Post-SRO assembly, and will be followed by the connection of the plant to the tokamak systems. Lessons learnt from the previous IC-I phase will be included in the preparation of the detailed plan for IC-II.

The licensing process to allow the introduction of tritium into the tokamak and to perform D-T plasmas shall be completed during this phase in advance of DT-1 operations. This will require the timely submission of the first conclusions of the safety-orientated knowledge acquisition programme including those from dust and in-vessel material sample analysis. The IC-II phase is planned to last 10 months and proceeds directly to the DT-1 phase.

Key outcomes of planned activities in the IC-II phase include:

- Commissioning of the Neutral Beam Injectors (excluding the NBI ducts) using hydrogen in the ion sources to accelerating voltages ~ 870 kV;
- Commissioning of the four TBMs and associated sub-systems;
- Commissioning of the controls, safety and interlock systems required for DT-1 operation;
- Commissioning of the Tritium Plant connected to the tokamak systems;
- Elaboration of the second update of the safety-orientated knowledge acquisition programme including analysis of SRO results and samples as well as of the qualification and commissioning test results during IC-II.

4.4 First Deuterium-Tritium Phase

The objective of the first Deuterium-Tritium (DT-1) phase is to achieve the first Project's goals in the demonstration of the scientific and technological feasibility of fusion power production foreseen in the ITER Project. For the fusion power production goal, this is formulated in a quantitative form in the Project Specifications [1], namely the demonstration of 500 MW of fusion power production with $Q \geq 10$ for lengths longer than 300 s. To meet the goals, the research programme in this phase addresses key scientific and technical issues for the demonstration of nuclear fusion as an energy source, including the self-heating of deuterium-tritium plasmas by alpha particles from the fusion process, the demonstration of operation with efficient tritium management, the demonstration of tritium-breeding with the TBMs, the validation of assumptions in the nuclear safety licence in DT-1 and the provision of the operational basis to define the licence details for the second Deuterium-Tritium (DT-2) phase.

The DT-1 phase is divided into five two-year operational cycles with 16 months of plasma operation followed by 8 months long term maintenance plus commissioning periods, as described in [7]. The achievement of the DT-1 goals requires installation of new systems or upgrades, in addition to those already available in SRO, particularly of the H&CD systems (ECH, ICH and NBI), the water-cooled first wall, diagnostics and the TBMs.

Before the start of DT-1 the licencing process for ITER to start deuterium-tritium operation should be completed [6]. Of particular importance for the DT-1 phase is the availability of the Tritium Plant to reprocess tritium and deuterium for fuelling and to stand ready to handle releases of tritium into the secondary containment during long-term maintenance. The neutron fluence in this phase will be limited to enable the performance of maintenance activities in the corresponding long-term maintenance periods, while respecting shutdown dose rate requirements for workers specified in the Project Requirements [5]; this fluence is evaluated to be of the order of ~1% of the ultimate project fluence goal as Project Specifications [1].

4.4.1 Fusion Power Operation–1 (FPO-1)

The objective of the FPO-1 campaign is to re-establish operation with the newly installed and upgraded systems in the Post-SRO assembly phase, first in hydrogen and then in deuterium plasmas. This will require the re-commissioning of existing systems and the commissioning with plasma of the new/upgraded systems, controls, interlocks, protection, diagnostics, etc. The scenarios developed in SRO (15 MA/5.3 T – L-mode in hydrogen and 7.5 MA/2.65 T H-mode in deuterium) will be reproduced and their operational ranges extended taking advantage of the new systems and the newly available capabilities. This will include the determination of the effects of new sources of error fields on plasma scenarios, such as those due to the TBMs, as well as their minimization. Similarly, the optimization of wall conditioning schemes (GDC, Boronization, ICWC, ECWC) in their final configuration will be carried out. The newly installed/operational water-cooled in-vessel components (blanket shield modules and first wall panels) will be subject to the highest electromagnetic loads, as well as to power fluxes comparable to those in Q = 10 operation, already in the hydrogen phase of FPO-1. This is ensured by operation in hydrogen plasmas with additional heating power up to 100-120 MW (depending on upgrades implemented by DT-1) and with plasma current/toroidal field up to 15 MA/5.3 T in this phase. This will allow the identification of possible design/manufacturing weaknesses of these water-cooled components leading to infant failures, which would be possible to solve by hands-on assisted corrective maintenance before deuterium operation starts.

Before the change-over from hydrogen to deuterium, tritium will be introduced in the tokamak and plasmas with varying hydrogen/tritium contents will be performed. This will require the use of the fuelling and T plant connected to the tokamak, injecting tritium into the plasma for the first time. These experiments will allow a first quantification of tritium retention in ITER. These T containing plasmas will be used to commission the DMS system, including the presence of high energy electrons from beta-decaying tritium during disruptions, and to demonstrate its effectiveness in suppressing runaways up to 15 MA/5.3 T with T plasmas. The DMS commissioning experiments will be followed by tests of the fuel (tritium) removal schemes for DT-1 to assess their efficiency and guide their optimization.

Key outcomes of the activities planned in FPO-1 include:

- Demonstration of routine operation up to 15 MA/5.3 T in hydrogen L-mode plasmas and 7.5 MA/2.65 T in deuterium H-mode plasmas with a water-cooled tungsten first wall and H&CD systems with enhanced capabilities;

- Commissioning of the installed H&CD (NBI with hydrogen in the ion sources, ECH and ICH) systems up to their nominal plasma coupled power levels (33 MW, 60-67 MW and 10-20 MW, respectively) for, at least, 50 s;
- Identification and optimization of the correction of error fields due to TBMs and NBI Magnetic Field Reduction Systems;
- Demonstration of effective disruption mitigation by DMS in tritium-containing plasmas up to 15 MA/5.3 T;
- First injection of tritium into an ITER plasma supported by the fuelling systems and the Tritium plant;
- Demonstration and optimization of wall conditioning schemes (GDC, Boronization, ICWC, ECWC) supporting tritium-containing plasma operation;
- First assessment of tritium retention and removal, as well as of hydrogen isotope control;
- Elaboration of the third update of the safety-orientated knowledge acquisition programme including the results obtained during operation with tritium (including disruption loads), as well as activities related to maintenance with the vast majority of components/systems in their final configuration;
- First operation with the four Test Blanket Systems (TBSs) operated and controlled from the Control Room, using high-temperature and high-pressure coolants (for more details on the TBM research programme in this campaign see [Annex A]).

4.4.2 Fusion Power Operation–2 (FPO-2)

The objective of the FPO-2 campaign is to perform the first D-T plasmas in ITER and to demonstrate fusion power production in excess of 100 MW with $Q \geq 1$ for durations of, at least, 50 s. To minimize neutron fluence consumption, D-D and D-T plasma scenarios, with a range of tritium concentrations up to their optimum value for fusion power production, will be developed with plasma currents/fields in the range of 7.5-10 MA/5.3T. From the results obtained in these experiments the plasma scenarios (i.e. plasma current level, optimum heating and current drive mix, etc.) with the potential to deliver 500 MW of fusion power with $Q \geq 10$ will be identified. Experiments in this phase will be accompanied by the application, further development and validation of plasma scenario models to ensure that they can reproduce the plasma parameters obtained in this phase. This should ensure the provision of reliable predictions for the required plasma scenarios to be explored to demonstrate the 500 MW of fusion power with $Q \geq 10$ goal in FPO-3.

The development foreseen in FPO-2 will require the re-tuning of the plasma control and protection schemes already commissioned (or re-commissioned) in FPO-1, in particular those required to provide acceptable power fluxes to plasma-facing components and core impurity content. The DMS will also be re-tuned to account for the increasing levels of plasma energy and tritium content in H-mode plasmas. First studies of T fuelling in H-mode plasmas will be performed in this phase and their results be used for the optimization of plasma fuelling and of the fuel cycle. He exhaust from deuterium-tritium fusion will be explored for the first time in ITER. Similarly, the schemes to remove tritium, provide good wall conditions, error field correction, etc., will be re-tuned/optimized and applied to the plasma scenarios with increasing levels of plasma current, additional heating, tritium content and fusion power production. In this phase burn control experiments will be carried out to commission with plasma the systems to be later applied with high fusion power levels in DT-1.

Prior to FPO-2, a decision will be made to maintain the NBI system using hydrogen in the ion sources or to change to deuterium depending on the outcome of the NBTF research plan [Annex B]. As part of the initial phase of this campaign the capabilities of the heating and current drive systems to support burning deuterium-tritium plasmas with durations of, at least, 300 s will be assessed. This assessment will require operation at maximum plasma coupled power for each of the systems for durations of, at least, 600 s.

Key outcomes of the activities planned in FPO-2 include:

- Assessment of the capabilities of the heating and current drive systems to operate at maximum plasma coupled power for each of the systems with durations of, at least, 600 s;
- Demonstration of routine operation up to 10 MA/5.3 T in deuterium-tritium plasma scenarios with fusion power production in excess of 100 MW with $Q \geq 1$, providing the first evidence of alpha particle effects on the plasma, for durations of, at least, 50 s;
- Validation of plasma scenario models with the plasma parameters obtained in deuterium and deuterium-tritium plasmas up to 10 MA/5.3 T;
- Identification of the plasma scenarios (i.e. plasma current level, optimum heating and current drive mix, etc.) with the potential to deliver 500 MW of fusion power with $Q \geq 10$;
- Demonstration of tritium fuelling in H-mode plasmas, tritium concentration control and helium exhaust for fusion power production in excess of 100 MW;
- Demonstration of in-vessel tritium management by the optimization of wall conditioning and tritium removal schemes for fusion power production in excess of 100 MW;
- Second validation step of radiation maps by measurements obtained during deuterium-tritium operation with fusion power in excess of 100 MW;
- Elaboration of the fourth update of the safety-orientated knowledge acquisition programme including the results obtained during the first operation with deuterium-tritium plasmas and fusion power in excess of 100 MW, as well as of the associated maintenance activities;
- First operation of the TBMs with medium levels (~ 100 MW) of fusion power from deuterium-tritium plasmas allowing the preliminary verification of neutronics, tritium permeation and heat extraction performance (for more details on the TBM research programme in this campaign see [Annex A]).

4.4.3 Fusion Power Operation–3 (FPO-3)

The objective of the FPO-3 campaign is to demonstrate fusion power production of 500 MW with $Q \geq 10$ for, at least, 50 s including stationary helium exhaust. This campaign will provide the first D-T plasmas in ITER dominated by alpha heating and a wealth of new physics and operational results. To minimize neutron fluence consumption, D-D and D-T plasma scenarios, with a range of tritium concentrations up to their optimum value for fusion power production, will be developed. This development will start from the plasma scenario identified in FPO-2 (foreseen to provide $Q \geq 10$ in D-T) to confirm the expected plasma performance in D-D plasmas. If the performance is confirmed this scenario will be explored in D-T. If the D-D plasma performance is not confirmed, new scenarios will be developed in D-D plasmas up to the performance level required and, then, explored in D-T.

The associated expansion of the operational space will require the gradual re-tuning of the plasma control and protection schemes already commissioned FPO-2, as well as of the DMS with increasing levels of plasma energy and tritium content in H-mode plasmas. By the end of this campaign all ancillary systems and control schemes necessary to perform high Q operation in D-T plasmas will be routinely utilized, in particular those necessary for the integration of core plasma confinement and purity requirements with acceptable first wall and divertor plasma power and particle fluxes. Similarly, the schemes to remove tritium, provide good wall conditions, etc., will have been optimized to sustain high Q operation as well.

This campaign will provide key results for the validation of safety-related evaluations for D-T operation in ITER, in particular: a) full validation of the radiation maps in nominal fusion power operating conditions, b) confirmation of the applicability of the in-vessel retained T management approach in Q ≥ 10 plasmas (50 s duration), c) evaluation of the dust production rates for Q ≥ 10 plasmas (50 s duration), etc. These will be used to refine the licencing requirements details in the follow-up DT-2 phase and for the plans of the FPO-4 and FPO-5 campaigns. The campaign will conclude with the first attempt to extend the stationary burn duration at 500 MW fusion power with Q ≥ 10 beyond 50 s. This is performed at this stage to determine the physics processes that may lead to the termination of burn before 300 s, which is essential for the refinement of the plans for burn extension in FPO-4.

Prior to FPO-3, and if the NBI system has been maintained with hydrogen in the ion sources in FPO-2, a decision may be taken to maintain the NBI using hydrogen in the ion sources or to change to deuterium (see NBTF research plan [Annex B]). Similarly, the capabilities of the heating and current drive systems to support burning deuterium-tritium plasmas with durations of, at least, 300 s will be confirmed (if FPO-2 tests were successful) or re-assessed at the beginning of this campaign.

Key outcomes of the activities planned in FPO-3 include:

- Demonstration of reproducible operation with fusion power of 500 MW and Q ≥ 10 for, at least, 50 s demonstrating stationary helium exhaust;
- First characterization of burning plasmas physics and associated control challenges;
- Demonstration of routine operation of the water-cooled first wall-shield block and divertor to nominal plasma power and neutron fluxes;
- Demonstration of in-vessel tritium management by the optimization of wall conditioning and tritium removal schemes for plasmas with nominal fusion power of 500 MW with Q ≥ 10 and 50 s duration;
- First assessment of the effects of fusion neutrons and nuclear heating at nominal power levels on diagnostics and superconducting magnets;
- Final validation step of radiation maps by measurements obtained during D-T operation with nominal fusion power of 500 MW and Q ≥ 10;
- Elaboration of the fifth update of the safety-orientated knowledge acquisition programme with consolidated measurements of dust production, tritium retention, activated corrosion products and TBM operation with the nominal fusion power of 500 MW and Q ≥ 10, as well as of the associated maintenance activities;
- First operation of the TBMs with nominal neutron and power fluxes including the demonstration of the achievement of coolant thermo-hydraulics conditions (both for water-coolant and Helium-coolant) relevant for electricity production (for more details on the TBM research programme in this campaign see [Annex A]).

4.4.4 Fusion Power Operation–4 (FPO-4)

The objective of the FPO-4 campaign is to demonstrate fusion power production of 500 MW with Q ≥ 10 for burn times up to 300 s, as per Project Specification [1]. Progress in the extension of burn duration from 50 to 300 s is foreseen to take most of the experimental time in this campaign. It is, thus, expected that the number of pulses demonstrating 500 MW fusion power with Q ≥ 10 for 300 s in this campaign will be very small. The extension of the burn from ~ 50 s to longer timescales is expected to be limited by the development of magneto-hydrodynamic (MHD) instabilities. These may appear in longer time intervals in ITER since the profile of the plasma current relaxes in timescales of several 100's of seconds. This current profile evolution can also affect plasma transport and, thus, impact the parameters of the plasma and its fusion performance. To control or avoid these instabilities both active control and passive avoidance strategies are considered. The former will make use of the H&CD capabilities of ITER for active MHD control while the latter relies on shaping of the current profile in the L-mode and early H-mode phases to avoid such instabilities developing when the profile of the current in the plasma relaxes.

To minimize neutron fluence consumption, D-D and D-T plasma scenarios, with the optimum tritium concentration, will be developed. This development will start from the D-D plasma scenario identified in FPO-3 (providing Q ≥ 10 in D-T plasmas for 50 s) by extending it to a high-performance duration of, at least, 300 s using active and passive MHD control strategies. The schemes providing a high-performance D-D plasma scenario with a duration of, at least, 300 s will then be explored in D-T. In this exploration the MHD control strategies will be re-tuned to account for D-T effects, alpha particle effects, etc., up to the demonstration of the project goal of 500 MW fusion power with Q ≥ 10 for 300 s.

The execution of the experiments in FPO-4 requires operation of all tokamak and ancillary systems, especially H&CD, for time scales supporting up to 300 s burn plasmas. To this end specific commissioning of the systems with plasma will be carried out at the beginning of FPO-4, if the previous assessments in FPO-2 or FPO-3 have not been successful. For FPO-4 the NBI system will be kept in the same configuration as that used for the demonstration of the fusion power production goal of 500 MW with Q ≥ 10 for burn times of, at least, 50 s in FPO-3.

Key outcomes of the activities planned in FPO-4 include:

- Demonstration of first operation with fusion power of 500 MW with Q ≥ 10 for 300 s with stationary helium exhaust demonstrating the main Project's fusion power goal for DT-1;
- First characterization of burning plasmas physics and associated control challenges in nominal Q ≥ 10 operating conditions over timescales of 300 s;
- First assessment of the effects of fusion neutrons and nuclear heating at nominal power levels on diagnostics and superconducting magnets in nominal Q ≥ 10 operating conditions (burn duration of 300 s);
- Demonstration of in-vessel tritium management by the optimization of wall conditioning and tritium removal schemes for plasmas with nominal fusion power of 500 MW with Q ≥ 10 and, burn duration in the range of 50 to 300 s;
- Elaboration of the sixth update of the safety-orientated knowledge acquisition programme including, for the first time, measurements of dust production, tritium retention, activated corrosion products and TBM operation the with nominal fusion power of 500 MW, Q ≥ 10 and burn duration of 300 s, as well as of the associated maintenance activities;
- Depending on the number of pulses with high fusion power and long burn duration achieved in this phase, several of the TBM research goals foreseen for the last two DT-1 campaigns may already be demonstrated by the end of FPO-4 (for more details on the TBM research programme in the FPO-4 and FPO-5 campaigns see [Annex A]).

4.4.5 Fusion Power Operation–5 (FPO-5)

The objective of the FPO-5 campaign is to demonstrate reproducible fusion power production of 500 MW with Q ≥ 10 for burn times of, at least, 300 s. In addition, high-duty (1 pulse every 30 minutes) fusion power production of 250 MW for burn times off, at least, 300 s will be demonstrated.

The experimental programme in this campaign follows the path started in the FPO-4 campaign and will initially focus on the demonstration of reproducible fusion power production of 500 MW with Q ≥ 10 for burn times of, at least, 300 s. In DT-1, reproducible Q ≥ 10 operation with 500 MW fusion power and burn times of, at least, 300 s is quantitively formulated as the demonstration of pulses meeting these fusion performance requirements with a repetition time of, at most, 60 minutes (1 pulse every 60 minutes).

Together with this, scenarios to demonstrate the high-duty (1 pulse every 30 minutes) fusion power production goal of 250 MW for burn times of, at least, 300 s will be identified or additionally developed, if needed. These scenarios will provide the basis for dedicated experimental days in which high-duty operation will be demonstrated. These days will provide important technical information for the high-duty operation in DT-2 and key results for the TBM research plan, particularly the demonstration of tritium breeding.

Once the key goals of this campaign have been demonstrated, and depending on the neutron fluence available and the priorities of the ITER Project at the time, any remaining time in the FPO-5 campaign may be dedicated to the extension of the burn of the $Q \geq 10$ scenario to, at least, 500 s, as per Project Specification [1] or to the further exploitation of high-duty operation, for instance. Alternatively, the FPO-5 campaign may be terminated at this stage to proceed to the 2^{nd} Deuterium-Tritium phase (DT-2).

Key outcomes of the activities planned in FPO-5 include:

- Demonstration of reproducible operation with fusion power of 500 MW with $Q \geq 10$ for, at least, 300 s, demonstrating the main Project's fusion power goal for DT-1;
- Demonstration of high duty operation with fusion power of 250 MW for, at least, 300 s;
- Final assessment of the effects of fusion neutrons and nuclear heating at nominal power levels on diagnostics and superconducting magnets in nominal $Q \geq 10$ operating conditions (burn duration of, at least, 300 s);
- Extended characterization of burning plasmas physics and associated control challenges in nominal $Q \geq 10$ operating conditions over timescales of, at least, 300 s;
- Demonstration of in-vessel tritium management, dust production rates, etc., in nominal $Q \geq 10$ operating conditions to confirm the licencing requirements details in the second deuterium-tritium phase that will follow DT-1;
- Final report of the safety-orientated knowledge acquisition programme in the DT-1 phase including nominal results from operation with nominal fusion power of 500 MW, $Q \geq 10$ and burn duration of, at least, 300 s and from high-duty operation with fusion power of 250 MW for, at least, 300 s, as well as of the associated maintenance activities;
- First operation of the TBM in reproducible nominal $Q \geq 10$ operating conditions and in high-duty operation with fusion power of 250 MW for, at least, 300 s. This will demonstrate the achievement of coolant thermo-hydraulics conditions relevant for high-efficiency electricity production and of tritium breeding to confirm the Tritium Breeding Ratio (TBR) in demonstration fusion power reactors (for more details on the TBM research programme in the FPO-4 and FPO-5 campaigns see [Annex A]).

4.5 Second Deuterium-Tritium Phase (DT-2)

The objective of this phase is twofold: a) to demonstrate all the Project's fusion power production goals. These goals are the demonstration of 500 MW of fusion power with $Q \geq 10$ for lengths of 300-500 s, in high duty operation, and of long pulse and non-inductive steady-state scenarios with $Q \geq 5$ and burn lengths of 1000 s and 3000 s respectively, as defined in the Project Specifications [1] and Project Requirements [5] and b) to support the ITER Members' demonstration fusion reactor programmes including both scenario development issues (e.g. heat flux exhaust), design basis/operational issues (e.g. optimum H&CD mix, minimum sensor and actuator set for fusion reactors, etc.) and their TBM programmes, in principle, up to neutron fluences of, at least, 0.3 MWa/m^2 as per Project Specifications

[1], assuming this is confirmed by the licence for DT-2. We note that variants of the ITER long-pulse and steady-state scenarios to address the Project's fusion power production goals are presently considered as prime candidate operational scenarios for several demonstration fusion reactors and, thus, the research in this area is not only to fulfil the Project's goals but also to support the ITER Members' demonstration fusion reactor programmes.

The detailed research programme for this phase will be defined during DT-1, once high fusion power/high Q D-T plasmas have been produced in ITER and the licencing requirements for DT-2 have been defined in detail. The DT-2 phase is foreseen to last up to 10 years, i.e. it includes 5 experimental campaigns. It is presently considered to share the experimental time, starting from the first experimental DT-2 campaign, between the development of the two scenarios to demonstrate the Project's fusion power goals with that for dedicated operation/scenario development to address the needs of the ITER Members' demonstration fusion reactor programmes.

Operation and testing of different TBMs/TBSs could be envisaged in this phase, including more advanced TBS designs (depending on the evolutions of the demonstration fusion reactor studies) [Annex A]. Similarly, specific system upgrades may be implemented before DT-2, such as the installation of a third NBI (HNB-3) for the demonstration of full non-inductive, steady-state operation with $Q \geq 5$, the expansion of the Tritium Plant capabilities to support long pulse/steady-state scenarios, high duty operation and the expansion of the Hot Cell capabilities to manage the increasing amount of radwaste. Prior to the start of DT-2 a specific integrated commissioning campaign, whose details will be defined during DT-1, will be carried out to re-commission the available systems by the end of DT-1 and those that may be installed/upgraded before the start of DT-2 tokamak operation.

Key outcomes of the activities planned in DT-2 include:

- Demonstration of routine operation with 500 MW fusion power with $Q \geq 10$ for burn durations of 300-500 s at high-duty cycle;
- Demonstration of routine operation with $Q \geq 5$ for burn durations of 1000 s in long-pulse scenarios;
- Demonstration of routine operation with $Q \geq 5$ for burn durations of 3000 s in steady-state, non-inductive, scenarios;
- Exploration of physics, integration/control of $Q > 10$ plasma scenarios towards ignition up to $P_{fusion} = 700$ MW;
- Commissioning and demonstration of all required control, interlock, protection and ancillary systems required to support the scenarios to be demonstrated in DT-2;
- Assessment of fusion reactor physics and operational issues such as those related to the optimization of the H&CD mix, identification of the minimum set of sensors and actuators for the achievement of high Q plasmas and their control, the exhaust power and particles, etc.
- Consolidation of the tritium breeding efficiency evaluations for demonstration fusion reactors breeding blankets, etc. [Annex A].

5 Summary

The ITER Research Plan is summarized in Fig. 2. The expected progress toward the ITER operational objectives in the SRO and DT-1 phases is highlighted. The detailed research activities to be carried out in each of the phases and in the respective experimental campaigns will be developed at level-2 and level-3 in synchrony with the formal adoption of the new baseline 2024 as the reference baseline for the ITER Project from 2024 onwards. The successful implementation and execution of the ITER Research Plan relies on close collaborations between the ITER Organization and the ITER Member's fusion research institutes in both the experimental and theory/modelling areas.

6 Figures and Tables

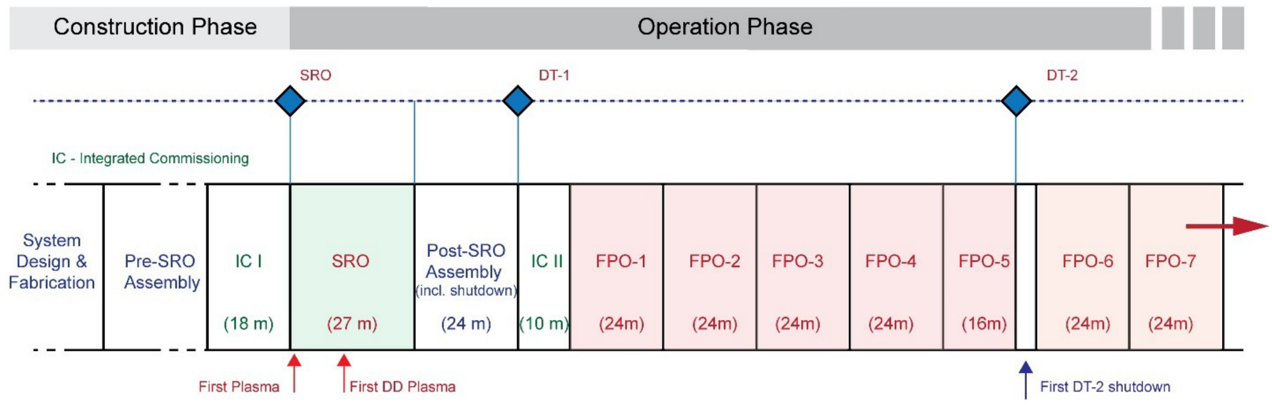

Figure 1. Schematic of the timeline for the new baseline 2024 ITER Research Plan.

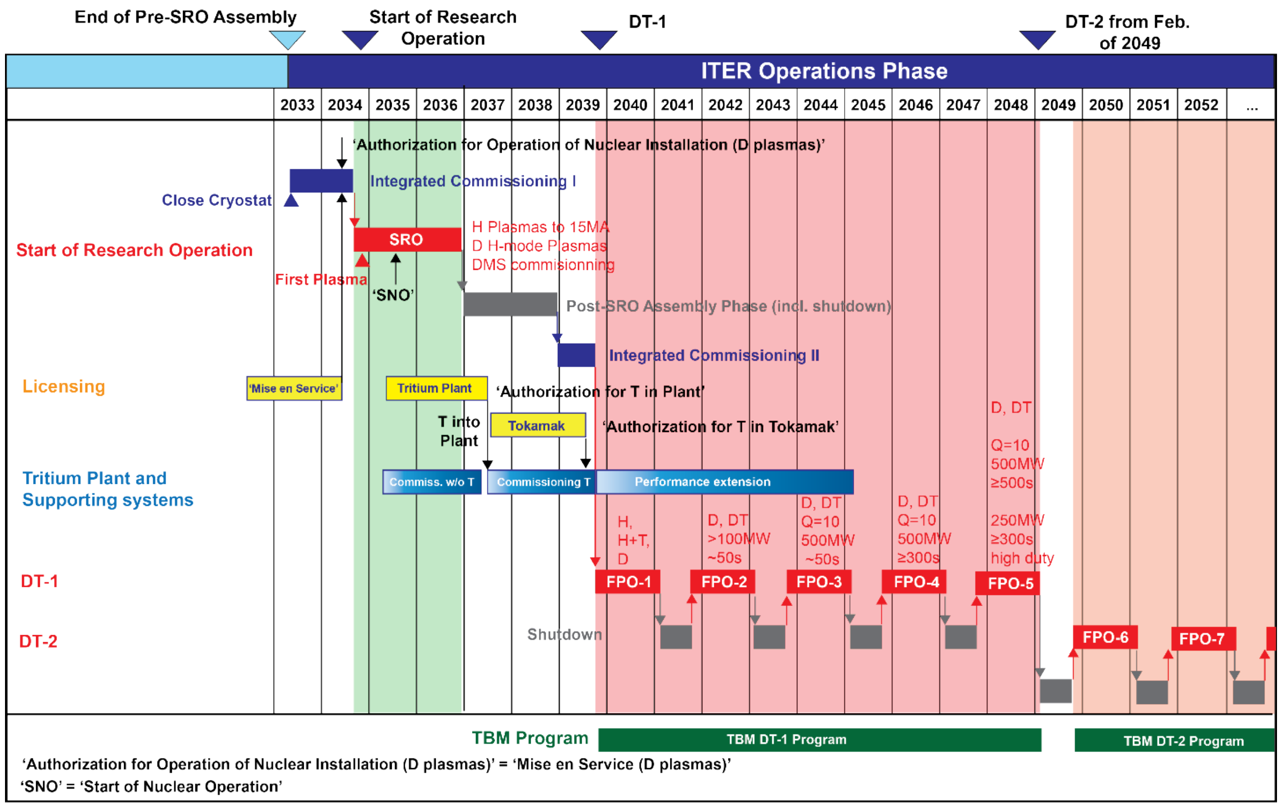

Figure 2. Operational plan for the execution of the new baseline 2024 ITER Research Plan to the demonstration of the $Q \geq 10$ 500 MW fusion power goal in the 1st Deuterium-Tritium phase and the initial campaigns of the 2nd Deuterium-Tritium phase.

System/Ancillary Available	Start of Research Operation	DT-1	DT-2
Vacuum Vessel, Thermal Shield and Cryostat	Final Configuration	Final Configuration	Final Configuration
Toroidal Field, Poloidal Field, Central Solenoid and Error Field Correction Superconducting Magnets and Power Supplies	Final Configuration	Final Configuration	Final Configuration
In-vessel Vertical Stability and ELM Control Coils and Power Supplies	Final Configuration	Final Configuration	Final Configuration
Cryostat and Torus Cryopumps	Final Configuration	Final Configuration	Final Configuration
Blanket Shield Modules and First Wall	Temporary Configuration (inertially cooled)	Final Configuration	Final Configuration
Divertor	Final Configuration	Final Configuration	Final Configuration
Glow Discharge System	Partial Configuration	Final Configuration	Final Configuration
Boronization Gas Distribution (B_2D_6)	Final Configuration	Final Configuration	Final Configuration
Gas and Pellet Injection Systems	Partial Configuration	Final Configuration	Final Configuration
Disruption Mitigation System	Final Configuration	Final Configuration	Final Configuration
Electron Cyclotron Heating	Upper Launchers installed (3 operational) 1 Equatorial Launcher (40 MW)	3 or 4 Upper Launchers operational 2 Equatorial Launchers (60-67 MW)	3 or 4 Upper Launchers operational 2 Equatorial Launchers (60-67 MW)
Ion Cyclotron Heating	1 Antenna (10 MW)	1 Antenna (10-20 MW)	1 Antenna (10-20 MW)
Neutral Beam Heating		2 Injectors (33 MW)	2 or 3 Injectors (33 – 49.5 MW)
Diagnostic Neutral Beam		Final Configuration	Final Configuration
Diagnostics	Basic set for SRO phase (incl. for the safety-related knowledge acquisition programme)	Near complete set, including DT fusion products	Complete set
Hot Cell Facility	Partial configuration for operation on TFA liquid radwaste, independently of Hot Cell building	Operational for DT-1	Operational with expanded capabilities for DT-2
Test Blanket Modules		DT-1 TBMs	DT-2 TBMs
Tritium Plant		Operational	Operational with expanded capabilities for DT-2

Table 1. Key tokamak and ancillary systems available for operation in the various phases of the ITER Research Plan.

7 Acronyms

APS – Advanced Protection System

CIS – Central Interlock System

D – Deuterium

DMS – Disruption Mitigation System

DT-1 – First Deuterium-Tritium phase

DT-2 – Second Deuterium-Tritium phase

GDC – Glow Discharge Cleaning

T - Tritium

ECH – Electron Cyclotron Heating

ECWC – Electron Cyclotron Wall Conditioning

FP – First Plasma

FPO – Fusion Power Operation

H-mode – High confinement mode

H&CD – Heating and Current Drive

HNB-1 – First Heating Neutral Beam

HNB-1 – Second Heating Neutral Beam

HNB-3 – Third Heating Neutral Beam

IC – Integrated Commissioning

ICH – Ion Cyclotron Heating

ICWC – Ion Cyclotron Wall Conditioning

L-mode – Low confinement mode

NBI – Neutral Beam Injector

NBTF – Neutral Beam Test Facility

PCS – Plasma Control System

FPO – Fusion Power Operation

Q – Fusion power multiplication factor

SNO – Start of Nuclear Operation

SRO – Start of Research Operation

TBM- Test Blanket Module

TBR - Tritium Breeding Ratio

TBS- Test Blanket System

TFA (radwaste) – "Très Faible Activité" (very low activity) radwaste

W - Tungsten

8 Annex A: Test Blanket Modules Research Plan

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Outline

1. Purpose

This document is the TBM Program Research Plan at Level 1 applicable to the 2024 ITER baseline. It is an Annex of the ITER Research Plan-Level 1 (IRP-L1) in which it is fully integrated. It gives an overview of the major tests planned during each DT-1 campaign to fulfil the main objectives of the TBM Program.

2. Background

One of the ITER missions is to test tritium breeding module concepts that would lead in a future reactor to tritium self-sufficiency, the extraction of high-grade heat and electricity production. All the activities related to this mission form the so-called "TBM Program". The plan is to install and operate simultaneously and independently four Test Blanket Systems (TBSs) that are mock-ups of complete DEMO Tritium Breeding Blankets (TBBs). The in-vessel components of the TBSs are called Test Blanket Modules (TBMs).

The four TBSs of the Initial Configuration are planned to be installed before the beginning of the DT-1 phase. It is assumed that they will be operated throughout the whole DT-1 phase. TBSs operations are expected to be continued during DT-2 either for the same TBSs or for more advanced TBSs.

3. Short description of the four TBSs of the Initial Configuration and of the Testing Strategy

The description of the four TBSs is given in [1, 2] and is shortly summarized below.

Each TBS is formed by a TBM (directly facing the plasma) and by associated sub-systems. Two EQuatorial Ports (EQP) (i.e., #16 and #18) are allocated to the TBM Program. Each EQP hosts two different TBMs forming the TBM Port Plug (PP). The various TBSs sub-systems (e.g., coolant, tritium extraction, coolant purification, instrumentation, and control systems) are partially located in the corresponding Port Cell and partially in other rooms of the Tokamak Complex [1,2].

The four TBSs are operated simultaneously and are independent each other. They are operated and controlled from the ITER Control Room where specific desks are dedicated to each TBS. The functional characteristics of the four TBSs are dictated by the operational conditions and requirements of the corresponding DEMO-TBB, and they are summarized in Fig.1.

Port N°	First TBS	Second TBS
16 (F)	TBS-1: *Water-Cooled Lithium-Lead (EU)* ➔ *Water at 15.5 MPa, 295-328°C*	TBS-2: *Helium-Cooled Ceramic Pebble (joint KO & EU)* ➔ *Helium at 8.0 MPa, 300-500°C*
18 (S)	TBS-3: *Water-Cooled Ceramic Breeder (JA)* ➔ *Water at 15.5 MPa, 280-325°C*	TBS-4: *Helium-Cooled Ceramic Breeder (CN)* ➔ *Helium at 8.0 MPa, 300-500°C*

Figure 1. The four TBSs of the initial configuration and their coolant main characteristics

For each TBS the testing strategy is to test different TBM design versions, each of them adapted to the operational conditions of the various ITER campaigns and integrating different instrumentation. This strategy implies that each TBM will have to be replaced several times and this requires the removal and the re-installation of the TBS components located in the TBM Port Cells (PCs). The adopted TBM replacement strategy is to substitute each TBM PP with a new one. The preparation of the new TBM PPs and of the associate PC components is made off-line.

4. Main planned R&D before TBS Installation

Essential information for a DEMO blanket can already be obtained by the R&D required in support of the TBSs manufacturing. Examples of required essential R&Ds concern: i) the development of the structural materials (i.e., reduced-activation ferritic-martensitic steels); ii) the development of functional materials such as lithiated ceramics pebbles, low-impurity liquid lithium-lead (LiPb), beryllium/beryllide; iii) the development of instrumentation for data acquisition and control compatible with the TBS materials and with the ITER operating conditions; iv) specific TBSs components such as those related to Tritium extraction and management; v) safety demonstration analyses, and vi) the development of tritium modelling to allow the extrapolation of the testing results to DEMO blankets.

5. Main Assumptions and Input Data for DT-1

Before starting the DT-1, an integrated commissioning campaign will be performed. Since a specific commissioning for each TBS is planned before the integrated one, it is considered that the TBSs will be operated in this phase in order to check the availability and the functionalities of the many interfaces (including, for instance the Central Safety System in relation with the TBSs safety functions) without any specific constraint on the integrated commissioning plan.

The assumed operational input data for each of the five DT-1 campaigns are derived from the IRP and are summarized in Table 1 below. To obtain sufficient DEMO-relevant information from the TBM Program during DT-1, a recent assessment has shown that it is necessary to implement/integrate specific operational conditions within the ITER Research Plan during DT-1 without impacting the DT-1 constraints. The conclusions of this assessment have led to the definition of a set of Minimal Requirements (MRs) that are described and justified in [1]. One of the most relevant MR is the one requiring the implementation of DT back-to-back pulse series for a whole day dedicated to the TBM Program during FPO-4/5.

The TBM-RP assumes that all the identified MRs in the various FPOs are satisfied and that the four TBSs are operated during the whole DT-1.

6. TBM Program Research Plan during DT-1

The TBSs starts the operation at the beginning of DT-1. It will be the first time that TBSs and all the associated sub-systems are simultaneously operated and controlled from the centralized Control Room. The main Top-Level Objectives (TLOs) during DT-1 are the following:

- **TLO-1**: Validation of structural integrity theoretical predictions under combined and relevant thermal, mechanical and EM loads.
- **TLO-2**: Validation of tritium breeding predictions.
- **TLO-3**: Validation of tritium recovery process efficiency and T-inventories in the relevant TBS materials.
- **TLO-4**: Validation of TBM thermal-hydraulic predictions with volumetric heat sources.
- **TLO-5**: Validation of main technologies relevant for future fusion reactors.
- **TLO-6**: Demonstration of the integral performance of the TBS sub-systems, including the achievement of coolant thermo-hydraulic parameters compatible with those required for high-efficiency electricity production.

The achievement of these objectives during DT-1 is considered as “full success” for the next-step DEMO breeding blanket design and manufacturing.

Most of the TLOs can be achieved progressively in one or more FPOs. Starting from these TLOs, several lower-level objectives have been identified for each campaign, the so-called Campaign Testing Objectives (CTOs). The achievement of each CTO requires the availability of some MRs, the implementation of specific instruments, the implementation of some TBM/TBS design changes specific to each campaign and the performance of some Post-Irradiation Examinations (PIEs) in ITER Members premises on shipped TBM samples.

Details and justification for the various CTOs can be specific for each TBS and can be found in the four TBSs Research Plans given in [3], [4], [5], [6].

6.1. Fusion Power Operation-1 (FPO-1) Campaign

It can be considered a learning phase with functional tests under a relevant tokamak environment. For the first time, the four TBSs will be operated and controlled from the Control Room, using high-temperature, high-pressure coolants and requiring the simultaneous operation of the various TBS sub-systems, with the corresponding feasibility demonstration. Other main objectives in FPO-1 are the following:

- Validation of the assessment of the impact of ferromagnetic TBM structures on plasma performance (error fields and their correction, plasma confinement and fast ion losses). Validation of the MHD prediction for the TBM using the liquid LiPb breeder.
- Validation of the EM modelling and TBM-Set integrity predictions under relevant heat and EM stationary and dynamic loads (especially during disruptions and vertical displacement events).
- Verification of the TBS response and the margins for control under off-normal events, such as plasma disruptions, Vertical Displacements Events, and power excursions.
- Verification of the operation and performance of calibration of D-D neutron sensors.
- Verification of ITER/TBS physical and functional interface aspects, and preliminary verification of the correct operation of the TBS internal functional interfaces.
- Confirmation of the I&C architecture and TBS instrumentation performance to ensure the correct TBS process functionalities with the required efficiency in a relevant magnetic field.
- Confirmation of the remote operations required for TBM replacement, and PC component removal and reinstallation during Long-Term Maintenance (LTM) shutdown.

6.2. Fusion Power Operation-2 (FPO-2) Campaign

During FPO-2, short low/medium fusion power D-T plasma pulses (~ 50 s burn) will be performed. Therefore, the expected additional general objectives are the following:

- Verification of the operation and calibration of D-T neutron sensors; supporting data (such as sensor operating temperature) are provided by the TBM box basic instrumentation.
- Preliminary validation of the TBM neutronic response by measuring the neutron flux and its energy distribution by sensors. The measured data are compared to modelling predictions to validate the simulation models and tools used in design analysis.
- Validation of the heat extraction performance predictions in thermo-hydraulic conditions relevant for a fusion power plant for the TBM, including the FW, and extraction of the heat transfer coefficient values and validation with the available correlations for complex geometries.
- Assessment and verification H/D permeation prediction from the plasma to the FW and then to the coolant under ITER condition.
- Thermo-mechanical characterization of the Li-based ceramic breeder and Be-based neutron multiplier (compatible temperature distribution only with heaters).

6.3. Fusion Power Operation-3 (FPO-3) Campaign

Specific conditions in FPO-3 are the high fusion power DT pulses of short DT duration (~ 50 s burn) but with Q = 10 nominal neutron flux and TBM First Wall heat flux. Therefore, the expected additional general objectives are the following:

- Demonstration of the achievement of coolant thermo-hydraulics conditions (both for water-coolant and Helium-coolant) relevant for electricity production.
- Validation of the thermo-mechanical response of the TBM box under DEMO relevant loads, including volumetric heat deposition.
- Neutronic analysis and tritium generation rate prediction validation against experimental measurements.
- Preliminary validation of tritium control and recovery predictions by measuring local tritium concentration in the process fluids, and transfer through the Tritium Accountancy System.
- Collection of experimental data for the validation of the predictions of the tritium transport models and simulation tools with particular focus on the tritium permeation into the primary coolant.
- Verification of the I&C architecture performance under D-T neutrons fluxes.
- Verification of the nuclear maintenance task performance during STM/LTM and associated ORE.

6.4. Fusion Power Operation-4/5 (FPO-4 & FPO-5) Campaigns

In FPO-4/5 the demonstration of reproducible 500 MW Q = 10 pulses with burn ≥ 300 s will take place. In addition, in FPO-4/5 few dedicated days to the TBM Program with medium fusion power back-to-back pulses (~ 30 minutes repetition rate) will be performed. The expected additional general objectives are the following:

- Demonstration of the achievement of coolant thermo-hydraulics conditions (both water-coolant and Helium-coolant) relevant for high-efficiency electricity production.
- Measuring local tritium concentration in TBS process fluids for validating modelling prediction and tritium transport simulation tools.
- Extrapolation of the results for confirming the DEMO Tritium Breeding Ratio (TBR). Validation of the TBM neutronic response and reconstruction of the achievable TBR.
- Validation of technologies and design solutions of subsystem components and extend the corresponding reliability and operational performance database.
- Assessment of the efficiency of Tritium Outgassing State (TOS) operation, specific for TBSs and aiming to reduce the Tritium inventory in the TBSs components by raising their temperature to the maximum possible extent.
- Performance characterization of RAFM steels and TBM manufacturing technologies under relevant load conditions and validation of the manufacturing processes.
- Performance characterization of the TBM functional materials under significant neutron flux.
- Performance characterization and its stability over the time of the TBM instrumentation under neutron and gamma irradiation.
- Long-term operations with relevant loads to validate inherent availability & RAMI analyses for the TBS sub-systems.

7. Considerations for DT-2

The objectives achieved in DT-1 can be further confirmed in DT-2 since higher neutron fluence and longer pulses will be attempted, and much larger quantities of Tritium will be produced. Therefore, the Tritium-related phenomena would reach equilibrium and the tritium breeding self-sufficiency of the corresponding DEMO blankets can be demonstrated with a much lower level of extrapolation. The reached coolant thermo-hydraulic conditions will be those required for electricity production. During DT-2, long steady-state pulses (≥ 3000 s) with fusion power ≥ 250 MW are the preferred scenarios for reaching operating conditions close to DEMO.

Operation and testing of different TBMs/TBSs could be envisaged, including more advanced TBS designs (depending on the evolutions of the DEMO studies). The obtained results will be applicable also to TBB types not directly tested ITER.

8. Conclusions

Assuming the availability of the established MRs, the TBM Program Research Plan, associated with the four preliminary TBSs-RPs, confirms the major relevance for DEMO of the TBM Program in DT-1. The most important part of the Top-Level Testing Objectives in support of DEMO design and construction can be completed (full success) by FPO-5.

9. Reference Documents

[1] ITER_D_9RNPCR v1.0 - Establishment of the TBM Program Minimal Requirements for DT-1.

[2] L. M. Giancarli, et al., Overview of recent ITER TBM Program activities, *Fusion Engineering and Design 158 (2020) 111674*.

[3] ITER_D_APS49A – I. Ricapito, WCLL-TBS Research Plan (April 2024).

[4] ITER_D_AQKUKL – M. Y. Ahn, HCCP-TBS Research Plan (April 2024).

[5] ITER_D_AQKZUQ – Y. Kawamura, WCCB-TBS Research Plan (April 2024).

[6] ITER_D_AQKZV8 – L. Zhang, HCCB-TBS Research Plan (April 2024).

Table 1: Assumed operational input data for each DT-1 campaign.

Phase	Duration (months)	Plasma scenarios	Heat flux on TBM FW (MW/m^2)	DT Neutron flux on TBM FW (MW/m^2)
FPO-1	16	H, DD, H+T, T @ 7.5 MA/2.65 T	0.05-0.25 (peak)	Negligible
FPO-2	16	DD, DT @ 7.5 MA/5.3T (~ 50 s burn) DD, DT @ 10 MA /5.3T (~ 50 s burn)	0.08-0.23 (peak) 0.09-0.24 (peak)	~ 0.18 (peak) ~ 0.30 (peak)
FPO-3	16	DD, DT @ $I_p \geq$ 12.5 MA /5.3T (~ 50 s burn)	0.12 - 0.3 (peak)	~ 0.7 (peak)
FPO-4 + FPO-5	32	DD, DT @ $I_p \geq$ 12.5 MA /5.3T (≥ 300 s burn)	0.12 - 0.3 (peak)	~ 0.7 (peak)

9 Annex B: Neutral Beam Test Facility Research Plan

The mission of the Neutral Beam Test Facility (NBTF) hosted by Consorzio RFX in Padova (Italy) is to demonstrate the target specifications of ITER Neutral Beam Injectors (NBI) and provide the design inputs to the ITER Diagnostic NBI (DNB) and Heating NBIs (HNB). The experimental plan for the NBTF is based on the synergistic operation of SPIDER (the prototype of the ion source) and MITICA (the full-scale prototype of one injector).

Experiments in SPIDER are orientated to validate the size scaling for the RF ion source concept, based on 1/8 and 1/2 scale prototypes developed in IPP-Garching in the last decades. It also provides an opportunity for further design optimisation to enable the demonstration of the source performance in terms of extracted current, uniformity and stability over time for both H and D species. In addition, it allows for non-focussed beam extraction and acceleration for ~ 100 keV beams which are similar in energy and current to those of the ITER DNB.

MITICA constitutes the full-size test bench of the HNB injector and shall demonstrate the ITER NB requirements in terms of beam energy (870/1000 kV, in H/D respectively) power (16.5 MW) and beam optics (divergence smaller than 7 mrad) This includes the validation of the design of the critical components such as the beam source (BS) and Beam-Line Components (BLCs): Neutraliser, Electrostatic Residual Ion Dump and Calorimeter.

The experimental plan of the two facilities shall alternate between operational phases (orange boxes in Figure 1) and maintenance phases (green boxes), during which the lessons learned from previous experimental campaigns will be integrated into the design.

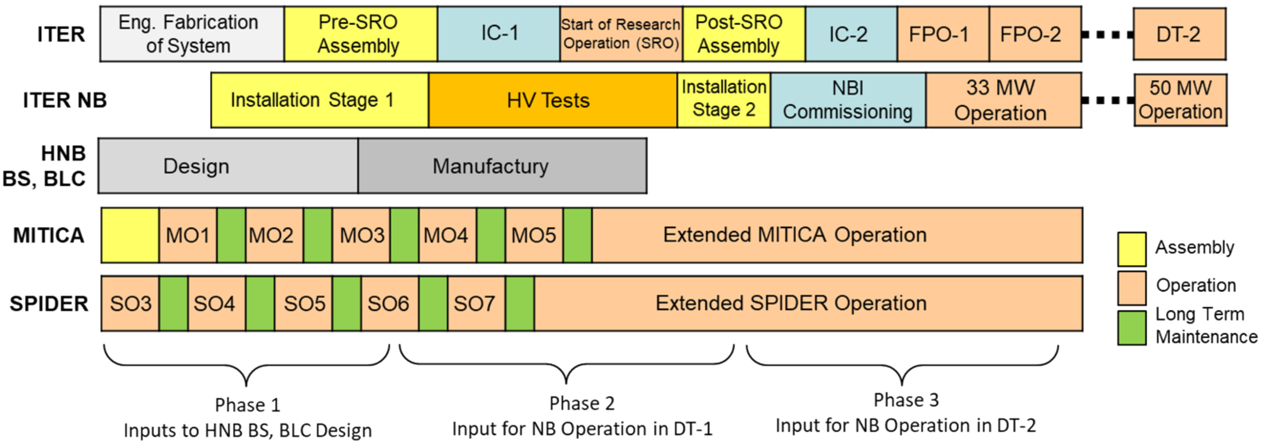

Figure 1. Schematic timeline of the NBTF experiments SPIDER and MITICA when compared with the timelines of the new ITER baseline and of the ITER NBI including the procurement of the HNB BS and BLC. MO and SO refer to MITICA and SPIDER Operation phases, respectively.

In a first phase, the experiments in NBTF will be focused on providing design input to the ITER injectors. In particular, the beam sources and beam-line components represent first-of-a-kind components, for which modifications (major or minor) might be needed to achieve the full performance or to overcome design issues found in the prototypes. In this phase the operation periods are relatively short (of the order of 1 year) and alternated with shutdown periods allowing the necessary time to perform upgrades to the main components. During this phase, the NBTF facilities shall confirm the non-existence of major showstoppers for the program (MO1-2 campaigns) and in particular, MITICA shall demonstrate beam parameters in the range expected for the HNB in FPO-1: hydrogen beams at full power, i.e. target current density and acceleration voltage for pulses in the range of tens of seconds with an acceptable divergence (MO-3 campaign).

Moreover, towards the end of the MO-3 campaign, the release of the final specifications for ITER BS and BLC is expected. This release shall occur not later than 6 years before the need date of the component at ITER to allow sufficient time for their procurement. Any eventual change required for the DNB components (operated in parallel in the Indian Test Facility), shall also be identified and formalised during this phase, so that the modifications can be implemented during the refurbishment phase, prior to the shipment to the ITER site.

A second operational phase will follow, where the NBTF will perform mainly longer experimental campaigns with the objective of optimising performance and demonstrating the NB scenarios required for the rest of DT-1: full power and pulse length of few hundreds of seconds. In this phase the shutdown periods are shorter, since only minor changes to the NBTF hardware are expected. As a first goal, the NBTF shall target the achievement of full power up to ~ 600 s, having higher priority to achieve full power for this duration over the beam isotope used, H or D. This goal will also include addressing issues related to hydrogenic isotope management in the NB resulting in the capability to operate a series of pulses at full power up to a cumulative duration of 10,000 s in two shift operational day at ITER. In fact, it has been demonstrated at accompanying experiments in IPP-Garching that the hydrogen target in terms of current density is less challenging to achieve than the deuterium target. Hence, prioritising the optimisation of H beams should guarantee an earlier validation of the full power target. Once the full power in hydrogen is demonstrated, the operation can focus on deuterium beams, that remain the preferred choice for the DT-1 campaigns after FPO-1 and for DT-2.

In the last part of this second phase, it is also expected to have the transfer of knowledge and manpower, to assure the availability of fully trained personnel to ITER, for the beginning of the NB operations.

Finally, a third phase is envisioned to run in parallel to the DT-1 phase of ITER. The need for continued operation of the NB test beds in parallel with the operation of NBI injectors, has been demonstrated on other fusion devices where large NBI systems were operated so far (such as JET, in preparation of DT experiments), and it is particularly true for the NBI based on the production of negative ions such as the LHD and JT-60U devices in Japan. At this stage, the NBTF experiments will assist ITER NB during their operation, to improve the reliability or to explore new and advanced scenarios. The main focus of the third phase will be the achievement of the NBI objectives for the DT-2 phase mainly steady state operation, with pulse lengths up to one hour in deuterium.

The R&D on NBI conducted in the NBTF will also benefit from the expertise of other research groups and facilities of ITER Members and Domestic Agencies. These can support the NB research on specific topics identified and agreed upon during the meetings of the NBTF Advisory Committees (NAC) and Experiment Advisory Committee, (EAC). In particular, during the first operational phase of NBTF, it is expected that the input from other facilities in the ITER Members can provide very valuable input to consolidate the final design of ITER NBIs.