THE 2024 NEW BASELINE ITER RESEARCH PLAN

Si-Woo Yoon

Korea Institute of Fusion Energy, Daejeon, Republic of Korea

International Tokamak Physics Activities Coordinating Committee

On behalf of ITER Organization co-authors and the ITER Research Plan development group

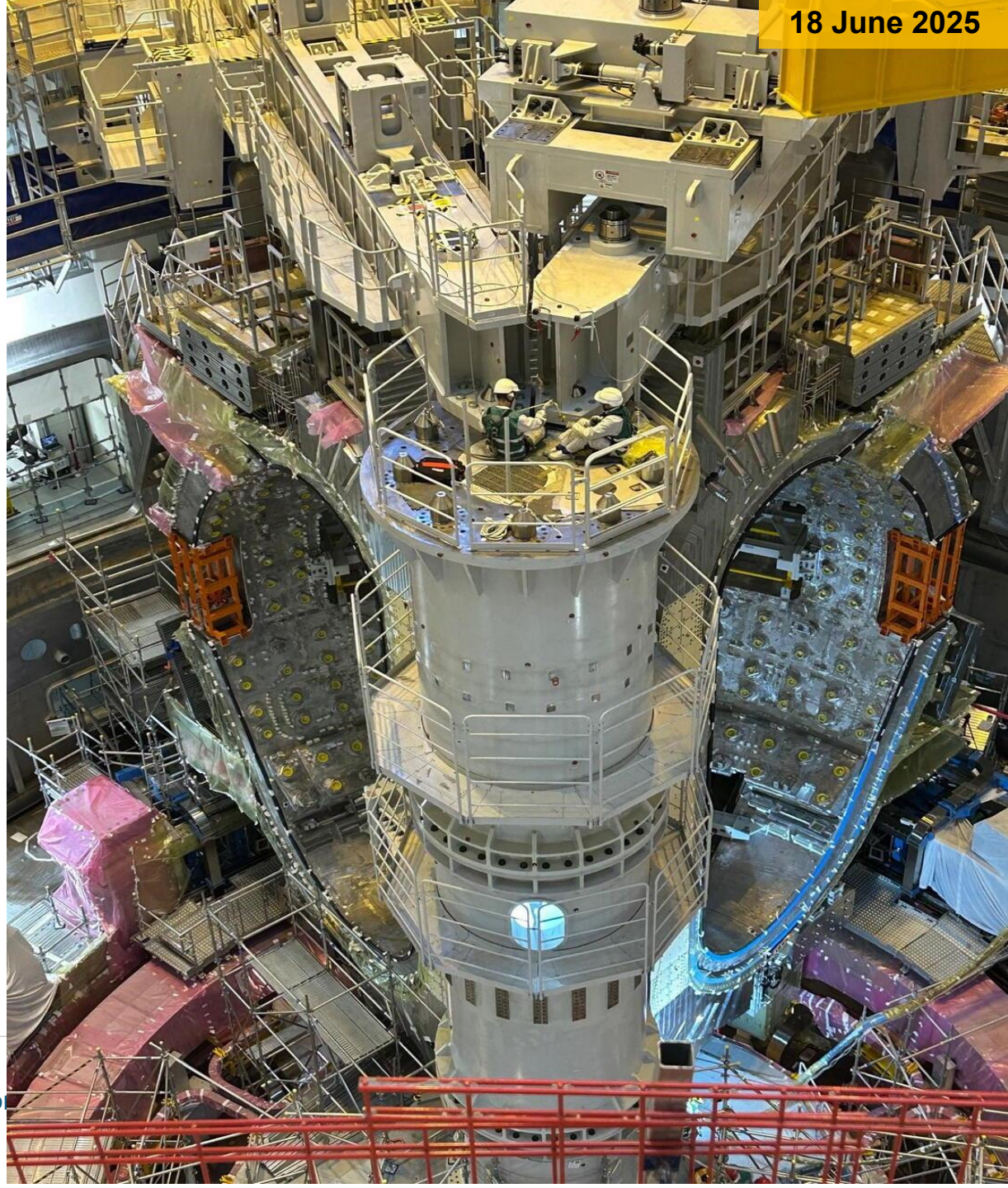
30th IAEA Fusion Energy Conference, Chengdu, China, 15 October 2025

iter

china eu india japan korea russia usa

Outline

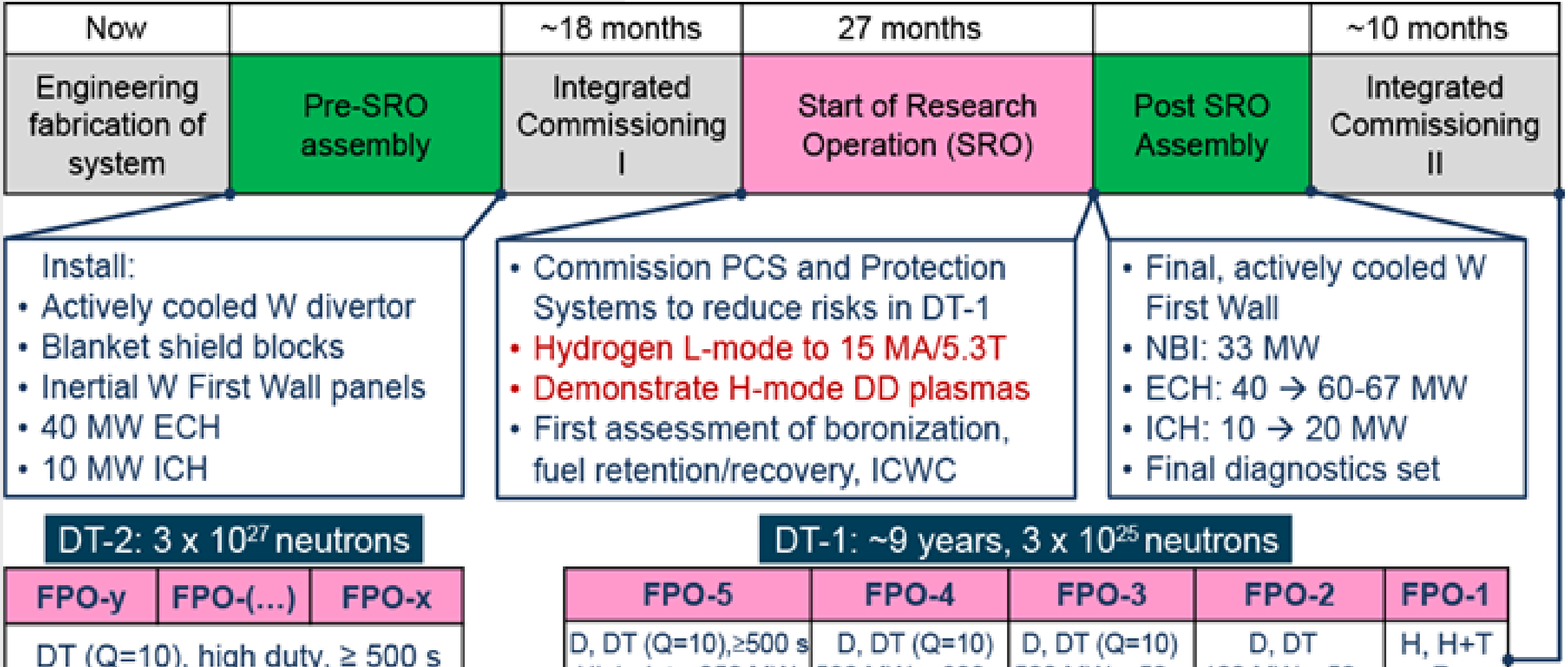
- Summary of new baseline IRP : Objectives and Configuration
  - Integrated Commissioning (IC)-I + Start of Research Operation (SRO)
  - Integrated Commissioning (IC)-II + Deuterium-Tritium (DT)-1
  - Integrated Commissioning (IC)-III + Deuterium-Tritium (DT)-2
  - IRP development process
- SRO
- DT-1
- DT-2
- Conclusions



ITER Research Plan (IRP)
Configuration and objectives

- Updated IRP required based on new ITER construction baseline
- Robust achievement of Projects' goals in three phases : Start of Research Operation (SRO), 1st DT phase (DT-1) + 2nd DT phase (DT-2)
- Realistic operational assumptions and minimization of technical risks
- Achievement of earliest start of ITER Nuclear phase (D-D) in SRO
- Stepwise Safety Demonstration (DT-1 & DT-2)
- DT-1 focus: achievement of specific Project goal(s) → Q ≥ 10, 300-500s
  - Limited neutron fluence (1/100 of present end-of-life) to facilitate licencing

    ~ 3.5×10^{25} neutrons ~ 550 pulses of P_{fusion} = 500 MW, Q ≥ 10, 300s discharges
  - DT-1 design requirements should not preclude possible future upgrades for DT-2
- DT-2 focus: full achievement of Project goal(s) in high duty operation : 1) Q ≥ 10, 300-500s, 2) Q ≥ 5, 1000s long pulse and 3) Q ≥ 5, 3000s steady-state with safety demonstration based on DT-1



IRP now part of Technical Baseline → Consistency between ITER configuration and IRP

ITER Research Plan Development Process (2023-2025)

- First ideas on IRP and new baseline discussed informally with ITER Members' fusion communities, STAC and ITPA in Q2-Q3 2023
- IO and nominated experts from ITER Members to develop IRP at high level from Q3 2023 to Q2 2024:
  - ✓ Outline IRP and supporting assessments reviewed by ITPA and endorsed by STAC in Q2 2024
  - ✓ Outline IRP presented at EPS, AAPPS and APS DPP in Q3-Q4 2024
- IRP to full detail developed by IO and nominated experts from Q3 2024 to Q2 2025:
  - ✓ Further feedback from ITPA groups, dedicated experiments and Members' fusion communities has been incorporated in the detailed plan
  - ✓ Detailed IRP reviewed and endorsed by STAC in Q2 2025

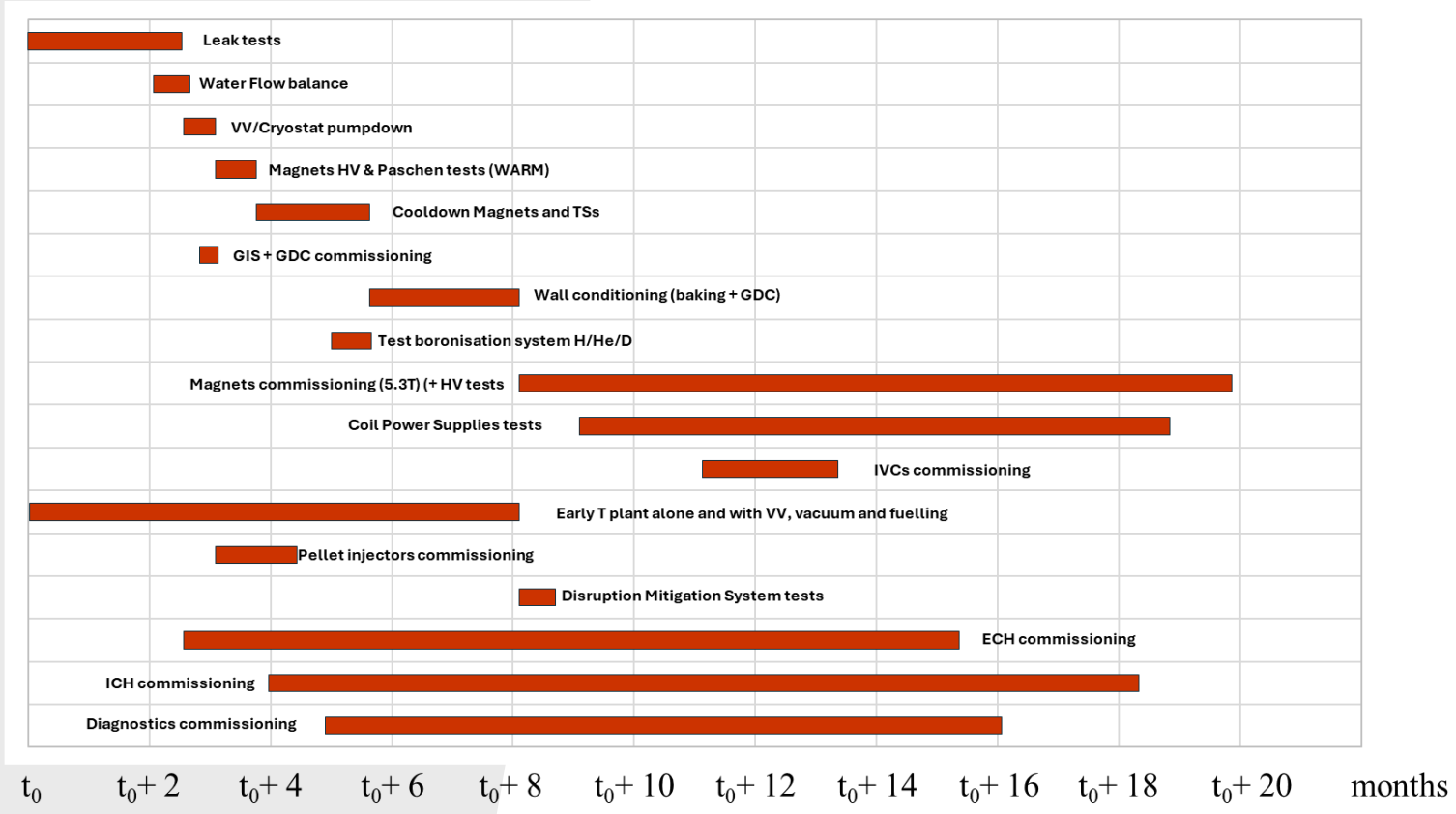
IRP is similar but not identical to the presentations in 2024 EPS, AAPPS, APS DPP

ITER Research Plan (IRP)

Integrated Commissioning - I

Integrated Commissioning – I

- Starts with cryostat pump-down after individual system commissioning completed
- 1st commissioning of systems in integrated way including SC magnets
- Main activities and sequence identified: 18 months (+ 6 months contingency)



ITER Research Plan (IRP)

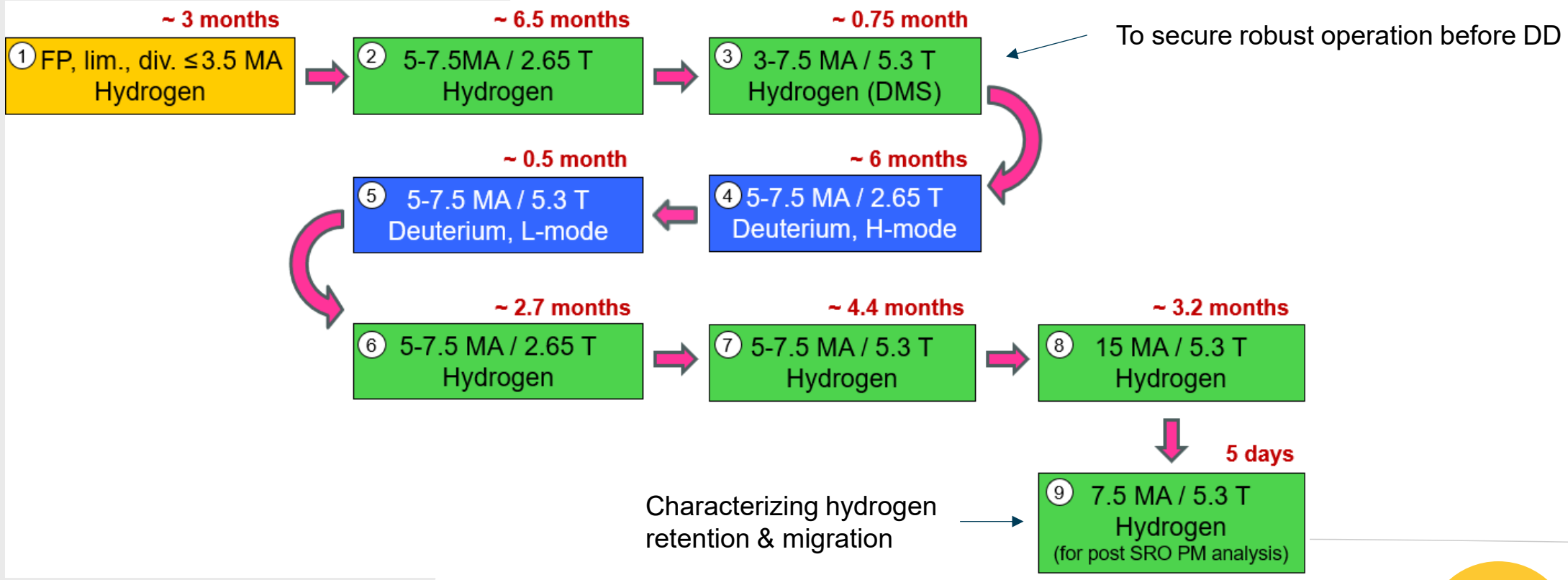
Start of Research Operation (SRO)

SRO objectives

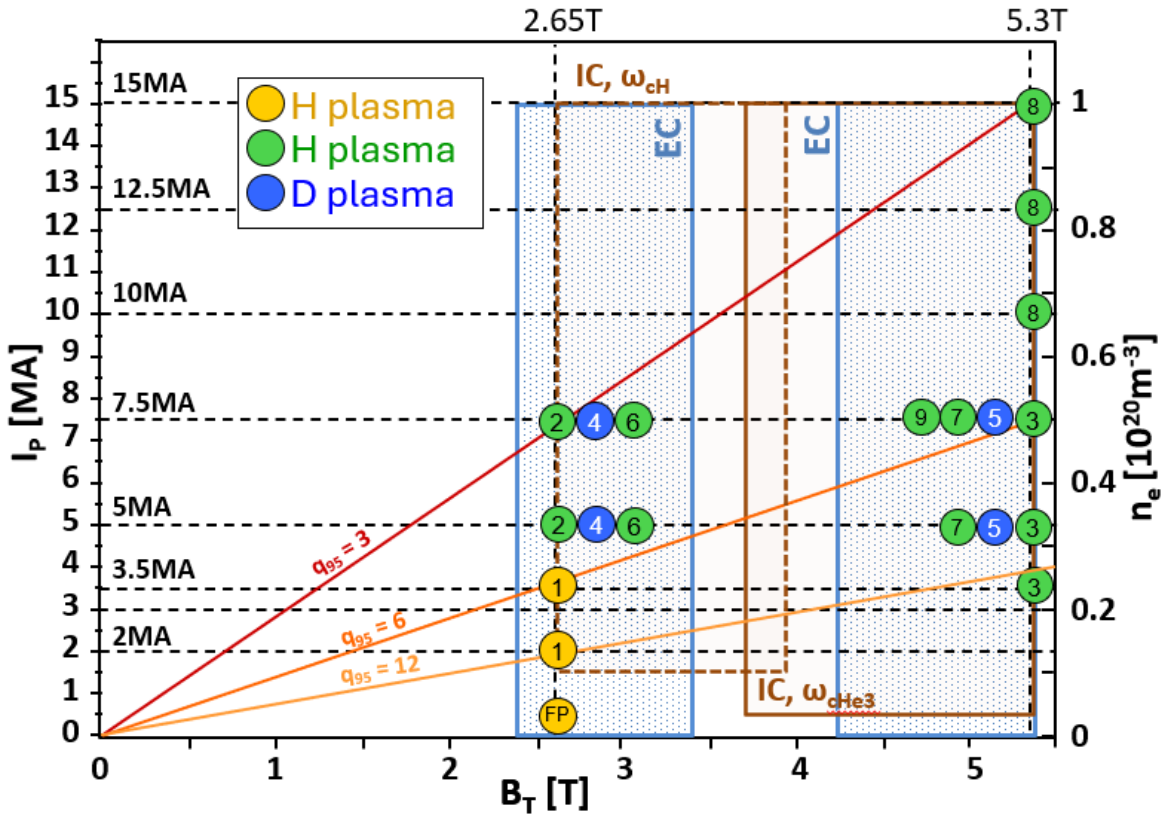
- Demonstration of superconducting coils capability to operate plasma scenarios up to 15 MA/5.3 T → Full Magnetic Energy operation
- Routine operation with shape/vertical position control up to 15 MA/5.3 T in L-mode (H)
- Characterization of disruption loads (potentially up to 15 MA/5.3 T, if electromagnetic forces allow) → in-vessel component verification
- Commissioning and demonstration of effective disruption mitigation up to 15 MA/5.3 T in L-mode and 7.5 MA/2.65 T in H-mode
- Identification and correction of error fields due to machine assembly and intrinsic toroidal asymmetric features of ITER
- Exploration of H-mode operational space up to 7.5 MA/2.65 T in D plasmas (inc. P_{ECH} required for stationary H-mode operation) including ELM control demonstration
- Commissioning of ECH and ICH systems up to their nominal SRO power levels (40 MW and 10 MW) including compatibility of ICH with W wall
- Demonstration/optimization of wall conditioning (GDC, Boronization, ICWC, ECWC)

SRO – Experimental Plan (27 months)

- Experimental plan designed to minimize risks (taking into account of risks for in-vessel entrance) and to allow post-SRO shutdown activities:
  - ✓ D operation completed ~ 1 year before VV entry within 1.5×10^{20} neutron budget
  - ✓ 7.5 MA/5.3 T H plasmas (disruption characterization and mitigation before D)



SRO – Scenario Path



(1) Establish initial operation to 3.5 MA in H

(2) L-mode scenario development up to 7.5 MA/2.65 T in H (q_{95} = 3 – 6)

(3) L-mode scenario development up to 7.5 MA/5.3 T in H (q_{95} = 6 – 12)

(4) H-mode scenario development to 7.5 MA/2.65 T in D (q_{95} = 3 – 6)

(5) L-mode scenario development up to 7.5 MA/5.3 T in D (q_{95} = 6 – 12)

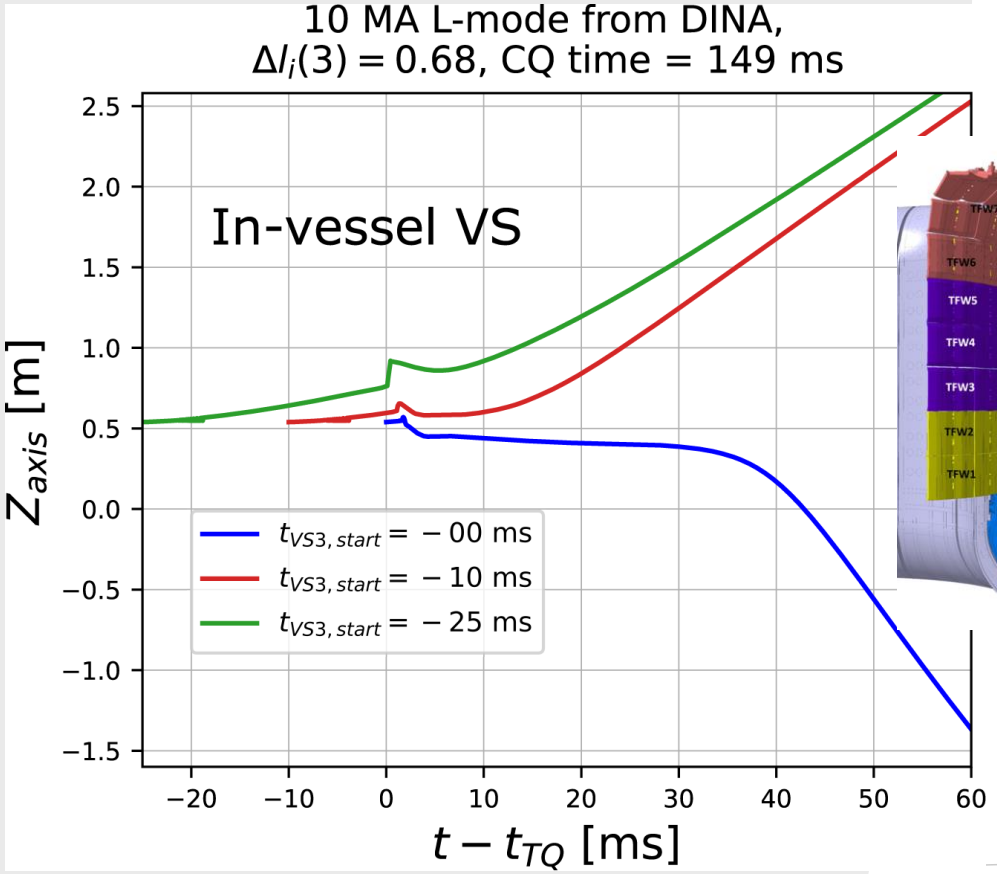
(6) Complete L-mode scenario development up to 7.5 MA/2.65 T in H (q_{95} = 3 – 6): start of deactivation

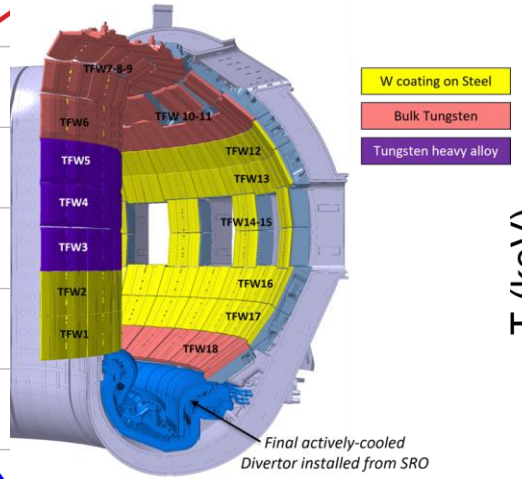
(7, 8) Expand L-mode scenario operational space up to 15 MA/5.3 T in H (q_{95} = 3 – 12): end of deactivation

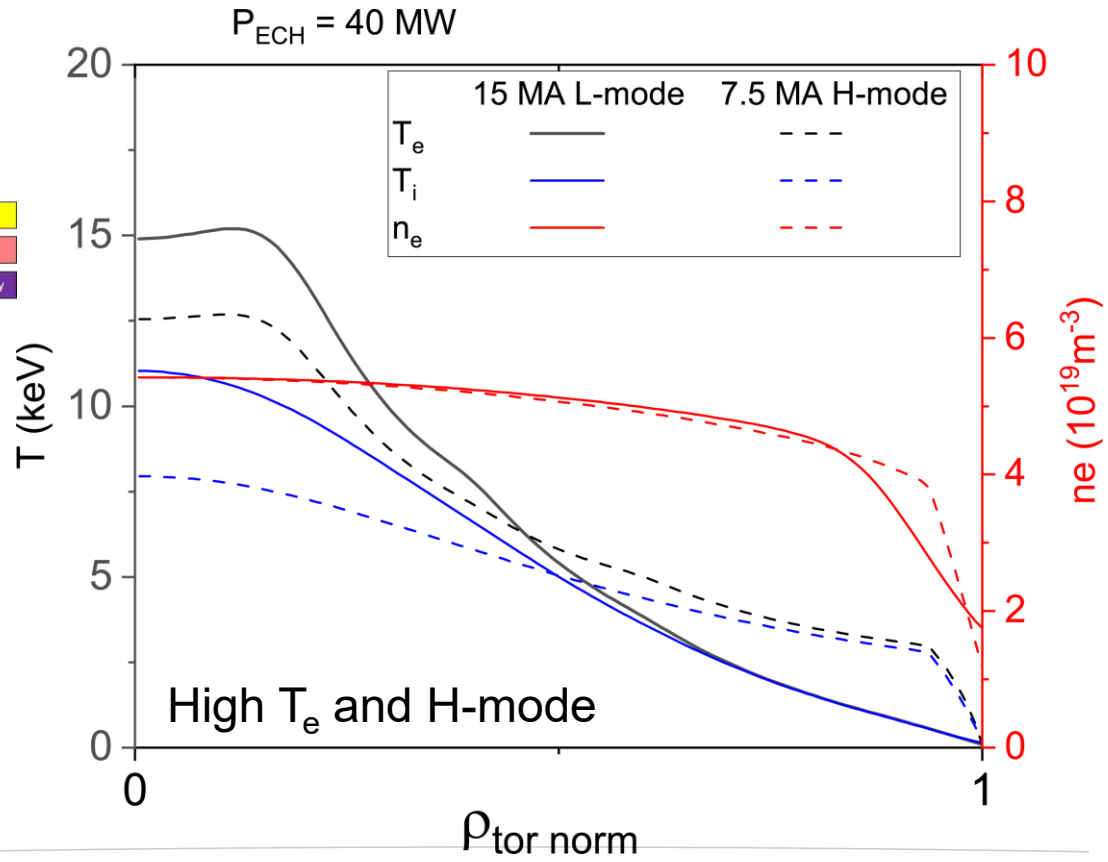
(9) Plasma operation for post-mortem analysis of migration patterns

SRO – Disruption Characterization and Mitigation

- Load characterization will be limited by TFW, divertor limits and EM loads → strategy to use VS to displace plasma upwards when above divertor limits
- Demonstration of mitigation at all steps (retirement EM load and hot-tail RE risk)

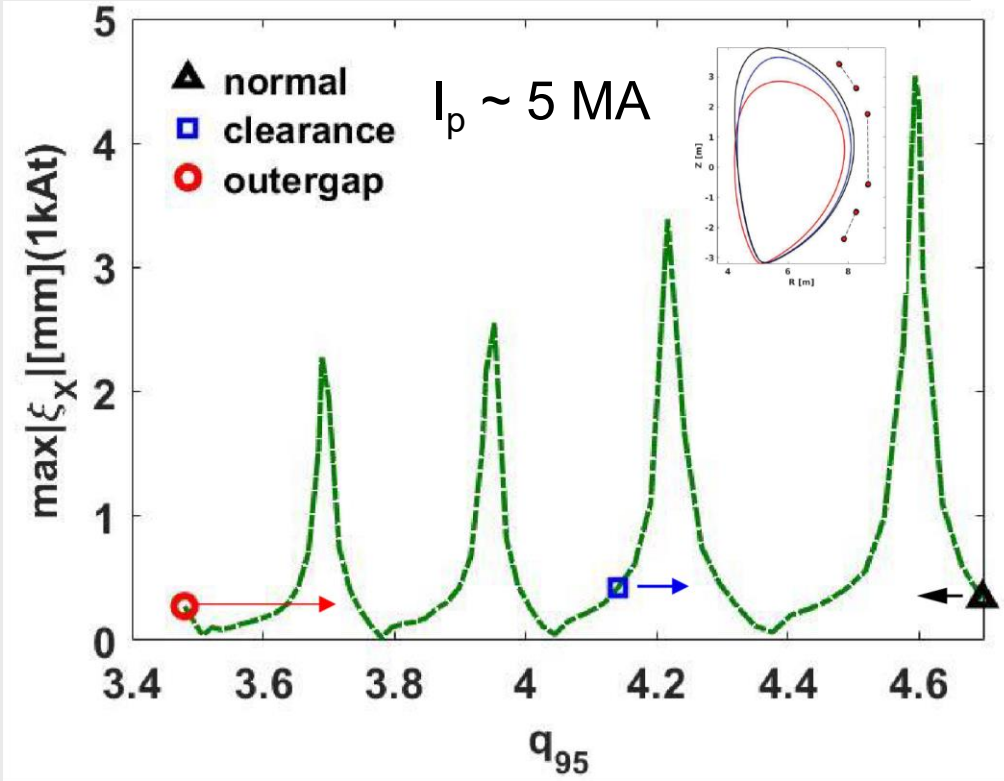


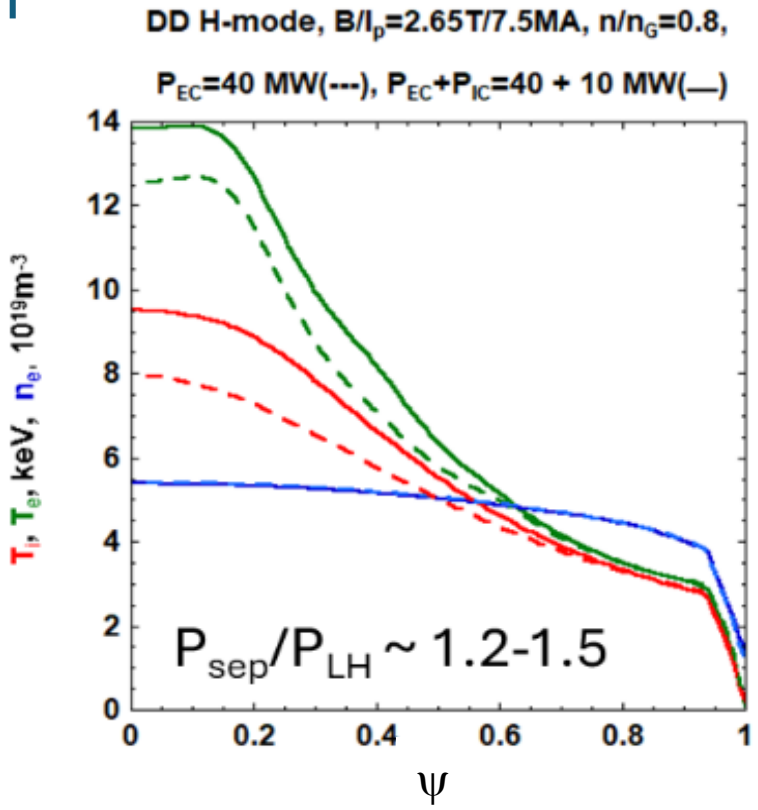




SRO – D H-mode exploration

- Start with 5 MA/2.6 5 T to avoid ELM divertor melting and to control W influxes from wall (scans as AUG, EAST) → ELM control demonstrated (f_{pellet} ≤ 60 Hz and RMPs)
- Then up to 7.5 MA/2.65 T H-modes incl. ICH (42 MHz) coupling and (ion) heating
- Test of H-mode access and ICH (53 MHz) at 5.3 T

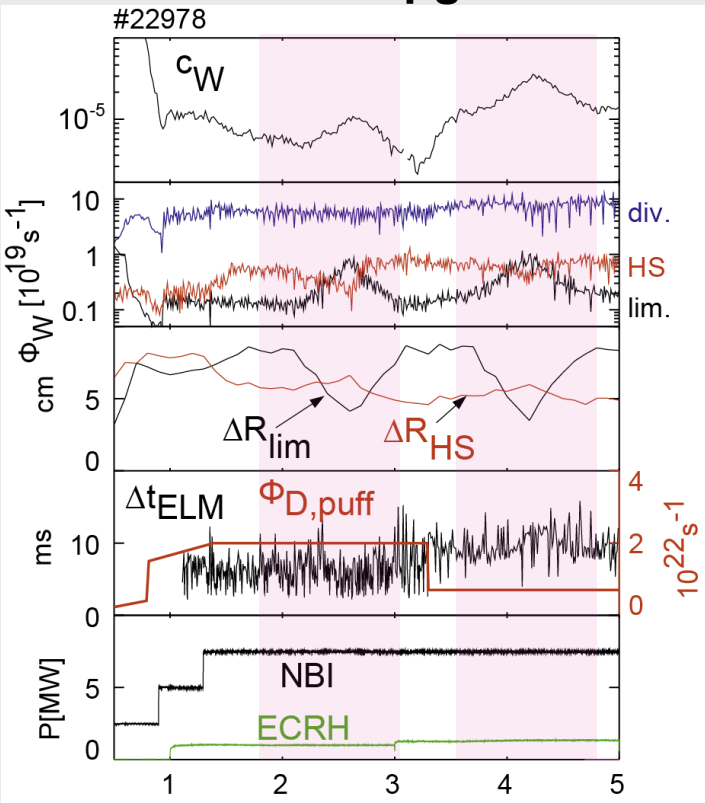




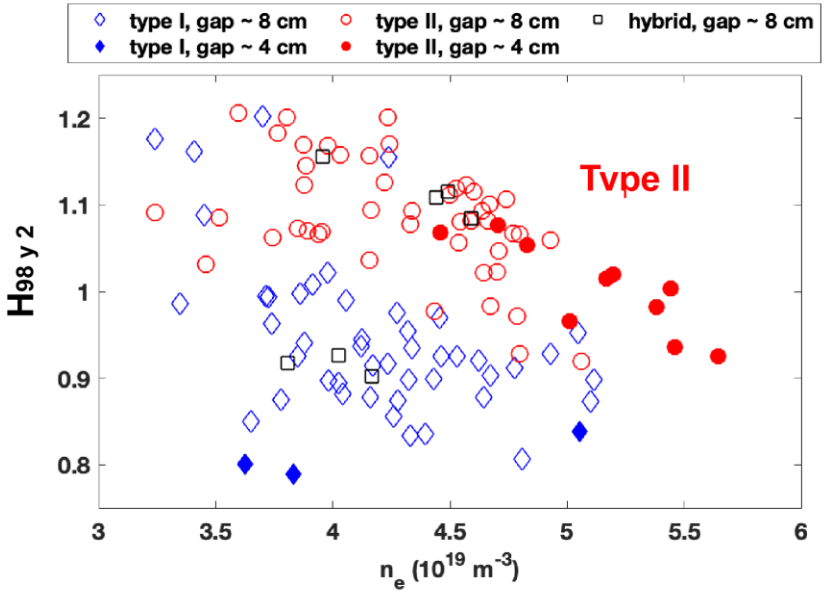
SRO – Edge-Core integration and PWI

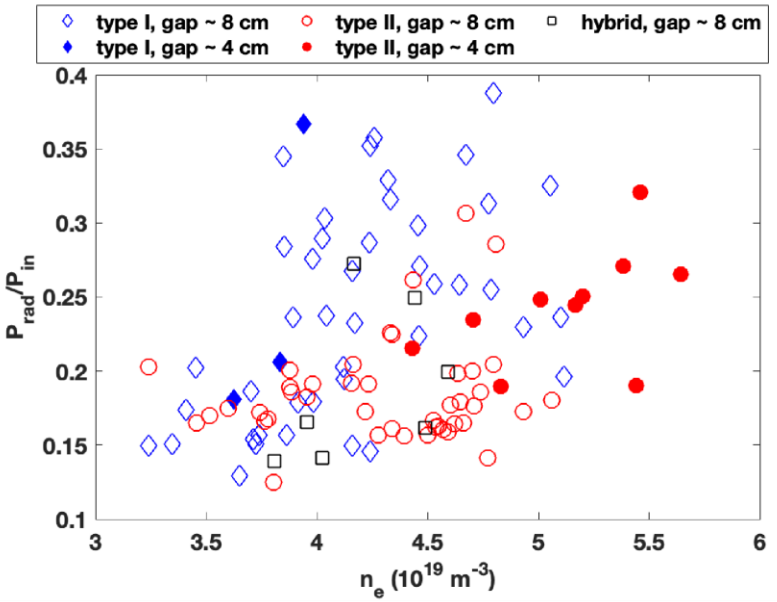
- SRO will address, for the first time in ITER :
  - ✓ W sources, impact on scenarios and core impurity control
  - ✓ Optimum conditioning strategies (O levels, recovery from disruption, use of DMS, …)
  - ✓ Fuel retention and removal (D campaign and D-to-H isotope exchange)
- SRO plans based on modelling and experiments

ASDEX - Upgrade



EAST



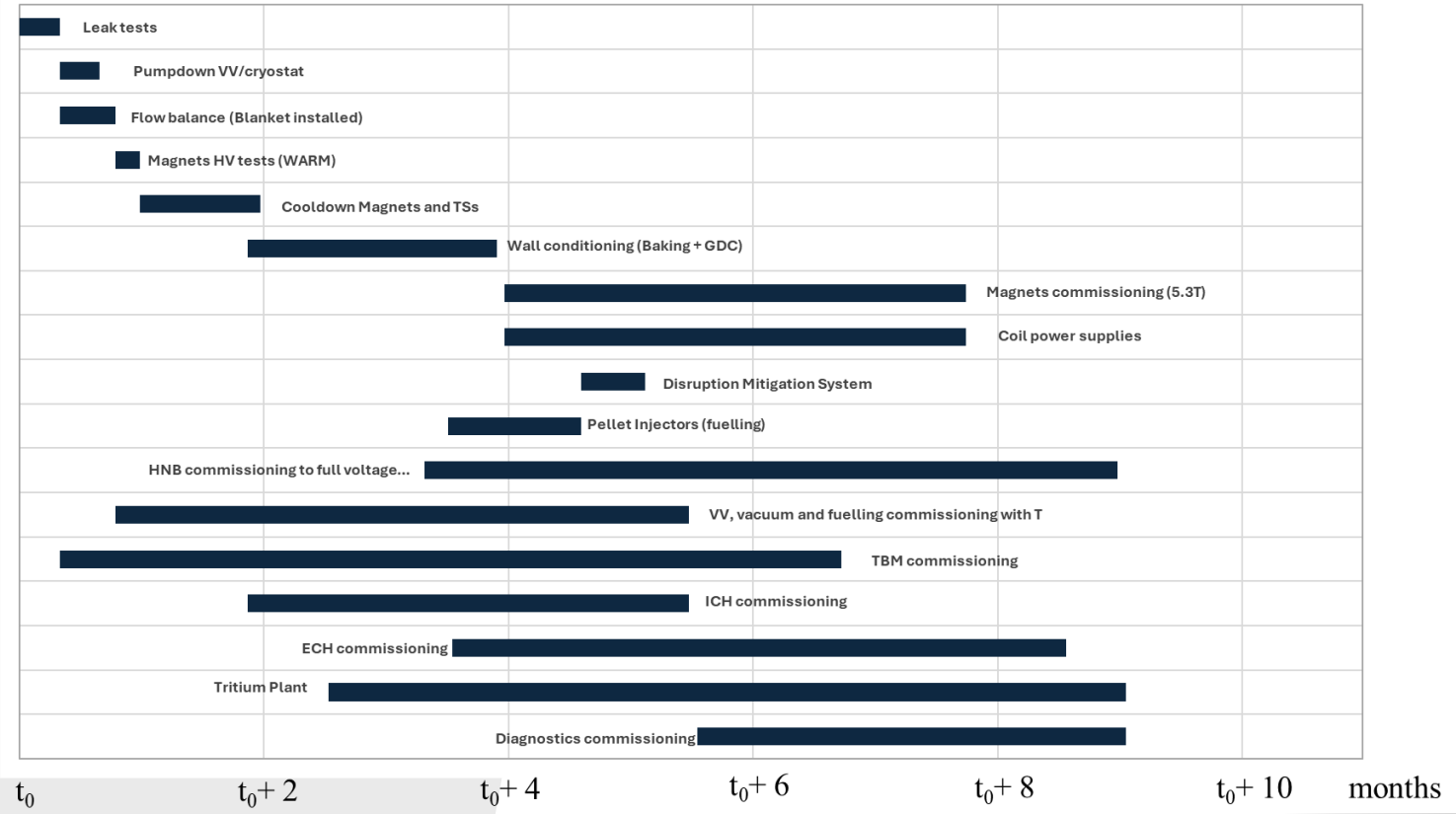


ITER Research Plan (IRP)

Integrated Commissioning - II

Integrated Commissioning – II

- Recommissioning of SRO systems and new IC-II systems (e.g. NBI, TBMs)
- Integrated commissioning of the T fuel cycle connected to the VV
- Main activities and sequence identified: 10 months (+ 3 months contingency)



ITER Research Plan (IRP)

1st Deuterium-Tritium Campaign (DT-1)

DT-1 Objectives (5 FPO campaigns = 80 months)

- Demonstration of reproducible operation with P_{fusion} = 500 MW with Q ≥ 10, t_{burn} ≥ 300s
- Demonstration of high-duty operation with P_{fusion} = 250 MW, t_{burn} ≥ 300s
- Qualification of all tokamak components and systems in nominal Q ≥ 10 operation
- Assessment of neutron effects and nuclear heating at nominal power levels on diagnostics and SC magnets in nominal Q ≥ 10 operation
- Characterization of burning plasmas physics and associated control and load mitigation challenges in nominal Q ≥ 10 operation
- Validation of radiation maps, demonstration of in-vessel tritium management, measurement of dust production rates, etc., in nominal Q ≥ 10 operation → Input to DT-2 licencing
- First operation of the TBM in nominal Q ≥ 10 operation and in high-duty operation with P_{fusion} = 250 MW
    - Coolant thermo-hydraulics conditions relevant for high-efficiency electricity production
    - Tritium breeding to confirm Tritium Breeding Ratio (TBR) in fusion power reactors

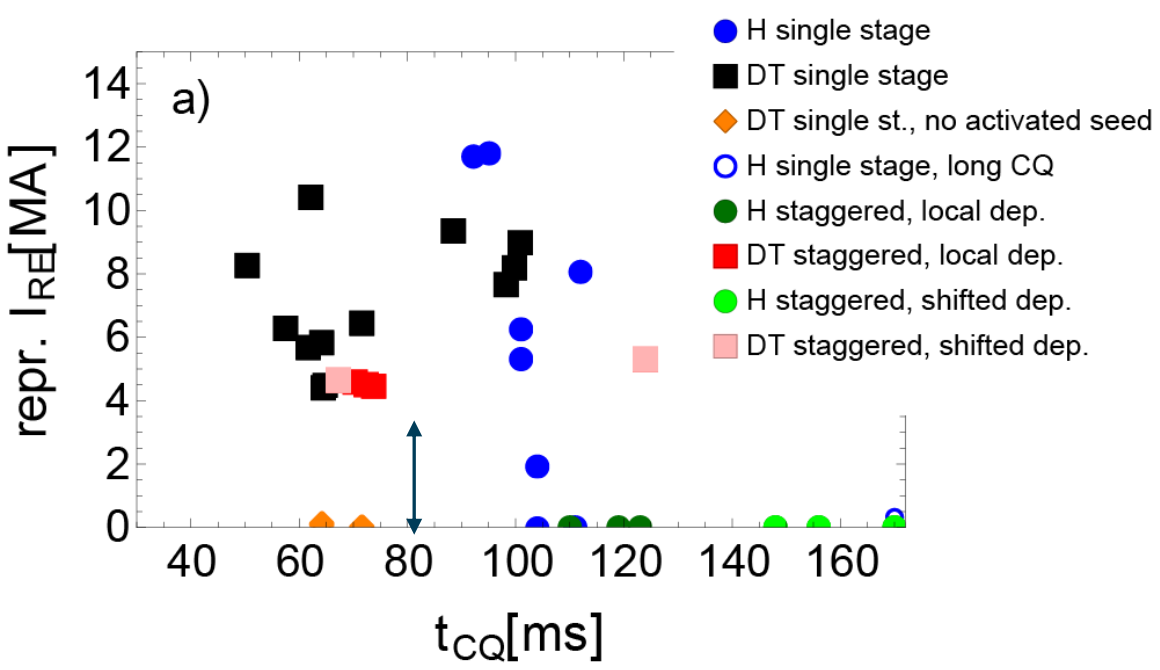
DT-1 – Experimental Plan (I)

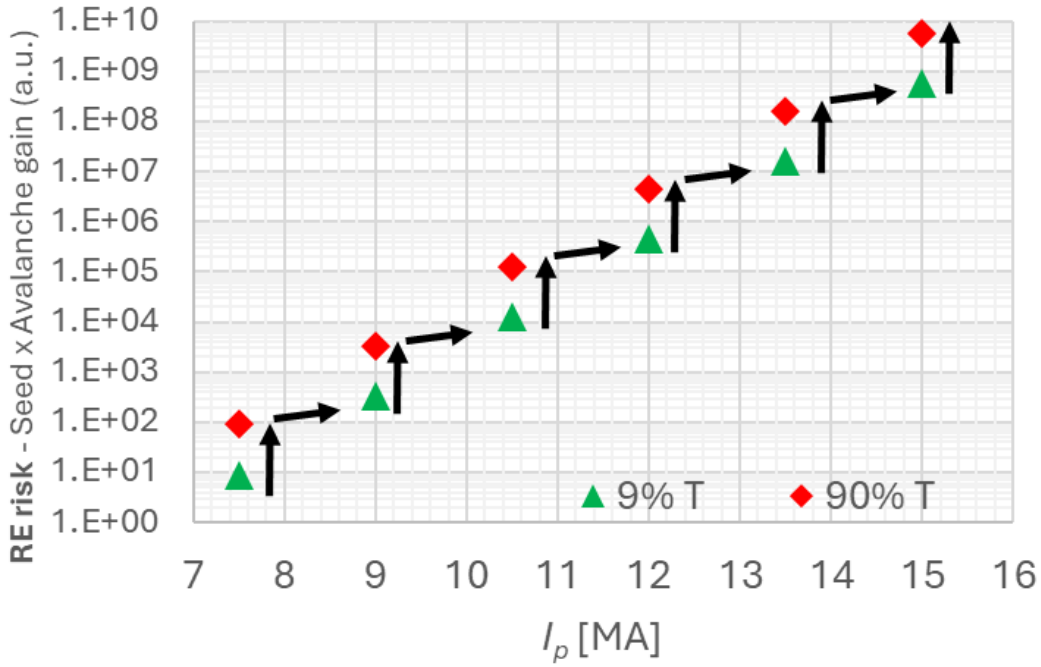
- Experimental plan designed to minimize risks (taking into account of risks for in-vessel entrance) and to achieve Q ≥ 10 within neutron budget of 3.5×10^{25}
- FPO-1
  - ✓ Initial commissioning of new in H plasmas in FPO-1 to P_{tot} ~ 100 MW to test PFCs
  - ✓ De-risking of disruption mitigation with T plasmas in (FPO-1) before D, DT activation
  - ✓ H-mode operation with P_{tot} ~ 100 MW to demonstrate/test control schemes at 7.5 MA/2.5 T before DT (NTMs, Sawteeth, AEs, divertor heat flux, ELM control, burn control, …)

T and disruption risk mitigation

- Mitigation of disruptions in DT pose specific challenges for runaway generation due to fast electron seeds and avalanche : β decay source and γ + e Compton scattering
  - ✓ γ by wall activation increases gradually → adjustment of DMS with increasing P_{fusion}, t_{burn}
  - ✓ β decay depends on T → I_{seed} x Gain (I_p) gradual increase from 7.5 MA/5.3 T in FPO-1

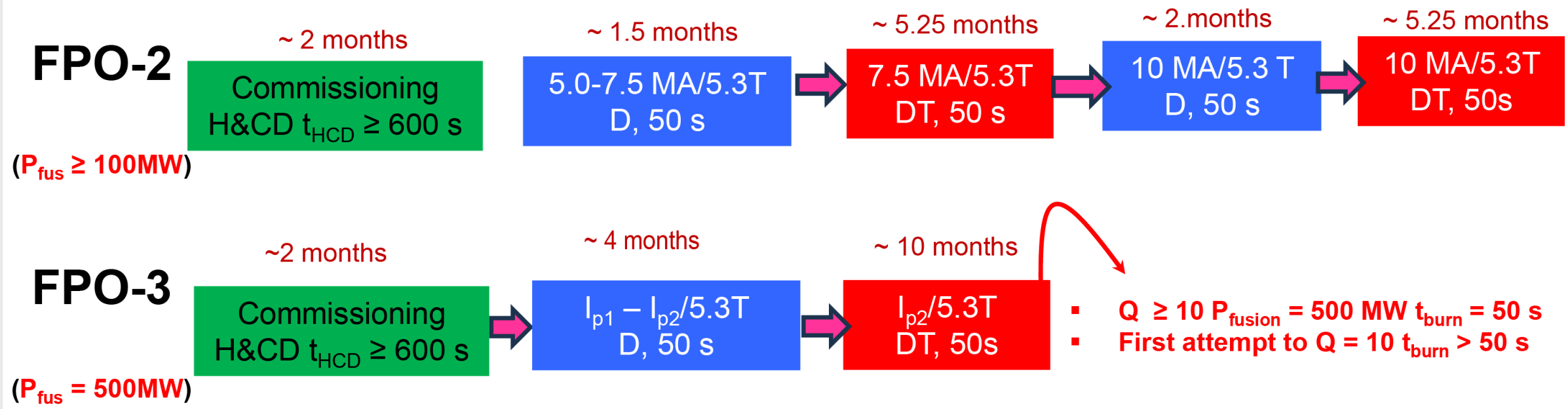
Vallhagen – DREAM - NF 2024





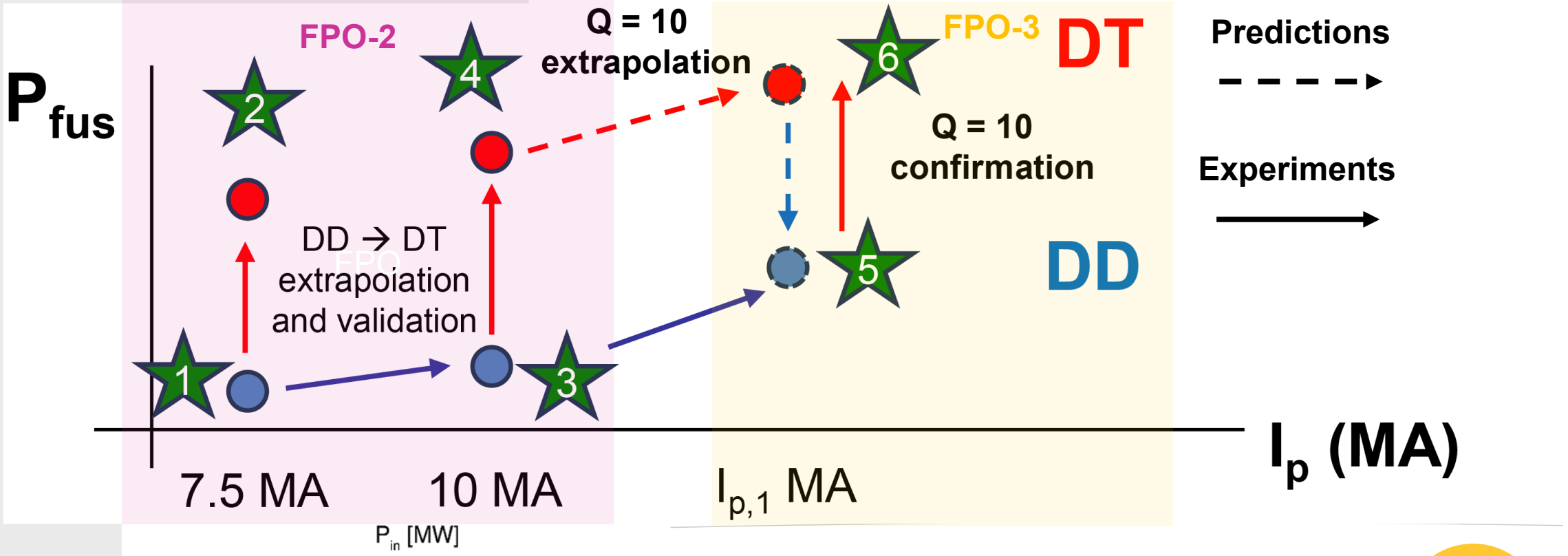
DT-1 – Experimental Plan (II)

- FPO-2 to FPO-3
  - ✓ Test long pulse system capabilities (in H L-modes) in advance of $Q \geq 10$, $t_{burn} \geq 300$ s
  - ✓ Gradual increase of I_p at 5.3 T : minimize risks, determine τ_E (I_p) at $q_{95} > 3$)
    - Determine minimum I_p for $Q \geq 10$ (i.e. scenarios with $q_{95} > 3$ and $H_{98} > 1$)
    - Identify potential scenarios with $q_{95} > 3$ for $Q \geq 5$ long-pulse/steady-state in DT-2



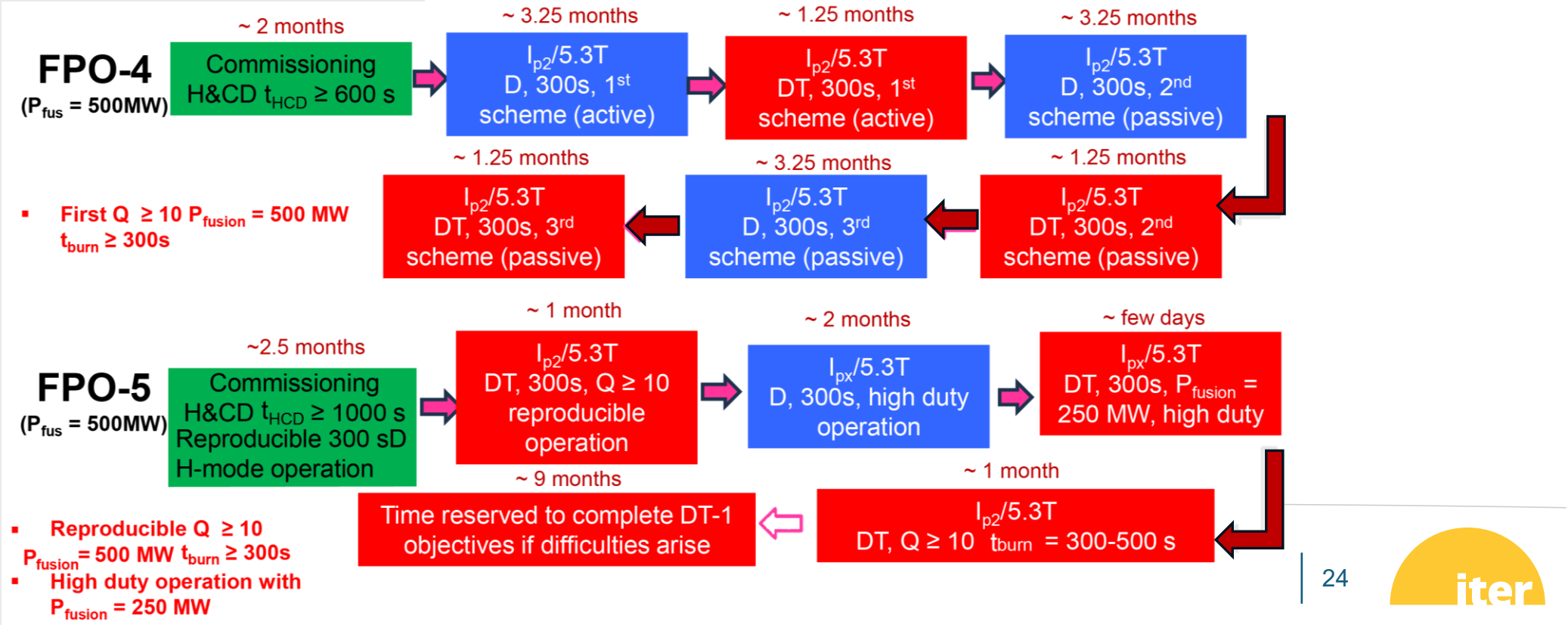
DT-1 – D and DT H-mode development strategy

- DT-1 fluence (3.5×10^{25} neutrons ~ 550 pulses of Q ≥ 10 P_{fusion} = 500 MW t_{burn} = 300s) → Scenarios developed in D and demonstrated in DT to minimize fluence
- Strategy for D and DT interleaving based on JET DT experience → use of D and DT at lower I_p to predict requirements for Q ≥ 10 in DT → try in D and if OK in DT



DT-1 – Experimental Plan (III)

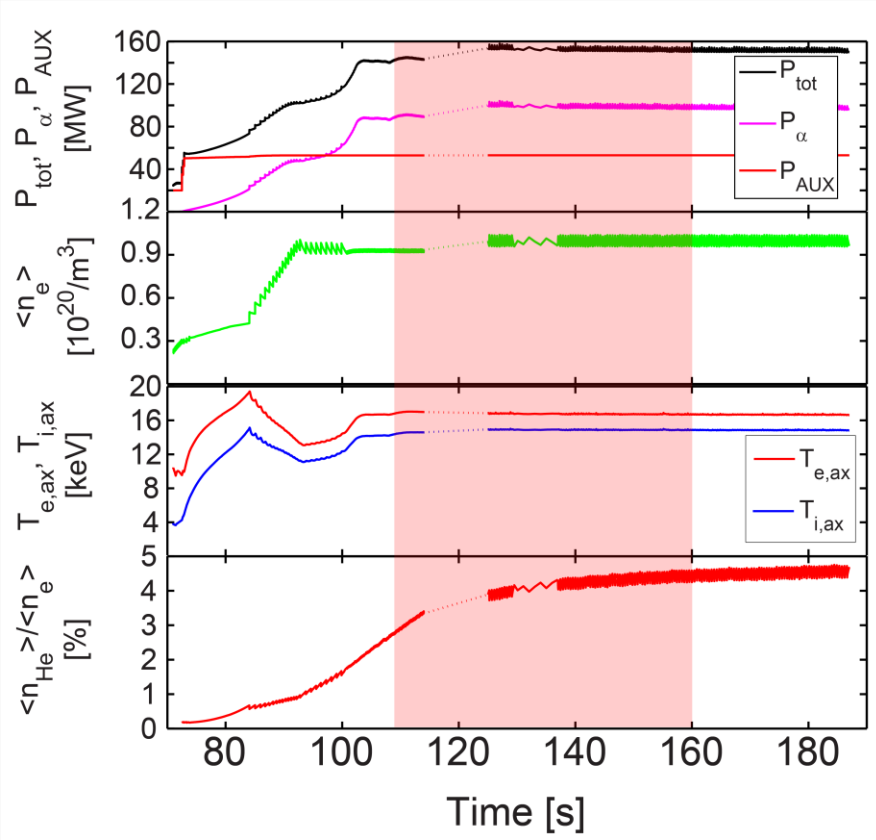
- FPO-4 to FPO-5
  - ✓ Pulse (t_{burn}) extension 300s may not be simple due to current profile relaxation effects:
    - Develop strategy for pulse extension in D plasmas and apply/tune to DT
    - Once t_{burn} ≥ 300s optimize scenarios for P_{fusion} = 500 MW, Q ≥ 10
  - ✓ Develop robust scenario for P_{fusion} ≥ 250 MW, t_{burn} ≥ 300s for high-duty operation

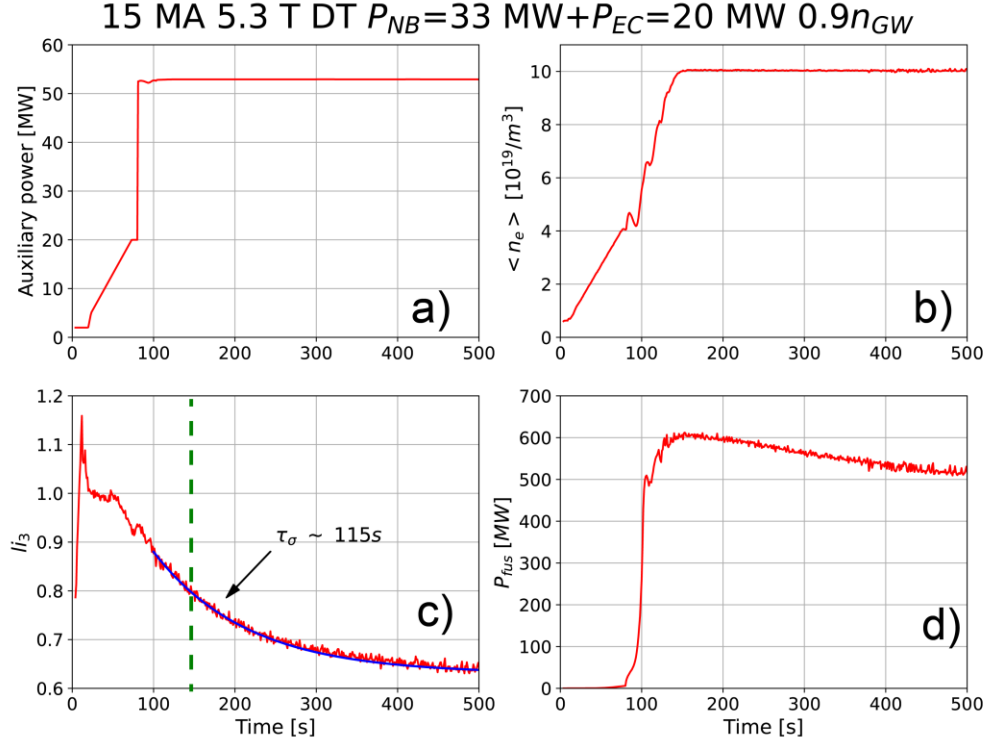


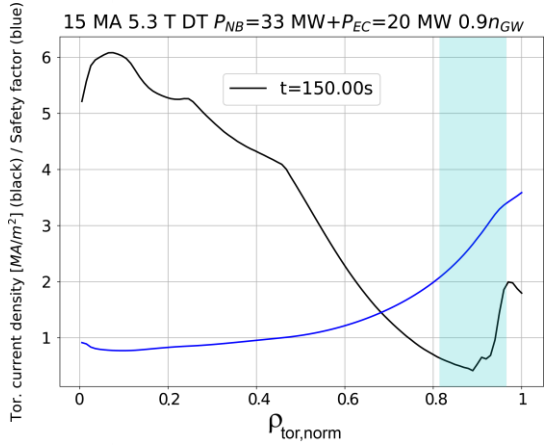
DT-1 – Q ≥ 10 demonstration

- Q ≥ 10 demonstration divided in two steps
  - ✓ FPO-3 : Demonstration with t_{burn} ≥ 50s including He exhaust (but transient j(r) avoiding issues)
  - ✓ FPO-4 : Demonstration with t_{burn} ≥ 300s including stationary j(r) incl. MHD, transport, etc. → strategies for extension based on present experiments [DIII-D, Turco 2024]

Köchl - JINTRAC - NF 2020







ITER Research Plan (IRP)

2nd Deuterium-Tritium Campaign (DT-2)

DT-2 Objectives (5 FPO campaigns = 80 months)

- Demonstration of high-duty operation with $Q \geq 10$, $P_{fusion} = 500$ MW for $t_{burn} = 300 – 500$;
- Demonstration of long pulse operation with $Q \geq 5$, $P_{fusion} = 400$ MW for $t_{burn} = 1000$ s;
- Demonstration of steady-state operation with $Q \geq 5$ and $P_{fusion} = 400$ MW for $t_{burn} = 3000$ s;
- Exploration of $Q \geq 10$ scenarios for a wide range of $P_{fusion} \leq 700$ MW;
- Exploration of burning plasma physics, scenario integration and integrated controls at high Q, high P_{fusion} operation;
- Assessment of fusion reactor physics and operational issues: Optimization of H&CD mix, minimum set of diagnostics and actuators, achievement of high Q plasmas with integrated control, and exhaust of power and particles;
- Consolidation of the tritium breeding efficiency evaluations, tritium management, conditions for high-efficiency electricity production, etc., for reactors breeding blankets, etc. up to the total neutron fluence of, at least, $3x10^{27}$

DT-2 Experimental Plan

- Experimental Plan developed to medium level (details depend on DT-1 outcome)
- FPO-6 to FPO-7
  - ✓ High-duty operation with $Q \geq 10$, $P_{fusion} = 500$ MW for $t_{burn} = 300 – 500$;
  - ✓ Exploration of $Q \geq 10$ scenarios for a wide range of $P_{fusion} \leq 700$ MW
  - ✓ Development of long pulse ($t_{burn} = 1000$ s) and steady-state scenarios ($t_{burn} = 3000$ s) with $Q < 5$
  - ✓ Assessment of fusion reactor physics/operational issues: optimization of H&CD, power exhaust, …
  - ✓ TBM research programme : T breeding, T management, etc.
- FPO-8 to FPO-10
  - ✓ Demonstration of long pulse operation with $Q \geq 5$, $P_{fusion} = 400$ MW for $t_{burn} = 1000$ s;
  - ✓ Demonstration of steady-state operation with $Q \geq 5$ and $P_{fusion} = 400$ MW for $t_{burn} = 3000$ s;
  - ✓ Assessment of fusion reactor physics/operational issues: Minimum set of diagnostics/actuators, ….
  - ✓ Completion of TBM research programme up to a neutron fluence of, at least, 3×10^{27}

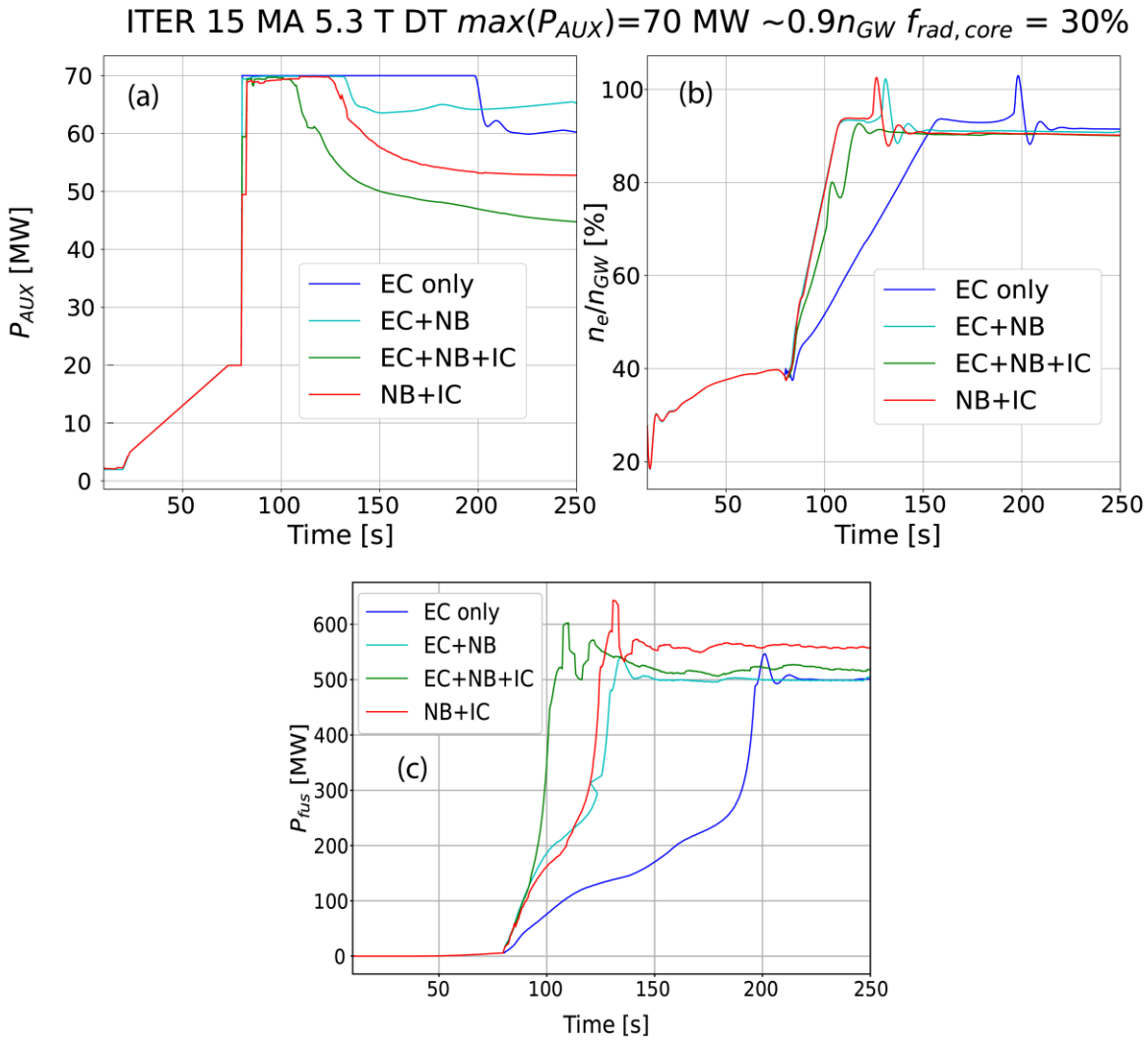
Example of early DT-2 fusion reactor research

- DT-1 H&CD optimization carried out for highest Q (NBI, ICH, ECH)

- DT-2 H&CD optimization considers:

✓ Minimization of systems to get to Q ≥ 10

✓ Impact on scenario design (e.g. access to high Q and $<n_e>$ (t)



Conclusions

- ITER Research Plan has been developed jointly with Members' fusion communities
  - ✓ Self-consistent set of goals, machine/system configuration and operational strategies for risk mitigation/retirement
  - ✓ Based on state of the art experimental/modelling/theorical plasma physics
  - ✓ Robust/realistic path to achievement of ITER Project's goals : success in experiments is not usually achieved at the first try
- Overall strategy and development lines to be followed are defined but details of Research Plan will change as R&D on open issues advances (ITR-25-005)
- To predict ITER plasma behaviour and planning of experiments, experimental validation of models and tools is essential for efficient implementation of IRP

Support by Members' fusion researchers is essential for ITER's success

IAEA FEC presentations directly related to IRP

- Overview presentations from all major tokamaks (14th – 15th October)
- 15th October
  - ✓ A. Loarte – Change of Wall Material - 11:20
  - ✓ M. Schneider - Integrated Modelling - 17:30
  - ✓ M. Jia – Divertor flux control with RMPs in EAST – 14:00 P 2
- 16th October
  - ✓ D. Mateev – Fuel retention and recovery in JET - 17:00
  - ✓ S. Pinches – Energetic particle distributions – 14:00 P4
- 17th October
  - ✓ S. Jachmich – ITER Disruption Mitigation System – 9:30
  - ✓ J. Hobirk - Tungsten limiter Start-up experiments (ASDEX Upgrade, WEST) - 17:30
  - ✓ S.H. Kim – Development of High-Fidelity Plasma Simulator – 14:00 P6
  - ✓ F. Poli – New approaches to ITER integrated modelling – 14:00 P6
- 18th October
  - ✓ J. Artola – Modelling of thermal Loads during VDEs at JET and ITER – 8:30 P7
  - ✓ D. Fajardo – Validated integrated modelling of W in experiments and ITER – 8:30 P7
  - ✓ E. Geulin – WEST wall conditioning with Boron – 8: 30 P7

Thanks for your attention !

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