The new ITER Baseline research plan and long-pulse / steady-state operations in ITER

S.H. Kim on behalf of many IO and ITER Members' contributors to the new ITER Baseline and research plan

The views and opinions expressed herein do not necessarily reflect those of the ITER Organization

china eu india japan korea russia usa

Outline

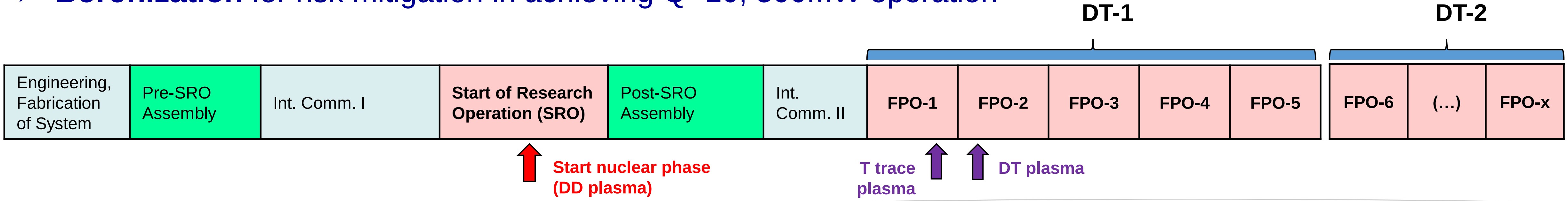
- The new ITER Baseline
- Start of Research Operation (SRO) phase
- First Deuterium-Tritium (DT-1) phase
- Second Deuterium-Tritium (DT-2) phase
- Long-pulse and steady-state scenarios

New ITER Baseline

- **Robust achievement of Project's goals**, in view of past challenges (technical challenges associate with First-of-a-kind components and Covid-19, etc.) and nuclear licensing
- Machine configuration and research plan to **gradually retire risks and provide robust path** to objectives
- **Stepwise Safety Demonstration**
  - DT-1: A first phase of safety demonstration with a limited neutron fluence (1% of present end-of-life Project Specification) → ~ **3.5×10^{25}** neutron fluence
  - DT-2: A second phase of safety demonstration → **~ 3×10^{27}** neutron fluence
- Achievement of **earliest start of ITER Nuclear phase** (D plasma in SRO) while minimizing technical risks

➢ **Tungsten (W) first wall** & **optimized HCD mix**

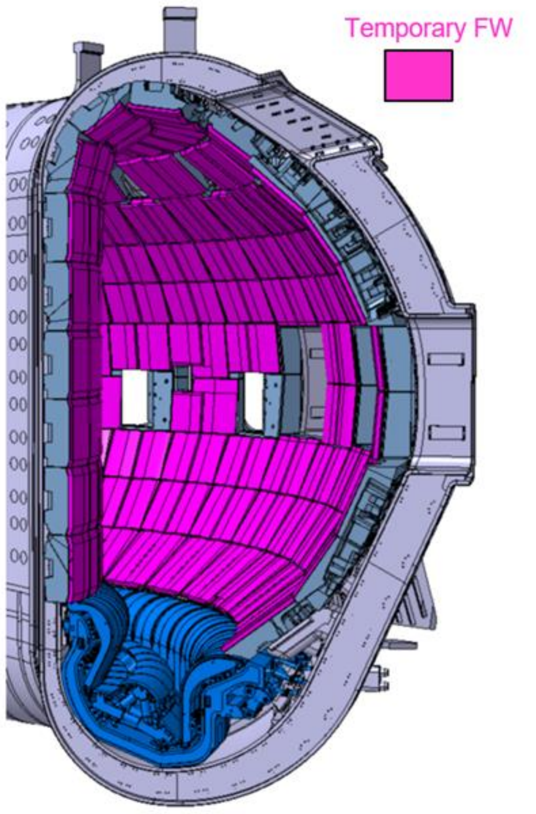
➢ **Boronization** for risk mitigation in achieving Q=10, 500MW operation



Start of Research Operation phase

(after Integrated Commissioning I)

Machine and ancillaries’ configuration for SRO



- **Inertially cooled** W first wall + **Water coole**d W divertor
- P_{EC} = **40 MW** (one equatorial and 3 or 4 upper launchers)
- P_{IC} = **10 MW** (ICWC and ICH tests in W environment)
- Disruption Mitigation System (DMS)
- **4 pellet injectors** for plasma fuelling and ELM control
- Complete set of in-vessel coils and power supplies for VS and ELM control coils
- **Boronization system** with (partial set of) **GDC** anodes
- Initial set of plasma diagnostics to meet SRO needs including redundancy
  - Diagnostics for basic tokamak operation up to 15 MA/5.3 T : magnetics, density, temperature, composition, radiated power, divertor-wall power loads, core impurities, tokamak monitoring, etc.
  - LFS density (ICH), stray radiation (ECH), neutron and ELM measurements (Deut. H-mode)
  - Disruption and DMS, plasma operation with W wall, and support to safety-orientated knowledge acquisition
  - **Current profile measurement** (e.g. Poloidal Polarimetry) under discussion

Objectives of Start of Research Operation

- **Commission control and protection systems** with plasma up to 15 MA/5.3 T
- Demonstration of **superconducting coils capability** to operate plasma scenarios up to 15 MA/5.3 T
- Routine operation with **shape and vertical position control** up to 15 MA/5.3 T in L-mode
- **Commissioning of installed H&CD (EC and IC) systems** up to their nominal power levels (40 MW and 10 MW, respectively) for at least 50 s
- Exploration of the **H-mode operational space** up to 7.5 MA/2.65 T in deuterium plasmas (incl. P_{EC} required for stationary H-mode operation)
- **Identification of error fields** due to machine assembly and intrinsic non-toroidally symmetric features of ITER's design and their optimization
- Demonstration of required **divertor and first-wall protection** and **core impurity control methods** necessary for high-performance H-mode scenarios in DT-1
- Characterization of **disruption loads** and demonstration of **effective disruption mitigation** up to 15 MA/5.3 T
- Demonstration and optimization of **wall conditioning** schemes (GDC, Boronization, ICWC,..)

Objectives of Start of Research Operation (cont.) and Strategy

- First update of **safety-orientated knowledge acquisition programme**:
  - Disruptions, VDEs, runaway electron loads, Dust creation and characteristics
  - Fuel retention determination and removal (using D, with low T production)
  - First validation step of radiation maps (D), Corrosion products

✓ **Minimize risks associated with wall damage** by using inertially cooled W wall

✓ **Limit neutron fluence in DD** to ~ 1.5×10^{20} neutron fluence to allow in-vessel installation work after SRO

✓ **Develop scenarios at 2.65 and 5.3 T** to provide effective central heating for the use of W wall

✓ Allocate most of **5.3T H operation** after 2.65T D campaign to ensure deactivation time within SRO

✓ Estimated duration of ~ 27 months (Hydrogen → Deuterium (~ 6 months) → Hydrogen)

Key plasma scenarios during SRO

- Limiter **3.5 MA**/2.65 T in H – apply boronization when needed
- First **5 MA**/2.65 T phase in H – commissioning key systems and develop scenarios for DD + PWI issues
- First **7.5 MA**/2.65 T phase in H – focused on scenario development for DD + disruption issues
- First 3.0-7.5 MA/**5.3 T** phase in H – focused on disruption issues before D operation
- **Deuterium** campaign at **2.65T** – H-mode access and operation at 5 MA and 7.5MA, identification of H-mode threshold power, W sources, ICH, disruption, PWI issues
- Second 5 and 7.5 MA/**2.65 T** phases **in H** – completion of scenario development and commissioning of advanced control functions (incl. NTM)
- Second 5 and 7.5 MA/**5.3 T** phases **in H** – completion of scenario development and commissioning of diagnostics, ECH and ICH at 5.3 T
- **15 MA**/**5.3 T** development in H – **L-mode** scenarios with disruptions up to 15MA and for PWI issues

First Deuterium-Tritium phase

(after Integrated Commissioning II)

Machine and ancillaries’ configuration for DT-1

- **Fully water-cooled** W first wall and divertor
- P_{EC} = **60 (or 67) MW** from two equatorial and **3 (or 4)** upper launchers
- P_{IC} = 10 → **20 MW** from one antenna
- P_{NB} = **33 MW** (H or D beams)
- Disruption Mitigation System
- **6 pellet injectors** for plasma fuelling and ELM control
- Complete set of in-vessel coils and PS for Vertical Stability and ELM control coils;
- Boronization system to deposit boron films by GDC
- Two ports equipped the **first set of 4 TBMs**
- **Near complete set of plasma diagnostics** to provide the measurements for plasma control and physics assessments for DT burning plasmas (except Collective Thomson Scattering and High Temperature Thomson scattering under discussion)

Objectives of DT-1

- Demonstration of reproducible operation with fusion power of **500 MW with $Q \geq 10$, $t_{burn} \geq 300$s**
- Demonstration of **high duty operation** with fusion power of 250 MW $t_{burn} \geq 300$s
- **Qualification** of tokamak components and systems in nominal $Q \geq 10$ operation
- Assessment of **neutron effects and nuclear heating** at nominal power levels on diagnostics and superconducting magnets in nominal $Q \geq 10$ operation
- Characterization of **burning plasmas physics** and associated control and load mitigation challenges in nominal $Q \geq 10$ operation
- **Validation of radiation maps** in nominal $Q \geq 10$ operation
- Demonstration of **in-vessel tritium management**, measurement of **dust production rates**, etc., in nominal $Q \geq 10$ operation
- **Safety-orientated knowledge acquisition programme** for the full DT-1 phase → **DT-2 licencing**
- First operation of the **TBM** in **nominal $Q \geq 10$ operation** and in **high-duty operation** with $P_{fus} = 250$ MW
    - Coolant thermo-hydraulics conditions relevant for high-efficiency electricity production
    - Tritium breeding to confirm Tritium Breeding Ratio (TBR) in demonstration fusion power reactors

✓ DT-1 Fluence ~ 3.5×10^{25} neutrons (~ 580 pulses at 500MW, 300s burn)

Strategy for DT-1

- **Commission with H plasma** all new DT-1 systems, components and control functions to sustain high P_{tot} (~100 MW) for 50s
- Assess **impact of T in disruption mitigation** and demonstrate **efficiency of T removal**
- Account for **operational risks impacting PFC lifetime** in scenario development path
- Develop **H-mode operation in q_{95} = 3-6** range first at 2.65 T, and then at 5.3 T to ensure central ECH heating (to minimize W accumulation risk)
- Develop **D H-mode scenarios, interleaved with DT,** to minimize neutron fluence consumption (1 % T to understand / optimize T fuelling, T ≤ 20% as steps between DD and 50-50 DT)
- **Earliest achievement of Q = 10 H-mode short pulse (~ 50s),** and then to 300s
- Maintain **NBI in H** in FPO-1 and consider **NBI in D** in FPO-2 or later if supported by NBTF R&D programme
- Re-tune disruption mitigation **at every I_P step** to account for increasing W_{plasma} and T-related effects
- Include **T removal** (including plasma operation and ICWC in addition to use of 2 days maintenance every 2 weeks) and maintain low T ~ (<1%) in D plasmas

➢ Preparatory experiments of Q=5 steady-state in DT-1 with short burn to be included to reduced risks in DT-2

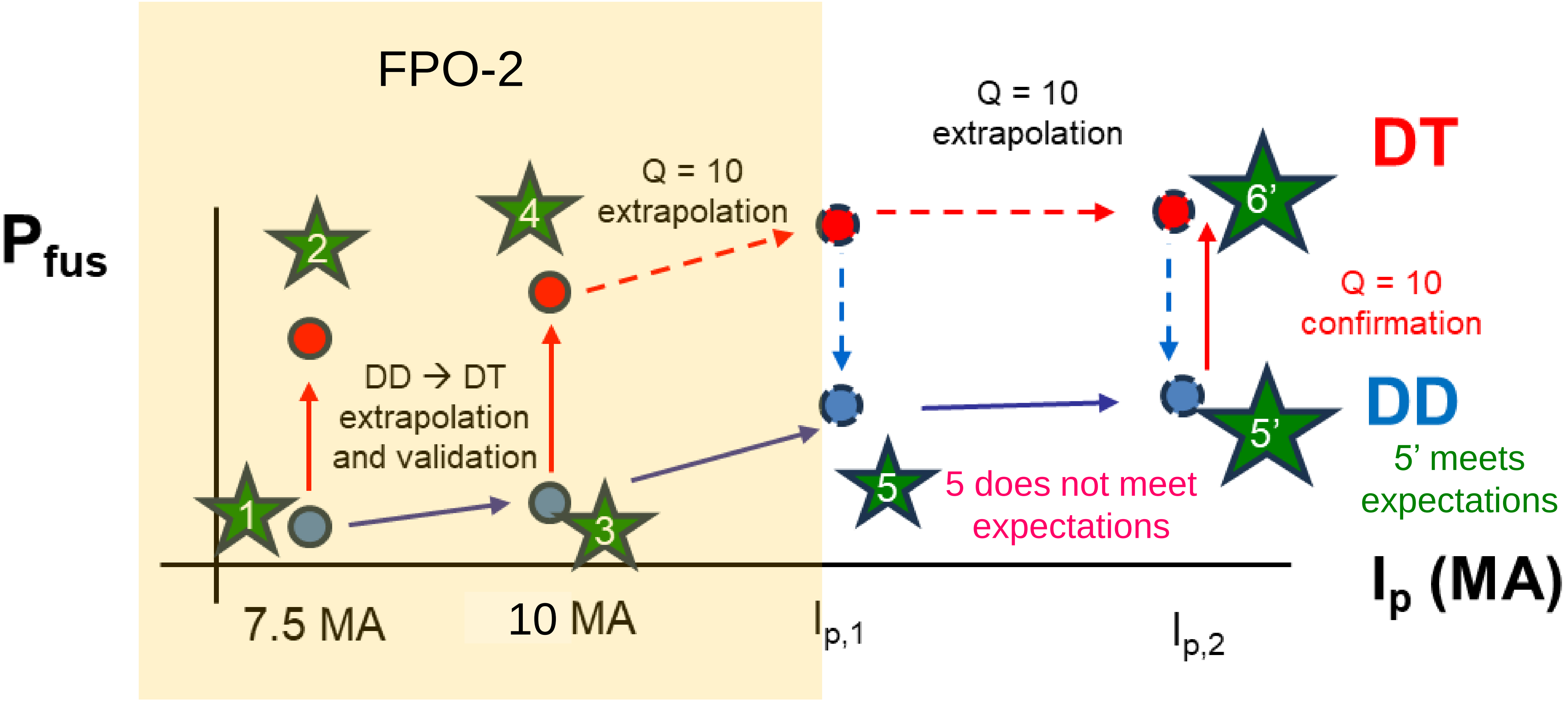
Five Fusion Power Operation (FPO) campaigns in DT-1 – FPO-1 & FPO-2

- Each FPO has 16 months operation (incl. ~30% contingency) + 8 months shutdown

- FPO-1
  - **H phase**: resume operation to SRO level with newly installed systems and components
  - **H+T phase**: retire risk of RE formation (associate with T seeds), demonstrate efficient T removal (~ 80% T removal from B layers)
  - **D phase**: re-develop H-mode scenarios in D
    - 3.75 / 5.0 / 7.5 MA at 2.65 T (**q_{95} = 6 / 4.5 / 3**), with limited **NBI** power (due to shine-through)

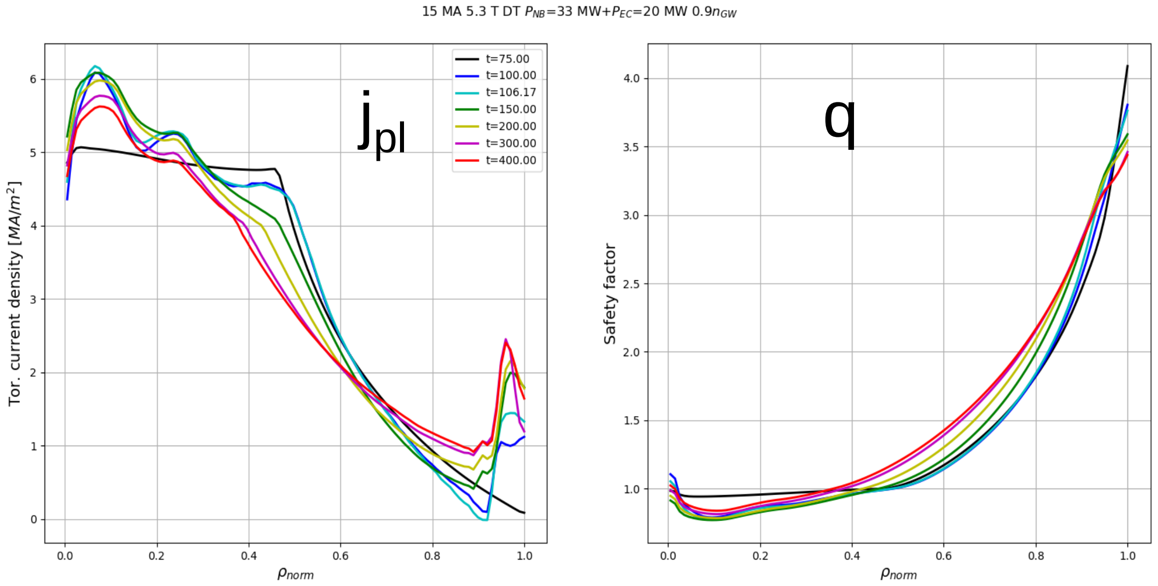
- FPO-2 : demonstrate **DT H-mode** plasma operation up to 10 MA/5.3 T with P_{fus} > 100 MW for t = 50 s including T management, He exhaust, DMS tunning, first TBM operation
  - Develop D plasmas from 5 MA to 7.5 MA/5.3 T (q_{95} = 9 → 6) to minimize ELM risks
  - Develop DT plasmas at 7.5 MA/5.3 T (**q_{95}= 6**) → exploring potential for Q ~ 5
  - Develop D plasmas at 10 MA/5.3 T to retune control schemes
  - Develop DT plasmas at 10 MA/5.3 T (**q_{95}~ 4.5**)→ potential for P_{fus} ≥ 200 MW and Q ~ 5

FPO-2 outcomes for FPO-3



Five FPO campaigns in DT-1 (II) – FPO-3

- FPO-3 : first operation with **nominal heat loads and neutron flux**
  - Demonstration of reproducible operation with fusion power of **500 MW** and **Q ≥ 10** for, at least, **50s**
  - Attempt to extend $Q \geq 10$ $P_{fus} = 500$ MW to $\mathbf{t_{burn} = 300s}$
    - Active MHD (TM) control or passive schemes need to be explored for $\mathbf{t_{burn} > 50s}$
    - Relaxation of current density profile



Five FPO campaigns in DT-1 (II) – FPO-4 & FPO-5

- FPO-4
  - Extension of $Q \geq 10$ with fusion power of 500 MW to **300 s** including **MHD active control/passive stabilization** - stop under-performing pulses to save neutrons
  - Development of all technical aspects of **long pulse burning plasmas** (control schemes, H&CD optim., ELM control, detachment control, disruption avoidance, disruption mitigation to highest W_{plasma} and I_p)

❖ **If progress in FPO-4 is as planned →** extension of FPO-4 by **6 months** and cancellation of FPO-5 should be considered

- FPO-5
  - Re-commission/confirmation of high P_{inp} for ~ 1000 s
  - Demonstration of reproducible operation with P_{fus} = 500 MW with $Q \geq 10$ $t_{burn} \geq 300$s
  - Demonstration of high duty operation with P_{fus} = 250 MW $t_{burn} \geq 300$s
  - Extension of $Q \geq 10$ with fusion power of 500 MW 300 s $\leq t_{burn} \leq$ 500s

Second Deuterium-Tritium phase

Machine and ancillaries' configuration for DT-2

- Fully water-cooled W first wall and divertor
- P_{EC} = 67 MW of ECH heating from 2 equatorial and 4 upper launchers
- P_{IC} = 20 MW from one antenna
- P_{NB} = **50 MW (+ 3rd NBI)**
- Disruption Mitigation System
- 6 pellet injectors for plasma fuelling and ELM control
- Complete set of in-vessel coils and PS for Vertical Stability and ELM control coils;
- Boronization system to deposit boron films by GDC
- Two ports equipped with of **4 TBMs**
- **Full set of plasma diagnostics** to provide the measurements for plasma control and physics assessments for DT burning plasmas

Objectives of DT-2

- **Commissioning and demonstration** of control, interlock, protection and ancillary systems to support DT-2 scenarios
- Demonstration of **routine operation with 500 MW** fusion power with Q ≥ 10 for burn durations of **300-500s** at high-duty
- Demonstration of routine operation with **Q ≥ 5** for **1000s in long-pulse** scenarios
- Demonstration of routine operation with **Q ≥ 5** for **3000s in steady-state, non-inductive**, scenarios
- Exploration of physics, integration/control of Q > 10 up to **P_{fus} = 700 MW**
- Assessment of **fusion reactor physics and operational issues**: optimization of H&CD mix, identification of minimum set of sensor/actuators for achievement and control of high Q plasmas, exhaust power and particles, etc
- Consolidation of the **tritium breeding efficiency evaluations** for demonstration fusion reactors breeding blankets

Strategy for DT-2

- **Five FPO campaigns** are tentatively considered - each has 16 months operation (incl. ~25% contingency) + 8 months shutdown

- 3rd NBI and improved systems will be commissioned for **1000s** at the beginning of DT-2
- Start development of long-pulse / steady-state operations for **1000s** at relatively **low Q** (≤ 2 foreseen, but not restricted to), and then increase burn duration to **3000s for steady-state**
- Approach **Q=5** long-pulse and steady-state operations towards the later FPO campaigns (~ FPO-8/9)
- Implement **TBM research and development programme** along with the development of high Q long-pulse/steady-state operation (from FPO-6 to ~ FPO-8/9)
- Perform assessment and studies for **fusion power plant research** starting from the early phase of DT-2
- As the Project's goals are achieved, **allocate more experimental time** to contribute to **fusion power plant physics and operation** (incl. restrictions from fusion power plant concepts)

Long-pulse / steady-state operation - a few preliminary analyses

Q=5 steady-state operation with alternative H&CD mixes

- Previous Q=5 SS scenarios, A2 & A3 [NF 60, Polevoi], analysed with **different combination of NB and EC power**, while keeping the total power (69.5 MW and 79.5MW respectively)
- The H-factor and plasma density were chosen to provide Q=5 operation with fully noninductive current

➢ **New cases with increased EC power** (A2′ and A3′) required higher confinement $H_{98}\geq 1.64$

(A.R. Polevoi)

Cases	P_{aux} (MW)	P_{NB} (MW)	$P_{EC,EL}$ (MW)	$P_{EC,UL}$ (MW)	n/n_{GW}	I_{BS}/I_p (%)	I_{EC}/I_p (%)	I_{NB}/I_p (%)	$H_{y2,98}$	$l_i(3)$	β_N
A2	69.5	49.5	13.4	6.6	0.716	33.6	9.4	56.6	1.53	0.95	3.03
A3	79.5	49.5	13.4	16.6	0.785	36.6	11.7	51.2	1.53	0.92	3.23
A2′	69.5	33	33.4	3.1	0.712	36	22.6	40.7	1.65	0.94	3.13
A3′	79.5	33	33.4	13.1	0.781	39.1	24.1	36.5	1.64	0.91	3.34

Core-edge-SOL/div JINTRAC modelling of 10MA/5.3T steady-state plasmas

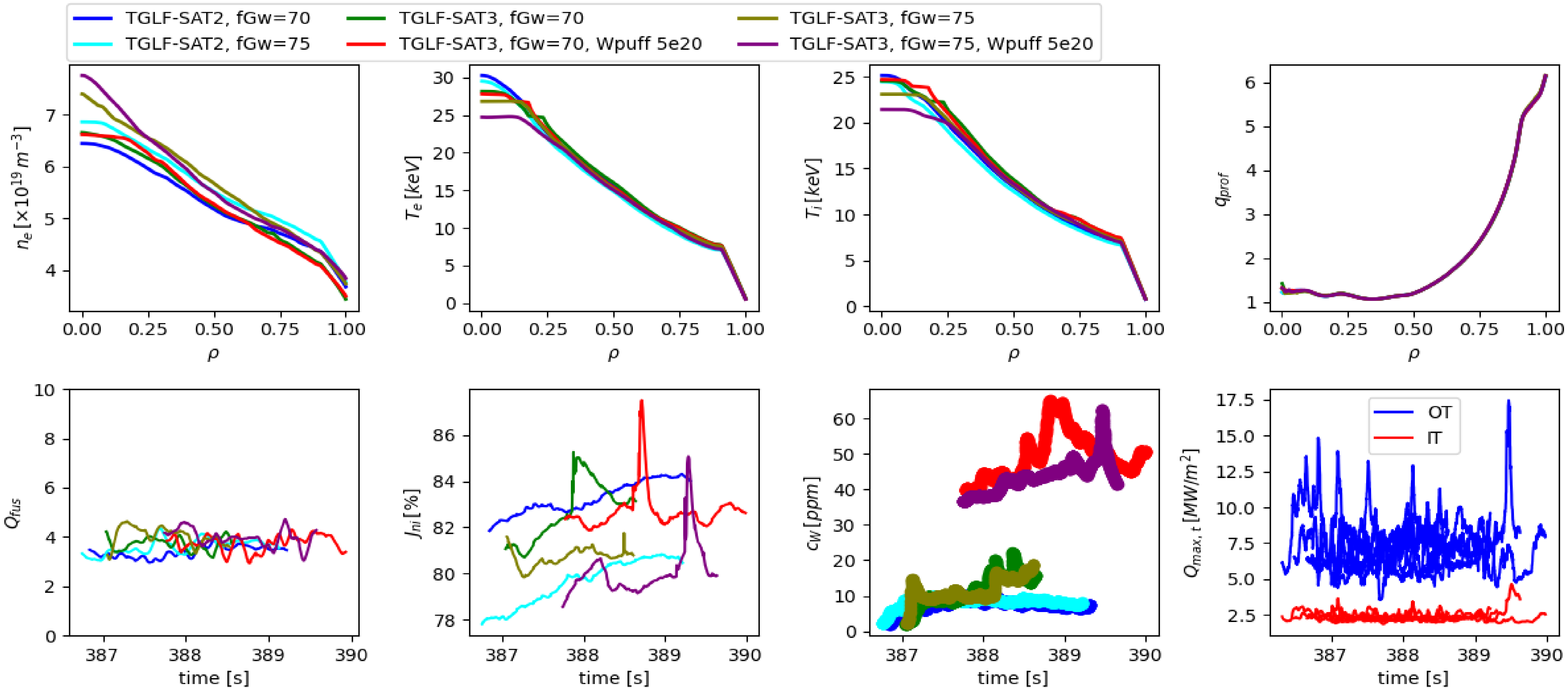
- 10 MA/5.3 T, 50MW NB+20MW EC
- Separated D & T fuel ions at the core, He, Ne and W impurities
- EDWM → TGLF-SAT2 and TGLF-SAT3
- 70% or 75% f_{GW}
- W gas puff (5×10^{20} ions/s) to include wall source

- **Q=3-4** even for **additional W puff** and **H_{98}<1.5**
- **Lower f_{NI} for higher f_{GW}** (next slide)
- Dependence of β_N on the transport saturation rules

(V. Parail, G. Suarez-Lopez)

Case	β_N	$l_i(3)$
$f_{Gw} = 70\%$, TGLF-SAT2	2.15	~ 1
$f_{Gw} = 75\%$, TGLF-SAT2	2.15	~ 1
$f_{Gw} = 70\%$, TGLF-SAT3	2.24	~ 1
$f_{Gw} = 70\%$, TGLF-SAT3, W puff	2.24	~ 1
$f_{Gw} = 75\%$, TGLF-SAT3	2.31	~ 1
$f_{Gw} = 75\%$, TGLF-SAT3, W puff	2.27	~ 1

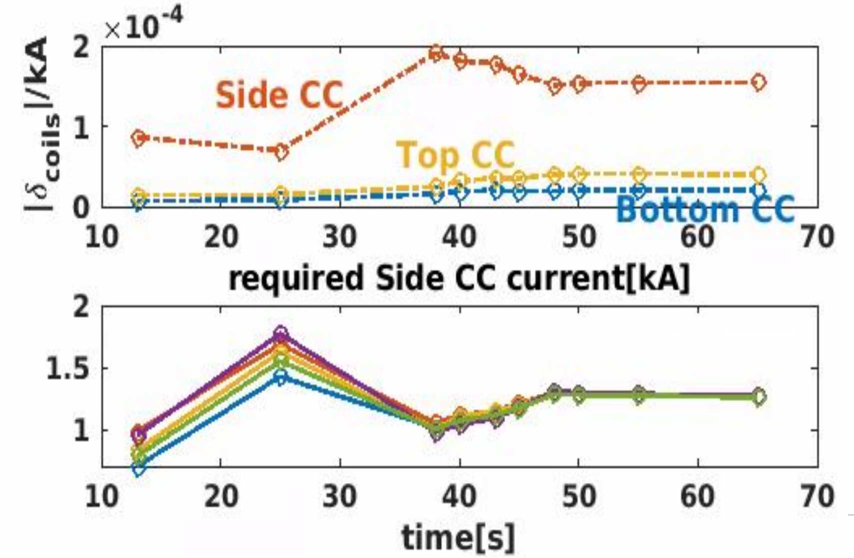
Core-edge-SOL/div modelling of Q=5 steady-state plasmas – Cont.



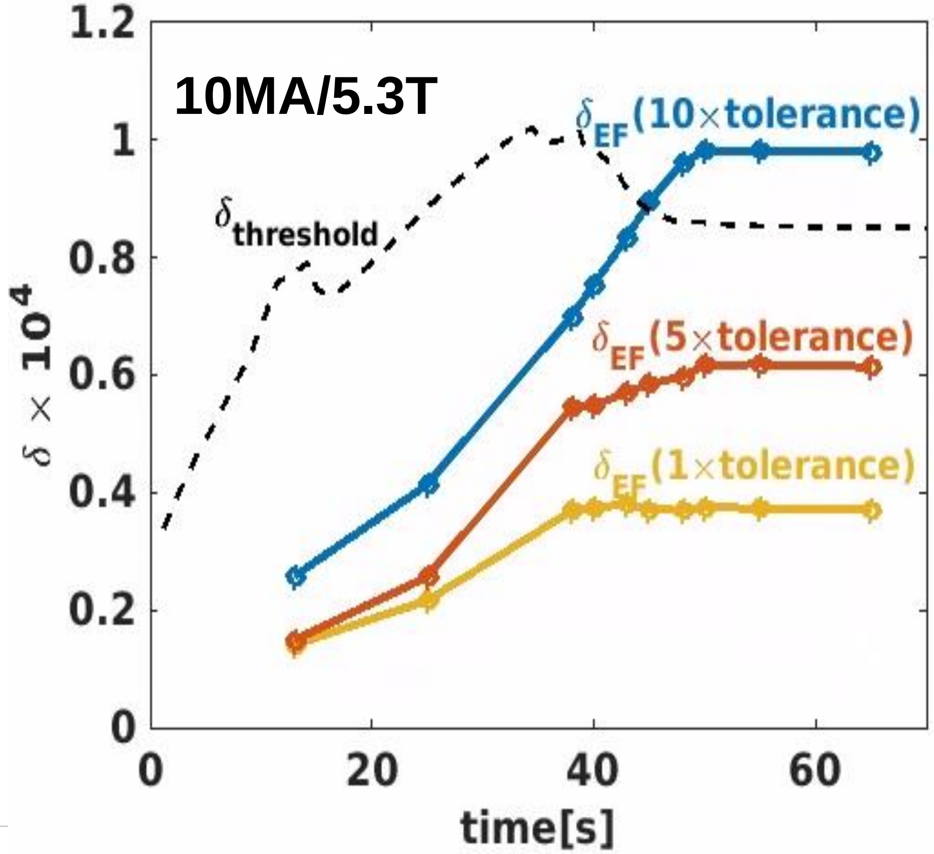
Error fields correction (EFC) required for Q=5 steady-state operation

- Time-dependent Q=5,10MA/5/3T scenario [Kim NF 2021]
- Total EFs = misalignment of coils + TBMs +FIs
- The overlap fields δ_{EF} **including the plasma response** are compared with the mode locking threshold, $\delta_{threshold}$ [Logan NF 2020]

- δ_{EF} increased significantly during the ramp-up phase but remained similar afterwards
- The required correction coil current is less than 2kA, well below the maximal 10kA limit.



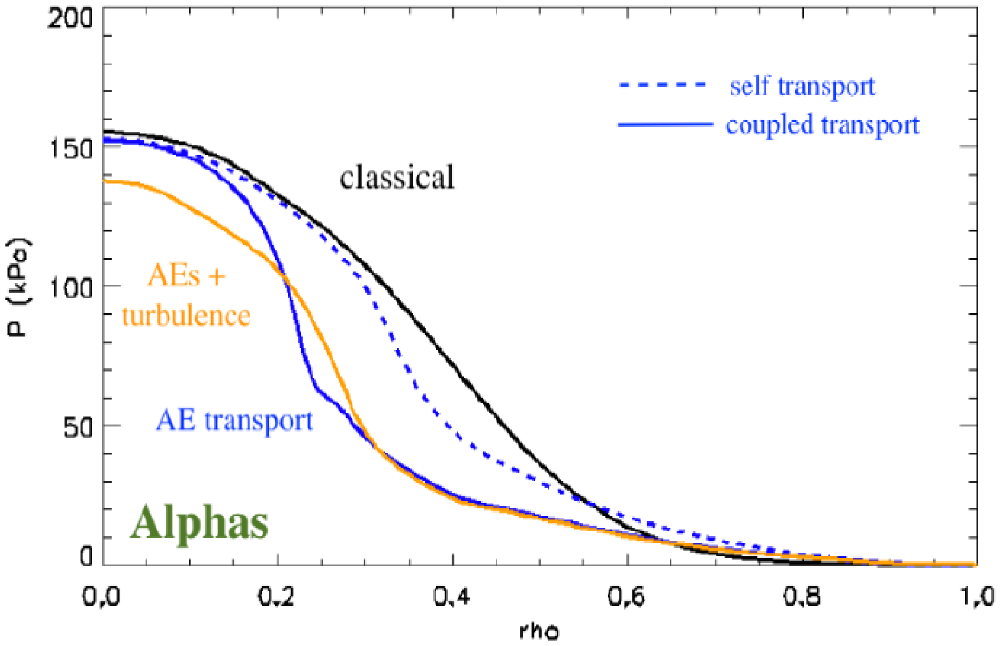
(X. Bai)

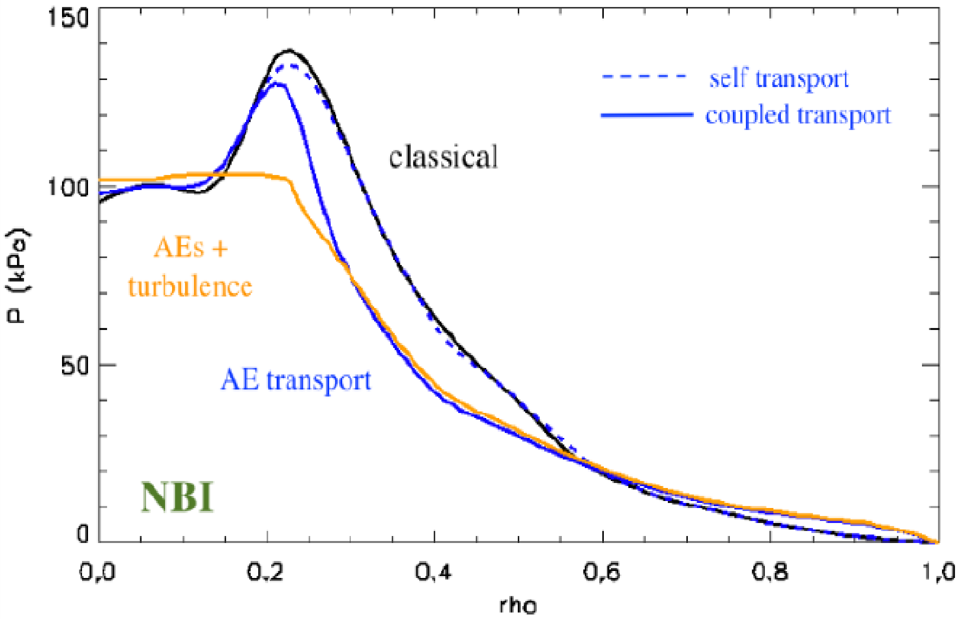


Alpha driven plasma instabilities in Q=5 steady-state plasma

- Energetic particle (EP) confinement study **predicted large α transport** – need further studies with **consistent EP and thermal profiles**
  - Global gyrokinetic (GTC) simulations find BAE/RSAE near q_{min} surface
  - Fully developed AE turbulence with many interacting modes predicted large EP transport (D~ 50m^2/s)
  - Coupled AEs and microturbulence predicted enhanced relaxation of alpha and beam ion profiles.

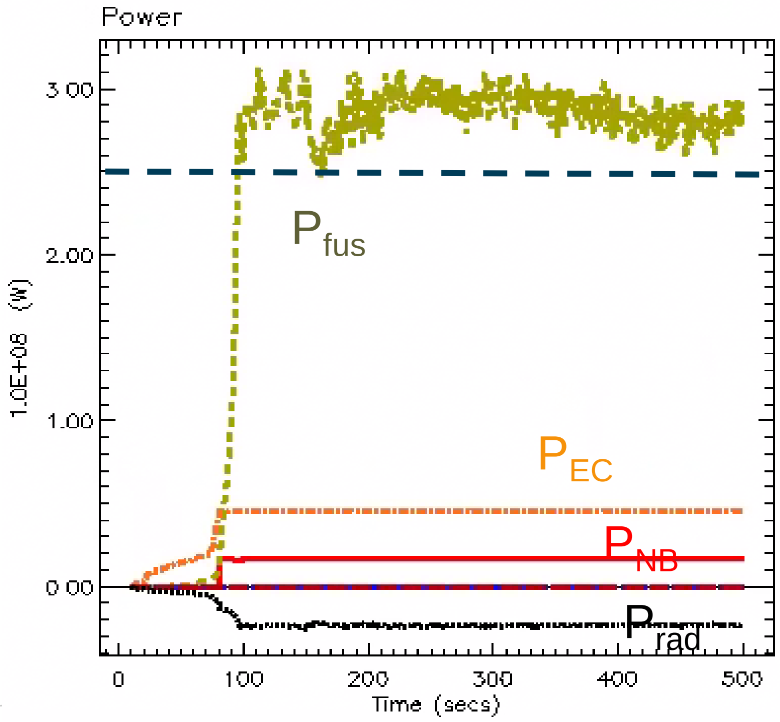
[Z. Lin, APS 2023]





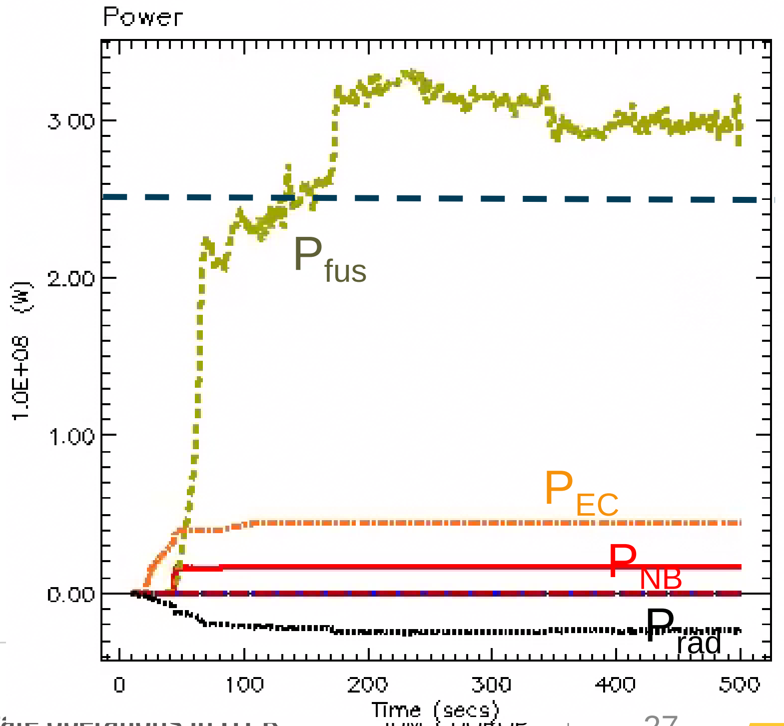
Candidate high-duty long-pulse scenarios for TBM operation (P_{fus} >250MW)

- Time-dependent core-only JETTO simulation to find **access to H-mode with P_{fus}>250MW**
  - 15MA/5.3T and 12.5MA/5.3T
  - 45MW EC + 16.5MW NB (**1/3 of EC and 1/2 of NB power reserved for high-duty**)
  - **20% core radiation fraction** assumed (without W impurity)
  - TGLF-SAT2 transport model **with (Pr=0.3) or without toroidal rotation**



← 15MA, on-axis NBI,
w/o rotation case

12.5MA, off-axis NBI,
with rotation case →



Key R&D issues for long-pulse/steady-state operation (not exclusive)

- **Diagnostics** tolerant for long life-time and compatible with ITER operation
- **W divertor/wall erosion** under controlled ELMs (sputtering + redeposition)
- **W surface modification** by high plasma fluence exposure and implications for tokamak operation
- Formation of **fuzz by He/W** interaction and critical fuzz thickness
- **Access to target plasma states** by optimizing current ramp-up phase
- **q profile feedback control** in medium/long timescales
- Demonstrate **RWM control and avoidance** in combination with ELM control
- Impacts of **fast-ion driven modes** on plasma confinement in high beta steady-state plasmas
- **He ash remove** (especially in presence of ITBs)
- **Alternative candidate scenarios** for DT-2
- …

Summary and Conclusions

- ITER Research Plan (IRP) for new ITER Baseline developed **to Level-I (high-level document)** with self-consistent goals, machine configuration and operational strategies for risk mitigation / retirement.
- IRP working groups have started activities to develop to **Level-II & Level-III (with more details)** for the new ITER Baseline.
- **Revision of IRP R&D issues** will be finalized soon to support the refinement of the new baseline IRP.

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