Assessment of neutron emission for ITER operation with deuterium fuelling in the new baseline ITER Research Plan

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ABSTRACT

Here we study the optimisation of operation with minimal neutron production for a range of plasma currents, densities, and mix of Electron, Ion Cyclotron (EC, IC) and Neutron Beam Injection (NBI) heating H&CD.

The emission of 2.45 MeV neutrons from DD reactions as well as 14 MeV neutrons from DT reactions, including slowing down of 1 MeV T ions born in DD reactions, is assessed for key plasma currents in the IRP and different plasma densities for full- and half-field operation.

The neutron emission from interactions of fast ions from ICH with Boron is assessed for primary and secondary reactions

The simulations are carried out by self-consistent 1.5D transport simulations of the core plasma parameters in the frame of ASTRA [2] with the pedestal and boundary conditions predicted by EPED1 and SOLPS codes, and with self-consistent gas puffing and pellet fueling, taking account of limitations on the NBI shine-trough losses [3].

The results of this assessment are used to provide the background for the choice of plasma scenarios for the ITER Research Plan in SRO and DT-1 phase, within the limits of the neutron budget imposed for such operational phases, and for associated assessments.

SRO phase: H&CD, passively cooled FW

Heating and current drive (H&CD) at SRO

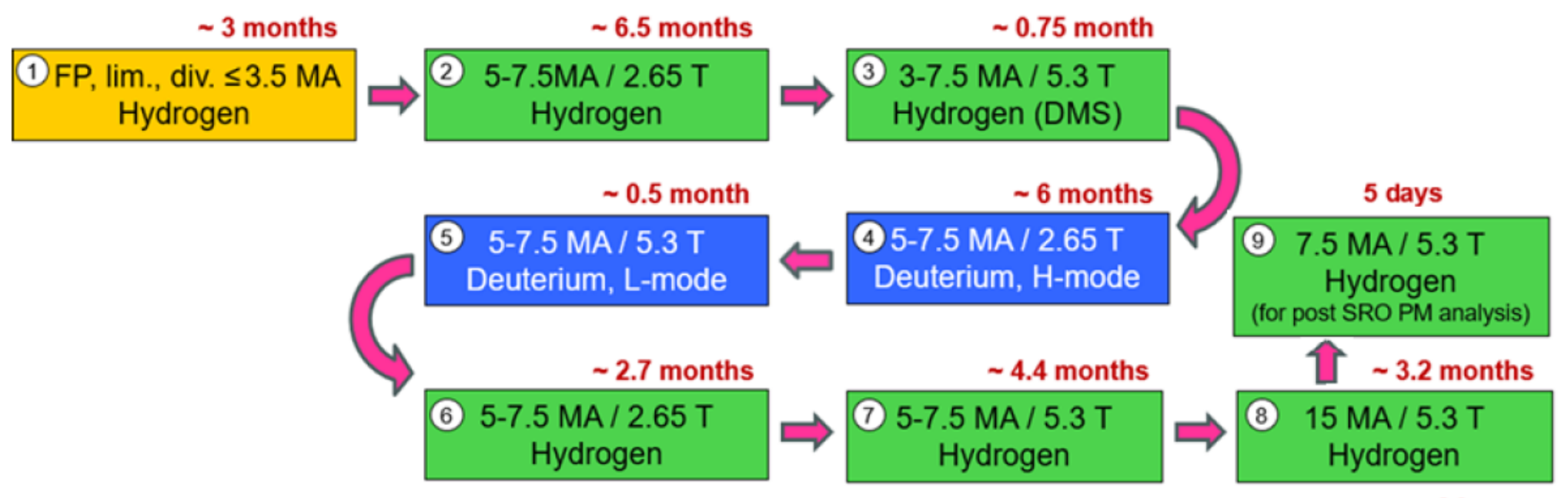
Electron Cyclotron H&CD: P_{EC} = 40 MW
(f_{EC}=170 GHz, 48 beams x 0.83 MW),

1 Equatorial Launcher (EL):	3 Upper Launcher (UL):
3 mirrors (x 8 beams)	2 mirrors (x 4 beams)
EL/TSM (counter-current!)	UL/USM
EL/MSM	UL/LSM
EL/BSM	

Ion Cyclotron H&CD: P_{IC} = 10 MW
(f_{IC}= 40 - 55 MHz,1 antenna, minority heating scheme)
hydrogen in DD at B=2.65 T (f_{IC}= 42 MHz)
^{3}He in hydrogen and DD at B=5.3 T (f_{IC}= 53 MHz)

SRO – D H-mode exploration

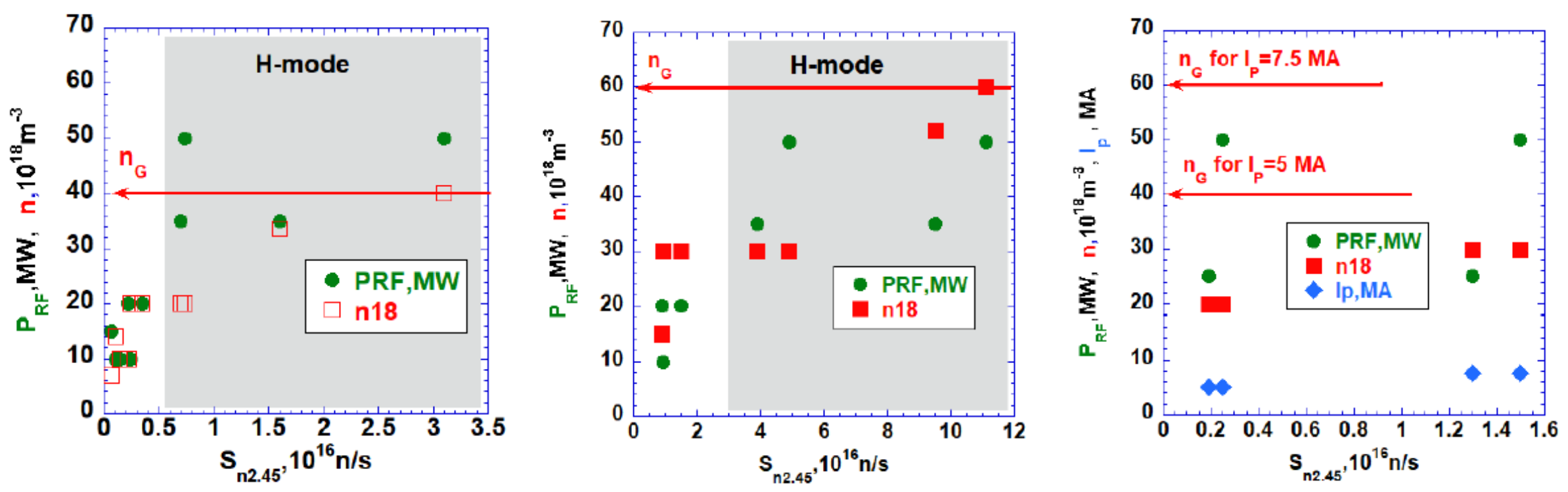
- Start with 5 MA/2.6 5 T to avoid ELM divertor melting and to control W influxes from wall (scans as AUG, EAST) → ELM control demonstrated (f_{pellet} ≤ 60 Hz and RMPs)
- Then up to 7.5 MA/2.65 T H-modes with ECH+42 MHz H-minority ICH
- Test of H-mode access at 5.3 T with ECH + 53 MHz 3He-minority ICH


~ 3 months ① FP, lim., div. ≤3.5 MA Hydrogen
~ 6.5 months ② 5-7.5MA / 2.65 T Hydrogen
~ 0.75 month ③ 3-7.5 MA / 5.3 T Hydrogen (DMS)
~ 6 months ④ 5-7.5 MA / 2.65 T Deuterium, H-mode
~ 0.5 month ⑤ 5-7.5 MA / 5.3 T Deuterium, L-mode
~ 2.7 months ⑥ 5-7.5 MA / 2.65 T Hydrogen
~ 4.4 months ⑦ 5-7.5 MA / 5.3 T Hydrogen
~ 3.2 months ⑧ 15 MA / 5.3 T Hydrogen
5 days ⑨ 7.5 MA / 5.3 T Hydrogen (for post SRO PM analysis)

- D operation completed ~ 1 year before VV entry within 1.5x10^{20} neutron budget
- Duration of a shot at full power is limited by 30 s due to passive cooling of the wall

Range of plasma parameters at SRO

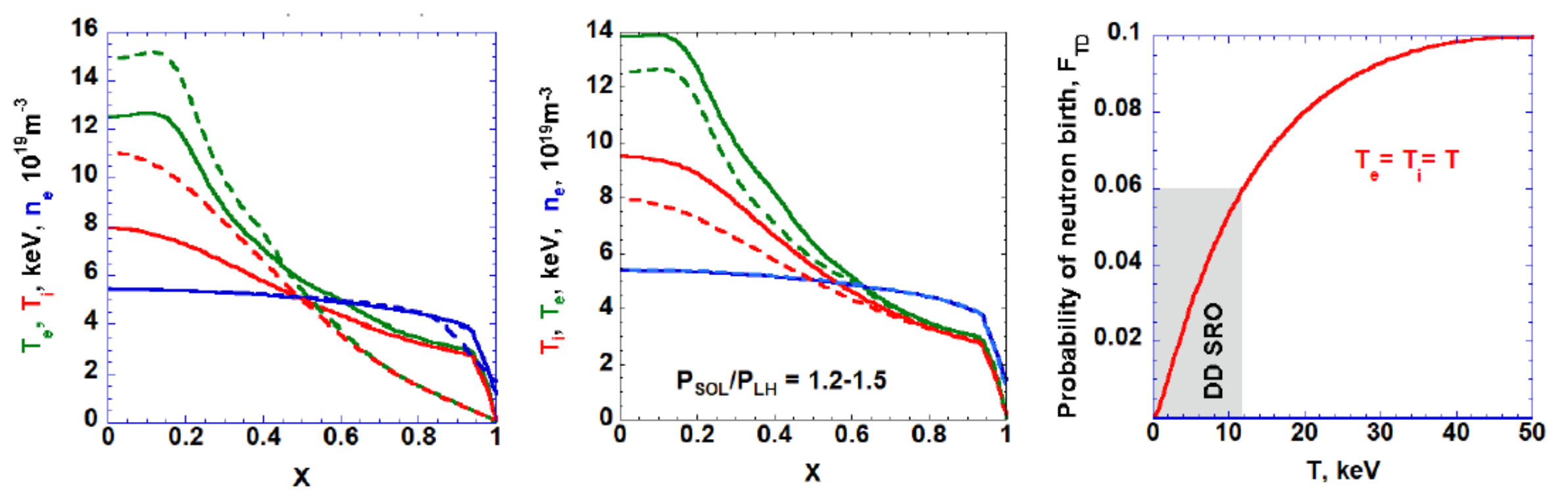
Simulations of DD SRO scenarios are carried out for B = 2.65 T and B= 5.3 T, in the range of plasma currents, I_p = 3.5 – 7.5 MA, safety factor, q_{95} = 3 - 9, densities, n_e/n_G = 0.25 - 1, and mix of the EC+IC heating, P_{RF} = 10 - 50 MW for L- and H-mode operation.



(a) B/I_p=2.65/3.5-5 T/MA (b) B/I_p=2.65/7.5 T/MA (c) B/I_p=5.3/5-7.5 T/MA

Operational space for DD L- and H-modes with P_{RF}=10-50 MW

The least neutron source corresponds to the minimal density



(a) P_{EC}=40 MW:
(---) B/I_p= 5.3/15 T/MA L-mode,
(—) B/I_p=2.65/7.5 T/MA H-mode

(b) B/I_p=2.65/7.5 T/MA H-mode
(---) P_{EC} = 40MW,
(—) P_{EC}+P_{IC}= 40+10 MW

(c) F_{TD}= $S_{n14}/S_{n2.45}$, [4]
$S_{T1MeV,DDth}$= $S_{n2.45,DDth}$
S_{n14}= $S_{n14,T1MeV+Dth}$
$S_{n2.45}$= $S_{n2.45,DDth}$

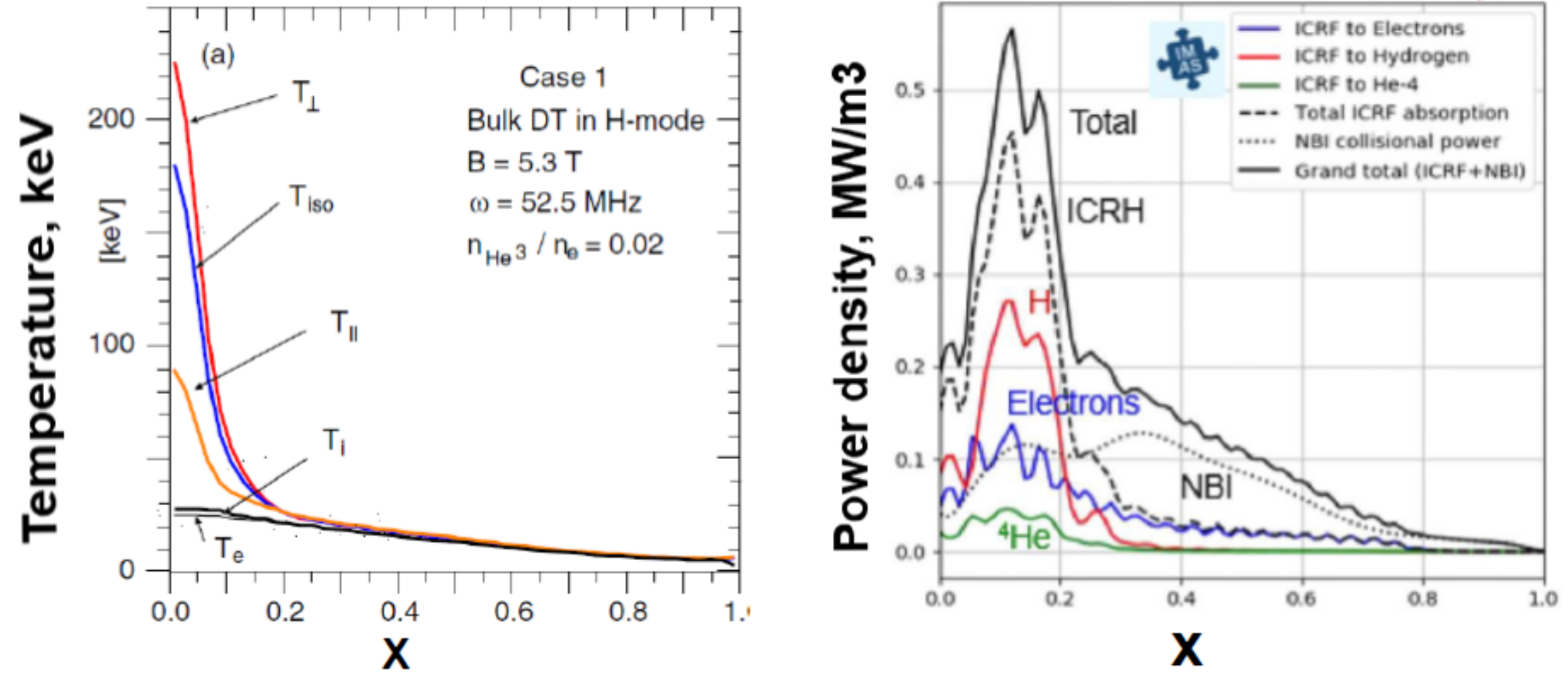
Assessment of 14 MeV neutron yield in DD phase of SRO:
(a), (b) T_i, T_e, n_e profiles predicted for maximal EC+IC heating in the L- and H-mode operation; (c) ratio of 14 MeV to 2.45 MeV neutron source

Predicted fraction of 14 MeV neutrons at SRO is below 6%

Neutron yield due to minority ICH and Boron

$$S_{n,fast+B} = \int n_B < \sigma_{n,fast+B} f_{fast} v_{fast} d^3 v_{fast} > dV$$

Fast ion distributions due to ICH minority heating f_{fast}

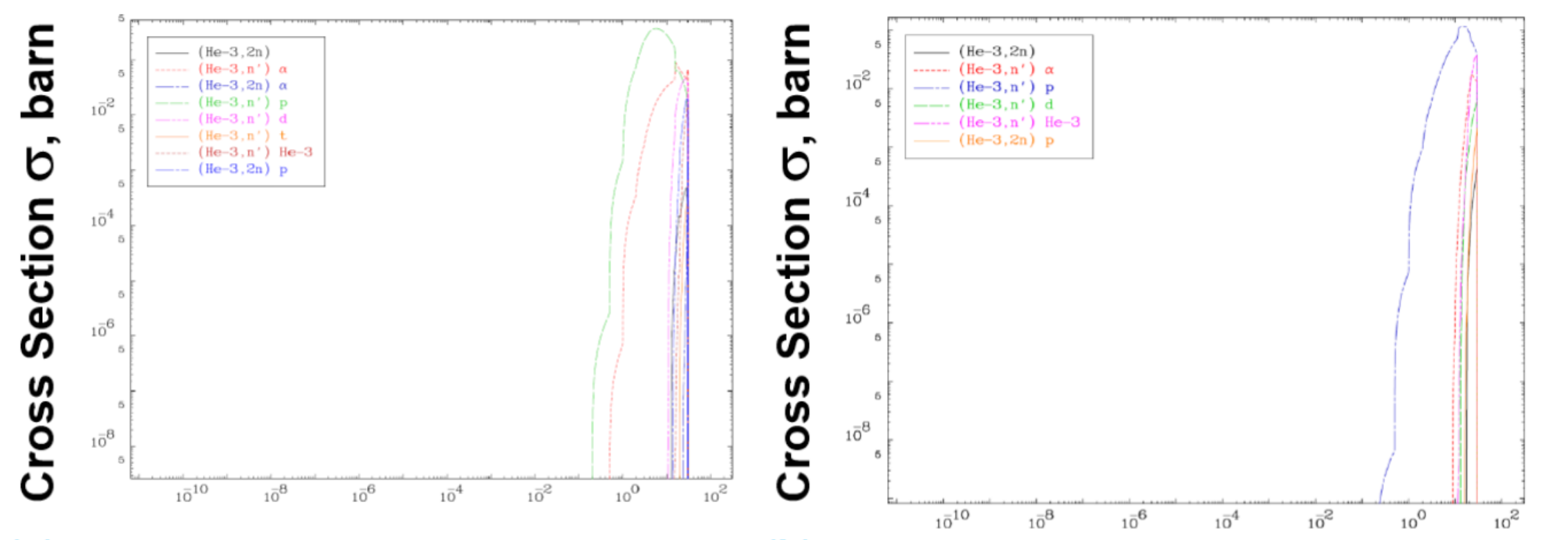


(a) 3He minority ICH, B=5.3T [5] (b) H minority ICH, B=2.65T [6]

Temperature T_{fast} < 0.2 MeV, location x < 0.2, (dV<35 m^3)

Neutron yield by fast 3He, H and Boron

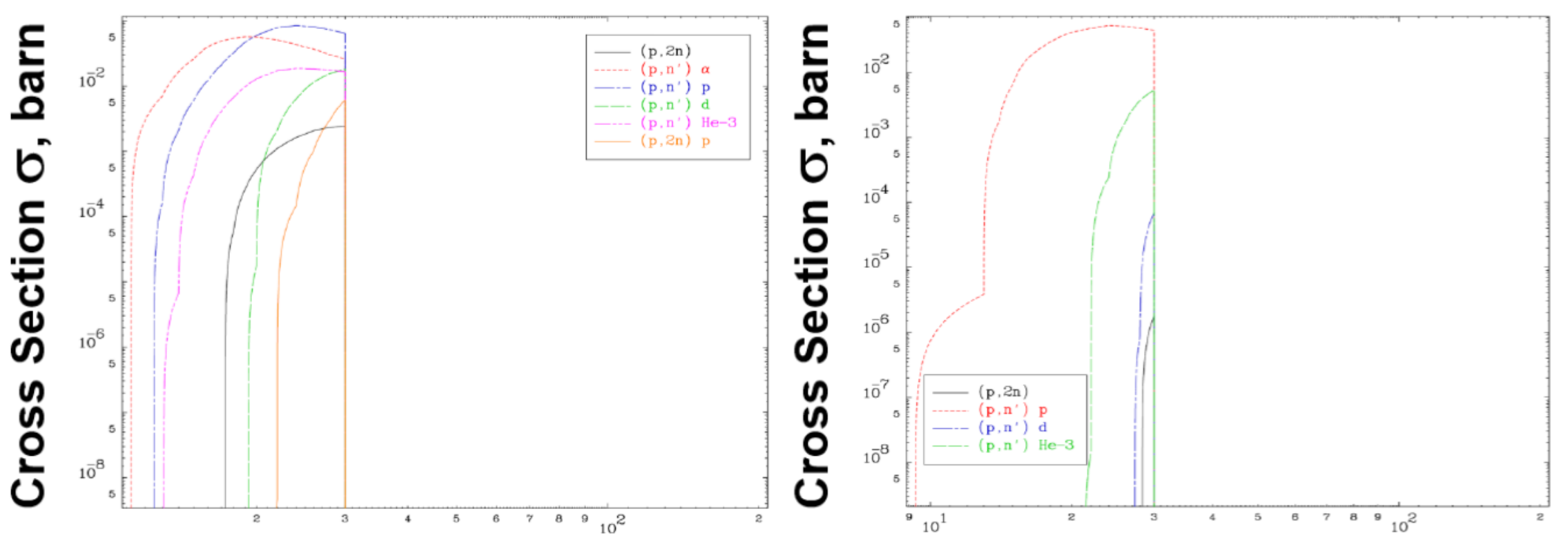
Stable Boron isotopes: 10B (20%) and 11B (80%)



(a) Incident Energy, MeV (b) Incident Energy, MeV

Cross-sections of fusion reactions with neutron products for fast 3He $\sigma_{n,3He+B}$ for 11B (a) and 10B (b) [7]

$$S_{n,3HeB,max}[n/s] \sim 2.4\ 10^{12} c_{3He,\%} c_{B,\%} n_{20}^2$$



(a) Incident Energy, MeV (b) Incident Energy, MeV

Cross-sections of fusion reactions with neutron products for fast protons $\sigma_{n,p+B}$ for 11B (a) and 10B (b) [7]

$$S_{n,pB,max}[n/s] \sim 9\ 10^{12} c_{H,\%} c_{B,\%} n_{20}^2$$

$c_{H,\%}, c_{3He,\%}, c_{B,\%}$, are concentrations of Hydrogen, 3He and Boron

Cumulated contribution due to interaction of ICH minorities with Boron is assessed as < 6 10^{18} n in 8.5 month of operation

DT-1: extended H&CD + active FW cooling

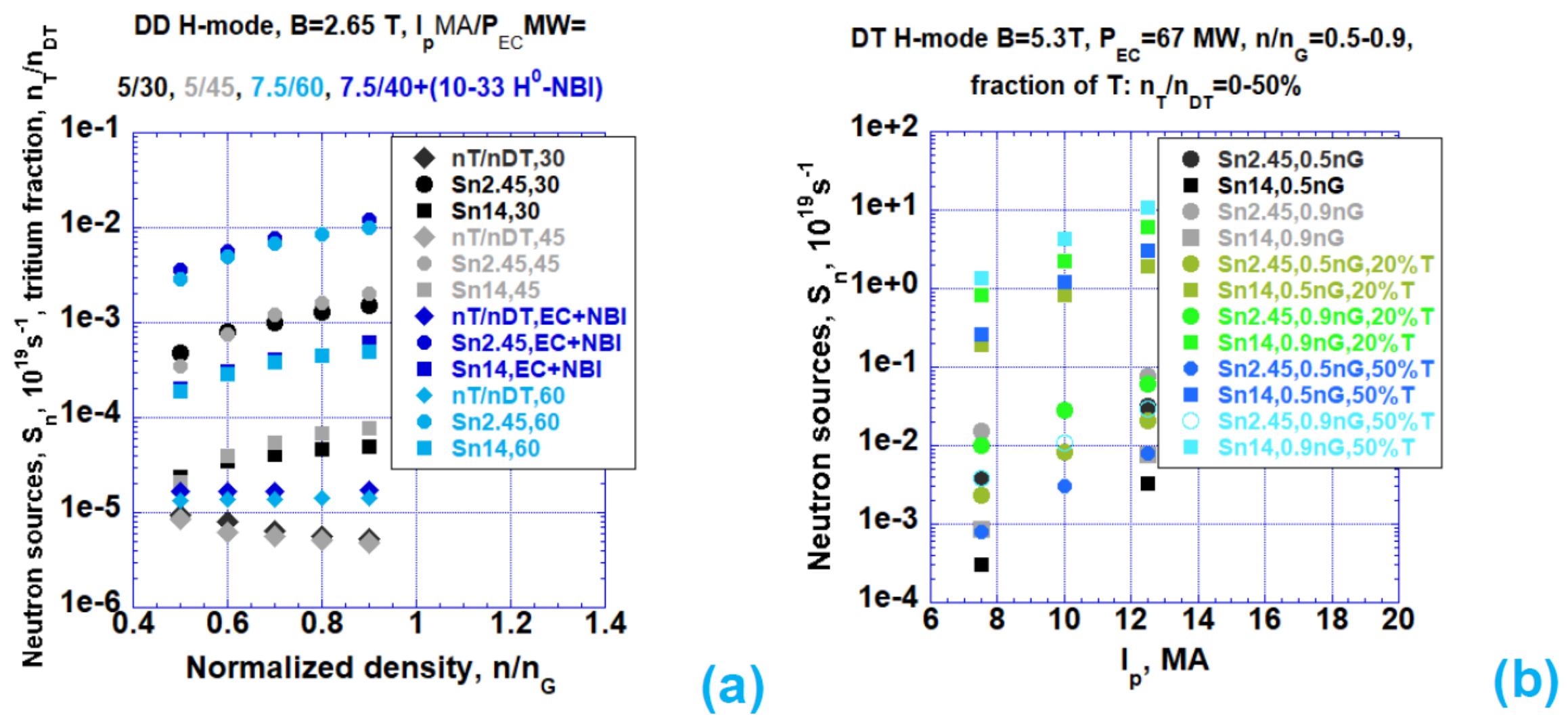
Heating and current drive at DT operation

Electron Cyclotron H&CD: P_{EC}= 60-67 MW (72-80 beams)
2 EL*: 48 beams 40 MW
3-4* UL: 24-32 beams 20-27 MW

Ion Cyclotron H&CD: P_{IC} = 10 (20) MW
Frequency range f_{IC}= 40 - 55 MHz
enables using of minority heating scheme of hydrogen in DD half-field operation at 42 MHz and ^{3}He minority heating at 53 MHz for full field operation, B=5.3 T.

Neutral Beam Injection: P_{NBI} = 33 MW
(2 beams up to 16.5 MW each)
Hydrogen NBI with energy E_b=0.87 MeV or
Deuterium NBI with energy E_b=1 MeV

Neutron sources at DT-1 operation



Neutron sources, S_n, and tritium fraction, n_T/n_{DT} for n/n_G=0.5-0.9:
(a) DD, I_p/B=5-7.5/2.65 MA/T P_{aux}=30-73 MW,
(b) DD - 50:50 DT, I_p/B=7.5-12.5/5.3 MA/T P_{aux}=67 MW.

Contribution of DT neutrons ~10^2 is much higher than DD

DT-1 Experimental Plan

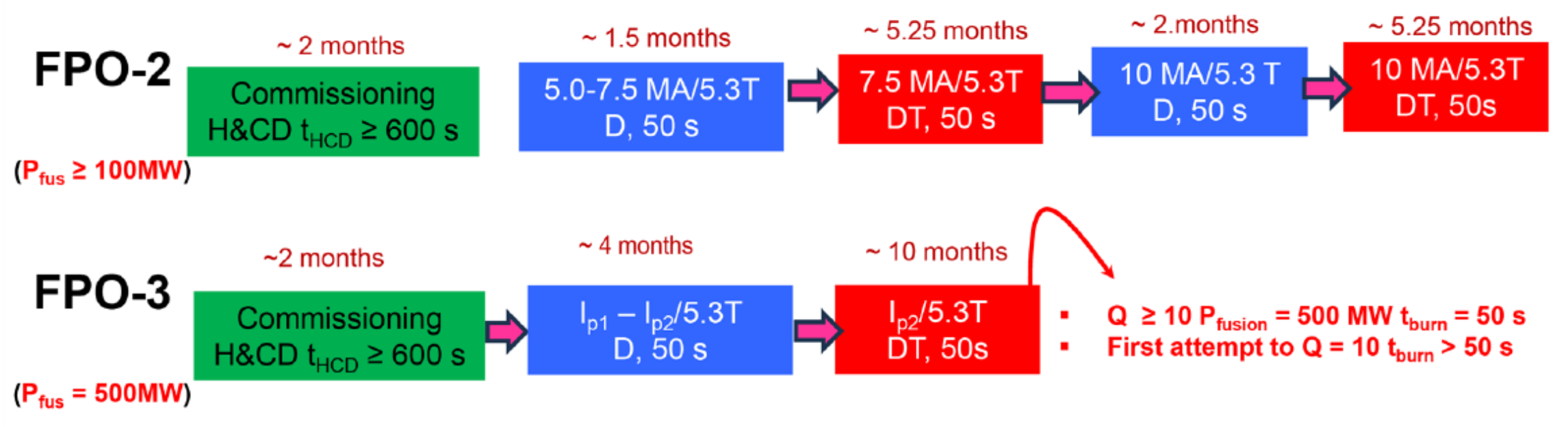
FPO-1

- Initial commissioning 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/2.65 T before DT (NTMs, Sawteeth, AEs, divertor heat flux, ELM control, burn control, …)


FPO-1
~ 11 months Commissioning 15 MA/5.3 T H, L-mode, 50 s
~ 1 month 15 MA/5.3T H+T, 50 s
~ 4 months 3.75 - 7.5 MA/2.65T D, H-mode 50 s

FPO-2 to FPO-3

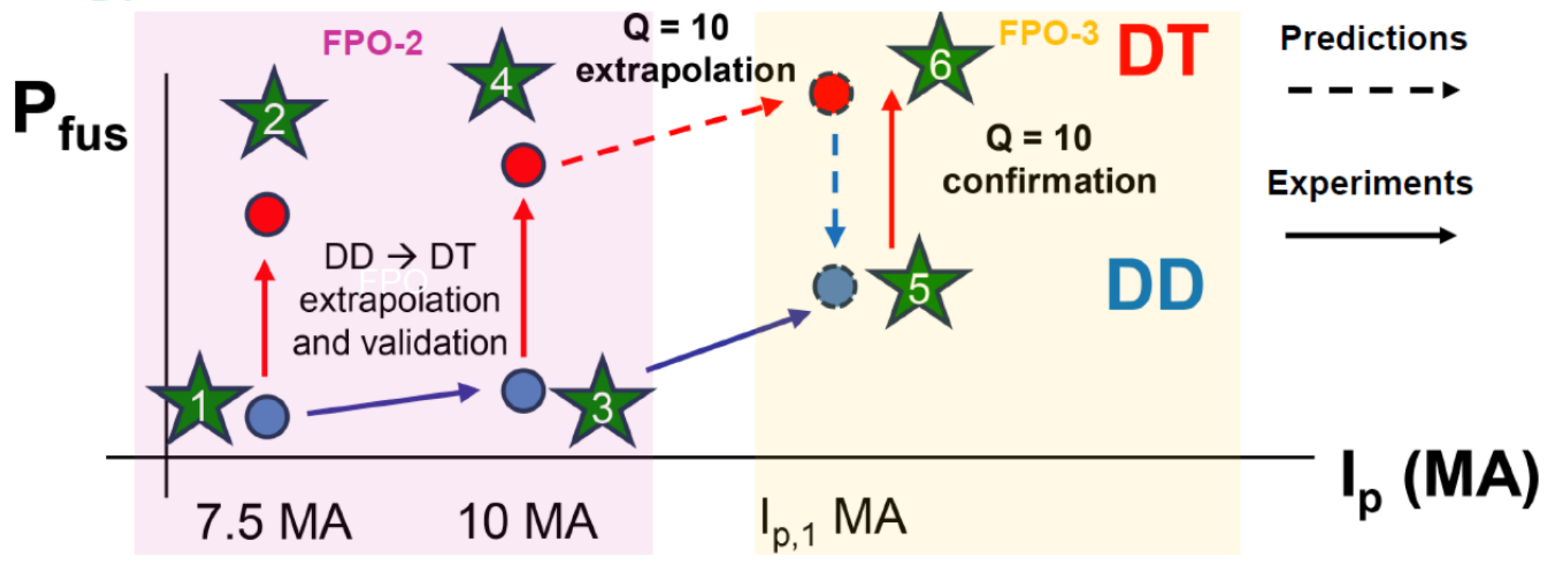
- ✓ Test long pulse system capabilities (in H L-modes) in advance of Q≥10, t_{burn}≥300 s
- ✓ Gradual increase of I_p at 5.3 T: minimize risks, determine τ_E (I_p) at q_{95} > 3)
  - Determine minimum I_p for Q ≥ 10 (i.e. scenarios with q_{95} >3 and H_{98} > 1)
  - Identify potential scenarios with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


FPO-2 (P_{fus} ≥ 100MW)
~ 2 months Commissioning H&CD t_{HCD} ≥ 600 s
~ 1.5 months 5.0-7.5 MA/5.3T D, 50 s
~ 5.25 months 7.5 MA/5.3T DT, 50 s
~ 2.months 10 MA/5.3 T D, 50 s
~ 5.25 months 10 MA/5.3T DT, 50s

FPO-3 (P_{fus} = 500MW)
~2 months Commissioning H&CD t_{HCD} ≥ 600 s
~ 4 months I_{p1} – I_{p2}/5.3T D, 50 s
~ 10 months I_{p2}/5.3T DT, 50s
- Q ≥ 10 P_{fusion} = 500 MW t_{burn} = 50 s
- First attempt to Q = 10 t_{burn} > 50 s

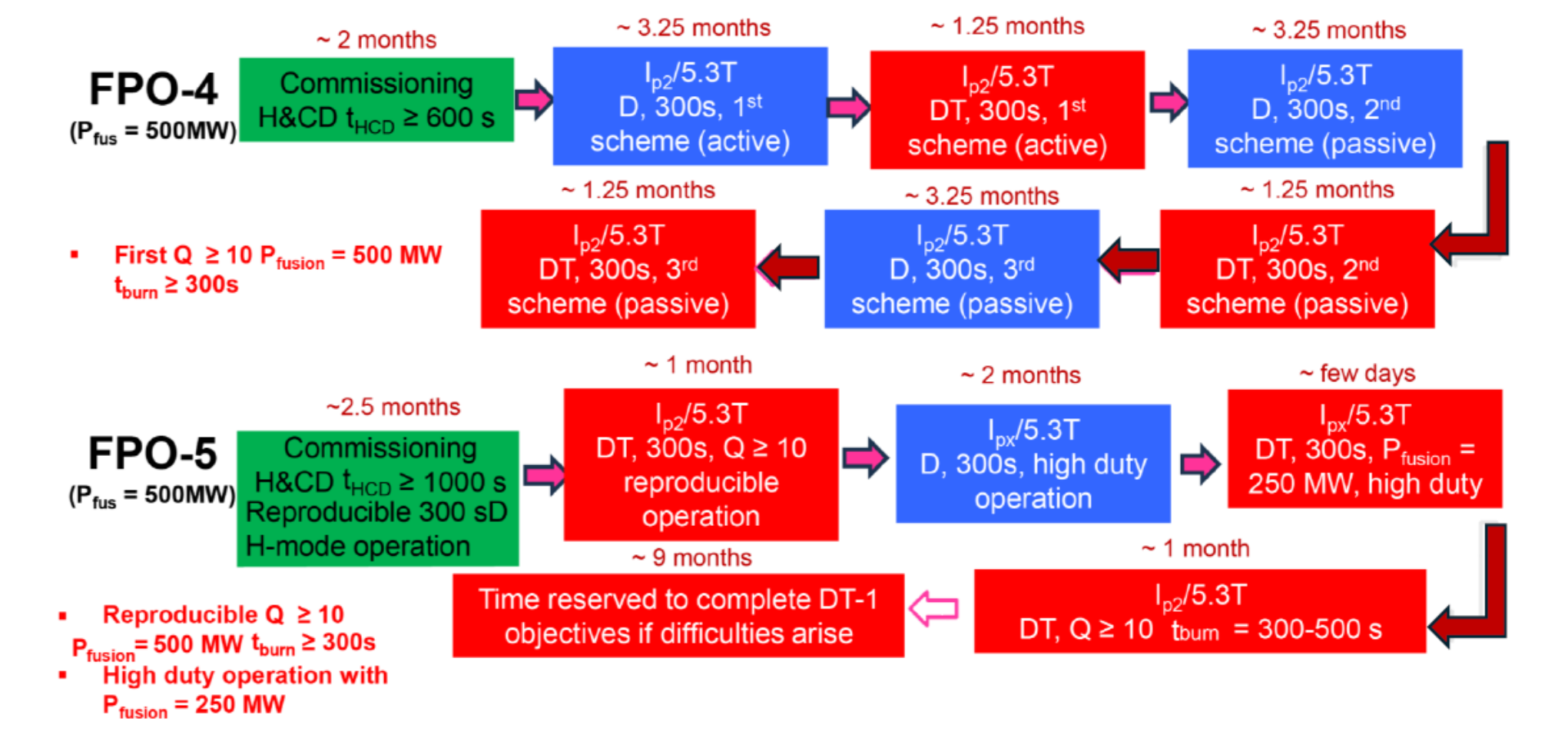
D and DT H-mode development strategy

- DT-1 fluence (3.5x10^{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



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 adapt 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


FPO-4 (P_{fus} = 500MW)
~ 2 months Commissioning H&CD t_{HCD} ≥ 600 s
~ 3.25 months I_{p2}/5.3T D, 300s, 1st scheme (active)
~ 1.25 months I_{p2}/5.3T DT, 300s, 1st scheme (active)
~ 3.25 months I_{p2}/5.3T D, 300s, 2nd scheme (passive)
~ 1.25 months I_{p2}/5.3T DT, 300s, 2nd scheme (passive)
~ 3.25 months I_{p2}/5.3T D, 300s, 3rd scheme (passive)
~ 1.25 months I_{p2}/5.3T DT, 300s, 3rd scheme (passive)
- First Q ≥ 10 P_{fusion} = 500 MW t_{burn} ≥ 300s

FPO-5 (P_{fus} = 500MW)
~2.5 months Commissioning H&CD t_{HCD} ≥ 1000 s Reproducible 300 sD H-mode operation
~ 1 month I_{p2}/5.3T DT, 300s, Q ≥ 10 reproducible operation
~ 2 months I_{px}/5.3T D, 300s, high duty operation
~ few days I_{px}/5.3T DT, 300s, P_{fusion} = 250 MW, high duty
~ 1 month I_{p2}/5.3T DT, Q ≥ 10 t_{burn} = 300-500 s
~ 9 months Time reserved to complete DT-1 objectives if difficulties arise
- Reproducible Q ≥ 10 P_{fusion}= 500 MW t_{burn} ≥ 300s
- High duty operation with P_{fusion} = 250 MW

Discussion and conclusions.

Duration of the shots at full power at SRO is limited by 30 s due to passive cooling of the wall

DD H-mode operation at the lowest densities at SRO is preferable for reduction of the neutron yield, ~10^{16} n/s

Predicted level of 14 MeV neutron yield at SRO does not exceed 6% of total flux.

Cumulated contribution of neutrons originated from interaction of fast ions accelerated by ICH minority heating with Boron B(p,n), B(^{3}He,n) is below 4% of total fluence during the SRO.

The results of this assessment are used to provide the background for the choice of plasma scenarios for the ITER Research Plan, within the limits of the neutron budget imposed for such operational phases, 1.5x10^{20}n for SRO and 3.5x10^{25}n for DT-1, and for associated assessments.

Presence of deuterium during hydrogen operation due to limited purity (n_D ~ 1.5 10^{-4} n_H) is negligible.

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