Optimisation of operational space for long-pulse scenarios

in support of ITER Physics Operation Workprogram (DT-phase)

Motivation

Long-pulse operation is attractive for a regular routine operation in ITER for the Test Blanket Modules (TBMs).

Predictive modelling is required to identify the optimal parameters the most comfortable for TBMs and comfortably far from the operational space boundaries.

Identification of the optimal parameters for such operation in ITER will help to organise experiments in present day machines in support of ITER long pulse scenarios. *(comments in Italic)*

Long-pulse operation is foreseen for support of DEMO program.

Proposals

(1) Assessment of operational space (OS) for long-pulse scenarios by 1.5D modelling

(2) Sensitivity studies of OS to model assumptions

Goal of simulations:

- **To identify the OS comfortable for regular ITER operation**
  (actually Hybrid in ITER definition but not necessary in terms of experimentalists);

- **To identify the sensitivity of OS for comfortable regular ITER operation to assumptions which are not inherent for the original validated models (taken from experiments);**

- **To identify the present day experiments, which have similar characteristics and can be used in support of regular ITER operation;**

- **To identify the OS suitable for DEMO support program**

(1) Assessment of operational space (OS) for long-pulse scenarios by 1.5D modelling

Scope of the task:

The OS for long-pulse scenarios should be assessed by 1.5D modelling with GLF23, MMM, B-GB, CDBM, etc. models validated in present day experiments;

- **The OS should be comfortable for TBM tests:**
  $P_{fus} \geq 250$ MW, $P_{fus}\Delta t \geq 200$ GJ, $\Delta t \geq 1000$ s;

- **The OS should be limited by comfortable control boundaries:**
  $P_{fus} \leq 500$ MW, $P_{SOL} \leq 110$ MW, $\Delta t \leq 3000$ s, $n/n_G \leq 1$, $n \geq n_{NB,shine} \sim 3\ 10^{19} m^{-3}$, $\beta_N \leq 4\ l_i$;

- **The pedestal parameters should fulfil peeling-ballooning stability limit**
  (my 1st guess is EPED1: $\beta_{N,ped} \sim const$, $\Delta_{ped} = 0.076\ (\beta_{p,e,ped})^{1/2}$);

- **The modelling should assume H&CD combination only from day 1 H&CD ITER set:**
  Set 1: 16.5 MW on-axis + 16.5 MW off-axis NBI, (*) (maximal Q, maximal I_{CD}/P_{aux})

  Set 2: Set 1+ 13.4 MW co- 6.7 MW ctr- ECCD (EL), located within x < 0.45, (**)

  Set 3: Set 2 + 20 MW ICRH/FWCD (***) (minimal Q, maximal I_{CD})

***) If both NBIs have the same tilting (both on-axis/both off-axis) excitation of TAE is very probable;**
****) It is not necessary to use the whole available power if it is not optimal;**
*****) It is useful to analyse what choice is preferable for $P_{fus}\Delta t \geq 200$ GJ, longer pulse or ion heating.**

- **The OS (at least OS boundaries) should be obtained for each of the H&CD sets in the range:**
  I_p = 8 -15 MA, n = 3 $10^{19} m^{-3}$ - n_G;

- **Simulations should include simulation of 1D heat transport, current density, and ash transport self-consistently with 2D equilibrium with full field, full bore, fixed boundary at current flat-top phase.**

- **Simulations also can include 1D transport of particle density (electron, ion, impurities), and momentum transport if such transport is well described by the validated model. Otherwise density profiles should be prescribed and momentum transport simulated with $\chi_\phi = \chi_\iota$, and later should be included in the sensitivity studies, provided it affects the results.**

- **The output should include for each of the models:**
  Boundaries of the OS, I_p,n for each set of H&CD;
  H-mode quality, P_{SOL}/P_{LH};
  Fusion gain factor, Q;
  Confinement quality, $\tau_E/\tau_{E,y2,98}$;
  TBM relevant parameters, P_{fus}, $P_{fus}\Delta t$, Δt;
  Proximity to comfortable control boundaries, $P_{SOL}/100$, n/n_G, β_N, β_p, l_i, $\beta_N /4l_i$
  Characteristics of profiles, $q(0)/q_{min}/q_{95}$, A(0)/<A>, $A(0)/A_{ped}$ (A = p,T_e,T_i,n_e)
  Pedestal characteristics, $\beta_{N,ped}$ Δ_{ped} , $\beta_{p,e,ped}$, ν^*_{ped}, A_{ped} (A = p,T_e,T_i,n_e)

We do not require 100% of noninductive current neither q > 1 nor Q > 5!!!

(2) Sensitivity studies of OS to model assumptions

Scope of the task:

The sensitivity of OS for regular ITER operation to assumptions which are not inherent for the original validated models (are taken from experiments or were prescribed at phase (1) of the OS identification)

- **OS exercise (1) described above has to be repeated for variation of plasma density peaking (if it was assumed at (1))**
- **OS exercise (1) described above has to be repeated for variation of helium ash transport (if it was assumed at (1));**
- **OS exercise (1) described above has to be repeated for variation of contamination by high-Z Impurities (if it was assumed at (1))**
- **OS exercise (1) described above has to be repeated for variation of plasma pedestal parameters (if it was assumed at (1));**
- **OS exercise (1) described above has to be repeated for variation of plasma momentum transport (if it was assumed at (1) and affects the other transport coefficients);**

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Possible time breakdown:

2011	**Assessment of OS for long-pulse scenarios by 1.5D modelling**
2012-???	**Sensitivity studies**

(****) Almost everybody has GLF23 benchmarked with others, so it could be shared in community as the most time consuming, or taken by FASTRAN, (and ASTRA) which has special solvers to speed-up calculations (as far as I know FASTRAN calculates just final steady solution of GLF23. All other models are pretty fast.)

Why we can assume that such a space exists.

1) **Length of plasma current flat-top phase, Δt depends on plasma current, I_p , noninductive current, I_{NI} and resistivity, $Res(Z_{eff},T_e)$:**

$$V_{loop}\,\Delta t = (240 - 14\, I_p), \qquad (1)$$

$$V_{loop} = (I_p - I_{NI})\, Res(Z_{eff},T_e) \qquad (2)$$

=> $I_p = (240 + I_{NI}\, \Delta t\, Res(Z_{eff},T_e))/\, (14 + \Delta t\, Res(Z_{eff},T_e))$

2) **If our model describes ITER reference scenario, I_p = 15 MA, Δt = 400 s, then:**

$$V_{loop} = (240 - 14 \times 15)/400 = 3/40\ V, \qquad Res(Z_{eff},T_e) = 3/40/(15 - I_{NI})$$

=> $I_p = (240 + I_{NI}\, \Delta t\, 3/40/(15 - I_{NI}))/\, (14 + \Delta t\, 3/40/(15 - I_{NI}))$ **(3)**

3) **If the model is stiff, it depends only on pedestal (does not depend on q, I_p) Then if we reduce I_p, $Res(Z_{eff},T_e)$ = const, I_{NI} does not decrease.**

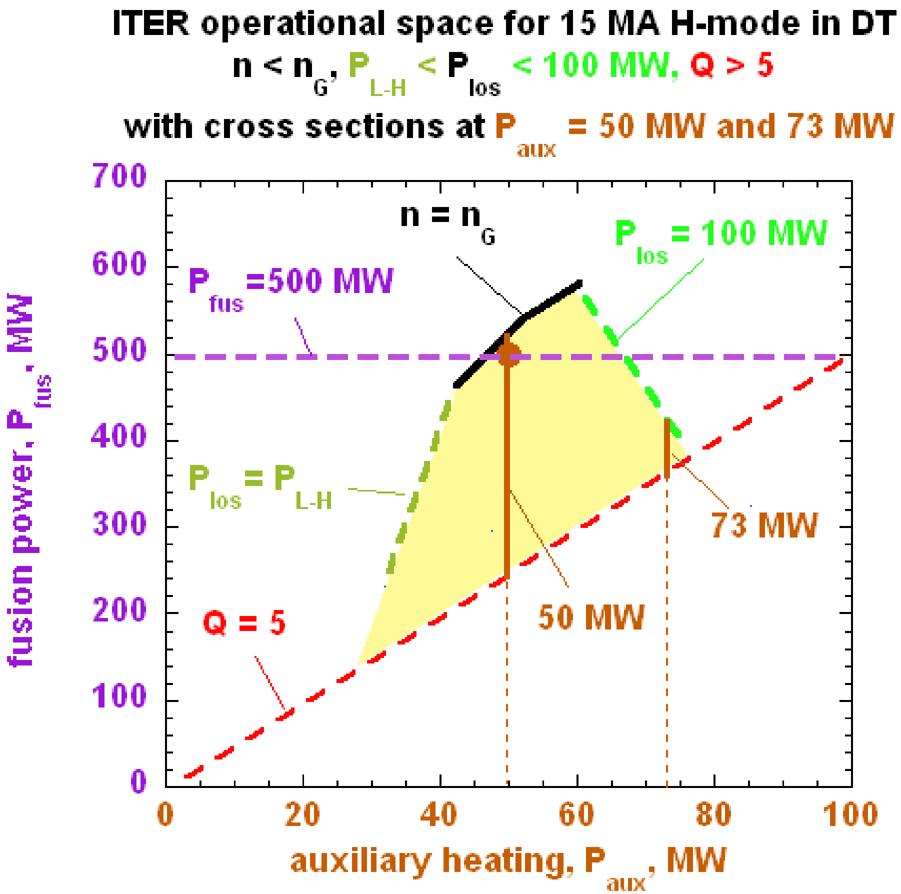
Example: I_{NI} = 5 MA =>

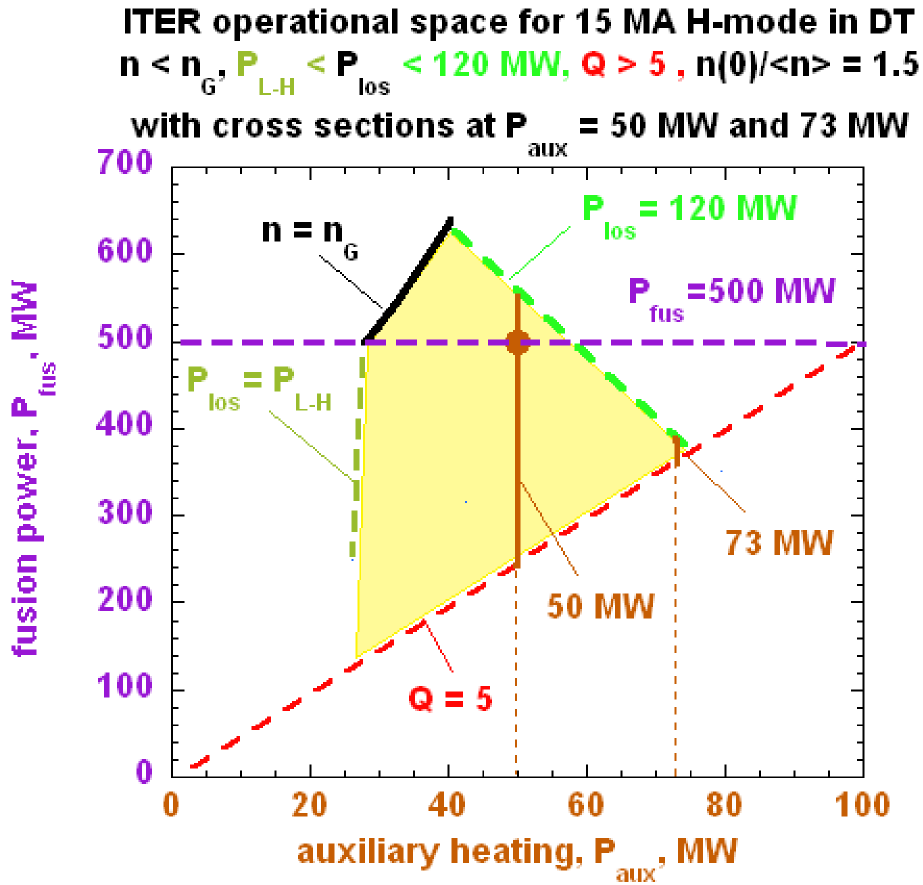
$I_p(\Delta t$=1000s)=12.9 MA

$I_p(\Delta t$=3000s)=9.65 MA

EXAMPLES OF CROSS SECTIONS OF THE OPERATIONAL SPACE
(Sensitivity studies)

INDUCTIVE SCENARIOS fixed: I_p=15 MA, $H/H_{y2,98}$ =1 variable: P_{aux}, n



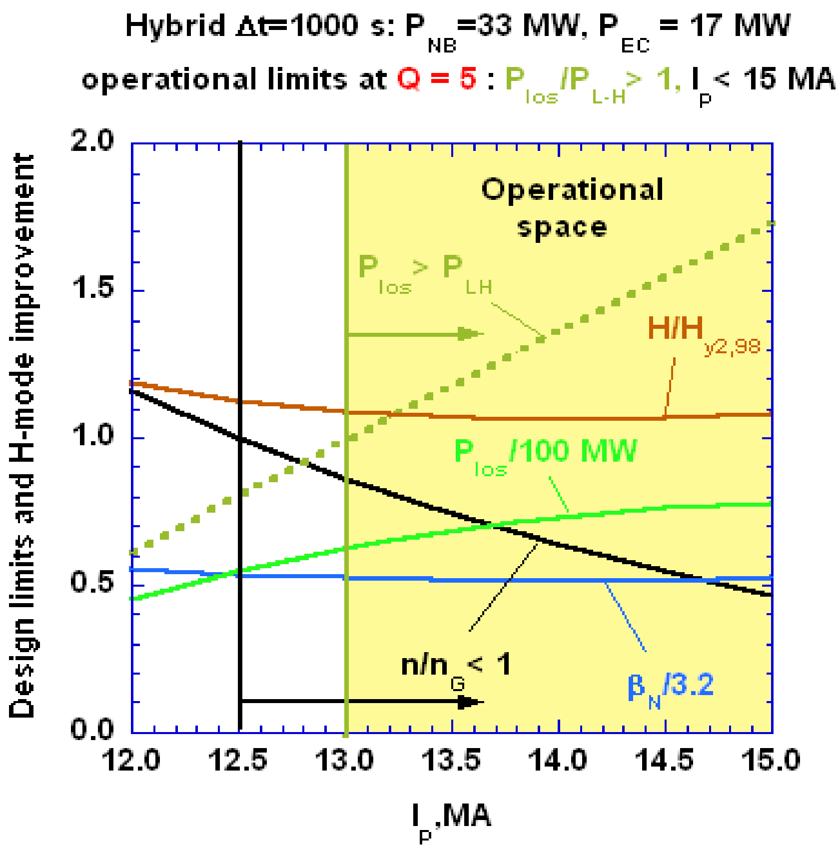


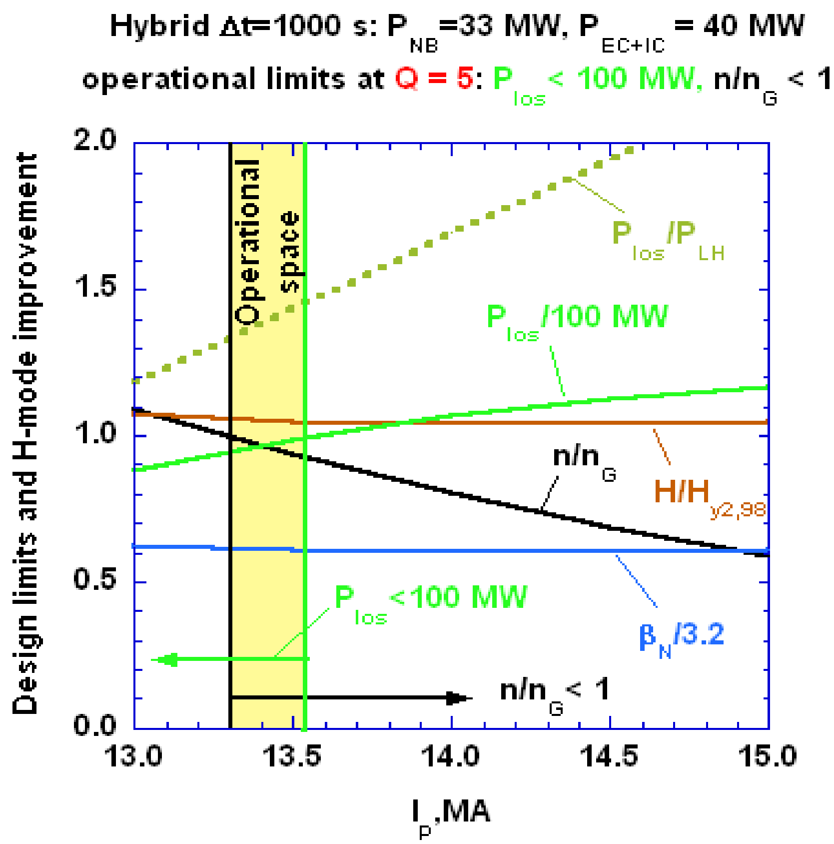
Flat density: n(0)/<n> ~1.1 **Peaked density: n(0)/<n> ~1.5**

- **Operational boundaries depend also on density profile shaping**
- **Operational space shrinks for high P_{aux} due to P_{los} < 100 MW**

HYBRID SCENARIOS fixed: Δt =1000 s, P_{aux}, q_{min} = 1, Q = 5 variable: I_p

P_{aux} = 50 MW (NBI:EC=33:17) **P_{aux} = 73 MW (NBI:EC:IC=33:20:20)**

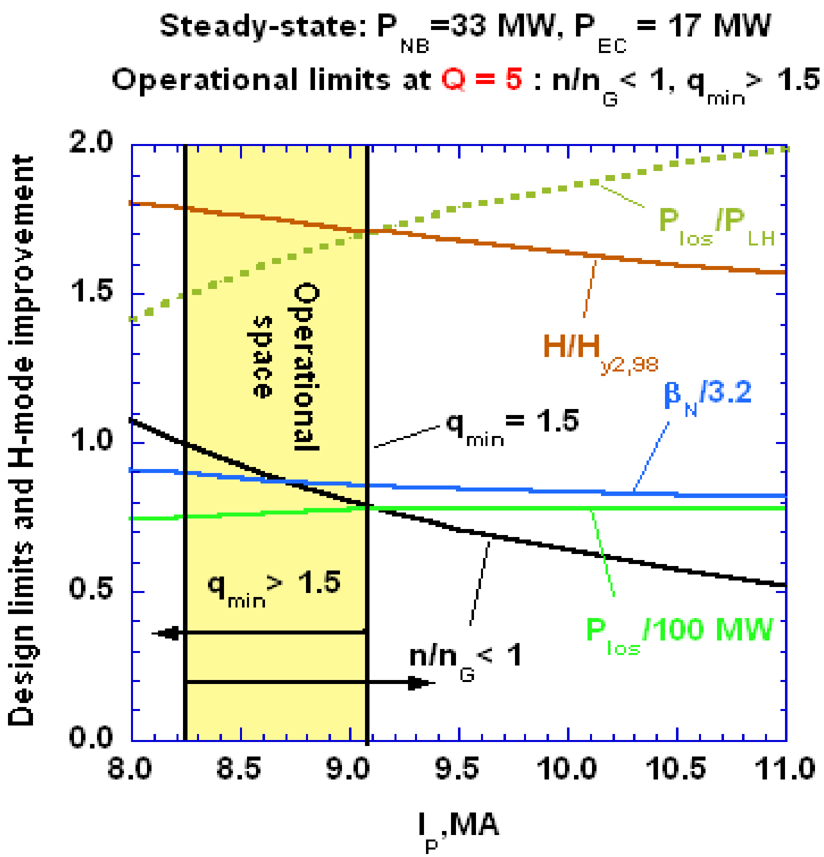




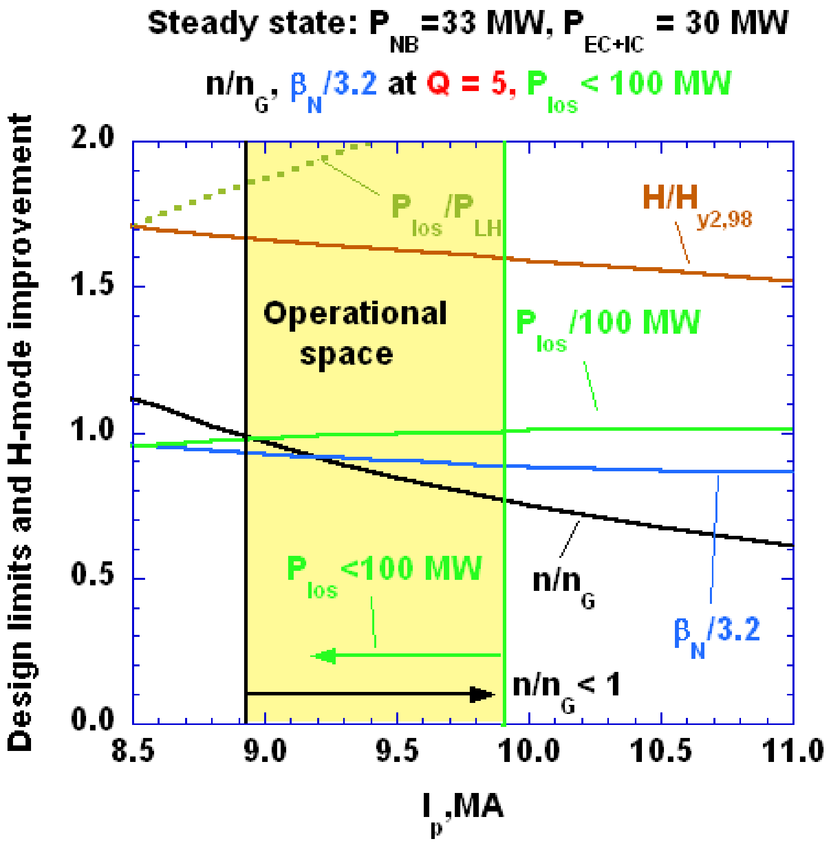
Hybrid scenarios with Q = 5, Δt= 1000 s, P_{fus}= 250-365 MW (P_{aux}= 50-73 MW) are possible for H ~1-1.1, P_{los}/P_{L-H} ~ 1-1.5 , n/n_G ~ 0.5 – 1, q_{95} ~ 3 - 3.7, i.e. in the ordinary Type-I H-mode regimes!!!!

STEADY STATE SCENARIOS fixed $\Delta t^{-1} = 0$, P_{aux}, q_{min}= 1.6, Q = 5 variable: I_p

P_{aux} = 50 MW (NBI:EC=33:17)

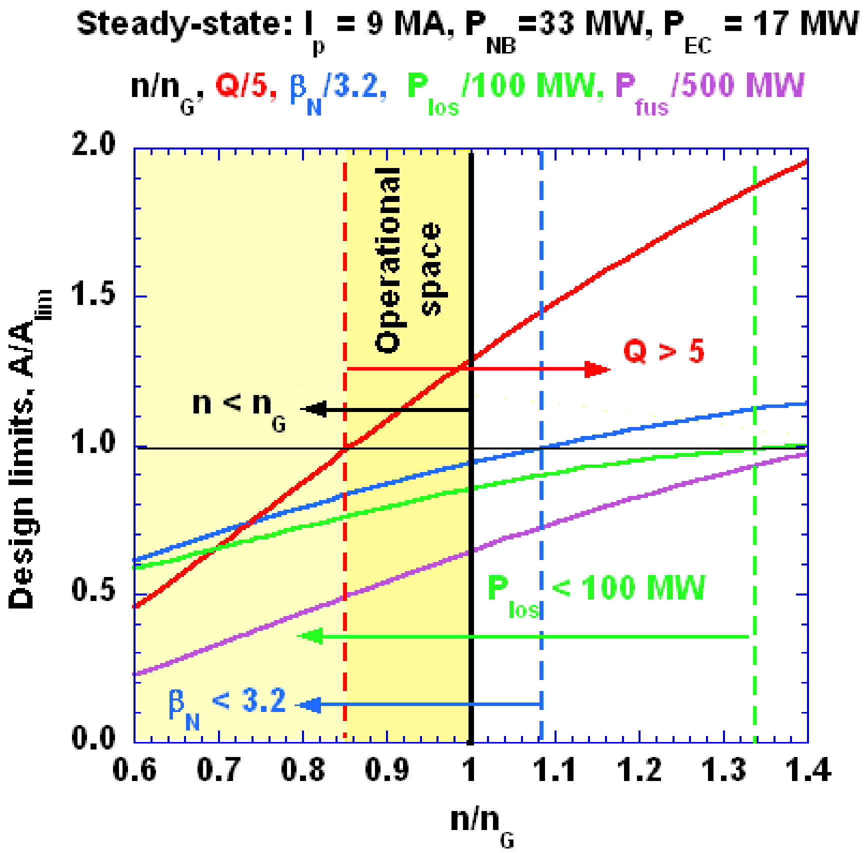


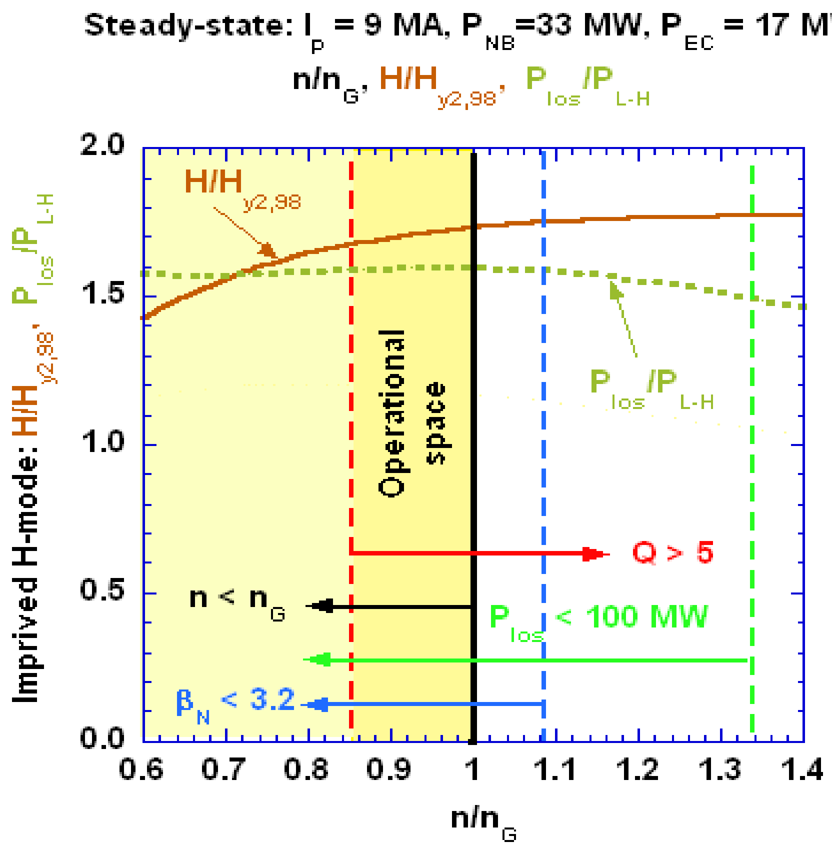
P_{aux} = 63 MW (NBI:EC:IC=33:17:10)



- **Operational limits: n/n_G< 1, q_{min}> 1.5, P_{aux}< 63 MW (P_{loss} < 100 MW)**
- **Operational range: P_{fus}=250-315 MW, $P_{los}/P_{L\text{-}H}$~1.5-2, q_{95}~5-6, H~1.5-1.8, n/n_G~0.8-1**

STEADY STATE SCENARIOS fixed: $\Delta t^{-1} = 0$, P_{aux}, q_{min}= 1.6, I_p= 9 MA variable: n





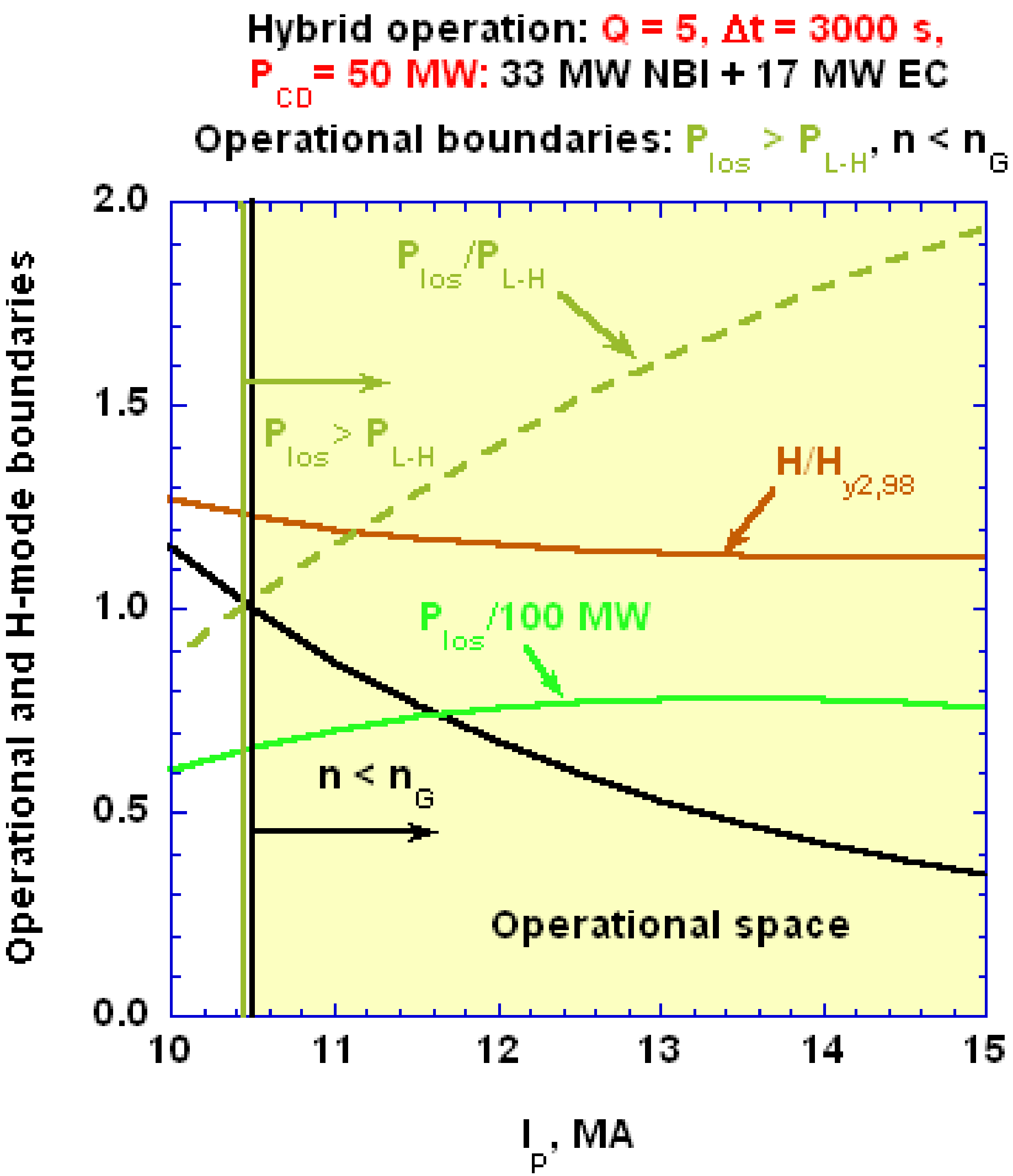
Operational space boundaries:

n/n_G<1, Q > 5

Transport features required for SS:

$H/H_{y2,98}$ ~ 1.7, P_{los}/P_{L-H} ~ 1.6

Increased density n/n_G<1 is required to keep Q = 5, q_{min}> 1.5 if extra EC power is needed for NTM stabilisation at q=2. For baseline operational point we assume $P_{EC,NTM}$ = 4 MW.


Hybrid operation: Q = 5, Δt = 3000 s,
P CD = 50 MW: 33 MW NBI + 17 MW EC
Operational boundaries: P los > P L-H, n < n G
P los/P L-H
P los > P L-H
H/H y2,98
P los/100 MW
n < n G
Operational space
Operational and H-mode boundaries
I P, MA
2.0
1.5
1.0
0.5
0.0
10
11
12
13
14
15