H, He and DD operational space and sensitivity studies

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ABSTRACT

The results of assessment of stationary Type-I ELMy H-mode operation in H, D and He plasmas studied by 1.5D modeling is presented. Sensitivity studies are carried out. Possible extension of the operational space (OS) is discussed. List of issues for further studies (by IOS TG?) is proposed.

OUTLINE

- **H-mode OS: benefits, issues, back-up solutions:**
  - **Hydrogen**
  - **Helium**
  - **Deuterium**
- **Summary**
- **Discussion**

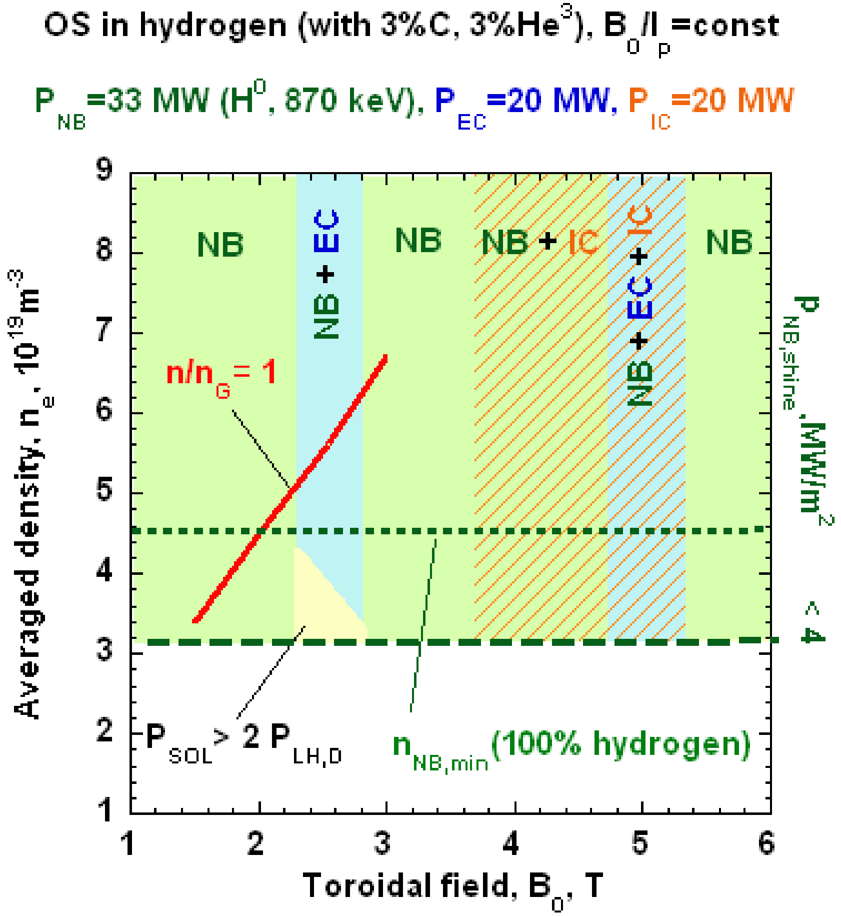
Hydrogen plasma: Benefits

Independent core fuelling and divertor control:

At high power, P_{SOL}= 50-100 MW predicted core fuelling from gas puffing is small, S_{core}< 10 Pa m^3/s [2]

Gas puffing is used to control the divertor load, q_{pk}<10 MW/m^2 and to avoid the plasma detachment, $\mu \leq 1$

Density control in the core can be provided by High Field Side (HFS) injection of hydrogen pellets



Type-III ELMy H-mode: P_{SOL}> 2 $P_{L-H,D}$

Full bore plasma [1]

Hydrogen plasma: Issues

I. Power deficit for “good” H-mode:

High L-H threshold: $P_{L\text{-}H,H} = 2\ P_{L\text{-}H,D}$

Reduced power: $P_{aux} < 20 + 33$ MW (EC + NB) no ICRH for B = 2.65 T

II. High NBI shine-through density limit: $P_{NB,load}(n_{NB,min}) = 4\ \mathrm{MW/m^2}$

$n_{NB,min} \sim 4.5\ 10^{19} \mathrm{m^{-3}}$ (for E_b = 870keV in 100% hydrogen plasma)

$n_{NB,min}$ can be reduced by impurity seeding (at $Z_{eff} \sim 2$)

$n_{NB,min}$ can be reduced by the NB energy reduction,
E_b = 870-740 keV, but with further reduction of power, P_{aux}: $P_{NB} \sim E_B^{2.5}$

III. More demanding fuelling requirements: $\tau_p \sim \tau_E \sim 0.16\ \tau_{E98,y2}$?

0.16 = 0.65 x 0.5 x 0.5 (Hydrogen x half current x L-mode)

Type-I ELMy H-mode looks unlikely.

Back-up solution: Operation in He

Helium plasma: Benefits

I. Full installed power operation

$P_{aux}< 20 + 20 + 33$ MW (IC + EC + NB)

II. Lower L-H threshold:

$P_{LH,He}= 1 - 1.4\ P_{LH,D}$

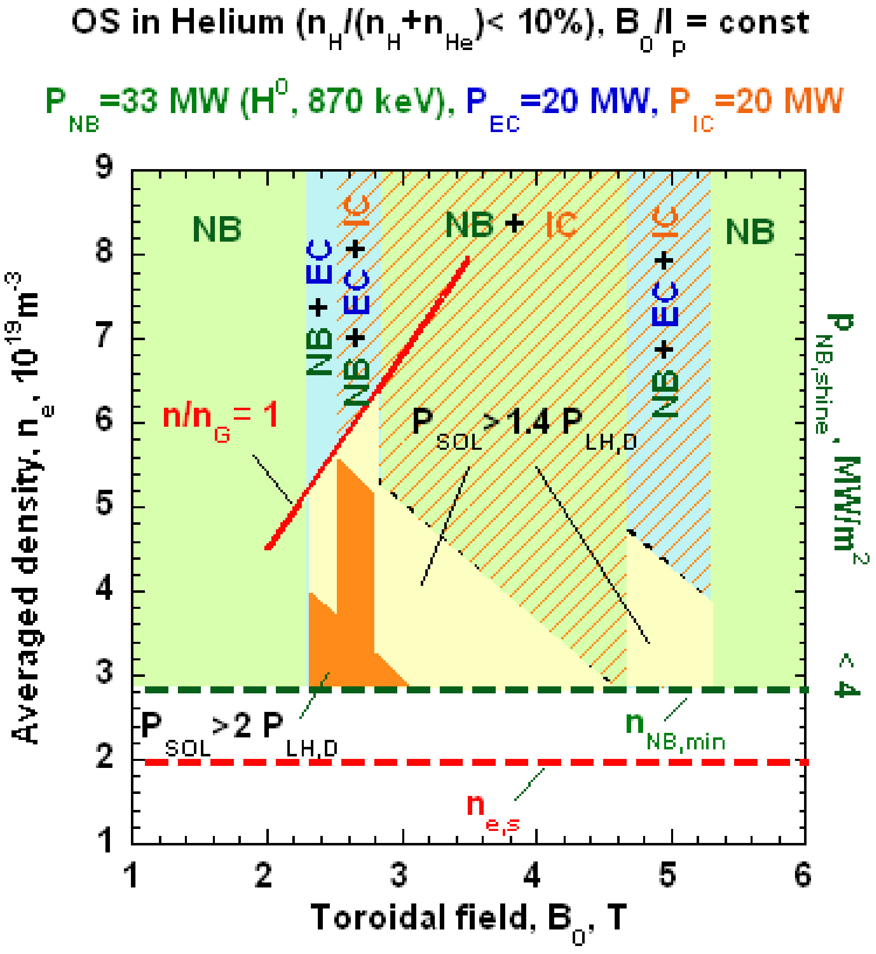
III. Lower shine-through limit

$n_{NB,min}$~$2.9\ 10^{19}m^{-3}$ for E_b= 870keV

IV. OS for Type-I ELMy H-mode:

$P_{SOL} > 1.4\ P_{LH,He} = 2\ P_{LH,D}$:

$n_{NB,min}$~ $2.9 - 5.3\ 10^{19}m^{-3}$



Type-I ELMy H-mode: $P_{SOL}> 2\ P_{L\text{-}H,D}$

Full bore plasma, 100% He [1]

Helium plasma: Issues

I. Low edge density:

$n_{e,s}$~ 2 $10^{19}m^{-3}$ for fuelling by He only. (SOLPS [2])
An anomalous pinch is required to provide n > $n_{NB,min}$ in 100% helium or extra core fuelling by pellets (see next)

II. Capability of density control is limited.

Density increase for He puffing is limited by detachment, $\mu \leq 1$, and for hydrogen pellets/puffing it is limited by He dilution. (no He pellets).

III. He dilution by hydrogen

increases shine-through and P_{L-H} from the H^0-NBI heating and in the cases if pellet fuelling is required to provide acceptable shine through (small pinch), and for ELM pacing .

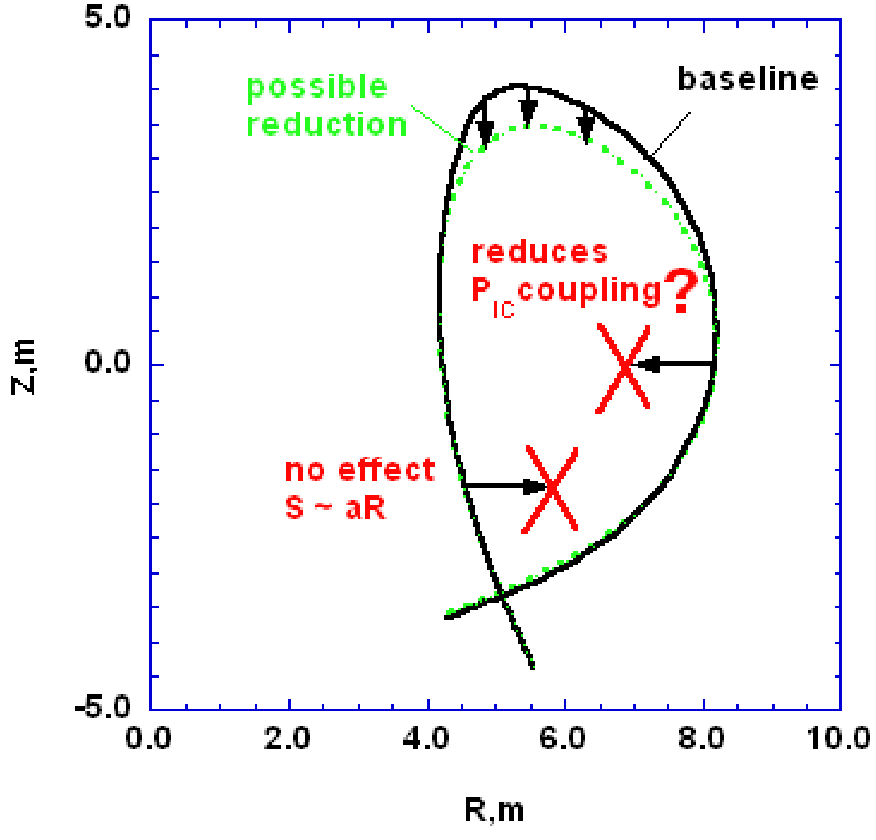
IV. Heating control

Could be complicated in case of possible synergy of H-NBI and ICH

Back-up solutions:

- Plasma shaping (reduced P_{L-H} ~ S by size reduction) [9]
- Transient H-mode [2]
- DD operation

Type-I ELMy H-mode Operational Space: scan of shape and power



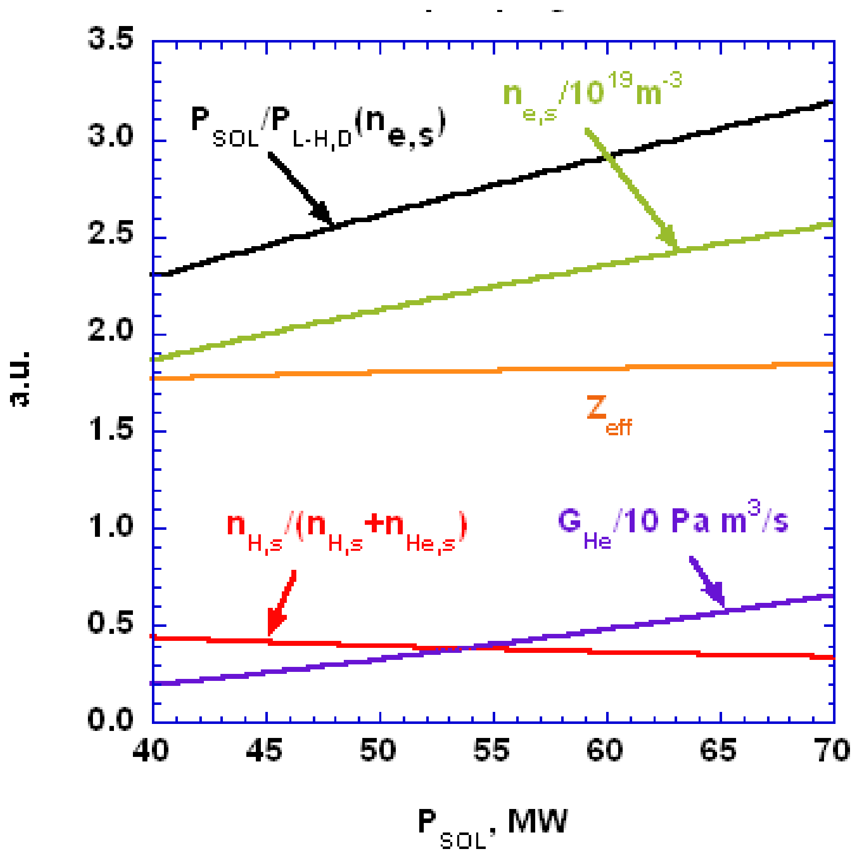
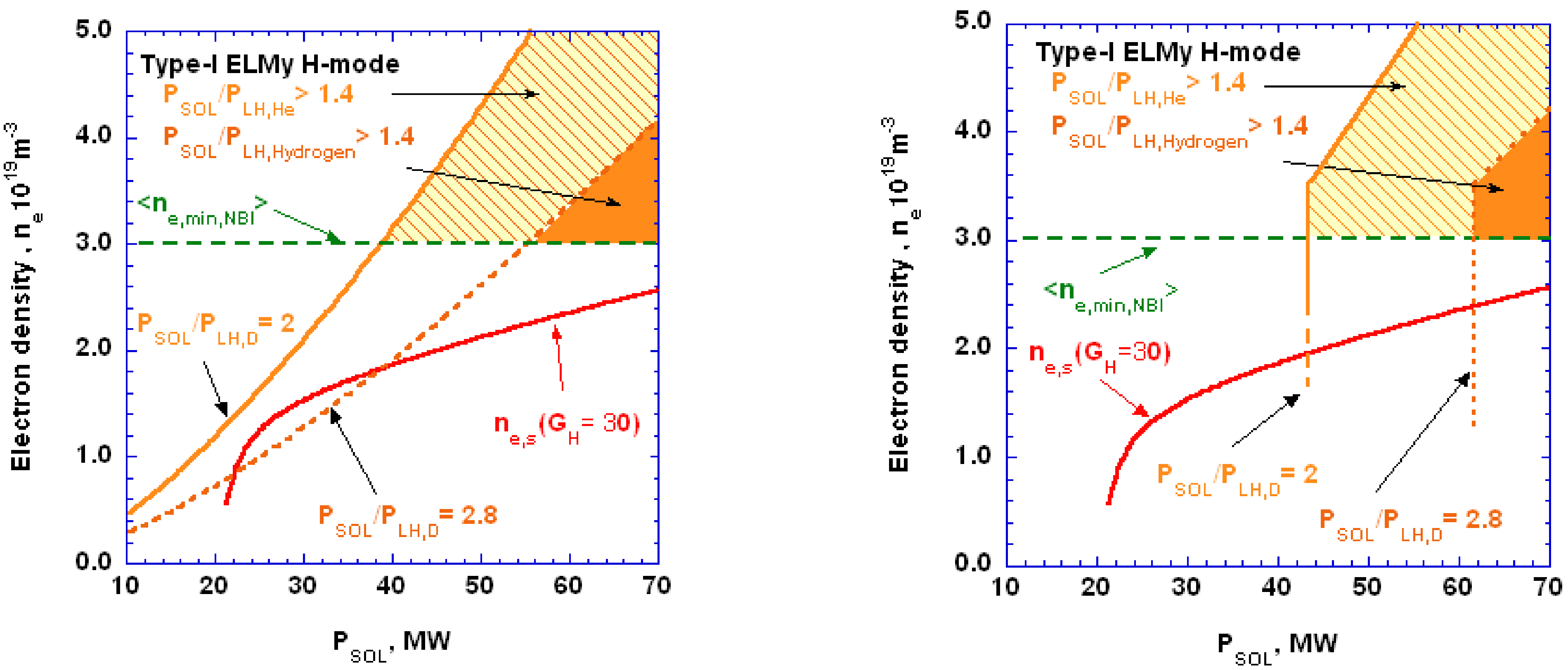


Fig. 1 Maximal possible reduction of power threshold by plasma shaping. Current is reduced from I_p= 7.5 MA to I_p= 6.5 MA to keep q95 > 3 at B_0 = 2.65 T.

Fig. 2 Separatrix densities, $n_{e,s}$, $n_{He,s}$ $n_{H,s}$, and helium source in the core, G_{He} depend on power, P_{SOL} (SOLPS [2]).

Maximal OS for Type-I ELMy H-mode with He+H:

Minimal S (fig.1) + parameters from (fig.2). $<n_{e,min,NBI}>$ for 0.87 MeV H^0-NBI.



a) scaling [8] $P_{LH} \sim B^{0.8} S^{0.94} n^{0.7}$

b) saturated $P_{LH,min} = P_{LH}(n = 3.5\ \ 10^{19} m^{-3})$

Fig. 3 $P_{SOL} > 1.4$ $P_{LH,He+H}$ = (2 - 2.8) $P_{LH,D}$ = (100%He - 100%H)

a): $P_{SOL,min}$ ~ 36 MW (100%He) - 55 MW (100%H)

` b): $P_{SOL,min}$ ~ 43 MW (100%He) - 62 MW (100%H)

Type-I ELMy H-mode Operational Space for He dilution by hydrogen

ASDEX-U experiments (fig. 5):

F. Ryter, 2010

For moderate dilution by hydrogen,

$f_H = n_H/(n_H + n_{He}) < 40\%$

$f_{He} = n_{He}/(n_H + n_{He}) > 60\%$

For dominant heating of electrons

ECRH

P_{LH} dependence on dilution is week:

$P_{LH}(f_{He}=0.6) \sim 1.2\ P_{LH,He}(f_{He}=1)$

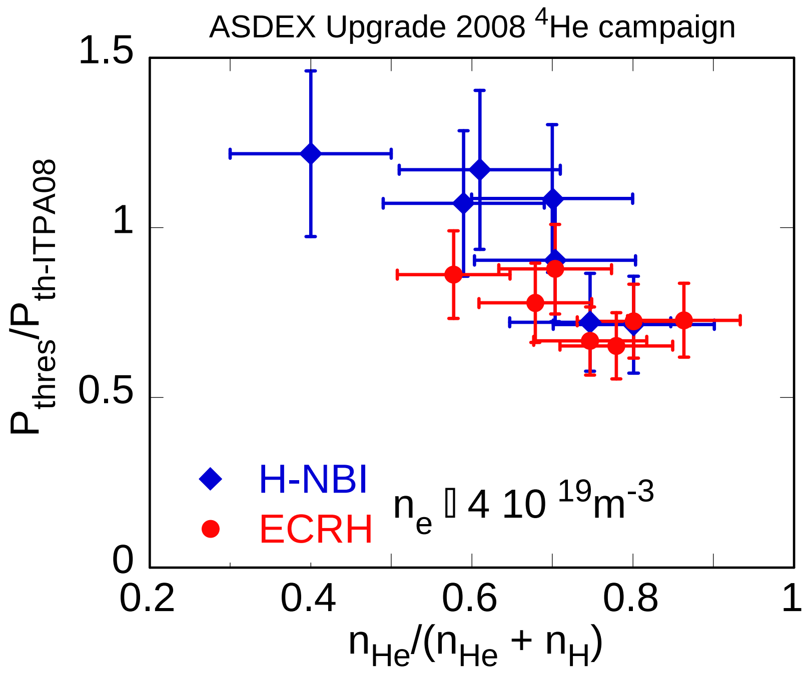


Fig. 5 $P_{L\text{-}H,He}$ normalized to $P_{L\text{-}H,D}$ [8]

In ASDEX-U experiments for conditions similar to ITER, dependence of the L-H threshold on dilution is weak.

If auxiliary power is insufficient for Type- I ELMy H-mode in He + H:

Backup solutions: (1) Transient H-mode considered in [2],

(2) DD operation [considered below]

DD plasma: Benefits

I. Full installed power operation

$P_{aux} < 20 + 20 + 33$ MW (IC + EC + NB)

II. Lower L-H threshold:

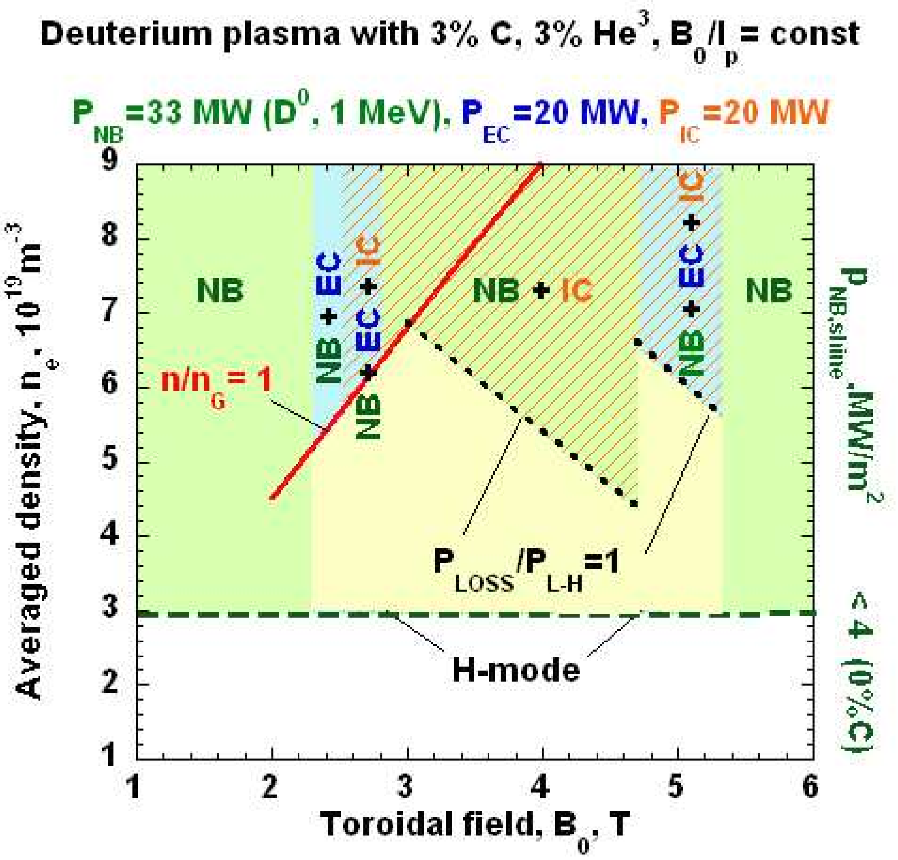
$P_{LH} = P_{LH,D}$

III. Low shine-through for D^0-NBI

$n_{NB,min} \sim 3\ 10^{19} m^{-3}$ for $E_b = 1$ MeV

IV. Independent core fuelling (by pellets) and divertor control (by puffing)

V. Wide H-mode OS



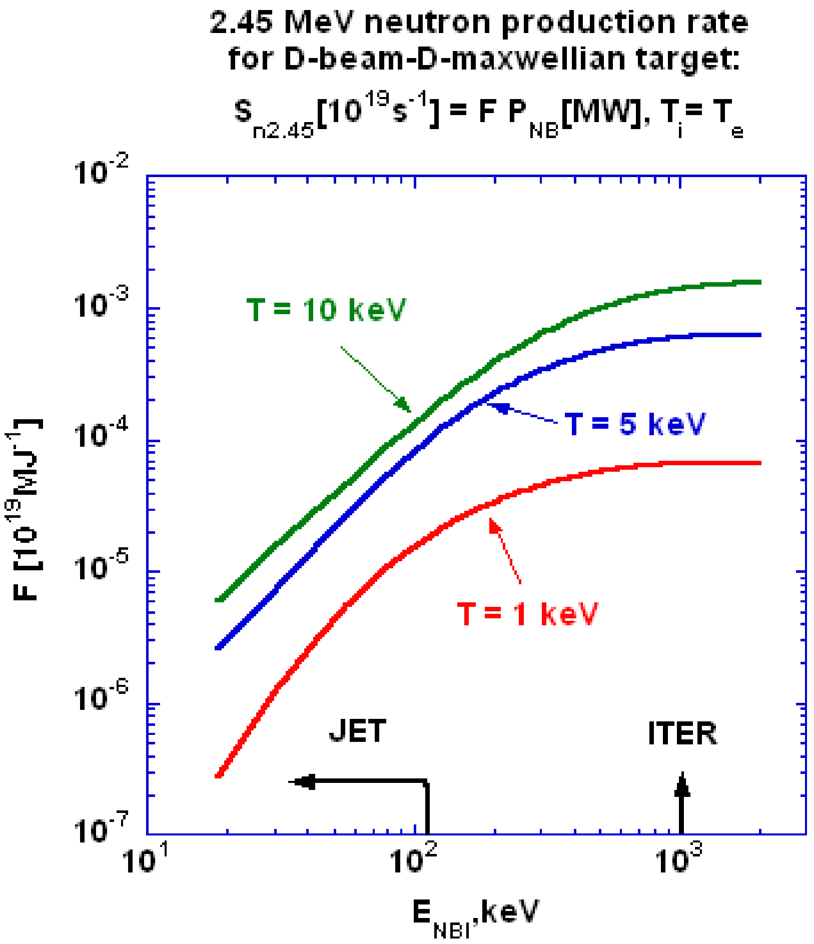
H-mode OS: $P_{SOL} > P_{L-H,D}$

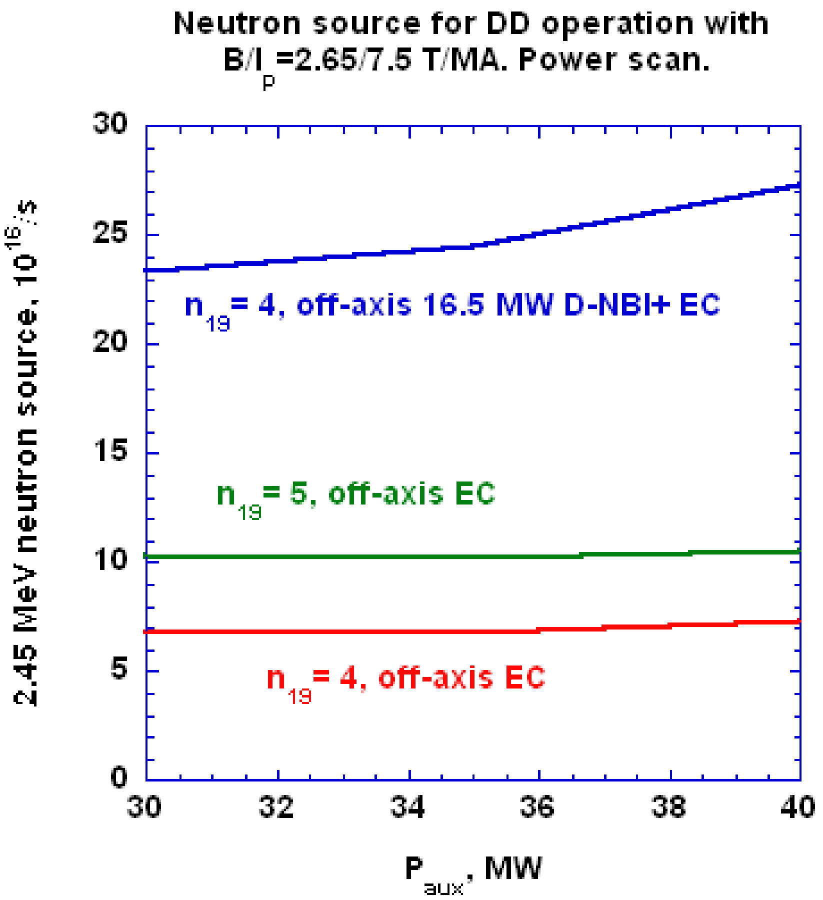
Full bore plasma [1]

Goal for pre-DT commissioning in D: Type-I ELMy H-mode with minimal neutron yield => short pulse, half-filed (minimal power)

Pre-DT commissioning in DD plasma: Issues

I. High neutron/tritium yield, $S_t \approx S_n$ in fusion reaction: D_{beam}-$D_{thermal}$:





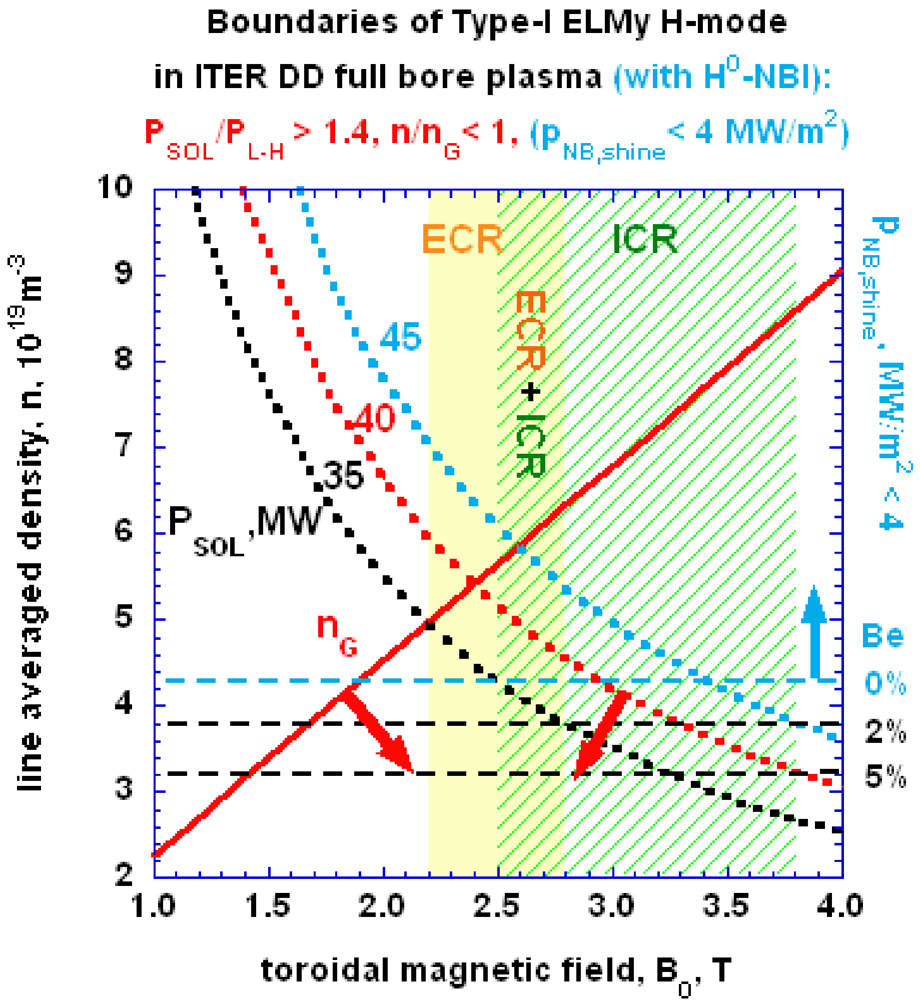
> 10 times higher than in JET

> 3 times higher than w/o D-NBI

Backup solution: Replace D^0-NBI by H^0-NBI

Pre-DT commissioning in DD plasma: Issues

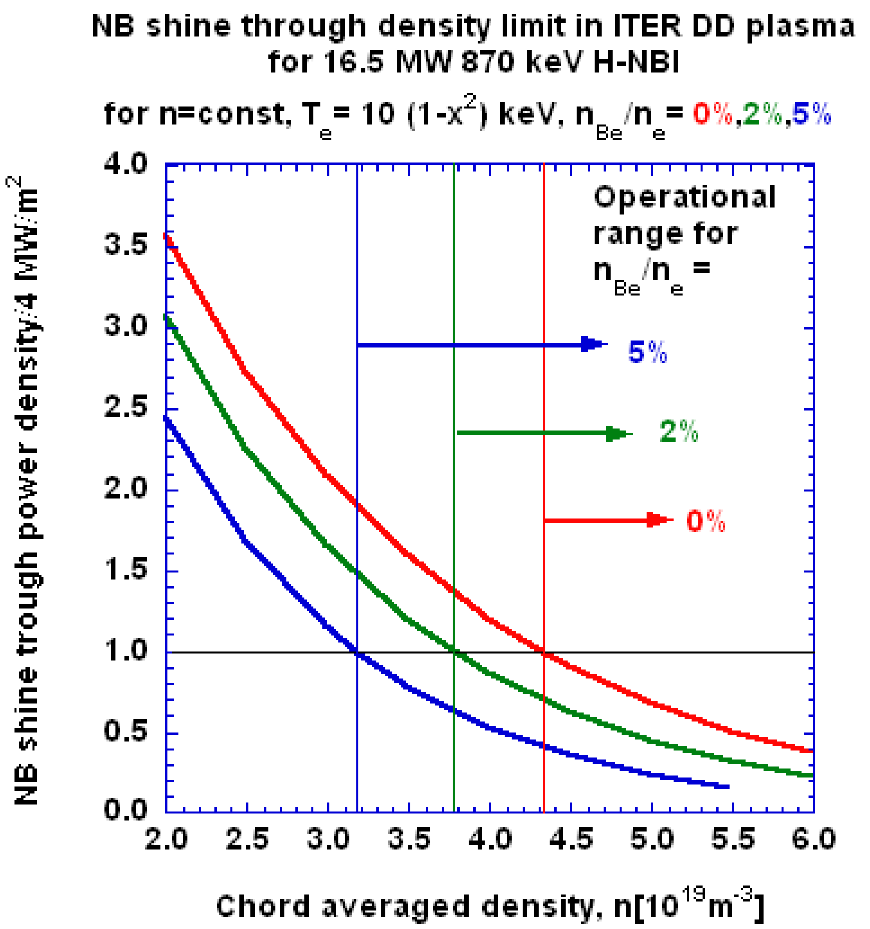
II. Low P_{SOL} w/o NBI ($P_{SOL}< 0.9\ P_{aux}$), high shine-through for H^0-NBI



Boundaries of Type-I ELMy H-mode

in ITER DD full bore plasma (with H^0-NBI):

$P_{SOL}/P_{L-H} > 1.4$, $n/n_G < 1$, ($p_{NB,shine} < 4$ MW/m^2)



NB shine through density limit in ITER DD plasma for 16.5 MW 870 keV H-NBI

for n=const, $T_e = 10\ (1-x^2)$ keV, n_{Be}/n_e = 0%,2%,5%

Low $P_{SOL,RF} < P_{EC+IC} \leq 40$ MW

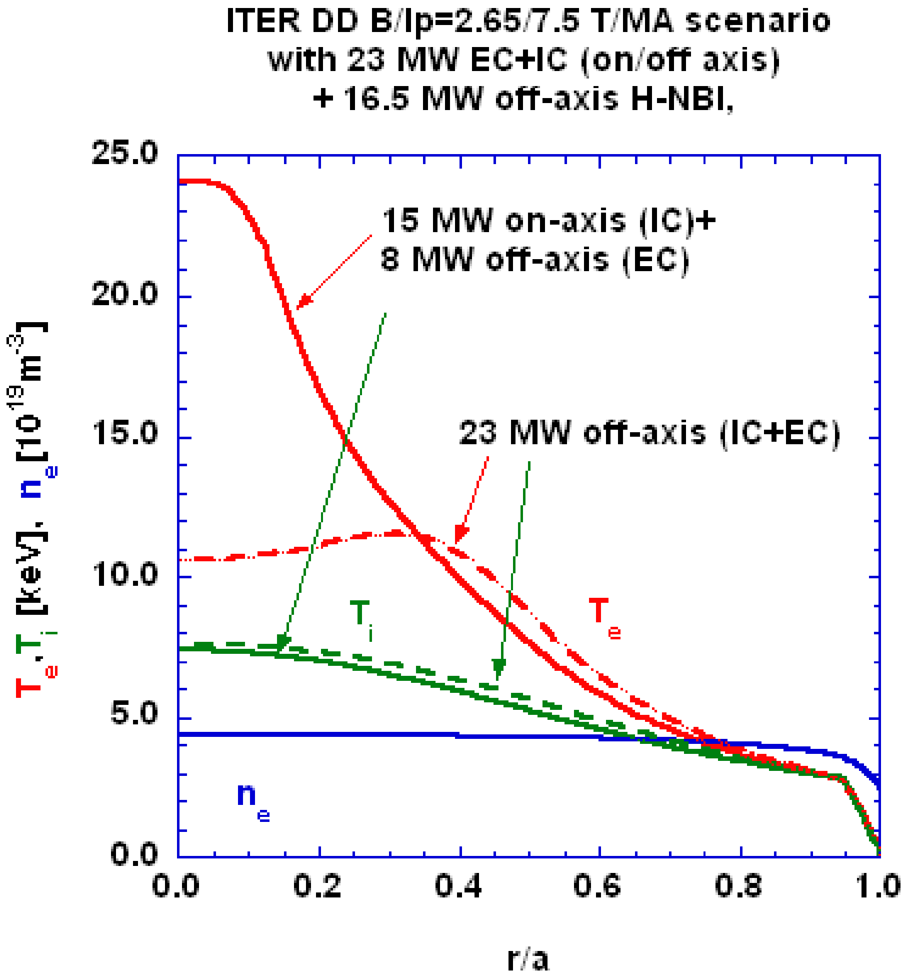
Backup: H^0-NBI is required

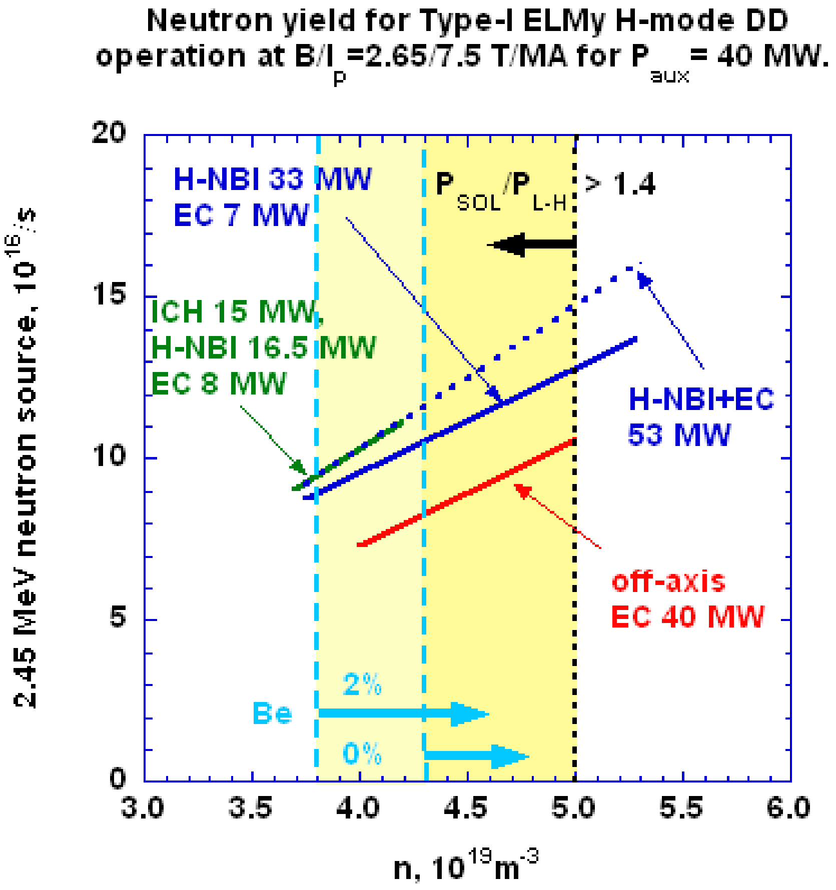
High NBI shine-through for H^0-NBI

Backup: Seeding by Be would help

DD plasma: Sensitivity studies - I

Heating mix, power, deposition and density scan: $S_t \approx S_{n2.45}$~1-1.5 $10^{17}s^{-1}$





See more in the table below

DD plasma: Sensitivity studies – II

Comparison of neutron yield with reference case (=) in the range of uncertainty

n_{19},m^{-3}	n_0/n_p	EC, MW		NBI, MW		χ_i/χ_e	mode	S_t,10^{16}/s	S_n,10^{16}/s
		on-ax.	off-ax.	H^0	D^0				
4	1.25	0	40	0	0	2	H	7	7.3
=	=	15	25	=	=	=	=	6.4	6.7
=	=	15	25	=	=	1	=	7.9	8.3
=	1.8	=	=	=	=	=	=	9.8	10.4
=	=	=	23.5	=	16.5	=	=	23	27
4.2	=	=	23	16.5	=	=	=	8.3	8.8
4.2	=	15	8	16.5	=	=	=	7	7.4
=	=	=	4	=	=	=	L	0.58	0.58
=	=	=	=	=	=	=	OH	0.017	0.017
3	=	=	=	=	=	=	OH	0.031	0.031

Summary - I (issues for R&D and simulations are highlighted)

Hydrogen

- Commissioning of NBI at full power in hydrogen is possible if fuelling can provide $n > n_{NB,shine}$ (~ $4.3\ 10^{19} m^{-3}$ for 100% H) (high fuelling demanding?

- Type-III ELMy H-mode would be possible in half field case if Sh-thr. density can be reduced to $n_{NB,shine}$~$3\ 10^{19} m^{-3}$ by impurity seeding

Summary - II (issues for R&D and simulations are highlighted)

Helium

- Boundary density is governed by DIV control. W/o anomalous pinch density by SOLPS is not sufficient to inject 16.5 MW NBI in 100% He. In this case fuelling by hydrogen in He is required.
- LFS ELM pacing by hydrogen pellets dilutes He by residual fuelling and recycled hydrogen
- Type-I ELMy H-mode is more likely at half-field with reduced k and I_p even in He + H if $P_{NBI} + P_{EC} + P_{IC} > 60$ MW. (P_{IC} coupling?)
- Dilution by hydrogen increases NBI shine through loss and $P_{L\text{-}H}$. Dedicated experiments to define limitation are required.
- Anomalous particle pinch (if any) increasing density increases power required for Type-I ELMy H-mode
- Possible synergy of IC and H-NBI can affect control Purely IOS task!

Summary - III (issues for R&D and simulations are highlighted)

Deuterium

- DD operation in half-field will enable H-mode operation with smaller neutron and tritium production, than for full field: S_t, $S_n \sim 10^{17} s^{-1}$
- Ohmic operation at maximal density minimise S_t, S_n at current ramp-up
- Commissioning in Type-I ELMy H-mode in short pulses in DD looks possible for $n_e \sim 4\ 10^{19} m^{-3}$ provided P_{SOL}>40 MW. Thus, NBI is required.
- Neutron yield can be reduced by a factor of 3 using H^0-NBI instead of D^0-NBI.
- Usage of H^0-NBI increases the NBI shine through, shrinking the OS. Seeding by Be pellets (~ 5%) could help to recover the OS
- For short flat-top operation $\Delta t \sim 10$ s ratio D/χ becomes critical for scenario feasibility (both minority(=>heating) and fuel (=>neutrons)).
- Fraction of ion heating as a function of minority density for neutron yield reduction
- Possible synergy of IC and H-NBI (neutron yield) **Purely IOS task?**

DISCUSSION

Findings above should be taken into account in pre-DT scenario development (simulations)?

Issues should be addressed in the analyses of experimental data (new experiments/simulation with validated codes?):

(1) - Particle confinement: I_p scan, H, He, D plasmas, OH, L, H modes? All?

(2) - Particle transport: Dynamical experiments are required to assess D/χ for minority and fuel? Anomalous pinch (in He)? C-mod, …???

(3) - Residual fuelling from LFS pellets? DIIID, AUG, MAST, JET, …???

(4) - Dedicated experiments to define limit of He contamination by H for H-L transition in ITER like conditions (e-heating, pellet fuelling) same?

(5) - P_{IC} coupling for low densities in He (experiment? simulations?) ???

(6) - Optimization of P_{IC} to minimize ion heating. Goal opposite to DT!!

(7) - Development of DD scenarios with minimal neutron yield All?

(8) - Possible synergy between H-NBI & ICH PTRASP, TORIC, …?

BACKUP VIEWGRAPHS

(density vs heat transport, transport model, He plasmas, references)

Uncertainty of density transport:

Tritium puff experiments in JET (I. Voitsekhovitch, et al, PoP 12, 052508 s2005d, (see Fig.7):

Ratio (χ_i + χ_e)/D strongly depends on density and varies by an order of magnitude.

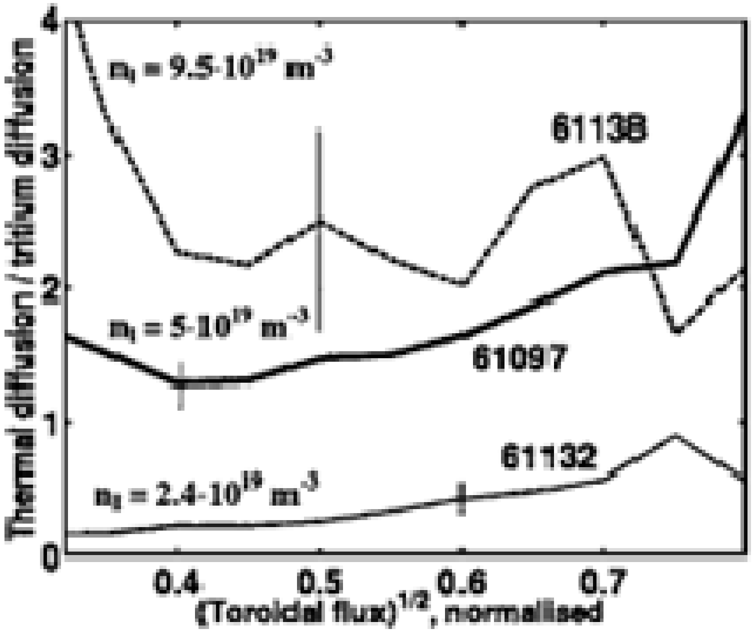


FIG. 7. The ratio of thermal effective diffusivity to tritium diffusion coefficient in gradient region. The thermal diffusivity is averaged over 1 s during the tritium puff. The error bars for the thermal diffusivity are estimated as a maximum deviation from the averaged value during the time of averaging and divided by the D_T value.

Plasma Transport Model

Heat transport in the core

For core transport we use the scaling based model [4].

The heat diffusivities, $\chi_i = 2\chi_e$, at the core are fitted to provide $\tau_E = 0.7\tau_{98y2,D}$, from the scaling prediction for deuterium $\tau_{98y2,D}$, which is valid both for hydrogen and He plasmas [7].

Heat transport in the pedestal

At the Edge Transport Barrier (ETB) the heat diffusivities, χ_i, χ_e are fitted to provide the pedestal pressure according to [5]:

$T_{ped}n_{ped}/I_p^2 \sim \beta_{p,ped} \sim A_i^{0.48}(P_{SOL}/P_{LH,D})^{0.144}n_{ped}^{-1/3}$, taking $A_i = 1$, as for hydrogen with the ETB width from [6], $\Delta_{ped} = 0.076\ \beta_{p,ped}^{1/2}$.

Particle transport coefficients

For all plasma species we assume the same diffusivities, $D = 0.1 (\chi_i+\chi_e)$.

To assess the effect of density peaking, $F_n = n(0)/n_{ped} = 1 - 1.5$ we vary particle pinch, $V = 2 C D r/a^2$, $C = 0 - 0.6$.

Helium transport

Helium throughput, given by $G_{He}= 0.027\mu^{1.61}P_{SOL}^{1.69}S_n- 0.2\ G_H$ [2], is fitted to avoid plasma detachment: $\mu\leq 1$, where μ is the normalized gas pressure in the divertor. Operation with higher power enables higher edge densities, $n_{He,s}\sim P_{SOL}^{0.66}$. Maximal pumping speed, $S_n = 1.27$ ($S_{eng}= 75\ m^3/s$ [2]) close to detachment, $\mu\sim 1$, reduces edge hydrogen density, $n_{H,s}\sim (G_H/S_n\mu)^{0.86}$, reduces the hydrogen core source, $G_{H,core}\sim G_H/S_n\mu^{1.13}$ and increases the He core source, $G_{He,core}\sim \mu^{0.8}$. Thus, it is favorable for minimization of undesirable helium dilution by hydrogen (fig.2).

Hydrogen transport

Residual fuelling from the LFS hydrogen pellets for ELM pacing is calculated [3]. For the pedestal parameters considered, the residual core fuelling from pellets is negligible due to the outward drift. Thus, the source of hydrogen is counted only in total throughput, G_H.

The pellet frequency required to keep the ELM energy loss at the acceptable level, $\Delta W_{ELM} < \Delta W_{max}$ is determined from the scaling, $f_{pel} = 0.2\ P_{SOL}/\Delta W_{max}$. We assume the conservative value, $\Delta W_{max} = 0.6$ MJ, required for $I_p = 15$ MA.

Hydrogen throughput, $G_H = f_{pel}\ N_{pel}$ is calculated for the minimal foreseen pellet size, $N_{pel} \sim 1.5$ Pa m^3.

Boundary conditions and particle sources

in the core are taken from the parameterization of [2].

Type-I ELMy H-mode Operational Space

The OS is assessed for the maximal pumping speed, $S_{eng}= 75\ m^3/s$ at the detachment limit, $\mu = 1$ with the plasma model described above. This model provides the boundary and pedestal parameters and core fuelling as functions of P_{SOL}. The plasma density is scanned by varying the pinch velocity and the input power P_{aux}. Control of density peaking by variation of the ECH location is limited. Thus, the operational point should be chosen to provide the Type-I ELMy H-mode conditions, $P_{SOL} > \alpha\gamma_k P_{LH,D} \sim B^{0.8}S^{0.94}n^{0.7}$ [8] for any density peaking expected in ITER. In our analysis we assume $\alpha= 1.4$, and $\gamma_H= 2$, $\gamma_{He}=1.4$. The OS is limited by $n \leq n_{max,k} \sim (\alpha\gamma_k P_{SOL}/S)^{1.4}$ and the NBI shine through limit, $n \geq n_{min,NBI}$ (shown in fig. 3 for full bore plasma for pure hydrogen and pure helium cases). As follows from the scaling [8], with assumed α and γ_k, such operation will be possible even in pure hydrogen for $P_{SOL}> 55$- 58 MW for $F_n =1$.

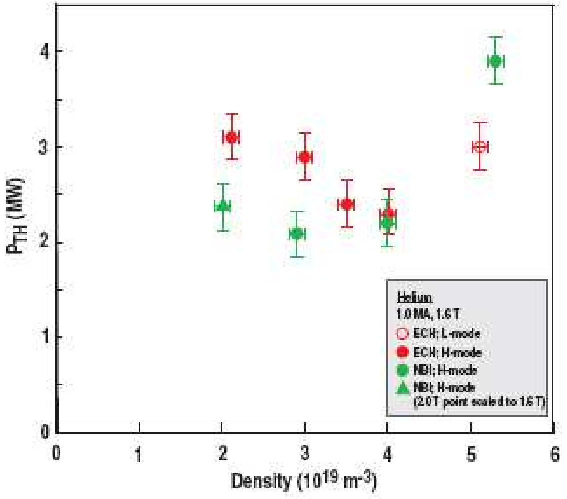
Type-I ELMy H-mode Operational Space: shrinking at low density

Dependence on density changes

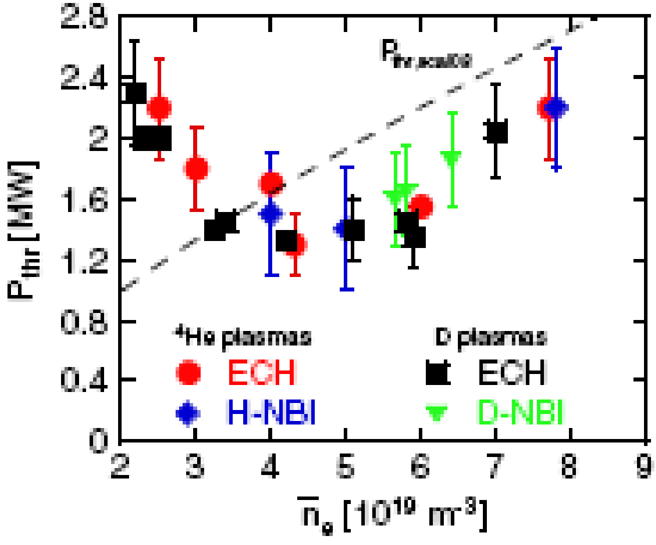
Power threshold has a minimum

$P_{L-H} > P_{L-H,D}$ (n~ 3.5 $10^{19} m^{-3}$)

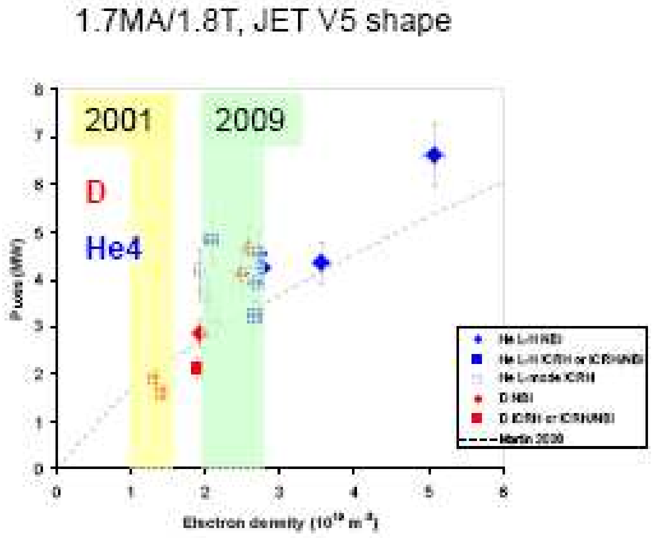
DIII-D, Gohil 2010



ASDEX-U, Ryter 2009



JET, McDonald 2010



Type-I ELMy H-mode Operational Space for **Full bore plasma.**

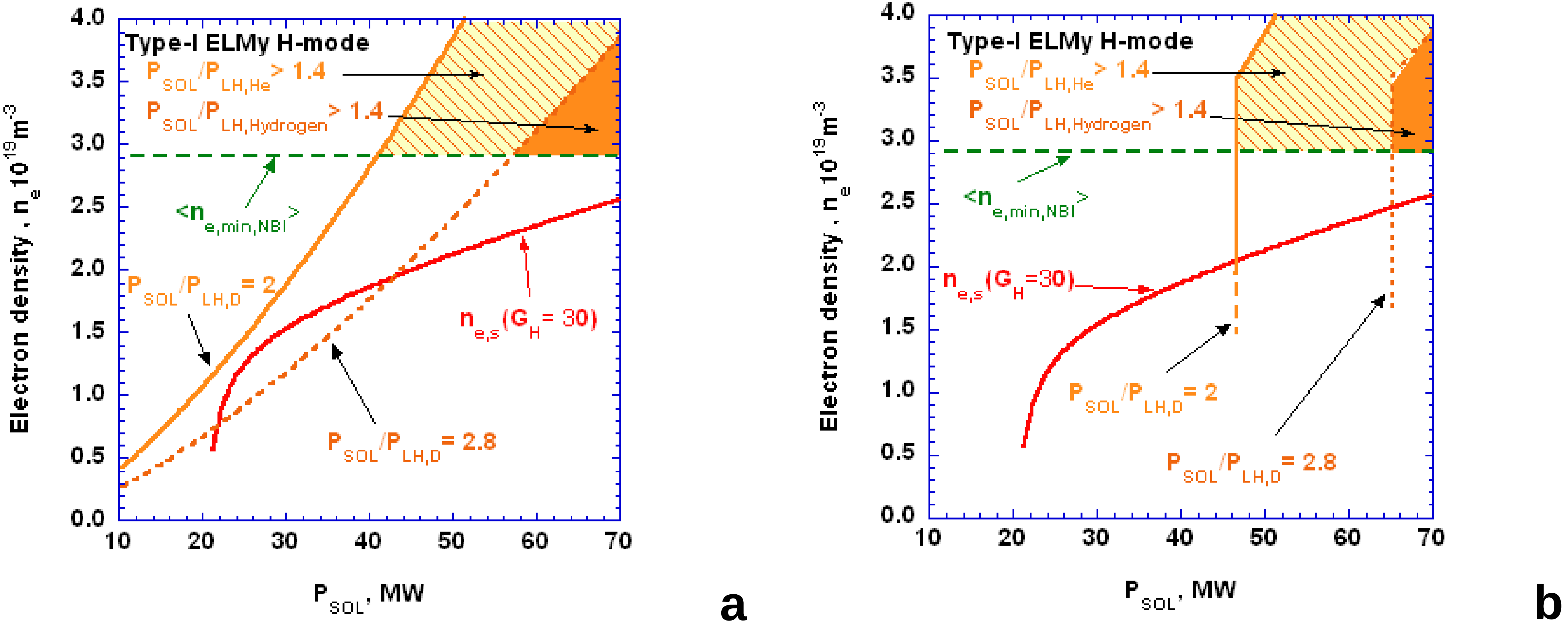


Fig. 4 The same as fig. 3, but with full bore plasma.

With decrease of plasma size (fig. 1) boundaries of the operational domain with $P_{SOL}/P_{LH,D} > 2.8$ spread (compare (figs. 4a, 4b): P_{SOL}~65→60 MW, $n(0)/n_{ped}$~1.3→1.7

Discussion

The OS where the stationary Type-I ELMy H-mode can be expected for any contamination by hydrogen exists and corresponds to high power operation. It is shown in orange in figures 3 and 4. This part of the OS in full bore plasma exists for density peaking in the range F_n= 1 - 1.3.

The OS can be extended by reduction of plasma surface, S. In practice the possibility of such reduction is limited (fig. 1) by variation of plasma elongation. In the case of the reduced elongation, the part of the OS where the stationary Type-I ELMy H-mode is expected for arbitrary dilution extends from P_{SOL}~ 60 MW for the range of moderate peaking, F_n= 1 - 1.2 to P_{SOL}~ 70 MW for the range with high peaking F_n=1 - 1.7 (fig.4b).

It is worth noting that, for high power operation, the predicted separatrix density is rather high [2], $n_{e,s} \sim 2.5 - 2.6\ 10^{19} m^{-3}$. For $D = 0.1\ (\chi_I + \chi_e)$, this $n_{e,s}$ is sufficient to keep plasma density above the NBI shine-through limit, $n \geq n_{ped}$: $n \geq n_{ped} \sim 3\ 10^{19} m^{-3} > n_{e,min,NBI}$ even without an anomalous pinch. This is important because for helium operation, the achievable density is limited by the detachment condition, $\mu \leq 1$ for He puffing, and by the dilution for hydrogen pellet fuelling if the pinch is not sufficient.

The core plasma radiation, predicted for low B_0, n and T, expected in He plasmas without the impurity injection, is a factor of 10 smaller than predicted for Q = 10 DT operation, $P_{rad,He} < 4$ MW. In the high power case, $P_{aux} - P_{rad} = P_{SOL} > 60$ MW our modeling predicts rather moderate fraction of hydrogen, $n_H/(n_H + n_{He}) < 40\ \%$, $(n_H/n_e < 25\%)$.

Conclusions

It is shown that for B_0 = 2.65 T, $I_p \leq$ 7.5 MA the operational space for the stationary Type-I ELMy H-mode in Helium plasmas with substantial dilution by hydrogen can exist for a range of density peaking, F_n = 1 - 1.7, if the power coupled to the plasma is sufficient to provide P_{SOL}~ 60 - 70 MW.

Predicted stationary contamination by hydrogen remains moderate, $n_H/(n_H+n_{He})$~ 38%, (n_H/n_e~ 24%). Thus, if the P_{LH} dependence on the dilution is weak (see ECRH in Fig. 5), the OS can spread on a wider range of n and P_{aux}.

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