ITER CONFINEMENT AND STABILITY MODELING

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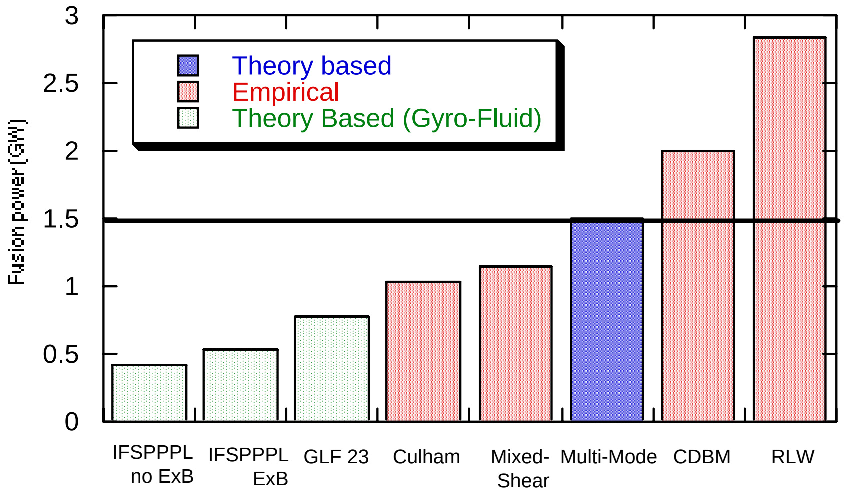
BACKGROUND

Comparative analysis of the different transport models available at present reveals [1] that no single model agrees well with the equilibrium temperature profiles measured in experiment. It was found [2,3] that the models predict significantly different transport levels for the same instabilities governing the radial transport.



Fusion power predicted by various models for ITER-98 [3].

So, at present it is premature to recommend any single 1D model for the ITER predictive analysis. And we use semi empirical approach based on energy confinement scaling.

Benchmarking of the ITER transport model vs. experimental data and robustness of chosen scenarios vs. model assumptions and physical limitations are subjects of our consideration.

[1] DeBoo J C *et al* 1999 *Nucl. Fusion* 39 1935
[2] Dimits A M *et al* 2000 *Phys. Plasmas* 7 969
[3] *ITER Physics Basis* 1999 *Nucl. Fusion* 39 2178

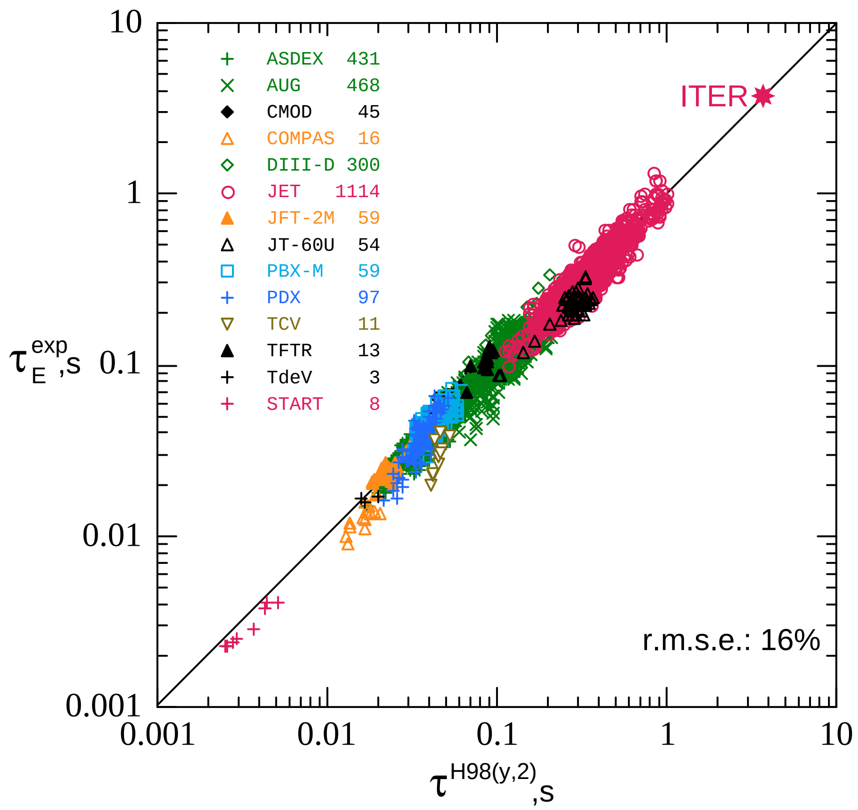
ITERH-98P(y,2) Global Confinement Scaling

The Confinement Database and Modelling Expert Group recommended for ITER design the ITERH-98P(y,2) confinement scaling,

$$\tau_E^{H98(y,2)} = 0.0562 I^{0.93} B^{0.15} n_{19}^{0.41} P^{-0.69} R^{1.97} \kappa_a^{0.78} \varepsilon^{0.58} M^{0.19}$$

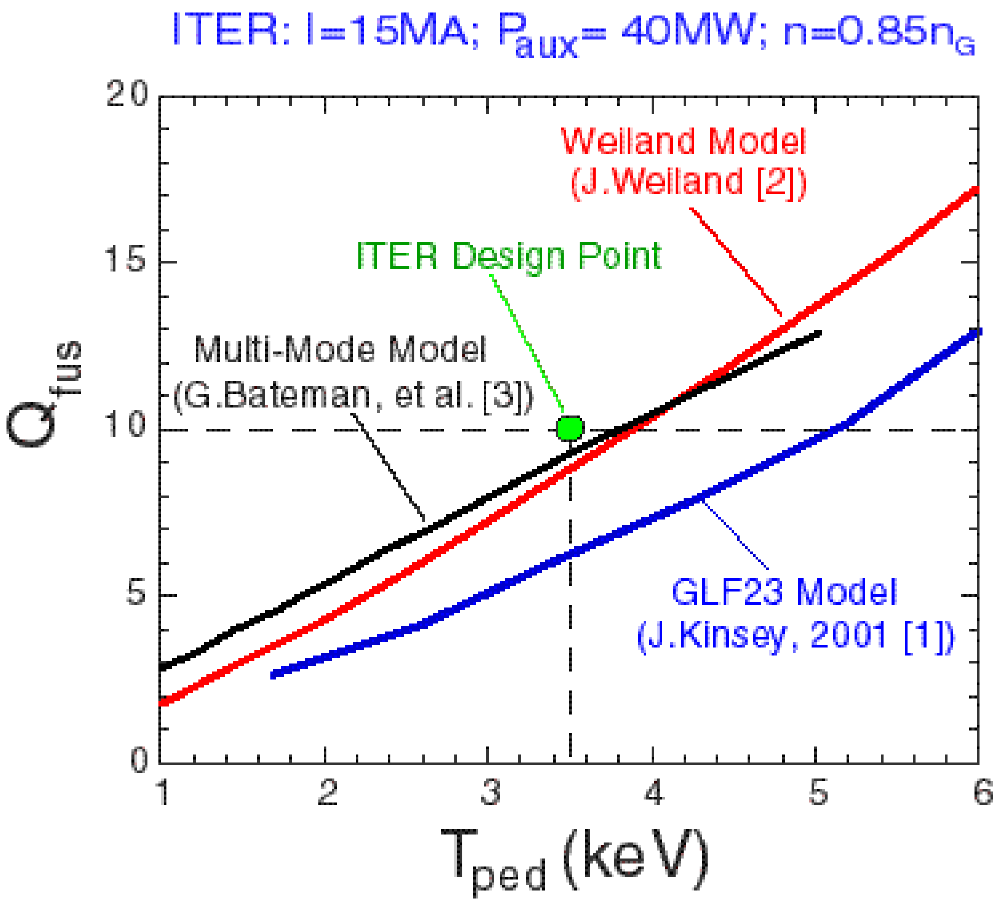
The point prediction for the thermal energy confinement time in ITER is τ_E = 3.6 s.
The 2σ log-linear interval was determined as ±20%.

By recent analysing the enlarged ITERH.DB3 ('final') dataset, the practical reliability of the ITERH-98(y,2) scaling was confirmed and 2σ log-linear interval was reduced[1]
to ±14%.



[1] O. Kardaun, "Interval estimate of the global confinement time during ELMy H-mode in ITER FEAT, based on the international multi-tokamak ITERH.DB3 dataset," IPP-IR 2001/5 1.1 http://www.ipp.mpg.de/ipp/netreports, in preparation; O. Kardaun, "On estimating the epistemic probability to realise $Q=P_{fus}/P_{aux}$ larger than specified lower bound in ITER," Nucl. Fusion (2001), in press.

COMPARISON OF PREDICTIONS BY PHYSICS BASED MODELS WITH ITER DESIGN POINT

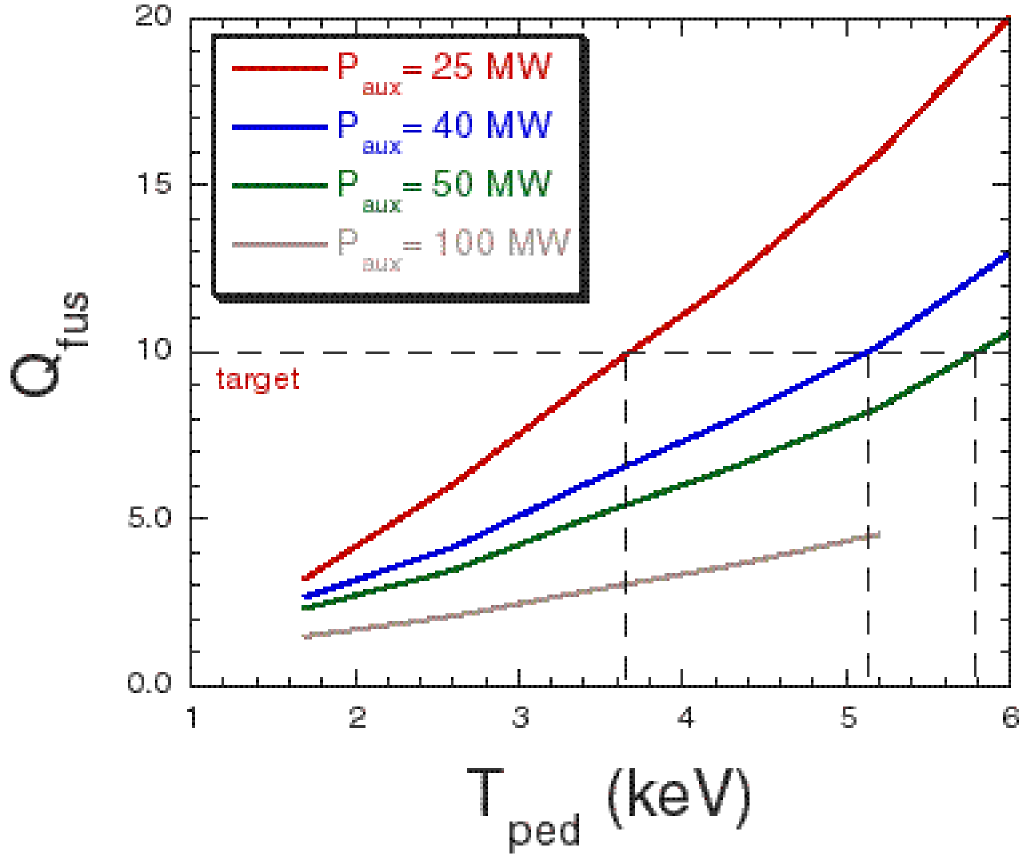


[1] A.H.Kritz, J.Kinsey,T.Onjun, I.Voitsekhovich, G.Bateman, R.Waltz, G.Staebler, "Burning Plasma Projections with Internal Transport Barriers", ITPA Meeting on Burning Plasma Transport, 10-12 September 2001, NIFS, Toki, Japan.

[2] J.Weiland, "Predictive Simulations of ITER-FEAT Performance," 28th EPS Conference, Madeira, 2001, P2.039.

[3] G. Bateman, A. H. Kritz, T.Onjun and A. Pankin, Private communication, 7 Dec., 2001.

GLF23 MODEL PREDICTION FOR ITER



Temperature at the top of pedestal required for obtaining Q=10 drops with reducing P_{aux}

MODEL DESCRIPTION (PRETOR & ASTRA)

HEAT, MOMENTUM AND PARTICLE TRANSPORT

1D transport modelling for T_e, T_i, n_e, n_{He}, ψ, V_{tor} evolution with self-consistent 2D equilibrium (1.5D modelling)

Heat, toroidal momentum and particle diffusivities:

$$\chi_{i,e,\phi} = \chi_{i,e,\phi}(0) f(\rho)\, h(\rho) + (1-h(\rho))\, \chi^{neo}, \qquad \chi_{I,\phi}(0) = 2\, \chi_e(0),$$

$$D = D(0)\, f(\rho)\, h(\rho) + (1-h(\rho))\, \chi^{neo} \qquad D(0) = \chi_e(0)$$

Neoclassical edge pedestal transport χ^{neo}:

$$h(\rho) = 1 \quad (\rho < 0.9), \qquad h(\rho) = 0 \quad (\rho \geq 0.9),$$

where ρ is the square root of the normalised toroidal flux.

Profile dependence, used for ITER simulations:

ASTRA: $f(\rho) = 1 + 3\rho^2$
PRETOR: $f(\rho)$ **by Rebut-Lallia-Watkins-Boucher [1]**

Semi empirical approach:

$\chi_e(0)$ is fitted to provide the scaling dependence at the proper phase of the discharge [2]:

$$H_{H98} = \tau_E/\tau_{E,H98(y,2)} = 1$$

$$\tau_{E,H98(y,2)} = 0.0562\, I^{0.93} B^{0.15} n^{0.41} R^{1.39} P^{-0.69} k^{0.78} a^{0.58} M^{0.19}$$

Plasma heating and current drive, plasma fuelling by gas puffing, pellets and neutral beam are also simulated. Impurities (other than He) are prescribed as $n_{zk} = f_k n_e$, the fuel densities n_D, n_T are calculated from the quasineutrality conditions:
$n_e = n_D + n_T + 2\, n_{He} + \Sigma_k Z_k n_{zk}$.

[1] P. H. Rebut, et al., in Proc. 12th Plasma Physics and Controlled Nuclear Fusion, Nice, 1988 (IAEA, Vienna, 1989) p.191
[2] ITER PHYSICS BASIS, Nucl. Fusion, 39, 1999

SAW-TOOTH MIXING

For ITER simulations two approaches were used:

ASTRA: **Semi-empirical approach is chosen:**

ST Trigger: $q = 1$ at any radial position somewhere;

ST mixing width: $\rho < 1.4\rho\ (q=1)$;

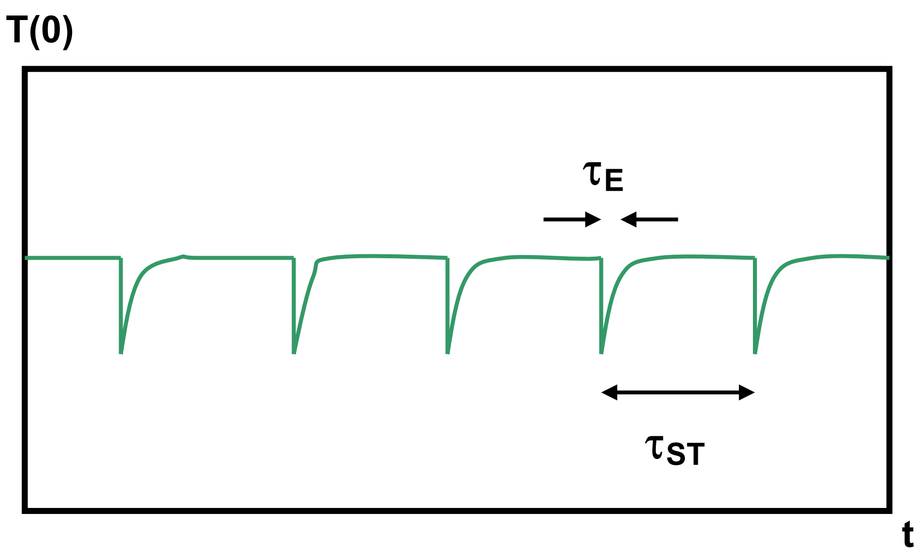
PRETOR: **Complete reconnection model by F. Porcelli et. al [1]**

ST Trigger: $\delta W_{mag} > W_{thr}$ (perturbed magnetic energy > threshold)

ST mixing width: ρ_{ST} is calculated from flux continuity ;

In both approaches particles and temperatures are flattened over the ST zone taking account of particle and energy conservation.

Pressure profile recovers faster than plasma current profile:
$\tau_{ST} >> \tau_E$. So, the details of the ST modelling have minor effect on plasma performance.



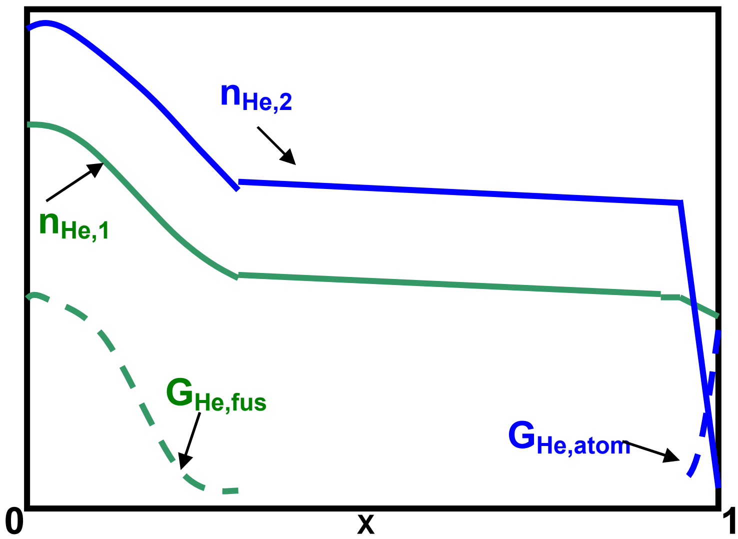
[1] F. Porcelli, D. Boucher and M. N. Rosenbluth, Plasma Phys. Control. Fusion 38 (1996) 2163

HELIUM TRANSPORT

Two approaches are tested:

1. **No neutral He influx at the core boundary, He pumping at the boundary (τ^*_{He}/τ_E) is controlled independently. The reference operational point is chosen to be $\tau^*_{He}/\tau_E = 5$, where $\tau^*_{He} = \int n_{He} dV / G_{He,fus}$, $G_{He,fus} = \int S_{He} dV$ is the fusion He source.**

2. **By parameterisation of B2Eirene [1] calculation for SOL/DIV we calculate boundary He density $n_{He}(\rho_a)$ and He atomic influx $G_{He,atom}$ self-consistently with core/SOL/DIV parameters. Operational point τ^*_{He}/τ_E is calculated.**



Qualitative behaviour of He density profiles $n_{He,1,2}$ with

$G_{He,1} = G_{He,fus}$, $G_{He,2} = G_{He,fus} + G_{He,atom}$

Higher fuel dilution by He is expected for type 2 approach

[1] A. S. Kukushkin, et al., "Basic Divertor Operation in ITER-FEAT", 18th IAEA Fusion Conference, Sorrento, Italy, Oct. 2000

BOUNDARY CONDITIONS

We consider separatrix as a boundary of plasma core 1.5 transport analysis.

Two approaches are used:

1. **PRETOR Simplified SOL/DIV model, which gives relatively high boundary density $n_e \sim 6\ 10^{19} m^{-3}$ and temperature T ~ 1 keV.**

2. **Analytic interpolation of self-consistent B2-Eirene SOL/Div simulations [1] for core boundary conditions.**

   This interpolation calculates the boundary conditions as functions of the pumping speed and particle circulation and heat/particle loss to the SOL/divertor region.

   For the reference P_{fus} = 400 MW inductive operation it gives lower boundary density $n_e(a) \sim 3\ 10^{19} m^{-3}$ and temperature $T(a) \sim 200$ eV for loss power < 100 MW.

MODEL VALIDATION:

MODEL PREDICTIONS VS. EXPERIMENTAL PROFILE DB[1] [1]

MODEL	$\Delta T_{e,std}$,%	$\Delta T_{i,\ std}$,%
Weiland	18	23
Multi-mode	13	15
GLF23	25	24
IPS/PPPL	24	16
CDBM	35	36
RLWB	20	21
Culham	24	22
Mixed-shear	18	33
T11/SET	14	18
ITER[2]	14	12

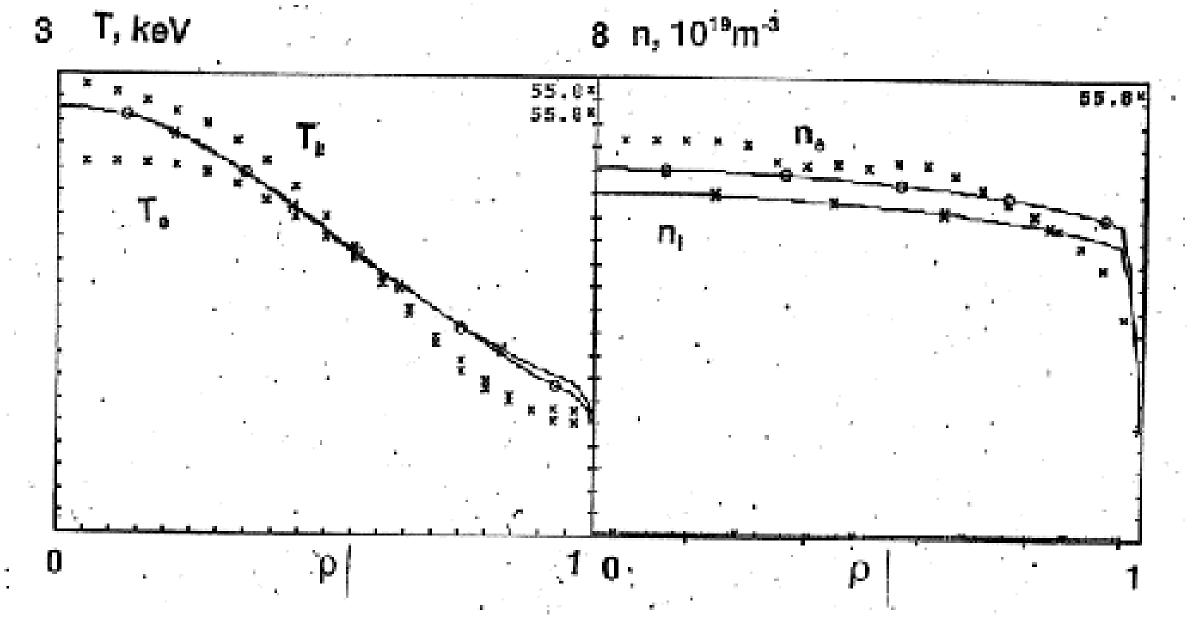
[1]Mean standard deviation $\Delta T_{,std} = (\Sigma (T_s - T_x)^2 / (\Sigma T_x^2))^{1/2}$, where T_s is simulation, T_x is an experiment.

[2]ITER model used experimental boundary conditions, other models start from the top of the edge pedestal. ITER model is applied to reduced set of data (H_{H98} ~ 1, high density n/n_{GW} > 0.5 with flat density profile). So, direct comparison with other models is not appropriate. It is presented just for scale to conclude, that

Semi-empirical model used for ITER predictions satisfactorily reproduces experimental profiles from the profile database.

[1] *ITER Physics Basis* 1999 *Nucl. Fusion* 39 2178

ITER MODEL BENCHMARKING VS. PROFILE DATABASE.



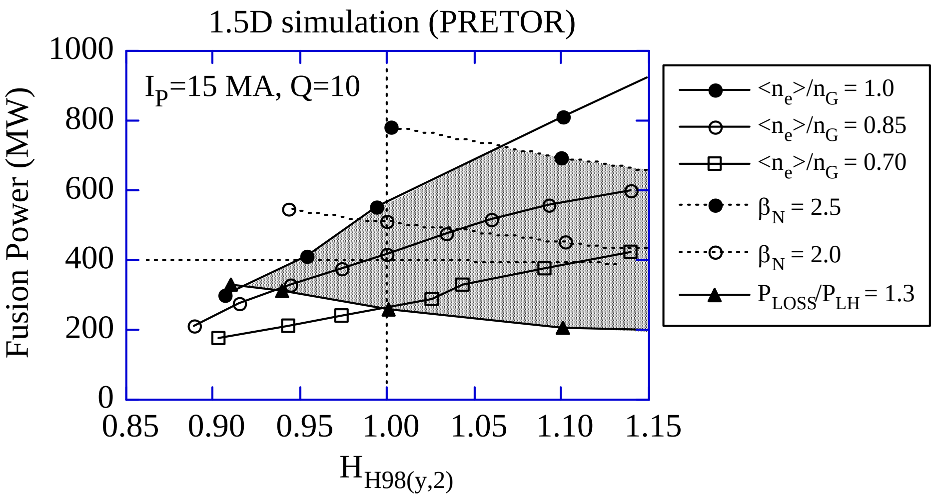
Temperature T_i,T_e and density n_e profiles simulated by semi-empirical model. Experimental profiles are shown by crosses. Input power profiles and boundary conditions are taken from the experimental DB.

JET#35156 H-mode: n/n_{GW} = 0.84 Q_{NBI} = 9 MW

Semi-empirical model used for ITER predictions satisfactorily reproduces experimental profiles from the profile database.

ITER OPERATIONAL SPACE FROM 1.5D SIMULATIONS

Operational Domain for I_P = 15 MA and Q = 10



Operation boundaries (shaded area) are given by

$\langle n_e \rangle / n_G$ = 1.0, β_N = 2.5 and $P_{LOSS}/P_{L\text{-}H}$ = 1.

REFERENCE OPERATIONAL POINT:

$H_{H98(y,2)}$ = 1.0 and $\langle n_e \rangle / n_G$ = 0.85, P_{fus} = 400 MW.

Calculations [1] were carried out by PRETOR code [2]

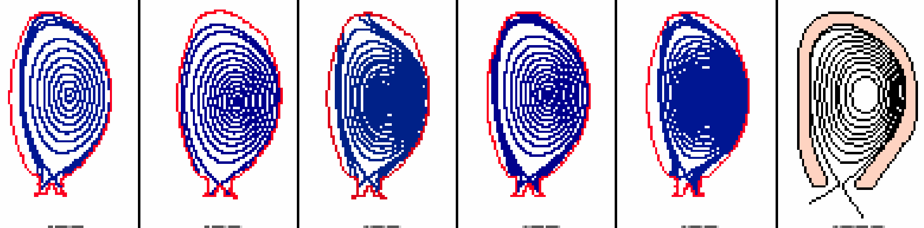
β_N is the normalised beta,
n_G is the Greenwald density limit,
P_{LOSS} is the power loss,
P_{LH} is the power required for the H-mode transition [3].

Good confinement is supposed for P_{LOSS} > 1.3 $P_{L\text{-}H}$.

[1] Y. Murakami, et al., J. Plasma and Fusion Res. 77 (2001) 712
[2] D. Boucher, *et. al.*, in *Proc. 16h IAEA Fusion Energy Conference*, Montreal, 1996 (IAEA,Vienna, 1997) 945.
[3] ITER Physics Basis, Nucl. Fusion 39 (1999) 2137.

ITER RELEVANT JET EXPERIMENTS

Three Different Methods used to match ITER Requirements

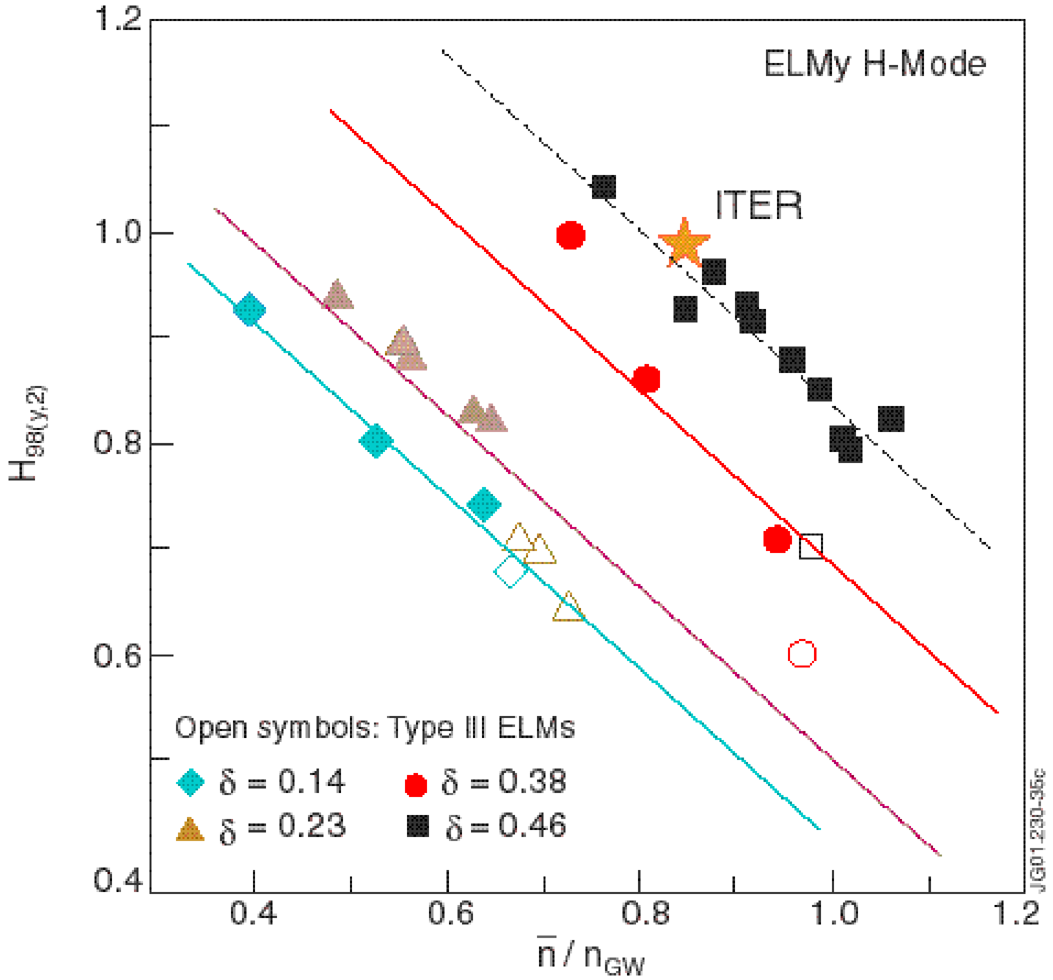


	PELLETS	IMPURITY SEEDING		SHAPING		
	JET HT HFS Pellets Pulse No: 53212, 2.5MA/2.4T	**JET** LT Ar seeded Pulse No: 53030, 2.5MA/2.4T	**JET** EHT Ar seeded Pulse No: 53550, 2.3MA/2.4T	**JET** HT High power Pulse No: 50844, 1.9MA/1.9T	**JET** "ITER shape" Pulse No: 53299, 2.5MA/2.7T	**ITER**
$H_{98\,(y,2)}$	0.8 – 0.95	1.00	0.96	0.91	0.91	1.0
$\beta_{N,th}$	1.7 – 1.8	1.75	2.00	2.00	1.90	1.81
n_e / n_{GW}	1.0 – 1.1	0.86	0.9 – 1.1	1.00	1.1	0.85
Z_{eff}	1.8 – 2.0	1.9	2.2	1.4	1.5	1.7
P_{rad} / P_{tot}	0.50	0.50	0.7	0.44	0.40	0.58
κ_X, δ_X	1.7, 0.32	1.66, 0.22	1.7, 0.4	1.74, 0.34	1.74, 0.48	1.84,0.5
q_{95}	3.0	3.0	3.1	3.4	3.2	3.0
τ_{pulse} / τ_E	~5	12	10	17	15	110

Experiments on JET tokamak demonstrated possibility of high confinement H_{H98}=1 in the configuration, similar to ITER with plasma density close to Greenwald limit n/n_{GW} ~ 1.

[1] J.Ongena et. al. EPS-28, Madeira, 2001

ITER RELEVANT JET EXPERIMENTS



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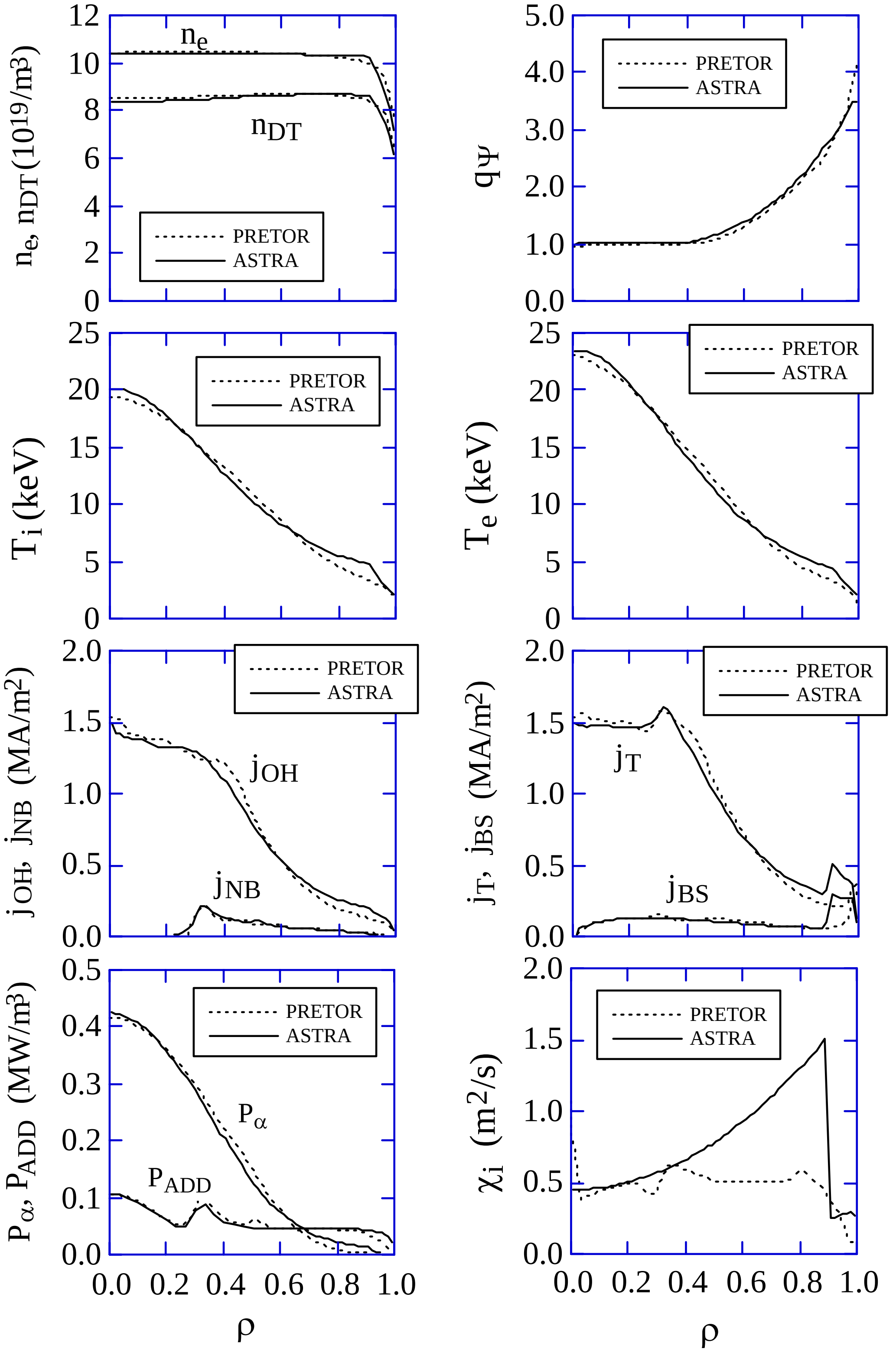
1.5D SENSITIVITY ANALYSES:

DIFFUSIVITY PROFILE



ASTRA and PRETOR give similar profiles for the same boundary conditions

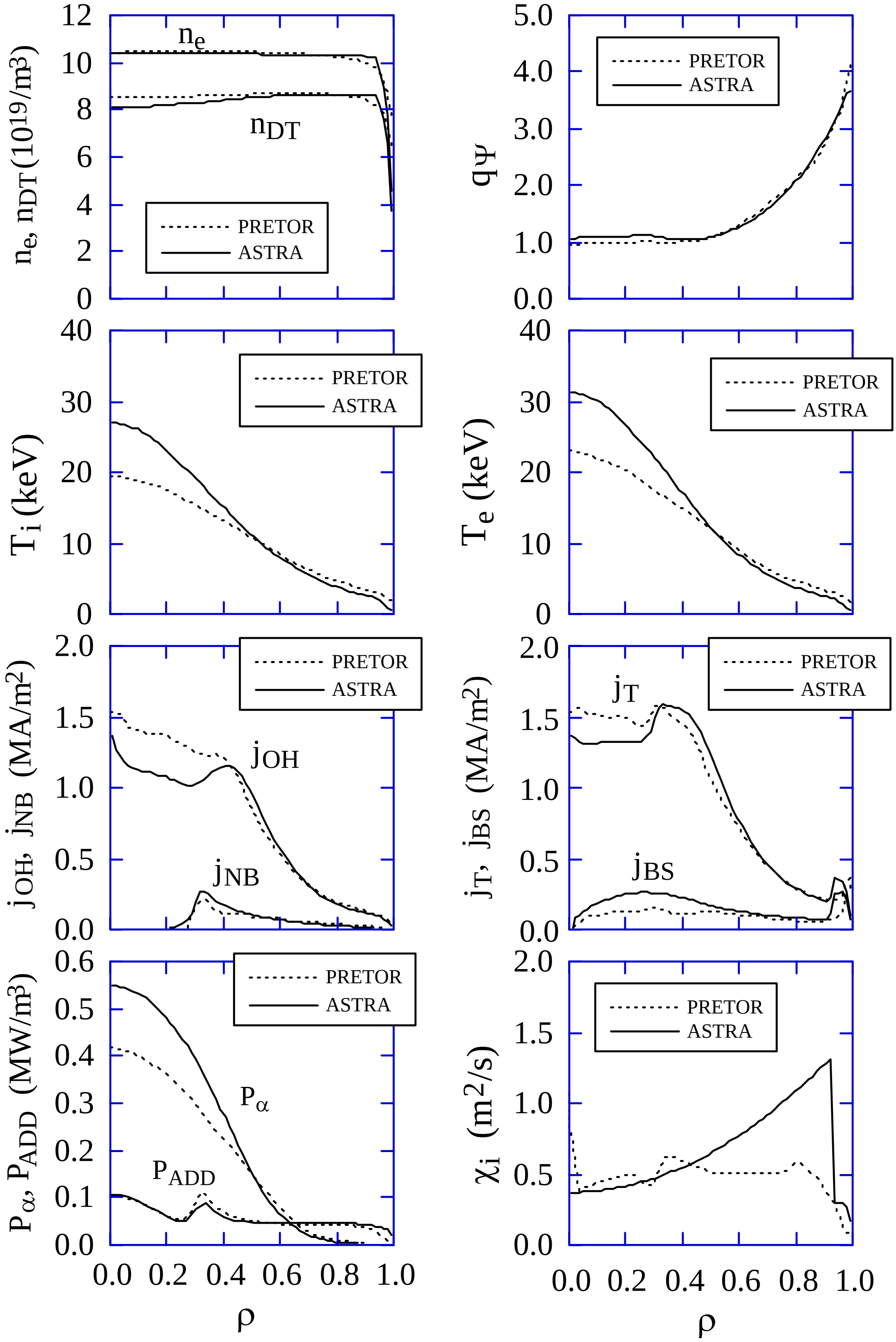
Central zone ρ < 0.5 transport seems essential $\chi_{PRETOR} \sim \chi_{ASTRA}$

1.5D SENSITIVITY ANALYSES: DIFFUSIVITY PROFILE

	ASTRA	PRETOR
R/a (m/m)	6.2 / 2.0	←
B_T (T)	5.3	←
I_p (MA)	15.0	←
κ_{95} / δ_{95}	1.7 / 0.33	←
$<n_e>$ ($10^{19}m^{-3}$)	10.1	←
n/n_G	0.85	←
$<T_i>$ (keV)	8.3	8.0
$<T_e>$ (keV)	8.9	8.8
β_T (%)	2.53	2.49
β_N	1.78	1.76
P_{FUS} (MW)	394	400
P_{NB} (MW)	33	←
P_{RF} (MW)	7	←
$Q = P_{FUS} / (P_{NB} + P_{RF})$	9.84	10
W_{th} (MJ)	327	320
$P_{LOSS} / P_{L\text{-}H}$	1.8	1.8
τ_E (s)	3.73	3.71
$f_{He,ave}$ (%)	3.1	3.2
$Z_{eff,\ ave}$	1.66	1.66
P_{RAD} (MW)	43	47
l_i (3)	0.84	0.85
I_{CD} / I_P (%)	7.9	7.6
I_{BS} / I_P (%)	16	15
χ_i/χ_e	2.0	←
$H_{H98\ (y,2)}$	1.0	←
τ_{He}^* / τ_E	5.0	←

Semi empirical approach predicts for ITER similar results for similar boundary conditions but different diffusivity profiles.

1.5D SENSITIVITY ANALYSES: BOUNDARY CONDITIONS



Normalization HH98 =1 gives higher central temperatures (ASTRA) for lower boundary values. Central zone $\rho < 0.5$ transport seems essential $\chi_{PRETOR} > \chi_{ASTRA}$

1.5D SENSITIVITY ANALYSES: BOUNDARY CONDITIONS

	ASTRA	PRETOR
R/a (m/m)	6.2 / 2.0	←
B_T (T)	5.3	←
I_p (MA)	15.0	←
κ_X / δ_X	1.7 / 0.33	←
$\langle n_e \rangle$ ($10^{19}m^{-3}$)	10.1	←
n/n_G	0.84	0.85
$\langle T_i \rangle$ (keV)	8.9	8.0
$\langle T_e \rangle$ (keV)	9.7	8.8
β_T (%)	2.78	2.49
β_N	1.97	1.76
P_{FUS} (MW)	471	400
P_{NB} (MW)	33	←
P_{RF} (MW)	7	←
$Q = P_{FUS} / (P_{NB} + P_{RF})$	11.8	10
W_{th} (MJ)	348	320
P_{LOSS} / P_{L-H}	1.9	1.8
τ_E (s)	3.45	3.71
$f_{He,ave}$ (%)	4.7	3.2
$Z_{eff,\ ave}$	1.69	1.66
P_{RAD} (MW)	46	47
l_i (3)	0.81	0.85
I_{CD} / I_P (%)	8.9	7.6
I_{BS}/ I_P (%)	22	15
χ_i/χ_e	2.0	←
$H_{H98\ (y,2)}$	1.0	←
$\tau_{He}*/ \tau_E$	6.7	5.0

Semi empirical approach predicts enhanced performance for B2-Eirine boundary conditions.

1.5D SENSITIVITY ANALYSES: SAW-TOOTH MIXING AND BALLOONING LIMIT

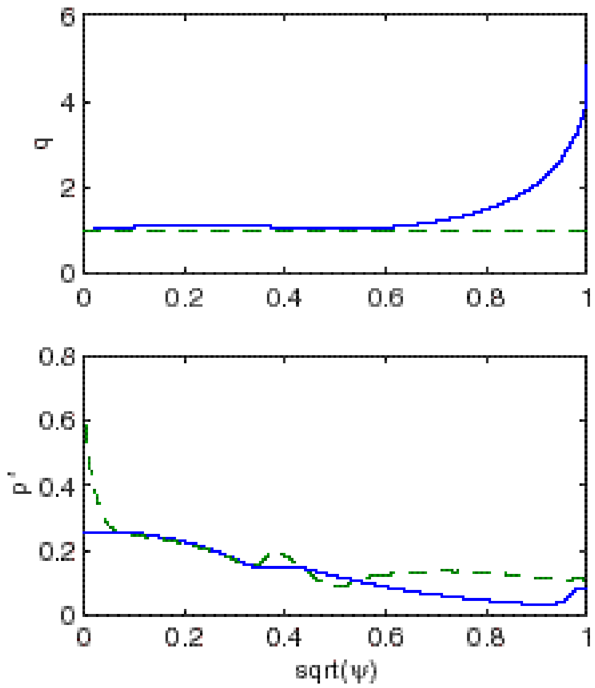
BACKGROUND FOR ANALYSIS

Saw Tooth mixing zone is large ρ/ρ_a ~ 0.5 with high pressure gradient p′ before the saw-tooth and low magnetic shear $s = \rho q'/q << 1$

Mercier criterion gives the limit for ballooning stable pressure gradient $s^2 > -8\,\rho\mu_0 p'\,(1-q^2)/B^2$

ANALYSIS OF IDEAL MHD MODE STABILITY

Is carried out by KINX code [1] coupled with ASTRA



Pressure gradient is close to ballooning/Mercier stability limit p′ ~ p'_{lim} in the saw-tooth mixing zone q ~ 1 before the saw-tooth in the inductive scenario.

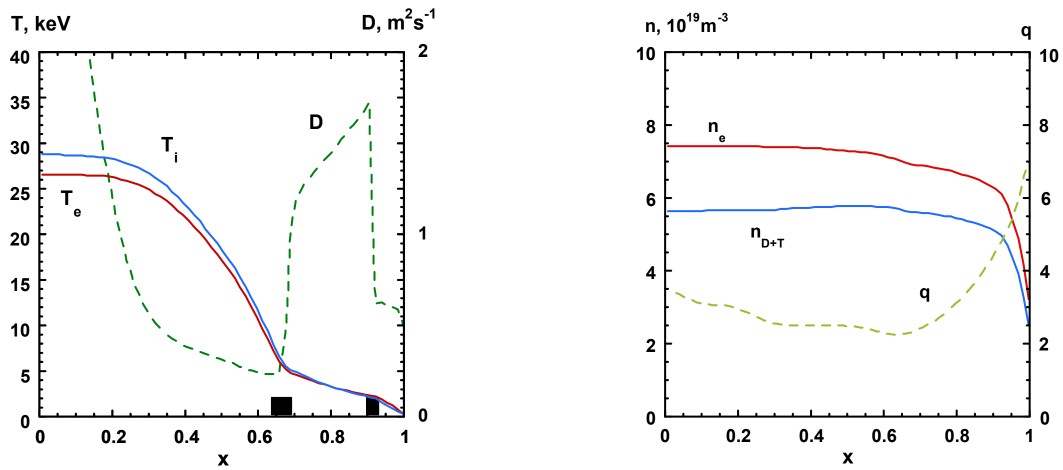
[1] Degtyarev L, Martynov A, Medvedev S, Troyon F, Villard L, Gruber R *1997 Comput. Phys. Comm.* 103 10

STEADY-STATE HIGH-Q OPRATION

Steady state operation with high Q > 5 requires high beta $\beta_N > 4\ l_i$ operation where the Ideal kink modes become unstable.

High bootstrap current fraction in the SS operation produces reversed shear configurations q(0) > q_{min}.

a **b**



a) T_e, T_I and diffusivity D radial distributions
b) safety factor q, electron and fuel dencities n_e, n_{D+T}.

SS is possible for the same global parameters: geometry, B, I_p, n_e with different safety factor profiles (different q_{min}) and multiplication factor Q (which decreases when q_{min} increases).

STEADY-STATE HIGH-Q OPRATION

SS is possible for the same global parameters: geometry, B, I_p, n_e with different safety factor profiles (different q_{min}) and multiplication factor Q (which decreases when q_{min} increases).

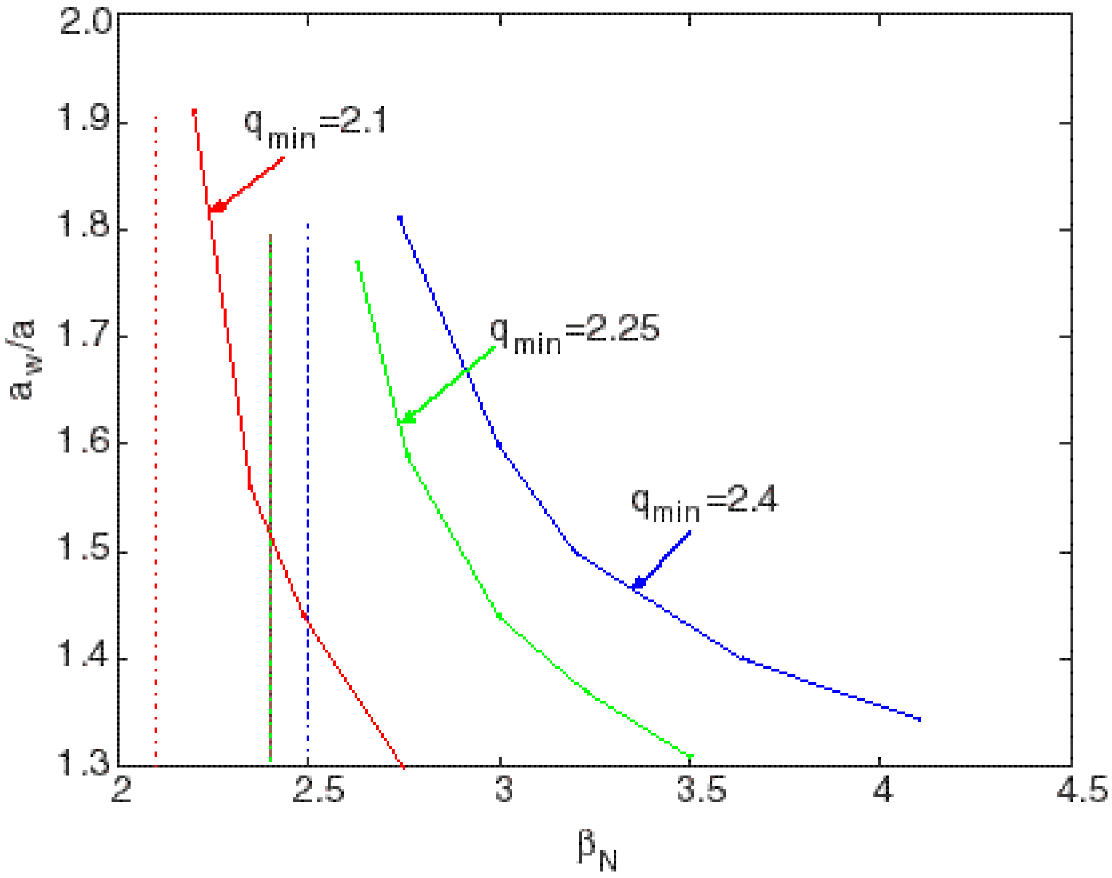
Maximal distance to the conducting wall, which can provide the kink mode stabilisation, increases with q_{min}. So, the ITER design wall position implies lower limit on q_{min} (upper limit on Q) for chosen global parameters.

ITER plasma parameters for the SS WNS scenario different q profiles.

Parameter	Value	Parameter	Value
R/a, m	6.35/1.85	$<n_e>$, $10^{19} m^{-3}$	6.74
δ_{95}/k_{95}	0.41/1.84	$<T_e>_n/<T_i>_n$, keV	11/12-10.5/11
q_{95}	5.16-5.13	W_{th}/W_{fast} , MJ	273/60-255/50
q_{min}	2.1-2.4	H_{H98}	1.41-1.3*
β_N	2.8-2.56	Q	5.7-5
l_i	0.72-0.63	P_{NB}/P_{LH}, MW	34/29-33.7
$<Z_{eff}>$	2.2-2.17	P_{fus}/P_s, MW	361/93-338/97
I_p, MA	9	τ_E, s	2.54-2.32
BR, Tm	32.86	n/n_G	0.83

*In SS simulations we used the neoclassical ion heat diffusivity in the reversed shear zone.

IDEAL n=1 KINK MODE STABILISATION BY CONDUCTING WALL



STABILISING WALL POSITION a_w/a VS. NORMALISED BETA β_N FOR DIFFERENT SCENARIO

No-wall limit is shown by dashed lines

Pressure scan is carried out for fixed q profile with different q_{min}

Maximal distance to the conducting wall that can provide the kink mode stabilisation increases with q_{min}.

The ITER design wall position, $a_w/a \approx 1.4$, implies lower limit on q_{min} (upper limit on Q) for chosen global parameters.

CONCLUSIONS

1. **Semi-empirical model used for ITER predictions satisfactorily reproduces experimental profiles from the profile database.**

2. **Semi-empirical approach predicts for ITER weak sensitivity of plasma performance to diffusivity profiles for similar boundary conditions. Simulation predicts enhanced performance for B2-Eirene compatible boundary conditions.**

3. **The details of saw-tooth modelling do not affect plasma performance provided the size of the mixing zone is similar and ST period is higher than the pressure recovery time. The pressure gradient in the mixing zone is marginally stable vs. ballooning modes in the reference inductive scenario.**

4. **High Q > 5 steady state operation would require stabilisation of low-n ideal kink modes. There is an operational window for the stabilising wall position compatible with the ITER design $a_w/a > 1.4$.**

SO, THE REFERENCE ITER SCENARIOS ARE ROBUST AGAINST THE CONSIDERED EFFECTS.