Divertor Requirements and Performance in ITER

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Contents

Overview of requirement and prediction for divertor performance taking ITER case as an example

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1. Required divertor performance

(i) **Heat removal**
(ii) **Fuel density control**
(iii) **Exhaust of helium ash and other impurities**
(iv) **Providing proper magnetic configuration for enhanced confinement (H-mode)**

Requirements	
1. Peak power load on the target plates (q_{pk})	$q_{pk} \le 10\ MW/m^2$
2. Helium concentration in the core plasma (C_{He})	$C_{He} \le 0.06$
3. Z_{eff} in the core plasma	$Z_{eff} \le 1.6$
4. Upstream plasma density (n_s)	$n_s \le \bar{n}_e/3$
5. D-T particle throughput (Γ_{DT})*	$\Gamma_{DT} \le 200\ Pa \cdot m^3/s$
6. Core fuelling (Γ_{DT}^{core})*	$0 \le \Gamma_{DT}^{core} \le 100\ Pa \cdot m^3 s^{-1}$

- **6 requirements must be simultaneously satisfied**

* **are also control actuators**

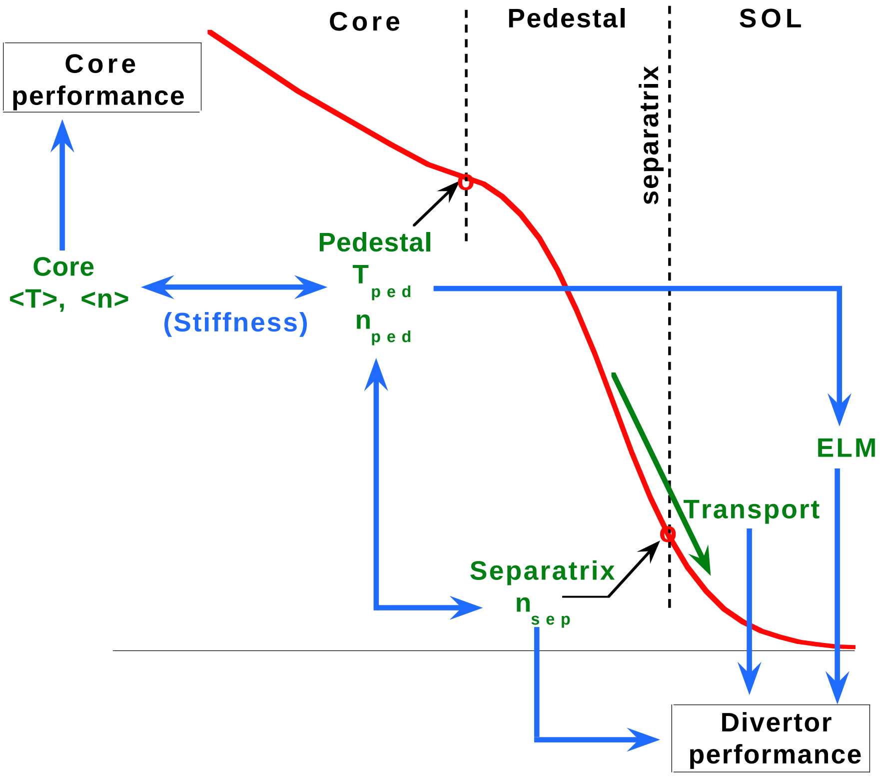
Specific features for divertor control

(i) Control actuators; not so many

- Divertor geometry
- Gas-puffing (Throughput ; Γ_{DT}) *
- Core fuelling (Γ_{DT}^{core})*
- Pumping speed
- Impurity seeding (Ne, Ar)

(ii) Divertor and Core Performance are closely linked ;

SOL/Divertor ⇔ Pedestal ⇔ Core



- Development of Modelling to include Pedestal continues, but not yet complete.
- Presently CEI (5cm inside separatrix) is calculation boundary and transport barrier is not yet properly modelled.

2. Predicted divertor performance

Prediction by B2/Eirene divertor code

Basic models

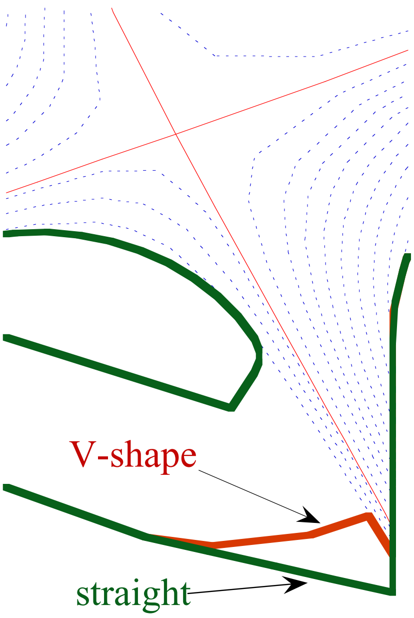
- $D = 0.3\ m^2/s,\ \chi = 1\ m^2/s$
  w/o parameter and spatial dependence
- ELM effect is not included (time averaged)
- Carbon sputtering (physical + chemical), but they are absorbed at every surface encounterd
- Partial detachment (only near separatrix is detached)

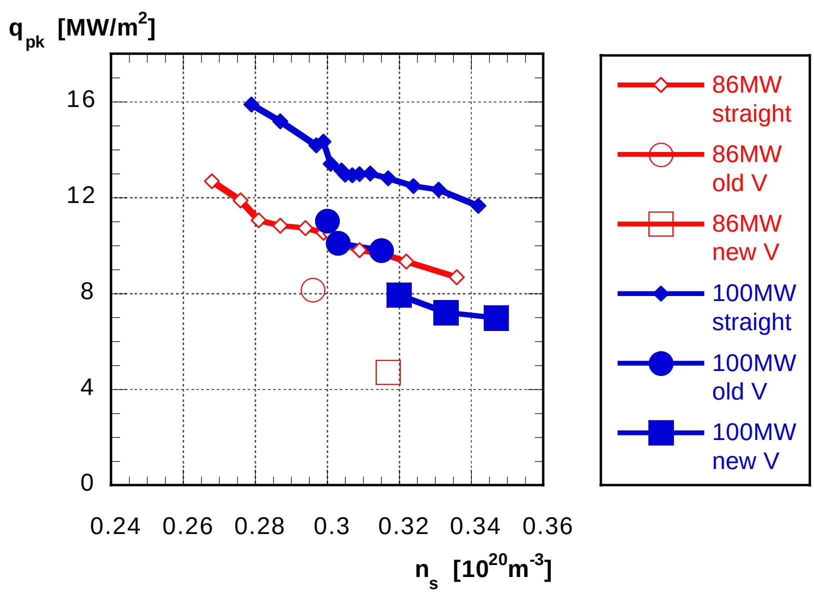
Optimization of divertor geometry

Key strategy to reduce peak power load:
Enhance neutral accumulation, in particular, near the separatrix region for outer target plate

- **Vertical Target Plate + Divertor Dome**
- **V-shape Target geometry ;** effective in accumulating neutrals near separatrix (JET)

⇒ ≈ 30% reduction of q_{pk} in ITER



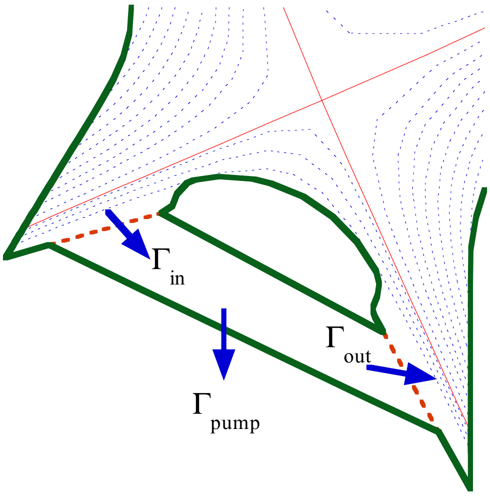


(Kukushkin, EPS 2001)

- **Gas flow between inner and outer divertor;**

  ⇒ **increase neutral recirculation in the outer divertor target region (higher power flux)**

  ⇒ **reduce peak heat load (JET, JT-60U)**



- ≈ 20% reduction of q_{pk} by gas flow between inner and outer divertor

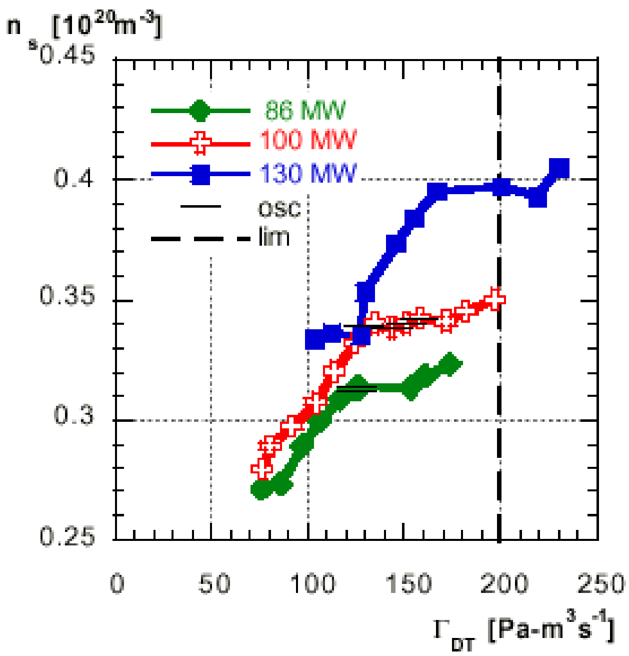
Separatrix density

Dominant effect on divertor performance and can be controlled by gas puffing (throughput; Γ_{DT}) to some extent

$$\Gamma_{DT} = \Gamma_{DT}^{gas} + \Gamma_{DT}^{core}$$

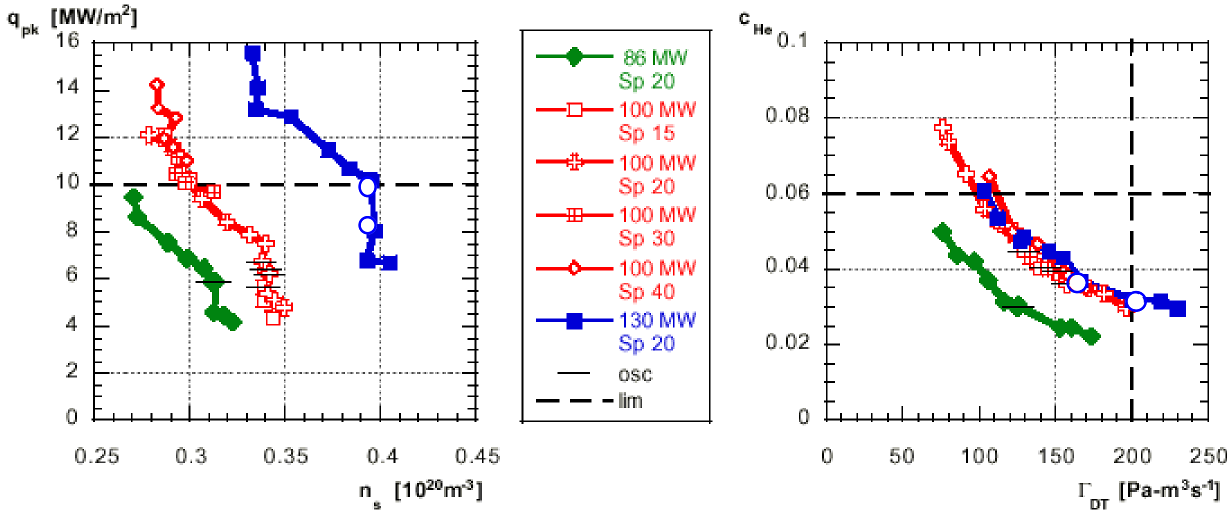
- **Saturation corresponds to detach. of inner divertor (increased neutral density)**

- **Higher n_s for higher power to detach**



Inductive operation

- **Peak power load and helium concentration**



Reference operation

P_{SOL}=86MW(P_f=410MW, P_{total}=123MW, Q=10, f_{rad}=0.3)

High fusion power with high Q

P_{SOL}=100MW (P_f=600MW, P_{total}=145MW, Q=24, f_{rad}=0.4)

High fusion power with low Q

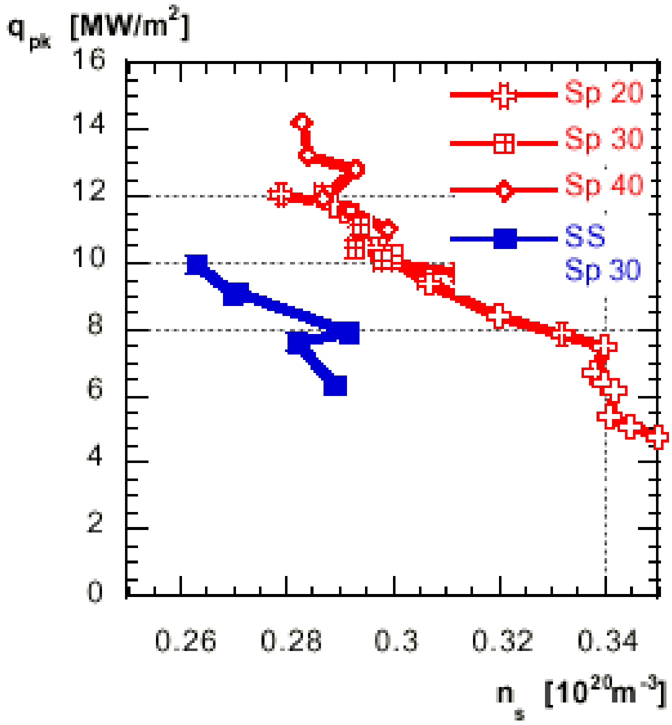
P_{SOL}=130MW (P_f=600MW, P_{total}=187MW, Q=9, f_{rad}=0.3)

- **Peak power load and helium concentration for reference operation mode is well within the requirement.**
- **Fusion power (helium source) and throughput dominate helium concentration, while pumping speed is less important**
- **Reasonably wide operation window is available for the reference inductive operation mode, while density window is not so wide (Δn_s between q_{max} and complete detachment)**

Steady state operation

Steady state
P_{SOL}=100MW
P_f=340MW, Q=5.7,
P_{total}=128MW, f_{rad}=0.2
Longer connection length with q95=4.5
=> same q_{pk} with lower n_s

cf.
Inductive operation
P_{SOL}=100MW
q95=3.0



(Kukushkin)

- **n_s(at q_{pk}=10MW/m^2)=0.26**
  => somewhat higher than $n_s \approx \bar{n}_e/3 \approx 0.23$
  => Impurity seeding will be needed

- **Initial calculations with neon seeding (0.4%) ;**
  $\Rightarrow \approx$ 30% reduction of q_{pk} (radiation region is getting far from target plate compared with carbon)
  q_{pk}=10MW/m^2 at $n_s \approx 0.23 - 0.24$
  $\Delta Z_{eff} \approx$ 0.4 (total $Z_{eff} \approx$ 1.6)

3. Further model development needed and remaining uncertainty

(1) Transport in SOL region

(2) Separatrix density under good H-mode confinement

(3) Consistent pedestal model is not yet developed;

- $D = 0.3\ m^2/s$, $\chi = 1\ m^2/s$ are too large in the pedestal (transport barrier) region

=> low pedestal density ($n_{ped} \approx (3.5 - 4.5) \times 10^{19} m^{-3}$)

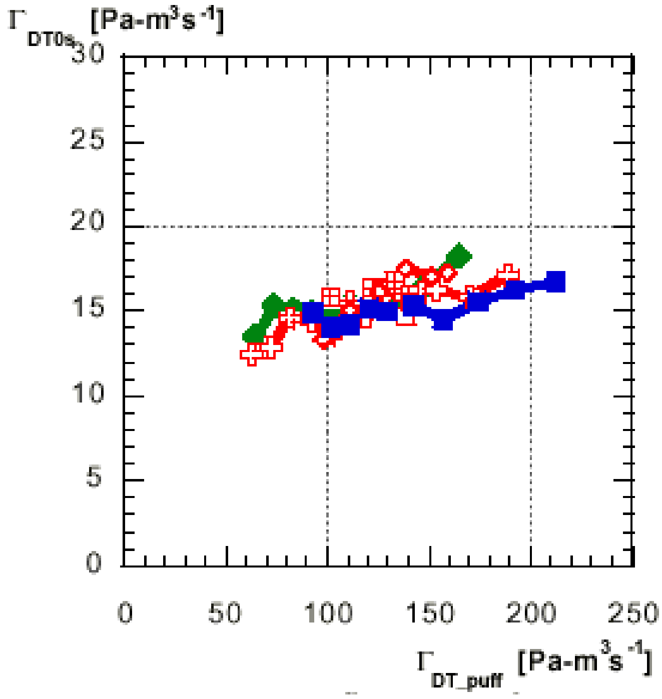
=> e.g., neoclassical level $D \approx 0.06\ m^2/s$ and proper width model for pedestal must be implemented

=> Consistent boundary condition for core plasma transport (to be developed)

=> By proper pedestal model, core fuelling requirements can be properly specified, which is consistent with the expected density pedestal in ITER

Core fuelling is needed because;

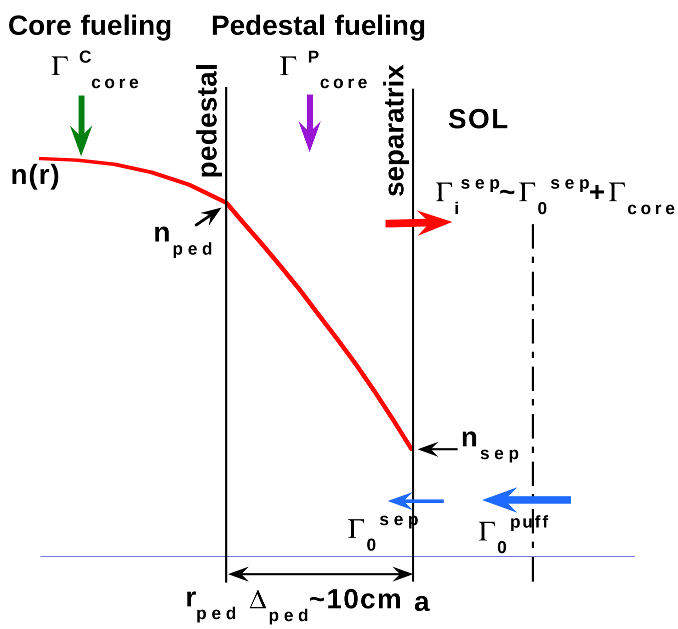
- Gas-puffing is very inefficient due to thick SOL in ITER
- Only small fraction of gas-puffed neutrals can penetrate across separatrix



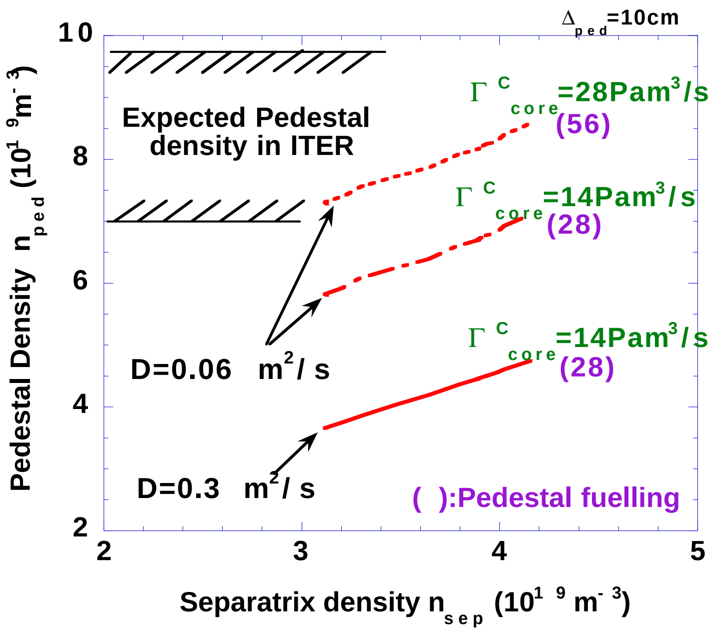
Specification of required core fuelling for expected density pedestal in ITER

Particle balance across separatrix and pedestal

- Core fuelling Γ^{C}_{core} ; Fuelling inside pedestal
- Pedestal fuelling Γ^{P}_{core} ; Fuelling between separatrix-pedestal



- With proper transport model in the pedestal and core or pedestal fuelling can achieve the expected pedestal density
- Fuelling in the pedestal region is also possible but factor of two larger fuelling is needed



- High field side pellet is prepared for ITER
  $\Rightarrow$ required core fuelling is possible

  50-100 $Pa \cdot m^3/s$

  500 m/s (deposition depth $\approx 0.15a$; inside pedestal)

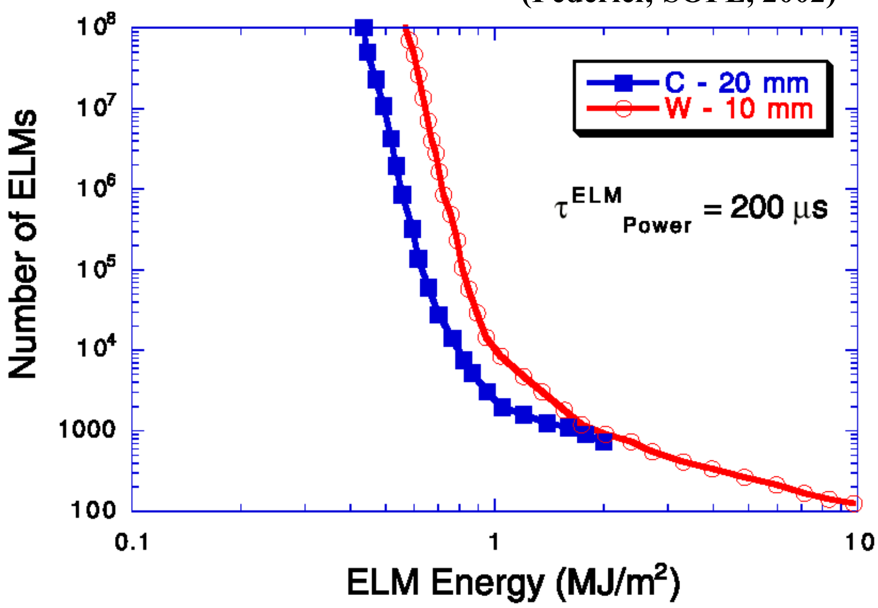
4. ELM effects and mitigation

High pedestal pressure required for good confinement can result in large divertor erosion due to Type-I ELMs

- **Limit for divertor erosion due to ELMs**

  $\Delta W_{ELM} / (S_{ELM} \sqrt{\tau_{ELM}})$; surface temperature rise

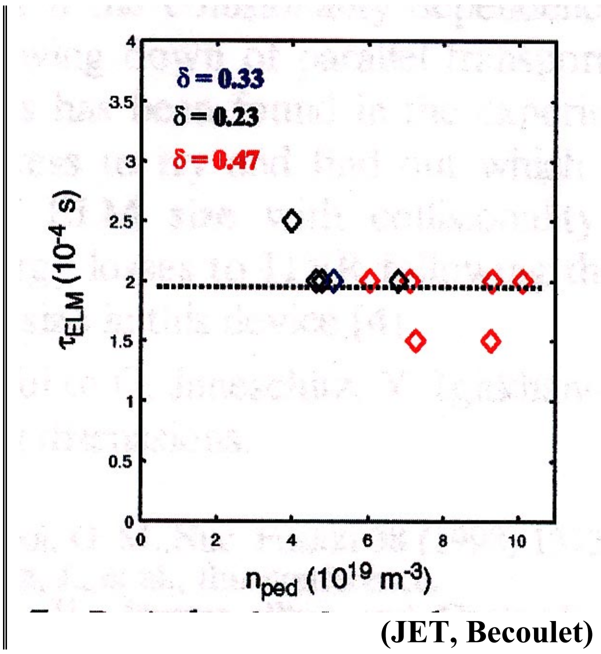
(Federici; SOFE, 2002)



- **Specification for $\tau_{ELM} \approx 200\ \mu s$**

- **τ_{ELM} in JET for various density and triangularity**

  $\tau_{ELM} \approx 200 \mu s$



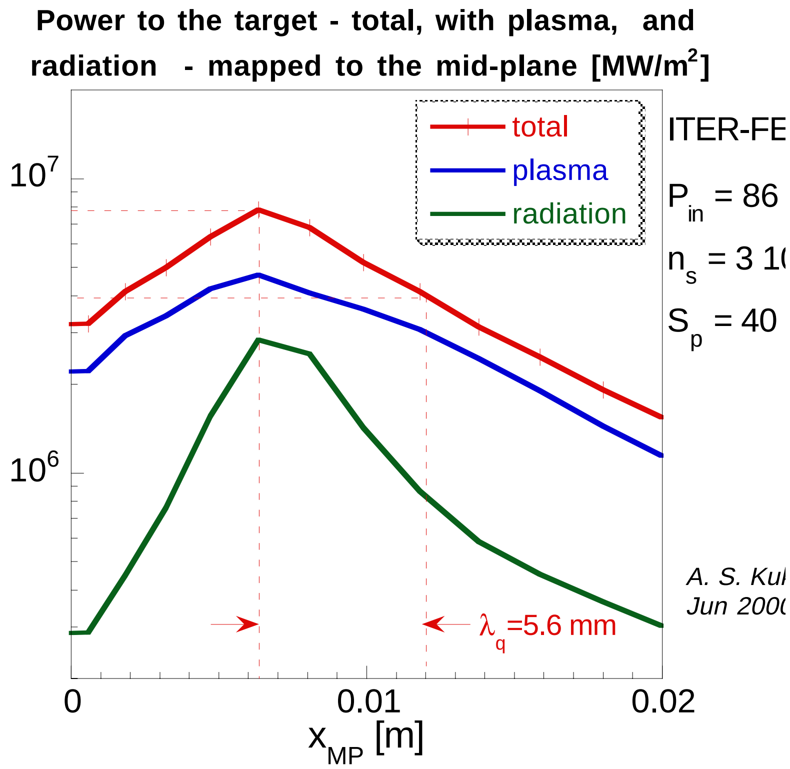
(JET, Becoulet)

- **Specification for** $S_{ELM} \approx 2 \times S_{ss}$

λ_q **; Power deposition width mapped on midplane has large uncertainty**

- **Experimental data for** S_{ss} **are mostly taken from attached condition**
  => $\lambda_q \approx$ **5mm**
  => $S_{ELM} \approx 6 \ \ m^2$

- **From power load profile in ITER ;**
  λ_q **=(10-13) mm due to detachment**
  => $S_{ELM} \approx 15 \ \ m^2$



- **Criteria of** $\Delta W_{ELM} / W_{ped}$ **for surface temperature rise up to critical one**

$\tau_{ELM} = 200 \ \ \mu s$

$S_{ELM} \approx 6 - 15 \ \ m^2$

	CFC	W
Allowable $\Delta W_{ELM} / W_{ped}$ (%) for 10^6 ELM events with deposition area $S_{ELM} \approx 2 \times S_{SS} \ \approx 6 - 15 \ \ m^2$ $W_{ped} \approx 100 \ \ MJ$	3.4- 8.3	4.4- 11

* This is also necessary to maintain plasma purity ($\approx 10^{22}$ carbon/ELM event is produced)

Proposed models for experimental data summary

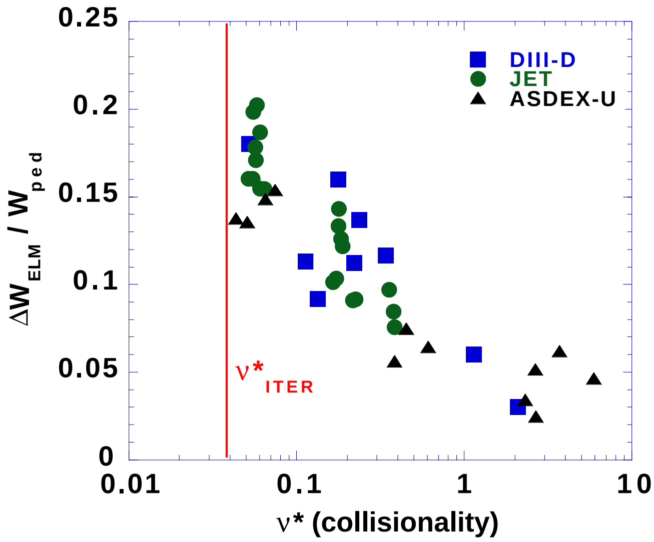
Collisionality (ν^*)

(Loarte, IAEA 2000)

$$\left(\frac{\Delta W_{ELM}}{W_{ped}}\right)^{\nu^*} \propto (\nu^*)^{P}$$

$$P \approx -0.33$$

(15-20) % for ITER



Parallel transport ($\tau_{//}$)

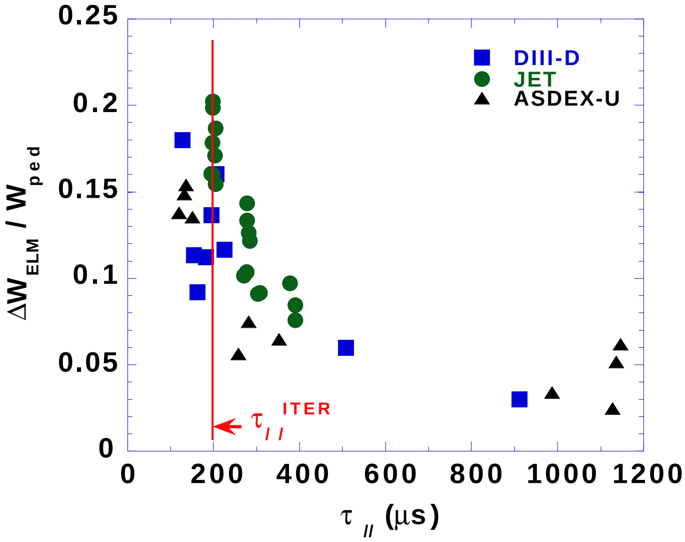
(Janeschitz, PSI 2000)

$$\left(\frac{\Delta W_{ELM}}{W_{ped}}\right)^{tau//} = \left(\frac{\Delta W_{ELM}}{W_{ped}}\right)_0 \frac{1}{1+\tau_{//}/\tau_{ELM}}$$

$$\tau_{//} = 2L/C_s\,(1+\sqrt{3/2}\,\nu^*)$$

$$\tau_{ELM} \approx 200\ \mu s$$

(12-15) % for ITER

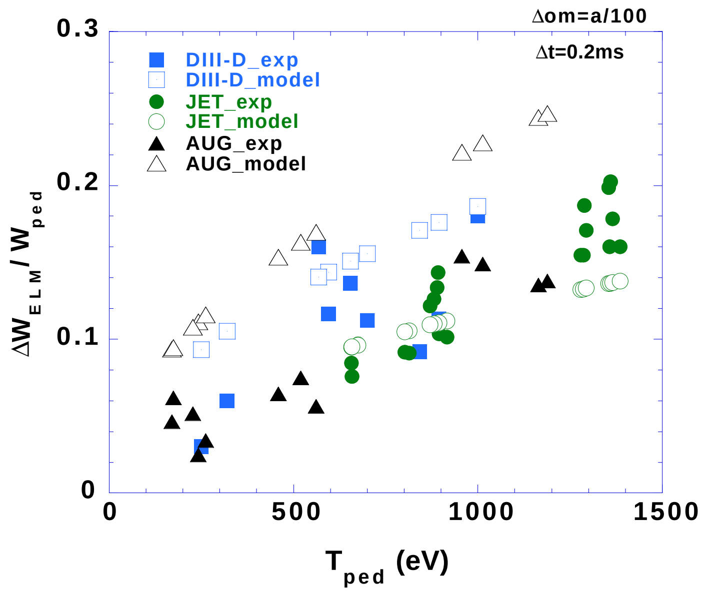


Sheath model

(Shimada, 2001)

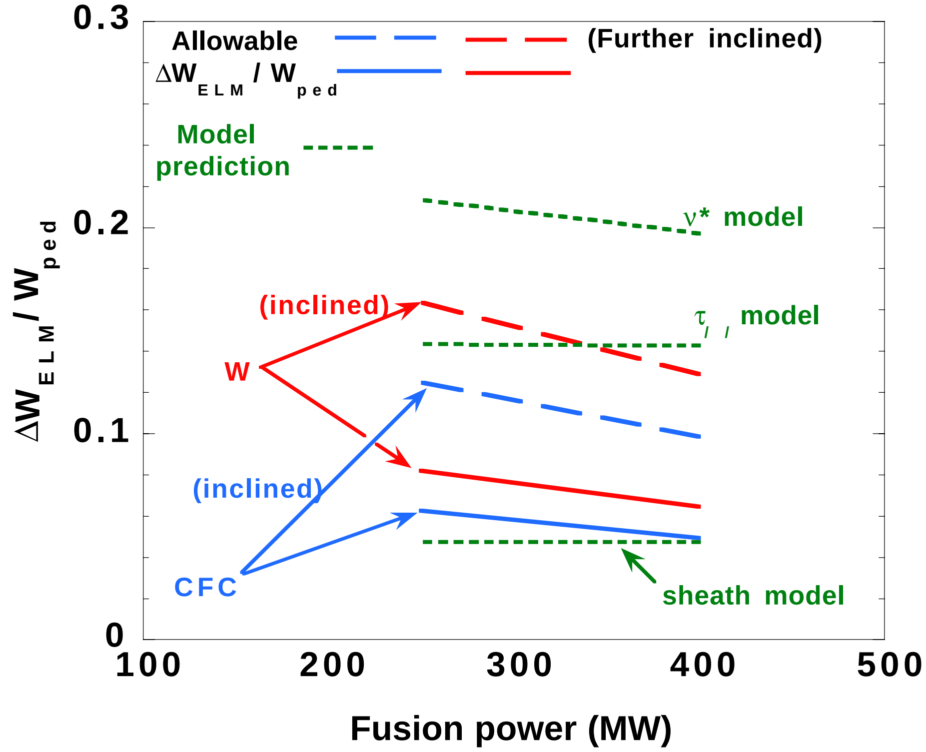
$$\Delta W_{ELM} = \gamma k \Gamma T_{ped} \times (B_p/B_T)_{om} 4\pi R_{om} \Delta_{om} \Delta t$$

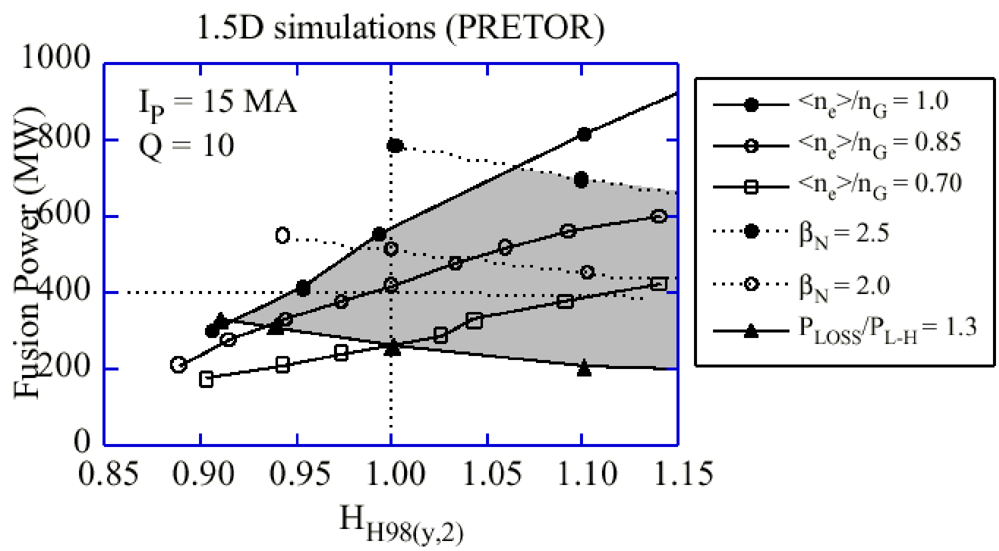
Upper limit
(≈ 5) % for ITER



All models still need much more work for ITER extrapolation

ITER Prediction



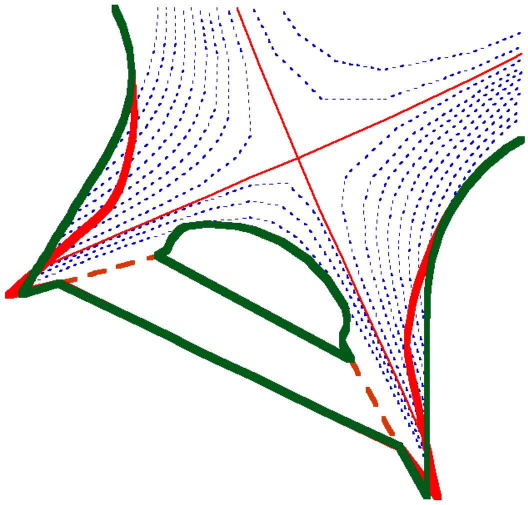


- **Very severe predictions based on ν^* and $\tau_{//}$ models.**
- **Range of uncertainty and difference between models are significantly large.**

Possible mitigation methods

(1) Further inclination of divertor plate

- **Poloidal projected angle 22.8° (2.1° real)⇒ 11.4°**



- **Possible disadvantage can be acceptable**

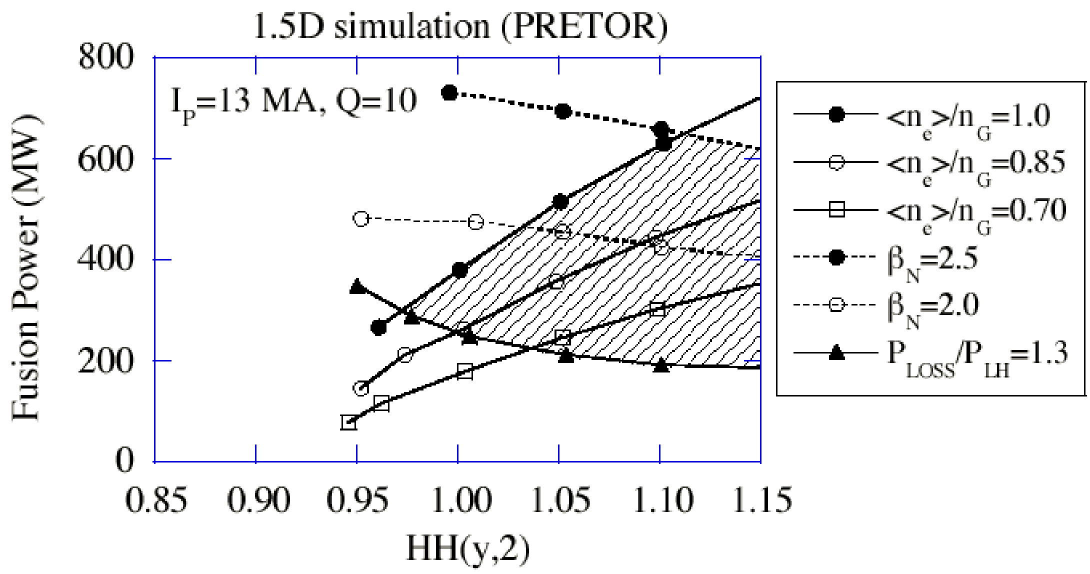
- Particle recycling on the upper part of divertor plate ;
⇒ not significantly increased (B2/Eirene)

- Separatrix line position control;
⇒ may be acceptable once operation mode is fixed for engineering testing (life time becomes a more important issue for this phase).
⇒ use of W divertor plate may also be possible during this phase due to low disruption probability.

(2) Discharge regime of high pedestal pressure with small ELMs (Type II)

- **Most of the present machines show that**
  - **high q_{95} ($\geq$ 3.5-4)**
  - **high δ_X ($\geq$ 0.4-0.5)**

  are needed to obtain this alternative ELM regime.
- **δ_X for ITER (=0.5) satisfies the required condition.**
- **Q=10 and $P_{fusion} \approx$250MW operation with q_{95}=3.5 (Ip=13MA) is possible, though window is narrow.**



Further increase of HH-factor
- with lower density (many machines)
- with higher q_{95} (HH=1.3 with q_{95}=3.6, $\bar{n}/n_G \approx 1$ and very small ELMs in AUG)
window becomes much wider.

- **This small ELM regime will be accessible for Hybrid and steady-state scenario (q_{95}>3.5).**

- **Further R&D is needed to extend this small ELM regime to the reference high Q inductive operation mode.**
  - **Type II ELMs in-between Type I (q_{95}=3, δ_X=0.5; JET) could be a clue for R&D**

5. Summary

- **Divertor requirements for ITER are summarised.**

- **B2/Eirene code calculations show that these requirements will be satisfied for inductive operation mode.**

- **For non-inductive operation mode, impurity seeding will reduce the peak heat load to meet the requirement.**

- **Further model development is necessary for B2/Eirene to include proper pedestal model. It is indicated that gas-puffing cannot fuel across the separatrix to form proper density pedestal. High field side pellet fuelling is prepared in ITER to fuel inside the pedestal.**

- **Effect of Type-I ELMs on divertor plate could be severe for high pedestal pressure required for good confinement, while present prediction by proposed models are still primitive, and thus further development/improvement of the models as well as the database are necessary.**

- **Possible mitigation methods for Type-I ELM effect are summarised; inclination of target plate and Type-II ELMs. Hybrid and steady-state scenarios can be operated with Type-II ELM regime. Further exploration to extend this regime to high Q inductive operation mode should be promoted.**