Power and Particle Exhaust in ITER

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R. Tivey, M. Sugihara, JCT and HTs

Outline

- **Vertical target Divertor, SOL and Divertor plasma modeling, impact on the ITER Divertor design**
  - ➡ Influence of divertor geometry on peak power load and He exhaust; operation window

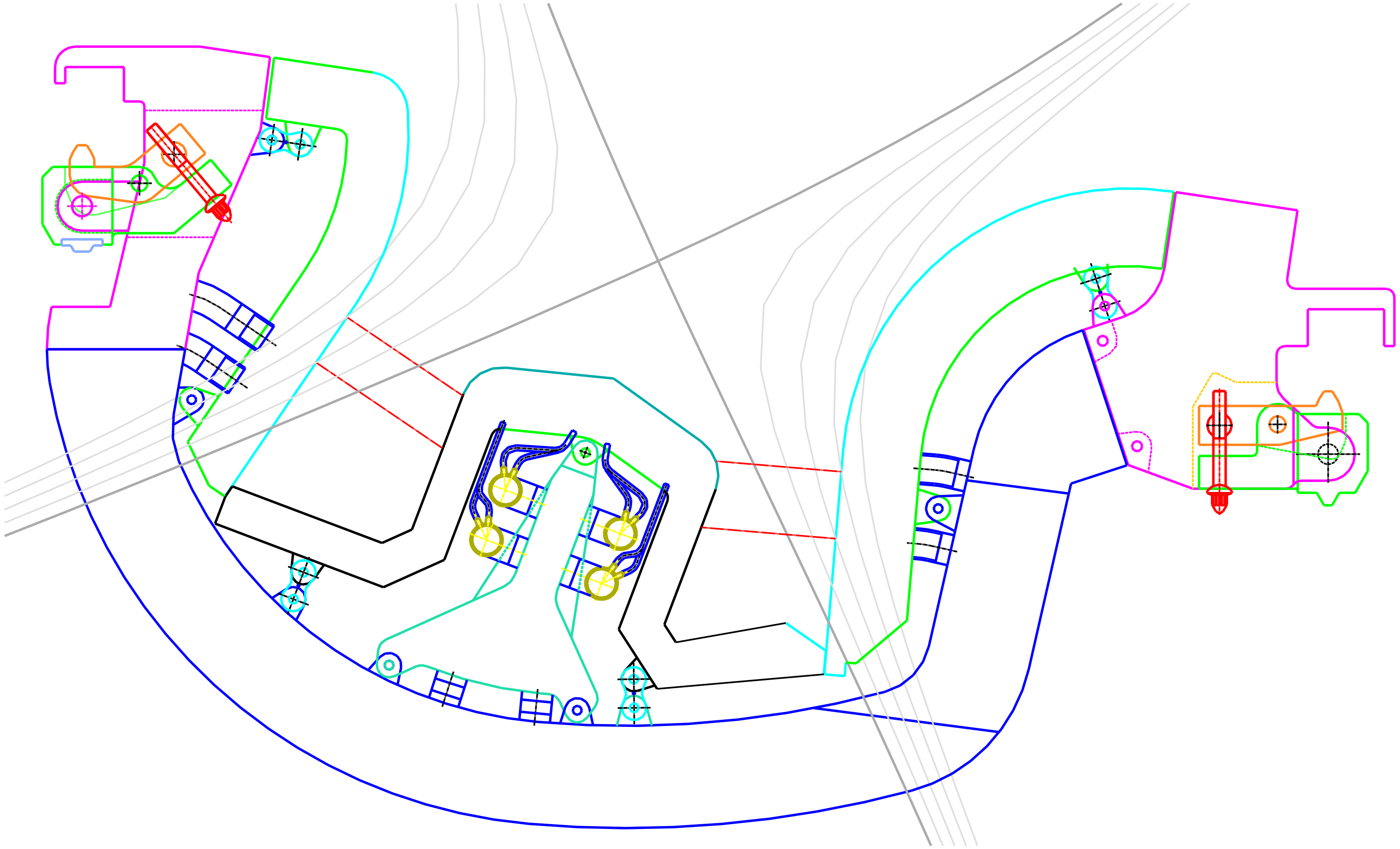
- **The importance of the H-mode pedestal for energy confinement and possible extrapolations to ITER**

- **Type I ELM Energy Load on the Divertor Targets, are Type II ELMs an alternative ?**
  - ➡ extrapolation of ELM energy loads, uncertainties, boundary condition for Type II ELMs

- **Summary and Conclusions**

- **Design of the ITER Divertor and Status of supporting R&D (optional)**
  - ➡ HHF components, Cassette body, attachments, analysis, gas conductance to pump

General Design Rules for a Vertical Target Divertor



- The following design rules have been used to assess if the space given to the target area is sufficient

- The angle of the vertical target is such that the peak heatflux does not exceed ITER 1998 design values ($20\ MWm^{-2}$)

- The normal to the target where the target intercepts the 3 cm flux line should point towards the dome

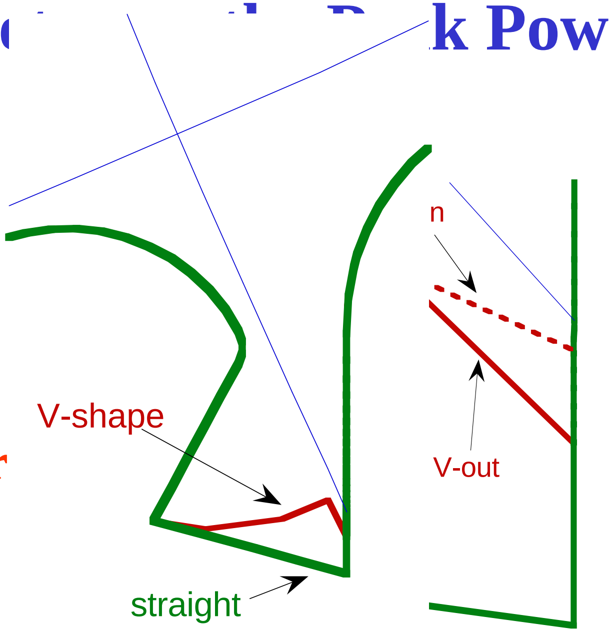
- These rules together with the allowable thickness of the cassette body (shieding, strength) define the minimum space required between X-point and VV

The B2-Eirene Code Package is used for predicting the ITER Divertor Performance

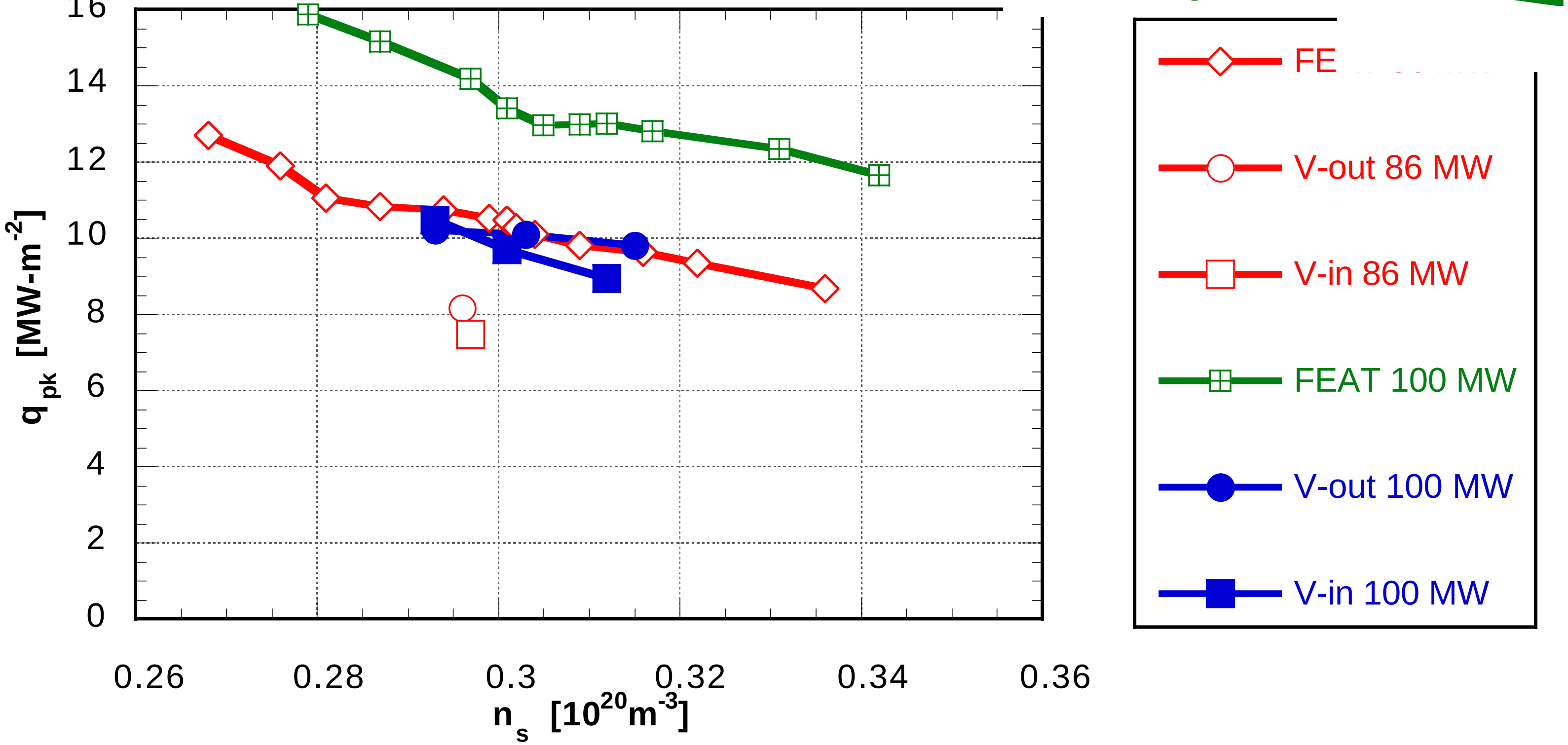
- **The Control Parameters used in the model are:**
  - ➡D (for DT): core fuelling + gas puff at the top, He: production in the core, pumping from Private Flux Region (20 m^3s^{-1} to 75 m^3s^{-1} were used)
  - ➡C: physical and chemical sputtering (1% yield) at the CFC targets and / or Ar, Ne, N: gas puff in the divertor, all impurities will stick 100% to any surface, no flux across the core boundary, pumping from PFR

- **Three main scenarios with different power levels crossing the separatrix were considered**
  - ➡86 MW: 410 MW fusion power; Q = 10 with 40 MW add. heating and 30% core radiation
  - ➡100 MW: 600 MW fusion power; Q = 24 with ~ 20 MW add. heating and 30% core radiation or Q = 13 with ~ 40 MW add. Heating and 40% core radiation
  - ➡130 MW: 600 MW fusion power; Q = 9 with 70 MW add. Heating and 30% core radiation

Effect of Divertor Geom k Power load



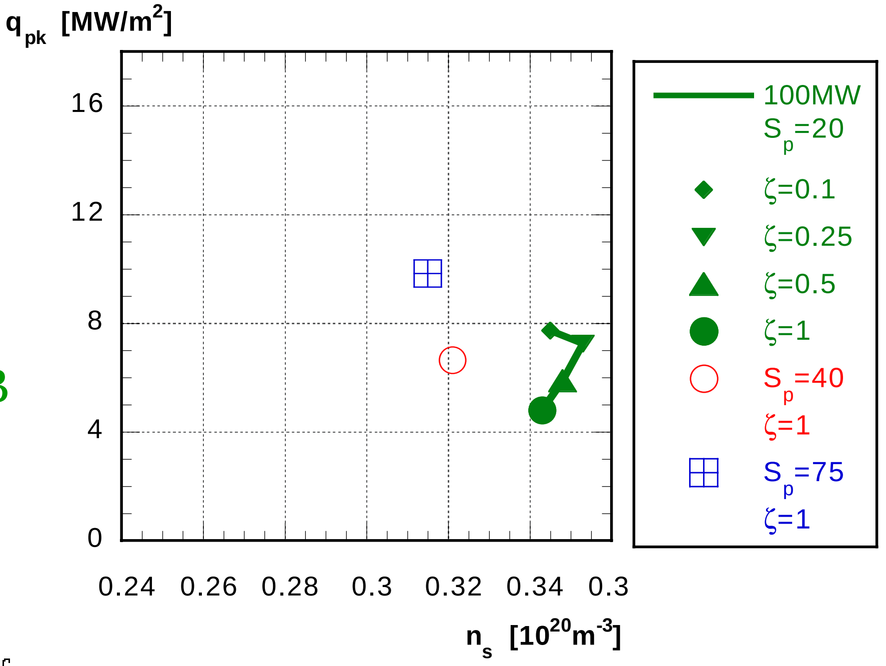
- A small neutral particle reflector plate opposite the strike zones enhances radiation losses there and thus reduces the peak power load on the vertical targets
- For the peak power it is not important if the strike zone is on the vertical target or on the reflector plate



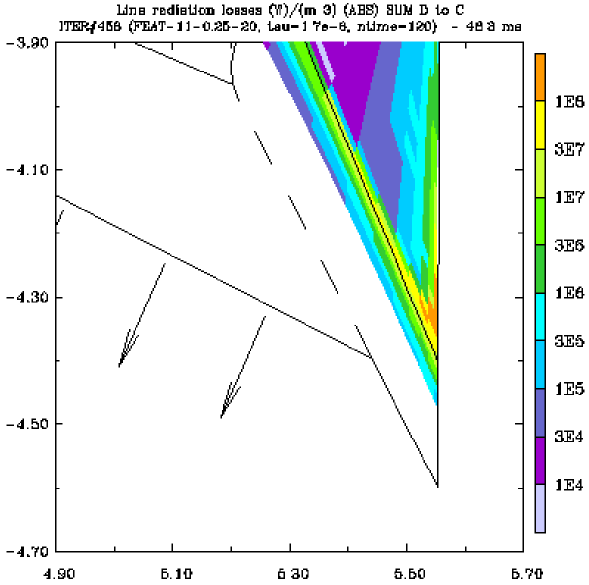
- 100 MW power from the core becomes acceptable with a "V" shaped target
  - ➡Minor differences for different "V" shapes
  - ➡*neutral trapping most important*
  - ➡No difference for helium pumping
  - ➡Consistent with JET experiments with separatrix sweeping
- ***"V" recommended for the ITER design***

Further reduction of the peak power load on the outer target if a large gas conductance between the two divertor channels exists

- Varying the probability for neutrals to cross the private region from 0.1 to 1 gives rise to increased neutral densities at the outer target and thus to enhanced radiation losses there
  - ➡ The enhanced radiation spreads the power on a larger surface and thus reduces the peak power load
  - ➡ This is consistent with JET experiments in the MKII-GB with the septum installed
  - ➡ In ITER 300 Pam^{3}s^{-1} are needed => consistent with the design

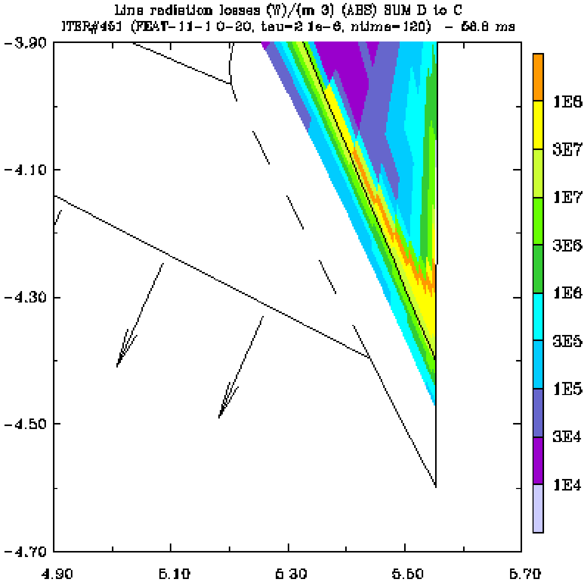


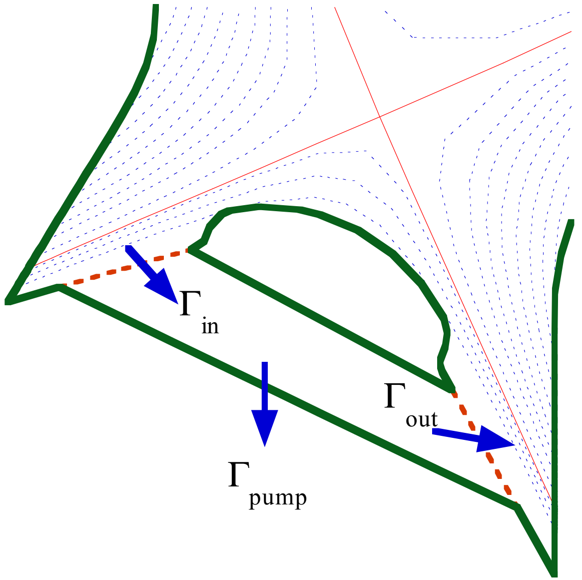
$ζ = 0.25$



q_{rad}

$ζ = 1$



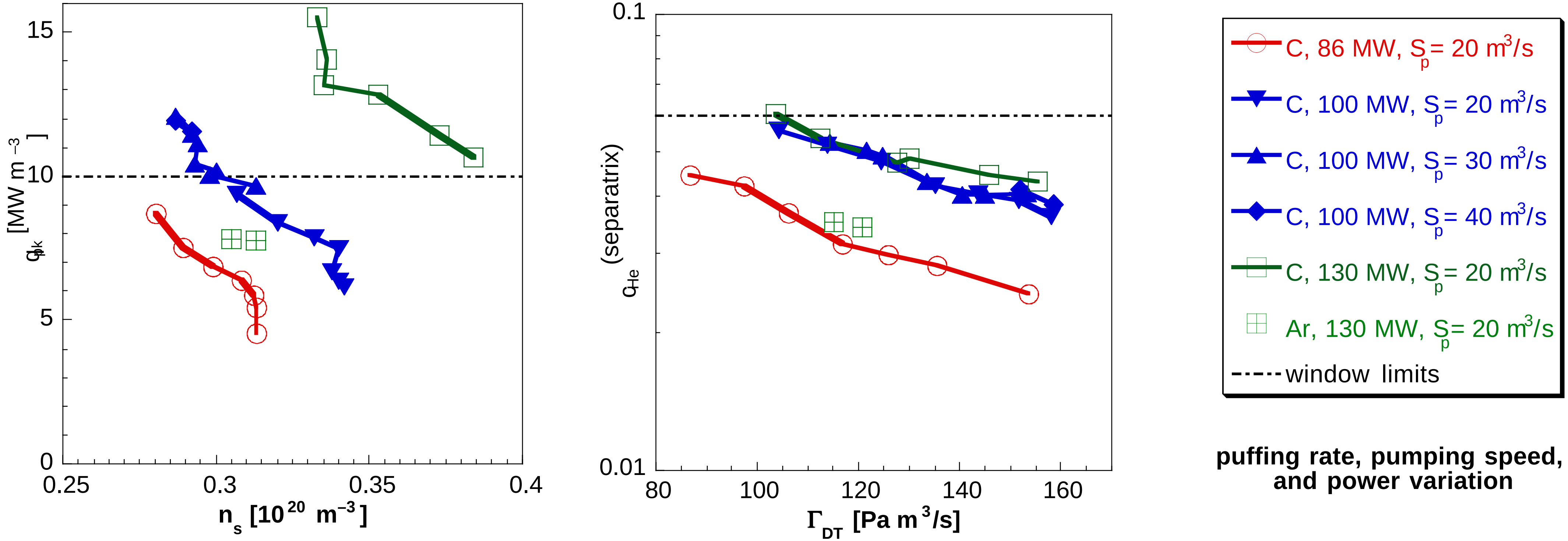


Operational Window for “V” shaped Targets and realistic Conductance between Divertor Channels ($\zeta = 0.56$)

- **Acceptable peak power loads and He exhaust are achieveable for up to 100 MW crossing the separatrix with C targets; for higher powers additional Ar seeding will be needed**
  - ➡ **A power dependent density saturation occurs; it may depend on strike zone position !!**
  - ➡ **He exhaust is o.k. even at peak power loads higher than 10 MWm^{-2}**
  - ➡ **R&D shows that the ITER HHF components may allow operation above 10 MWm^{-2}**

Peak power vs. upstream density

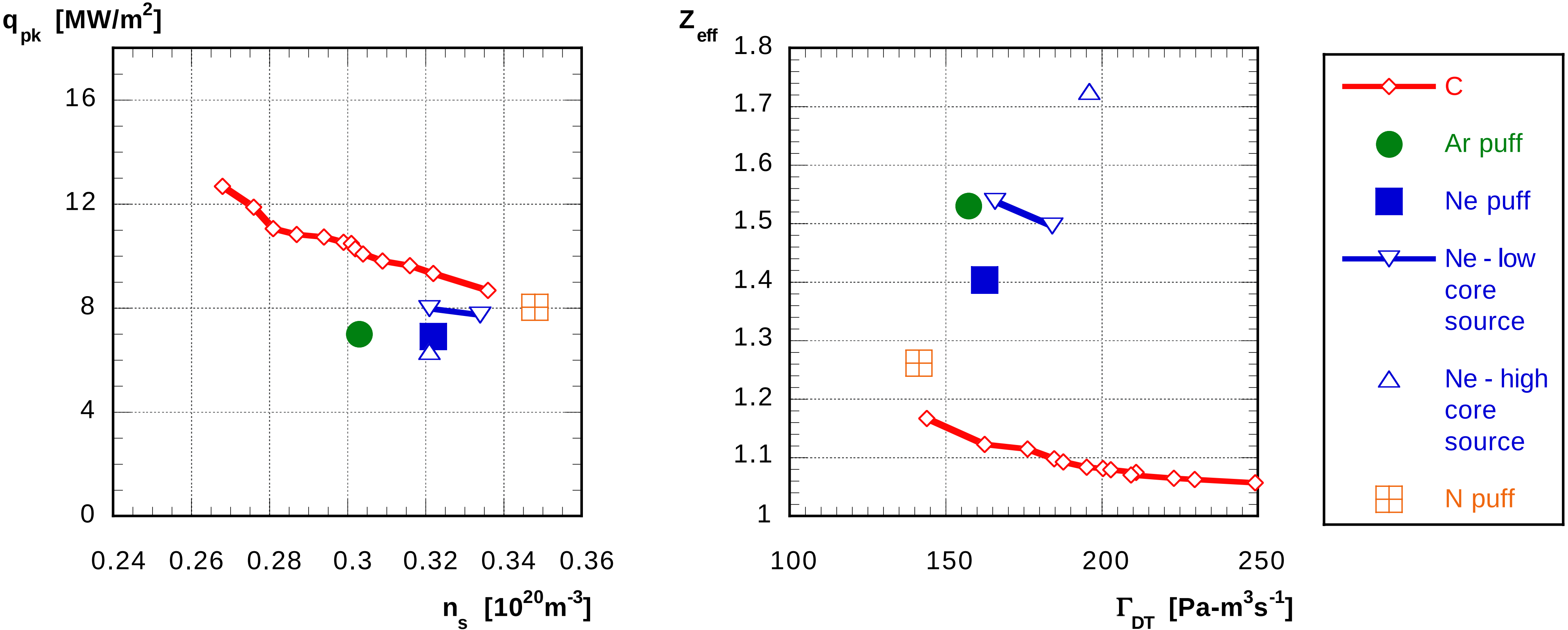
He concentration at the separatrix vs. DT throughput



puffing rate, pumping speed, and power variation

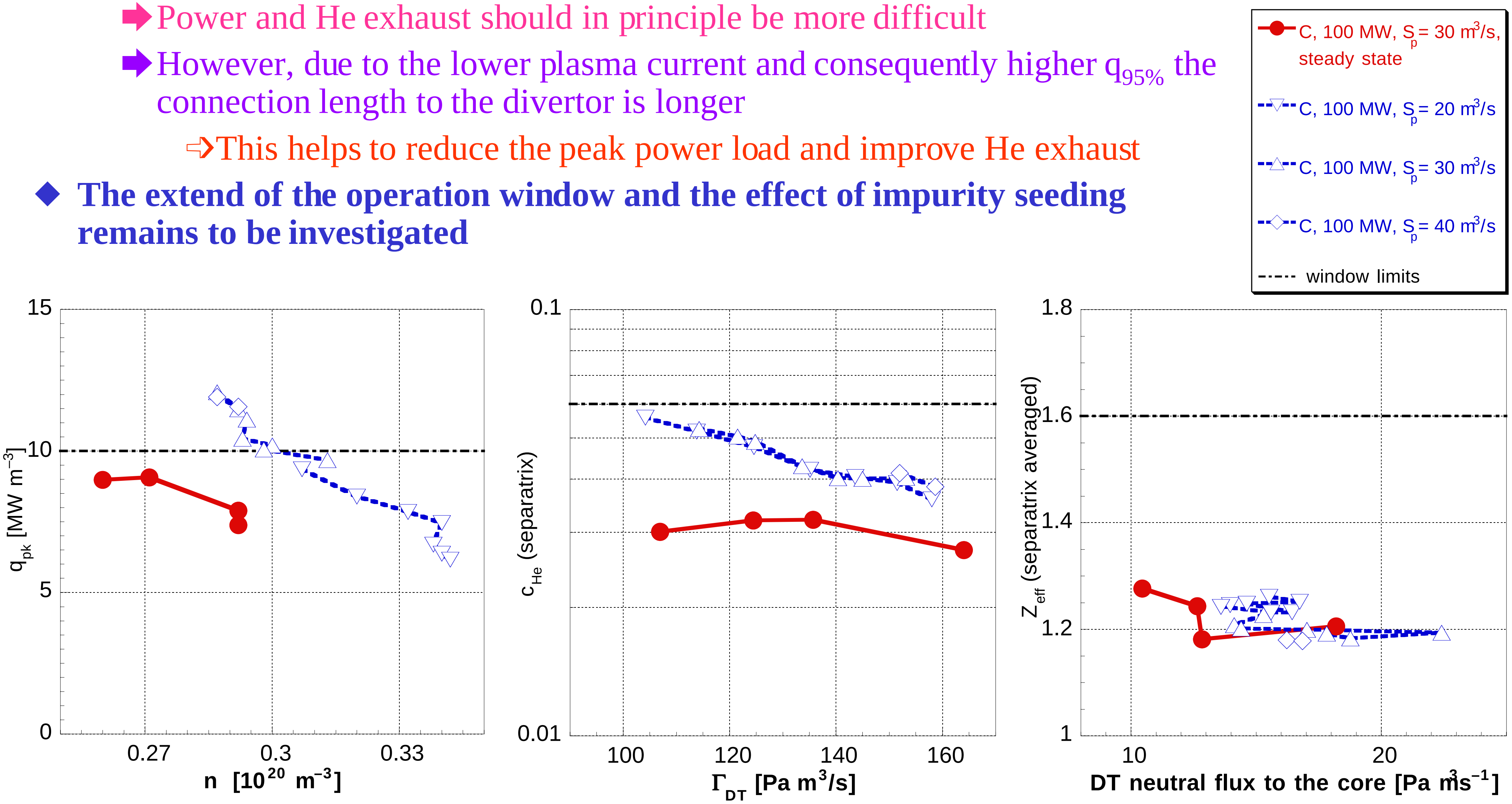
Seeding with Ar, Ne, N can replace C as radiator albeit at higher Z_{eff}

- **Seeding of gaseous impurities keeps the peak power at similar levels as the ones obtained with C sputtered from a CFC target**
  - **The impurity species used seems unimportant for the peak power load at a particular upstream density**
  - **The peak power load reduction depends mainly on Z_{eff}**
  - **From a divertor performance point of view CFC and W targets (with impurity seeding) are possible**



Compatibility of the Divertor with Steady State Operation

- **Steady state discharges are generally characterized by higher power across the separatrix and lower upstream density than in standard scenarios**
  - ➡ Power and He exhaust should in principle be more difficult
  - ➡ However, due to the lower plasma current and consequently higher $q_{95\%}$ the connection length to the divertor is longer
    - ⇨ This helps to reduce the peak power load and improve He exhaust
- **The extend of the operation window and the effect of impurity seeding remains to be investigated**



Summary of Divertor Modelling Results and consequences for the Design

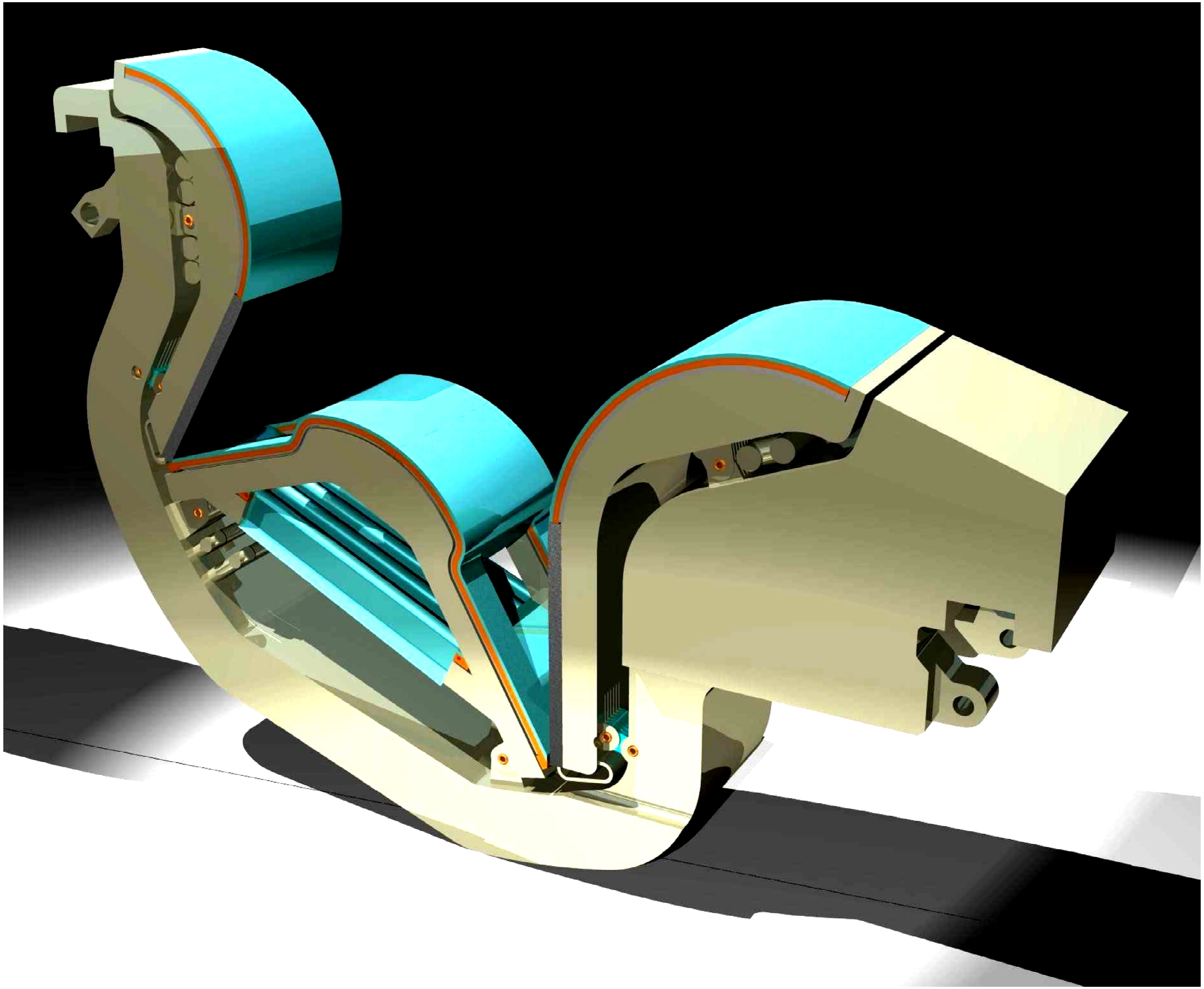
- **A significant operational window for inductive operation exists**
  - V-shaped target configuration is beneficial in particular for low upstream densities
    - It results in a reduction of the peak power load; no deterioration of helium removal
    - It can become restrictive if higher upstream densities are needed
    - SOL density limit can possibly be controlled by changing the strike point position
  - A large gas flow (~ 300 Pam^{3}s^{-1}) between divertor channels is essential for peak power load reduction

- **Different radiating impurities can be used if carbon has to be avoided (e.g. W target)**
  - The trade-off between radiated power and Z_{eff} in the core is not strongly affected by the choice of the seeded impuritiy (Ar, Ne, N)
  - The difference in fuel dilution for Ar, Ne, N is also not large for $Z_{eff} < 2$

- **Divertor performance seems also acceptable in non-inductive steady-state operation despite higher SOL-power and lower upstream density due to the increased connection length**
  - Higher $q_{95\%}$ results in lower peak power for the same upstream density
  - Further work necessary to map out the operation window and the effect of impurity seeding

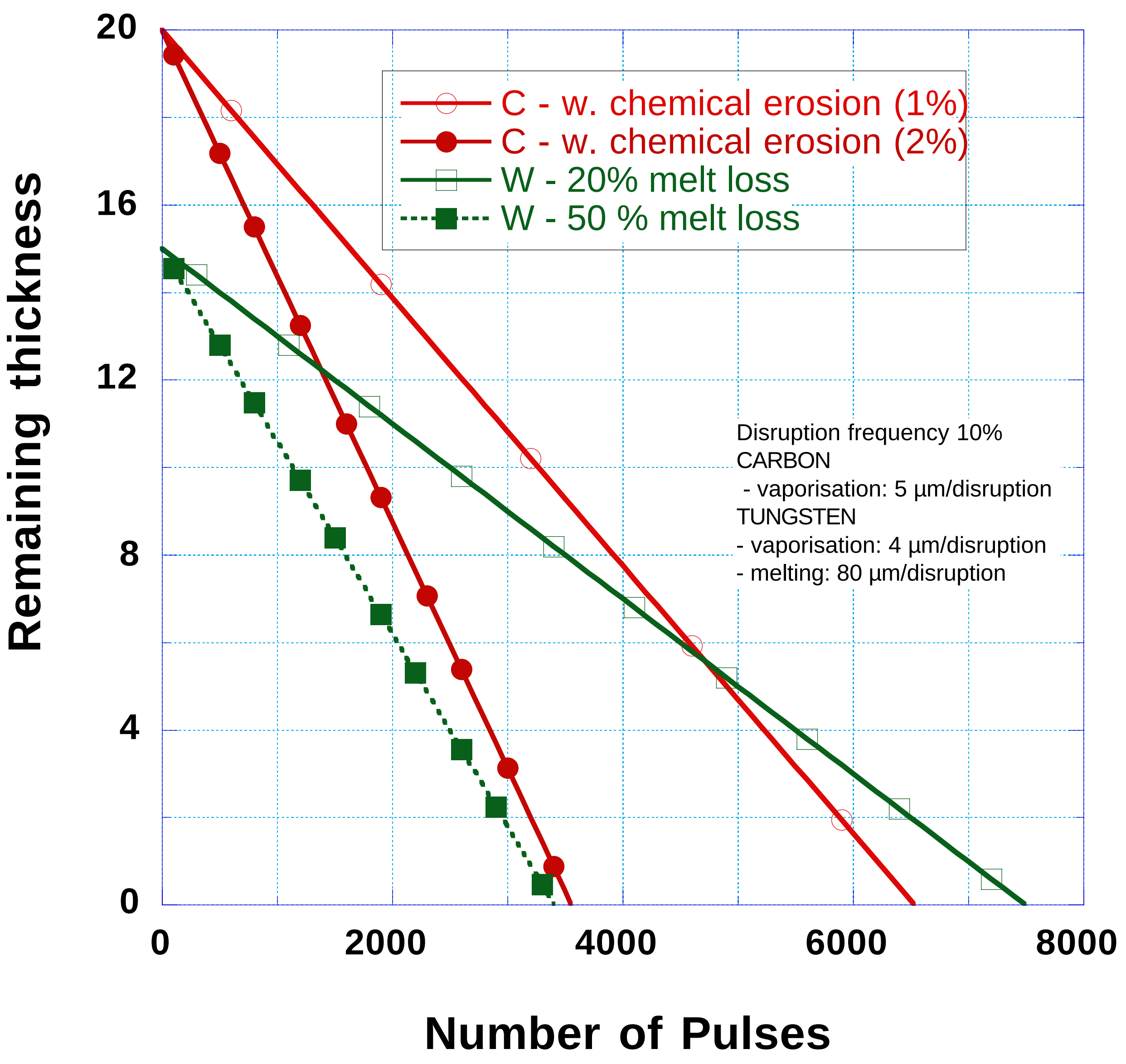
- **Beneficial divertor geometry features have been implemented into the ITER design**

The ITER FEAT Divertor



Erosion Lifetime of Vertical Targets in ITER

- **Composite lifetime of the target near the strike-points taking into account effects of sputtering, slow transients and disruption (exclude ELMs)**
  - **For a carbon target lifetime is dominated by chemical sputtering.**
  - **For a tungsten target the lifetime is dominated by loss of melt layer during disruptions.**



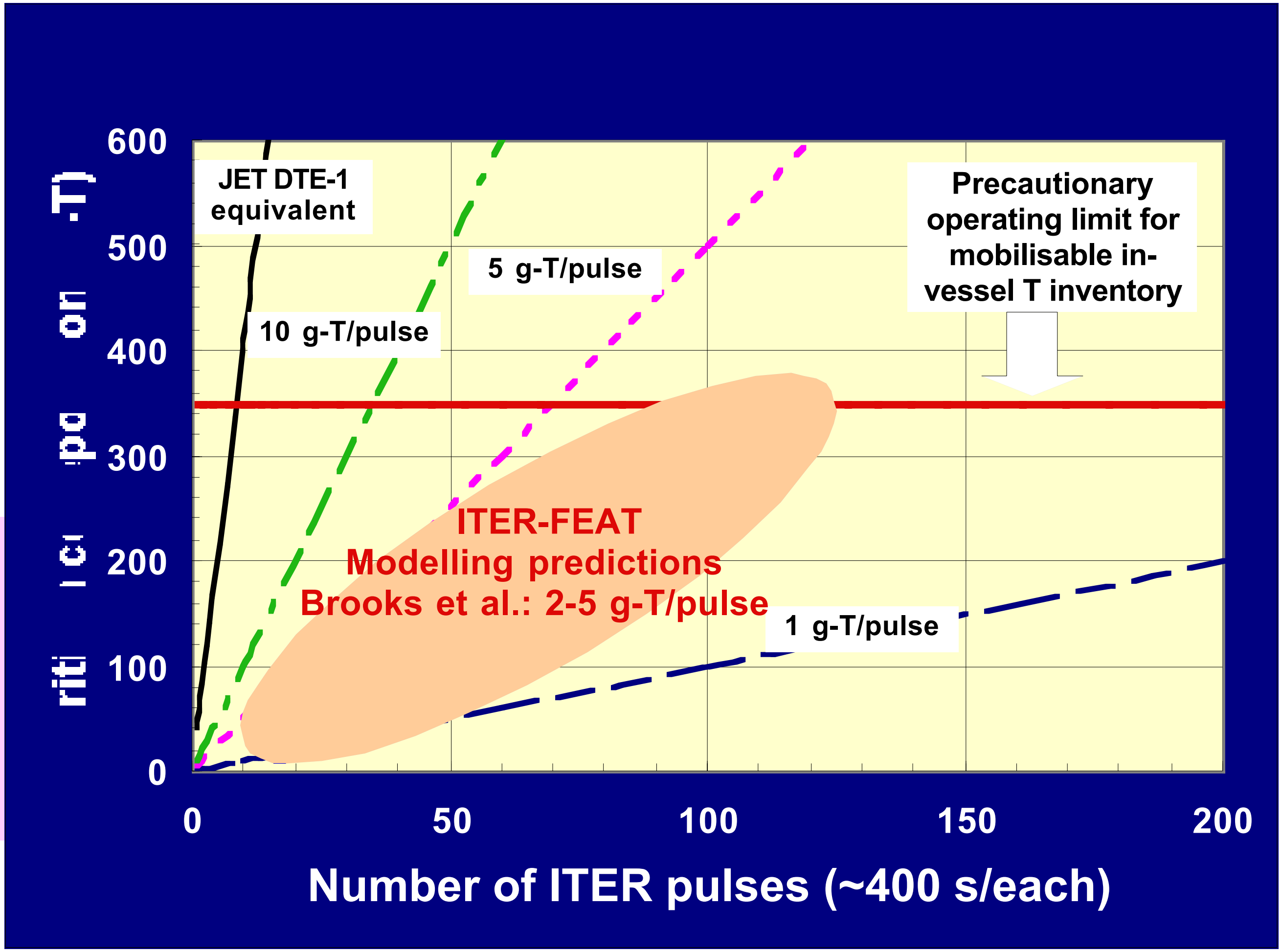
Disruption frequency 10%
CARBON
- vaporisation: 5 µm/disruption
TUNGSTEN
- vaporisation: 4 µm/disruption
- melting: 80 µm/disruption

Codeposited Tritium Removal Requirements

- Maintaining C in ITER has a strong impact on in-vessel T-inventory.
- Frequency of clean-up depends on the codeposition rate (modelling) and in-vessel tritium hold-up limits (safety).
- A precautionary operating limit of 350 g-T (1000g in 1998 ITER design) is now set in ITER-FEAT, based on safety considerations, for the mobilisable in-vessel tritium.

Codep. rate (g-T/pulse)	No. Pulses to reach limit 350 g-T
1	350
2	175
5	70
10	35

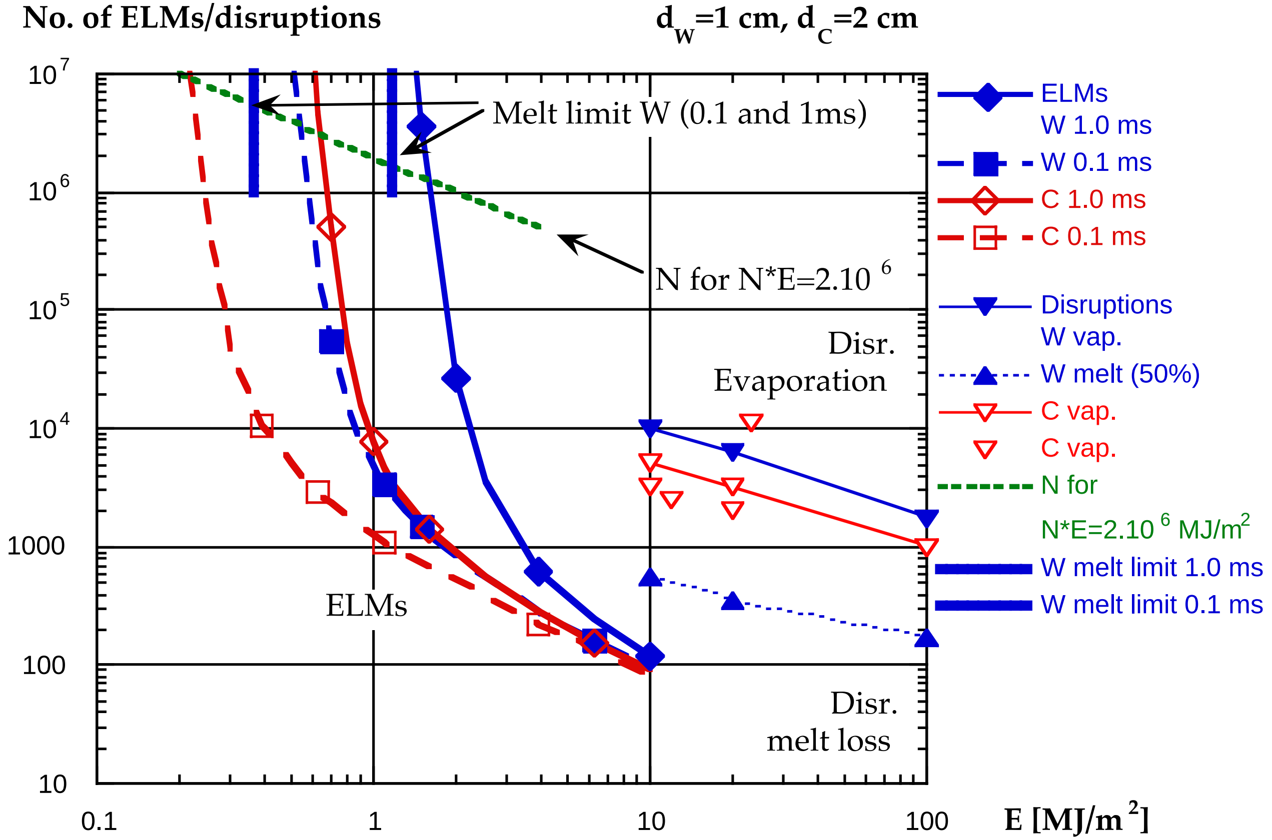
=>Codeposition prediction by Brooks (ANL): 2-5 g-T/pulse



Limits for ELM Energy Loads on the Divertor Targets

- **An ITER-FEAT discharge will have ~ 1000 Type-I ELMs and the divertor should achieve a lifetime of several 1000 discharges**
    - Targets have to withstand several 10^6 ELMs
    - permissible ELM energy load at vaporisation or melt limit whatever is lower !!
- **The ELM energy load depends on the energy stored in the pedestal and on the transport time along fieldlines**
    - Pedestal energy is not a free parameter !!
    - The SOL transport time for ITER-FEAT is ~ 200 µs

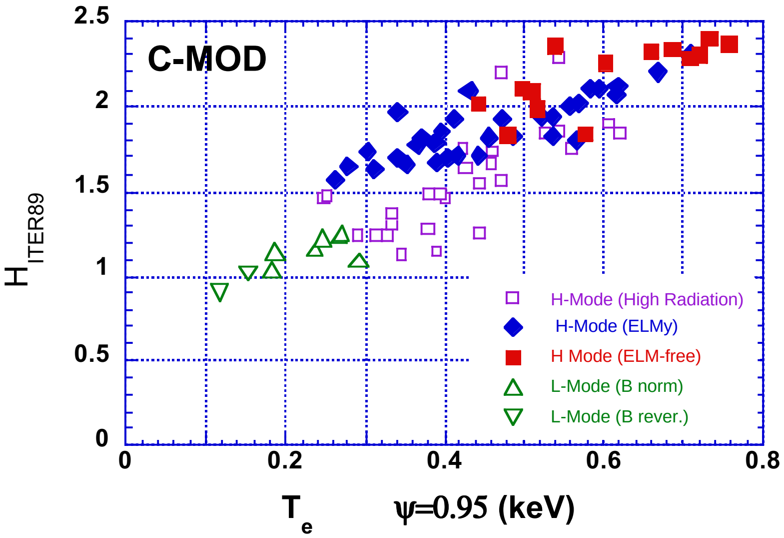
Vaporisation and melt limits for 0.1 to 1ms depoition-time

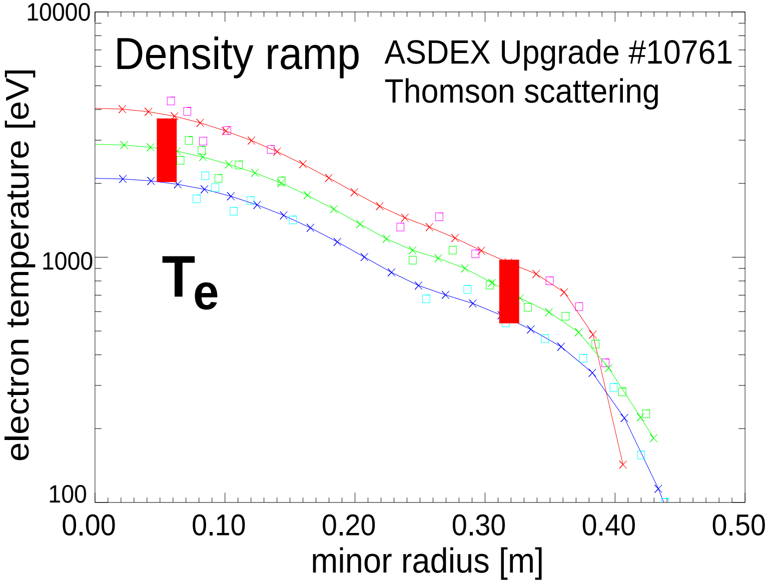


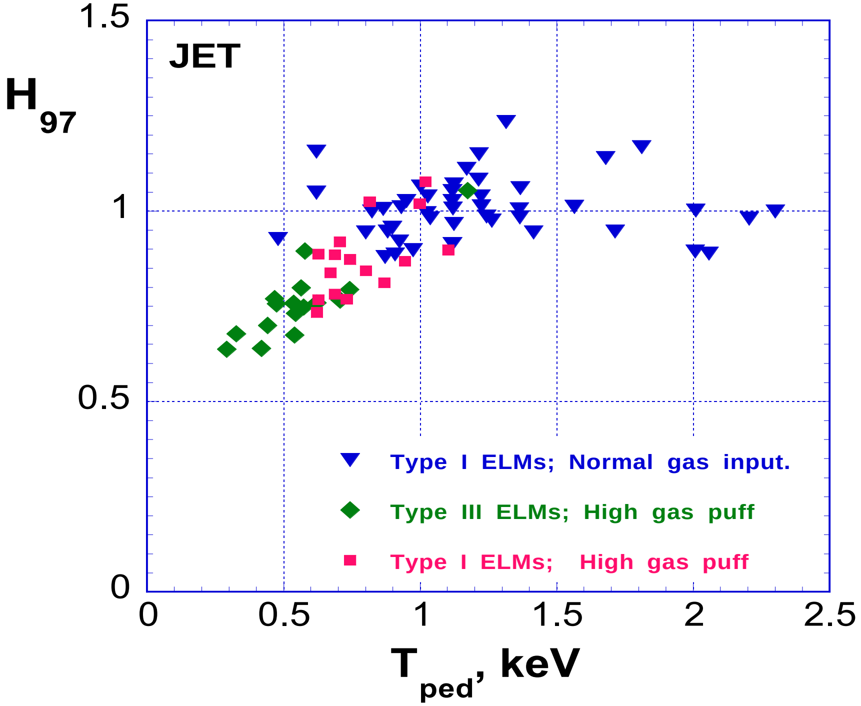
Allowable deposition for 10^6 ELMs	**C (0.2 ms)**	**W (0.2 ms)**
Energy MJm^{-2}	**0.33**	**0.52**
Energy for S = 8m^{-2}	**2.61**	**4.16**
Energy for S = 16m^{-2}	**5.22**	**8.33**

Dependence of Energy Confinement on the H-mode Pedestal

- On medium size machines (C-mod, ASDEX-UP) Energy Confinement (Central ion (electron) temperature) and H-mode pedestal temperature are proportional
- On large machines we see the same behavior only below a certain pedestal temperature

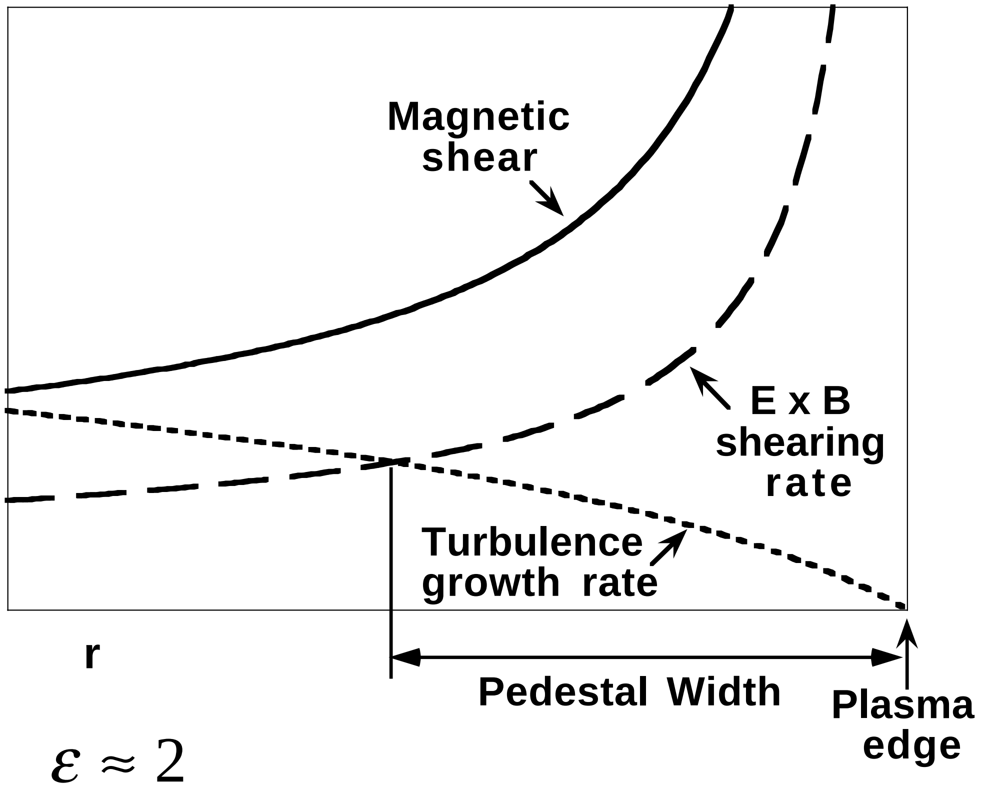






A possible Physics Model for the Pedestal Width

- **Hypothesis:**
  - Turbulence is suppressed by a combination of magnetic shear and ExB shear
  - The turbulence groth rate is reduced by an increasing magnetic shear $\gamma_s \sim 1/S^2$
  - IFSPPL formulation is taken as a typical turbulence
  - E_r is mainly produced by the pressure gradient; at the limit $\nabla p \propto S$
  - The width of the pedestal is defined at the point where γ_s and ExB shear are eaqual



$$\varepsilon \approx 2$$

- **The resultant dependence of $\Delta \propto \rho_{tor} S^{\varepsilon}$ gives:**
  - A $\rho_{poloidal}$ like Δ behavior
  - Explains the machine size dependence of Δ
  - Explains the lower width in ELM free conditions and for second stability access due to the high bootstrap current -> shear change !

$$\gamma_s \approx \chi_{GB}\kappa_\perp^2 \approx \rho_{tor} c_s \frac{\rho_{tor}}{x_0}\kappa_\perp^2 \frac{1}{S^\varepsilon} \approx \frac{c_s}{x_0}\frac{1}{S^\varepsilon}$$

$$\gamma_{ExB} \approx \frac{\partial}{\partial x}\left(\frac{E_r}{B}\right) \approx \frac{\partial}{\partial x}\left(\frac{1}{B}\frac{(\nabla p)_c}{n}\right) \approx \frac{\rho_{tor} c_s}{x_0^2}$$

Using the model for extrapolation to ITER gives T_{ped} ~ 3 to 4 keV

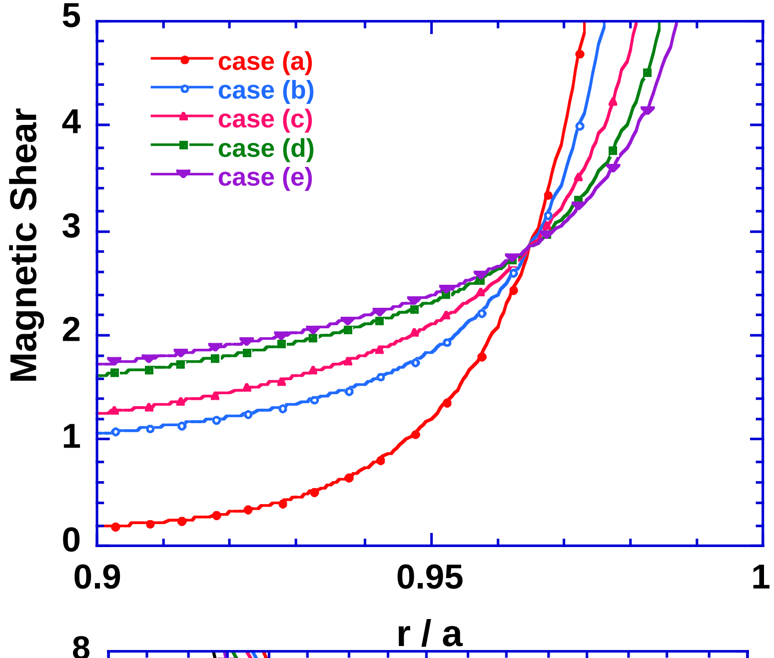
- In order to extrapolate the pedestal pressure to ITER we calibrate the shear profile and the resulting width with JET data (one discharge)
  - ➡ Different q profiles are investigated with the boundary condition that $q_{95\%} = 2.84$, $S_{95\%} = 2.86$ and that the pedestal width is 7 cm

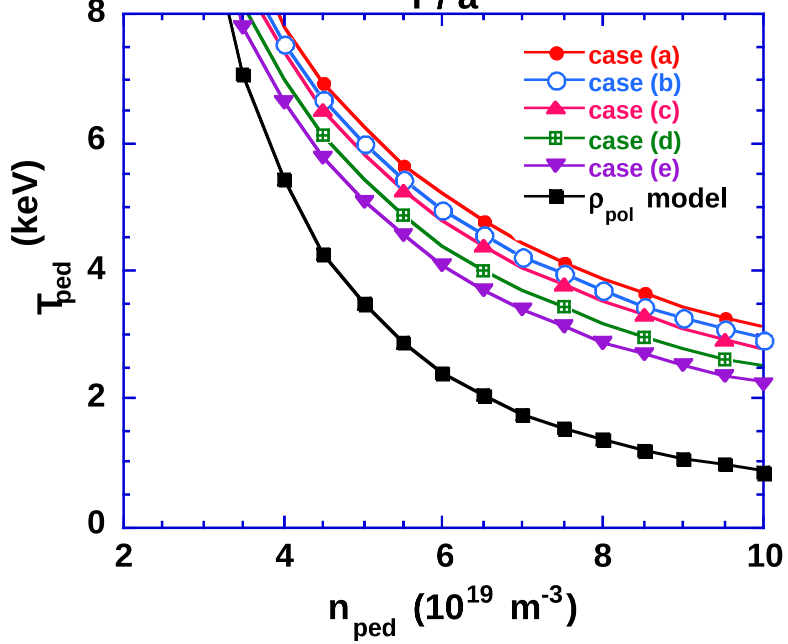
Pedestal Temperature *(keV)*	Pedestal Density *($10^{19}\,m^{-3}$)*	Pedestal Energy *(MJ)*	Pedestal Width *(cm)*
3 - 4	7 - 9	100 - 120	10 - 15

- The pedestal energy content is ~1/3 of the total energy content and T_{ped} is in line with requirements from 1st principle models

- For comparison the results of scaling:

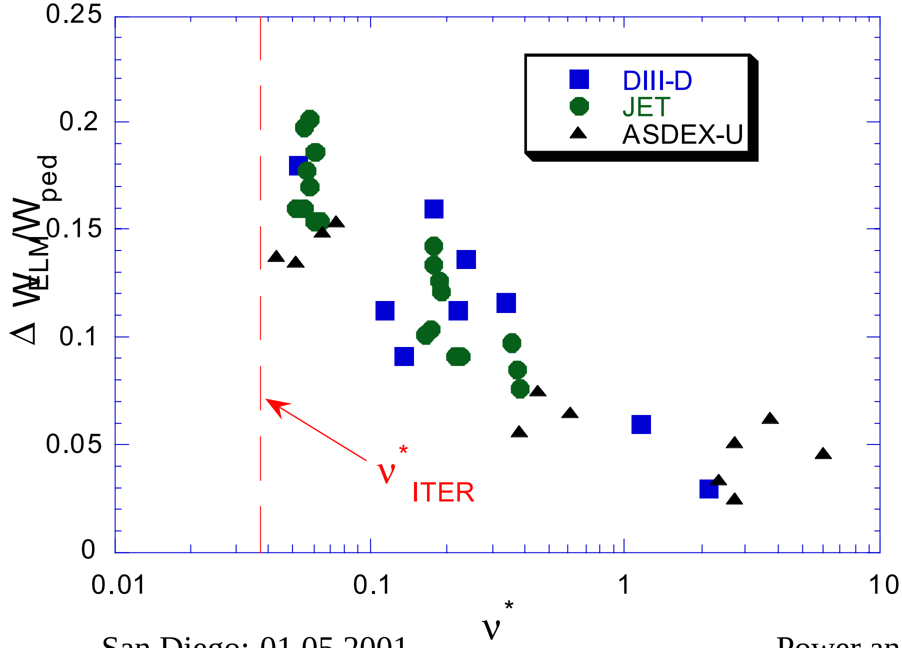
Scaling	Pedestal Temperature *(keV)*	Pedestal Energy *(MJ)*
Takizuka	2.9	97
Kardaun	9.9	330
Kardaun_Cordey new	2.9	96





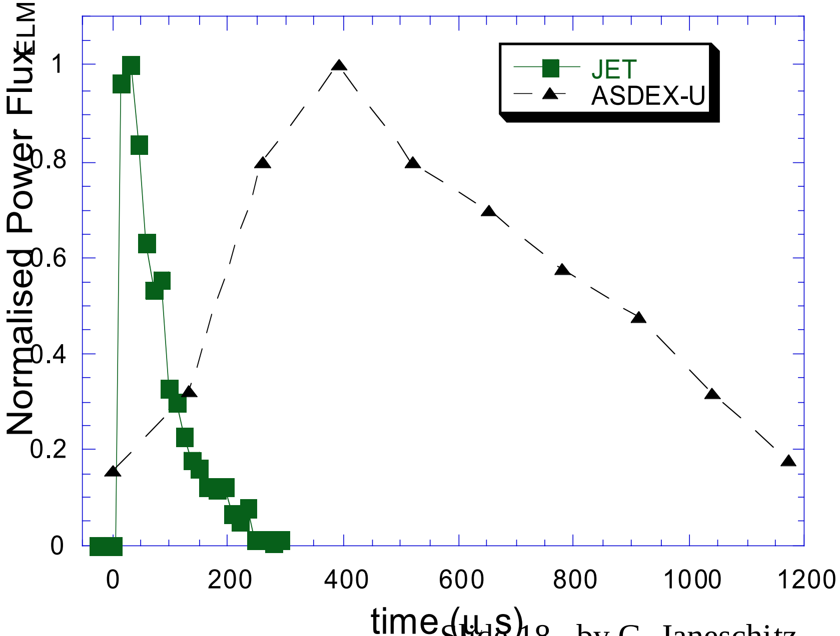
Energy Stored in the Pedestal, ELM Loss Fraction

- **T_{Ped} of 3.5 keV and $0.8 \times 10^{20} m^{-3}$ n_{Ped} results in W_{ped} = 107 MJ (53.5 in electrons)**
  - Based on the ITER ELM energy loss database 26% to 36% of the electron energy are lost during Type-I ELMs in JET and DIII-D (T. Leonard-PSI-98)
  - Thus 14 MJ to 19 MJ (4 to 5 % of the total stored energy) would be lost during a Type-I ELM in ITER-FEAT and in its majority deposited on the divertor targets (higher than allowable !!!)
- **On JET and JT60U the energy deposition time is ~ 100 to 180 µs which is comparable to the ion sound speed when assuming pedestal plasma parameters are relevant during an ELM**
- **In higher density DIII-D and ASDEX-UP discharges the energy deposition times seem to be significantly longer and the ELM energy loss fraction is ~ 2% of the total stored energy**
- **ELM energy loss fraction seems to depend on collisionality along fieldlines taking pedestal plasma parameter into account**



<---A. Loarte, IAEA 2000

Hermann, Clement-Gauthier--->



Ansatz for extrapolation of ELM energy loss fraction

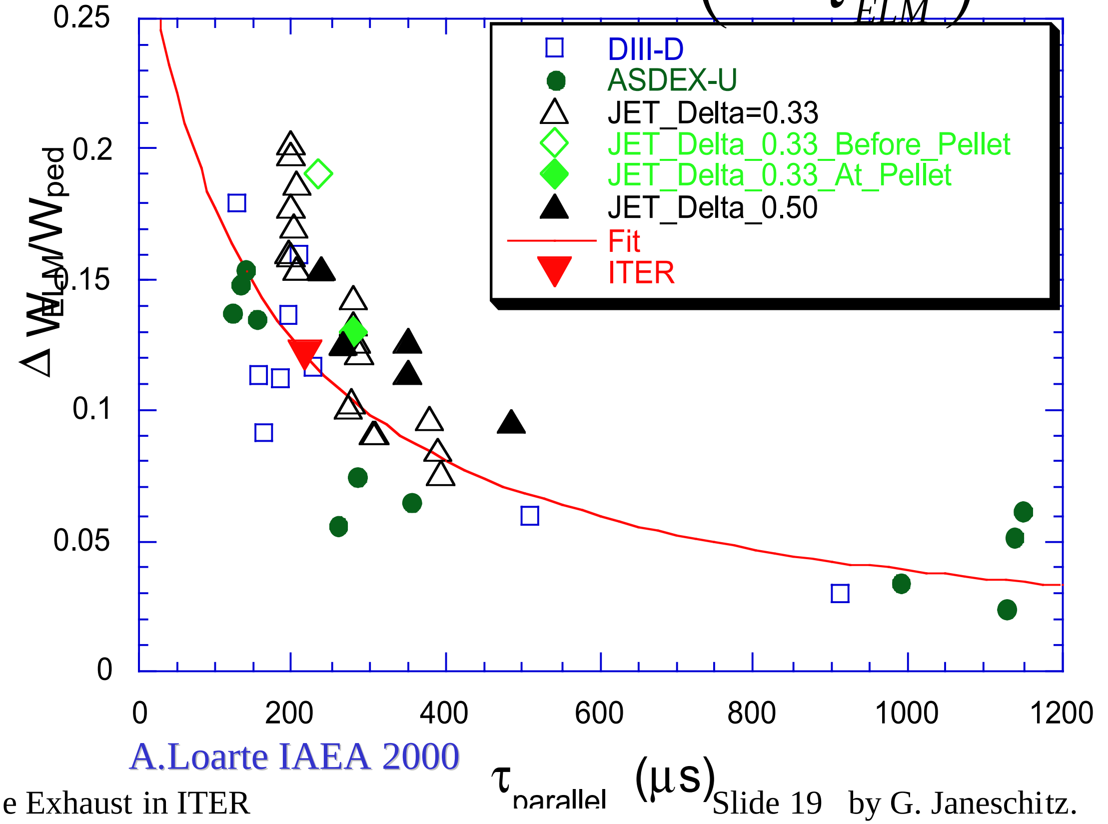
- **Hypothesis: ELM energy transport depends largely on ion convection time along fieldlines**
  - Low collisionality-> electrons cannot remove ion power, electrons repelled by high sheath, ambipolarity-> electron conduction removes fraction of e- energy (~20%)
  - Energy deposition time proportional to the pedestal temperature (a few 100 µs)

G. Janeschitz, PSI 2000-->

$$\tau_{\parallel} = {}^{2L}\!/_{c_s}\left(1 + \sqrt{{}^{3}\!/_{2}}\ \nu^{*}\right)$$

$$\frac{\Delta W}{W} = \left(\frac{\Delta W}{W}\right)_0 \frac{1}{\left(1+\dfrac{\tau_{//}}{\tau_{ELM}}\right)};$$

- **The energy which can be transported in a given time along fieldlines is therefore limited and depends on the pedestal temperature**
  - If the ELM turbulence time τ_{ELM} in the pedestal is short compared to the ELM transport time a “plugging” can occur which will limit the total amount of energy lost
- **Using this “ansatz” and fitting τ_{ELM} and the nonlimited W_{ELM} either to two extreme discharges or the whole dataset shows good agreement with experimental data!!**



A.Loarte IAEA 2000

Transient ELM power load in ITER; some consistency checks

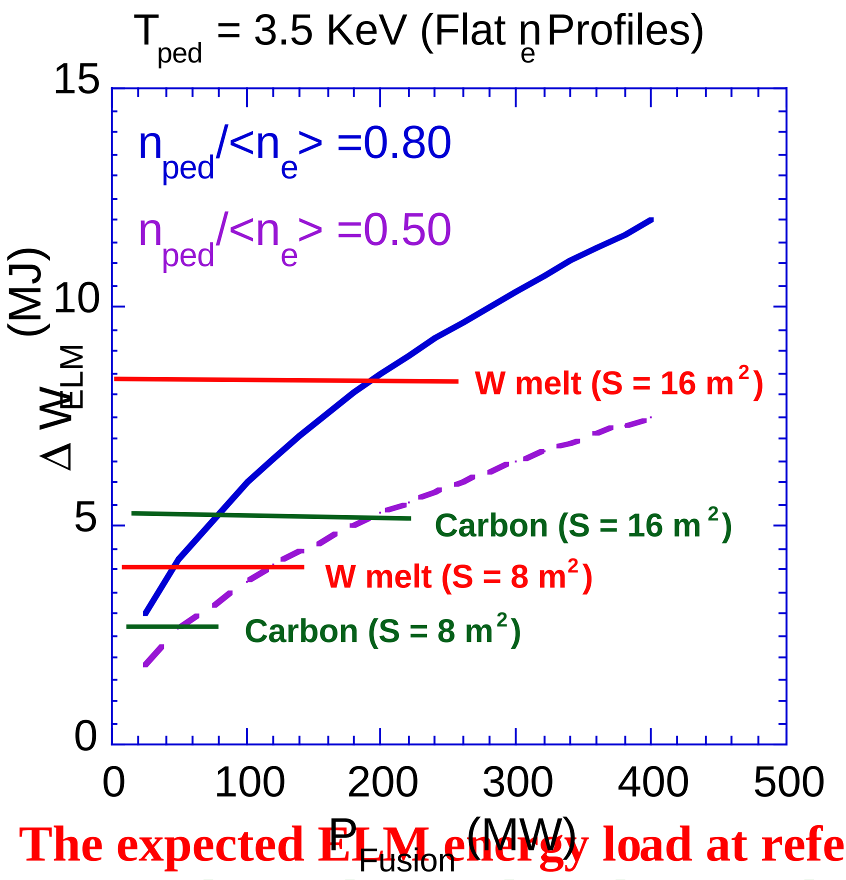
- **1. Plasma parameters between ELMs :**
  - n_{ped} = 8 1020 m-3 T_{ped} = 3.5 keV
  - n_{sep} = 3 1019 m-3 T_{sep} = 250 eV
  - $<n_{div}>$= 8 1020 m-3 $<T_{div}>$ = 5 eV
  - Ion $Flux_{div}$= 4.5 10^{24} s^{-1}, Power $Flux_{div}$= 30 MW

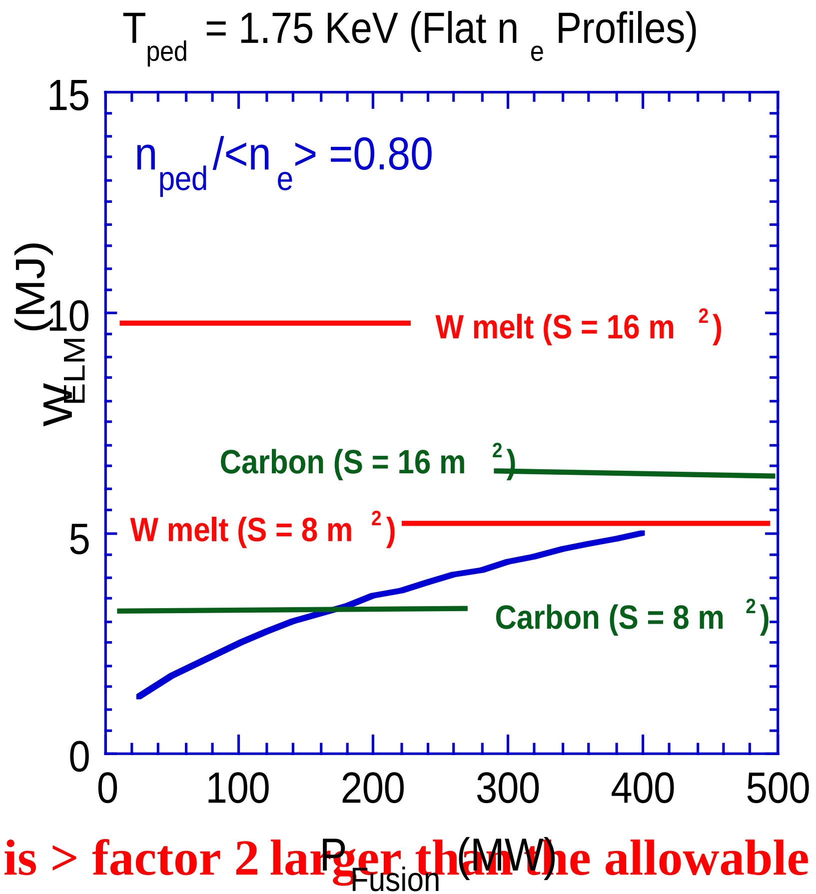
- **2. ELM expected Power Flux 25 – 50 GW**
  - (ΔW_{ELM} = 5 – 10 MJ, τ_{ELM} = 200 μs)

- **3. Possible ELM Phases :**
  - a)Connection of Pedestal to Divertor; b)Formation of Sheath in Equilibrium with Pedestal Electrons at 3.5 keV (reached in few μs)
  - c) Loss of Divertor Ions accelerated by new Sheath Electric Field (E_{sheath}= 2.8 T_{ped}= 10 kV)
    - **Power Flux = 7 GW -> 10% to 20% of ELM energy**

- **Divertor Plasma cannot thermalise with 3.5 keV Electrons, otherwise p_{divELM} = 2.8 10^{24}eVm^{-3} >$P_{ITERCore}$; Pressure balance causes density to go down !! No momentum source !**
  - d) Equilibration of p_{div} with p_{ped} in Ion Transport Time Scale (L/c_s) -> Large Energy Pulse
    - **Power Flux = 30 – 60 GW -> 80% to 90% of energy come with ion timescale**

Comparison of Expected and Allowable Energy Loads

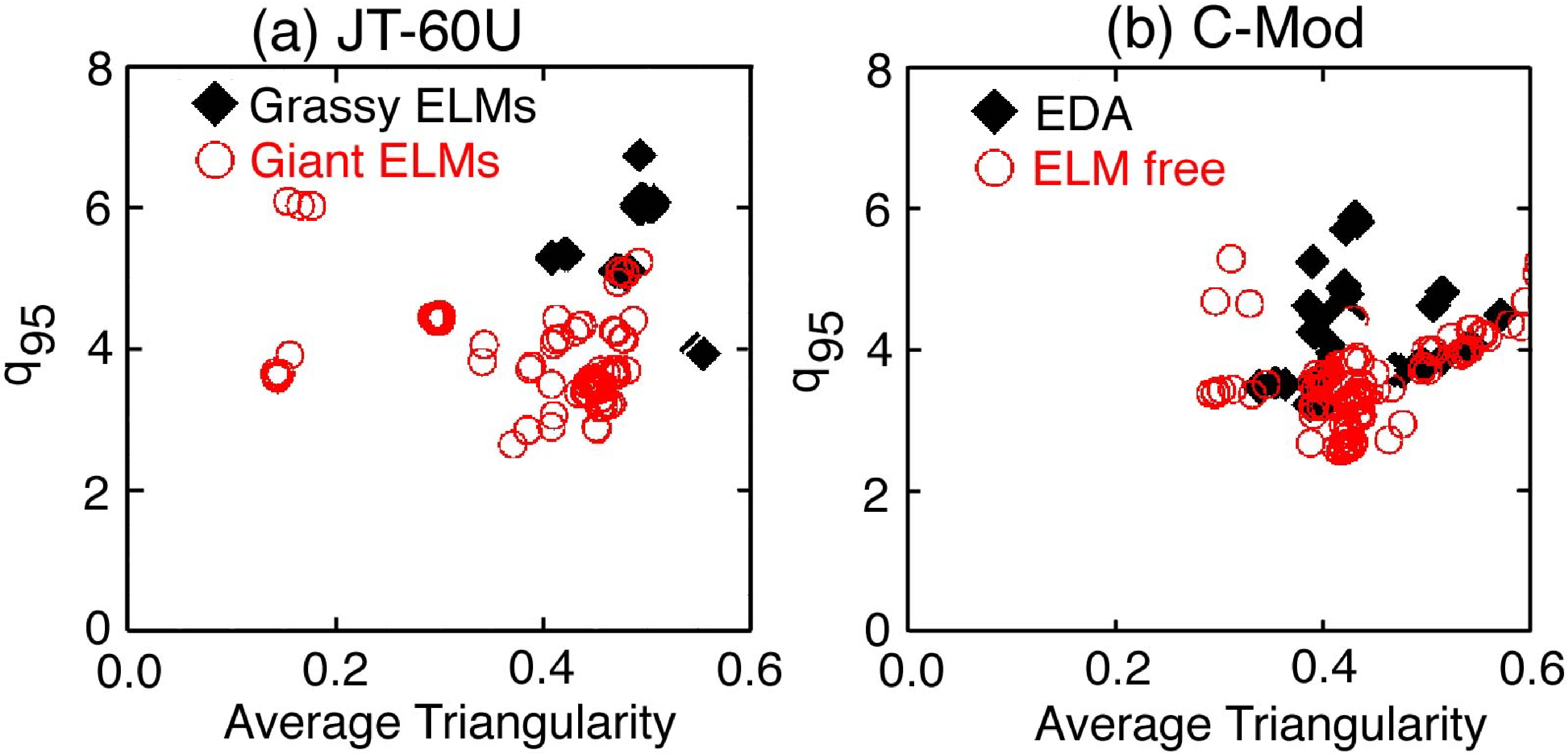

T_{ped} = 3.5 KeV (Flat n_e Profiles)


T_{ped} = 1.75 KeV (Flat n_e Profiles)

- **The expected ELM energy load at reference P_{Fus} is > factor 2 larger than the allowable for CFC and 30% larger than the W melt limit if S_{ELM} is 2 (4) x S_{SOL}**
  - ➡ A peaking of the density profile and a reduction of the pedestal density could make the ELMs marginally compatible with a W target
- **Method for mitigation of Type I ELMs without confinement loss at high pedestal pressure is difficult to be achieved (even ELMs generated by pellets are following general behaviour)**
  - ➡ Alternative regimes such as Type II ELMs and possibly RI-mode should be substantiated !!

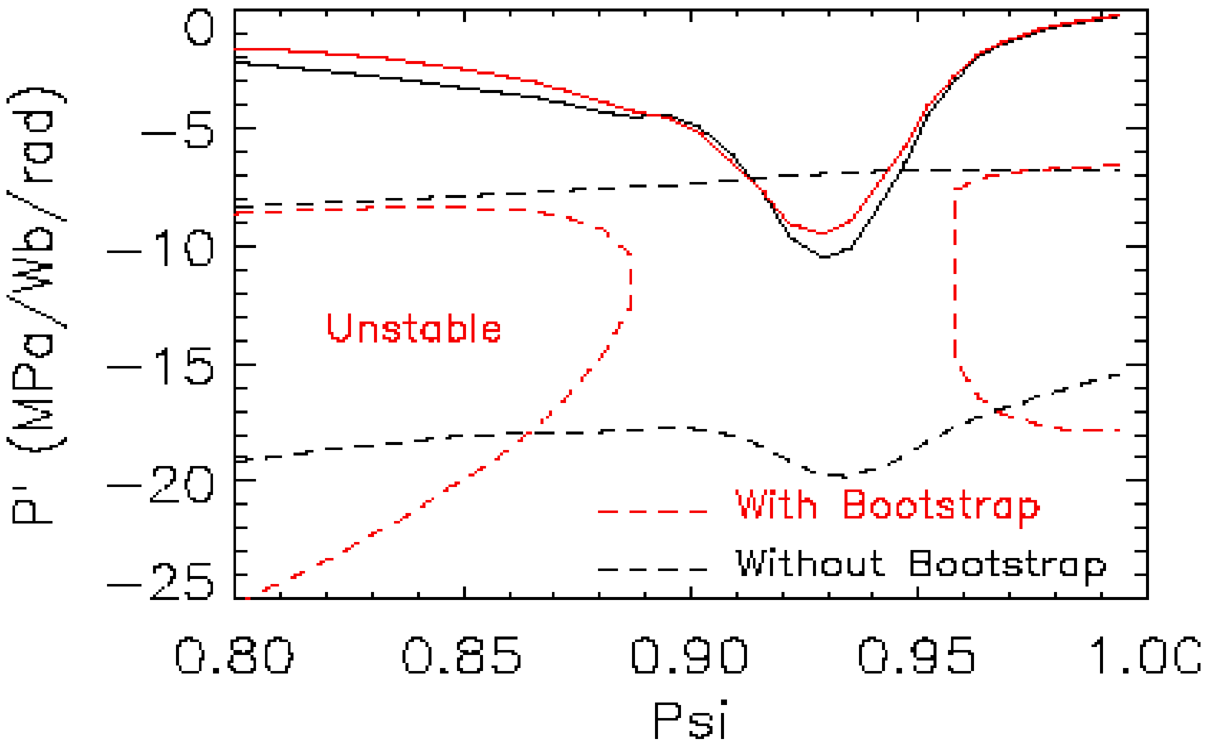
Are Type II ELMs or EDA a Solution for this Problem ?

- **Type II ELMs provide energy confinement similar to Type I ELMs but with lower pulsed energy loads and at high density (> 0.8 n_G in ASDEX-U) both favourable for ITER**
  - ➡ However, they seem to exist only at $q_{95\%}$ > 3.5 !!! -> loss of performance in ITER
  - ➡ The high triangularity (> 0.4) and the $q_{95\%}$ > 3.5 requirement suggest a connection to a second stability access for the high n ballooning limit (is this sufficient ? -> no !!)



(Too) Simple ?? Hypothesis for Type II ELMs

- **Type II ELMs or EDA (is the same) are in principle small Type I ELMs**
  - They only crash a small fraction of the pedestal near the separatrix
  - It is important that inside this crash region a second stability window exists (no pressure gradient limit) because the pressure wave due to the crash would otherwise propagate the crash inward -> would give a large Type I ELM !!
  - It is also important that the first stability limit is violated near the separatrix and not inside the pedestal -> would give a large Type I ELM !!



What can trigger the violation at the outer window boundary ?

One possibility is fuelling

which would cause a distortion of the pressure profile near the ionisation maximum (low D)

-> possibility to drive gradient over the edge if ionisation maximum is at the right position ??

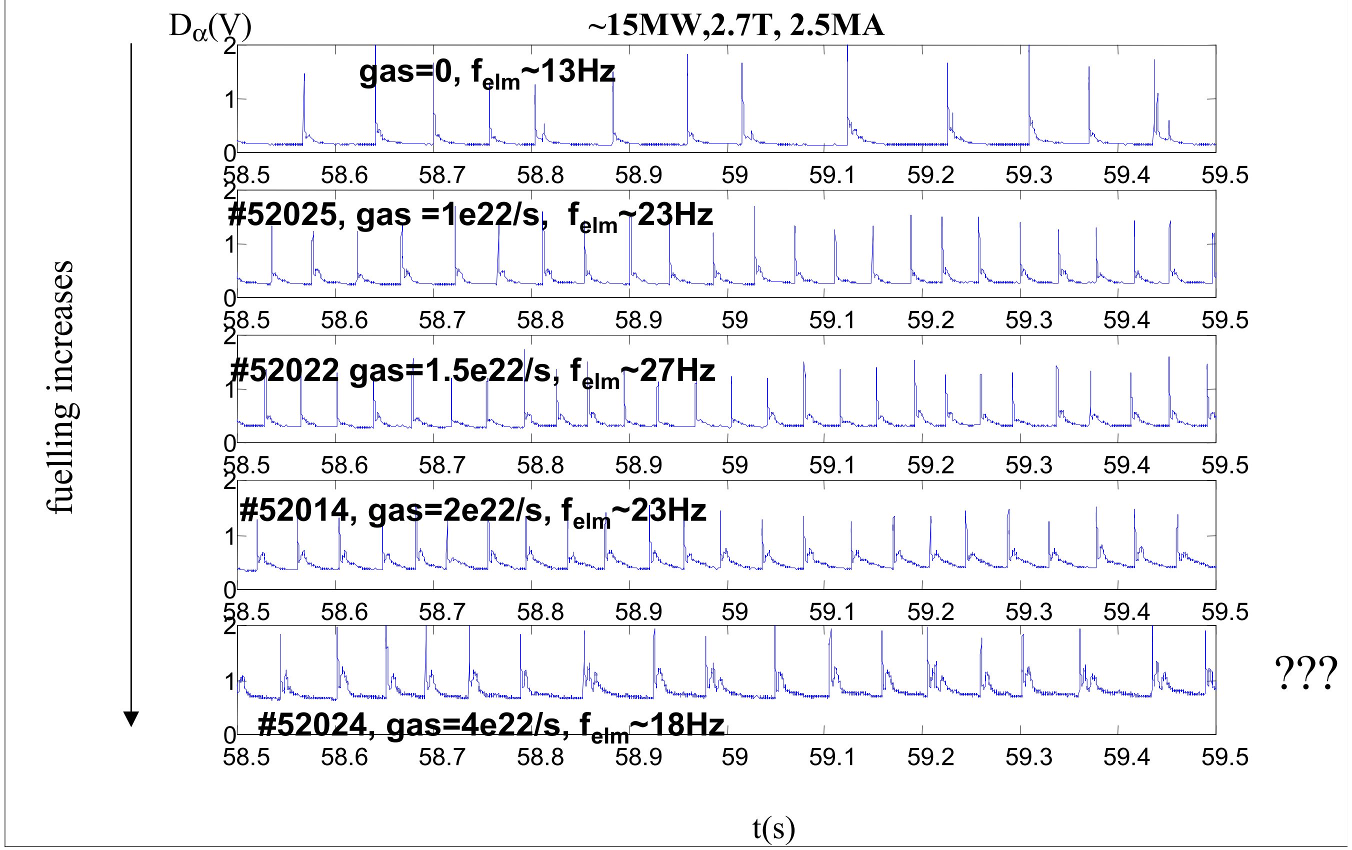
ELM behaviour at high triangularity and high gas puff rate in JET

- **At high gas puff rate the ELM frequency decreases again and another loss mechanism seems to exist between ~ELMs (Type II ELMs at $q_{95\%}$ ~ 2.8-3 ???)**
  - ➡ELM energy load follows nevertheless the general behaviour vs collisionality or $\tau_{//}$

G. Saibene, M. Becoulet

Type II ELMs - J. Stober

Gas injection and ELMs frequency at high triangularity u/l~ 0.47/0.4, elon~1.7



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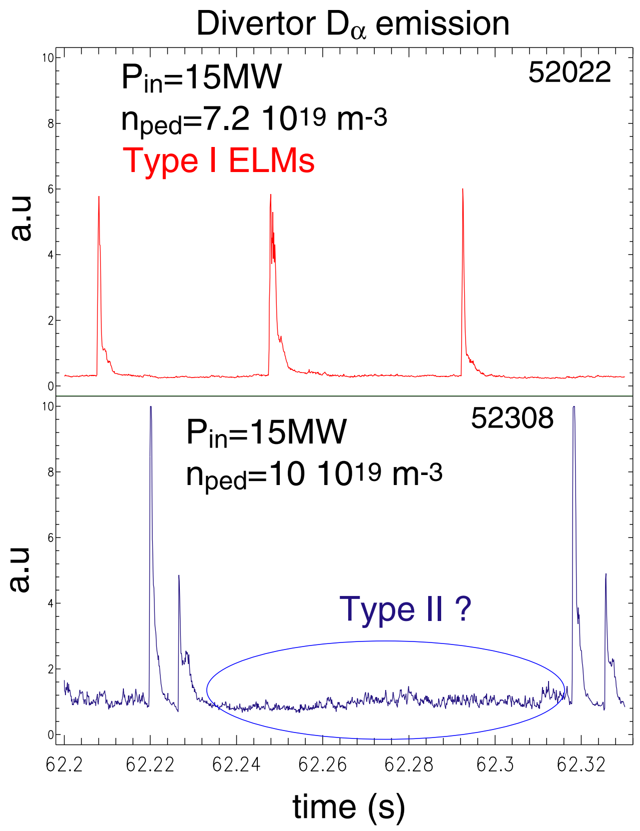

Summary and Conclusions

- **Divertor modeling shows a significant influence of the divertor geometry on the peak power load and on the SOL density limit -> input to engineering design:**
  - ➡“V” shaped baffles on the bottom of the vertical targets
  - ➡Large conductance for neutrals from inner to outer divertor
  - ➡R&D allows the use of CFC and W at the strike zones

- **T-co-deposition remains an issue for CFC clad targets while the melt layer loss during disruptions is the main issue for W clad targets**

- **A high H-mode pedestal pressure and thus energy content is important for good core confinement and therefore for achieving the goals of ITER**
  - ➡Pedestal width scales most likely as $\rho_T x\ S^2$ -> 10 to 15 cm in ITER
    - ➩T_{ped} ~ 3 to 4 keV, W_{ped} ~ 100 MJ --> good confinement and performance possible

- **The Type I ELM energy load seems to be related to W_{ped}, τ_{ELM} (the ELM duration) and to the transport time along fieldlines**
  - ➡Based on present extrapolations the Type I ELM energy load in ITER will be marginally too high for the divertor targets but a large uncertainty remains
  - ➡A regime with Type II ELMs is an attractive alternative which most likely can also achieve Q=10 in ITER