ELMs & ELM Scaling

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European Fusion Development Agreement

Close Support Unit - Garching

Contributions from : A. Herrmann, L. Horton, A. Sips, J. Stober → ASDEX Upgrade, A. Leonard, C. Lasnier, T. Osborne, G. Porter → DIII-D, M. Becoulet, T. Eich, C. Hidalgo, S. Jachmich, M. Laux, G. Saibene, R. Sartori →JET, N. Asakura, A. Chankin, Y. Kamada → JT-60U, D. Campbell, G. Federici, G. Janeschitz, K. Lackner, M. Shimada, M. Sugihara → ITER

EFDA-CSU Garching – IPP-Garching – General Atomics – LLNL – CEA-Cadarache
CIEMAT – FZ-Jülich – JAERI – FZ-Karlsruhe – ITER International Team

Outline of the Talk

1. Type I ELM Bulk Plasma Energy/Particle Losses

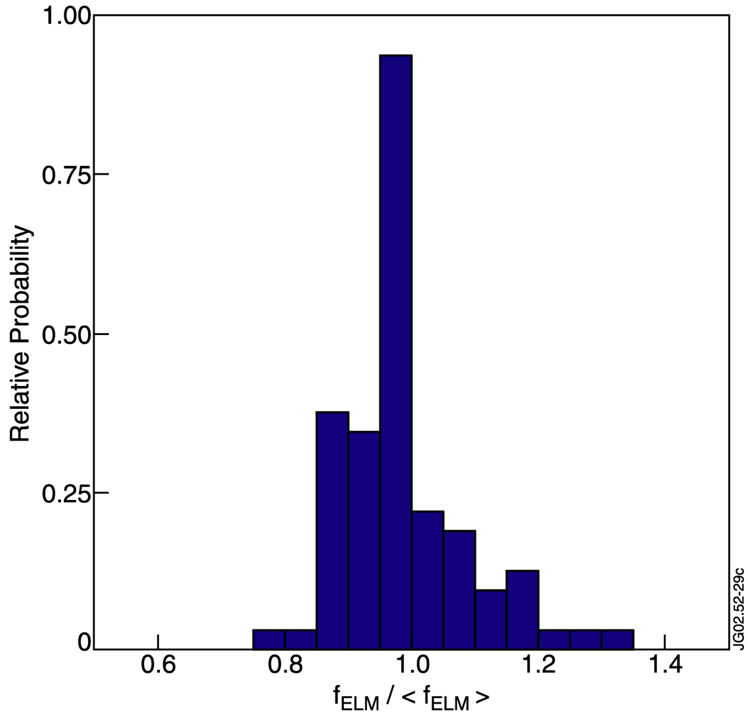
2. Type I ELM Divertor/Main Chamber Energy Fluxes

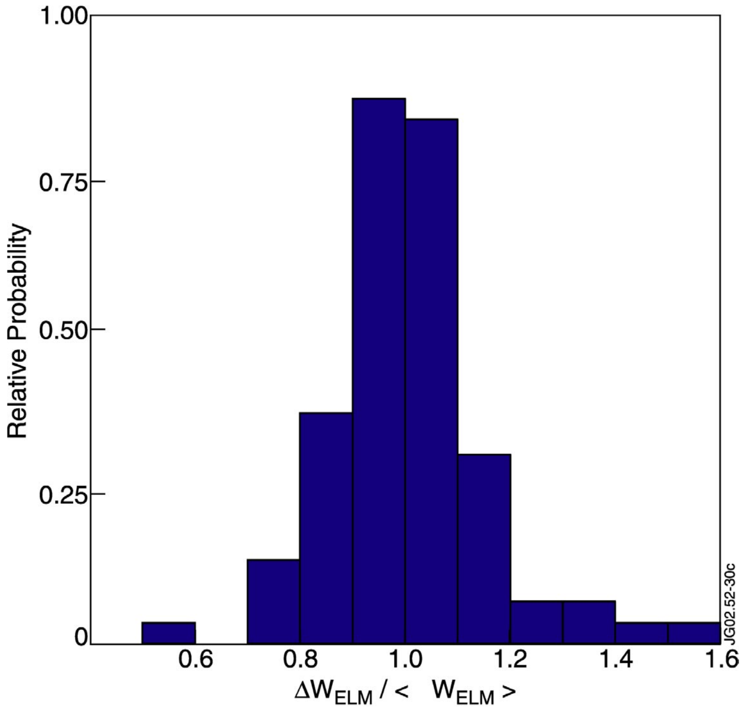
3. Regimes with small ELMs & good Confinement

4. Outlook & Conclusions

In steady State Type I ELM Losses are reproducible but not identical

JET "Steady-State" ELMy H-modes (Loarte PPCF 2002)





σ (f_{ELM}) ~ 10 %

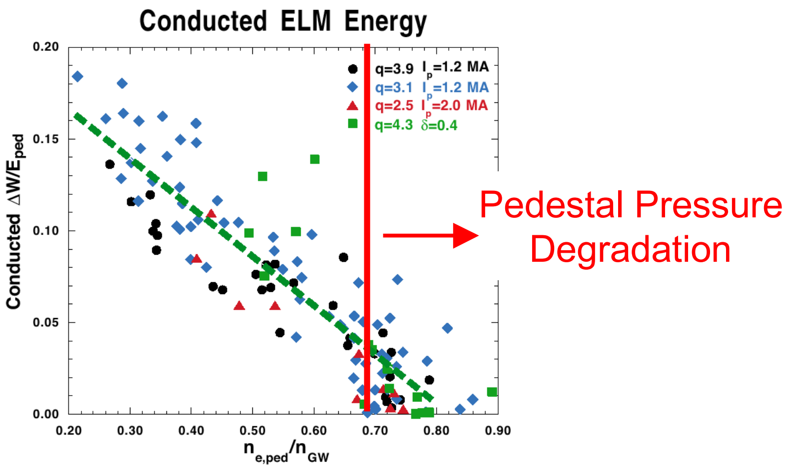
σ (ΔW_{ELM}) ~ 15 %

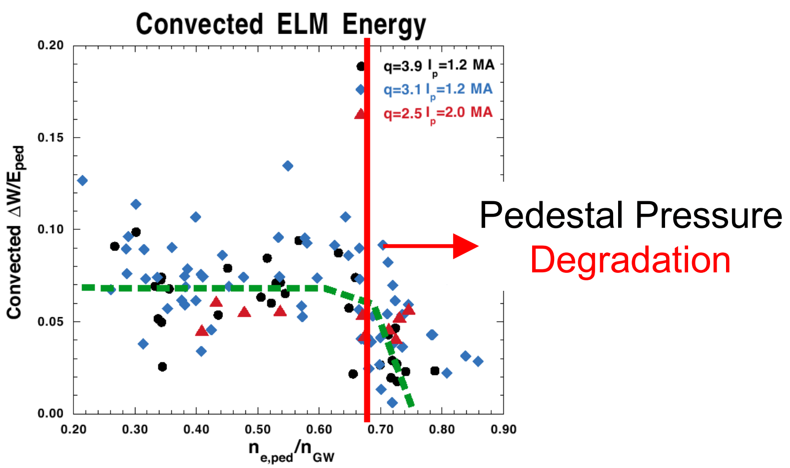
ELM Energy Losses (I)

Bulk Plasma Type I ELM Energy Losses : Conduction & Convection

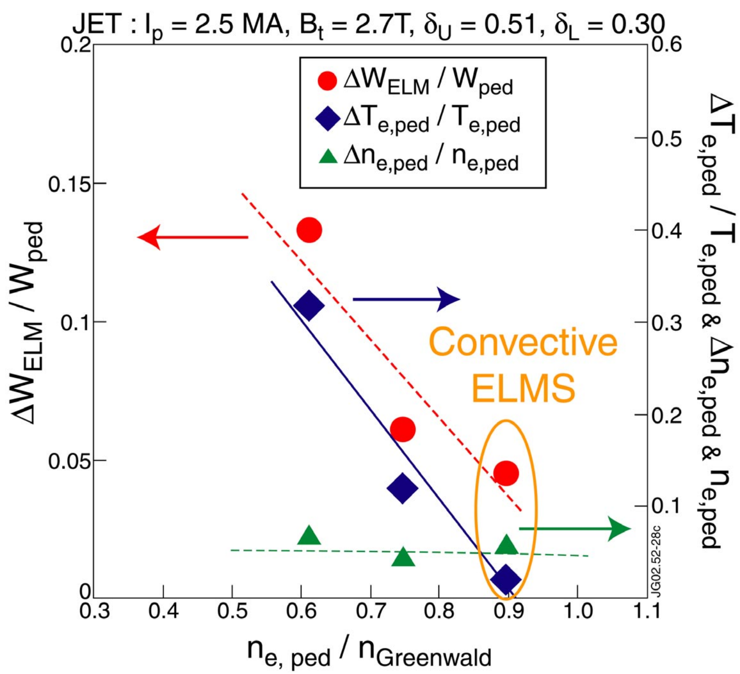
$\Delta W_{ELM}/W_{ped}$ decreases with increasing $n_{e,ped}$ because of $\Delta T_{e,ped}/T_{e,ped}$ ↘

DIII-D – Leonard PSI 2002





JET – Loarte PPCF 2002



With increasing $n_{e,ped}$ ELM Energy Losses are smaller and convection dominated

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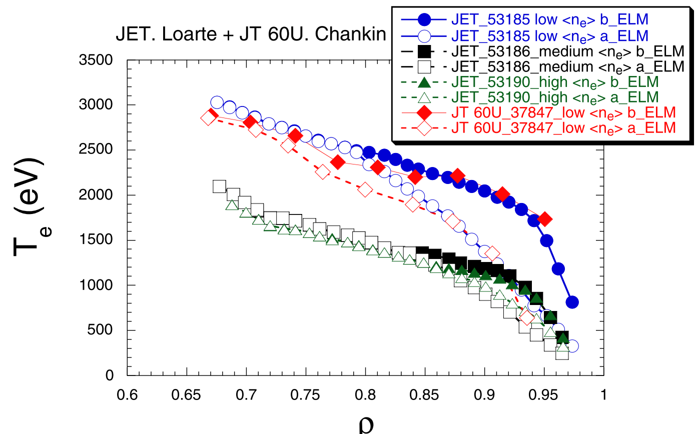
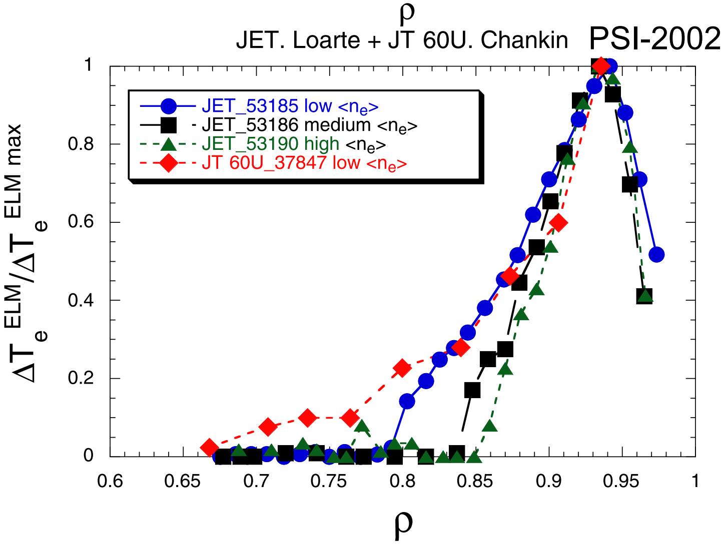
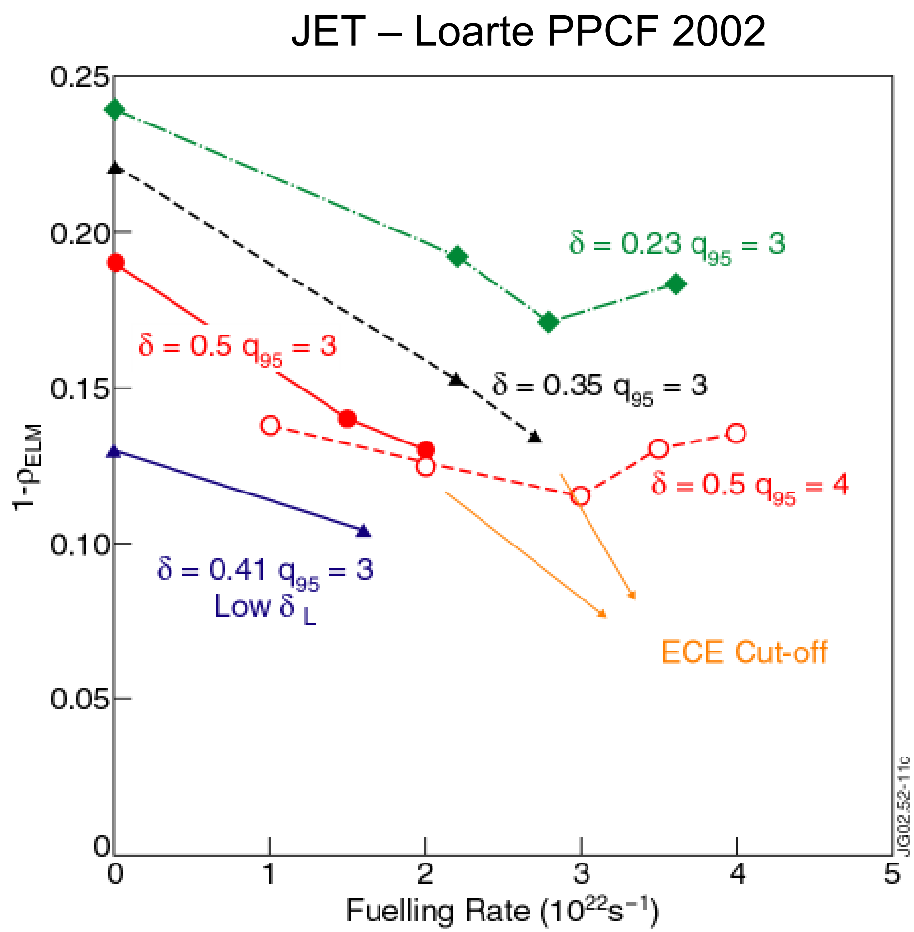
ELM Energy Losses (II)

In JET → Decrease of ΔW_{ELM} with $<n_e>$ due to $\Delta T_{e,ped}/T_{e,ped}$ decrease

not to large reduction of ELM affected volume

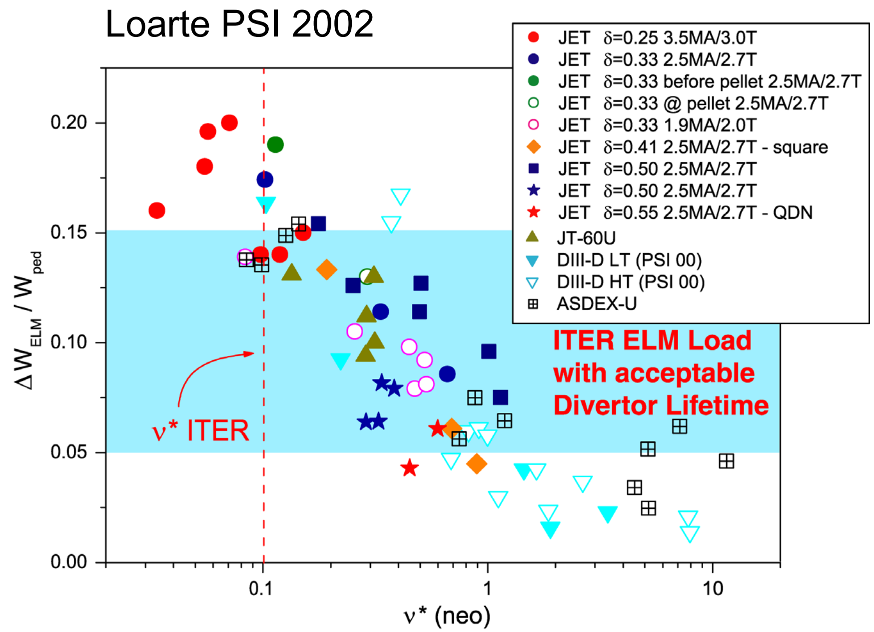


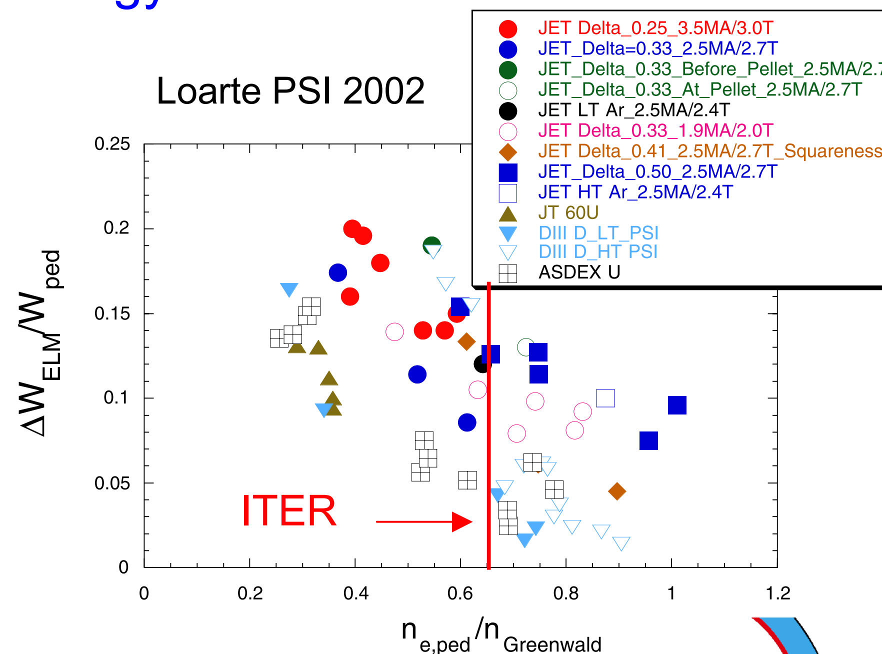




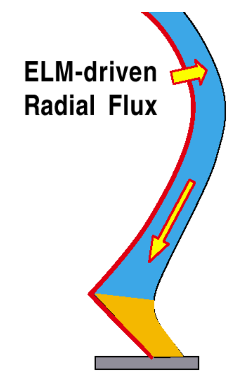
ELM Energy Losses (III)

Multi-machine Evaluation of ΔW_{ELM} indicates that ν^*_{ped} is an ordering Parameter for ELM Energy Losses





Not a ΔW_{ELM} Scaling ←→ Development of ELM Energy Loss

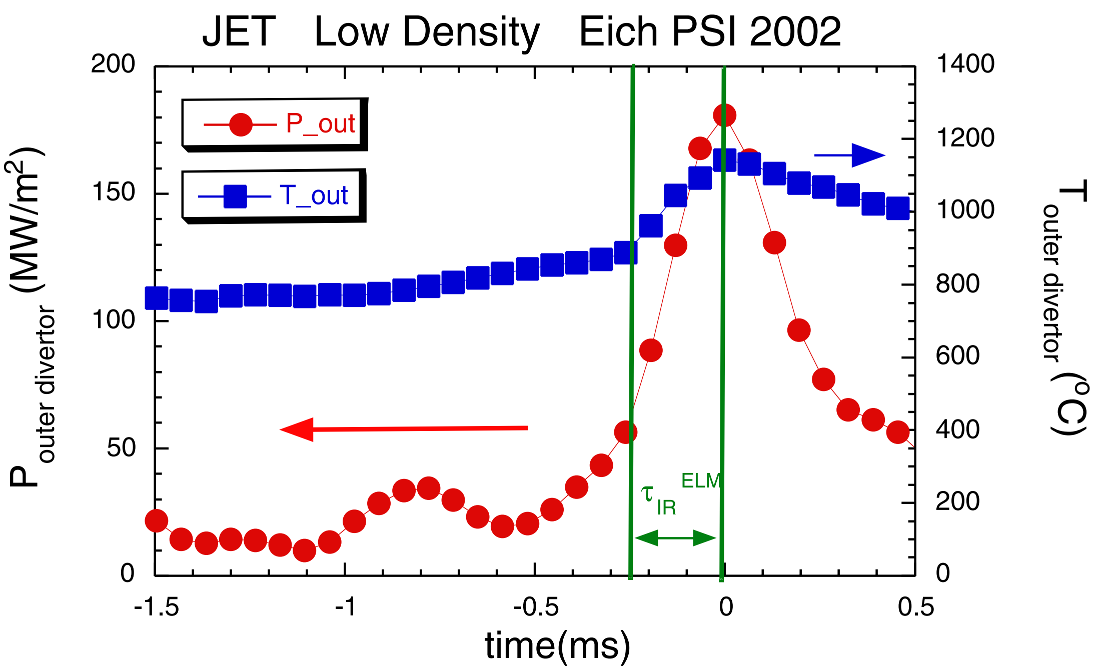


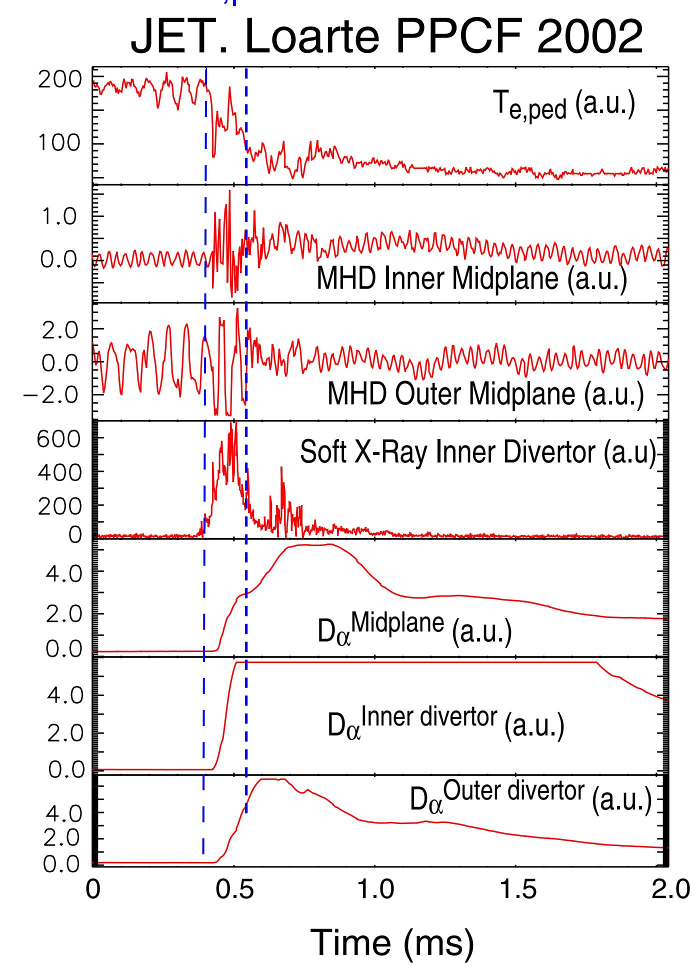
Physics Model :

1) ν^*_{ped} → MHD Trigger of ELM (Bootstrap Current)
2) ν^*_{ped} → ⊥ B Energy/Particle Transport during ELM
3) ν^*_{ped} → II B SOL Energy/Particle Transport during ELM

Time Scale for Divertor Power Flux Correlated with $T_{e,ped}$

$T_{e,ped}$~ 1.6 keV



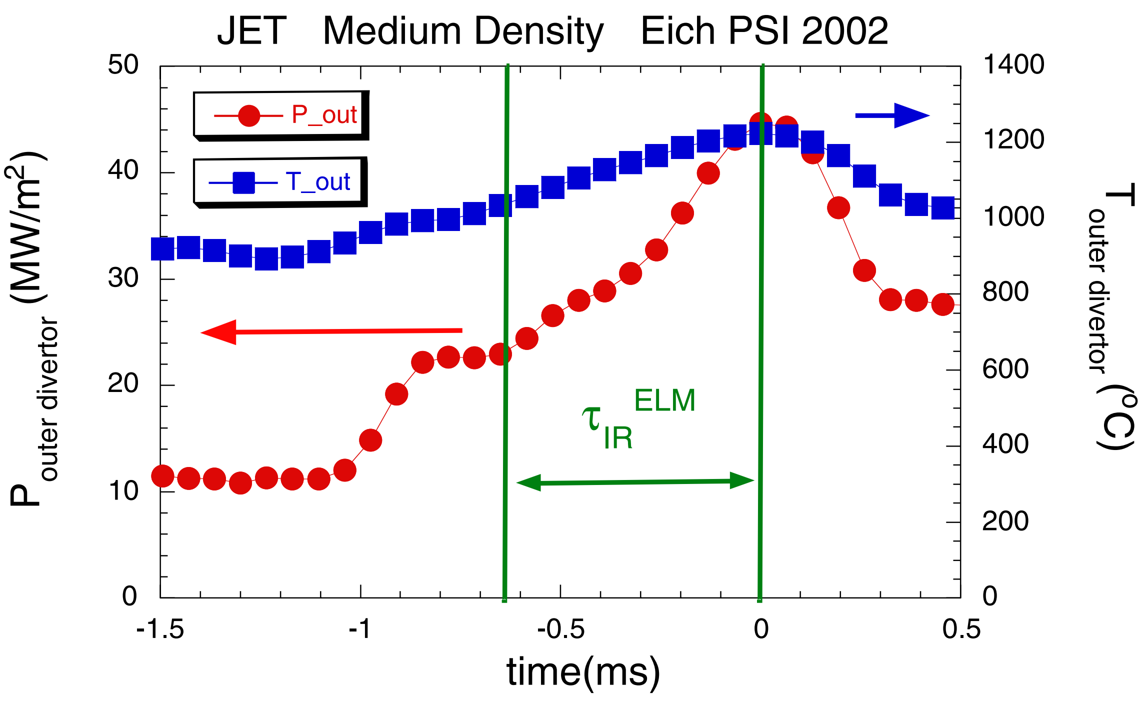


"MHD duration" of ELM Event well correlated with X-ray Bremsstrahlung Emission from the Divertor Target [Be(250μm)]→T_e > 0.8 - 1 keV]

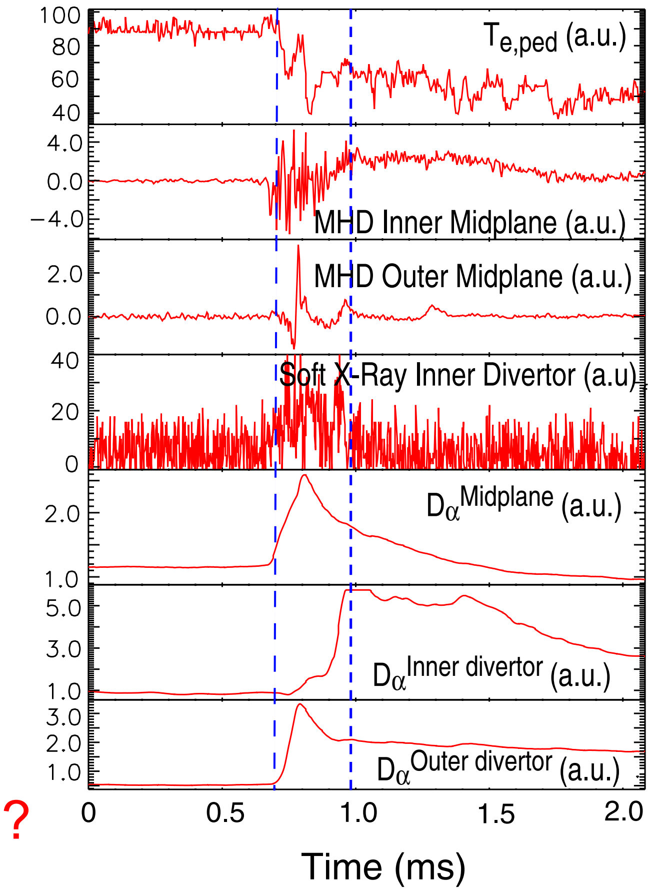
ELM Divertor Power Fluxes (I)

At lower $T_{e,ped}$ → τ_{IR}^{ELM} much longer than "MHD duration" of ELM and of hot Electron Energy Pulse on Divertor

$T_{e,ped}$~ 0.9 keV



JET. Loarte PPCF 2002



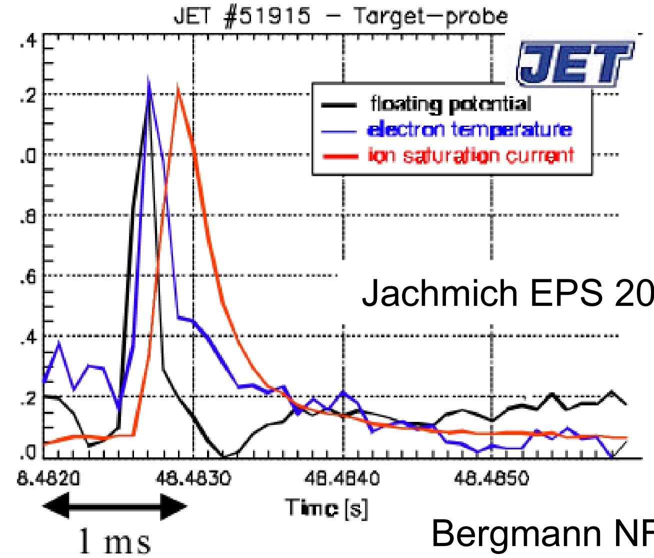
Sheath vs. Core ⊥ B impedance to Energy Loss?

ELM Divertor Power Fluxes (II)

Duration of Divertor ELM Energy Pulse correlated with II B Ion Transport (~ kinetic Simulations)

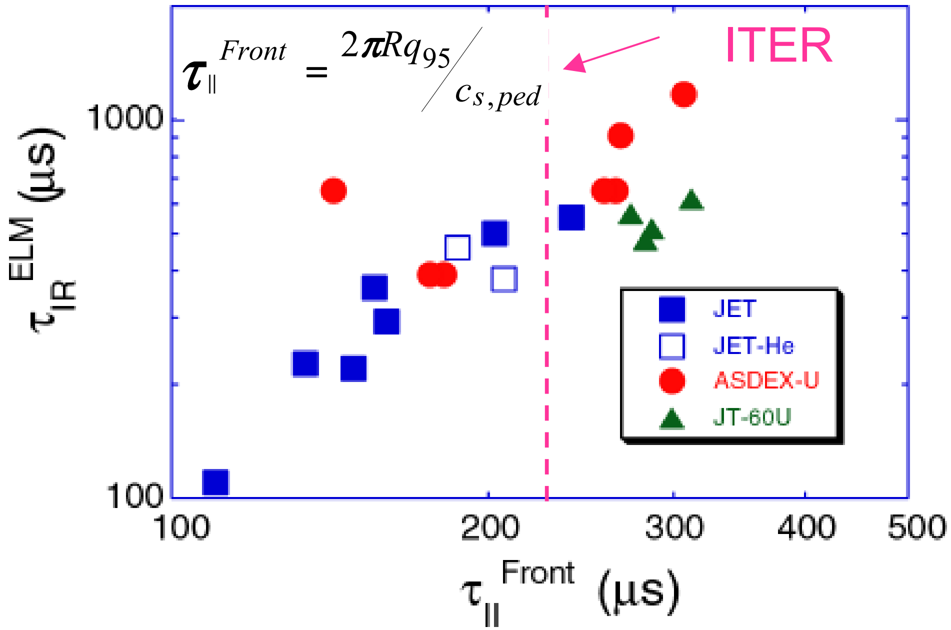
↓

Divertor Sheath may play a Role on determining ELM Energy Losses

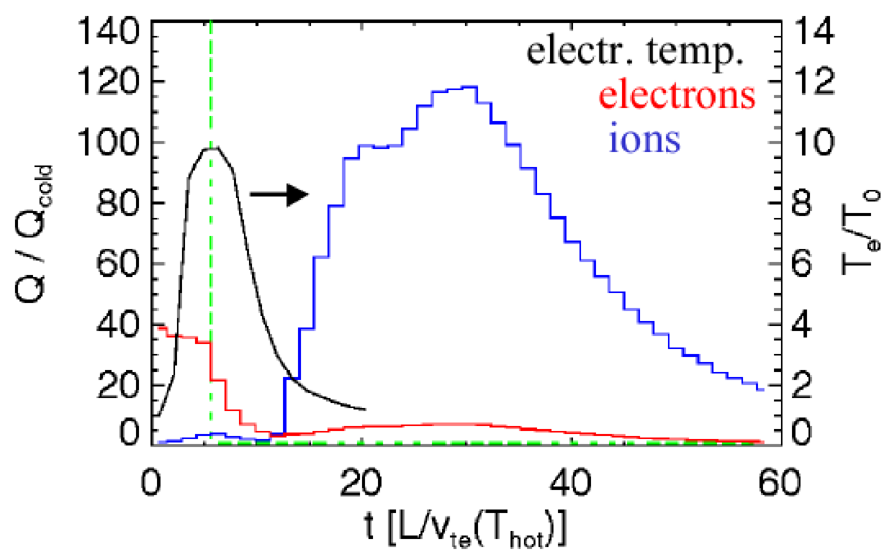


Jachmich EPS 2001

Loarte – Eich – Herrmann – Asakura PSI 2002

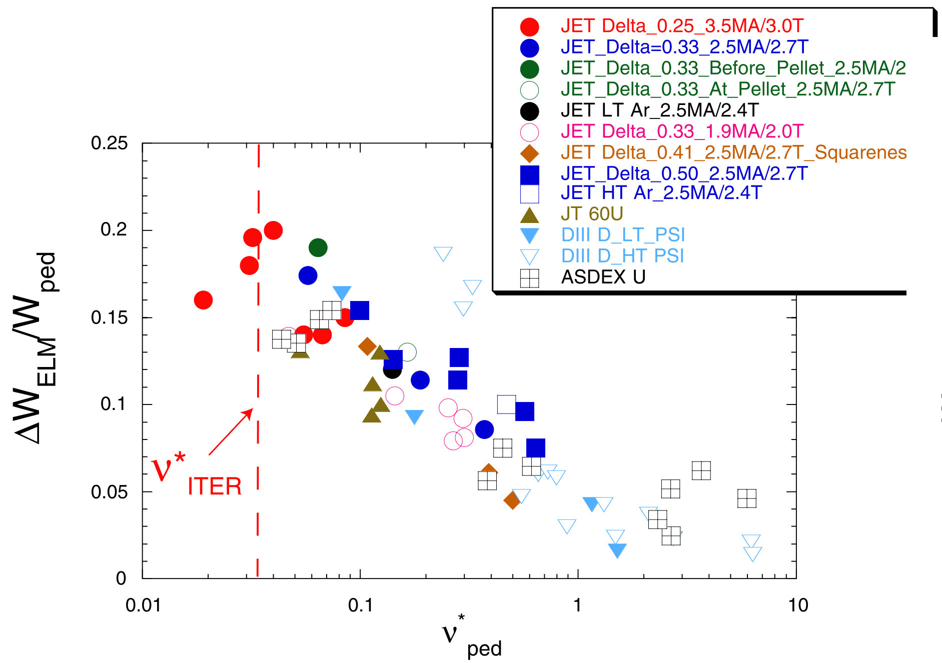


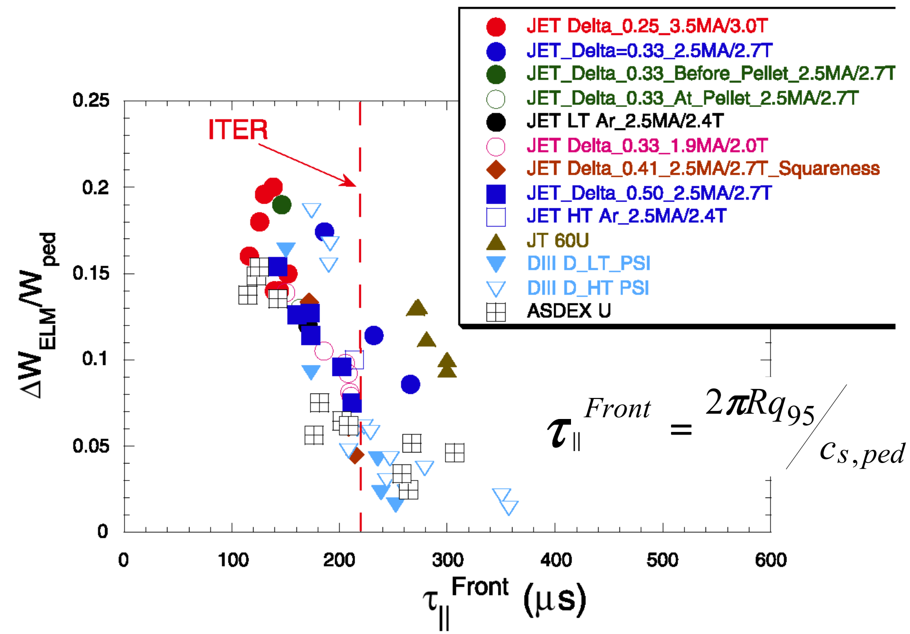
Bergmann NF 2002



ELM Divertor Power Fluxes (III)

Very different Extrapolation for ΔW_{ELM} if ν^*_{ped} or the Sheath Impedance to Energy Flux play a role

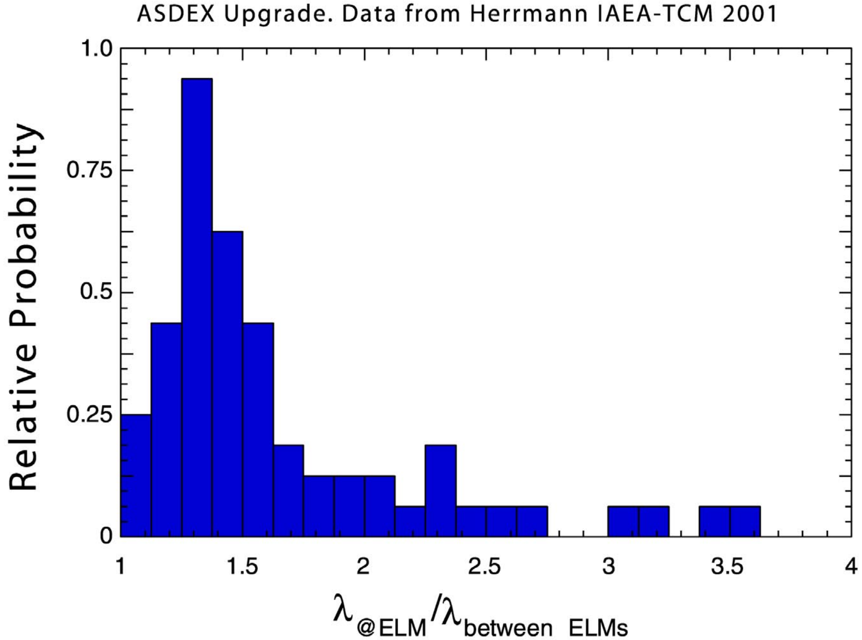




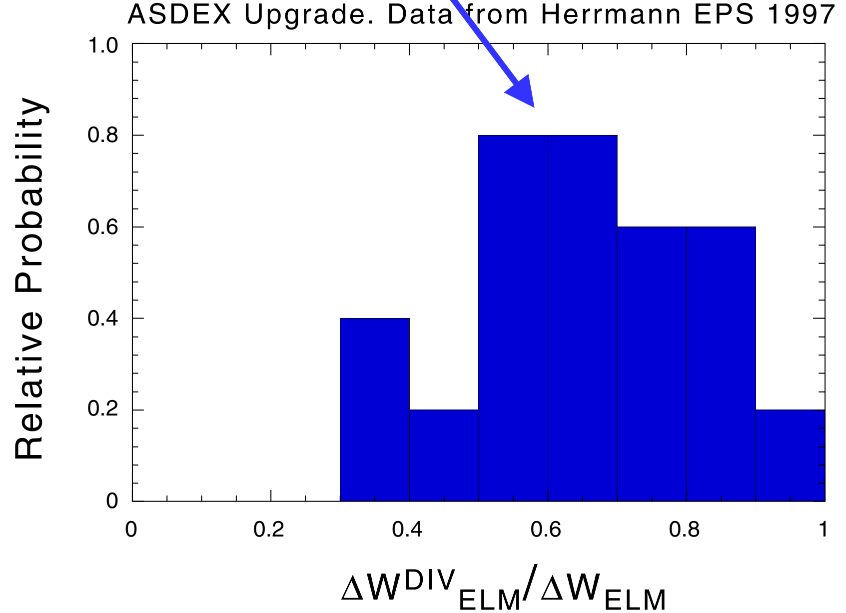
Experiments in JET, ASDEX Upgrade, DIII-D and JT-60U have been or will be carried out in the near Future to address this Issue

ELM Divertor/Main Chamber Power Fluxes (IV)

SOL Width for Energy Flux during ELM similar to between ELMs



Despite narrow $\lambda_{@ELM}$ $\Delta W_{ELM}^{div}/\Delta W_{ELM} \sim 0.6$



$$\left(\chi_{\parallel}/\chi_{\perp}\right)_{ELM} \approx \left(\chi_{\parallel}/\chi_{\perp}\right)_{between\_ELM}$$

Where does the Rest of ΔW_{ELM} go ?

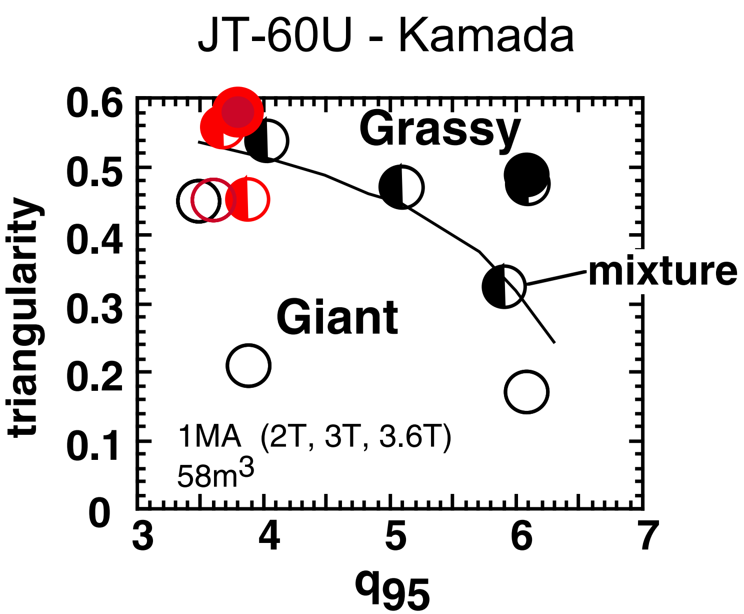
1) Toroidal Asymmetries (probably No)
2) Main Chamber (probably Yes)
3) Transiently enhanced P_{RAD}^{ELM} (probably No)

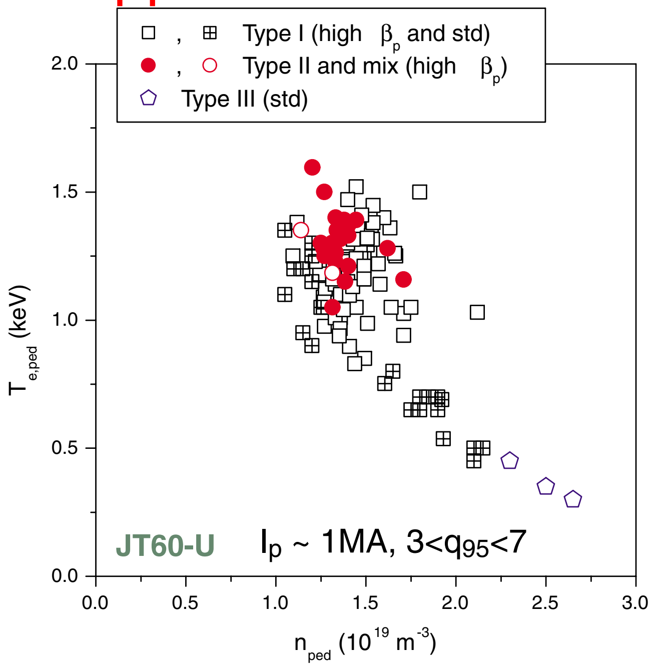
Regimes with small ELMs & good Confinement

Type I ELM suppressed at ~ const p_{ped} & ∇p_{ped}

High δ H-modes (ASDEX-U), high β_p H-modes in JT60-U, QDB modes of DIII-D + EDA (p_{ped} ↓, C-mod), mixed regimes (JET, DIII-D high δ H-modes)

High β_p,(>1.5) δ and q required for Type I suppression in JT60-U



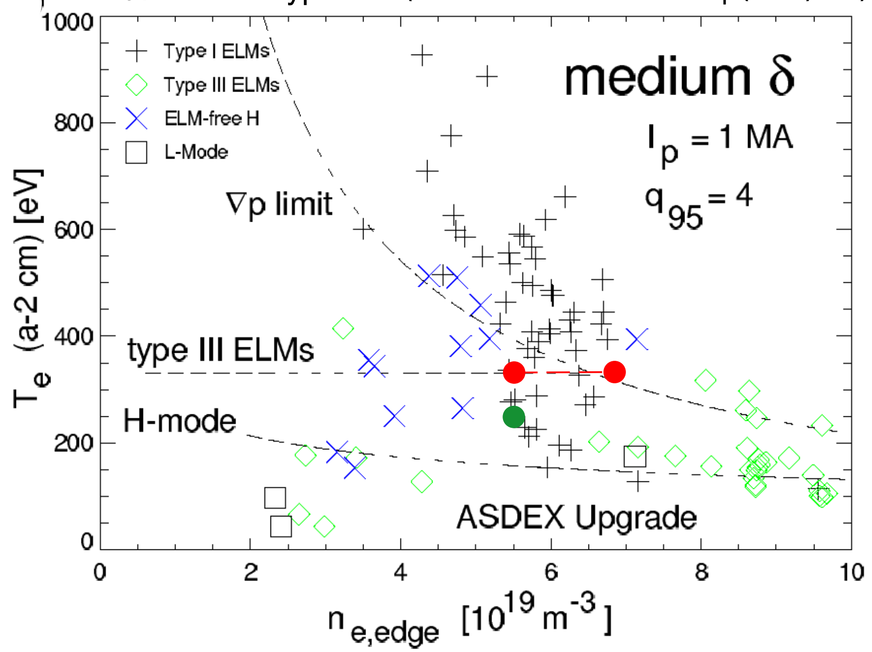


Shafranov shift → distortion of flux surfaces @ high β_p + high δ/high q_{95} ⇒ edge shear ⇑

Local pedestal parameters do not play a major role

Type II ELMs in ASDEX Upgrade occur at high Density

● Type II ● Type III (0.35<δ<0.42, 0.8<I_p(MA)<1)



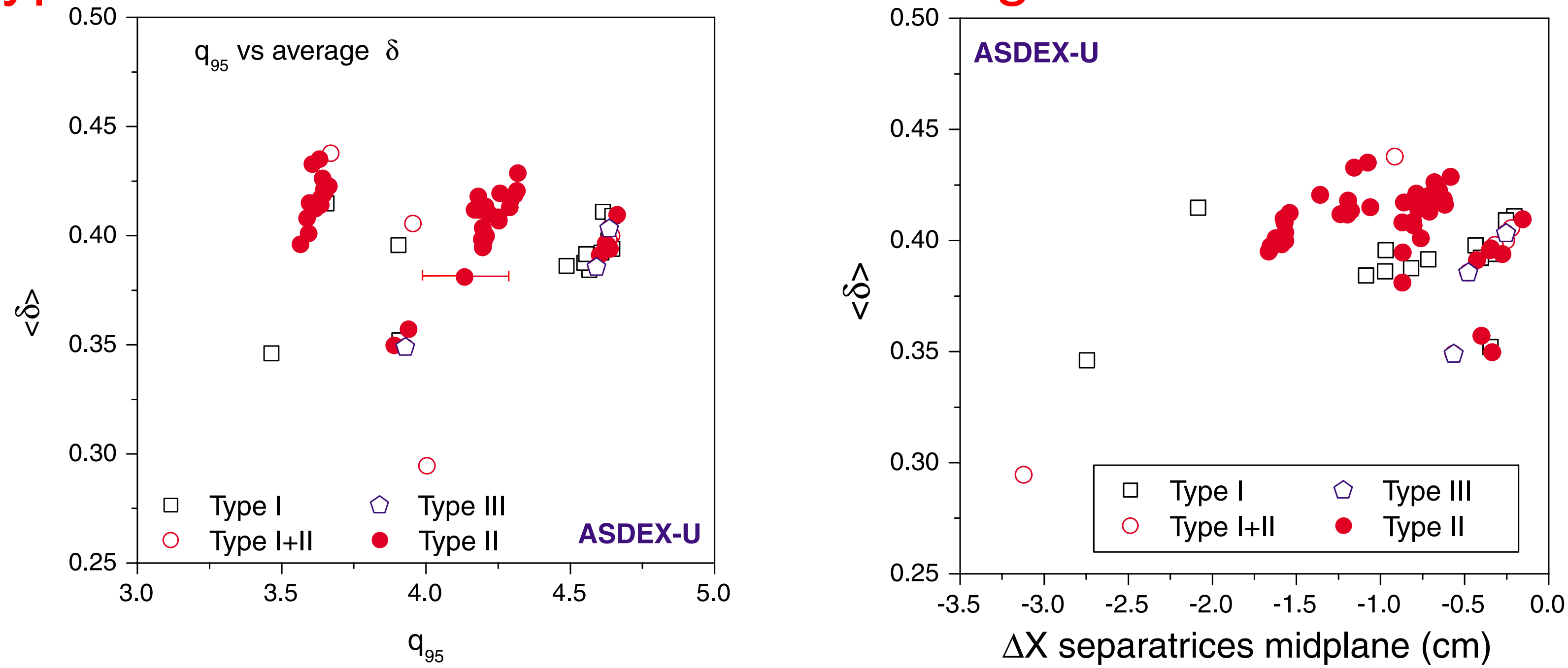
Transition Type I → II occurs with little change in p_{ped} compared to Type I phase → core confinement similar to Type I

s.s. Type II observed only at high n_e (similar to mixed case in JET)

The regime is robust to P_{in} ↑ (if fuelling adjusted, ASDEX-U)

Change in MHD stability or change in inter-ELM losses (or both?).

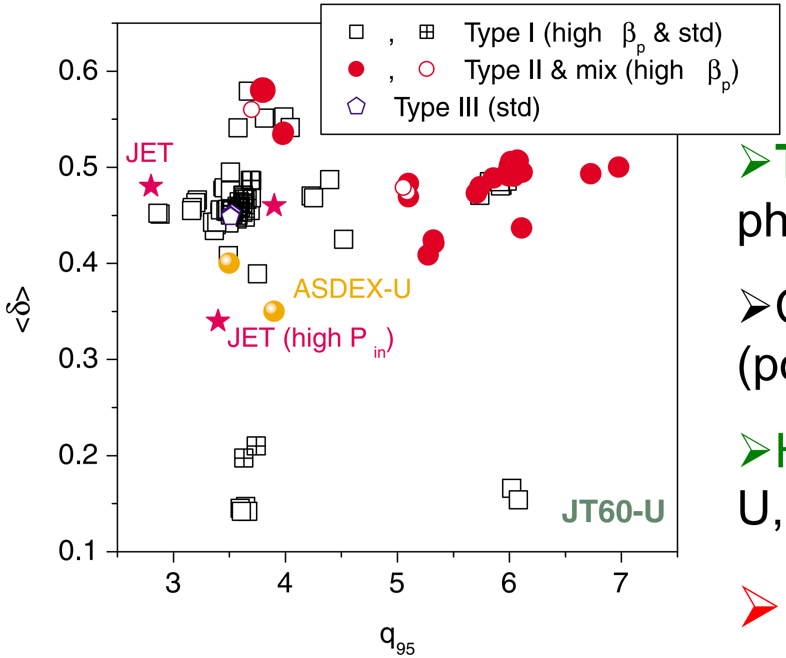
Type II in ASDEX-U : Quasi DN configuration



- ➢Type II require high δ (as JET and JT60-U) and n_e
- ➢Proximity to DN configuration is essential (no type II for ΔX_{mp}>2cm) + Trade-off δ/q_{95} ? DN to increase edge shear?
- ➢High β not required, but compatible with the regime! (β_N~ 3 obtained)

Type II (Grassy) ELMs

- Plasmas with good core confinement and small ELMs are observed in most experiments, in specific & reproducible circumstances.
- Total suppression of Type I ELMs in JT-60U, AUG & DIII-D QDB, partial in JET & DIII-D. C-Mod is a special case (no Type I ELMs!)



➢**Type II ELMs**

➢**Type I ELM suppression is gradual** (mixed phases) and occurs at ~ constant p_{ped} and ∇p_{ped}

➢Conditions of access vary: high δ is required (possibly q_{95} >3.5)

➢High β_p (JT60-U) and proximity to DN (ASDEX-U, JT60-U?)

➢**Key requirement : high edge shear!!**

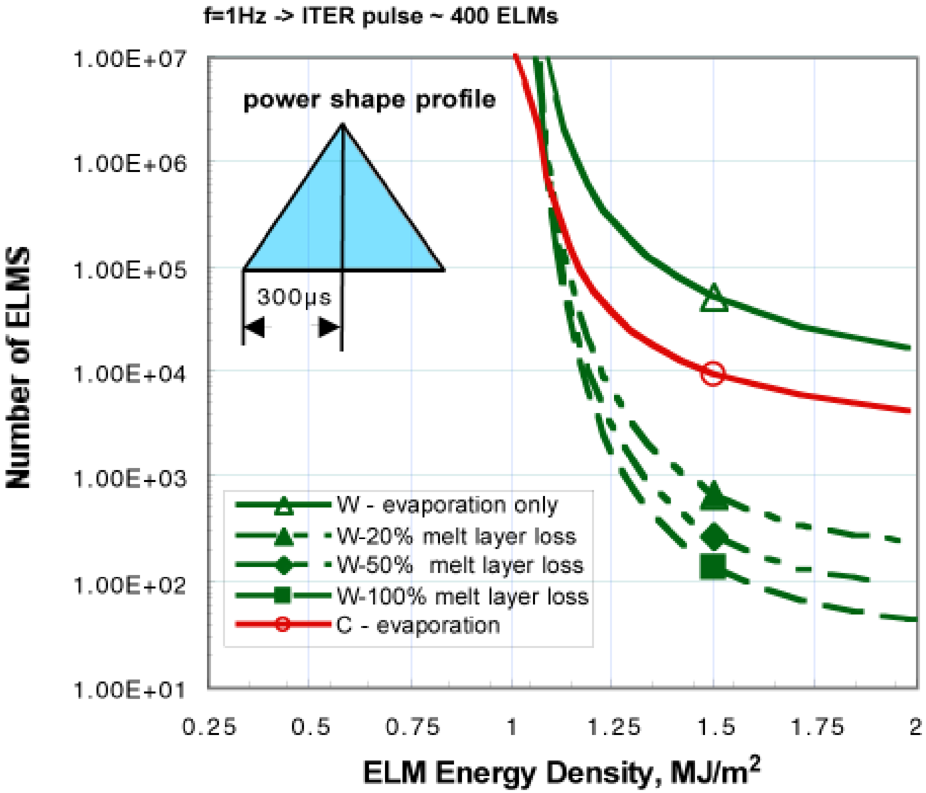
Conclusions

- Type I ELM Energy Losses determined by $n_{e,ped}$ & $T_{e,ped}$. Bulk Plasma ELM conductive Energy Losses decrease with ν^*_{ped} ELM convective Energy Losses independent of ν^*_{ped}
  - Physical Process that leads to ν^*_{ped} Dependence ?
  - Extrapolation of pure convective Type I ELMs?
  - Physics behind ELM Particle Losses (MHD?)
- ELM Divertor Energy Deposition Time is determined by $T_{e,ped}$
  - Is $T_{e,ped}$ Dependence due to Transport in ELM ergodised Layer or to Formation of high Energy e^- Sheath (or both)?
  - Radial Particle Fluxes → Erosion of Main Chamber Walls
    → ELM Energy Split Divertor/Main Walls
- Discharges with small ELMs (Type II) have been achieved in JT-60U (low ν^*_{ped}) and ASDEX Upgrade (high ν^*_{ped}). High Edge magnetic Shear is the Key to access these Regimes.

Quantitave Estimate of Edge magnetic Shear required for Extrapolation to BPXs
Other Regimes (QDB, EDA) should be explored and their BPX relevance assessed.

ELM Energy Losses (Ia)

ITER Divertor Lifetime determined by Type I ELMs Energy Loads leading to Ablation/Melting



Federici, G., 15th PSI Conference, Gifu Japan 2002

$W_{ped}^{ITER} \sim 100$ MJ

$A_{div}^{ITER} \sim 5 - 10$ m^2

$\Delta W_{ped}^{ITER} < 5$ -10 MJ

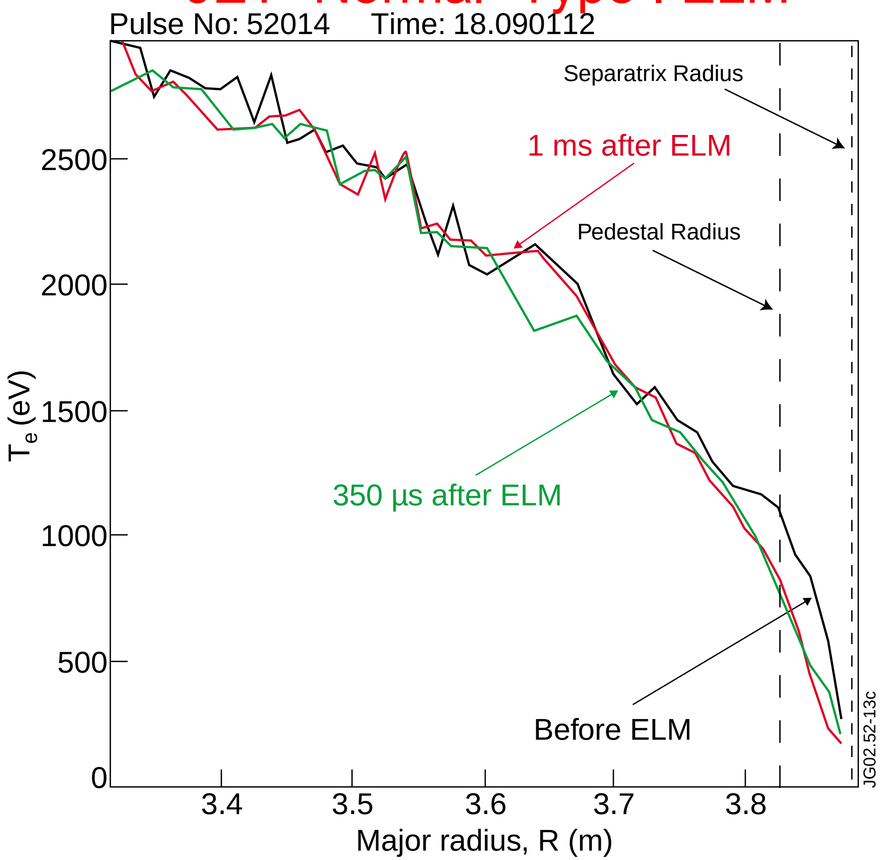
Extrapolation of present Results to ITER :

- Diagnostics that allow good Experimental Characterisation ELM Energy/Particle Losses
- Systematic Experiments for Type I ELM Characterisation
- Development of Physics Model for Type I ELM Energy and Particle Losses

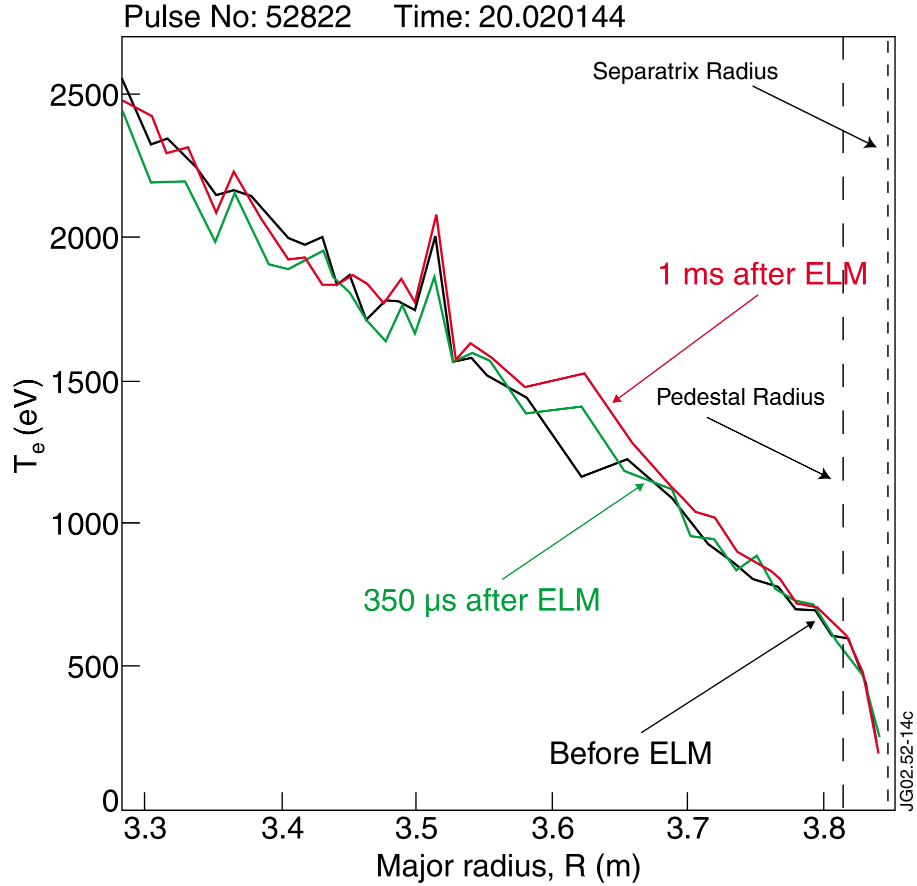
ELM Energy Losses (IIa)

"Minimum" Type I ELMs (Purely Convective) can occur at high density

JET "Normal" Type I ELM



JET "Minimum" Type I ELM

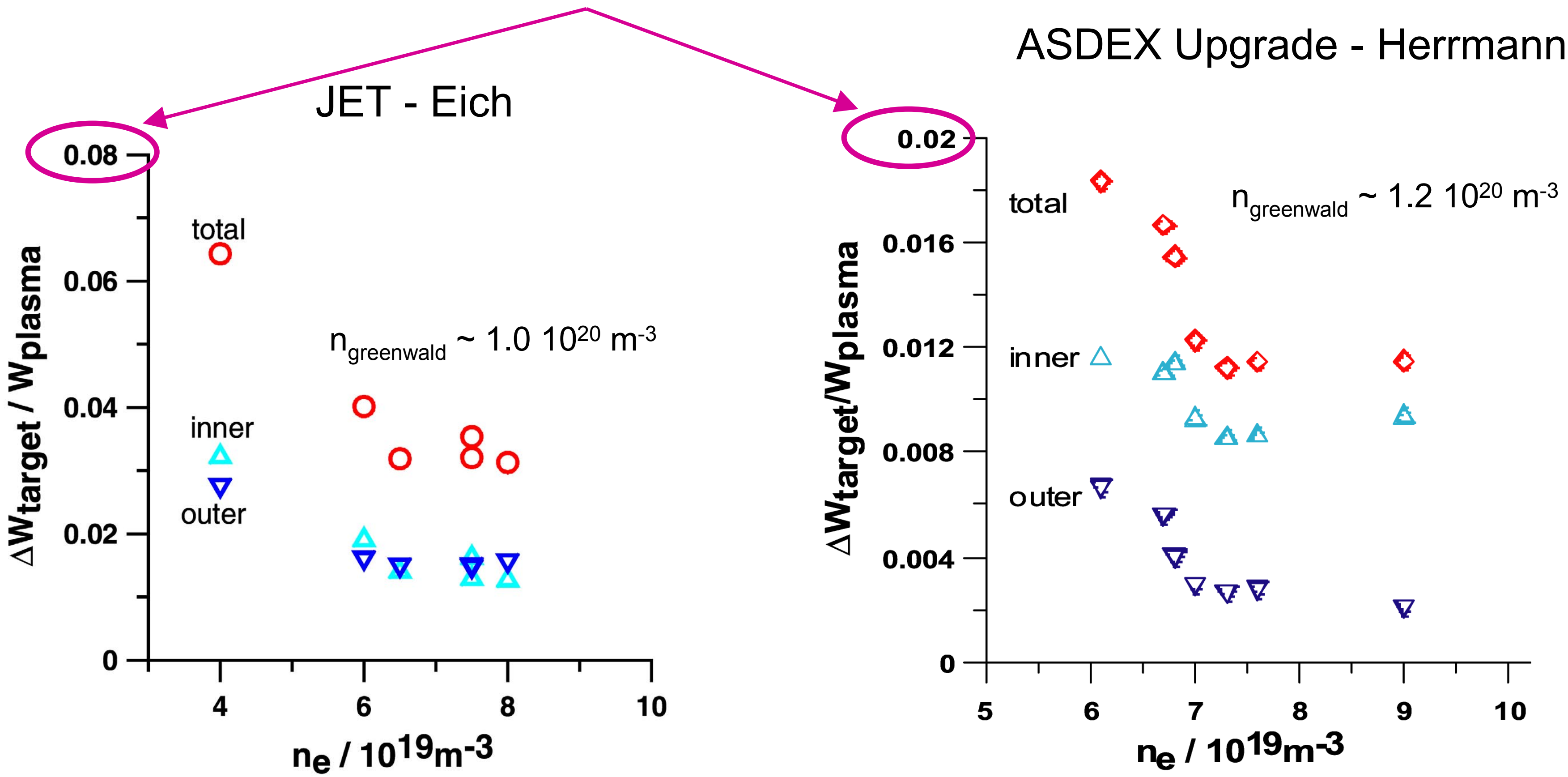


Loarte, A., et al., 43rd APS Conf. 2001 & Plasma Phys.Contr.Fus.(2002), Leonard, A., et al., Jour. Nuc. Mat. **290-293** (2001) 1097

ELM Energy Losses (IIIa)

$T_{e,ped}$ influences ELM Size → for similar $\langle n_e \rangle / n_{Greenwald}$

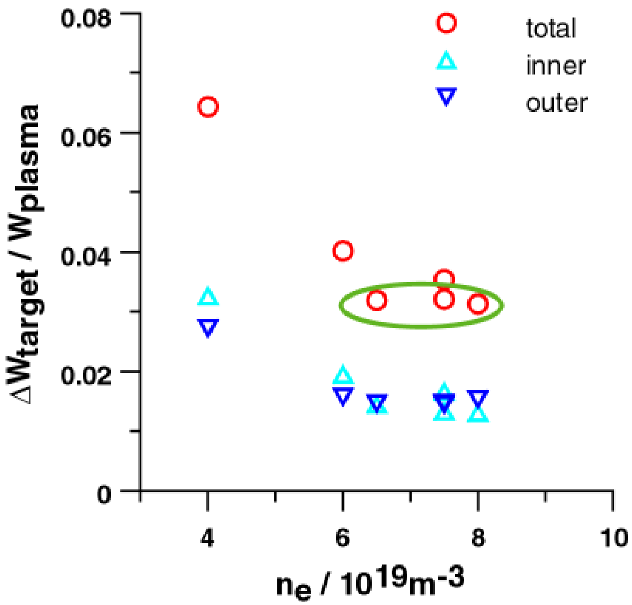
$(\Delta W_{ELM}/W_{dia})^{JET}_{Divertor} \sim 3 \times (\Delta W_{ELM}/W_{dia})^{ASDEX\ Upgrade}_{Divertor}$



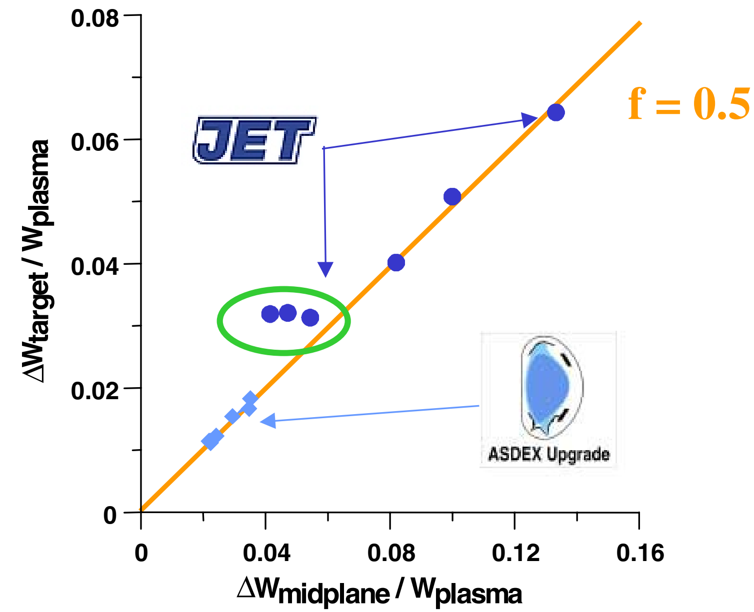
ELM Energy Losses to Divertor/Main Chamber (Ia)

JET : Divertor ELM missing Energy correlated with ELM size (<n$_e$>)

JET - Eich



JET+ASDEX Upgrade - Eich + Herrrmann



High n_e → $\Delta W_{ELM}^{div}/\Delta W_{ELM}^{Bulk}$ ↑ but possibly $P_{ELM}^{Rad, div}$ ↑

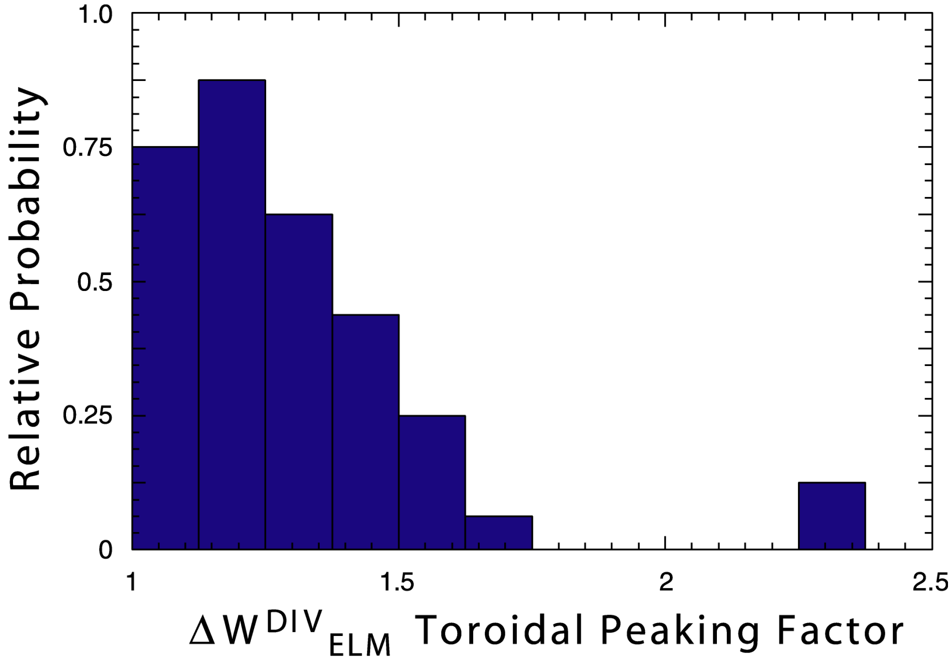
High n_e ELMs :

a) More toroidally symmetric

b) $\Delta W_{ELM}^{Main\ Chamber}/\Delta W_{ELM}^{Bulk}$ ↘

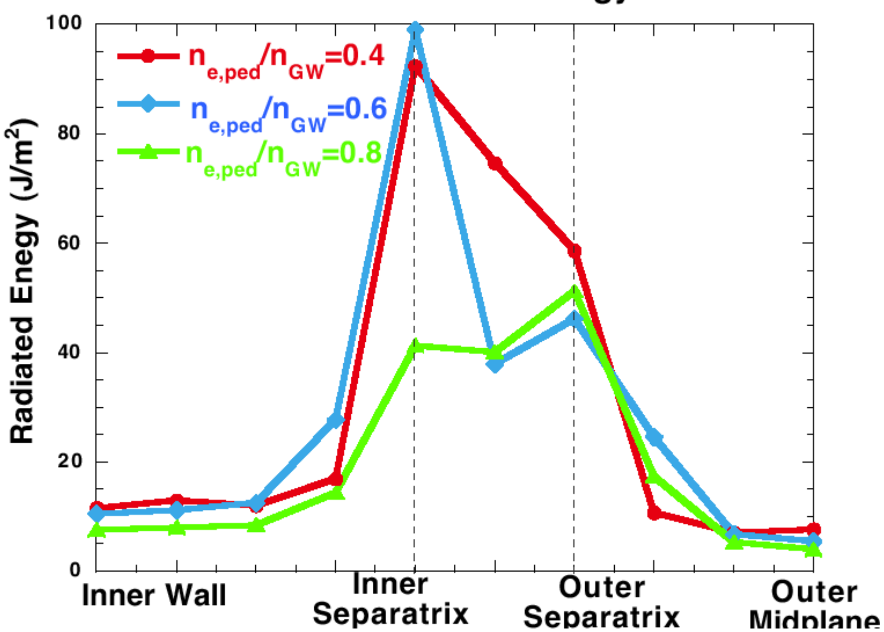
ELM Energy Losses to Divertor Main/ Chamber (IIa)

DIII-D. Data from Leonard PSI 1996



DIII-D Leonard PSI 2002

ELM Radiated Energy



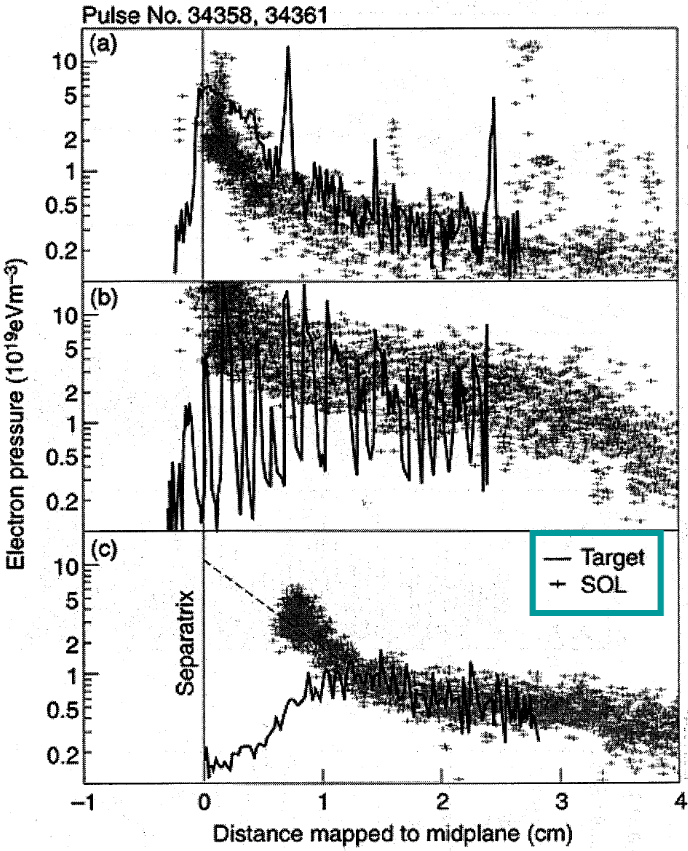
Divertor ELM Energy Loads are toroidally symmetric

Transient Radiation during ELM < 10 % ΔW_{ELM}

ELM Energy Losses to Main Chamber (Ia)

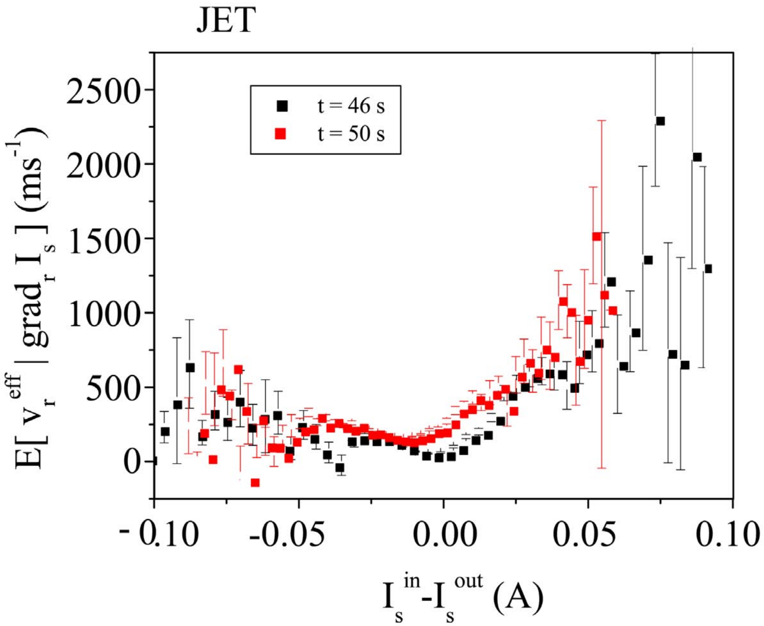
Divertor ELM missing Energy ←→ Fast radial ELM Particle Transport (?)

JET- Large ELM Plasma Fluxes in far SOL



For "large" ELM Events

(~ dI_{sat}/dr) → $v_{r,ELM}$ > 1 km/s



$$\tau_{\perp}^{ELM} \leq \quad 10\mu s$$

$$\tau_{\parallel}^{Energy} \sim \quad 10-100\mu s$$

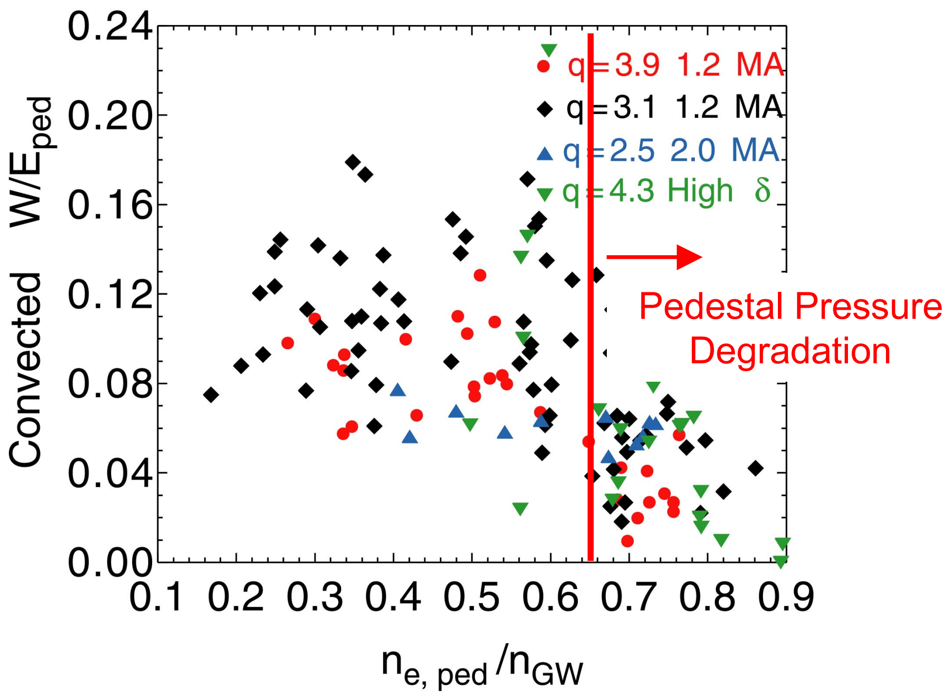
Radial ELM Propagation in MAST ~ 1500 m/s

Loarte, A., et al., Nucl. Fusion **38** (1998) 331
Hidalgo , et al., 29th EPS Montreux 2002
Counsell, G., et al., 15th PSI Conference, Gifu, 2002

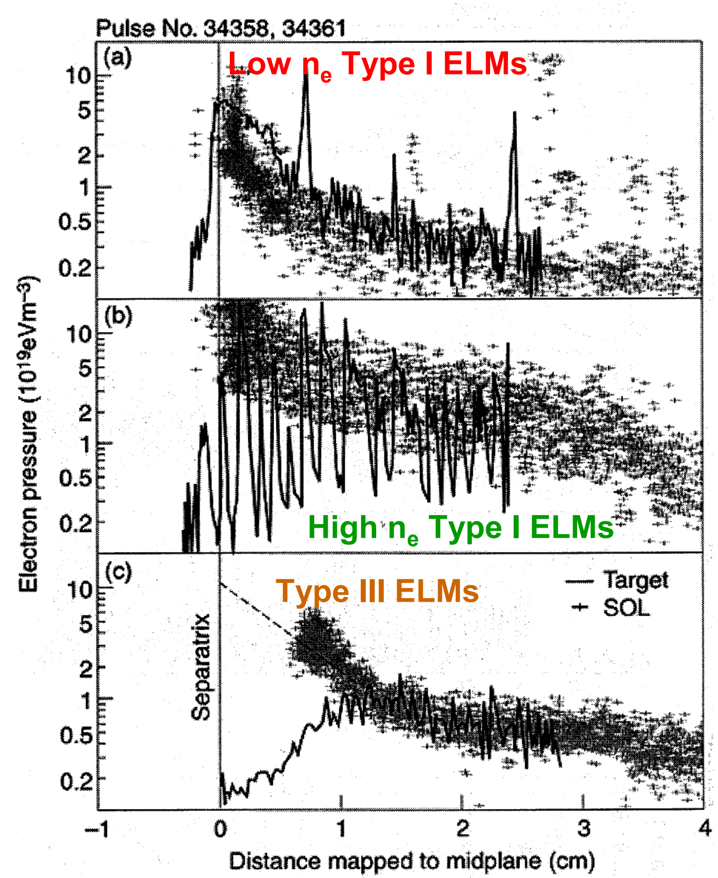
ELM Particle Losses (Ia)

Bulk Plasma ELM Particle Losses (& ⊥ B Energy Convection) not obviously correlated with $T_{e,ped}$ or $n_{e,ped}$ (→ MHD Nature of ELM?)

DIII-D



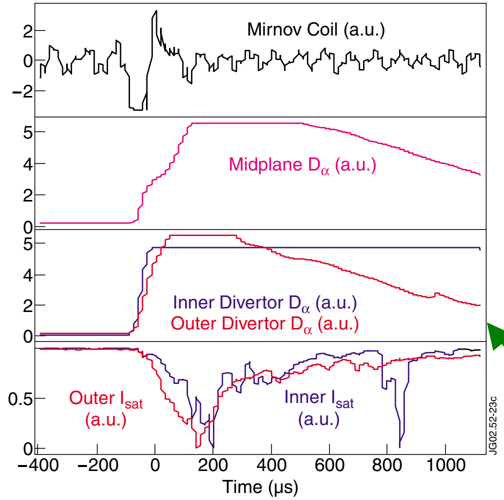
JET- Large ELM Plasma Fluxes in far SOL



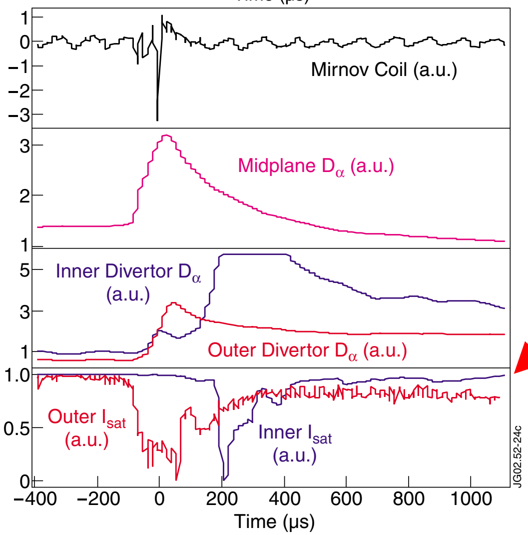
Leonard, A., et al., Plasma Phys. Contr. Fus. **44** (2002) 945
Loarte, A., et al., Nucl. Fusion **38** (1998) 331

ELM Particle Losses (IIa)

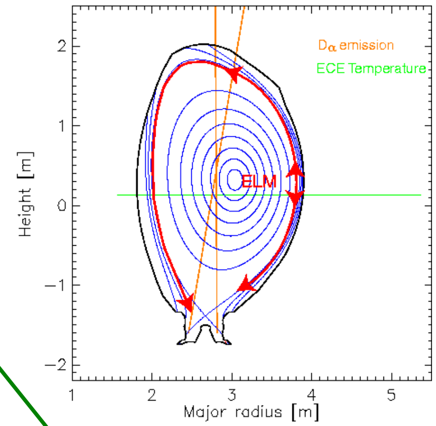
Divertor ELM Particle Flux Consistent Ballooning Origin of ELM MHD crash



τ_{II} = 150 μs



τ_{II} = 200 μs

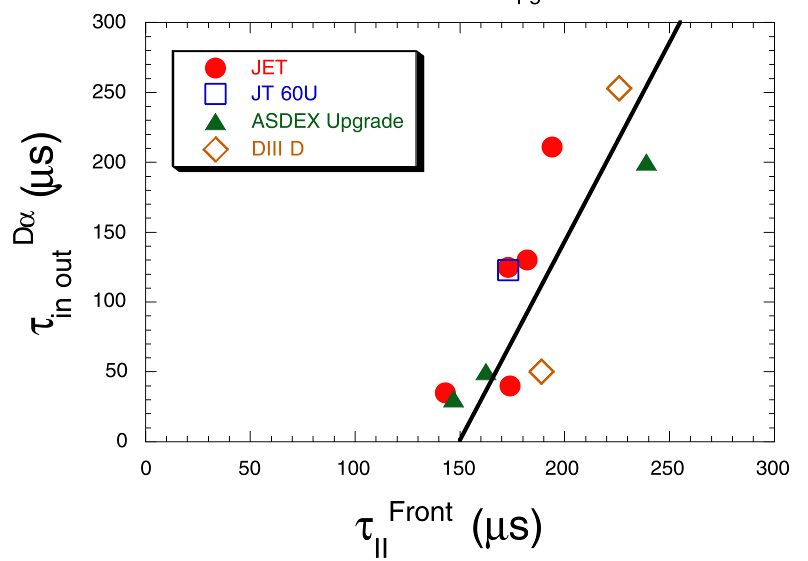


Similar Observations in several Divertor Tokamaks

↓

common ELM Origin & II B Particle Transport @ ELM

JET. Loarte + JT 60U. Chankin + ASDEX Upgrade. Horton + DIII D. Porter



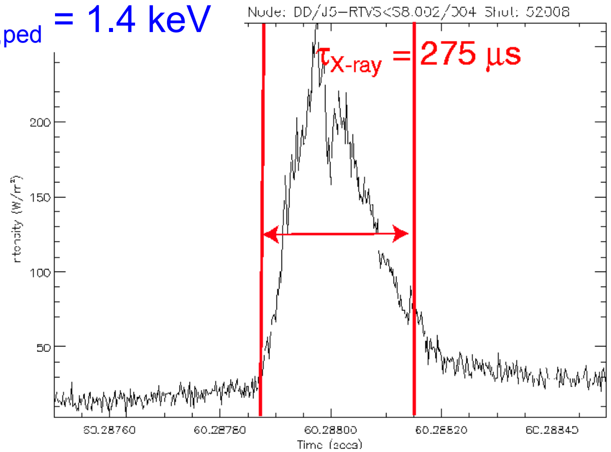
Loarte, A., et al., Plasma Phys. Contr. Fus. (2002), Loarte, A., et al., 15th PSI Conference, Gifu 2002

ELM Divertor Power Fluxes (Ia)

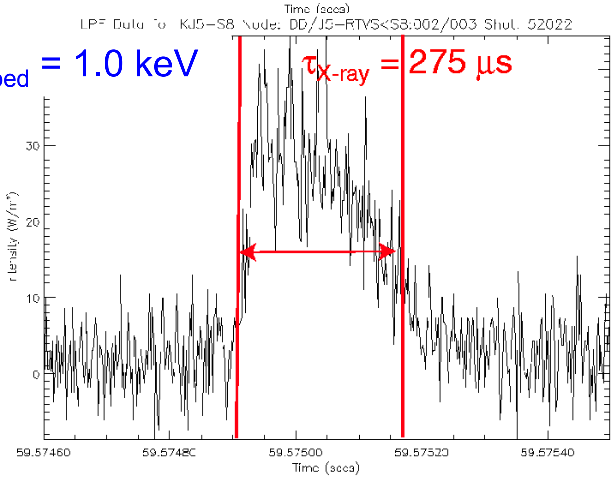
From Electron Bremsstrahlung ~ q_e can be estimated

$R_{Bremsstrahlung}$ (C) ~ $5\ 10^{-3}\ \ 3/2\ kT_e/m_ec^2$ (More precise Estimate → $f_e^{div}(x,t)$)

$T_{e,ped}$ = 1.4 keV

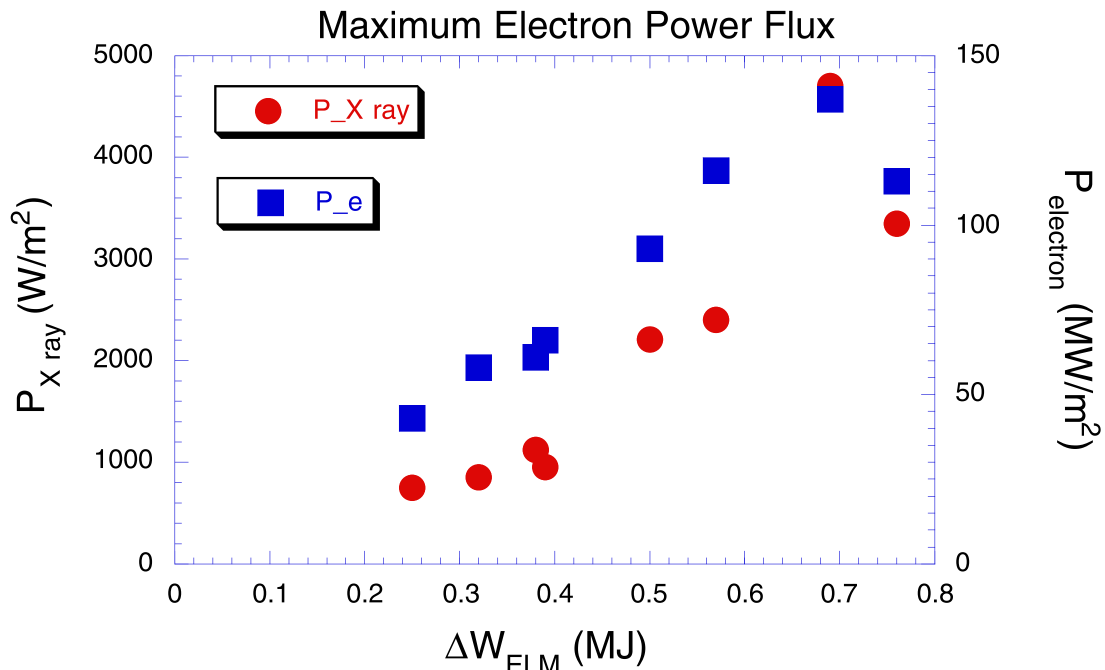


$T_{e,ped}$ = 1.0 keV



lower $T_{e,ped}$ → lower $\Delta W^{ELM}_{div,electron}$

τ_e^{ELM} ~ constant but τ_{IR}^{ELM} ~ $1/T_{e,ped}$



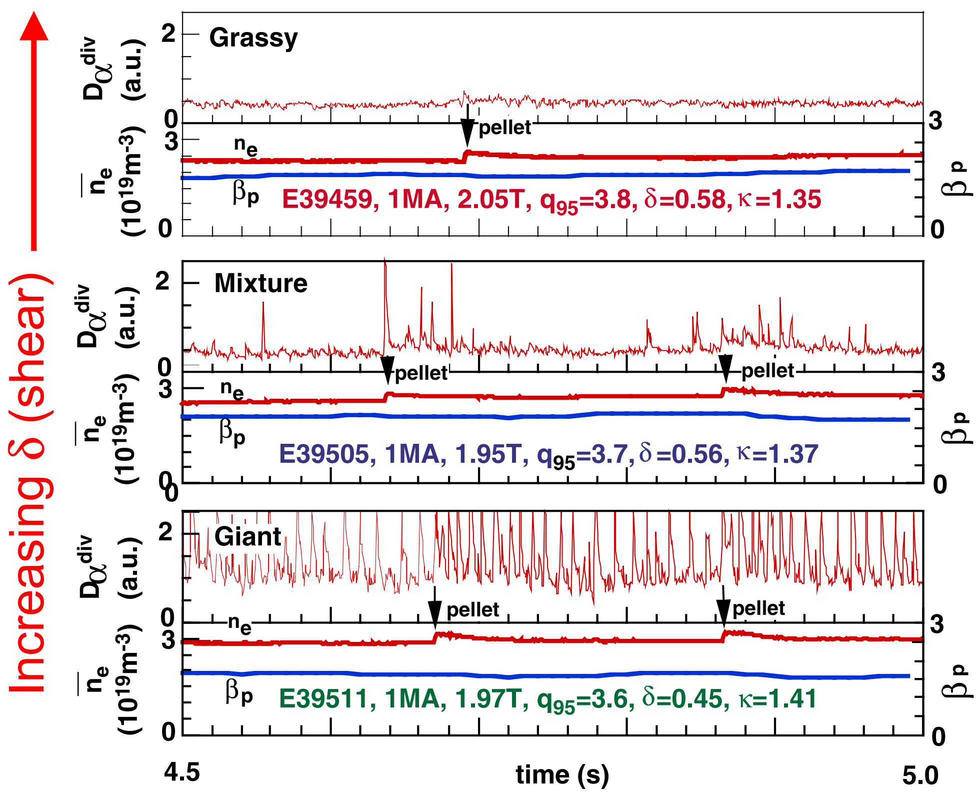
Sheath vs. Core ⊥ B impedance to Energy Loss?

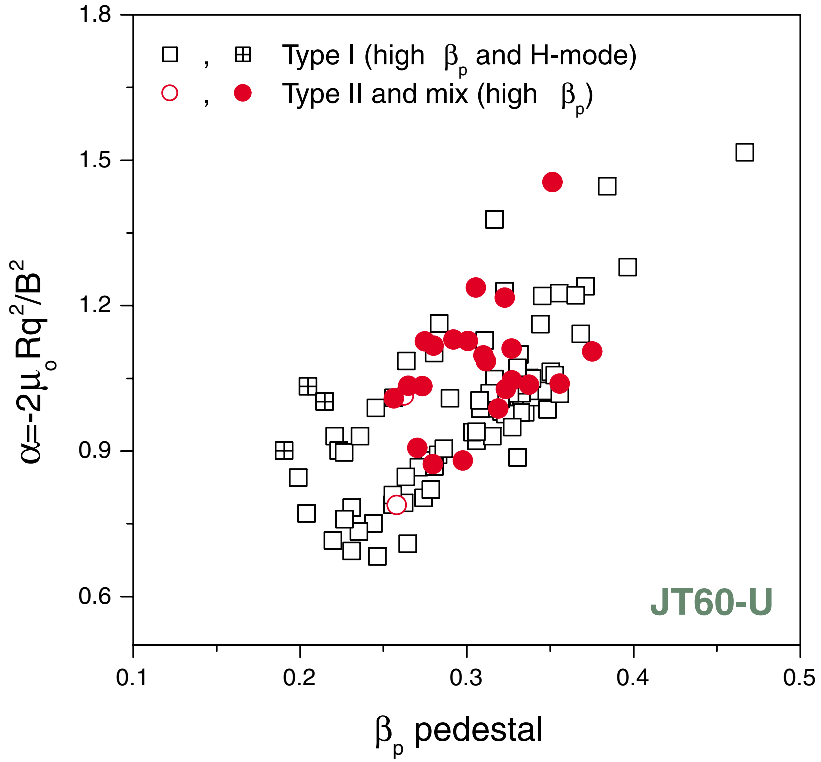
Gill, R., et al., Nucl. Fusion **38** (1998) 1461, Loarte, A., et al., 43rd APS Conf. 2001 & Plasma Phys.Contr.Fus.(2002)

Regimes with small ELMs & good Confinement (Ia)

Type I ELM suppressed at ~ const p_{ped} & ∇p_{ped}

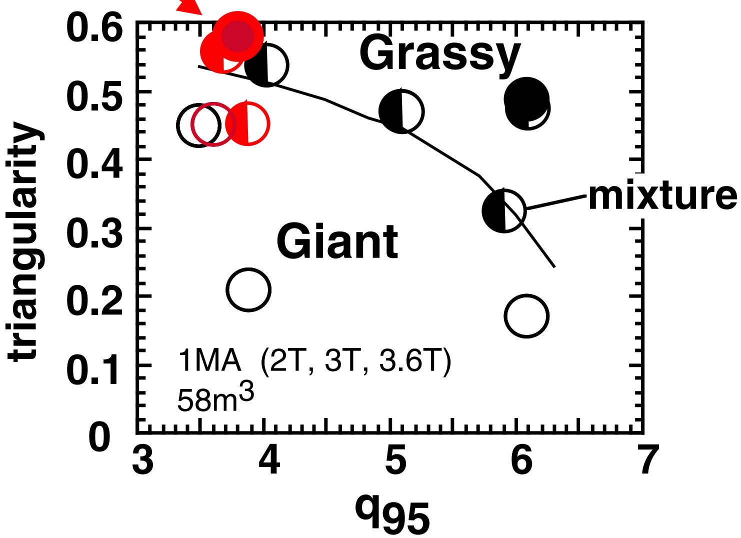
High δ H-modes (ASDEX-U), **high β_p H-modes** in JT60-U, **QDB modes** of DIII-D + **mixed regimes** (JET, DIII-D high δ H-modes)

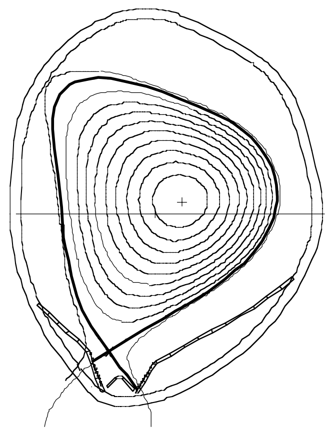




JT-60U - Kamada

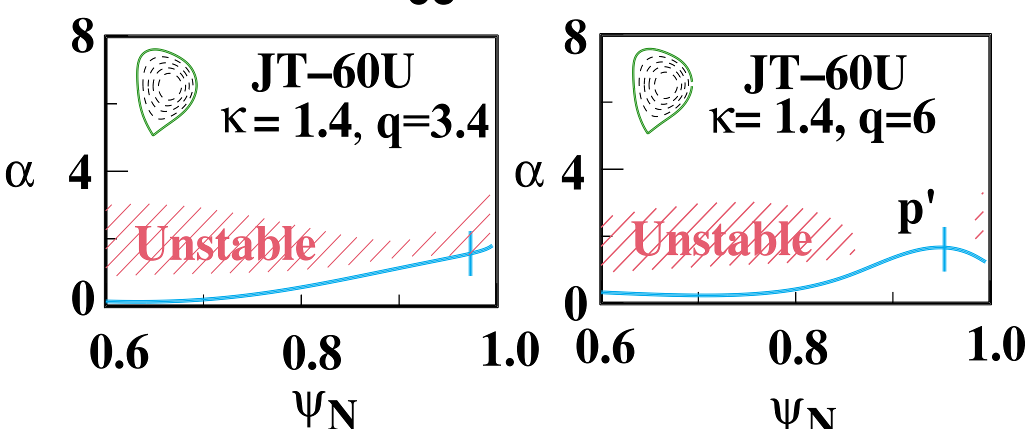
High β_p, δ and q required for Type I suppression in JT60-U





Distortion of the flux surfaces by Shafranov shift at high β_p + high δ / high q_{95} $\Rightarrow$ edge shear $\Uparrow$

$\Rightarrow$ Grassy/Type II ELMs

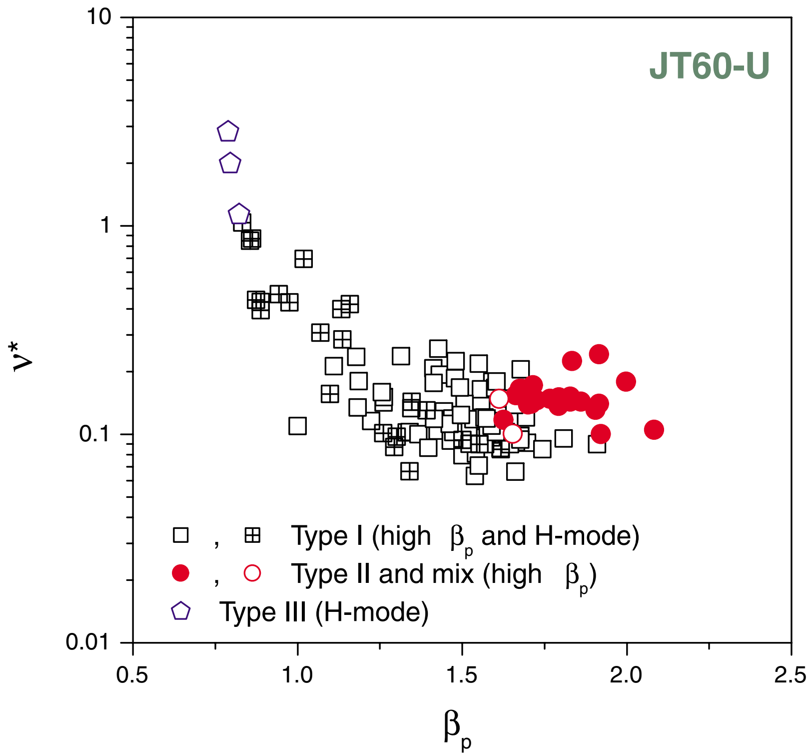


Lao - GATO analysis, n<10

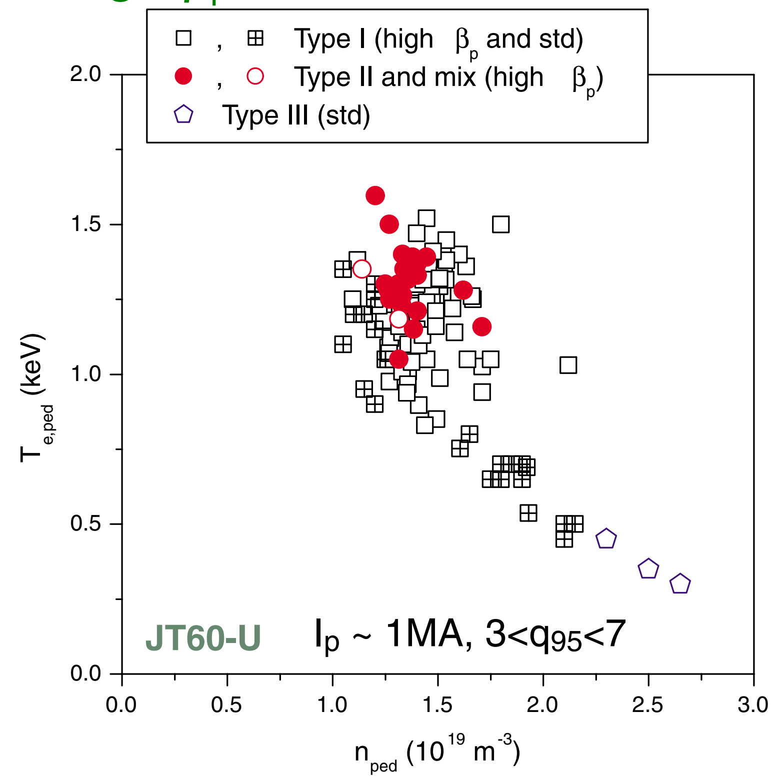
Local pedestal parameters do not play a major role (next).

JT-60U - Kamada

JT60-U Type II ELMs have high T_{ped} and low n_{ped}



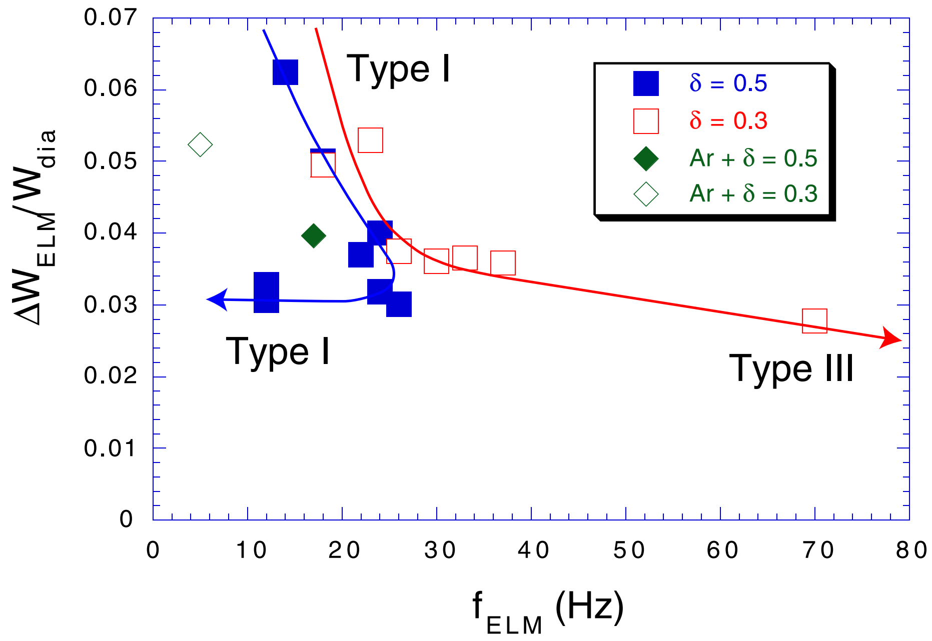
Type I→ II: similar n_{ped} and T_{ped} compared to standard high β_p H-modes

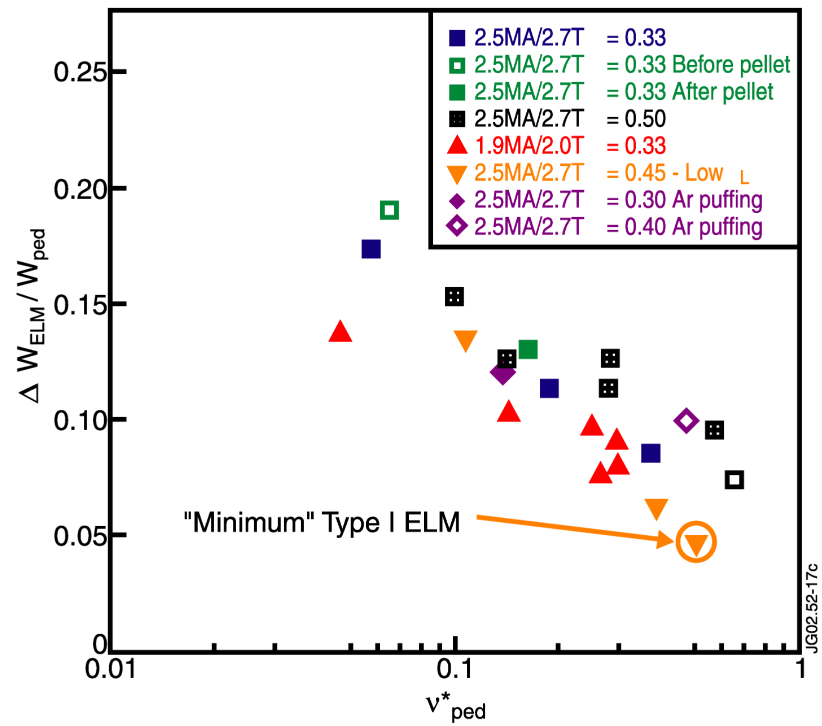


- Extrapolation to ITER: so far, n_{ped} too low (~30% n_{GR}) for high divertor radiation.

JT-60U - Kamada

Anomalous Type I ELM Behaviour at high δ

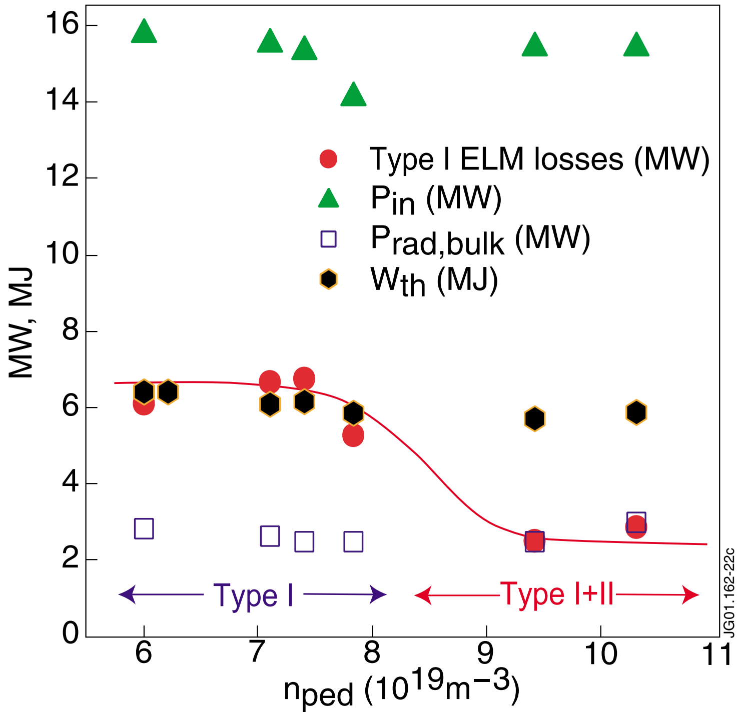




$\Delta W_{ELM}/W_{ped}$ depends on pedestal n_e and T_e, not on ELM frequency

JET – Becoulet - Loarte

Enhanced inter-ELM transport compensates for reduced Type I ELM losses



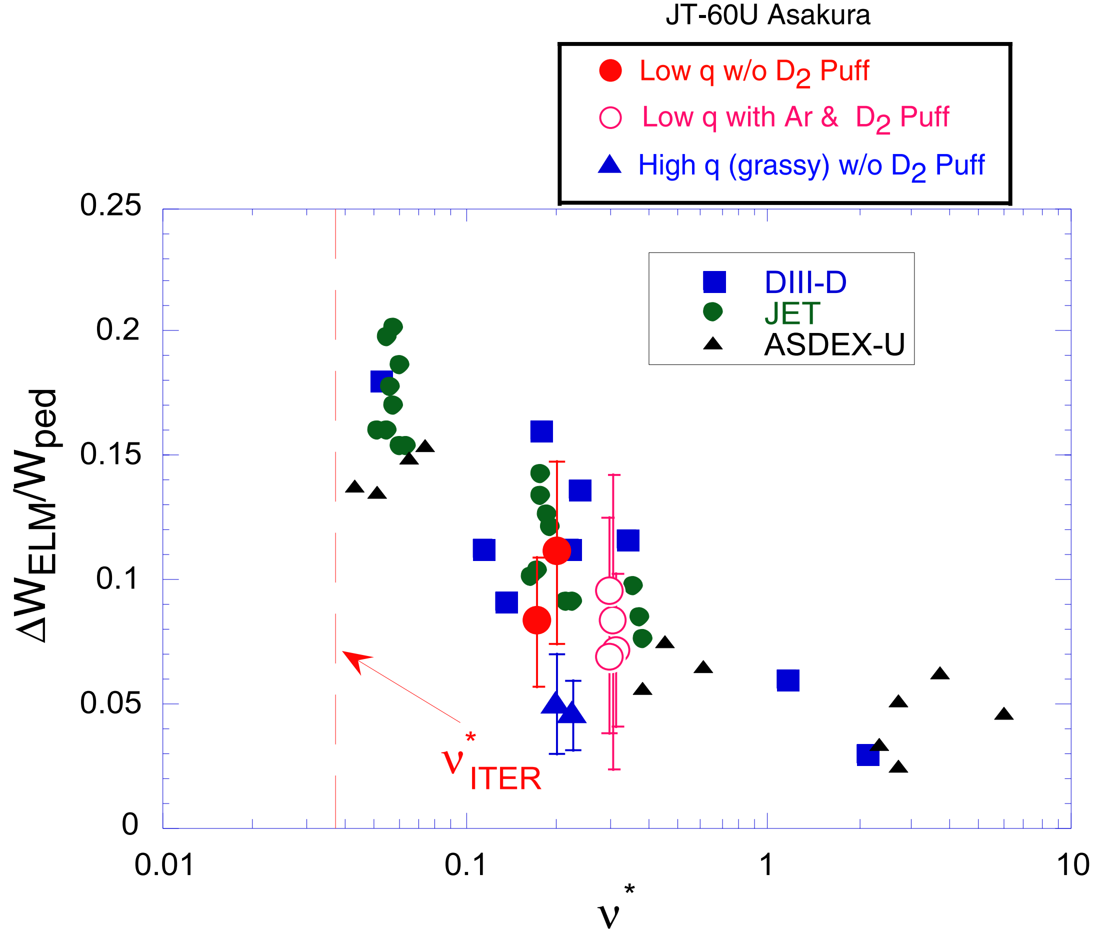
JET – Saibene

Gas scan at 2.5MA/2.7T, δ~0.48, P_{NB}=15MW

- Mixed Type I-II at n_{ped}~8 10^{19}
- Average Type I ELM losses reduced with mixed ELMs (f_{ELM}x< ΔW_{ELM}>)
- P_{loss} between ELMs increases, from ~ 6 to ~ 10MW
- Any MHD invoked to explain Type II ELMs, should generate enhanced particle and power losses replacing the ELM loss channel

Type II with NB only vs Type II with dominant electron heating

JT60-U : ELM Energy losses ↓ by a factor ~2-5 with Type II ELMs

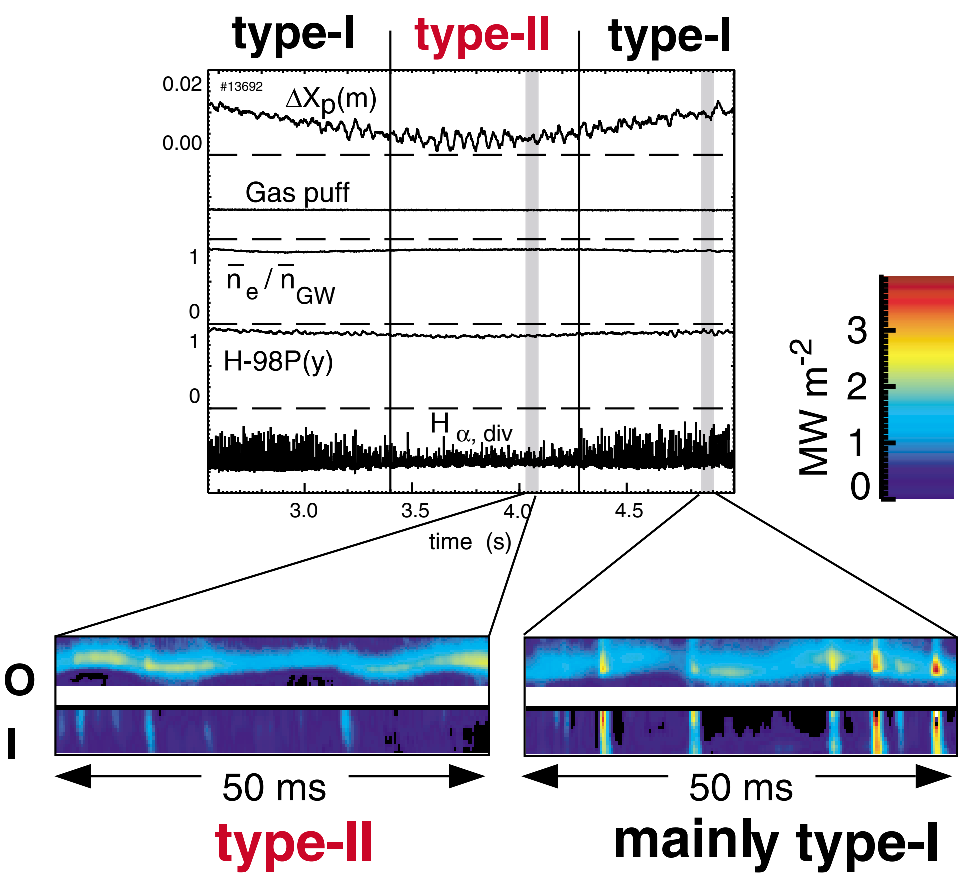


JT60-U - Asakura

The reduction of the ELM energy loss with Type II ELMs occurs at constant ν^*

Loarte – IAEA 2000

Small "bursty" heat pulses with Type II ELMs



ASDEX-U – Stober - Herrmann

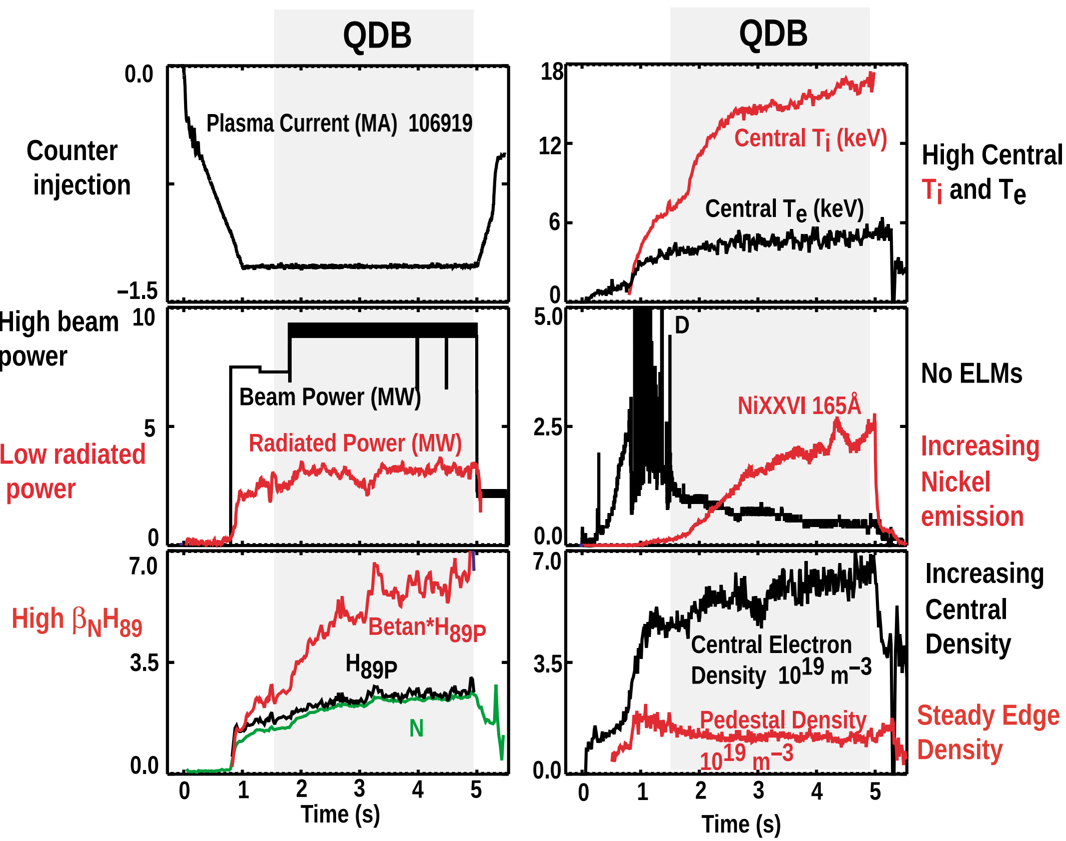
Periodic heat pulses with Type II ELMs (not correlated to D_α)

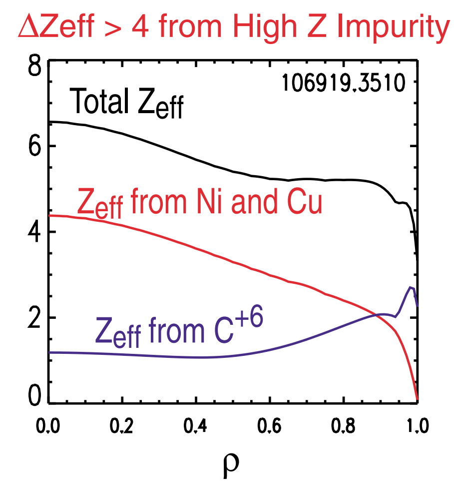
Peak power load reduced with Type II ELMs

Heat pulses in the divertor $\Rightarrow$ MHD modes?

Fast thermography for detailed power balance and λ_p measurements Type I vs II

ITB+ETB and no ELMs: QDB* modes of DIII-D





Counter-injection NBI, wide range of q and δ

High β_N (~3.5) and no ELMs (EHO at 6-10kHz)

But…

n_{ped} ~10%n_{GR}

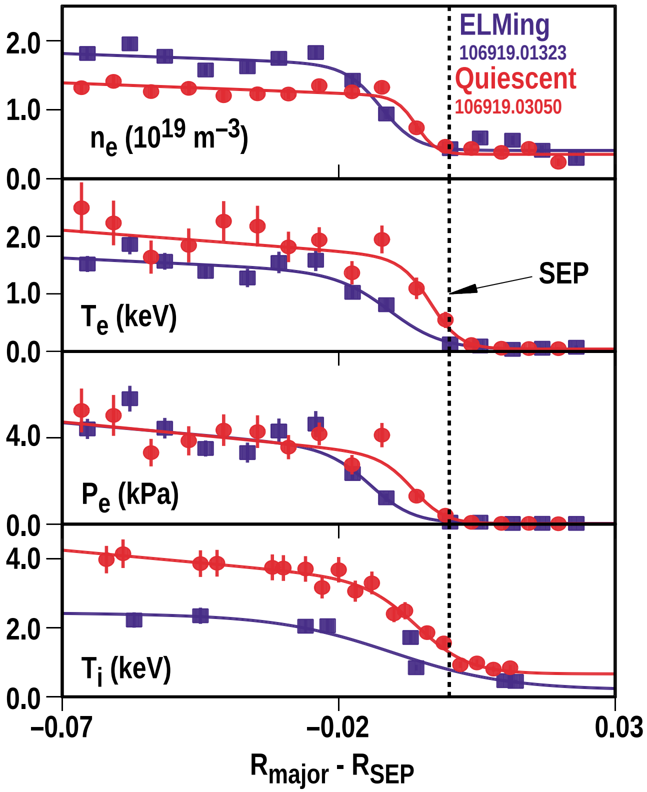
Z_{eff}~7 (transport or sources?)

Fast ion losses → power deposition far from separatrix

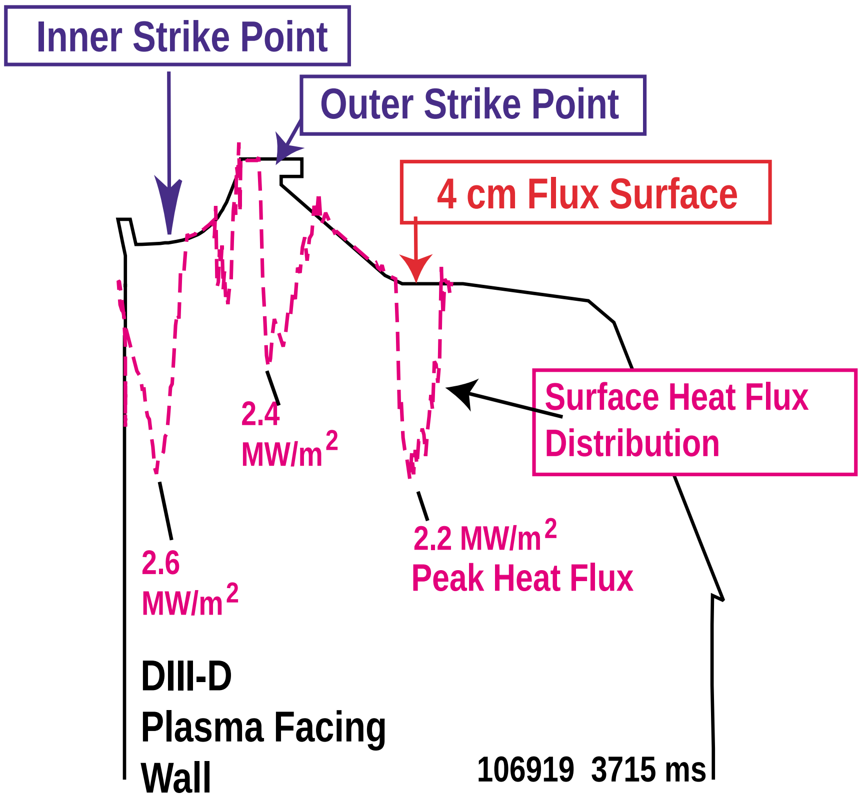
QDB modes require more development in order to be a solution for ITER.

West – APS 2001

QDB in DIII-D – more details



Pedestal profiles of ELMy and QDB

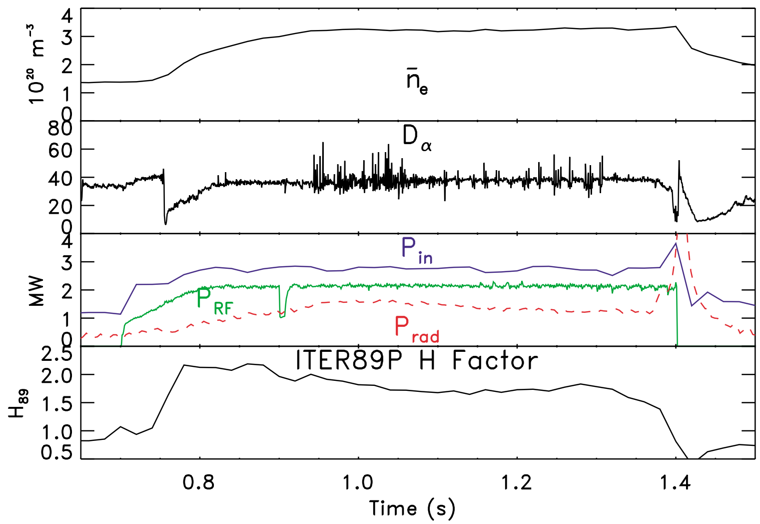


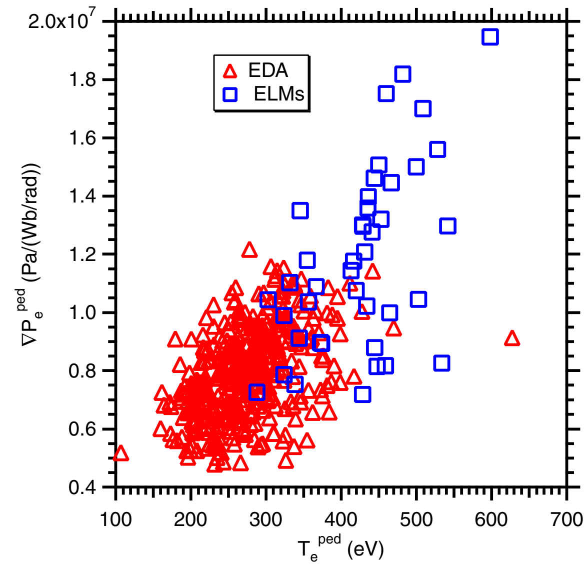
Power deposition patterns in QDBs

West & Lasnier – APS 2001

Regimes with small ELMs & good Confinement (Xa)

EDA (C-Mod)





Some EDA features:

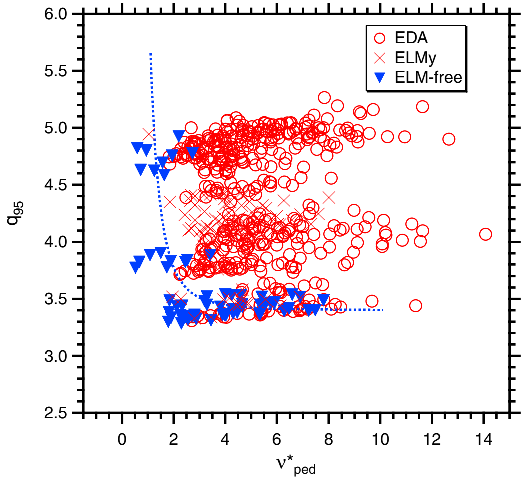
- EDA associated to QC edge mode (high ν*, low T_{ped})
- Resistive ballooning modes are candidate for EDA

If P_{in} is increased:

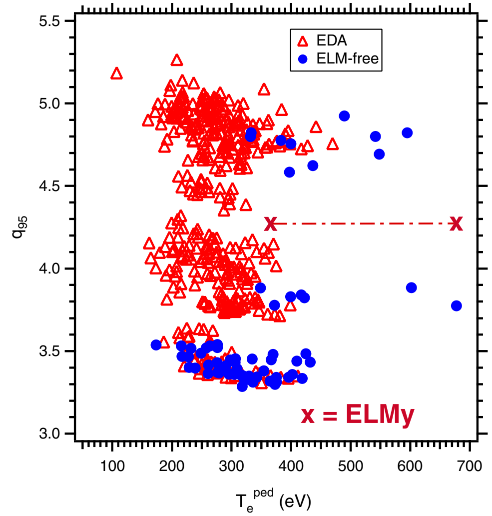
- QC disappears ⇒ broadband MHD
- Pressure gradient steepens and “grassy” ELM appear
- Pedestal unstable to peeling/ballooning modes

C-Mod
Mossesian
Hubbard
Snipes

Grassy ELMs in C-Mod: high T_{ped} (and n_{ped})



- T_{ped} similar to ELM free
- High density ($2\ 10^{20}\ m^{-3}$), similar to EDA
- Frequency of MHD fluctuations near to that of Type II in ASDEX-U (and JET)



C-Mod
Mossesian
Hubbard
Snipes