

ELM Energy/Particle Plasma Losses and Fluxes on PFCs

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Close Support Unit - Garching

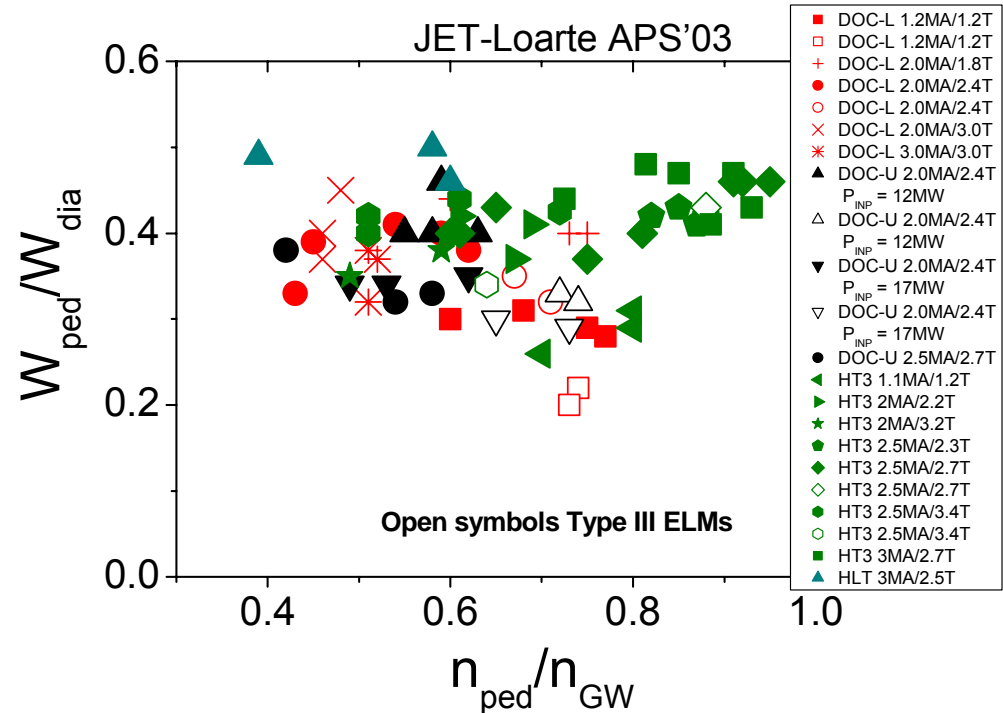
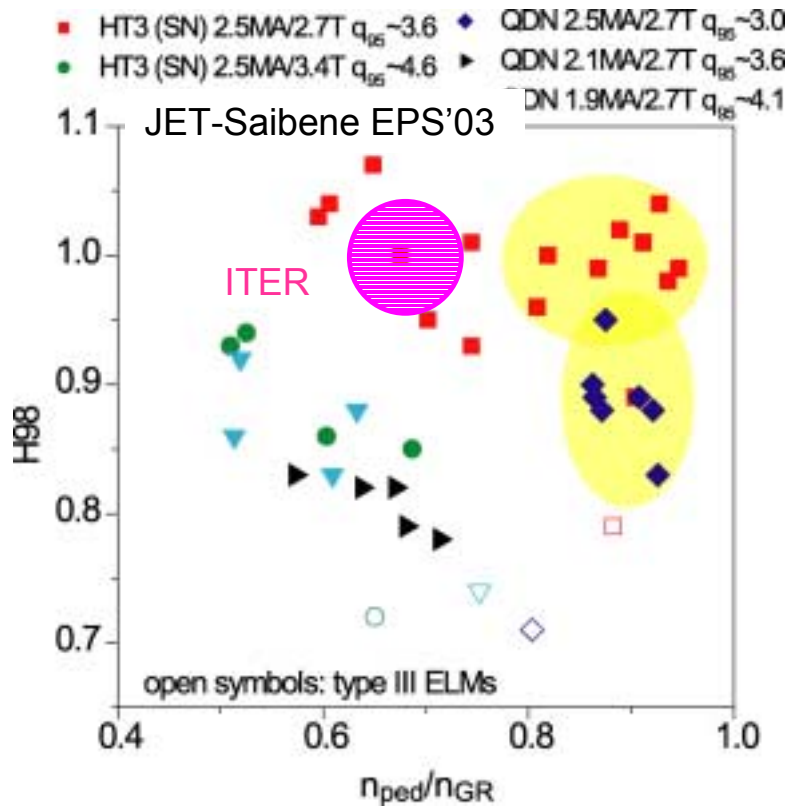
Contributions from : G. Saibene, R. Sartori, T. Eich, M. Kempenaars, M. Becoulet, G. Federici, P. Snyder, P. Ghendrih, G. Huysmans, C. Pérez, R. Koslowki, I. Nunes, B. Gonçalves, C. Silva, W. Fundamenski, T. Petrie, A. Leonard, M. Fenstermacher, J. Boedo, J. Stober, N. Oyama, Y. Kamada, N. Asakura, G. Counsell, A. Kirk, S. Saarelma, J Lönnroth, V. Parail,

Outline of the Talk

1. Introduction
2. Physics of ELM instability and experimental evidence
3. Main plasma ELM energy/particle losses
4. ELM energy/particle fluxes to PFCs
5. Regimes with high P_{ped} + small/no ELMs
6. Conclusions

Introduction (I)

$H \sim 1$ at $n \sim n_{GW}$ in Type I ELMy H-modes requires high W_{ped}



W_{ped}/W_{dia} (JET-Type I ELMs) $\sim 0.4 \pm 0.1$

➤ weak W_{ped}/W_{dia} dependence on :
 q_{95} ($2.8 < q_{95} < 5.2$), P_{inp} , δ ($\delta > 0.27$)

➤ lower W_{ped}/W_{dia} @ low I_p & Type III ELMs

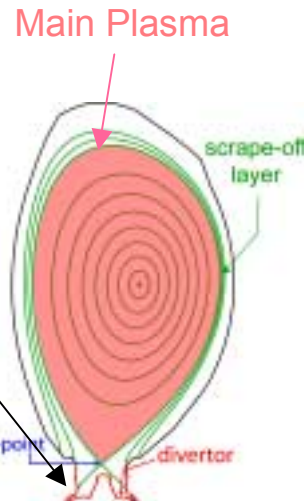
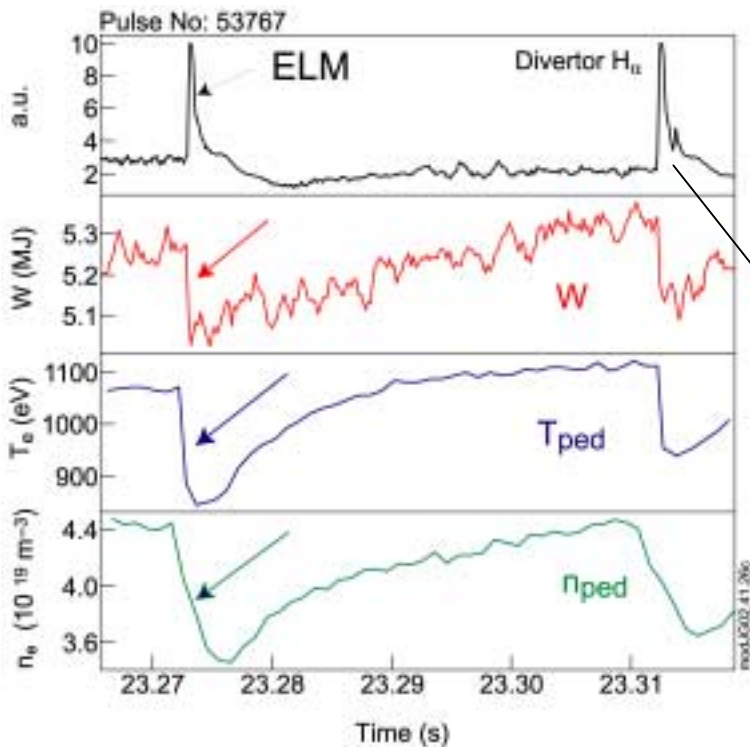
general result for Type I ELMy
 H-modes (ASDEX-U, DIII-D, JET, ...)

Introduction (II)

Pedestal plasma experiences quasi-periodic relaxations → ELMs

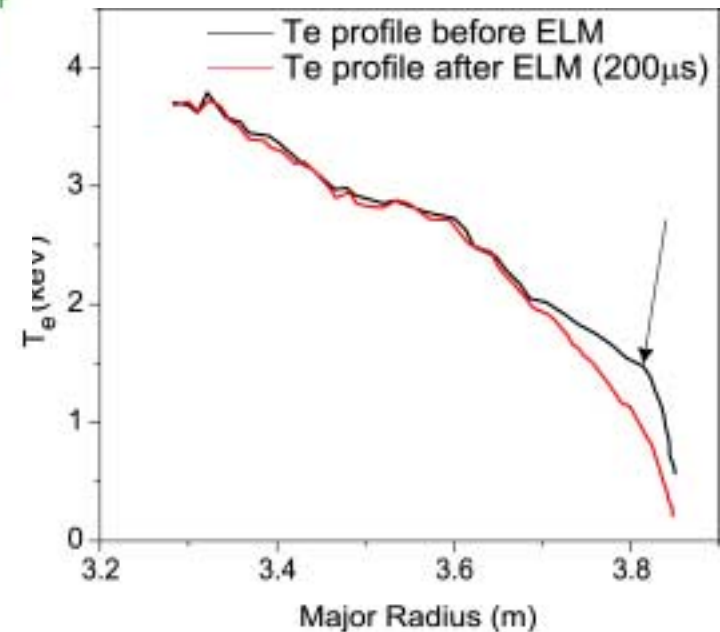
ΔW_{ELM} small fraction of W_{plasma} (<10 %) to divertor/wall in $\sim 200 \mu s$ → Large Energy Flux

JET – Type I ELM - Saibene



Only Pedestal Region of Plasma Affected by ELMs

JET – Type I ELM - Saibene



Introduction (III)

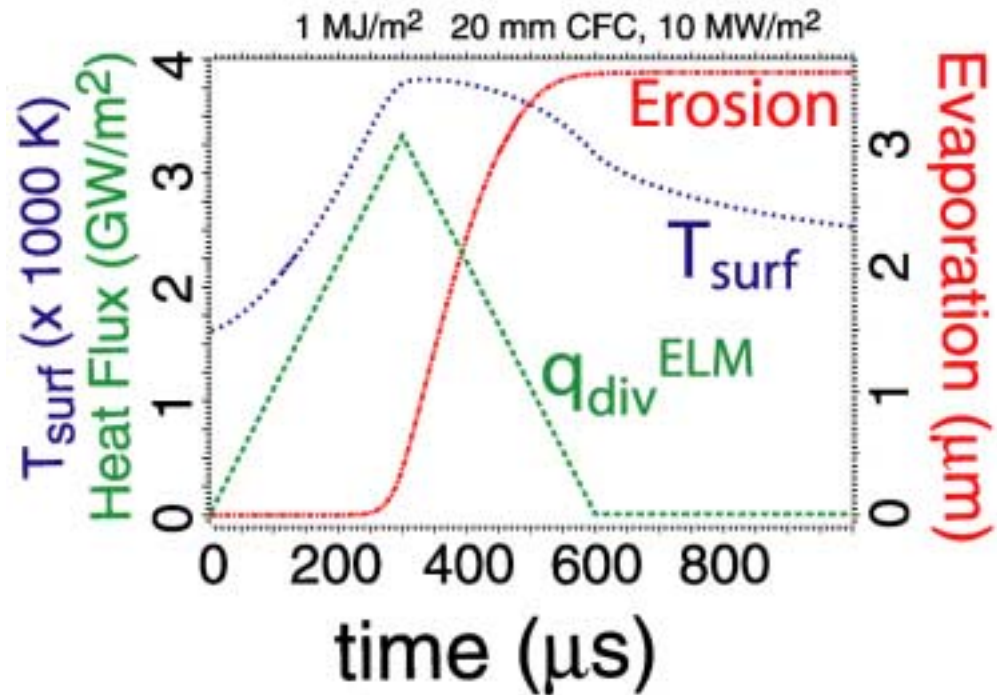
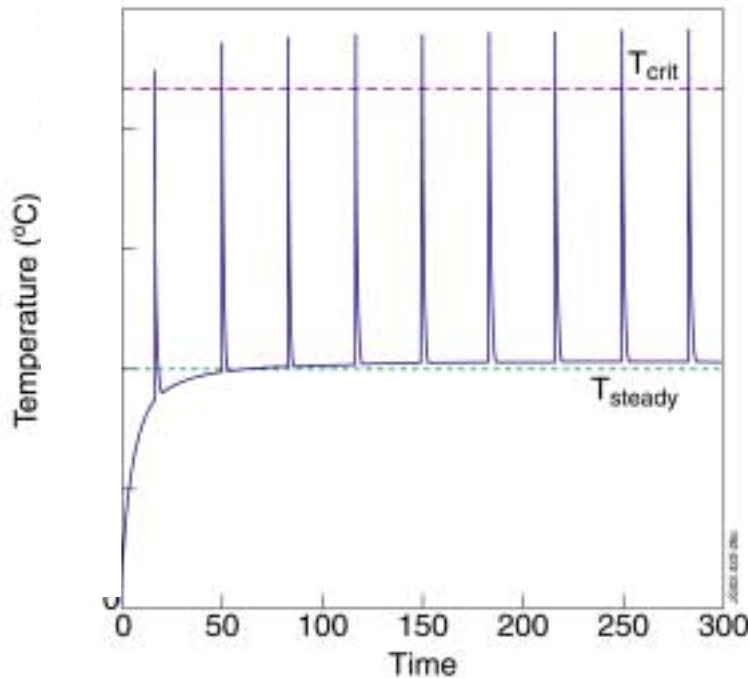
ITER rough estimates

$$W_{\text{dia}} = 350 \text{ MJ} \rightarrow W_{\text{ped}} = 90 - 150 \text{ MJ}, \Delta W_{\text{ELM}} = 10 - 30 \text{ MJ}$$

$$(A_{\text{div}} = 3 \text{ m}^2, \tau_{\text{ELM}} = 300 \mu\text{s})$$

$$T_{\text{max}}^{\text{ELM}} > T_{\text{ev,melt}}^{\text{C,W}} \rightarrow \text{ELM Erosion}$$

ITER-Federici PPCF'03



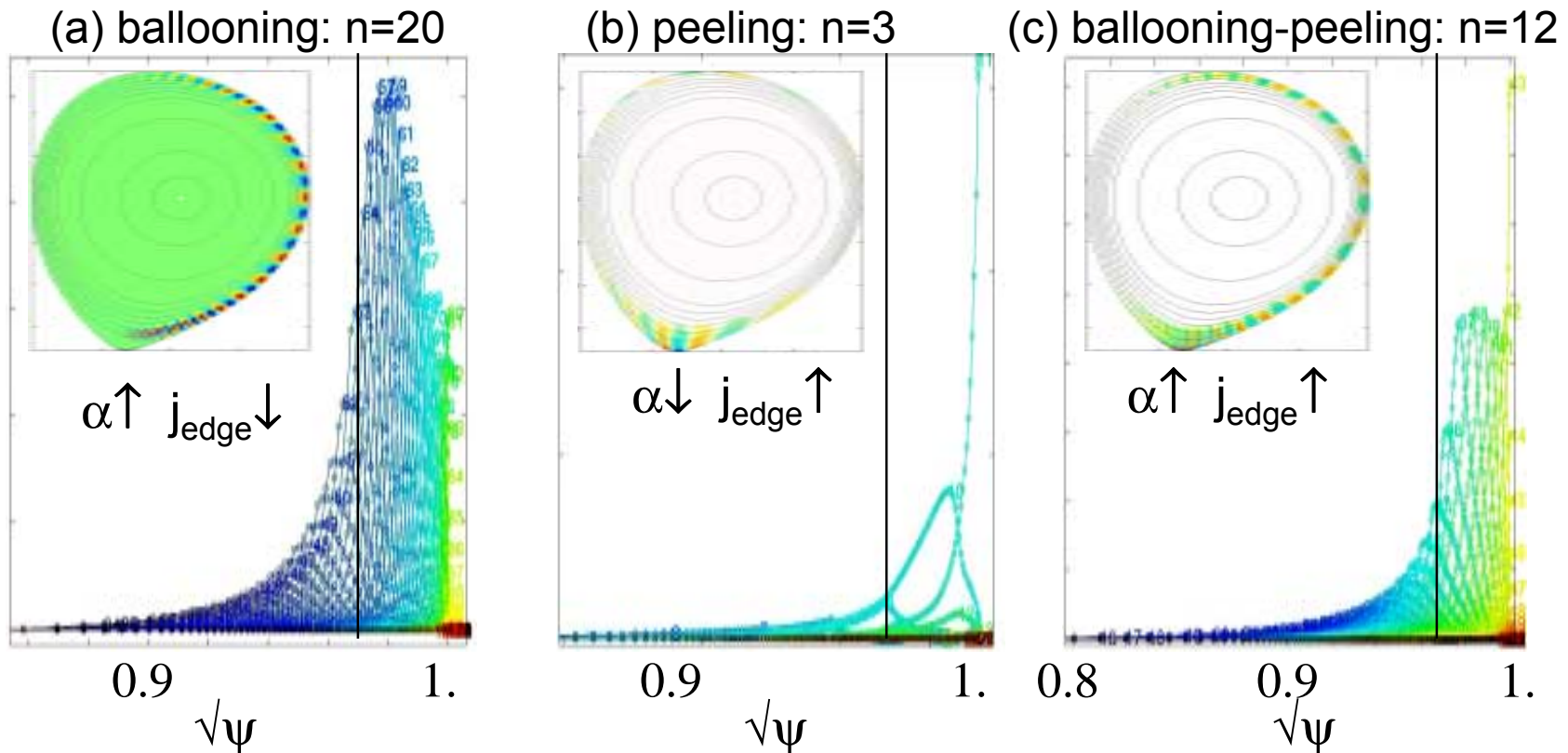
$$\Phi_{\text{ELM}}^{\text{C,W}} (\text{MJm}^{-2}\text{s}^{-1/2}) \leq 50 \text{ for small ELM erosion} \sim 3.5 \mu\text{m/ELM} + \text{C-target} = 2 \text{ cm} \rightarrow 6000 \text{ ELMs} !!$$

Physics of ELM instability (I)

Peeling-Ballooning model of the ELMs (Connor PPCF'98)

- Ballooning modes driven by grad P_{ped}
- Kink (peeling) modes driven by edge current (large $J_{bootstrap}$)
- Coupled peeling-ballooning modes

JET-Huysmans '01

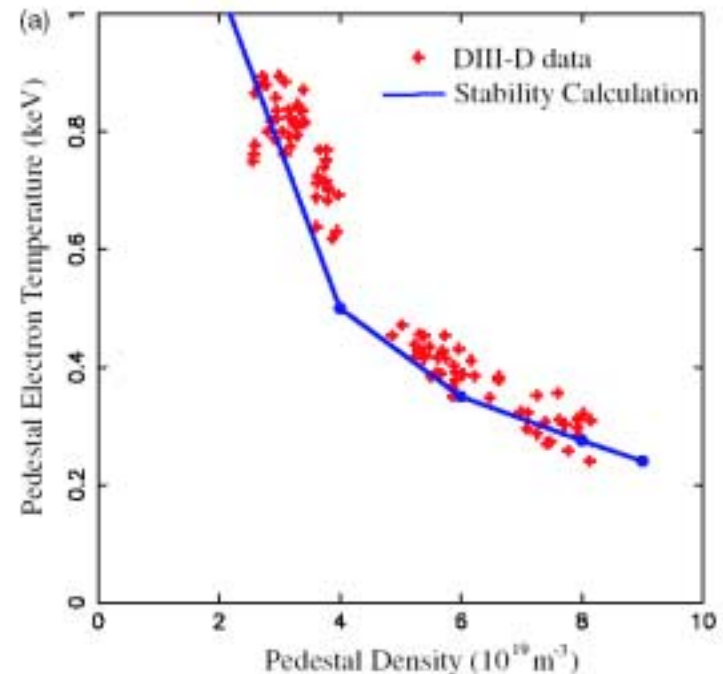
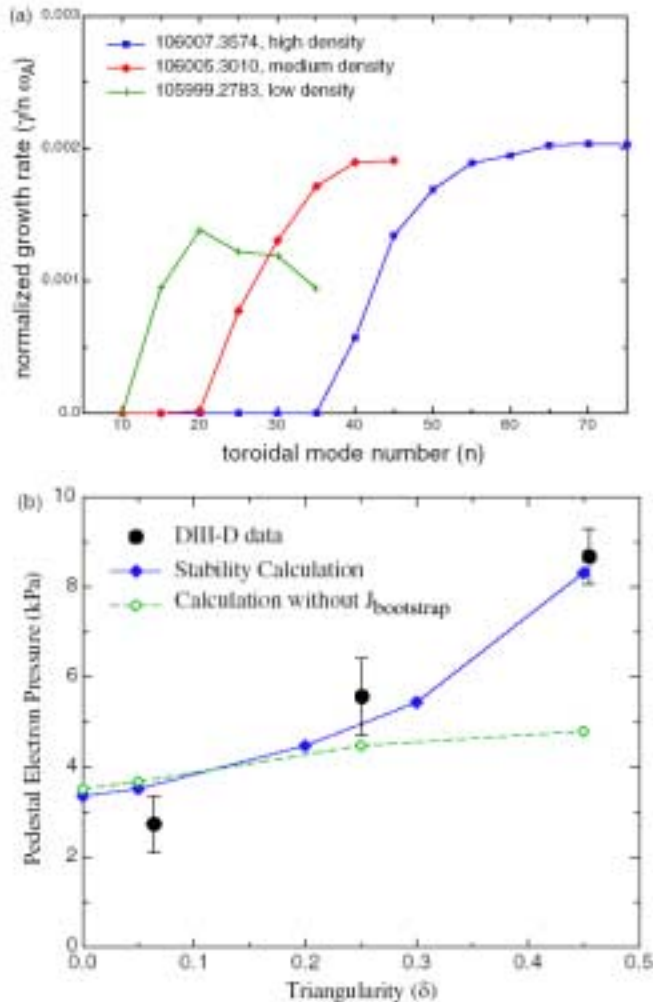


Physics of ELM instability (II)

Peeling-Ballooning calculations-experiment comparison

DIII-D-Snyder NF'04

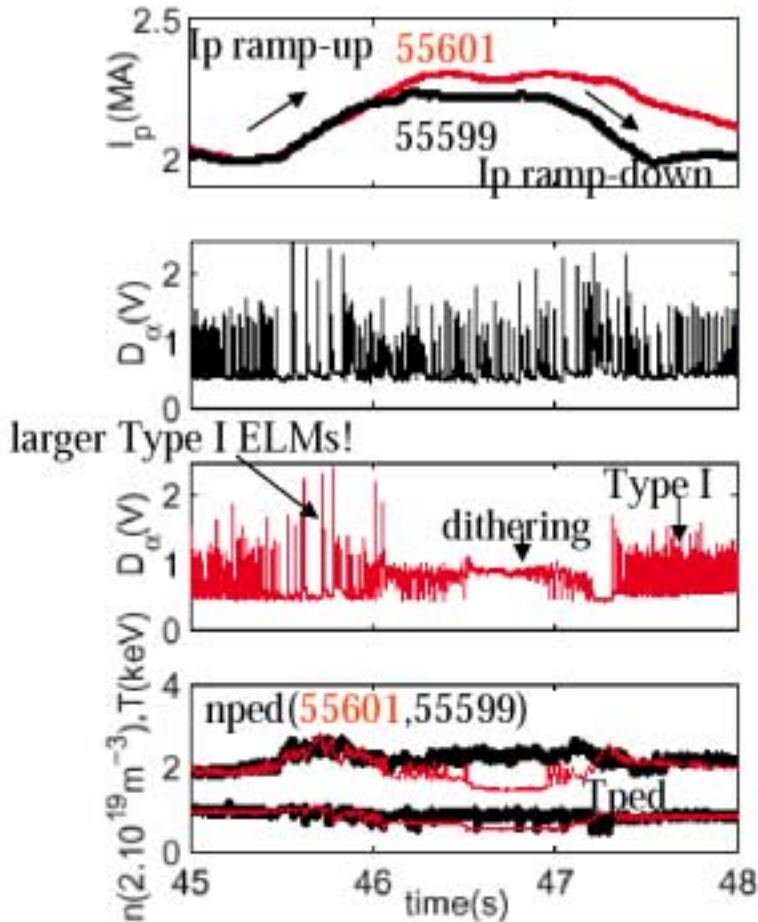
- P_{ped} matched with model
- Change of mode instability analysed
- Role of $j_{bootstrap}$ evaluated (+ measured)



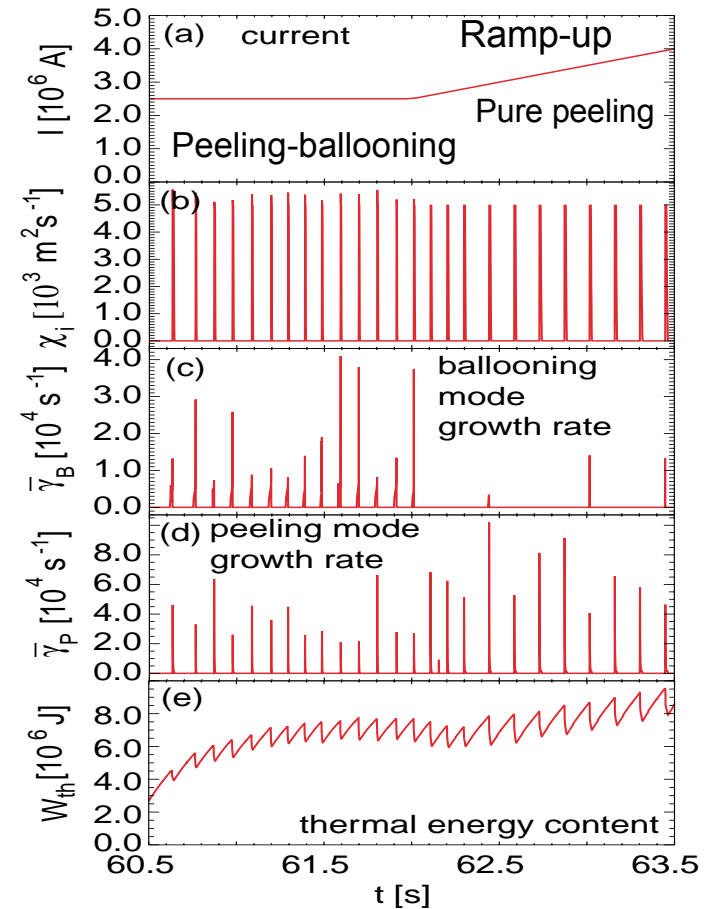
Physics of ELM instability (III)

Role of edge current on ELM triggering demonstrated

JET-Becoulet EPS'03



JET-JETTO-Lönroth-Parail '04



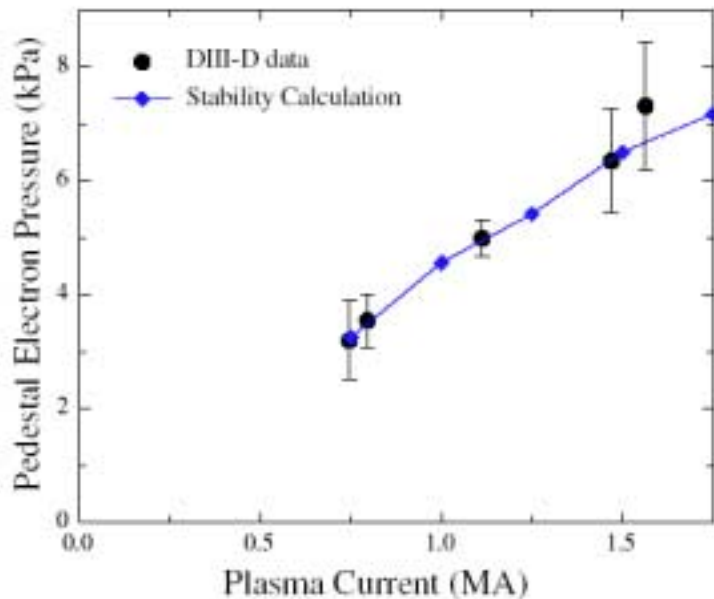
seen in COMPASS-D, MAST, JET

Physics of ELM instability (IV)

Scaling of pedestal pressure and peeling-ballooning model

DIII-D-Snyder NF'04

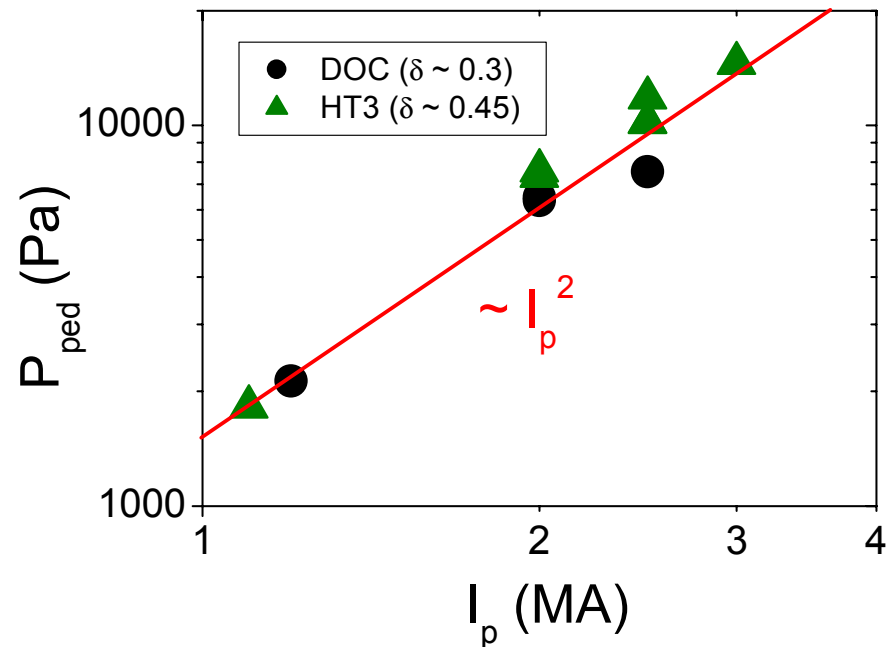
$$P_{ped}^{Type I} \sim I_p$$



JET-Loarte APS'03

$$P_{ped}^{Type I} \sim I_p^2 \text{ (ballooning-like)}$$

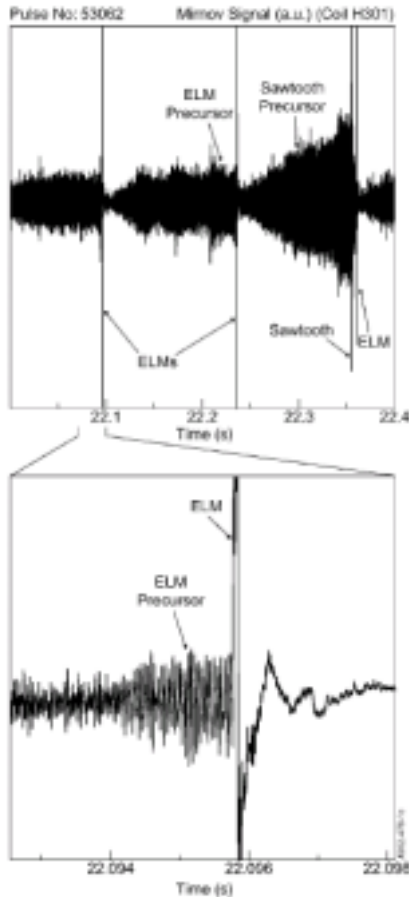
P_{ped} depends weakly on : q_{95} and $n_{e,ped}/n_{GW}$



comparison of model with various experiments required to identify physics processes

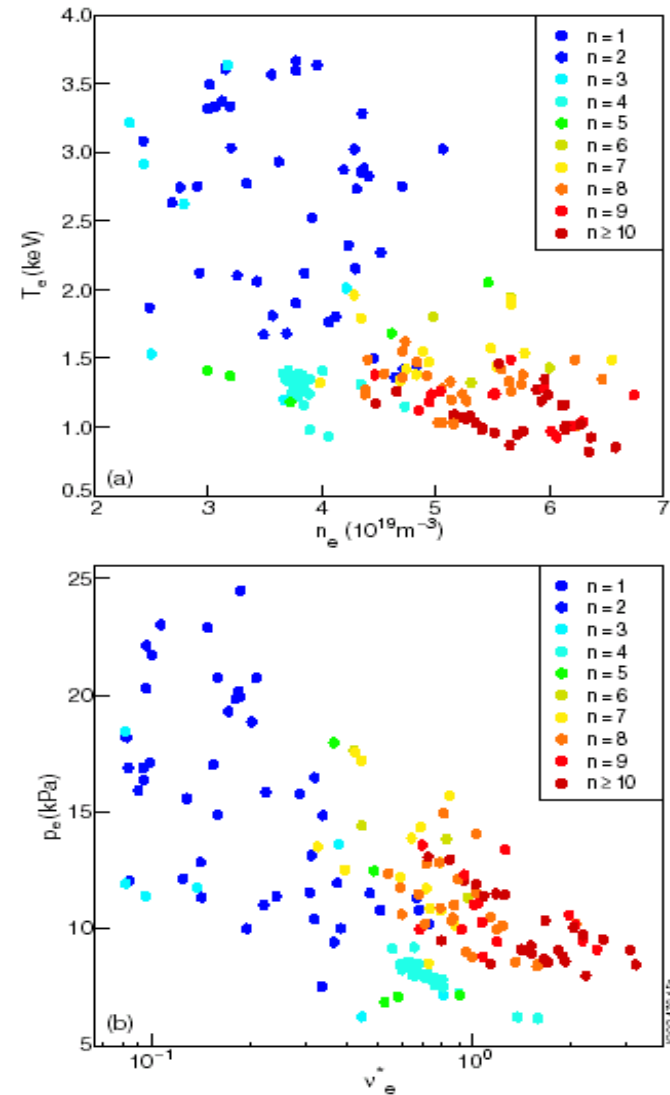
Physics of ELM instability (VI)

precursors seen before ELMs in many experiments with $n = 1-10$



JET-Pérez NF'04

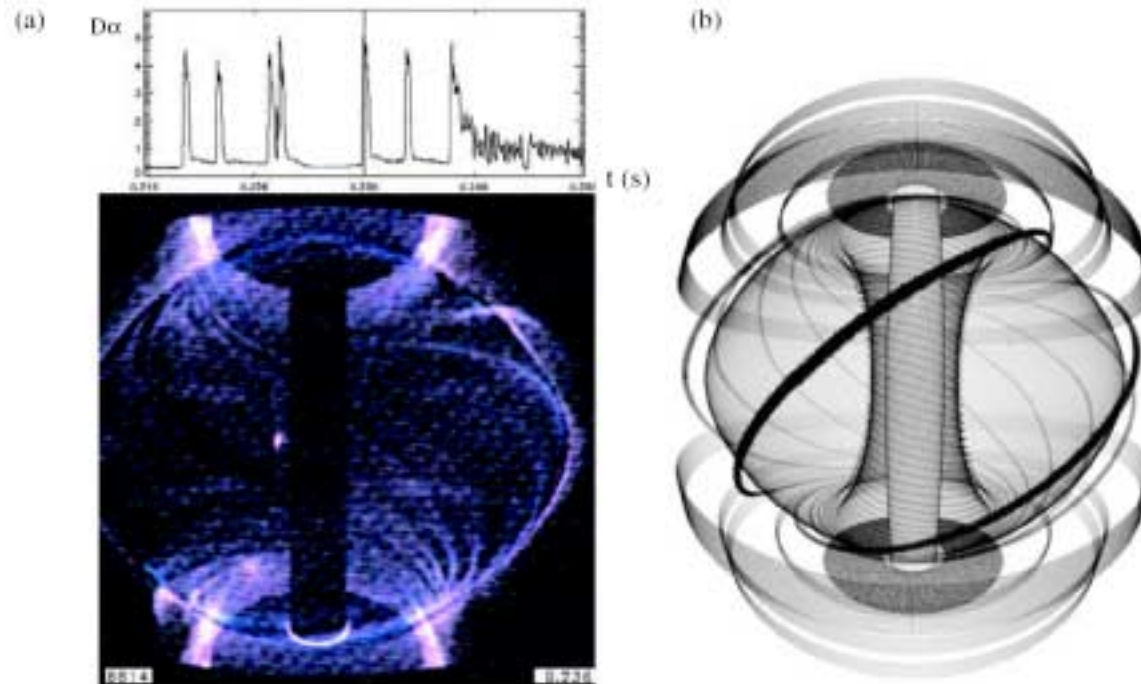
- precursors' n as expected from P-B
- precursors **do not** grow as linearly unstable modes $e^{t/\tau}$
- role of precursor on ELM trigger is unclear



Physics of ELM instability (VII)

Filaments are seen to appear in the plasma boundary prior to ELMs ($n = 10, q = 4$)

MAST-Akers PPCF'03

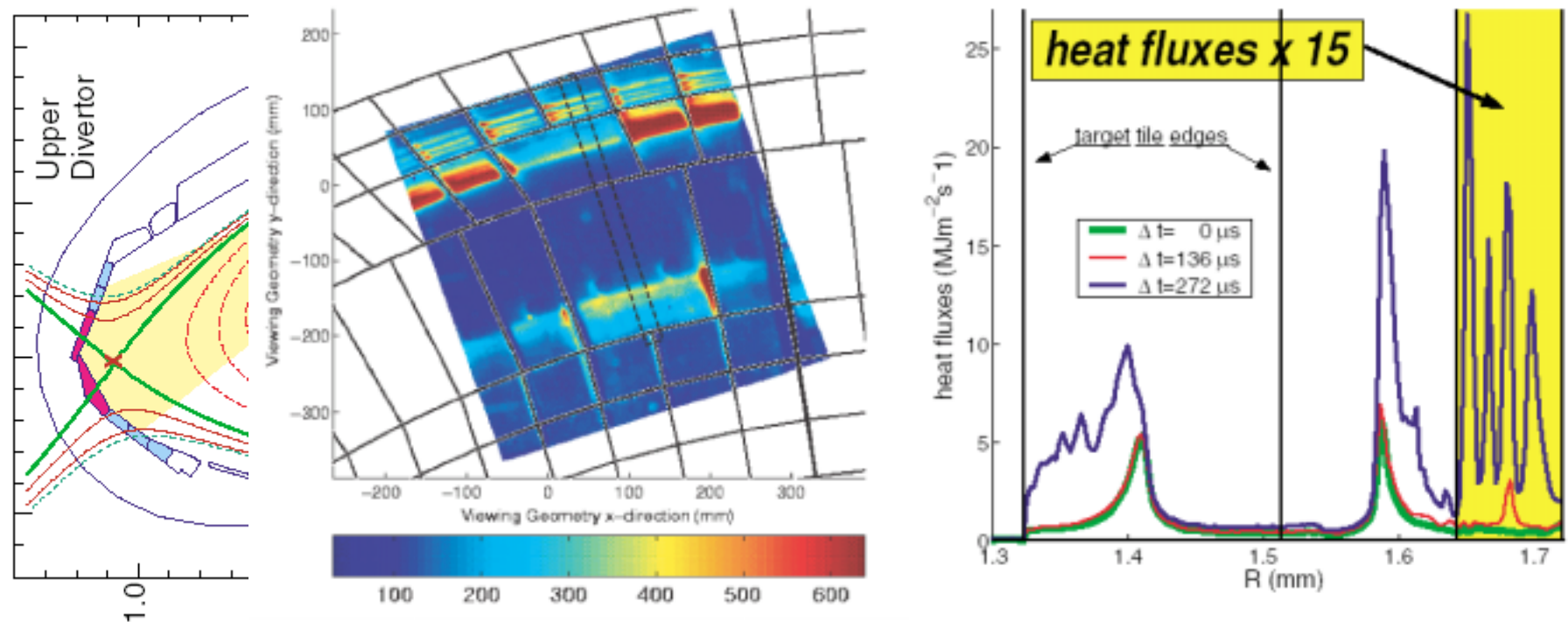


how much energy flows in the filaments?

Physics of ELM instability (VIII)

Analyses of energy fluxes far from strike point in ASDEX Upgrade are consistent with $n = 8 - 24$ modes

ASDEX Upgrade-Eich PRL'04

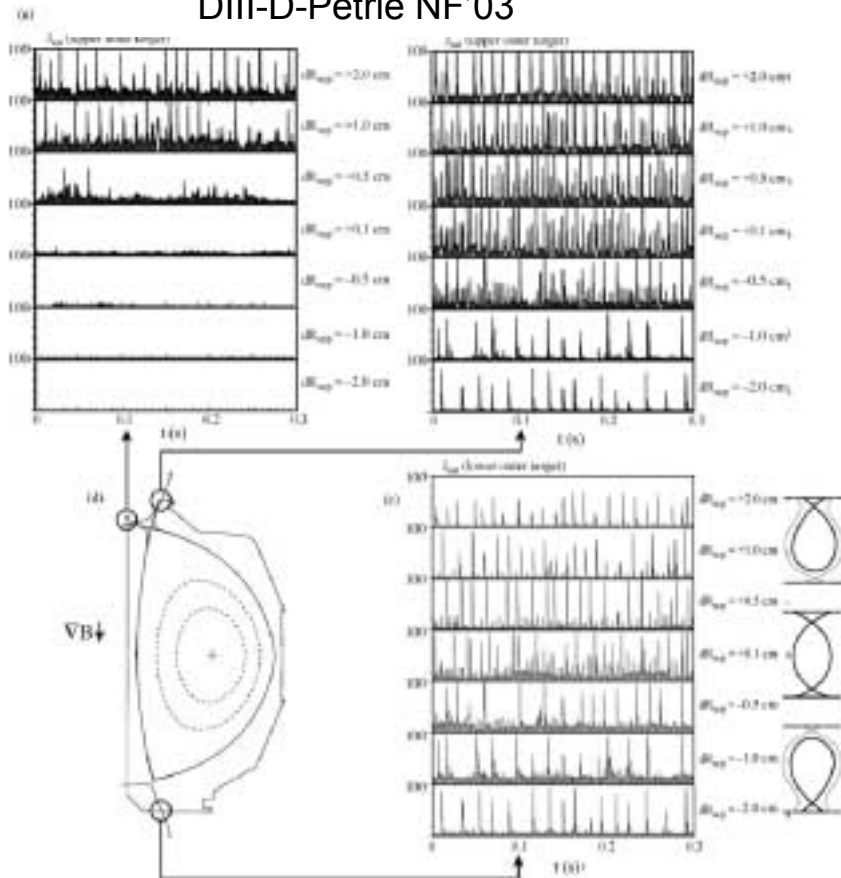


energy content in stripes less than 3% of $\Delta W_{\text{ELM}}^{\text{div}} !!$

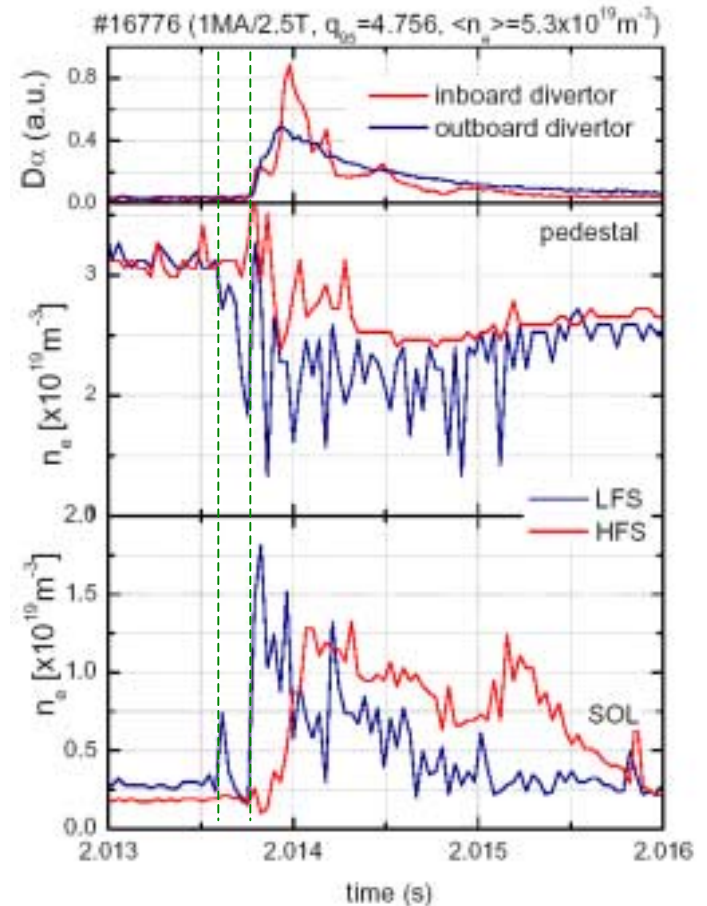
Physics of ELM instability (X)

ELM spatial and temporal ballooning character

DIII-D-Petrie NF'03



ASDEX Upgrade-Nunes EPS'03 subm. NF'04

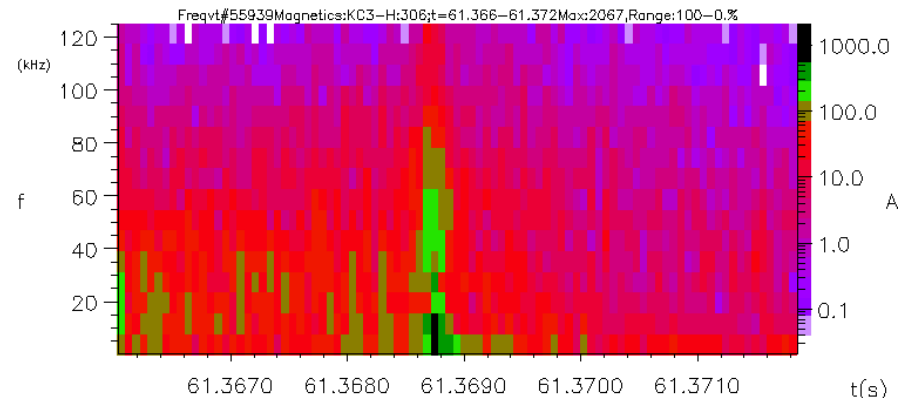
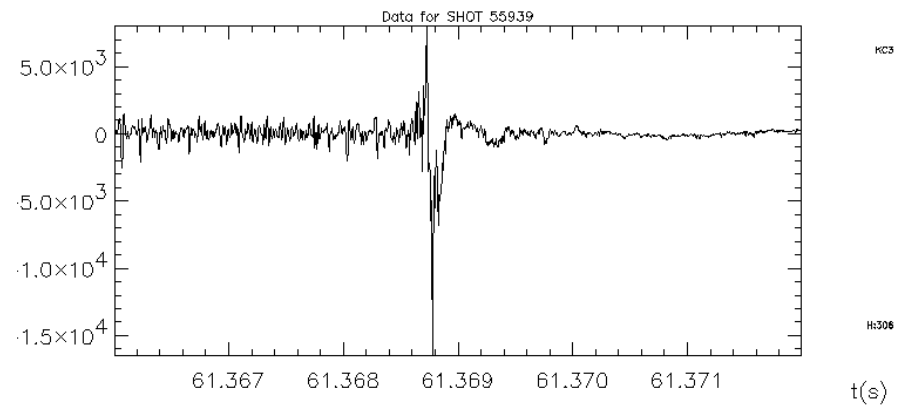
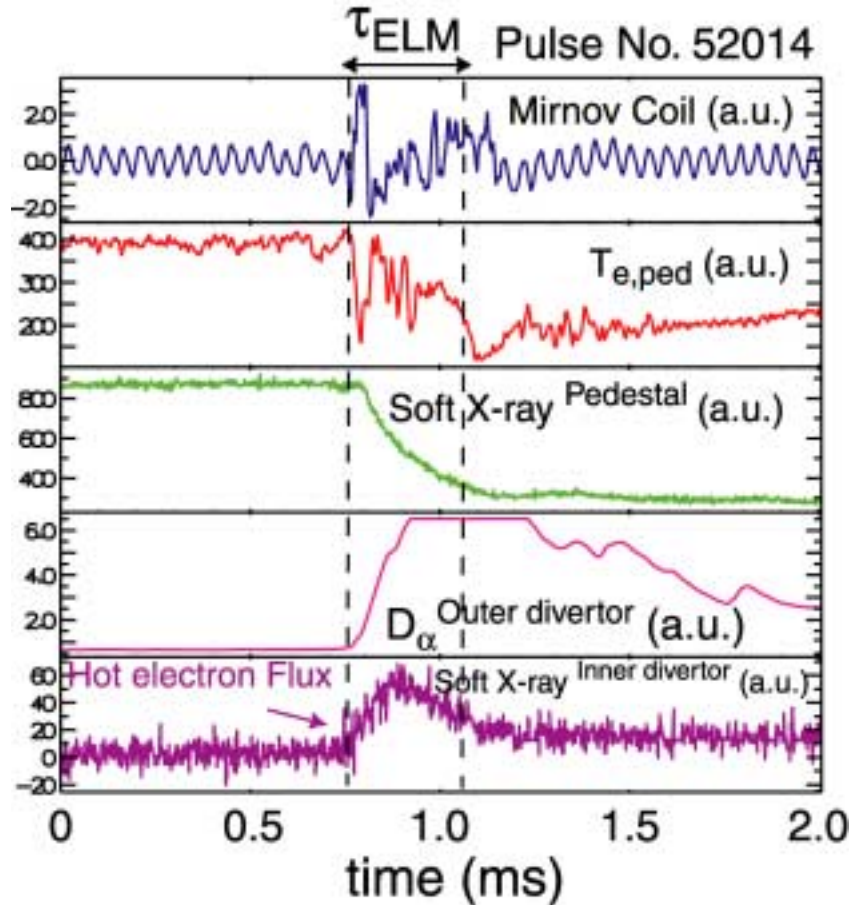


similar results on divertor fluxes from
ASDEX Upgrade, MAST, JET

Physics of ELM instability (XI)

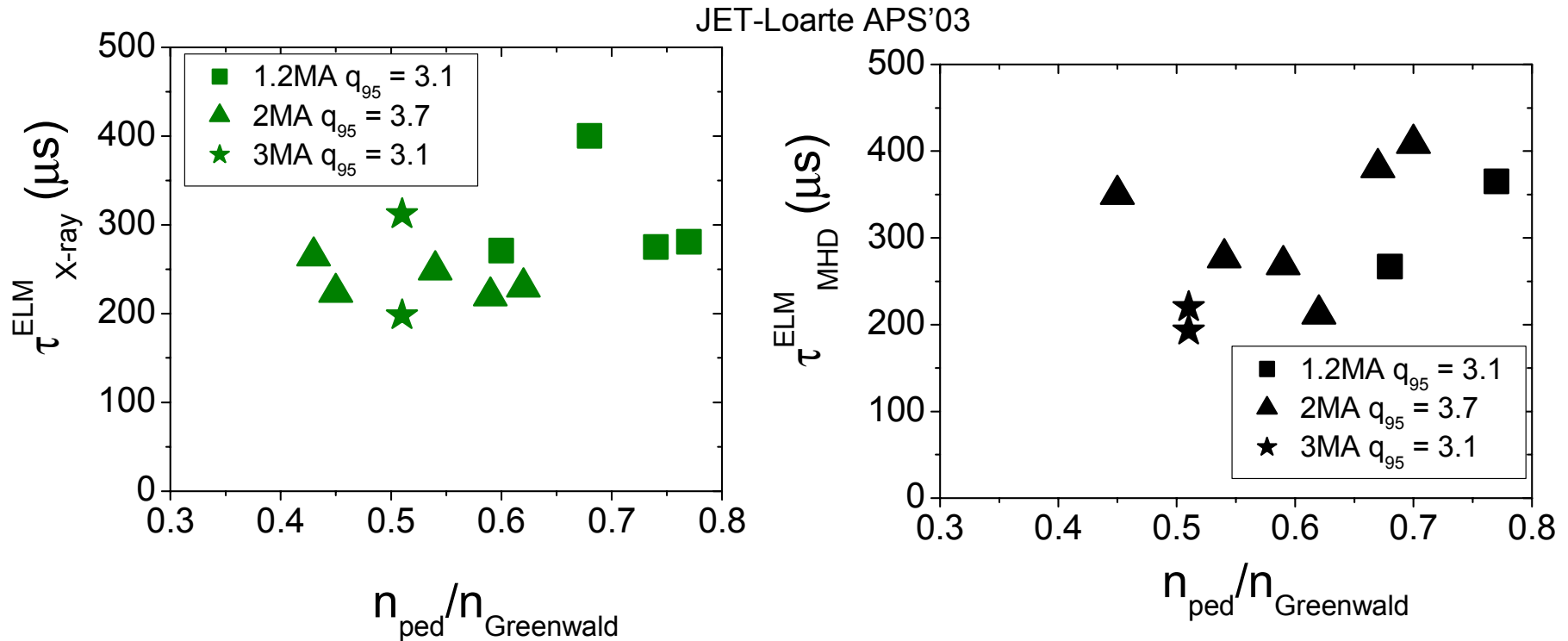
Timescale of ELM pedestal collapse/MHD phase timescale :
 collapse of pedestal - hot e⁻ impact on divertor - MHD

JET-Loarte APS'03



Physics of ELM instability (XII)

Timescale of ELM pedestal collapse $\sim 200 - 300 \mu\text{s}$ for JET Type I ELMs



Similar timescales in JT-60U, DIII-D, ASDEX Upgrade
MAST

Physics of ELM instability (XIV)

Physical mechanisms of ELM growth

- Non-linear explosive ballooning (Cowley PPCF'03)

$$\tau_{\text{ELM}} \sim (\tau_E \tau_A^2)^{1/3}$$

$$\tau_A \sim qRn^{1/2}/B, \tau_E ?$$

JET : $\tau_{\text{ELM}}(\tau_E) \sim 50\text{-}100 \mu\text{s}$ but $\tau_{\text{ELM}} \sim R^\alpha$ with $\alpha \sim 5/3$

$$\tau_{\text{ELM}} \sim (I_p^{-2/3} n^{1/3}) \times (P^{-2/9} n^{1/6} I_p^{1/3}) \sim I_p^{-1/18} \text{ (if } n \sim I_p, P \sim I_p) \text{ !!!}$$

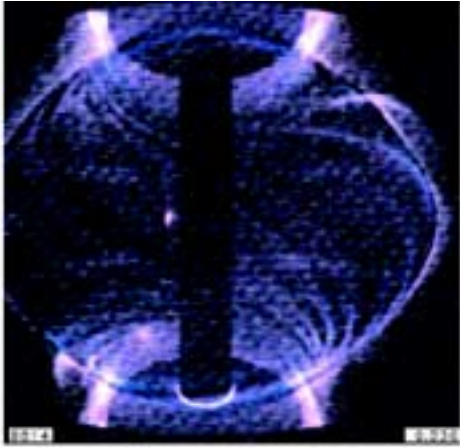
- Edge Reconnection (Igitkahnov EPS'01)

$$\tau_{\text{ELM}} \sim \tau_A (\tau_\eta / \tau_A)^\beta \quad (\beta = [1/3, 1])$$

$$\tau_{\text{ELM}} (\beta=1/2) \sim (R^{1/2} I_p^{-1/2} n^{1/4}) \times (a^{1/2} T^{3/4}) \sim R I_p^{1/2} \text{ (if } n \sim I_p, T \sim I_p)$$

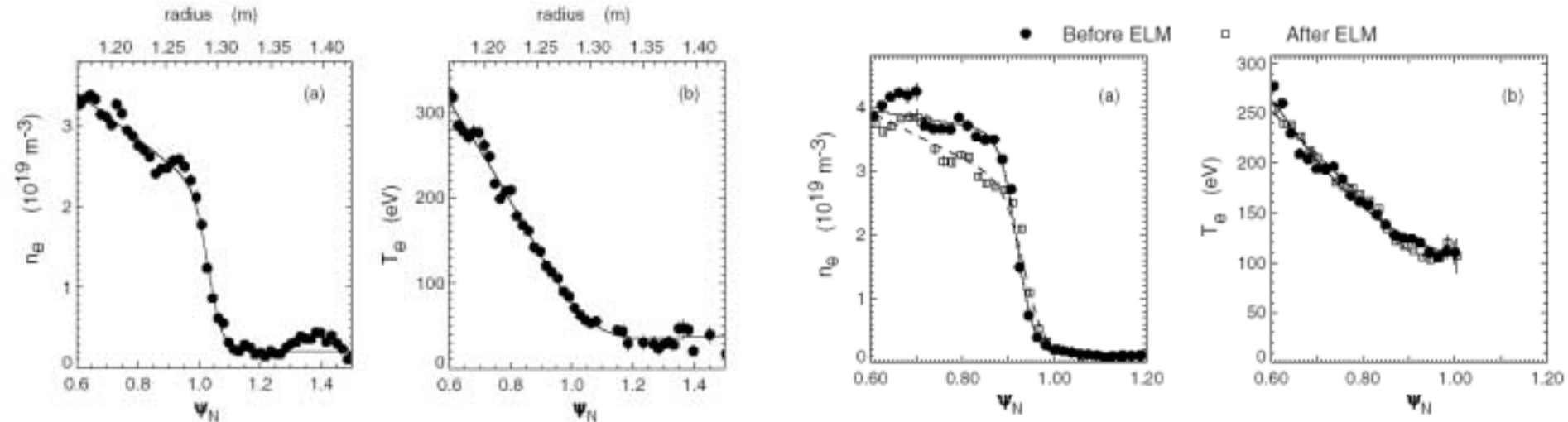
More experimental and theoretical work is needed!!!

Physics of ELM instability (XV)



how filaments evolve to an edge plasma collapse ?

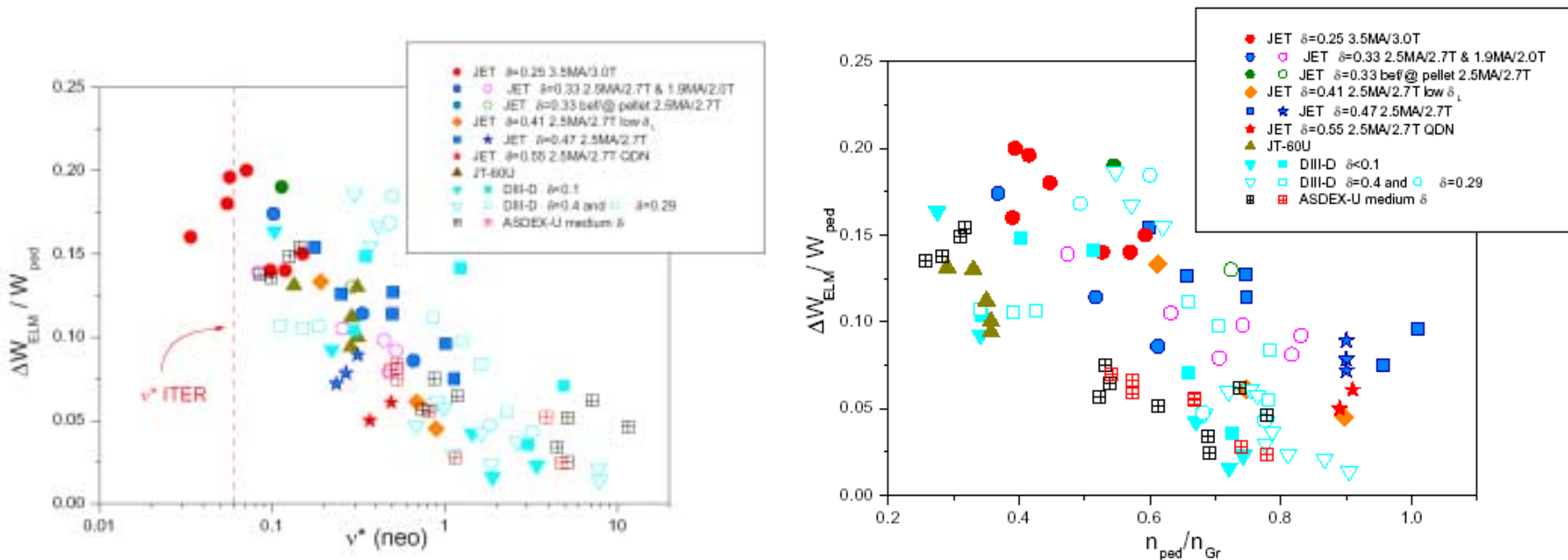
MAST-Kirk PPCF'04



Main plasma ELM energy/particle losses (I)

ELM energy/particle losses depend on pedestal parameters

ITPA-Loarte PPCF'03



Small $\Delta W_{ELM}/W_{ped}$ seen at high $n_{e,ped}/n_{GW}$ and/or high $v^*_{ped}(neo)$

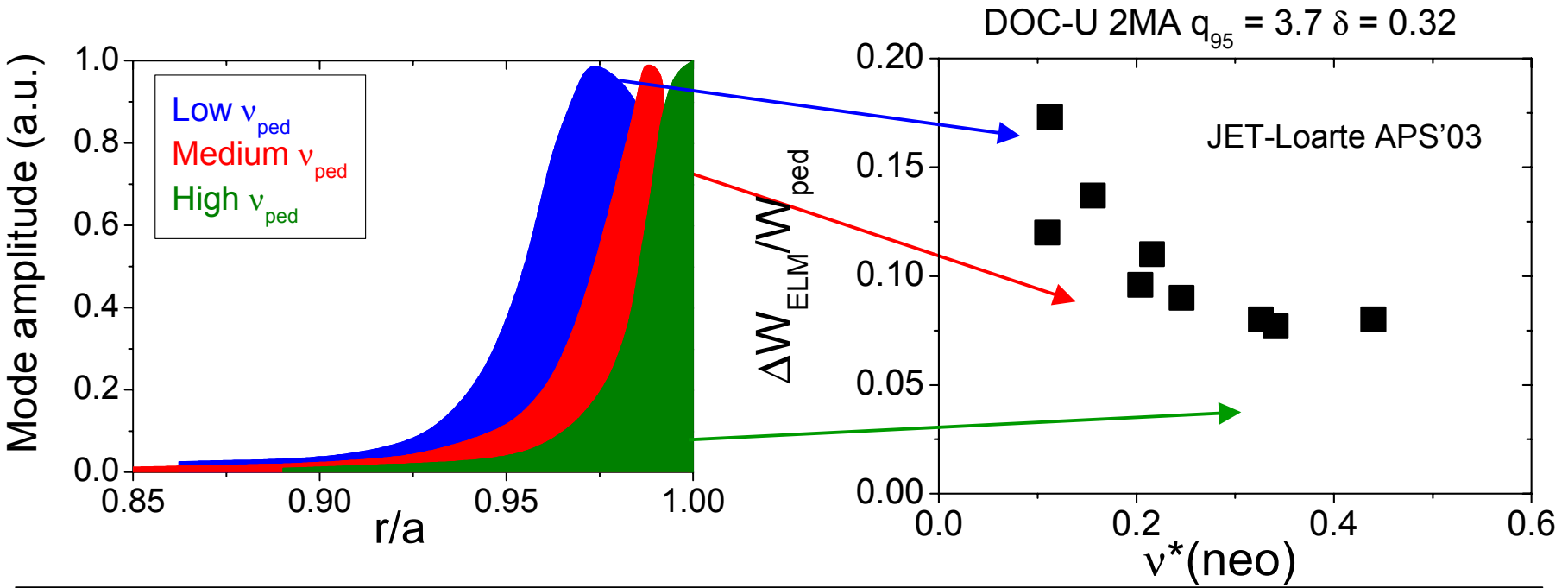
Main plasma ELM energy/particle losses (II)

Simple picture : small $\Delta W_{ELM} \leftrightarrow$ small volume of plasma affected by ELM

Peeling/Ballooning Picture : increasing $n_{ped} - v_{ped}^*$

n of unstable modes increase \leftrightarrow poloidal width of modes decrease

ELM affected volume (V_{ELM}) \rightarrow ΔW_{ELM} decreases



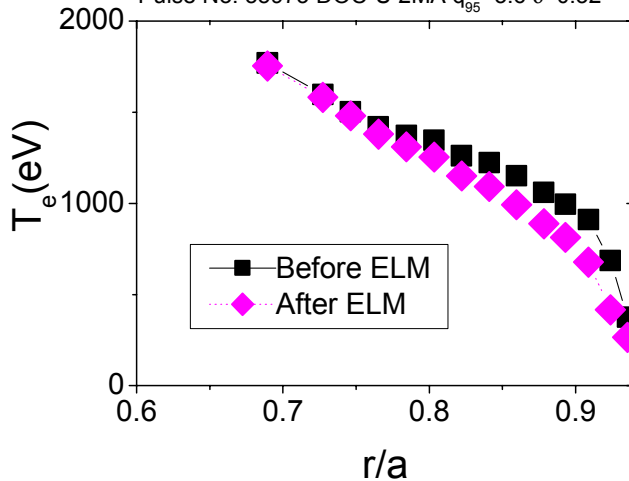
Main plasma ELM energy/particle losses (III)

ΔW_{ELM} ~~↔~~ ELM affected Volume

ΔW_{ELM} down by ~ 3 at $V_{ELM} \sim \text{constant}$!!

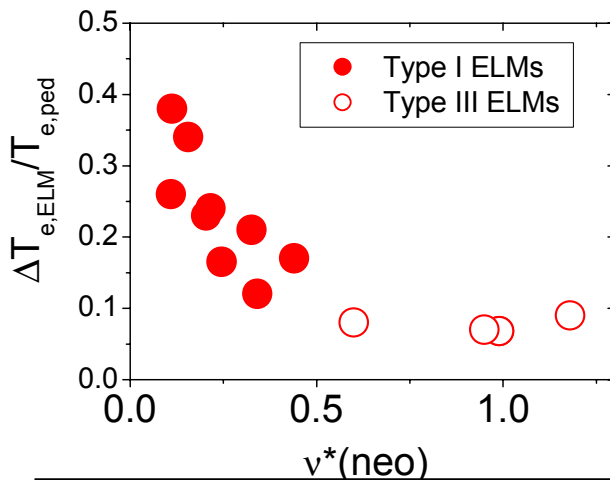
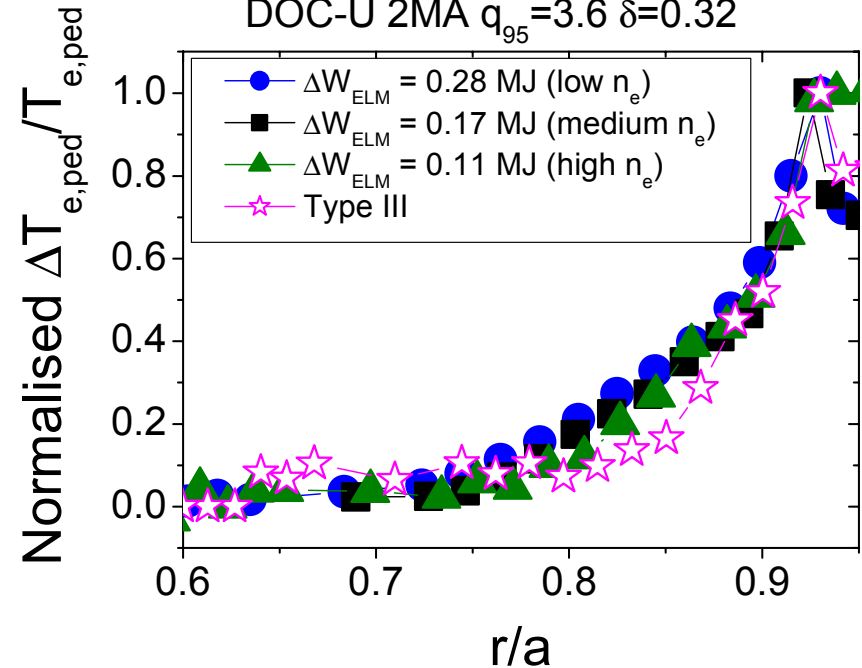
V_{ELM} from fast ECE

Pulse No. 55973 DOC-U 2MA $q_{95}=3.6$ $\delta=0.32$



JET-Loarte APS'03

DOC-U 2MA $q_{95}=3.6$ $\delta=0.32$



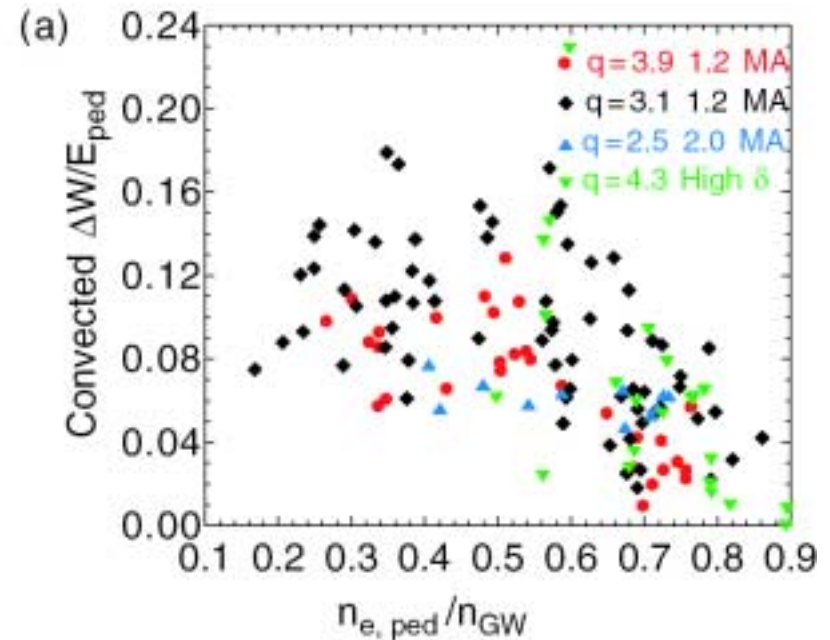
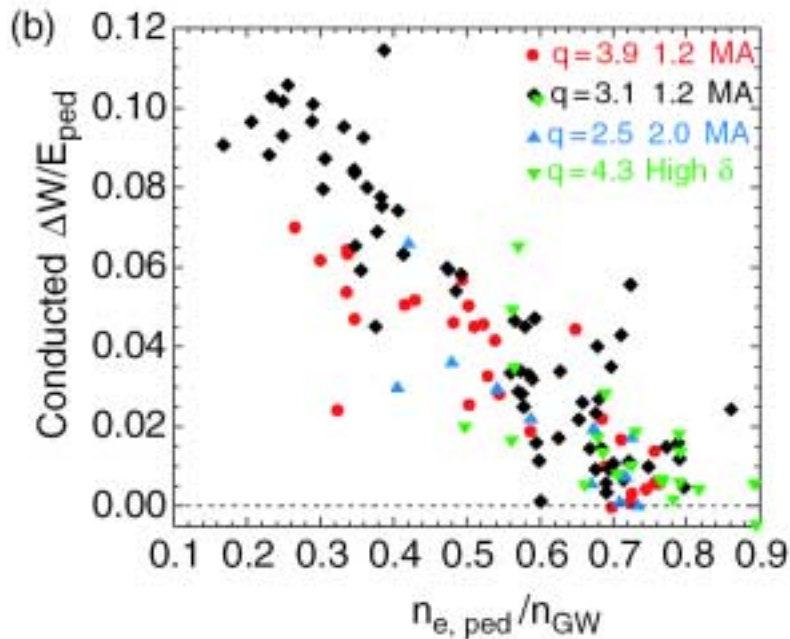
decrease of ΔT_{ELM} not of $V_{ELM} \rightarrow \Delta W_{ELM}$

similar results in DIII-D (Leonard)

Main plasma ELM energy/particle losses (IV)

Variation of $\Delta W_{ELM} \leftrightarrow$ ELM energy transport (DIII-D, JET)

DIII-D-Leonard PPCF'02



$$\Delta W_{ELM} = \Delta W_{ELM}^{cond} (\Delta T_{ELM}) + \Delta W_{ELM}^{conv} (\Delta n_{ELM})$$

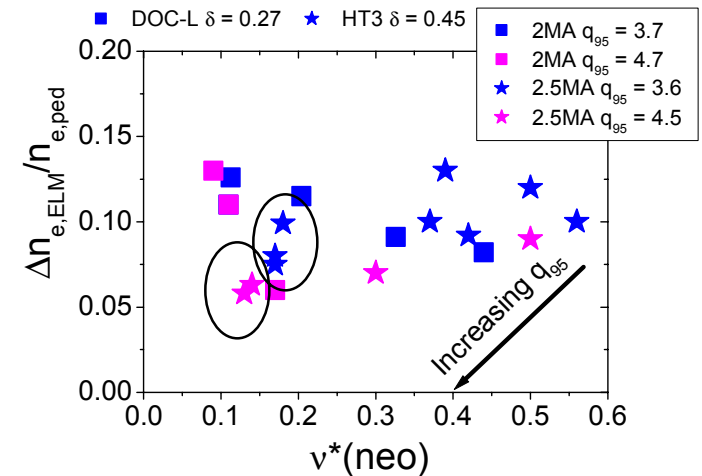
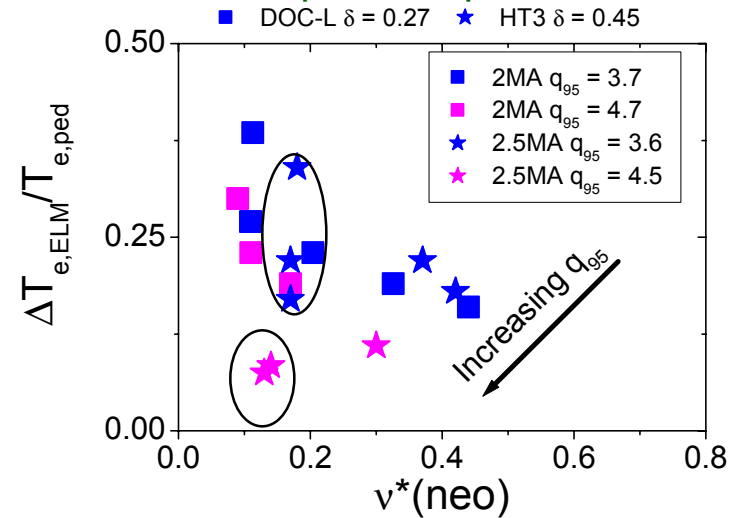
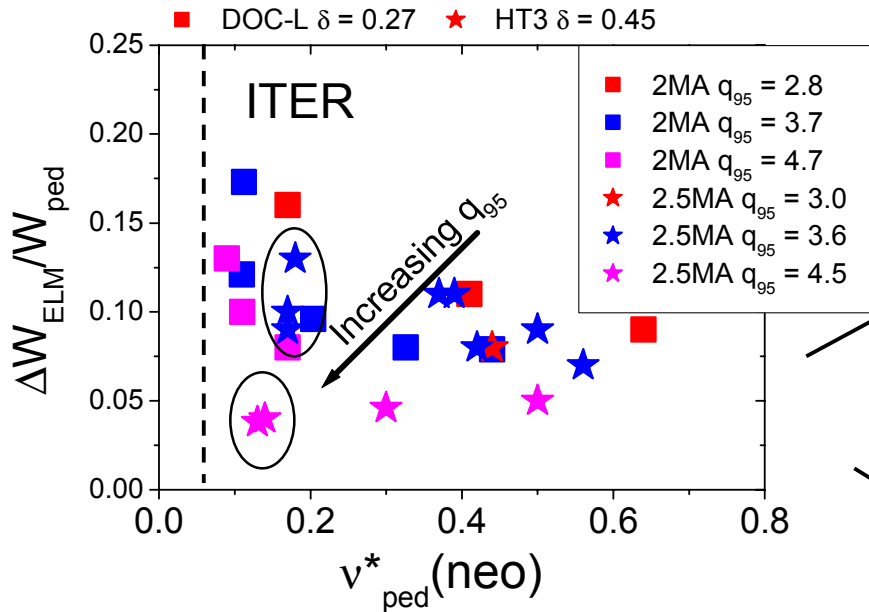
ΔW_{ELM}^{cond} decreases with $n_{e,ped}$ (or $v_{e,ped}$ (neo))

Smaller $\Delta W_{ELM} \leftrightarrow$ convective ELMs

Main plasma ELM energy/particle losses (V)

high $q_{95} + \delta \rightarrow$ small ΔW_{ELM} at low $v_{ped}^* - n_{ped}$

JET-Loarte APS'03



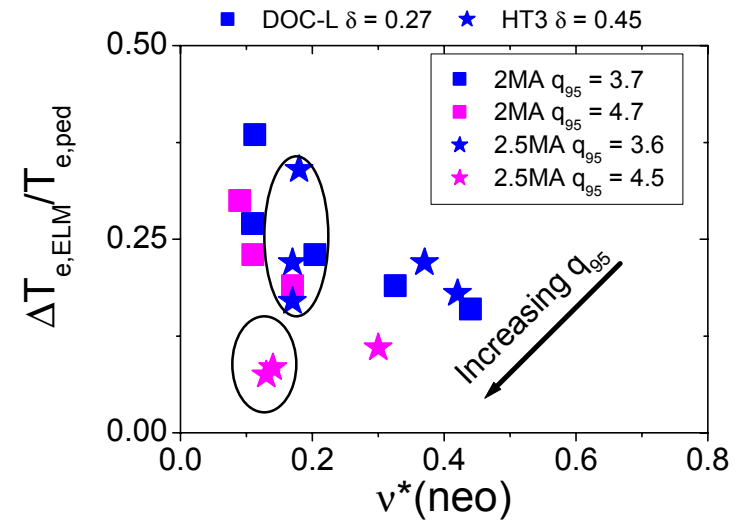
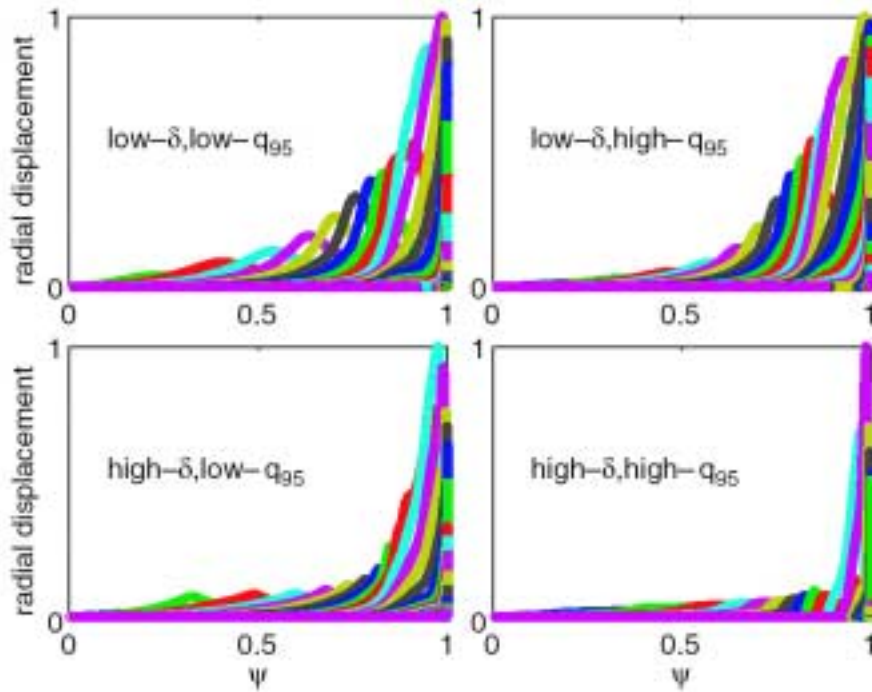
$\Delta W_{ELM} \leftrightarrow \Delta T_{ELM}$

MHD pedestal stability affects ΔW_{ELM} through ELM energy conduction

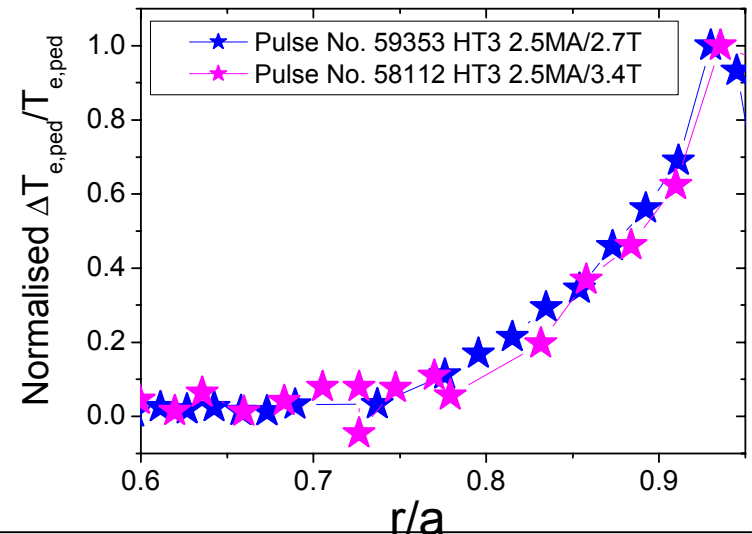
Main plasma ELM energy/particle losses (VI)

effect of high q_{95} on P-B stability largest at high δ

ASDEX Upgrade-Saarelma NF'03



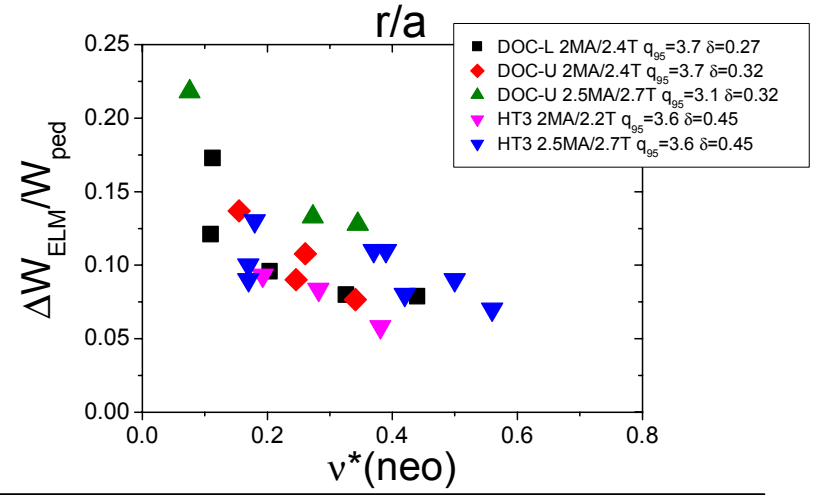
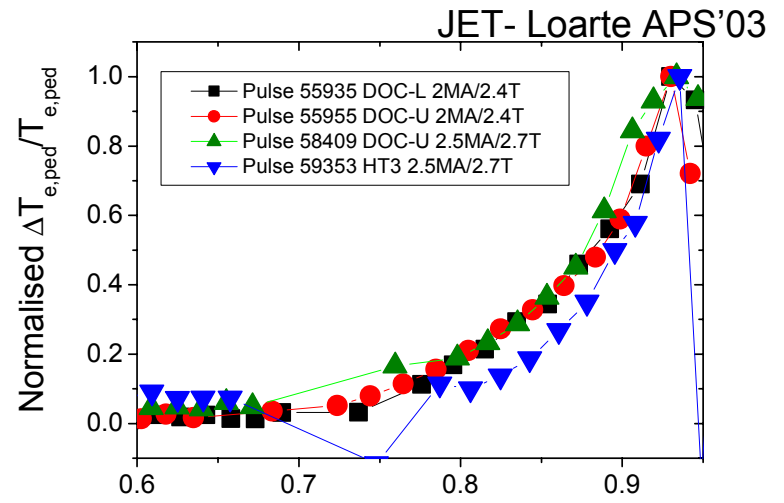
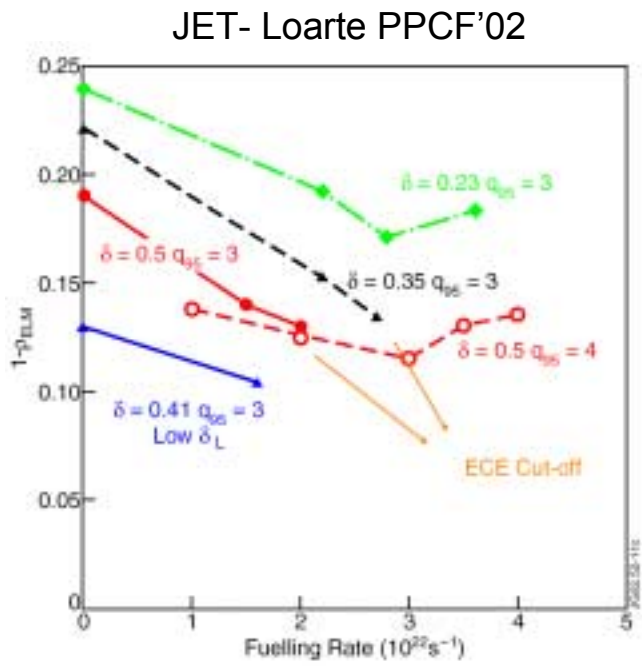
$V_{ELM} \sim \text{constant with } q_{95}!!$



P-B stability effect on ELMs \rightarrow non-linear evolution

Main plasma ELM energy/particle losses (VII)

Plasma shape (δ , κ , ...) changes V_{ELM} as expected from P-B analysis
 (JET & DIII-D (TTF'02-Córdoba) not ASDEX Upgrade (Urano PPCF'03))

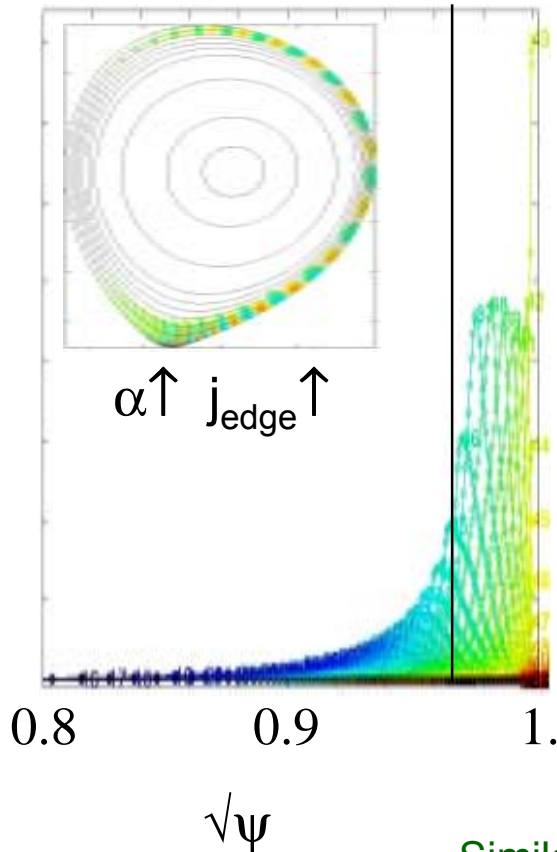


lower $\Delta W_{ELM} / W_{ped}$ for same v^*_{ped} at high δ
 but
 ΔW_{ELM} is larger for higher δ (higher W_{ped}) !!!

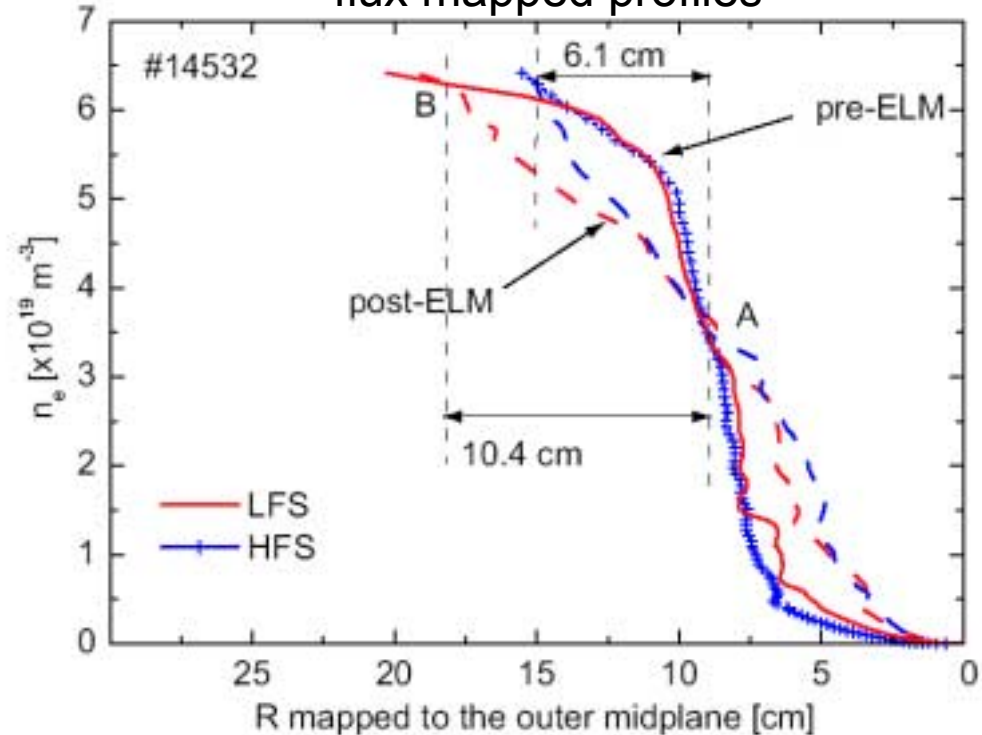
Main plasma ELM energy/particle losses (VIII)

Collapse of effect of pedestal plasma at ELM is not Θ symmetric

ASDEX Upgrade-Nunes EPS'03 subm. NF'04



flux mapped profiles

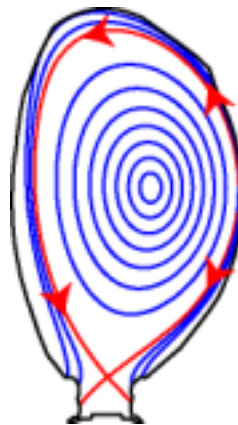
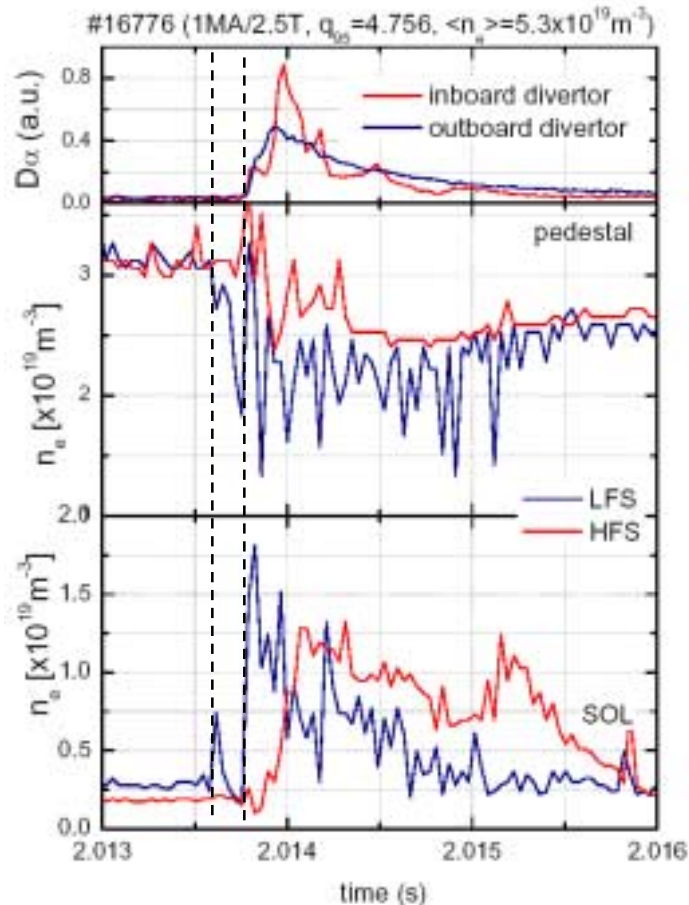


Similar results in JT-60U (Oyama NF'03 & NF'04) & MAST (Kirk PPCF'04)

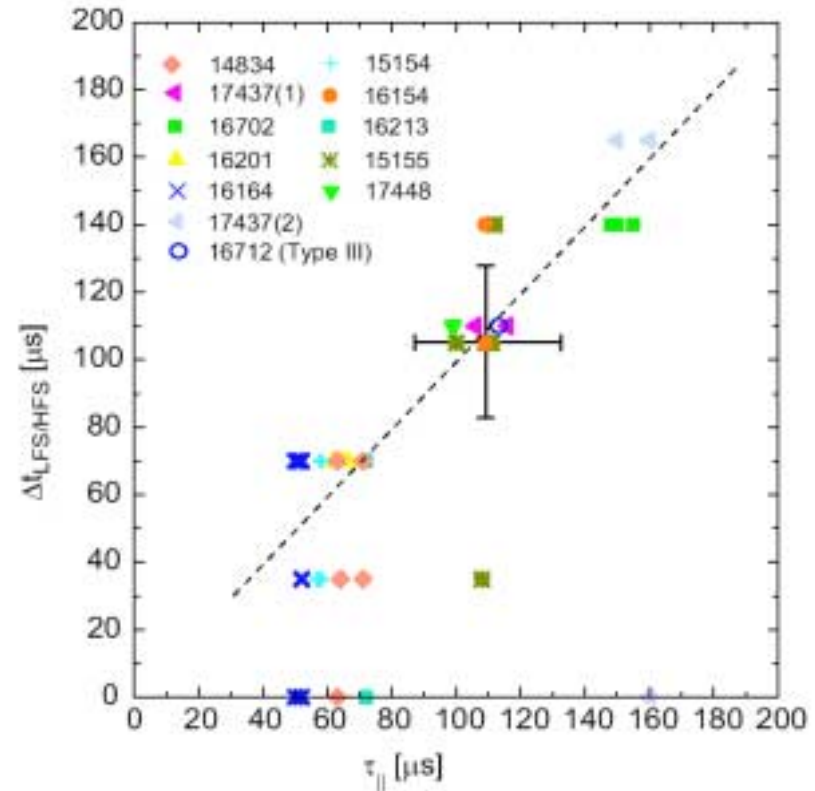
ballooning structure is maintained to the end of the ELM collapse

Main plasma ELM energy/particle losses (IX)

Collapse of pedestal plasma during ELMs is not simultaneous at all Θ



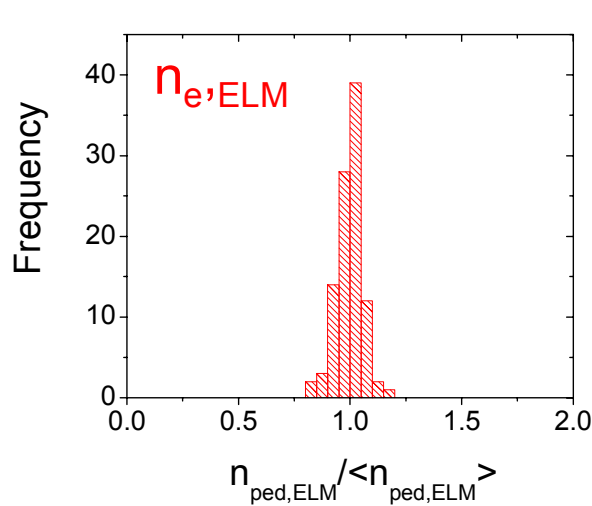
ASDEX Upgrade-Nunes EPS'03 subm. NF'04



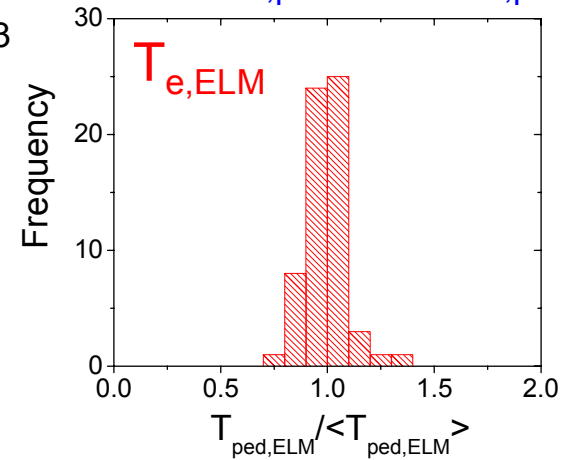
Delay scales with LFS-HFS ion transit time!

Main plasma ELM energy/particle losses (X)

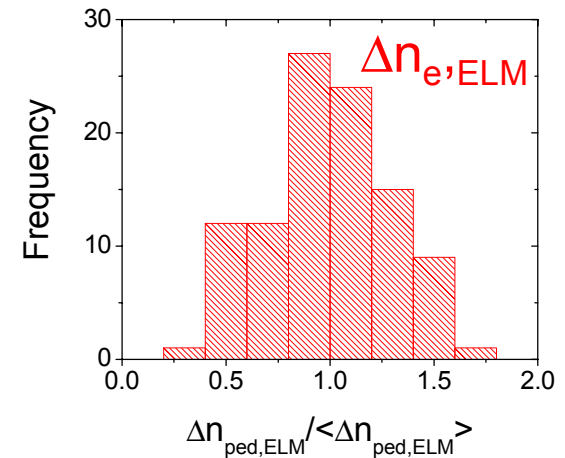
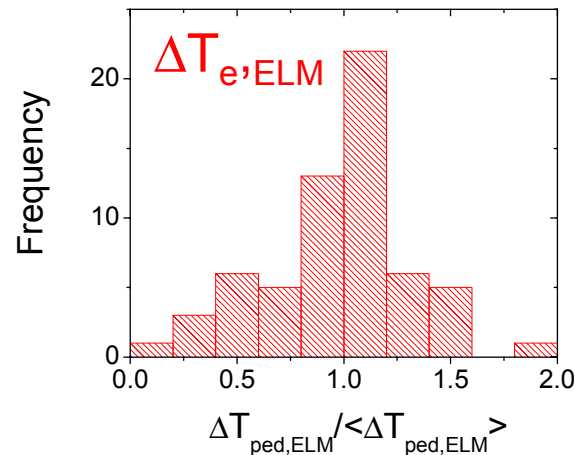
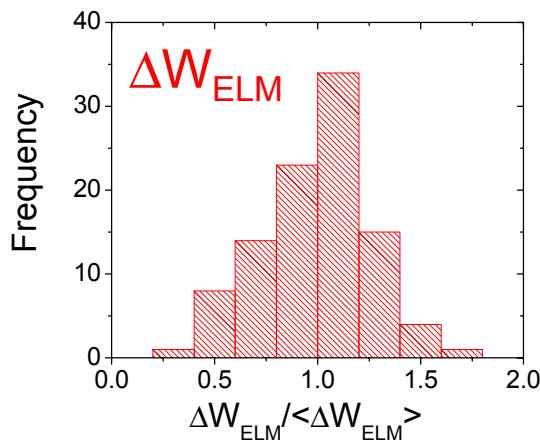
ELMs are triggered at precise values of $n_{e,ped}$ and $T_{e,ped}$



JET-Loarte APS'03



ELM crash has a much wider scatter for same $n_{e,ped}$ and $T_{e,ped}$

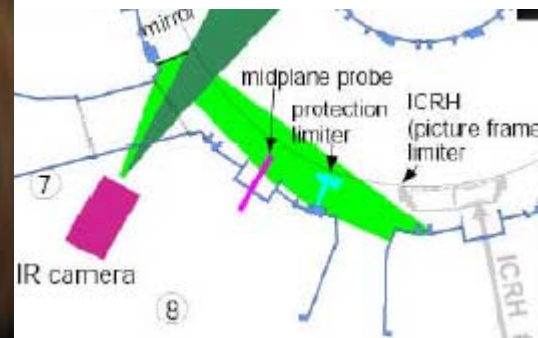
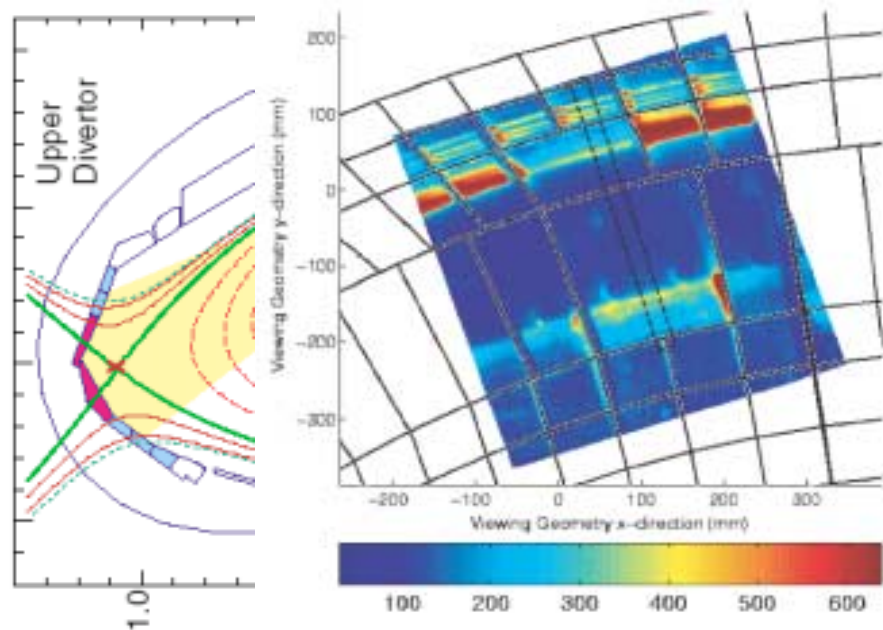


ELM energy/particle fluxes to PFCs (I)

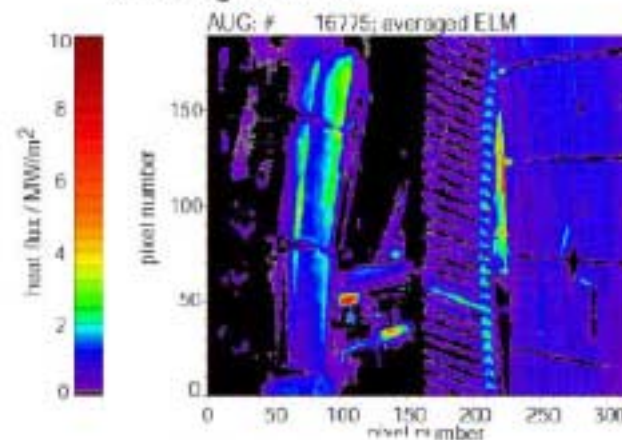
ELMs lead to fluxes both at the divertor and main chamber PFCs

ASDEX Upgrade-Eich PRL'04

ASDEX Upgrade-Herrmann EPS'03



averaged ELM



$\Delta W_{ELM} \rightarrow$ divertor and main chamber

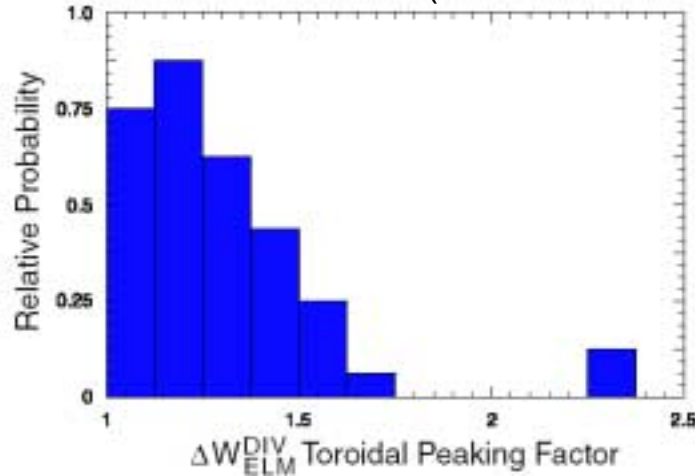
Parameters to be determined & understood :

- timescales and areas
- transport mechanisms (extrapolation)

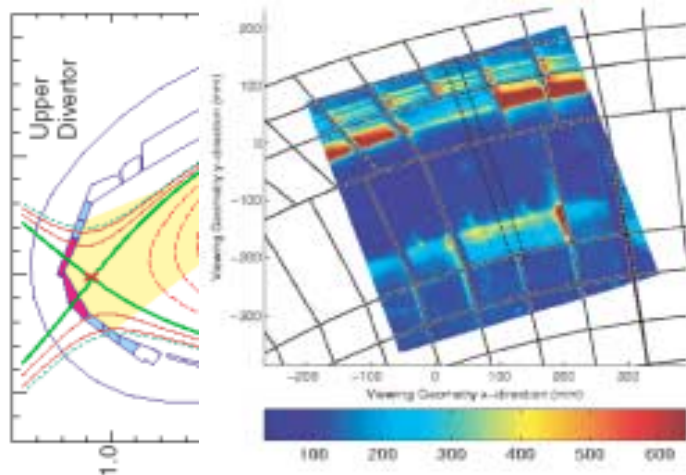
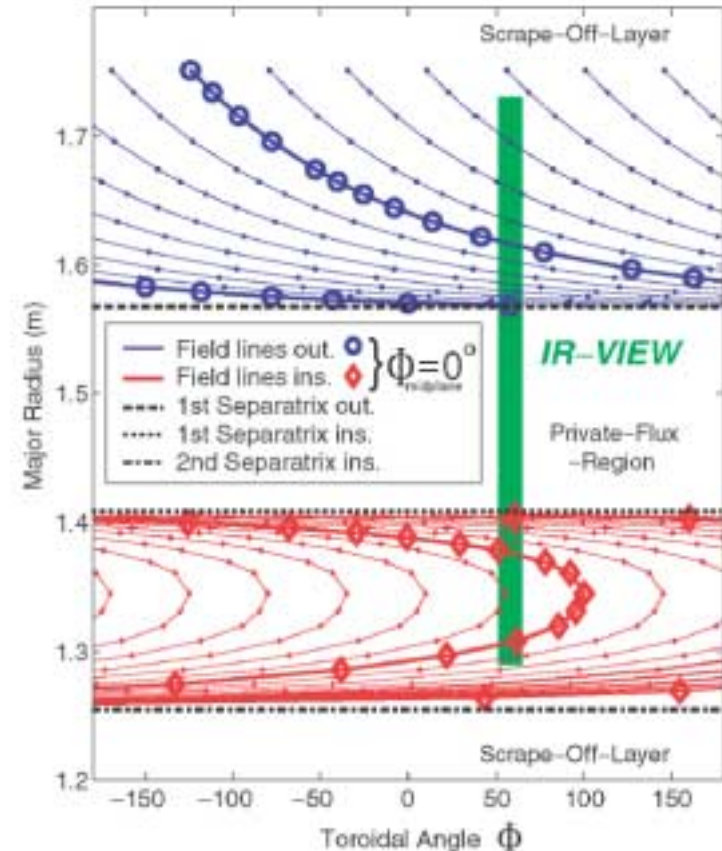
ELM energy/particle fluxes to PFCs (II)

divertor ELM fluxes are toroidally symmetric near separatrix (long L_c /high S)

DIII-D Leonard JNM'97 (Loarte PPCF'03)



ASDEX Upgrade-Eich PRL'04

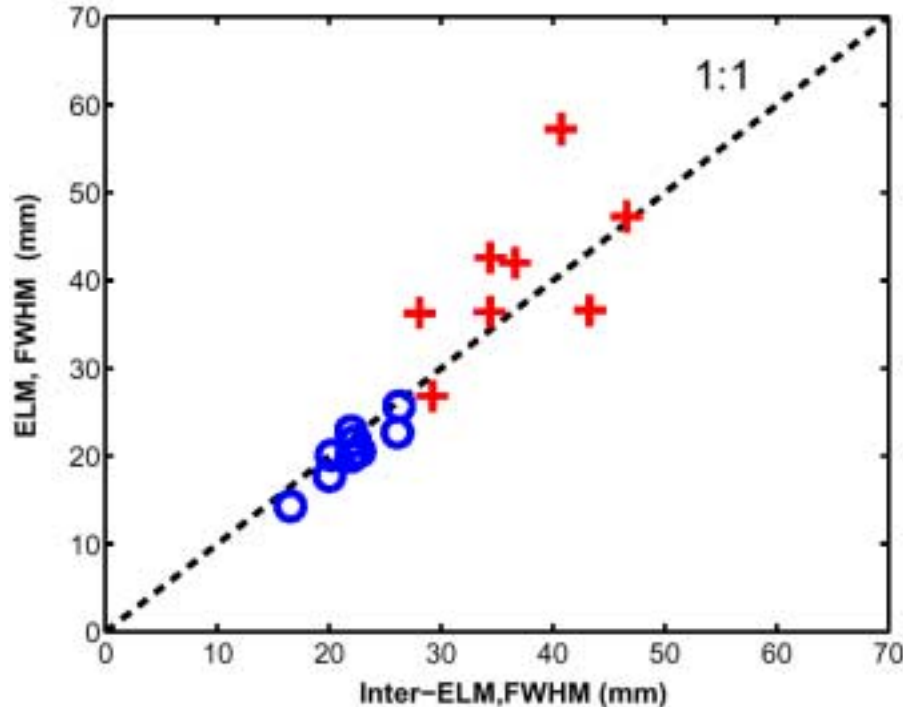


but ELM currents in DIII-D?

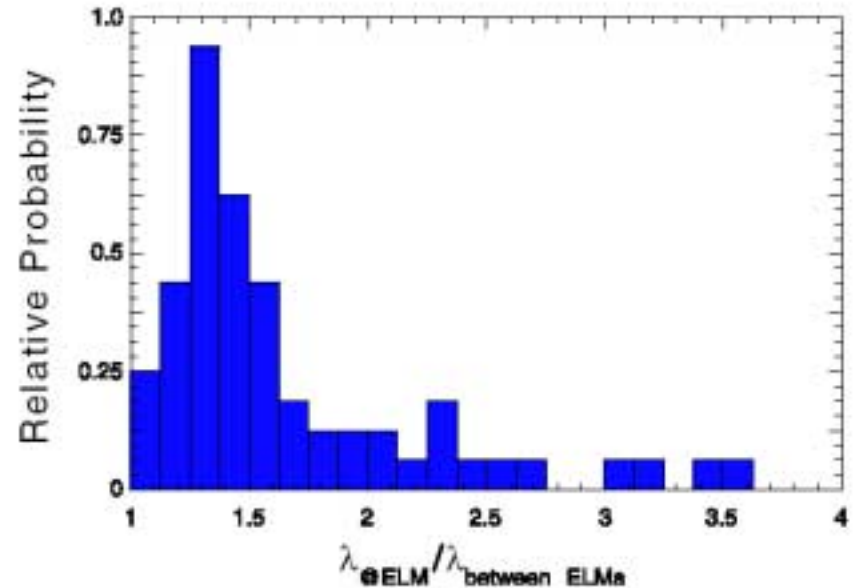
ELM energy/particle fluxes to PFCs (III)

divertor ELM energy wetted area \approx divertor wetted area between ELMs

JET-Eich PSI'04



ASDEX Upgrade-Herrmann PPCF'02 (Loarte PPCF'03)



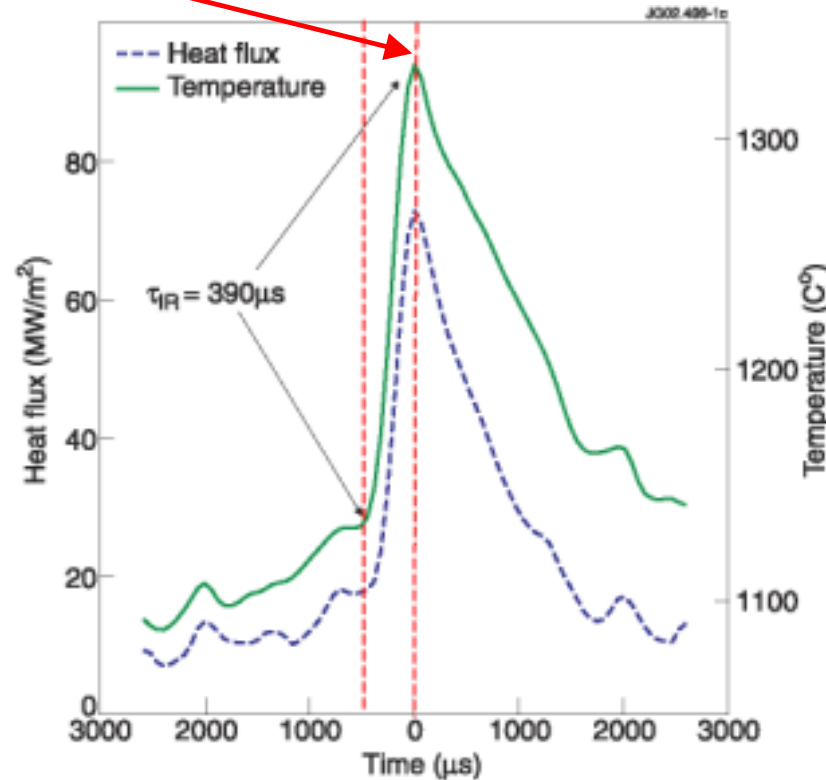
\perp B & II B are enhanced in a similar way during ELMs

Similar results in MAST (Kirk PPCF'04) and DIII-D (Fenstermacher PPCF'03)

ELM energy/particle fluxes to PFCs (IV)

Time history of divertor ELM energy is complex

T_{surf}^{max} JET-Eich PSI'02, Matthews NF'03



Significant fraction of ΔW_{ELM}^{div} arrives after T_{surf}^{max} !!!!

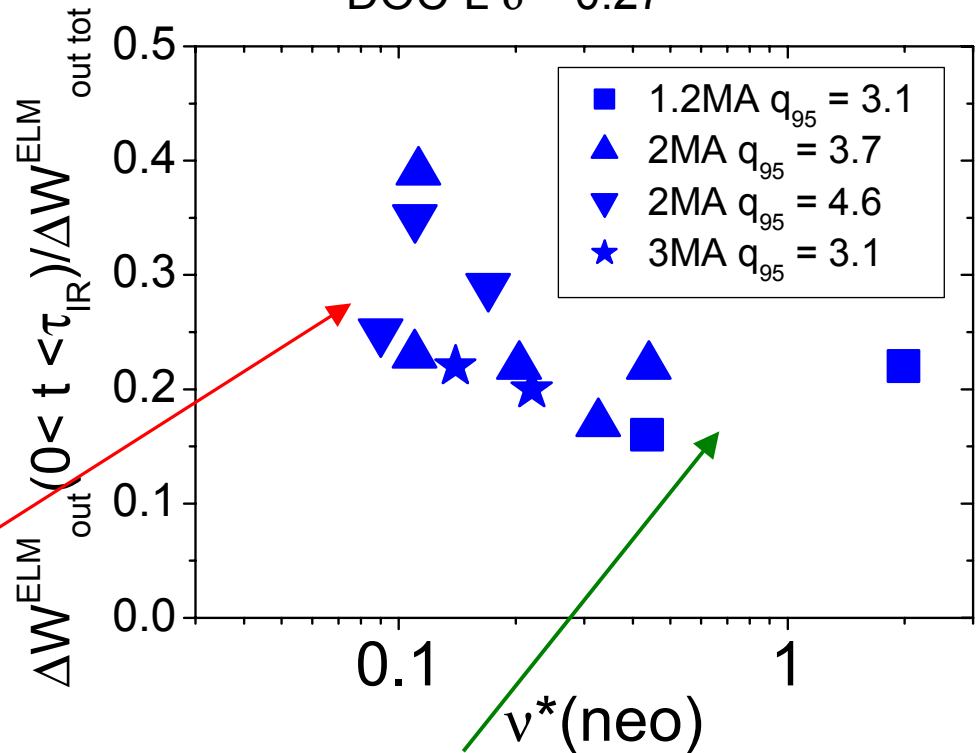
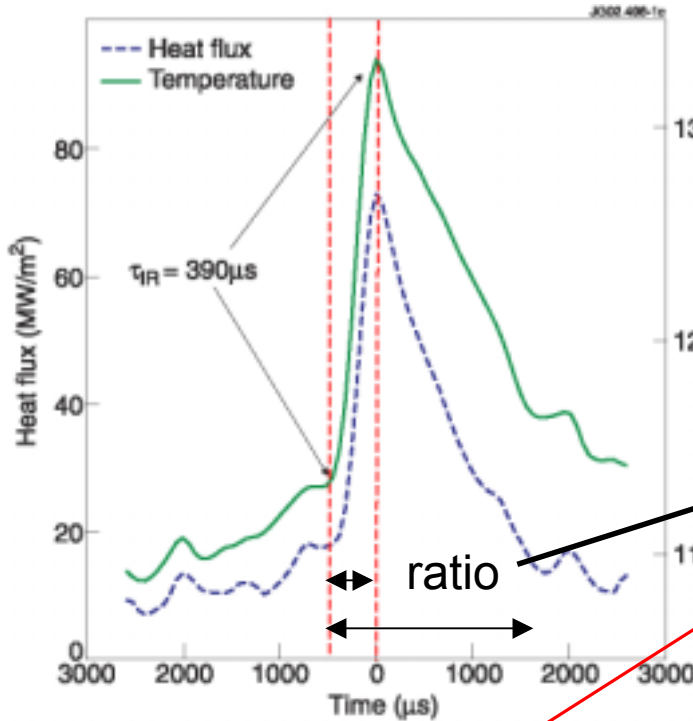
ELM erosion in ITER determined by $T_{surf}^{max} > T_{evap}^C$

ELM energy/particle fluxes to PFCs (V)

n_{ped} or $v^*(neo)$ \nearrow \rightarrow ELMs more convective \rightarrow more of ΔW_{ELM}^{div} after T_{surf}^{max}

JET-Loarte APS'03, Eich PSI'04

DOC-L $\delta = 0.27$



$$0.40 > \Delta W_{ELM}^{div} (0 < t < \tau_{IR}) / \Delta W_{ELM}^{div}_{tot} > 0.15$$

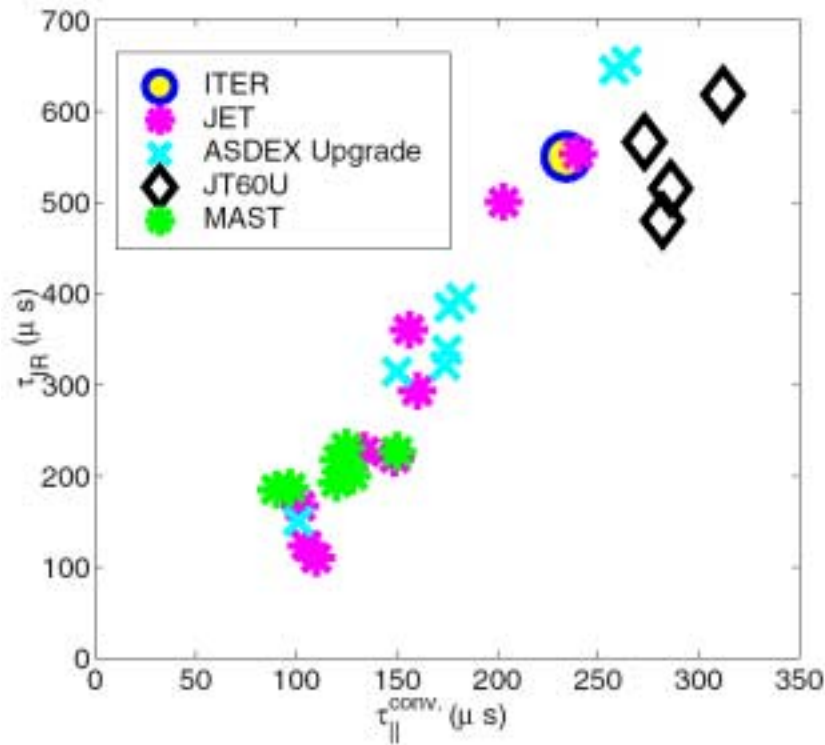
conductive ELM

convective ELM

ELM energy/particle fluxes to PFCs (VI)

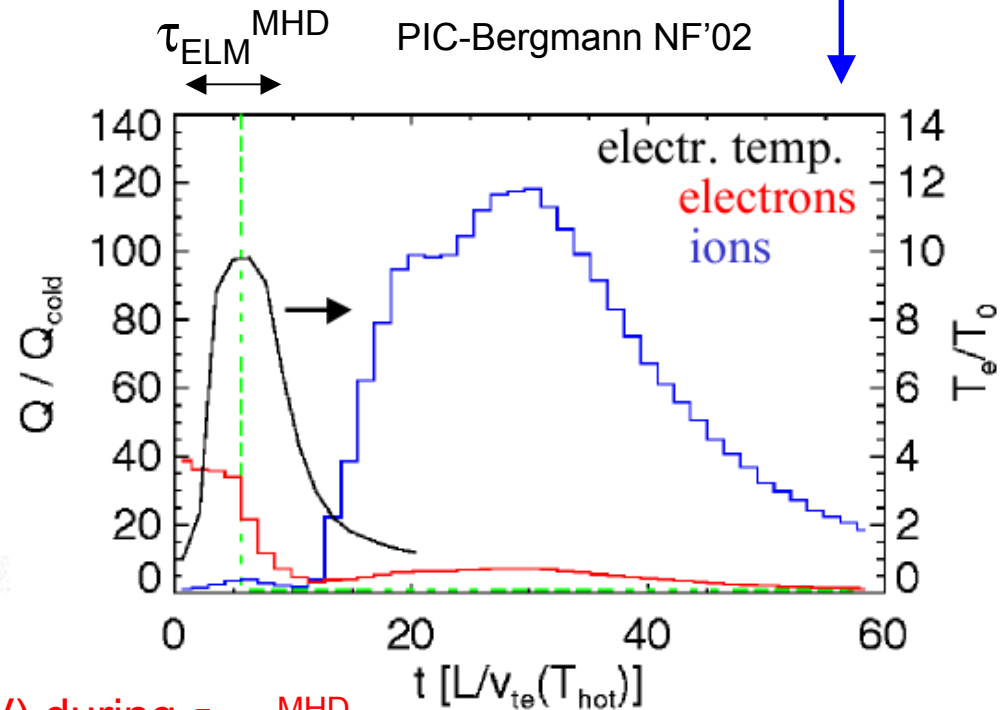
Timescale of ELM heat flux on divertor correlated with $\tau_{||} \sim L/c_{s,ped}$

JET- Eich, ASDEX Upgrade-Herrmann,
JT-60U Asakura, MAST-Kirk



$$\Gamma_{div} = \Gamma_{e,div}(\tau_{ELM}^{MHD}) + \Gamma_{i,div}(\tau_{||})$$

Formation of high energy sheath

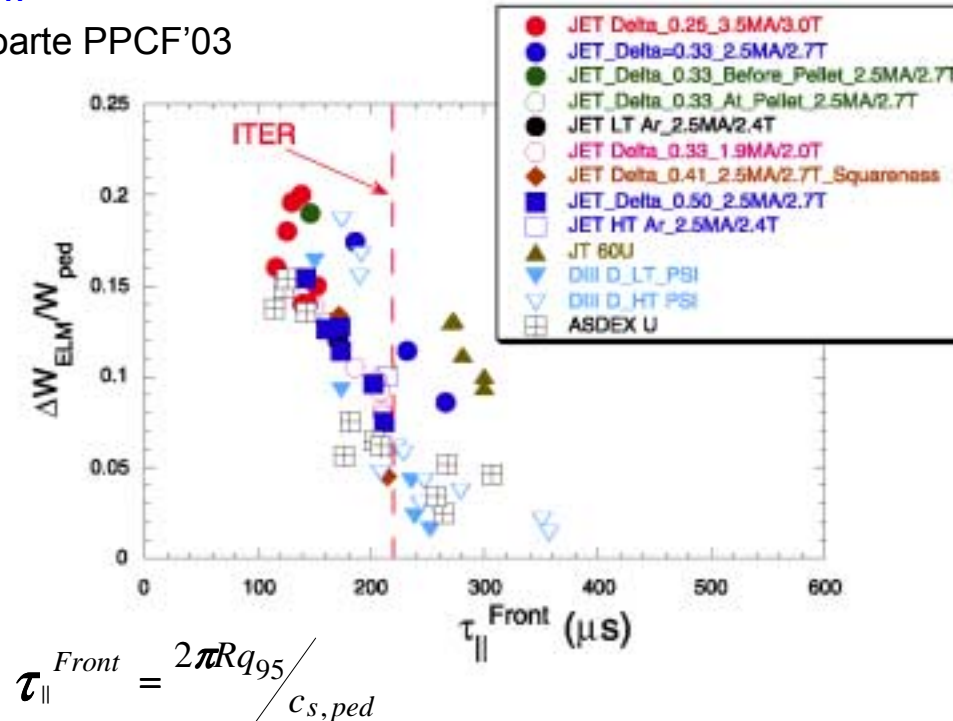
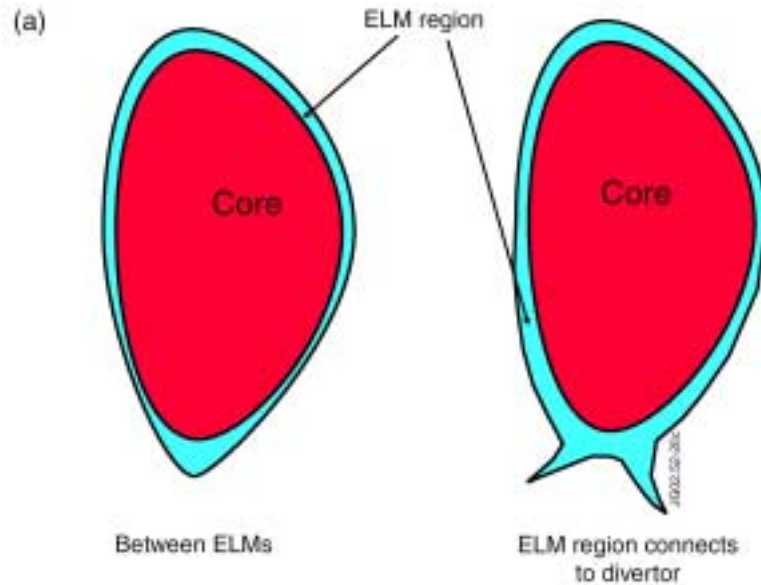


Experiment \rightarrow high Γ_{x-ray} (electrons \sim keV) during τ_{ELM}^{MHD}

ELM energy/particle fluxes to PFCs (VII)

- $\Delta W_{\text{ELM}}/W_{\text{ped}}$ decreases with τ_{\parallel}

ITPA-Loarte PPCF'03



Physics Model :

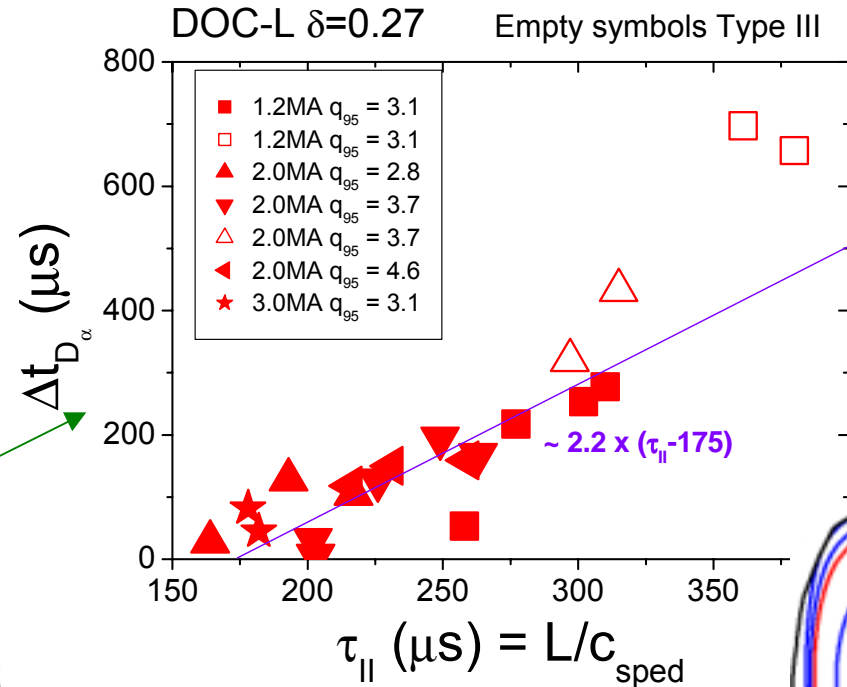
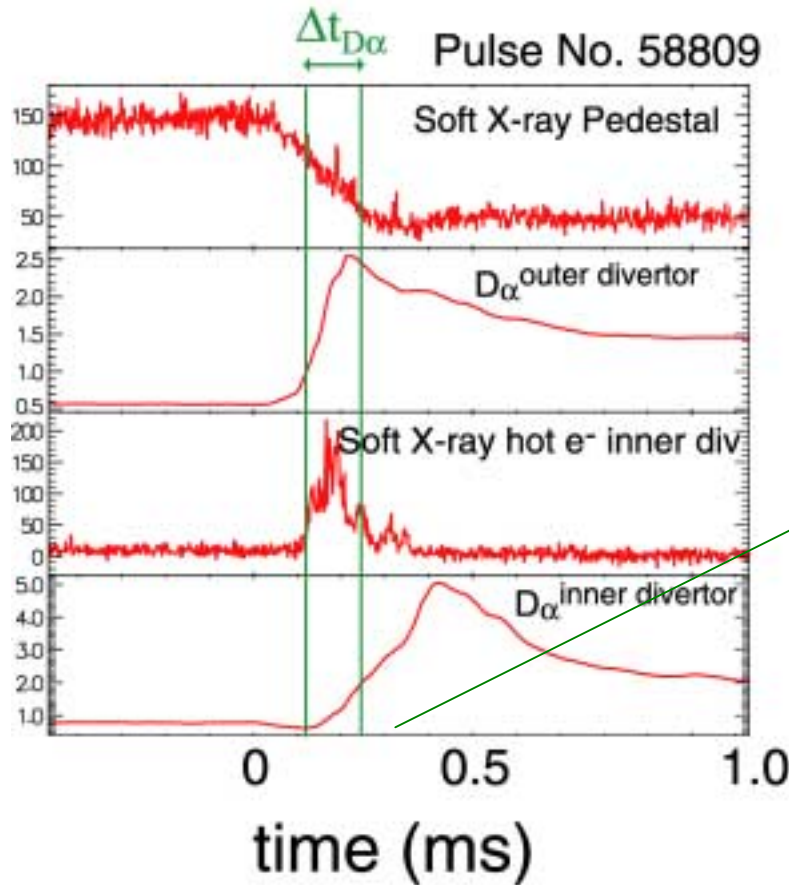
1) Pedestal connects to divertor for $\tau_{\text{ELM}}^{\text{MHD}}$

2) Energy flow restricted by sheath (τ_{\parallel}) $\rightarrow \Delta W_{\text{ELM}}/W_{\text{ped}} \sim (1 - \exp(-\tau^{\text{ELM MHD}}/\tau_{\parallel}))$

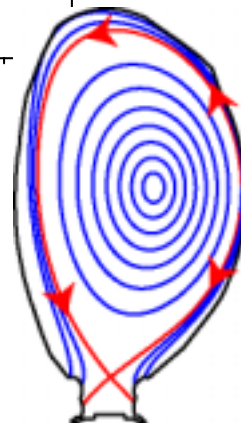
ELM energy/particle fluxes to PFCs (VIII)

separation of e^- flux (τ_{ELM}^{MHD}) & ion flux inner divertor

JET-Loarte, PPCF'02, PPCF'03, APS'03



$\Delta t_{D\alpha} \sim 0$ for finite $\tau_{||}$



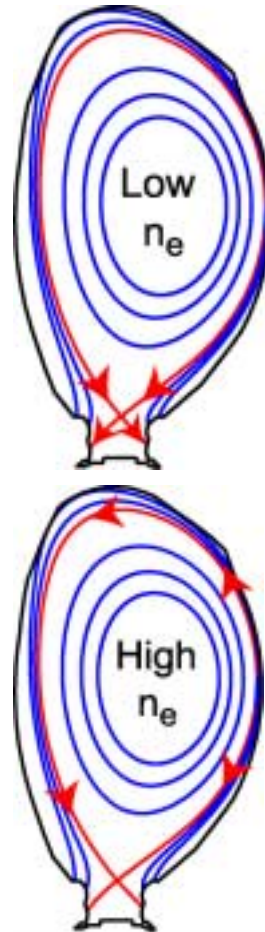
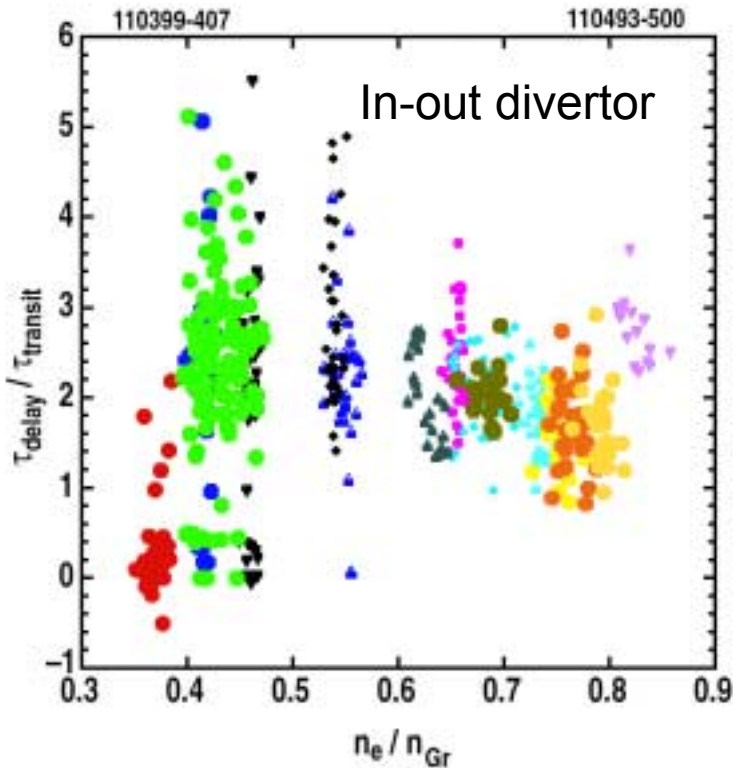
Similar results from DIII-D (Fenstermacher PPCF'03, Boedo APS'03)

ELM energy/particle fluxes to PFCs (IX)

$\Delta t_{D\alpha} \sim 0$ for finite $\tau_{||}$: a) main plasma collapse ($\tau_{ELM}^{MHD} \neq 0$) ?

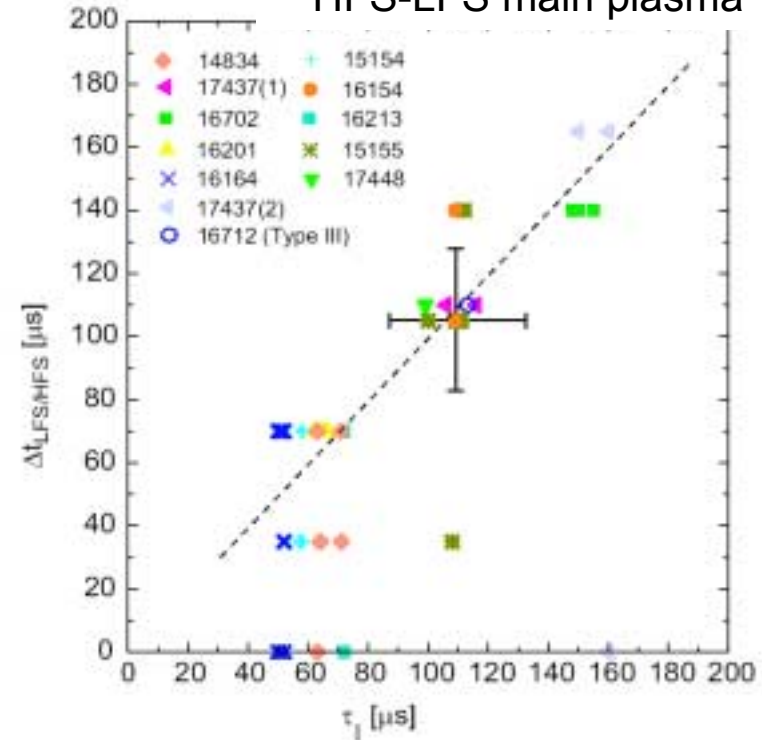
b) change of ELM start X-point \rightarrow midplane ?

DIII-D-Fenstermacher PPCF'03



ASDEX Upgrade-Nunes EPS'03 subm. NF'04

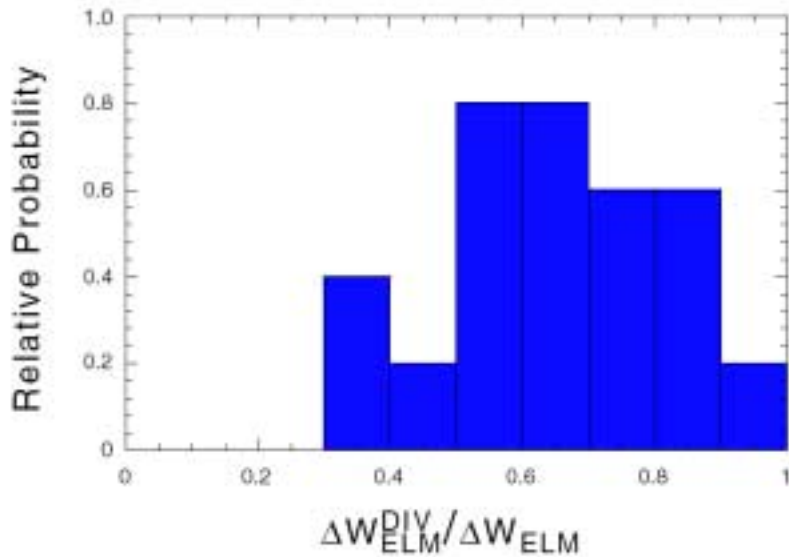
HFS-LFS main plasma



ELM energy/particle fluxes to PFCs (X)

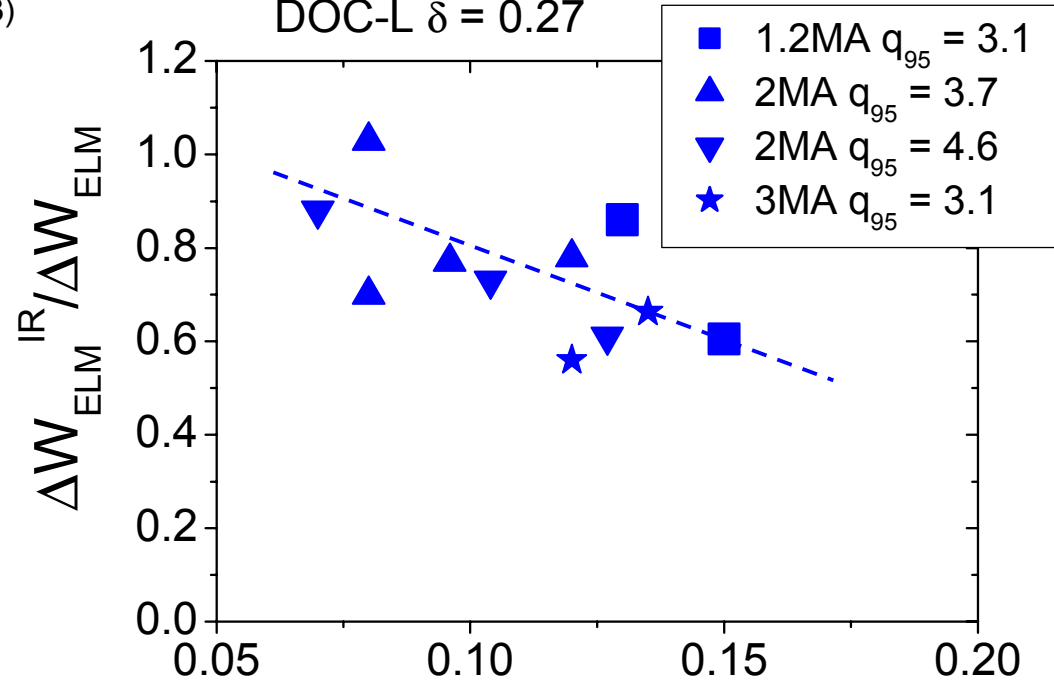
$$\Delta W_{ELM}^{div} < \Delta W_{ELM} \text{ but } \lambda_{ELM}^{div} \sim \lambda_{inter-ELM}^{div}$$

ASDEX Upgrade Herrmann EPS'97 (Loarte PPCF'03)



JET-Loarte APS'03, Eich PSI'04

DOC-L $\delta = 0.27$



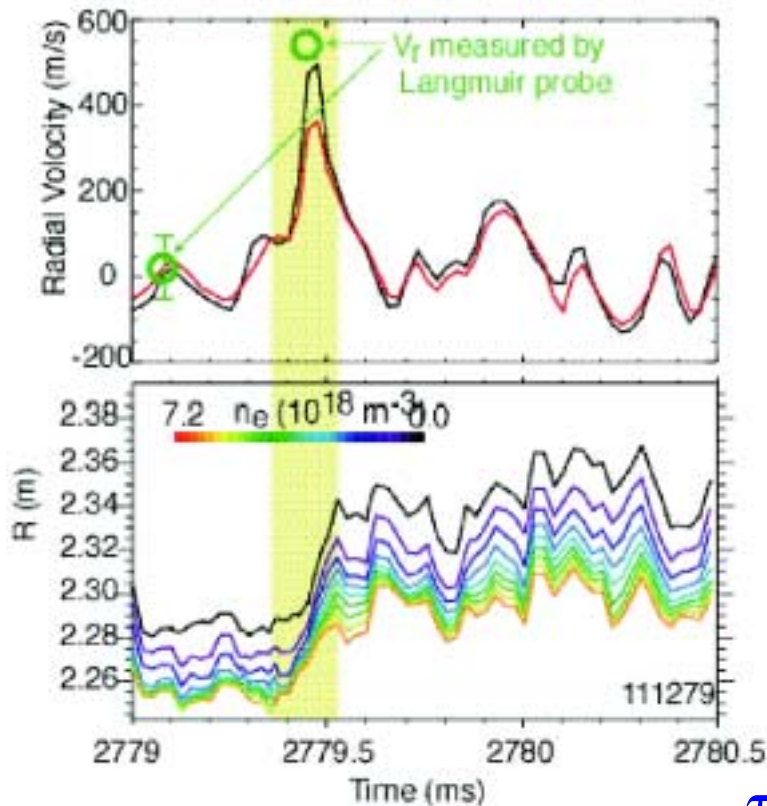
Transient radiation ~~\leftrightarrow~~ $\Delta W_{ELM}^{div} < \Delta W_{ELM} \frac{\Delta W_{ELM}}{W_{ped}}$

larger $\Delta W_{ELM} / W_{ped} \rightarrow$ smaller $\Delta W_{ELM}^{div} / \Delta W_{ELM}$

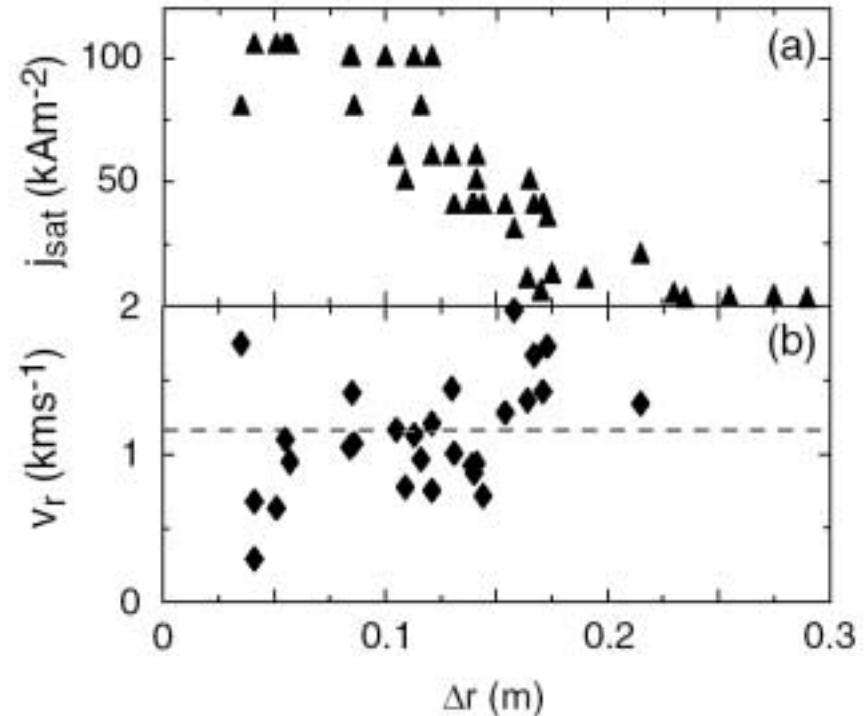
ELM energy/particle fluxes to PFCs (XI)

large particle fluxes measured far from separatrix at ELMs

DIII-D-Boedo+Zeng APS'03/PPCF'04



MAST-Counsell PPCF'02



$$\tau_{\text{perp,ELM}} \sim 100 \mu\text{s} \sim \tau_{\parallel} \rightarrow \text{large } \Gamma^{\text{main chamber}}$$

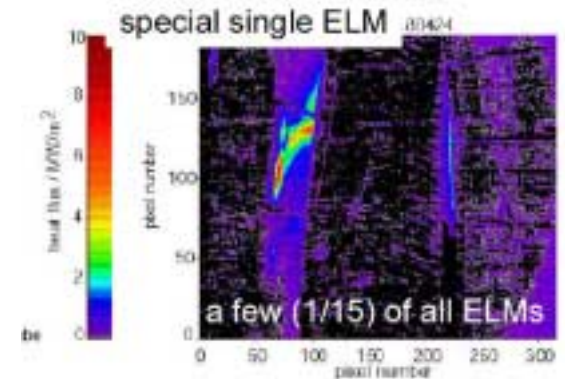
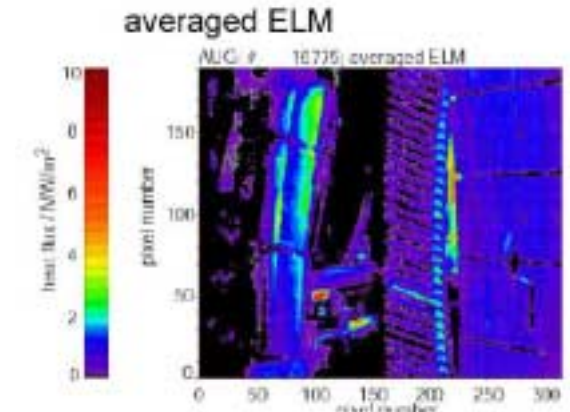
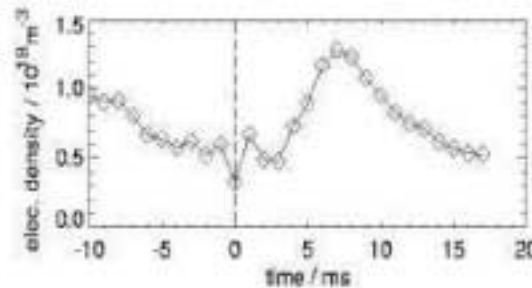
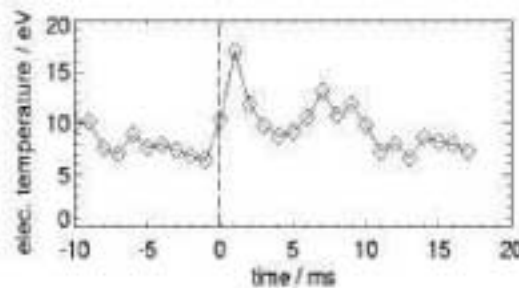
v_r (km/s): JET (0.5-1.2, Gonçalves PPCF'03, Fundamenski'04), MAST (0.2-1.7, Counsell PPCF'02, Kirk PPCF'04), DIII-D (0.2-0.6, Zeng PPCF'03, Boedo APS'3)

ELM energy/particle fluxes to PFCs (XII)

significant energy fluxes measured on main chamber PFCs



ASDEX Upgrade
Herrmann EPS'03



Energy on PFCs on large area of limiter (most ELMs)

$$\Delta W_{\text{ELM}}^{\text{wall}} \sim 25 \% \text{ of } \Delta W_{\text{ELM}}$$

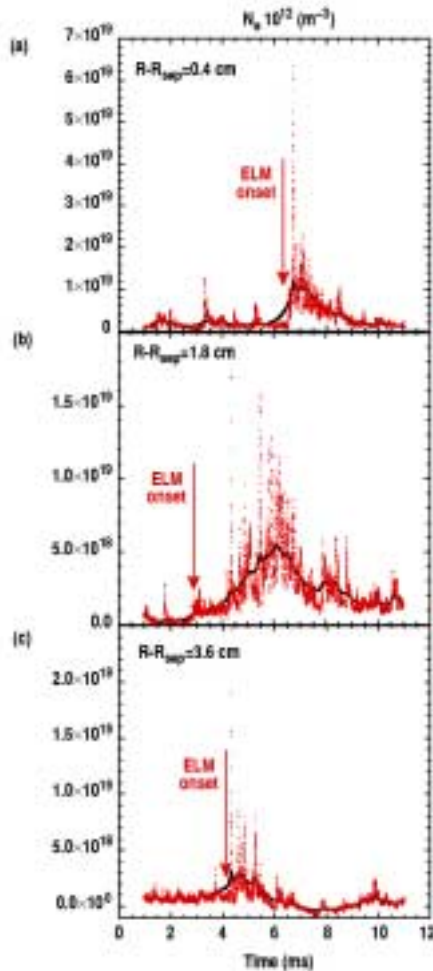
$$T_{e,\text{ELM}}^{\text{PFC}} \ll T_{e,\text{ped}} \rightarrow T_{i,\text{ELM}}^{\text{SOL}}$$

ELM energy/particle fluxes to PFCs (XIII)

What do we know about radial ELM fluxes ?

DIII-D-Boedo-Fenstermacher APS'03 /PPCF'03

DIII-D-Boedo APS'03



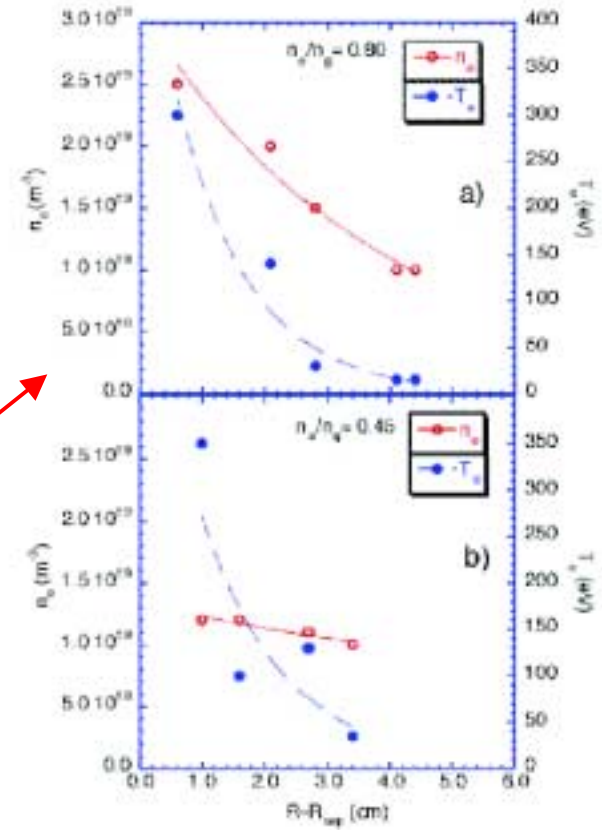
complex
filamentary
rotating
structure

$T_{e,ELM}$ decays
radially faster than

$n_{e,ELM}$

$$\tau_{E-e,SOL} < \tau_{II}$$

$v_{r,ELM}$ decreases
with n_e (and r ?)



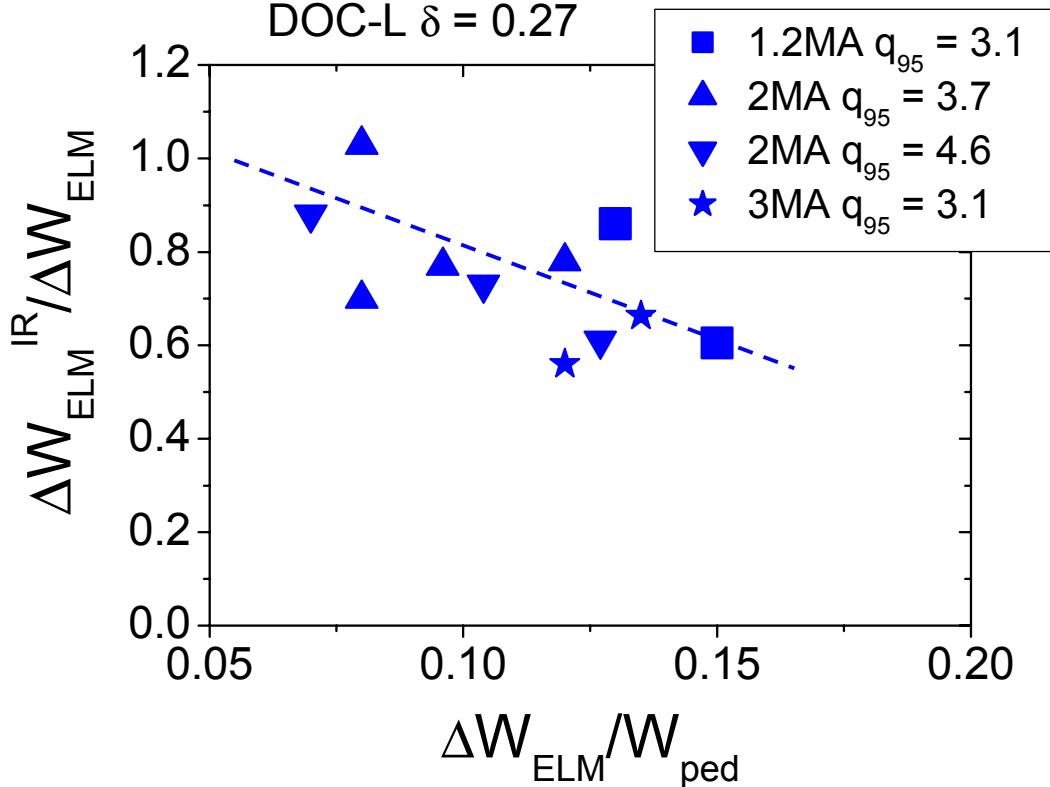
ELM energy/particle fluxes to PFCs (XIV)

decrease of v_r with n_e (and ΔW_{ELM} ?) compatible with

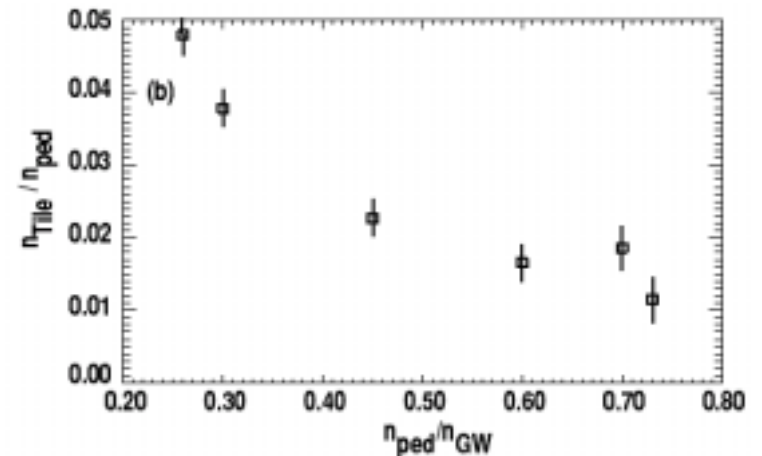
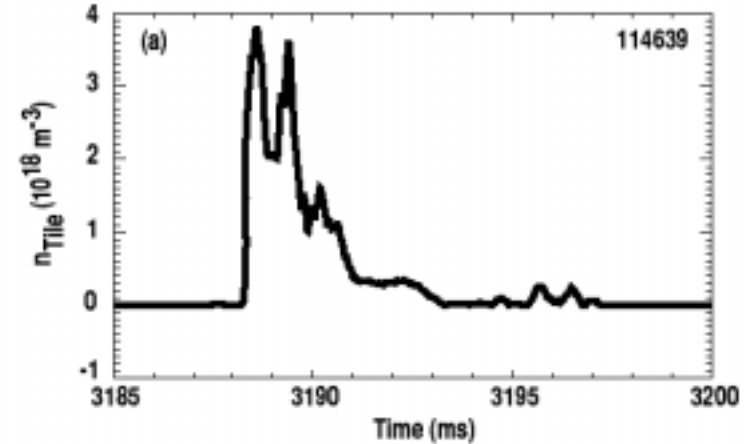
$$\Delta W_{ELM}^{div} / \Delta W_{ELM}$$

JET-Loarte APS'03, Eich PSI'04

DOC-L $\delta = 0.27$



DIII-D-Zeng PPCF'04

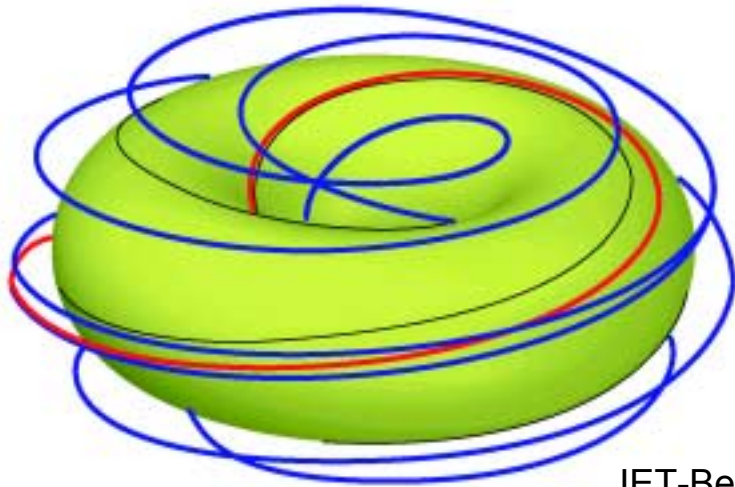


ELM energy/particle fluxes to PFCs (XV)

What determines v_r ?

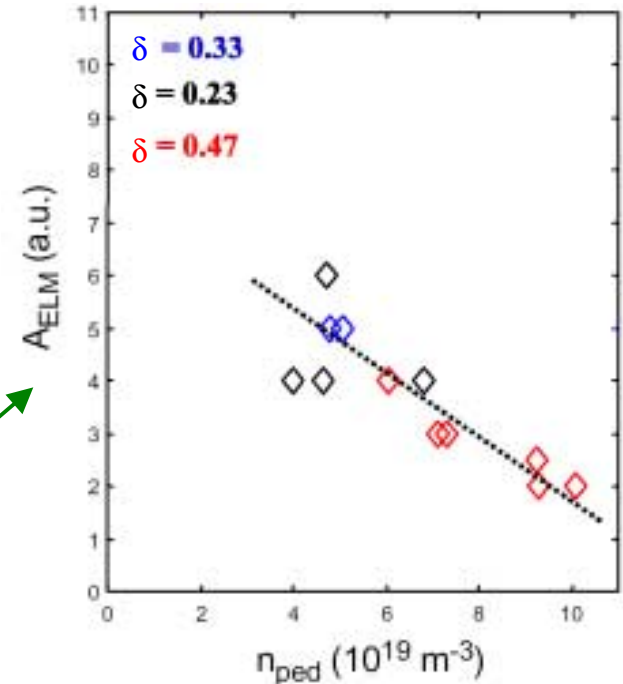
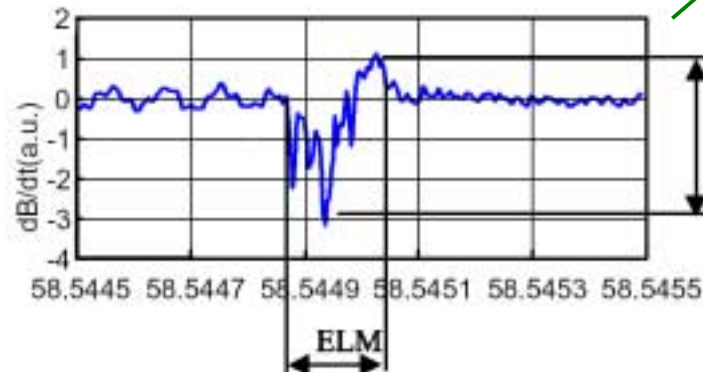
1. Non-linear ballooning explosive mode dependence on (n_e, T_e, v_{ped}^*)

S.Cowley-PPCF'03



ELM \tilde{B}_0 "amplitude" decreases with n_{ped}

JET-Becoulet-H-mode WS'01



ELM energy/particle fluxes to PFCs (XVI)

2. Dynamics of ELM pressure blob radial transport (Krasheninnikov, D'Ippolito,....)

$$v_r = c_s 2\rho^2 L / R r_b^2$$

➤ JET : $T_{ped} \sim 1.5$ keV, if $r_b \sim 20$ cm $\rightarrow v_r \sim 1$ km/s

➤ DIII-D : $T_{ped} \sim 0.5$ keV, if $r_b \sim 13$ cm $\rightarrow v_r \sim 1$ km/s

$$\text{Scaling of } v_r \sim T_{ped}^{3/2} r_b^{-2} \sim n_{ped}^{-3/2} r_b^{-2}$$

ASDEX Upgrade-Nunes EPS'03 subm. NF'04



dependence of r_b on n_{ped} , T_{ped} , 2 hypothesis :

➤ Empirical $\Delta N_{ELM} \sim n_{ped}$ (DIII-D, JET, ASDEX Upgrade)

$$\downarrow$$

$$r_b \sim \text{constant}$$

➤ $r_b \sim$ P-B mode width $\rightarrow r_b \sim n_{ped}^{-\alpha}$

Extrapolation of Type I ELMs to ITER

$$W_{\text{dia}}^{\text{ITER}} = 350 \text{ MJ} \rightarrow W_{\text{ped}} < 0.4 W_{\text{dia}}^{\text{ITER}} = 140 \text{ MJ} \quad (n_{\text{ped}} \sim 8 \cdot 10^{19} \text{ m}^{-3} \quad T_{\text{ped}} \sim 4.3 \text{ keV})$$

$$\tau_{\text{IR}}^{\text{ELM}} \sim 300 \mu\text{s}$$

$$A_{\text{ELM}}^{\text{ITER}} = A_{\text{S.S}}^{\text{ITER}} = 3 \text{ m}^2 \quad (\lambda_{\text{power}}^{\text{midplane}} = 5 \text{ mm})$$

Convective ELMs

Conductive ELMs

$\Delta W_{\text{ELM}}^{\text{ITER}} \text{ (MJ)}$	10	28
$\Delta W_{\text{ELM}}^{\text{ITER, div}} \text{ (MJ)}$	80%	50%
$\Delta W_{\text{ELM}}^{\text{ITER, div}} (0 < t < \tau_{\text{IR}}) \text{ (MJ)}$	20%	40%
$\Phi_{\text{ELM}}^{\text{ITER}} \text{ (MJm}^{-2}\text{s}^{-1/2})$	20	72

C-ablation in ITER $\sim 50 \text{ MJm}^{-2}\text{s}^{-1/2}$

$\Delta W_{\text{ELM}}^{\text{ITER, wall}} \text{ (MJ)}$	20%	50%
--	-----	-----

ELM erosion less critical than previously believed even for conservative assumptions

Conclusions (I)

- Peeling-Ballooning model provides a reasonable description of pedestal pressure limitation by Type I ELMs
 - Detailed multi-machine comparison (& pedestal width scaling) in progress
 - Which is the ELM triggering mechanism ?
 - Non-linear evolution of ELM and timescales

- Type I ELM energy losses determined by $n_{e,ped}$ & $T_{e,ped}$, q_{95} , δ
 Small ELMs \leftrightarrow Convective ELMs
 - What determines V_{ELM} ?
 - Physical process that produce convective ELMs (v_{ped}^* and high δ/q_{95}) ?
 (link between MHD stability \leftrightarrow ELM energy transport ?)
 - What determines the ELM variability ?

Conclusions (II)

- ELM energy fluxes determined by determined by $n_{e,ped}$ & $T_{e,ped}$
 - timescale of ELM energy flux on divertor by $\tau_{||}$ and not τ_{ELM}^{MHD}
 (role of sheath/IIB transport on divertor ELM energy Flux ?)
 - $\Delta W_{ELM}^{div} < \Delta W_{ELM}$ and fluxes to main chamber PFCs
 (convective radial ion transport versus IIB losses ?)
 - spatial distribution of ELM heat loads
 (toroidal symmetry ?, main chamber fluxes ?, in/out divertor balance ?)

Conclusions (II)

- ELM energy fluxes determined by determined by $n_{e,ped}$ & $T_{e,ped}$
 - timescale of ELM energy flux on divertor by τ_{II} and not τ_{ELM}^{MHD}
 (role of sheath/IIB transport on divertor ELM energy Flux ?)
 - $\Delta W_{ELM}^{div} < \Delta W_{ELM}$ and fluxes to main chamber PFCs
 (convective radial ion transport versus IIB losses ?)
 - spatial distribution of ELM heat loads
 (toroidal symmetry ?, main chamber fluxes ?, in/out divertor balance ?)

- Regimes with small/no Type II ELMs/good confinement exist **but**:
 - operational space is narrow and not well characterised
 (reproducibility in various experiments ?)
 - extrapolability to next step devices/compatibility with other requirements ?
 (low v_{ped}^* , low q_{95} , high $P_{rad}^{divertor}$, pellet fuelling, He pumping,)
 - operation close to double null required ?

Regimes with high P_{ped} + small/no ELMs (I)

Regimes with small or no ELMs and high P_{ped}

a) Regimes with high P_{ped} and small ELMs (Type II ELMs : JT-60U, AUG)

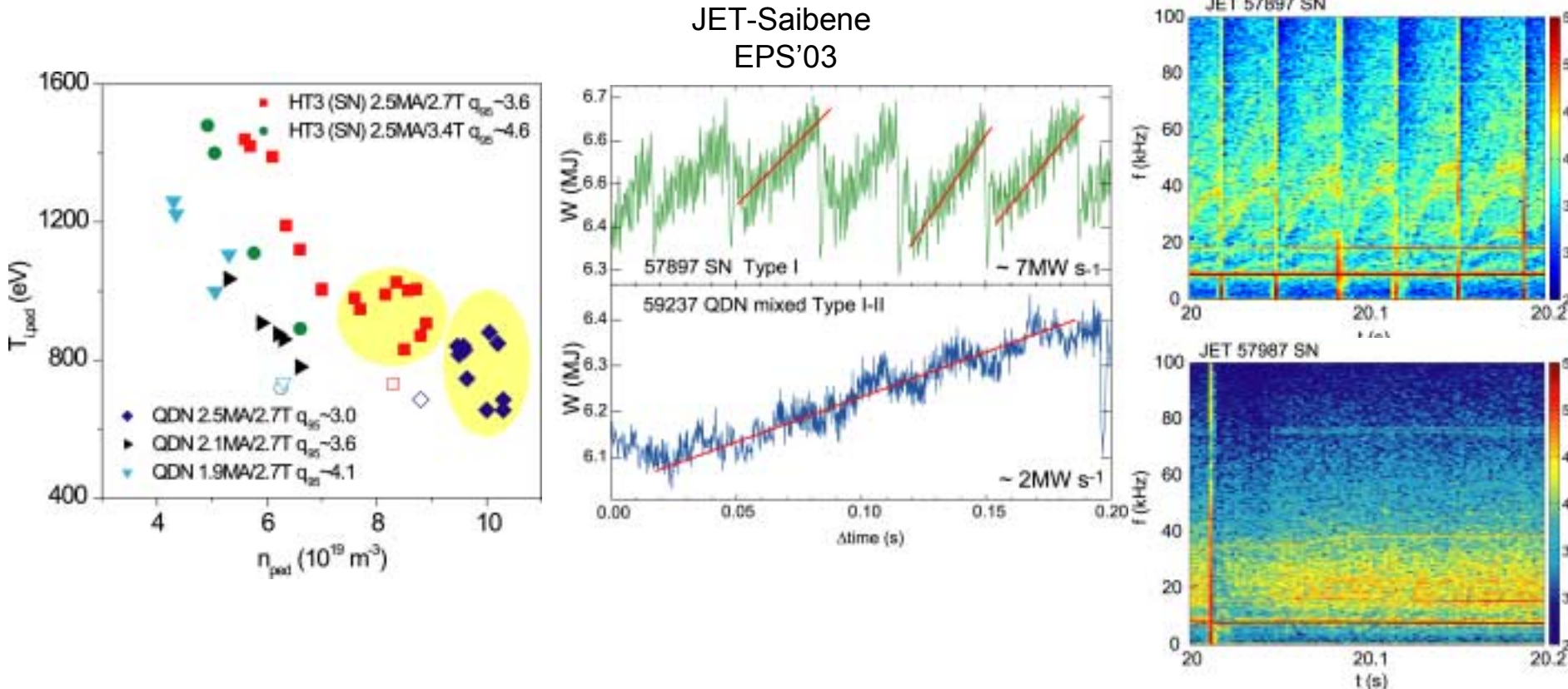
modification of edge MHD plasma stability

b) Regimes with no (or infrequent) ELMs and quasi-continuous losses (EDA, QH-mode, “mixed Type I-II ELMs” in JET)

triggering of transport losses “between ELMs” $P_{ped} \leq P_{ped}^{limit}$

Regimes with high P_{ped} + small/no ELMs (II)

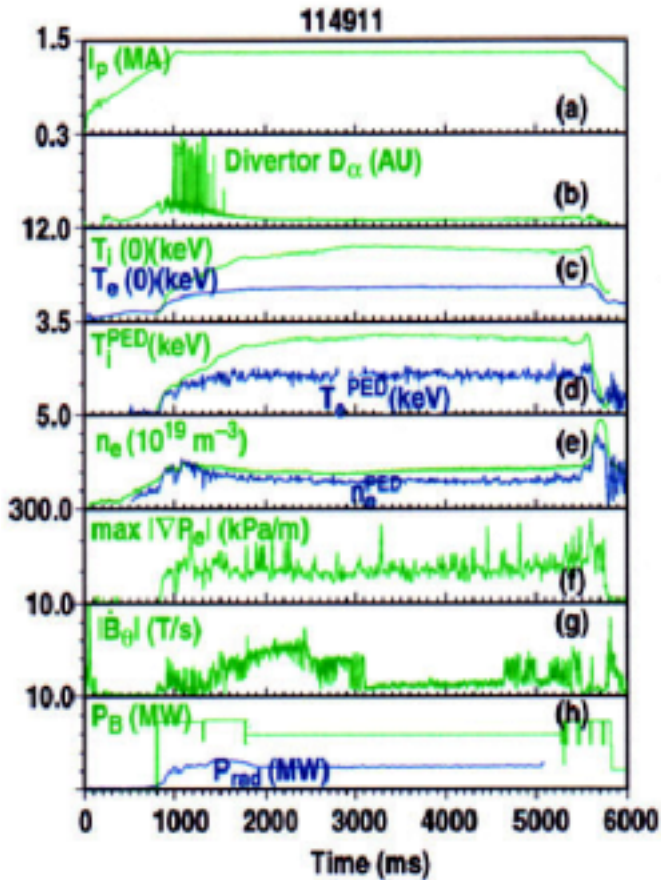
Mixed Type I-II in JET \leftrightarrow increased broadband MHD fluctuation at low f
 T_{ped} reaches steady state between type I ELMs with increased fluctuations but
 n_{ped} does NOT saturate in the Type II phases (\rightarrow end in Type I)



Increased Inter-ELM transport (+ washboard modes)

Regimes with high P_{ped} + small/no ELMs (III)

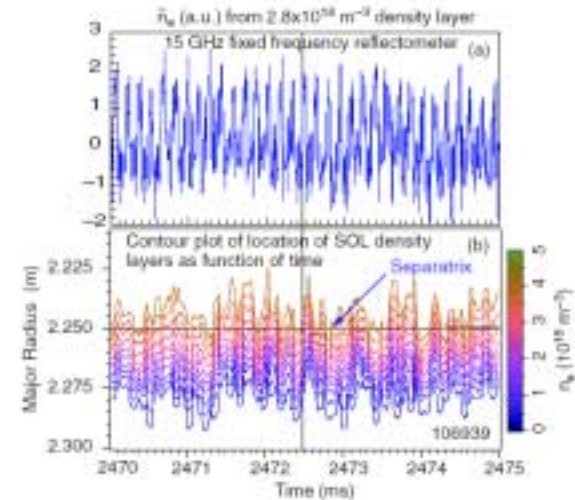
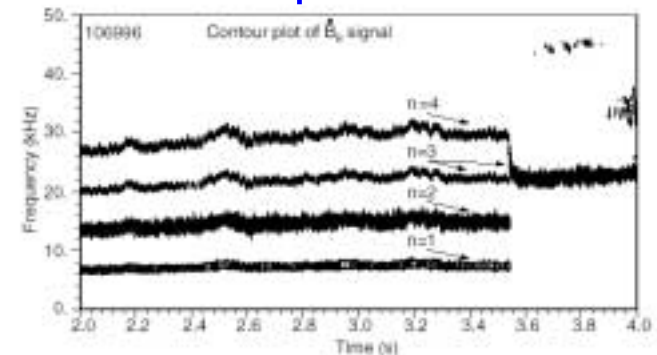
QH (and EDA) no-ELM regimes are associated with coherent MHD modes at the edge which lead to enhanced transport



DIII-D Doyle
PPCF'02, Burrell
PPCF'03

reproduced
in ASDEX
Upgrade

Suttrop PPCF'04

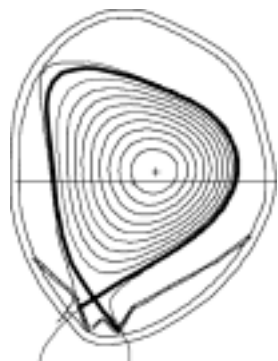
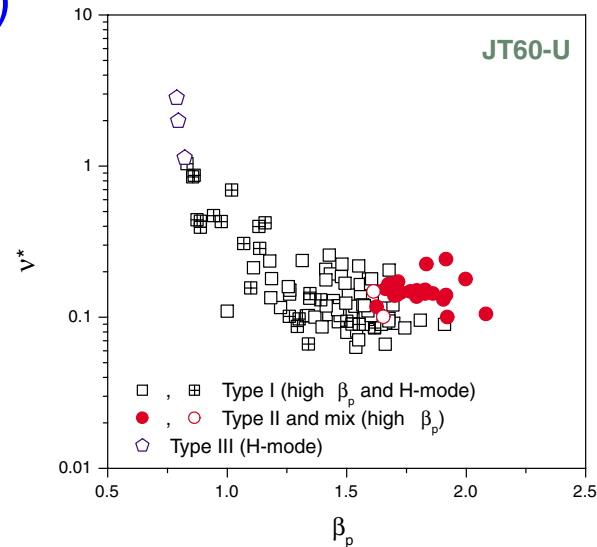
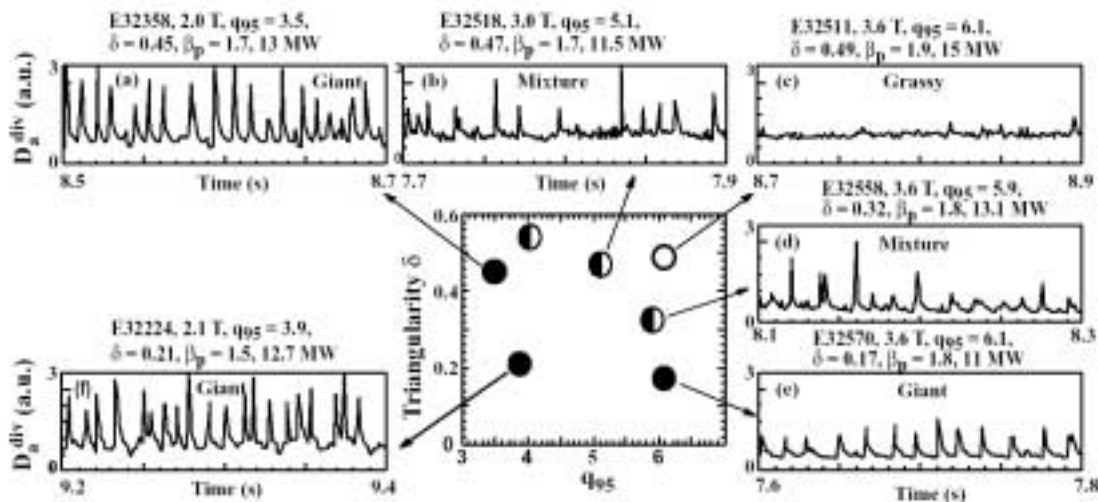


potentially interesting for next step devices but triggering of mode?

Regimes with high P_{ped} + small/no ELMs (IV)

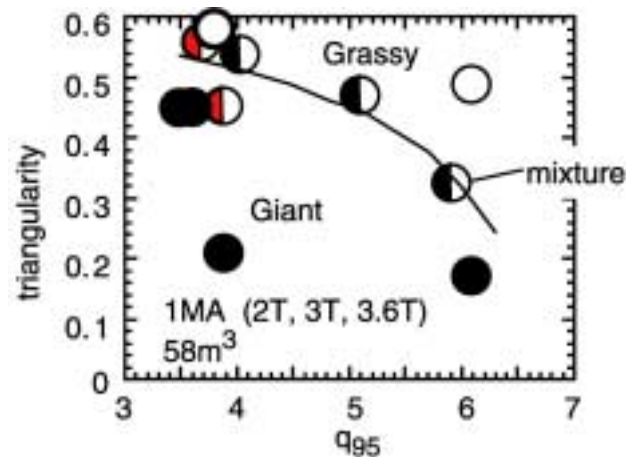
JT-60 Type II ELM (= Grassy ELM) discharges are obtained at high δ , high β_p and high q_{95} (low v_{ped}^*)

JT-60U – Kamada PPCF'02



change of ELM Type because of edge stability change due to Shafranov-shift

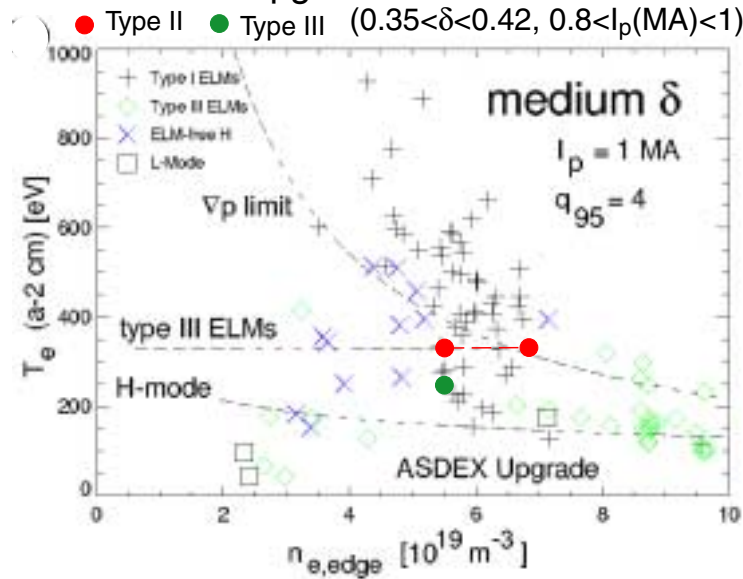
reproduced at JET Saibene EPS'04



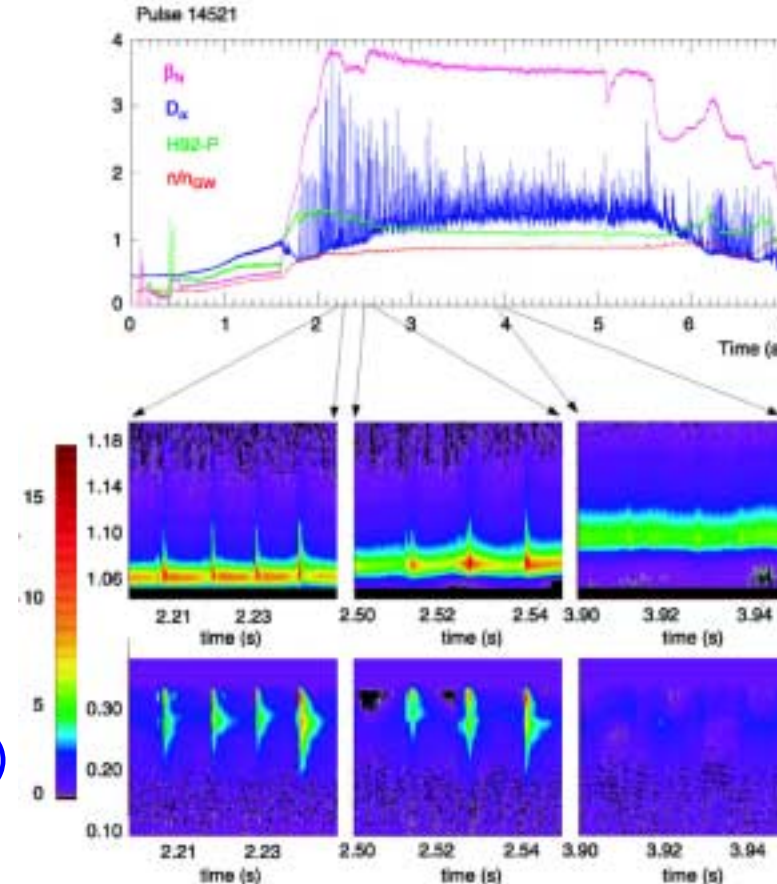
Regimes with high P_{ped} + small/no ELMs (V)

Type II ELMs in ASDEX Upgrade occur at high n_{ped} (v_{ped}^*)

ASDEX-Upgrade-Stober NF'02



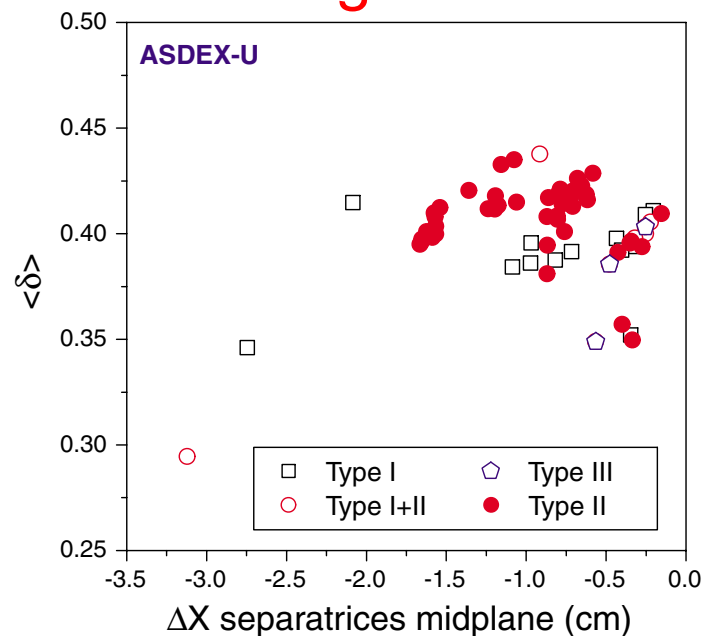
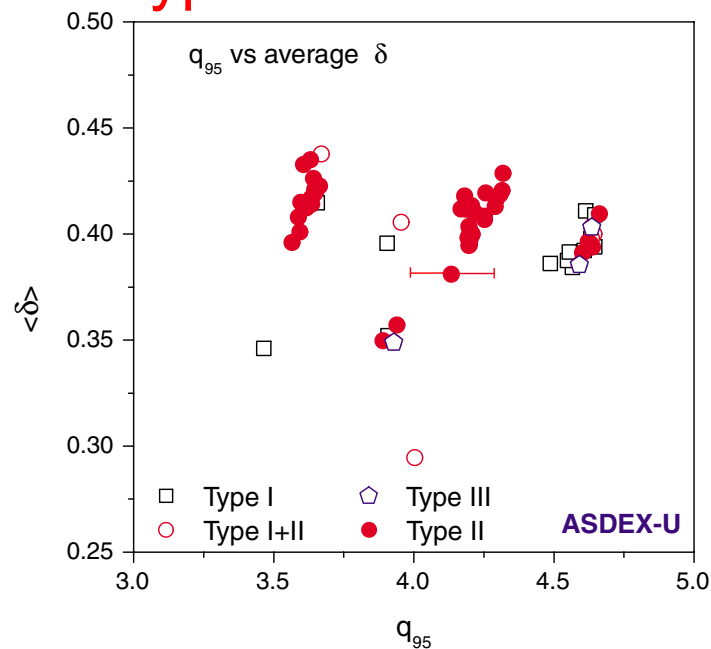
ASDEX-Upgrade-Sips NF'02



- $P_{ped}^{Type I} \sim P_{ped}^{Type II}$ transition
- Regime is robust to $P_{in} \uparrow$ (if fuelling adjusted)
- attributed to change in edge P-B stability
- compatible with high β (β_N , v_{ped}^* interplay?)

Regimes with high P_{ped} + small/no ELMs (VI)

Type II in ASDEX-U : Quasi DN configuration

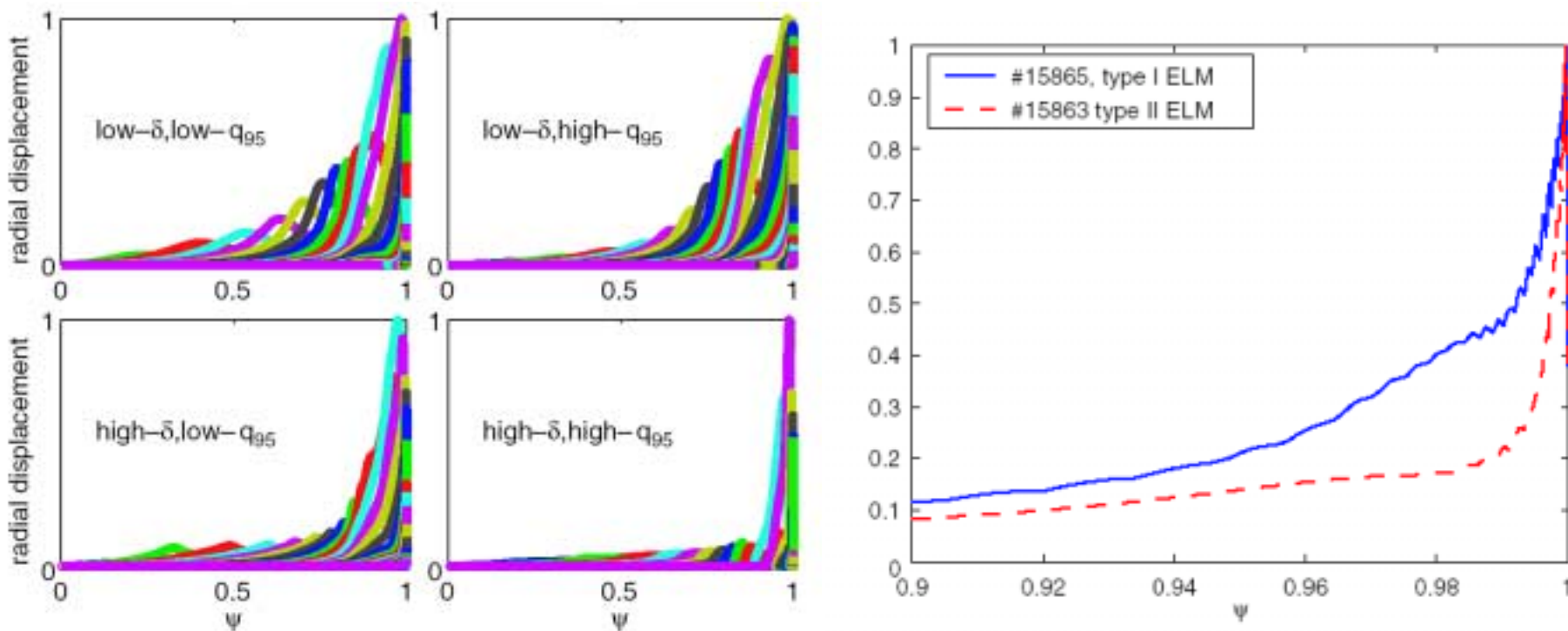


- Type II require medium/high δ and n_e
- Proximity to DN configuration is essential (no type II for $\Delta X_{mp} > 2\text{cm}$) + Trade-off δ/q_{95} ?
- High β not required, but compatible with the regime! ($\beta_N \sim 3$ obtained)

not reproduced at JET Saibene EPS'03

Regimes with high P_{ped} + small/no ELMs (VII)

ASDEX Upgrade-Saarelma NF'03

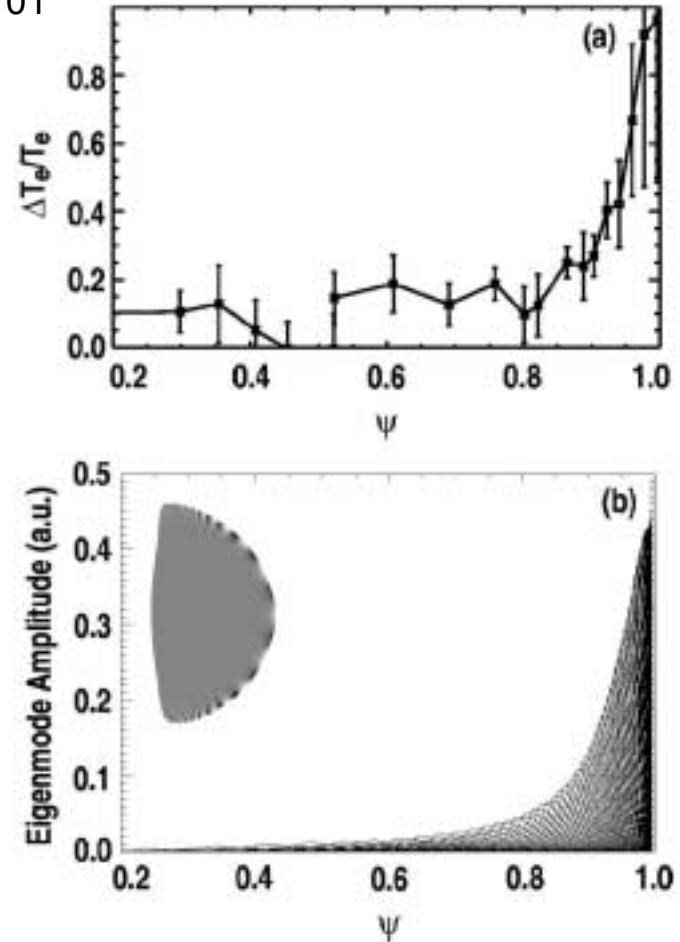
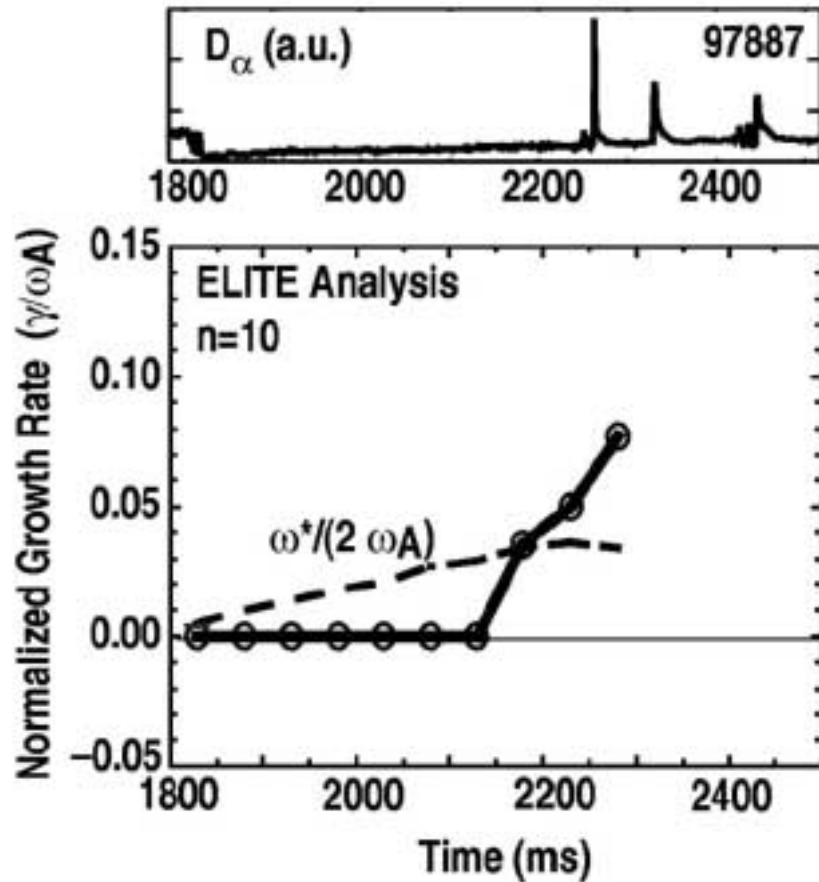


proximity to DN (#15863) leads to a sharp decrease of eigenmode width

Physics of ELM instability (V)

Growth of linear mode coincident con ELM crash (low n_e)

DIII-D-Snyder APS'01



Similar results for giant ELMs in JET - Huysmans

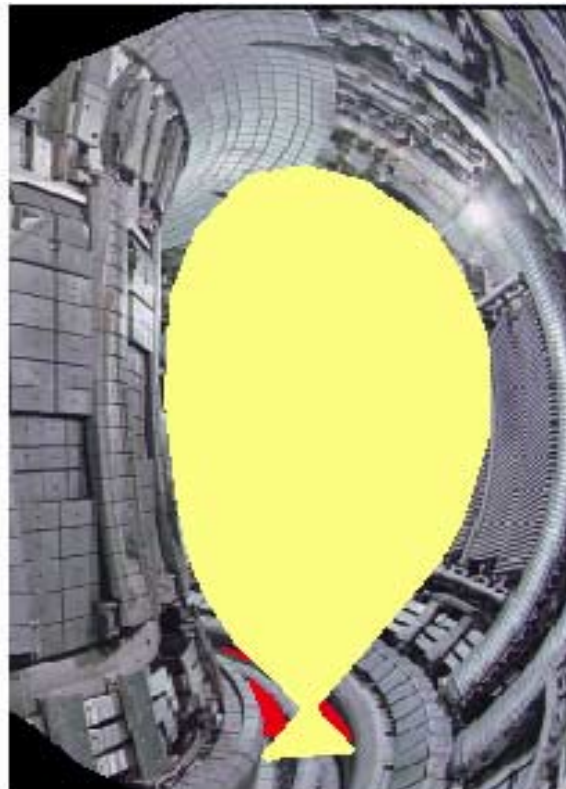
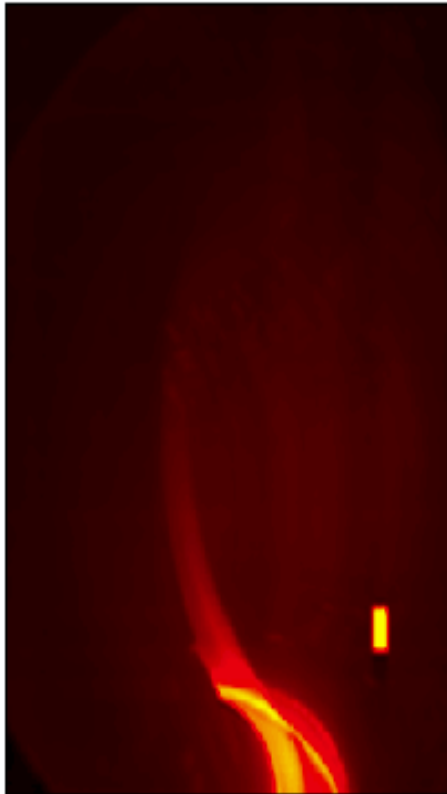
Physics of ELM instability (IX)

Analyses of particle impact patterns on JET main wall are consistent with ballooning mode $n = 12, m = 50$

Between ELMs

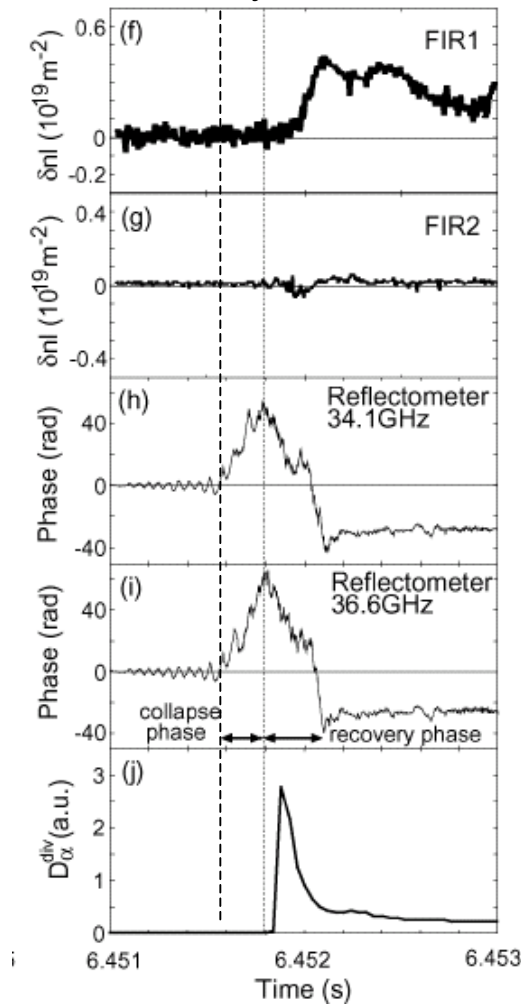
JET-Ghendrih JNM'03

At ELMs



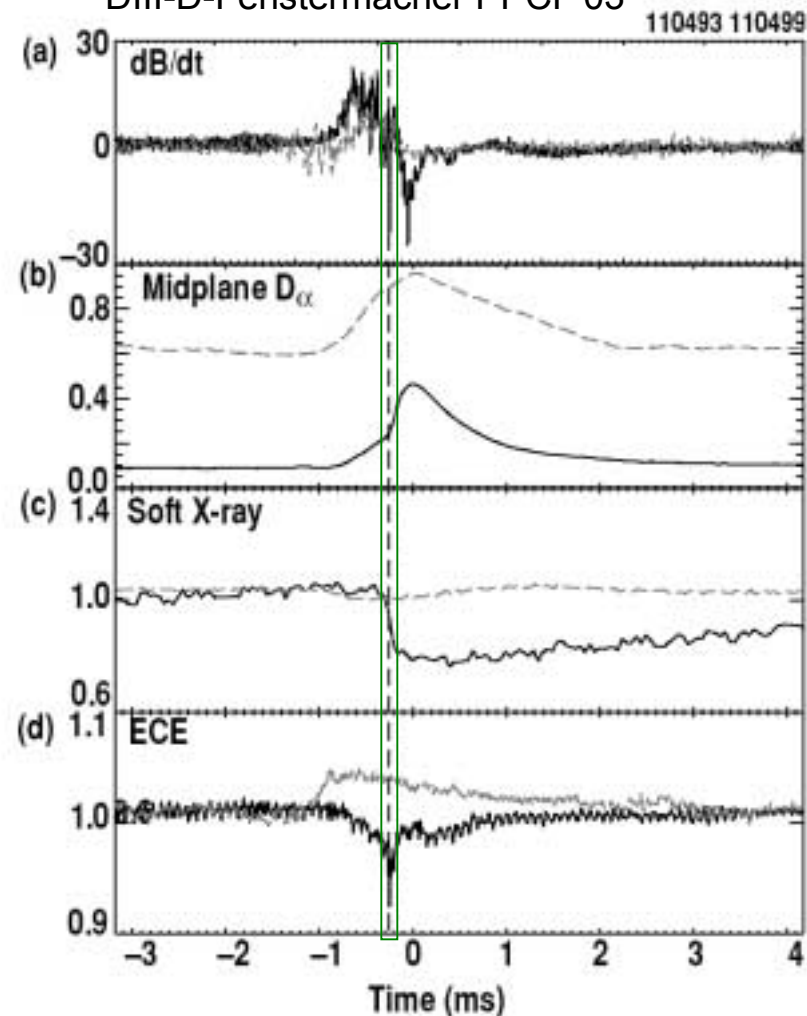
Physics of ELM instability (XIII)

JT60U-Oyama PPCF'01



$$\tau_{\text{ELM}} \sim 200 \mu\text{s}$$

DIII-D-Fenstermacher PPCF'03

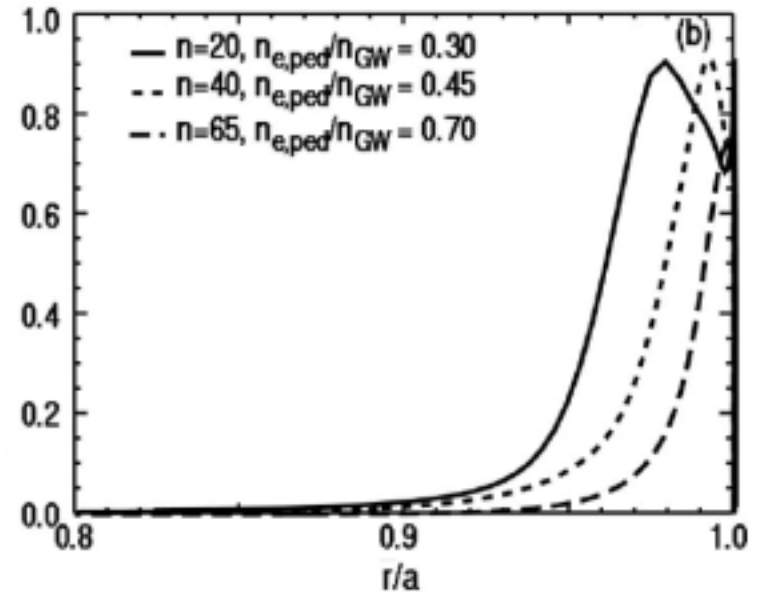
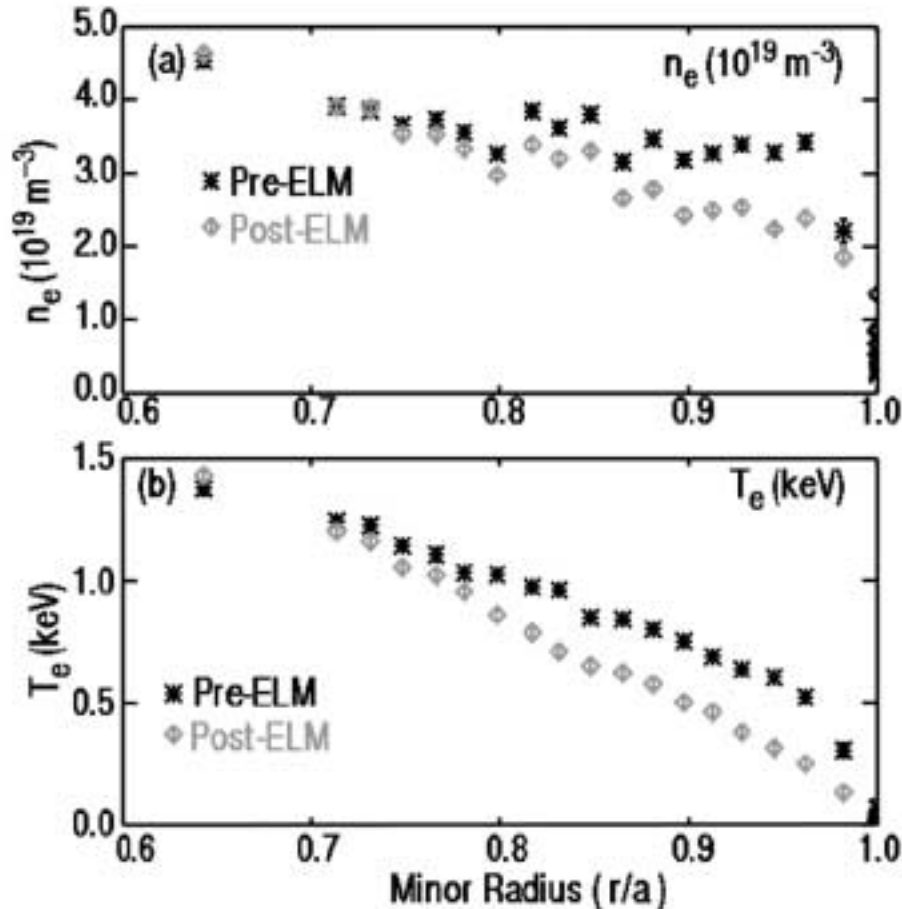


$$\tau_{\text{ELM}} \sim 200 \mu\text{s}$$

Main plasma ELM energy/particle losses (XI)

ELM perturbation into edge plasma much broader than P-B modes

DIII-D-Leonard APS'02

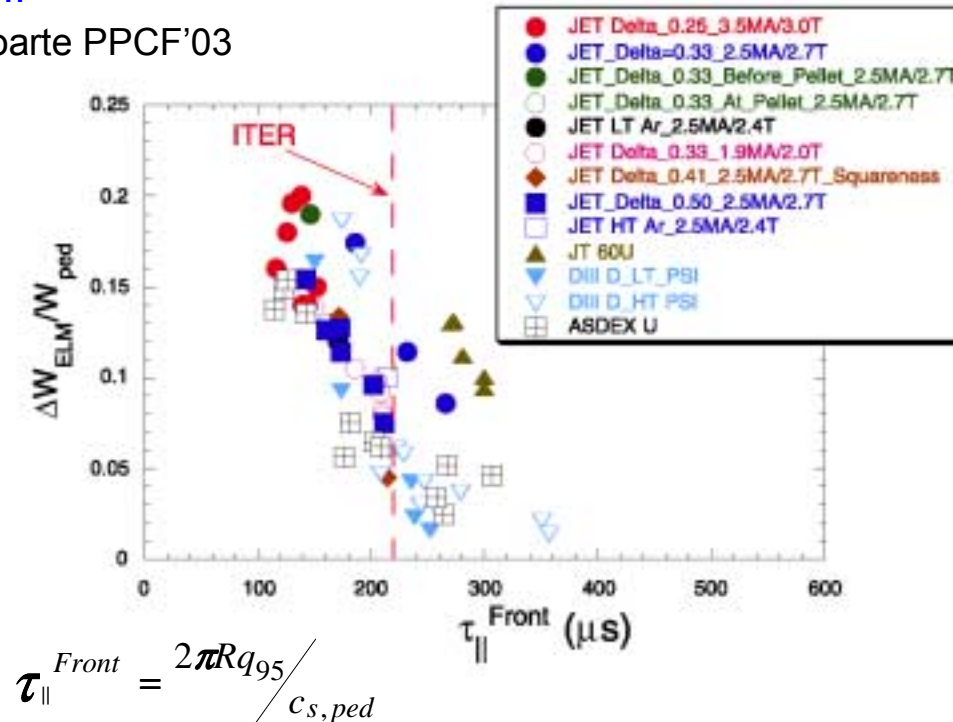
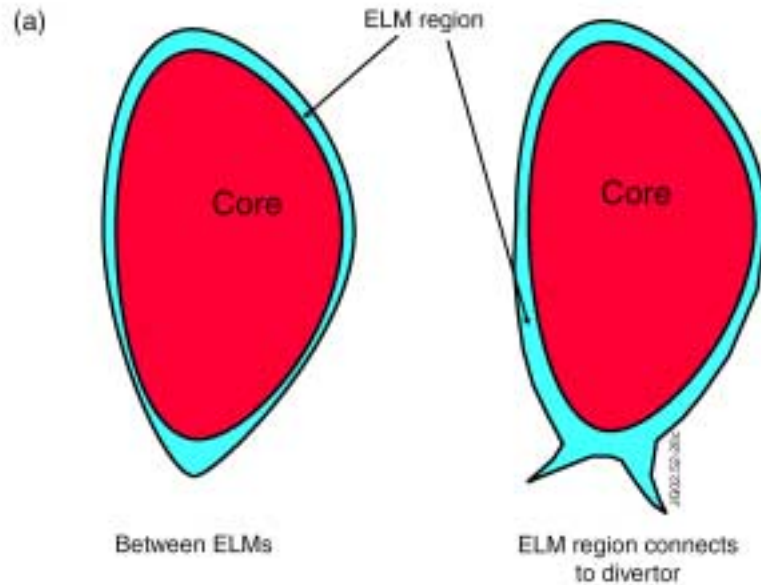


Relation between ΔW_{ELM}
and P-B modes ?

ELM energy/particle fluxes to PFCs (XVII)

- $\Delta W_{ELM}/W_{ped}$ decreases with $\tau_{||}$

ITPA-Loarte PPCF'03



Physics Model :

1) Pedestal connects to divertor for τ_{ELM}^{MHD}

2) Energy flow restricted by sheath ($\tau_{||}$) $\rightarrow \Delta W_{ELM}/W_{ped} \sim (1 - \exp(-\tau_{ELM}^{MHD}/\tau_{||}))$

ELM energy/particle fluxes to PFCs (XVII)

In/Out ELM energy balance changes at ELM and with divertor/main plasma conditions

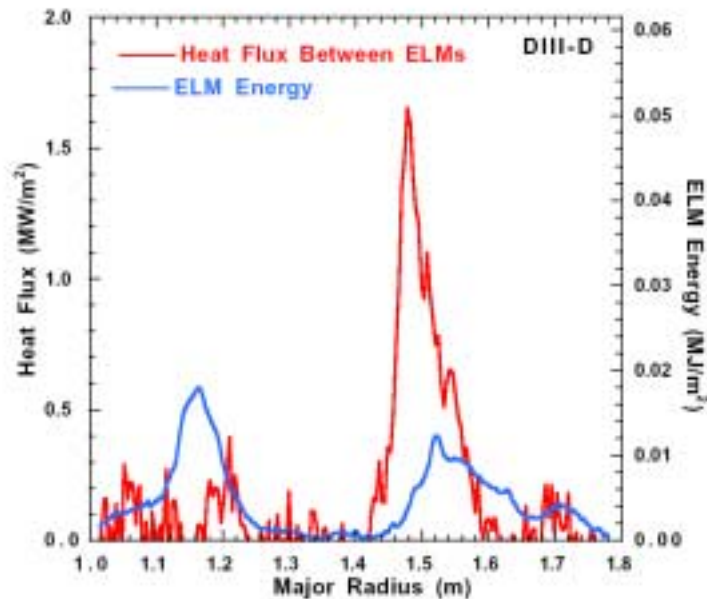
Inter-ELM

$$n_{\text{div}}^{\text{in}} > n_{\text{div}}^{\text{out}}$$

$$T_{\text{div}}^{\text{in}} < T_{\text{div}}^{\text{out}}$$

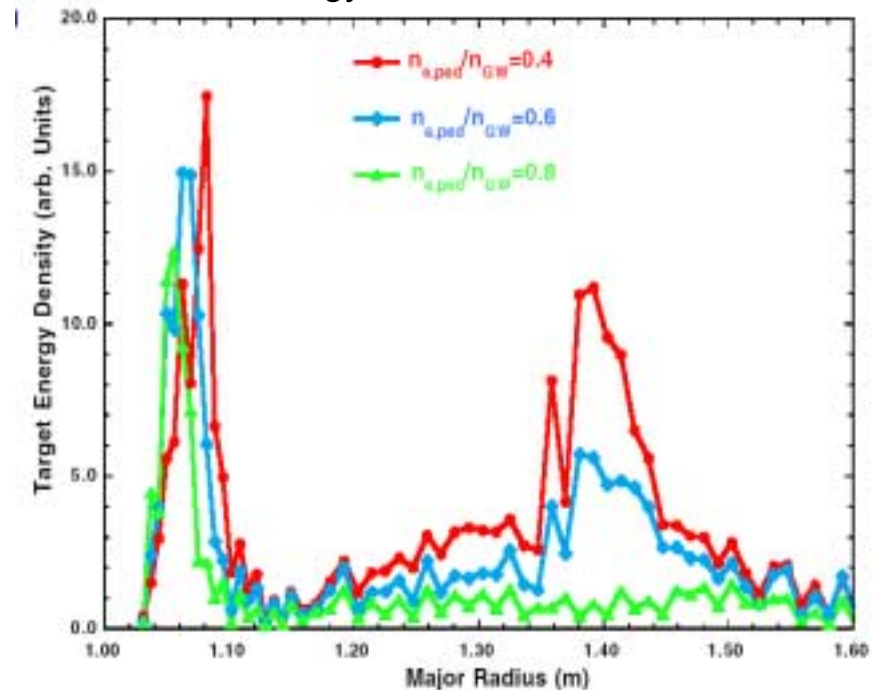
$$q_{\text{div}}^{\text{in}} < q_{\text{div}}^{\text{out}}$$

$$\Gamma_{\text{div}}^{\text{in}} > \Gamma_{\text{div}}^{\text{out}}$$



DIII-D-Leonard PSI'02, Fenstermacher PPCF'03

Energy fluxes at ELMs



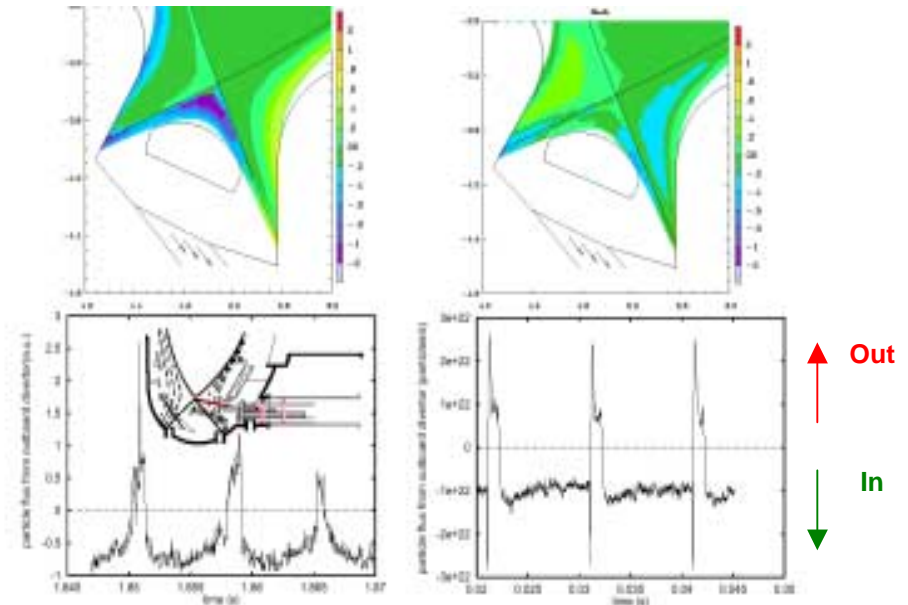
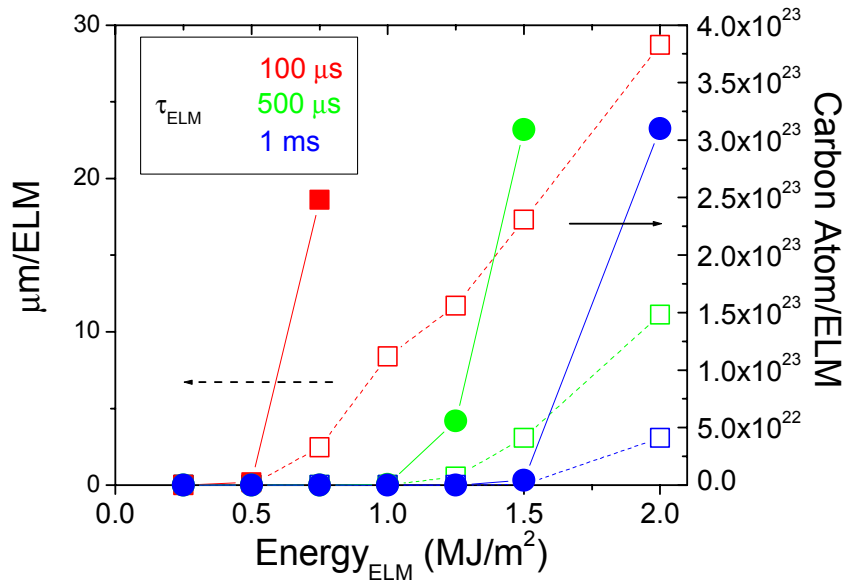
consistent with $N_{\text{div}}^{\text{in}} > N_{\text{div}}^{\text{out}} + \text{sheath}$ or changes in with energy flow with n_e

ELM energy/particle fluxes to PFCs (XVIII)

$E_{\text{ELM}} > 1 \text{ MJ/m}^2$ can lead to $\Gamma_{\text{C}} > 10^{23}$ C-atom/ELM

Poor C Retention in Divertor @ ELM
(Plasma flows out of the Divertor)

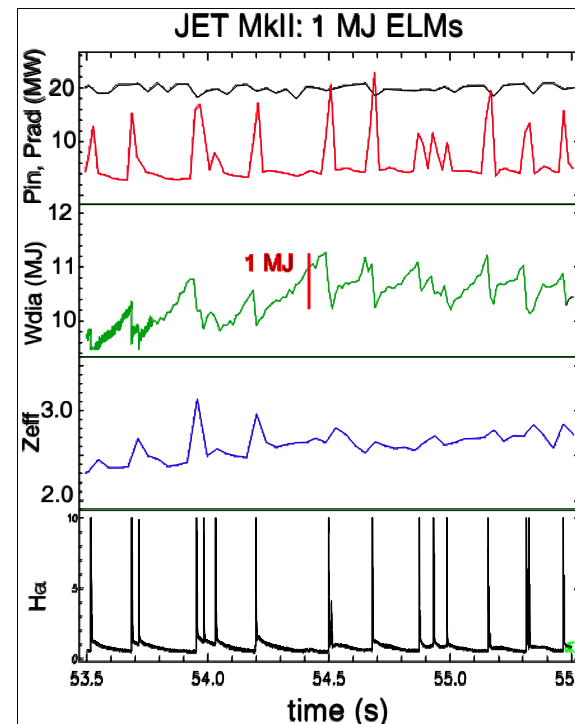
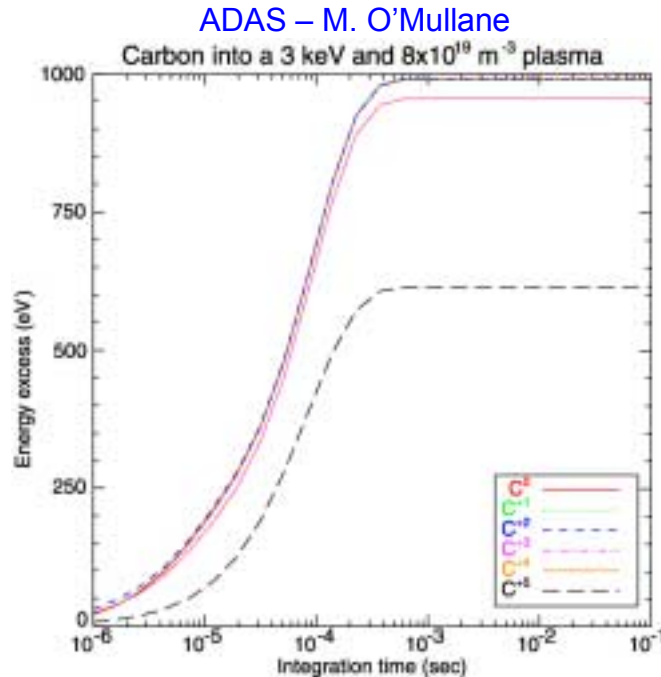
$N^{\text{D-T}}_{\text{ITER}} \sim 10^{23}$ particles



Large Proportion of Γ_{C} may get into Core Plasma \rightarrow increase of Z_{eff} at edge

ELM energy/particle fluxes to PFCs (XIX)

Energy loss by Carbon Transient Radiation → Probably small



$E_{\text{ELM}}^{\text{RAD}} \sim 0.5 \text{ MJ}$
(C. Ingesson)

$W_p \sim 11 \text{ MJ}$
 $\Delta W_{\text{ELM}} \sim 1 \text{ MJ}$

$n_{\text{ped}} \sim 8 \cdot 10^{19} \text{ m}^{-3}$
 $T_{\text{ped}} \sim 3 - 5 \text{ keV}$

➤ $E_{\text{transient}}^{\text{C-radiation}} (3 \text{ keV}, 8 \cdot 10^{19} \text{ m}^{-3}) \sim 1 \text{ keV/atom}$

$E_{\text{ELM}}^{\text{RAD}} \sim 16 \text{ MJ} \ll W_{\text{plasma}} (\sim 350 \text{ MJ})$

➤ JET Results agree qualitatively : Modelling/Extrapolation to ITER necessary