Comments on ELMs for FIRE and high δ Operation

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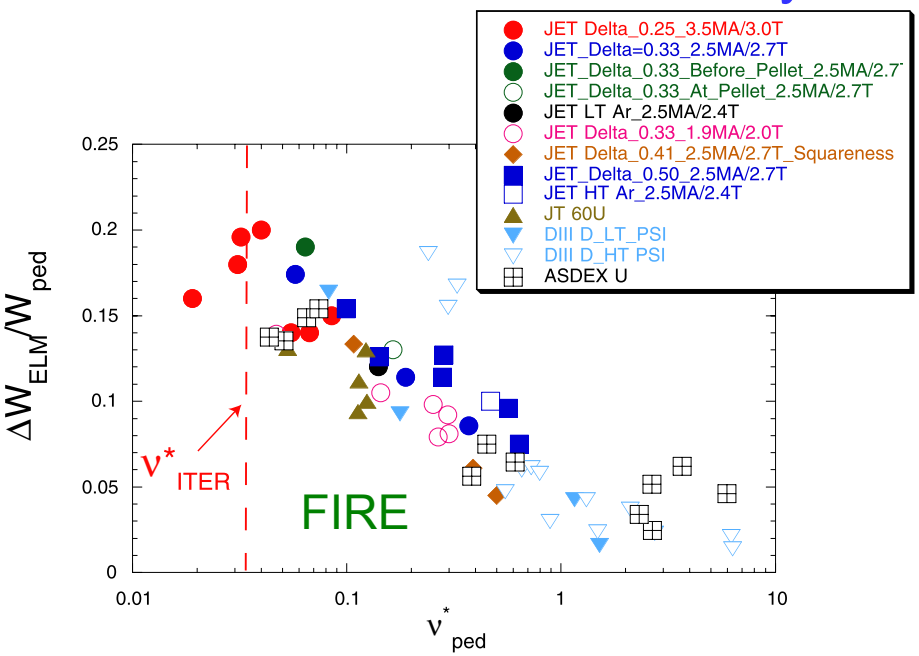
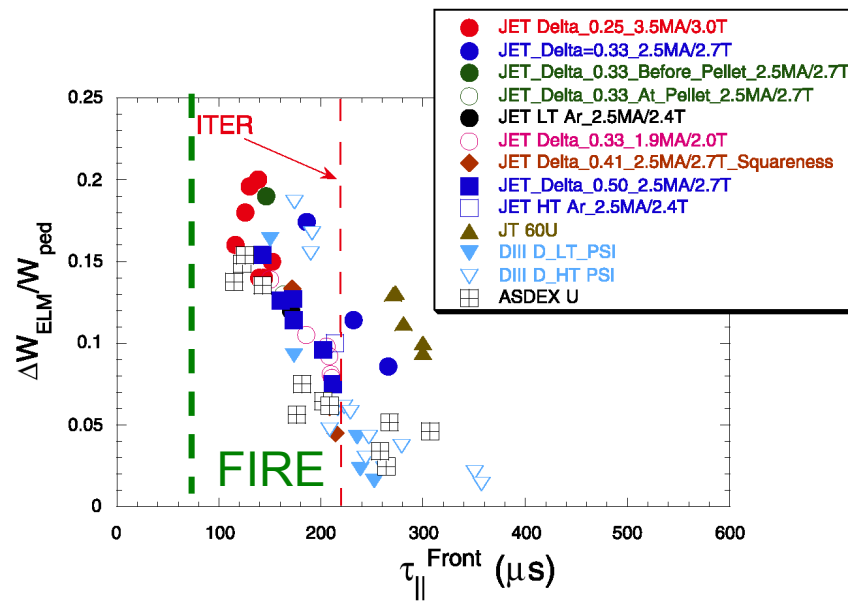
Evaluation of ELM Energy Losses FIRE/ITER

Similar Pedestal Collisionality ITER ←→ FIRE but very different τ_{II}





ν^*_{ped} purely empirical Scaling

$\Delta W_{ELM}^{FIRE} = 3.6$ MJ

$\Delta W_{ELM}^{ITER} = 20$ MJ

$A_{div}^{FIRE} = 1.2\ m^2$

$A_{div}^{ITER} = 3.6\ m^2$

τ_{II} purely empirical Scaling

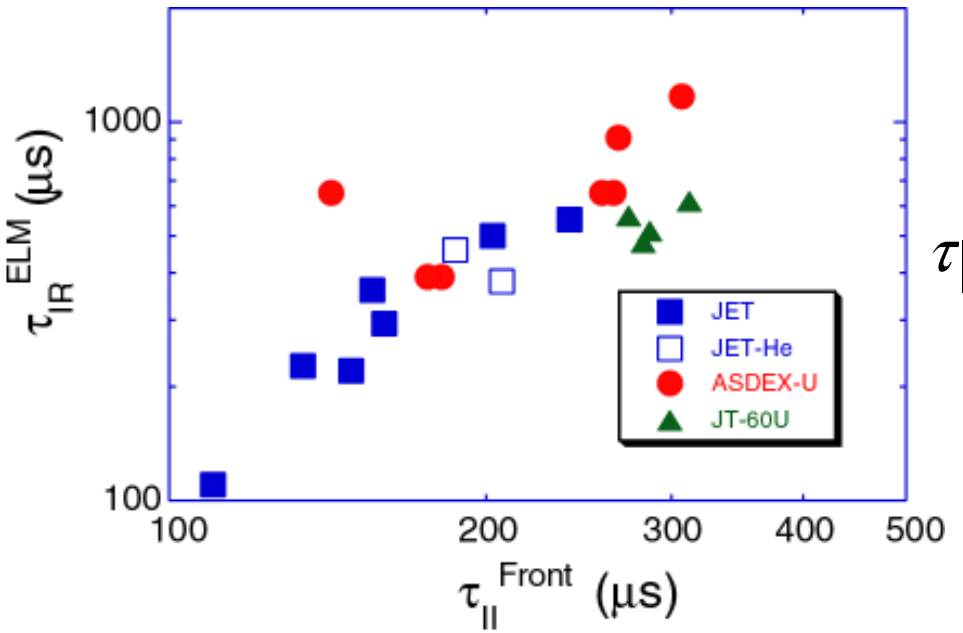
(τ_{MHD}/τ_{II})

$\Delta W_{ELM}^{FIRE} = 3.6$ MJ

$\Delta W_{ELM}^{ITER} = 10$ MJ

Caveat $\tau_{MHD} \sim 200\ \mu s$ but $B^{FIRE}_{\phi} = 10$ T???

Evaluation of ELM Power Deposition Time



$$\tau_{||}^{Front} = 2\pi R q_{95} / c_{s,ped}$$

220 μs → ITER

75 μs → FIRE

$$\frac{\Delta W_{ELM}}{A_{div} \sqrt{\tau_{||}}}$$

384 MJ m^{-2} s$^{-1/2}$ → ITER

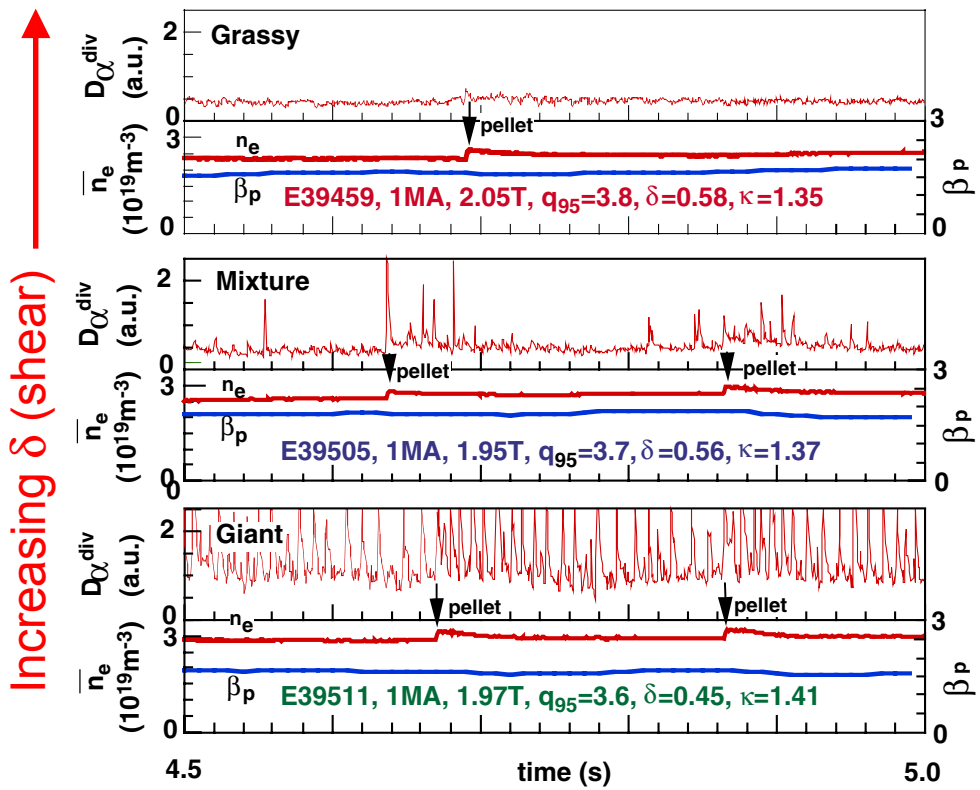
346 MJ m^{-2} s$^{-1/2}$ → FIRE

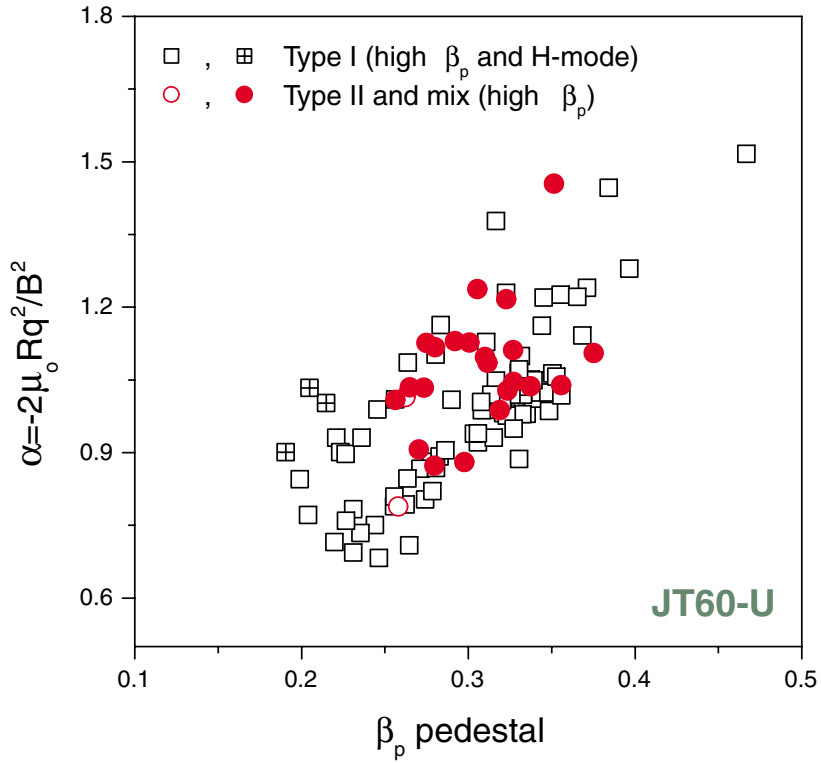
With $\tau_{||}$ → $\Delta W_{ELM}/W_{ped}$ scaling ITER power loads are ~ 2.7 lower

τ_{MHD} ~ 200 μs @ 10T ?

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

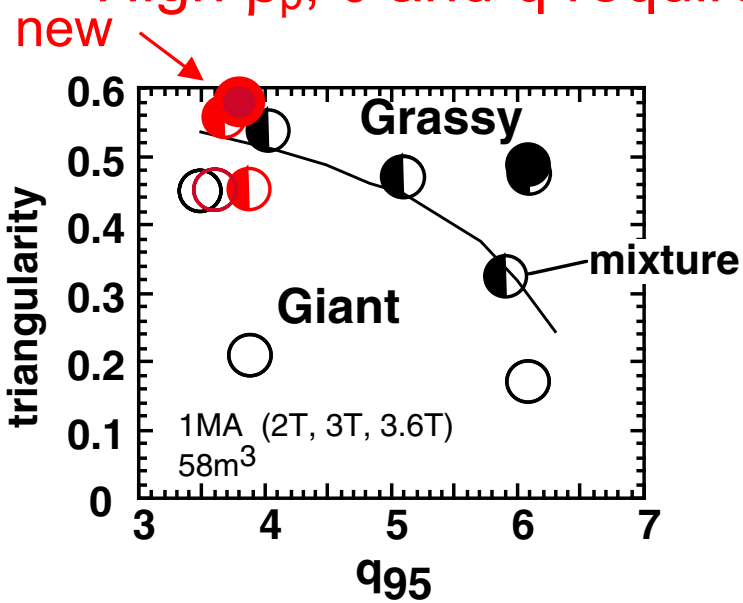
High δ H-modes (ASDEX-U), **high β_p H-modes** in JT60-U, **QDB modes** of DIII-D + **mixed regimes** (JET, DIII-D high δ H-modes)

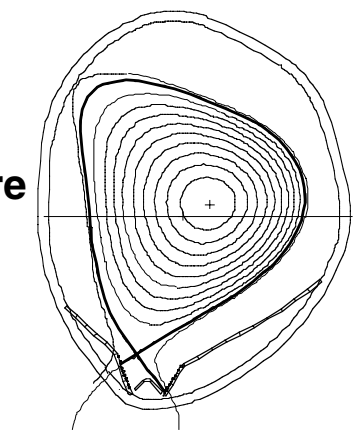




JT-60U

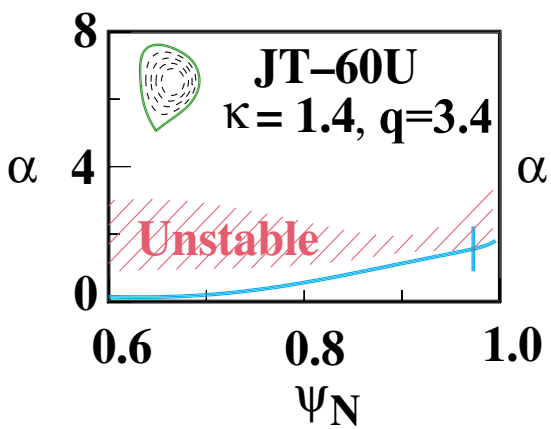
High β_p, δ and q required for Type I suppression in JT60-U

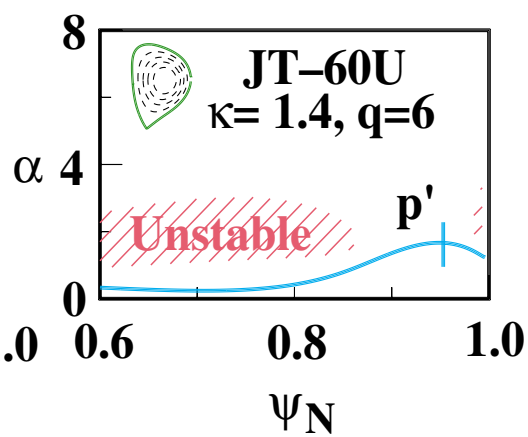




Distortion of the flux surfaces by Shafranov shift at high β_p + high δ / high q_{95} $\Rightarrow$ edge shear $\Uparrow$

$\Rightarrow$ **Grassy/Type II ELMs**

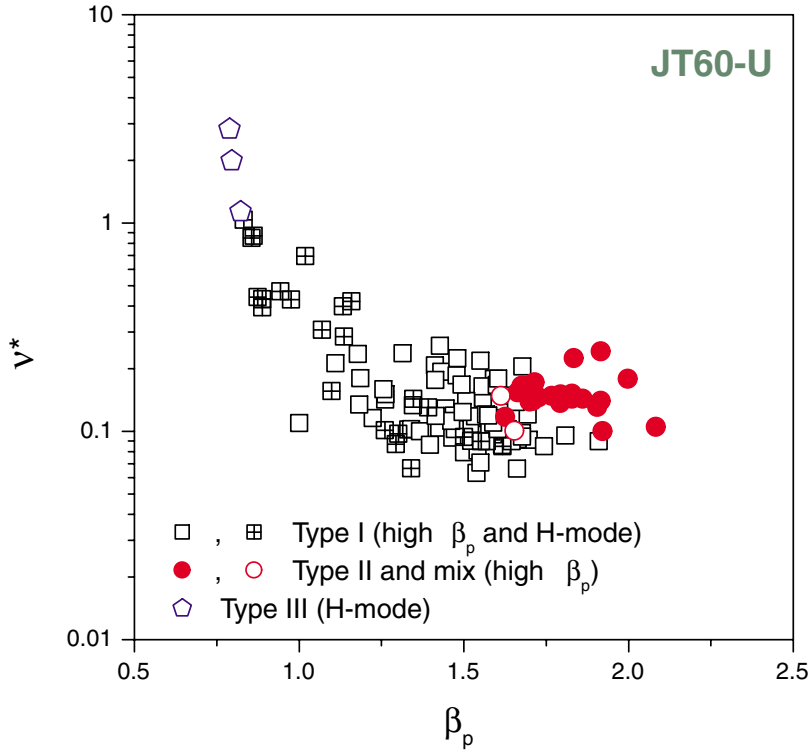




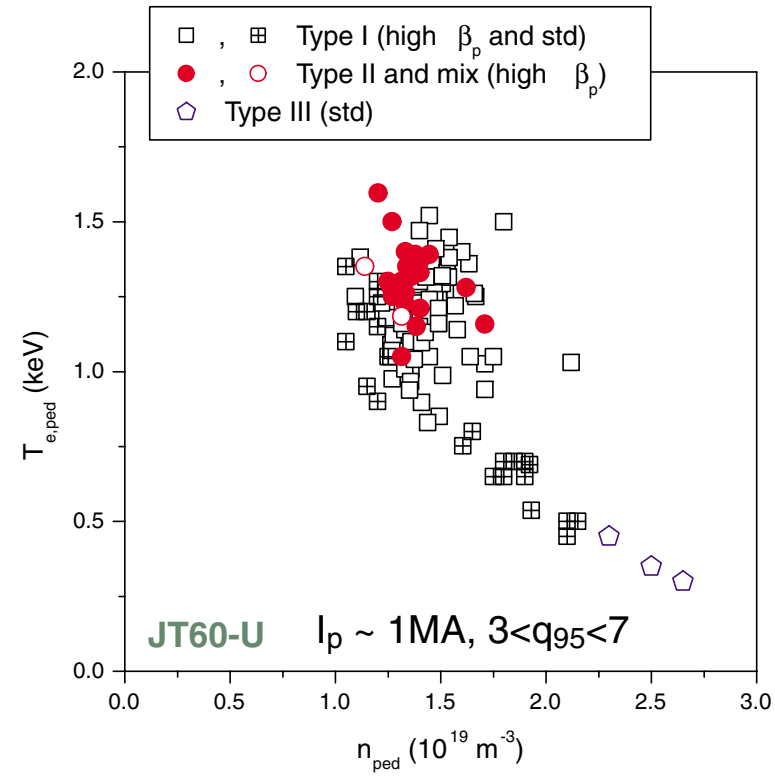
Local pedestal parameters do not play a major role (next).

GATO analysis, n<10

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

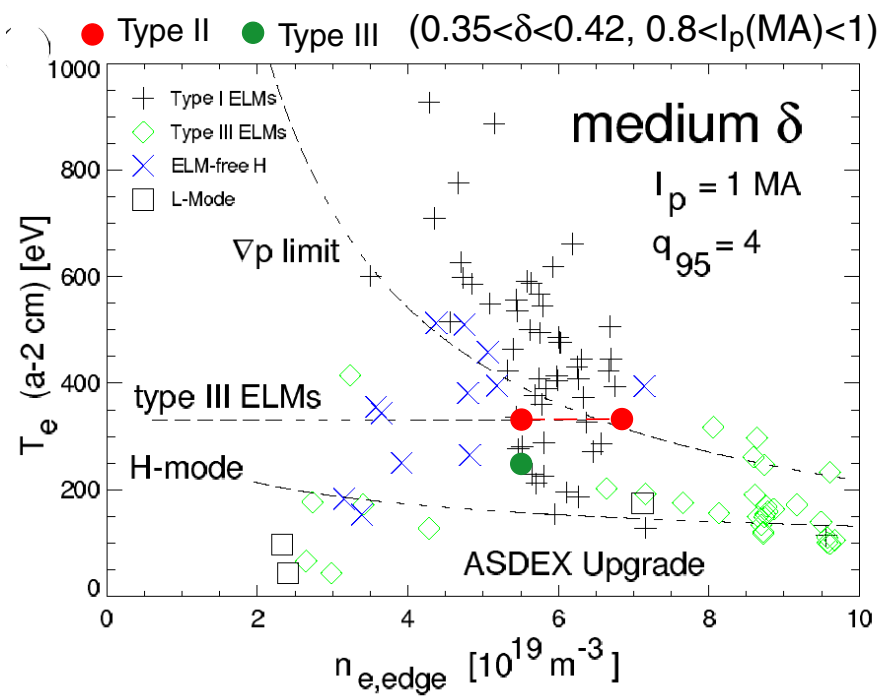


Type I→ II: similar n_{ped} and T_{ped} compared to standard high β_p H-modes



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

Type II ELMs in ASDEX Upgrade occur at high Density



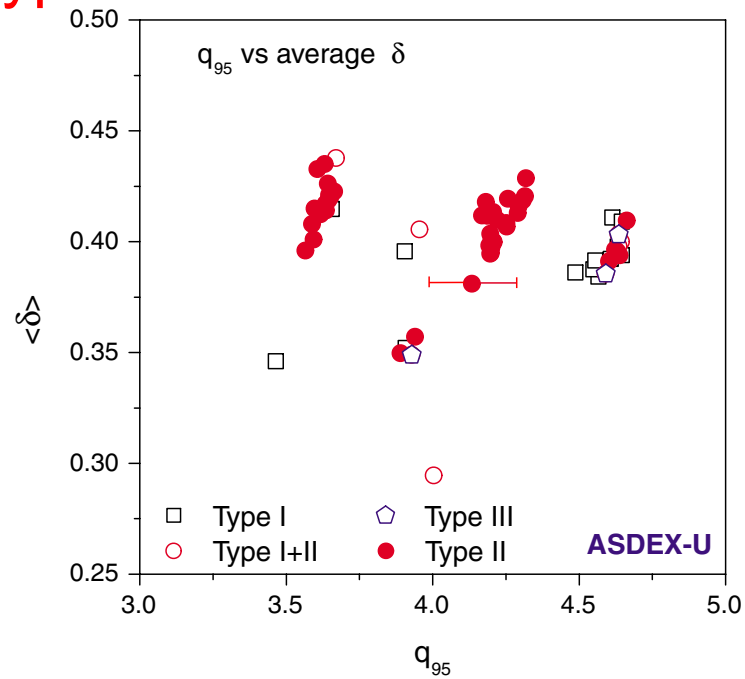
Transition Type I → II occurs with little change in p_{ped} compared to Type I phase → core confinement similar to Type I

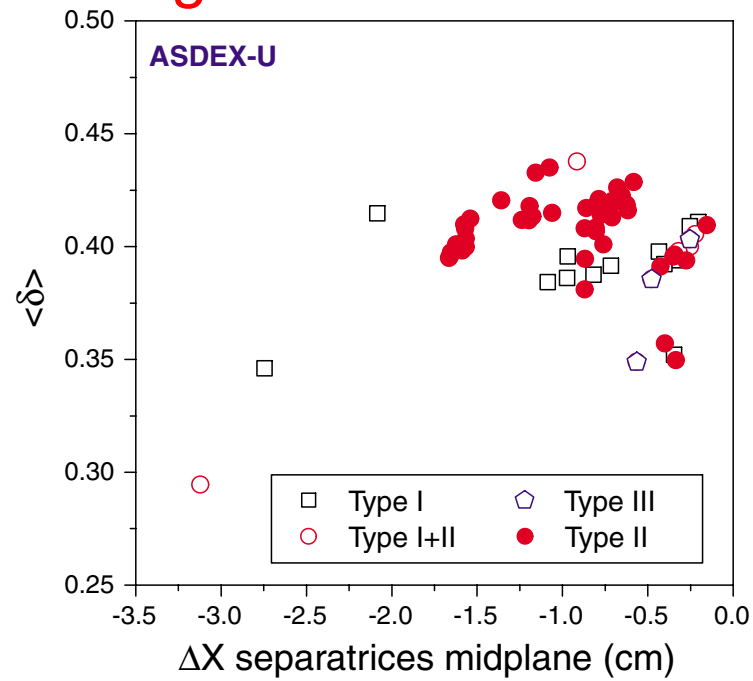
s.s. Type II observed only at high n_e (similar to mixed case in JET)

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

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

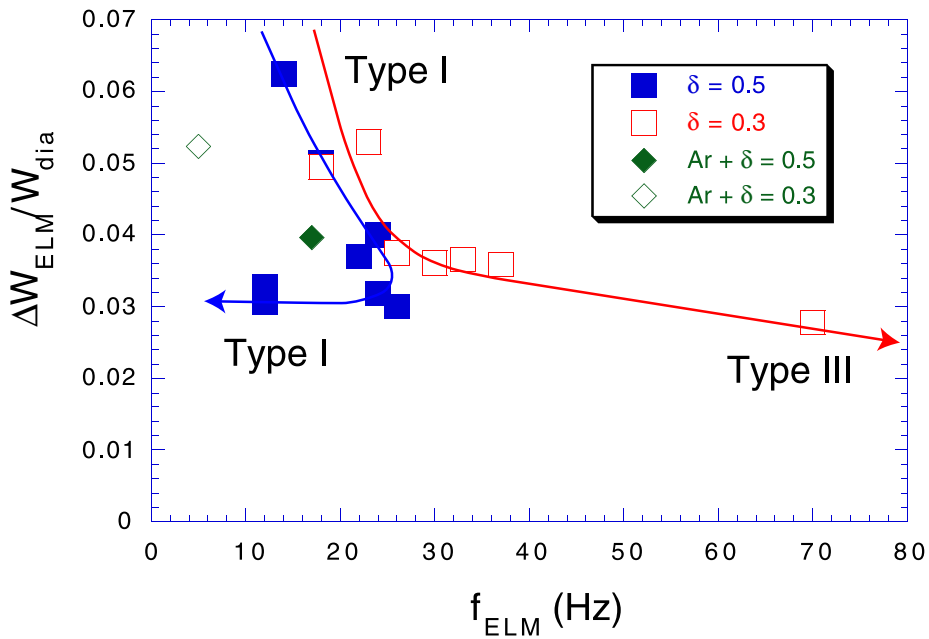
Type II in ASDEX-U : Quasi DN configuration

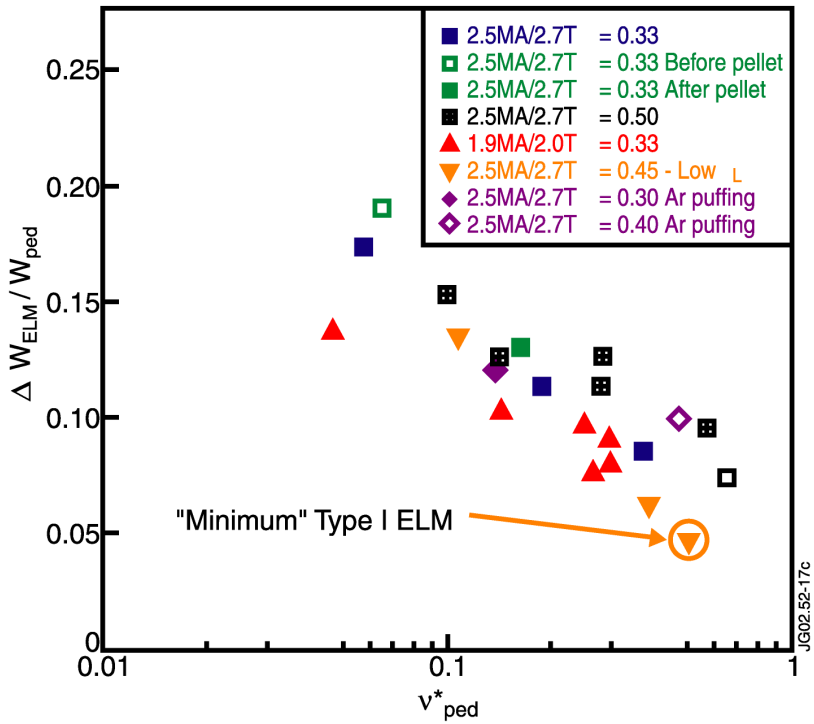




- Type II require high δ (as JET and JT60-U) and n_e
- Proximity to DN configuration is essential (no type II for ΔX_{mp}>2cm) + Trade-off δ/q_{95} ? DN to increase edge shear?
- High β not required, but compatible with the regime! (β_N~ 3 obtained)

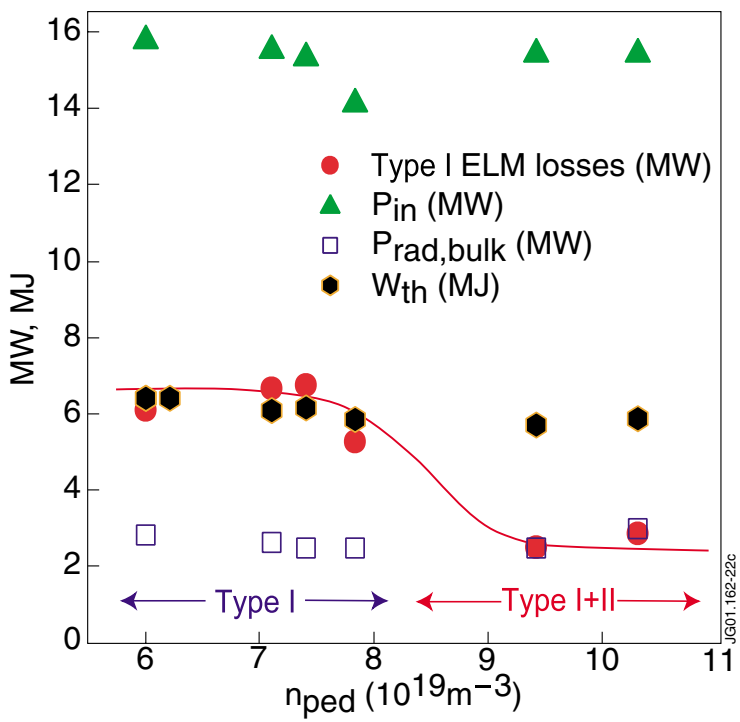
Anomalous Type I ELM Behaviour at high δ





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

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



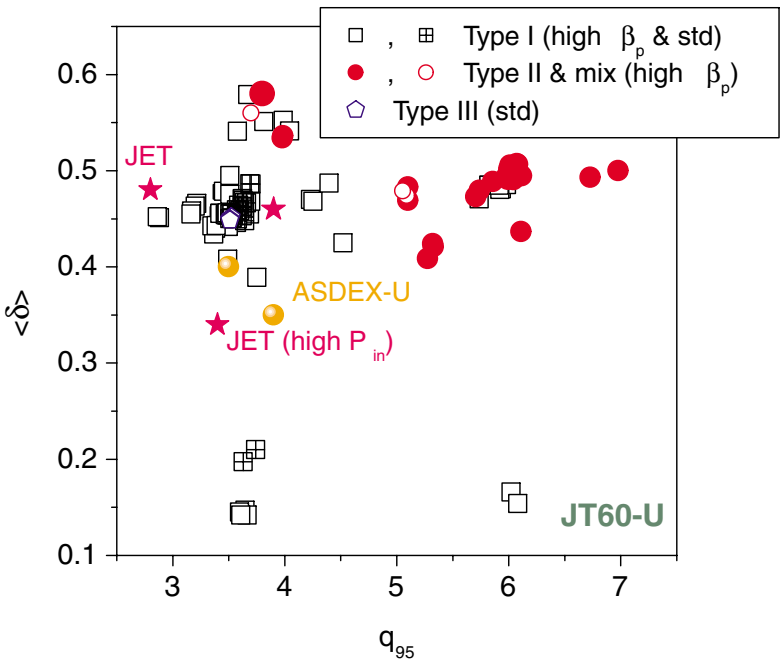
Gas scan at 2.5MA/2.7T, δ~0.48, P_{NB}=15MW

- 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

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**

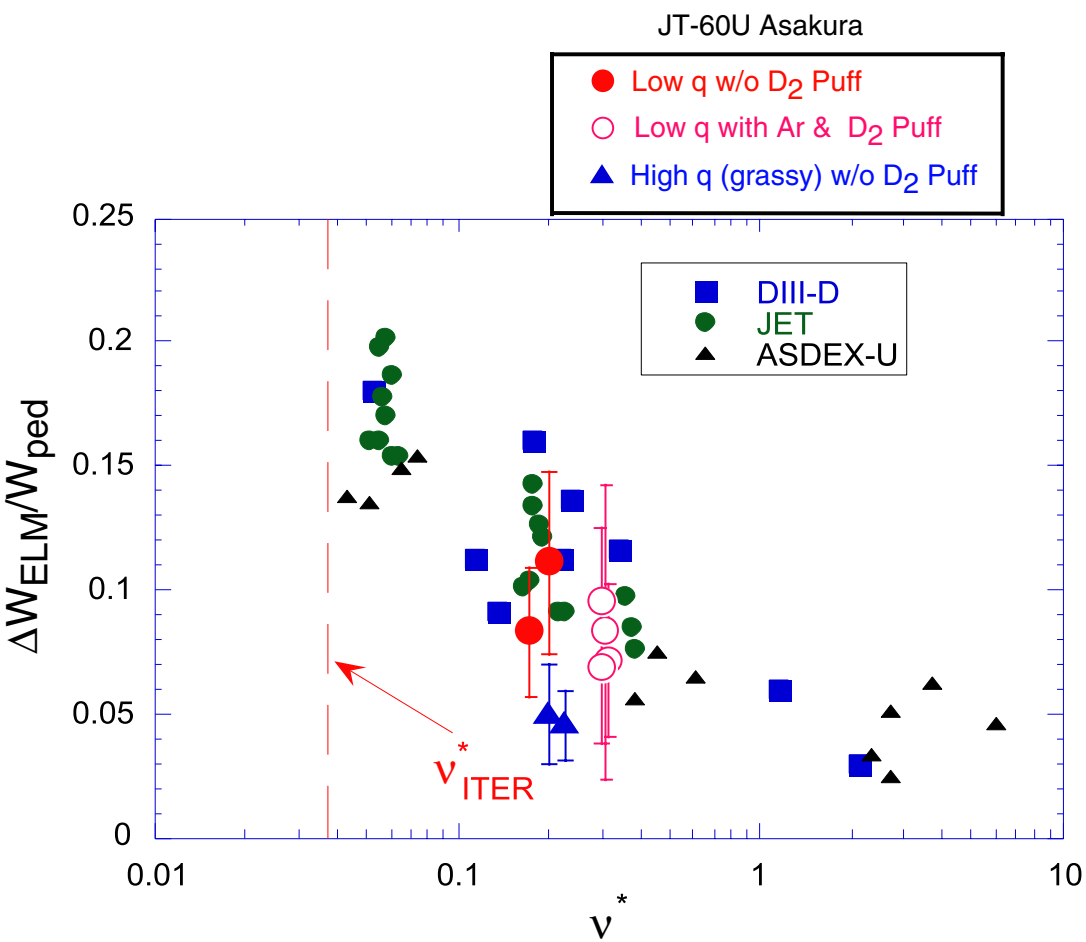
➢**Type I ELM suppression is gradual** (mixed phases) and occurs at ~ constant p_{ped} and ∇p_{ped}

➢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!!**

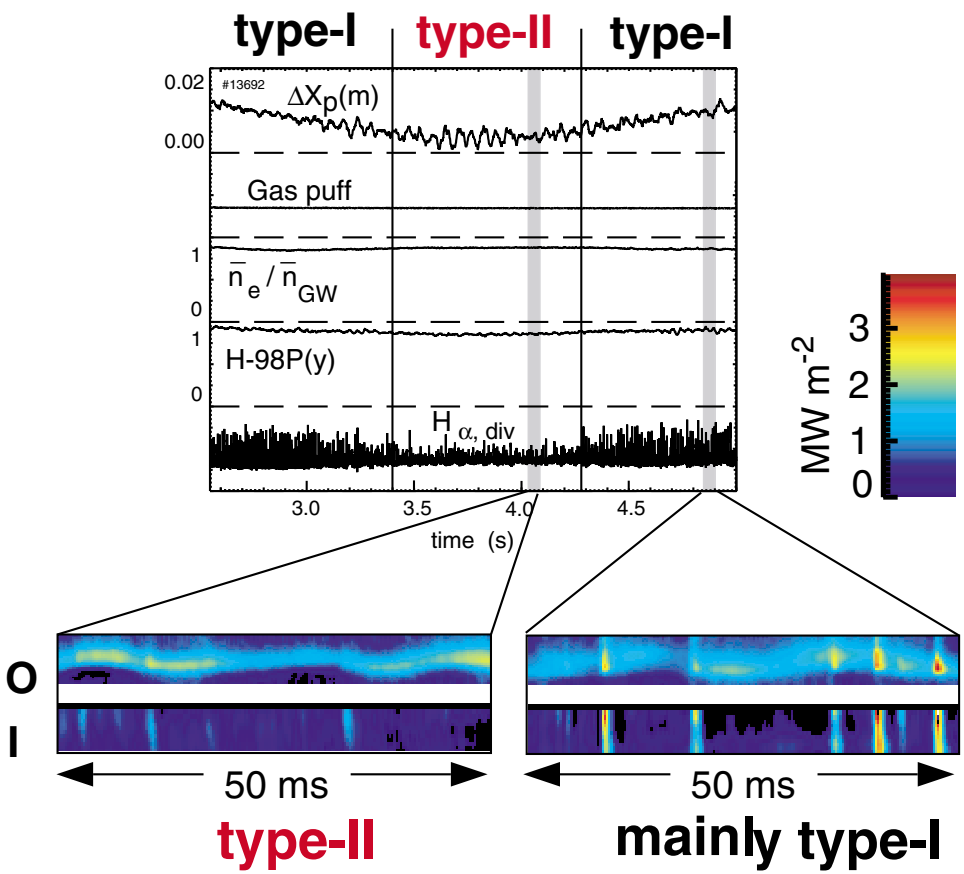
JT60-U : ELM Energy losses ↓ by a factor ~2-5 with Type II ELMs



JT60-U

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

Small “bursty” heat pulses with Type II ELMs



ASDEX-U

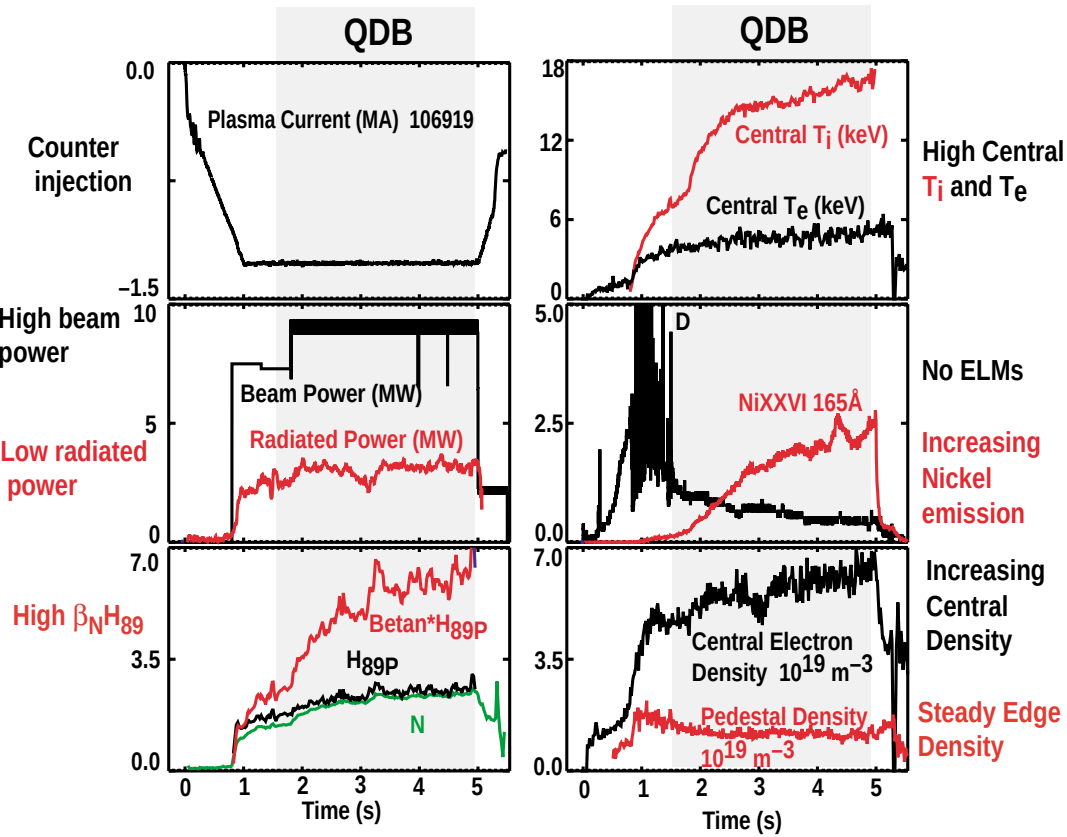
Periodic heat pulses with Type II ELMs (not correlated to D_α)

Peak power load reduced with Type II ELMs

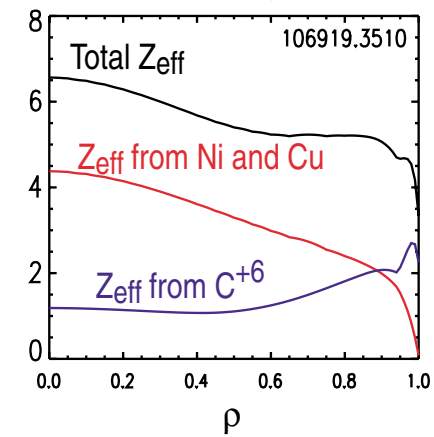
Heat pulses in the divertor $\Rightarrow$ MHD modes?

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

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



ΔZ_{eff} > 4 from High Z Impurity



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}

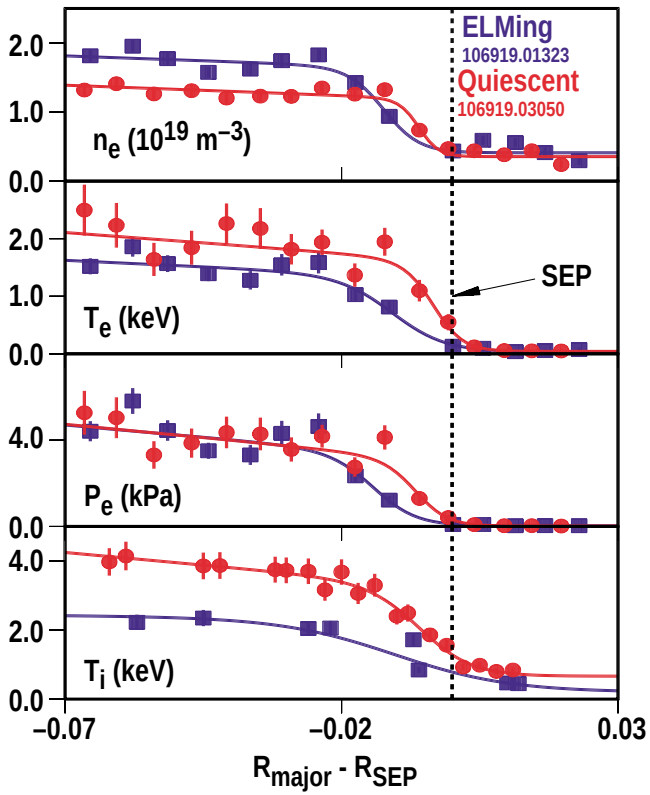
Z_{eff}~7 (transport or sources?)

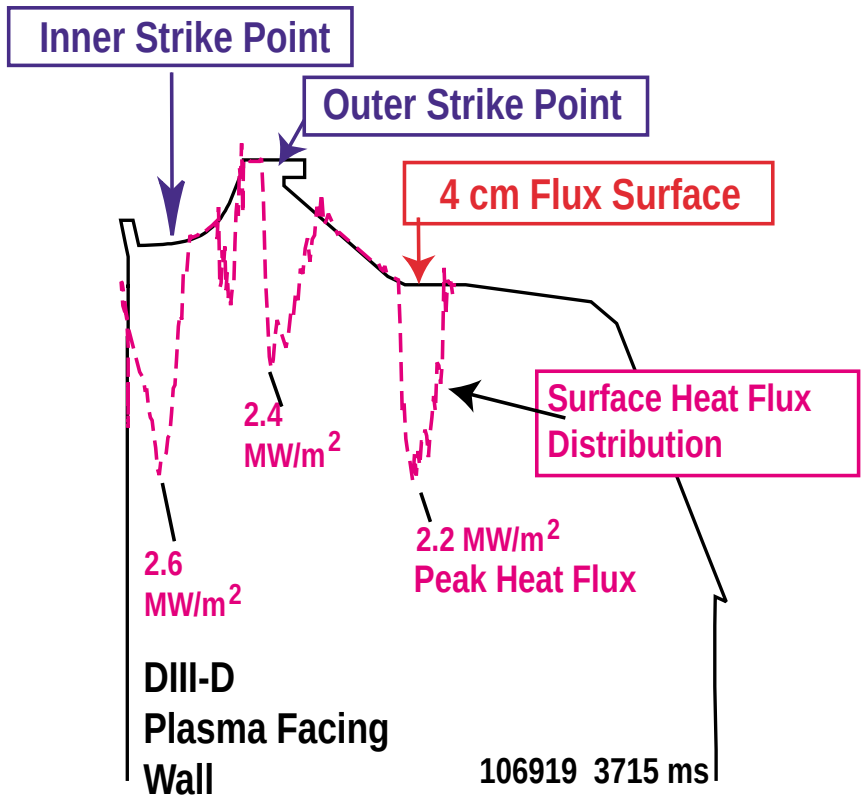
Fast ion losses → power deposition far from separatrix

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

* QDB: Quiescent Double Barrier

QDB in DIII-D – more details

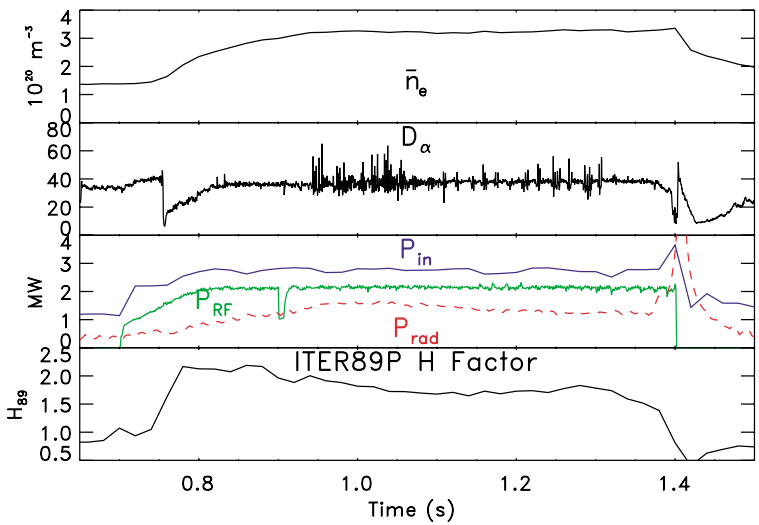




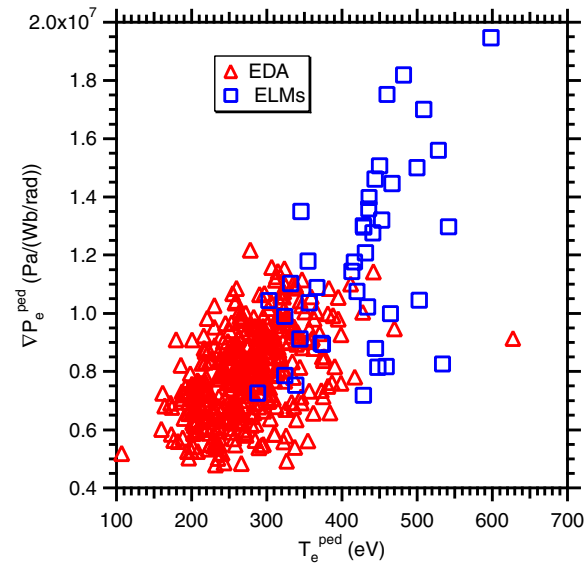
Pedestal profiles of ELMy and QDB

Power deposition patterns in QDBs

EDA (C-Mod)



C-Mod



C-Mod

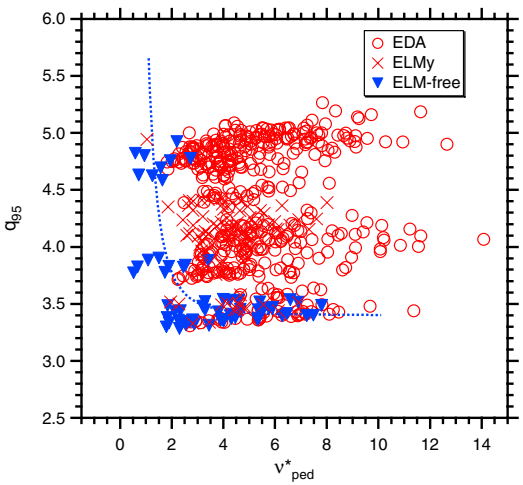
Some EDA features:

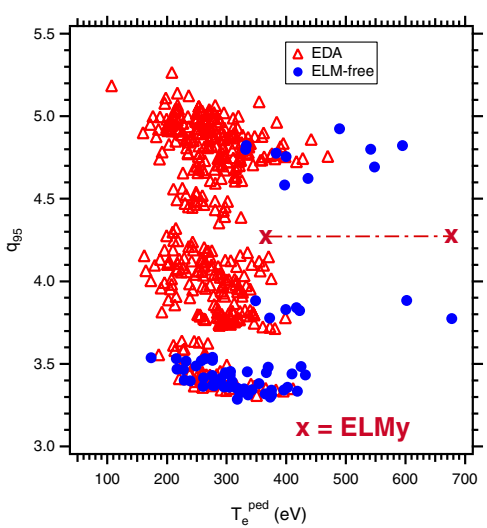
- EDA associated to QC edge mode (high ν^*, low T_{ped})
- Resistive ballooning modes are candidate for EDA

If P_{in} is increased:

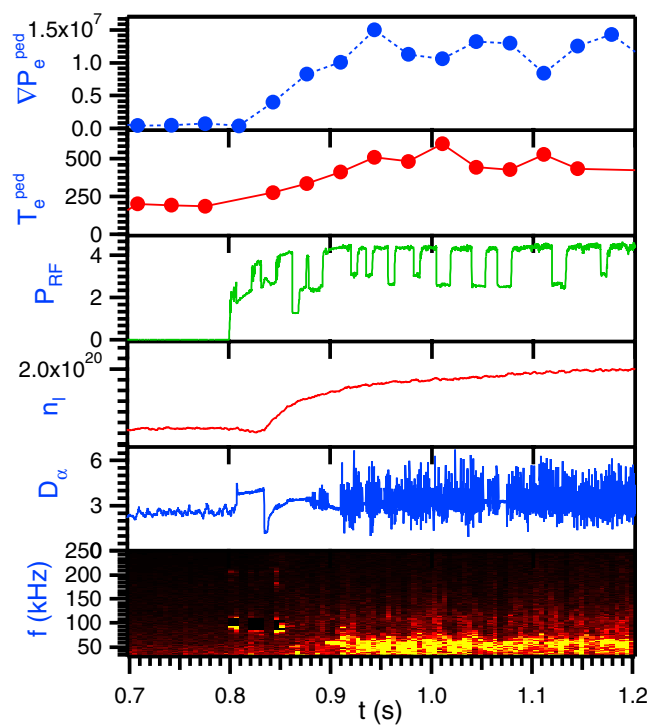
- QC disappears $\Rightarrow$ broadband MHD
- Pressure gradient steepens and “grassy” ELM appear
- Pedestal unstable to peeling/ballooning modes

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