Broadening of divertor heat flux footprints with increasing number of ELM filaments in NSTX

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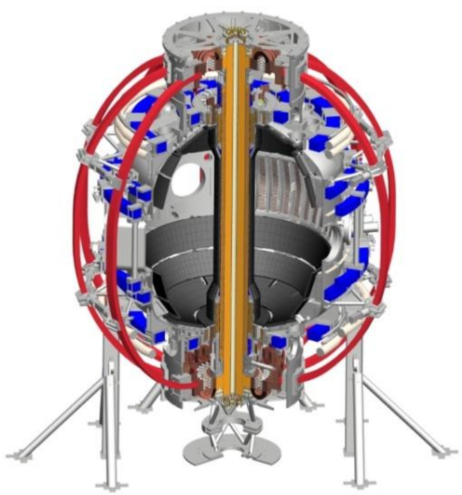

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Motivation

- ELM heat flux characterization is important to determine requirement of ELM control system performance in future machines

- Relationship of wetted area (A_{wet}) to the size of ELM energy loss directly impacts peak heat flux (q_{peak})

- Larger A_{wet} allows larger total ELM energy loss (ΔE_{ELM}) to be acceptable, however uncertainty on A_{wet} remains unresolved yet

Outline

- Introduction - why ELM wetted area (A_{wet}) is important?
- Measurement techniques and examples in NSTX
- Relationship between # of ELM filaments and A_{wet}, its impact on ELM size dependence of A_{wet} and q_{peak}
- ELM stability regime with different toroidal mode number
- Conclusions

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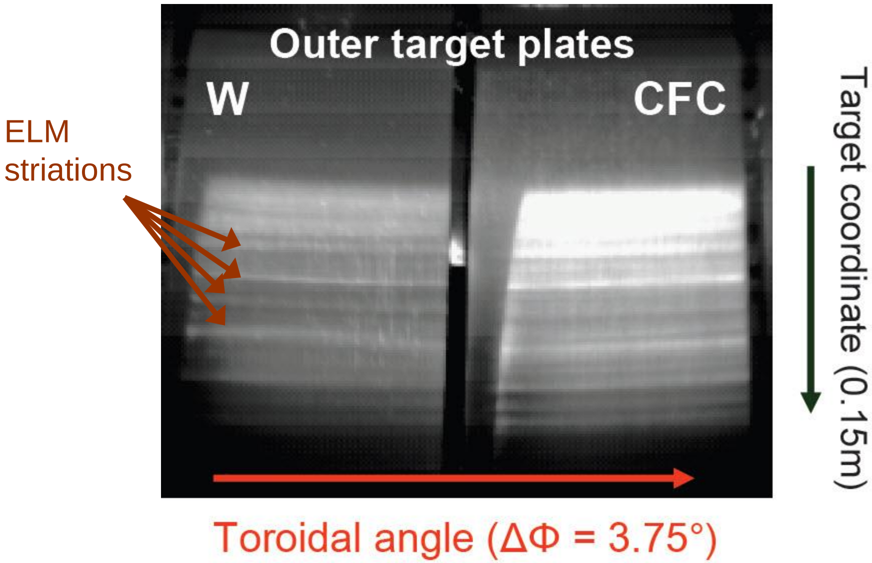
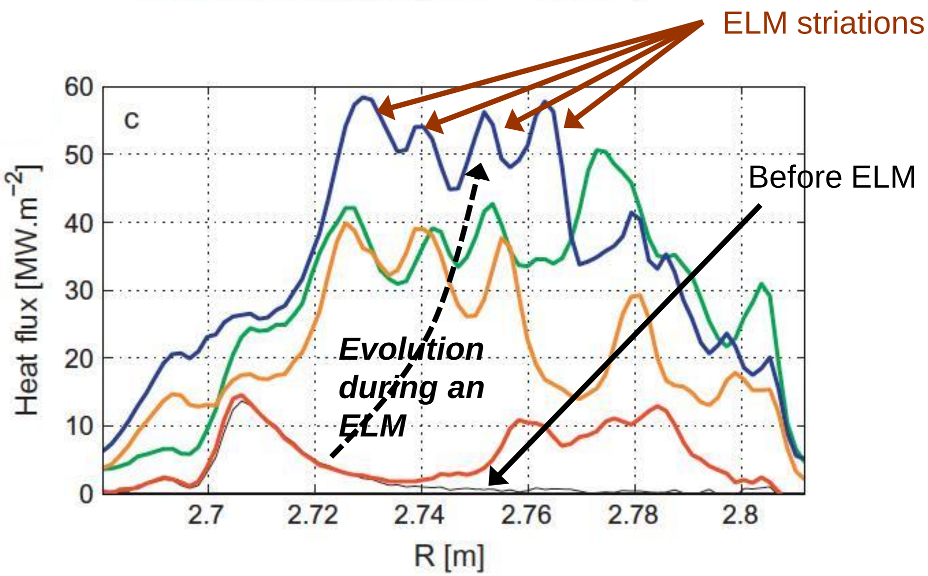
Example of ELM striations to broaden heat flux profile in JET



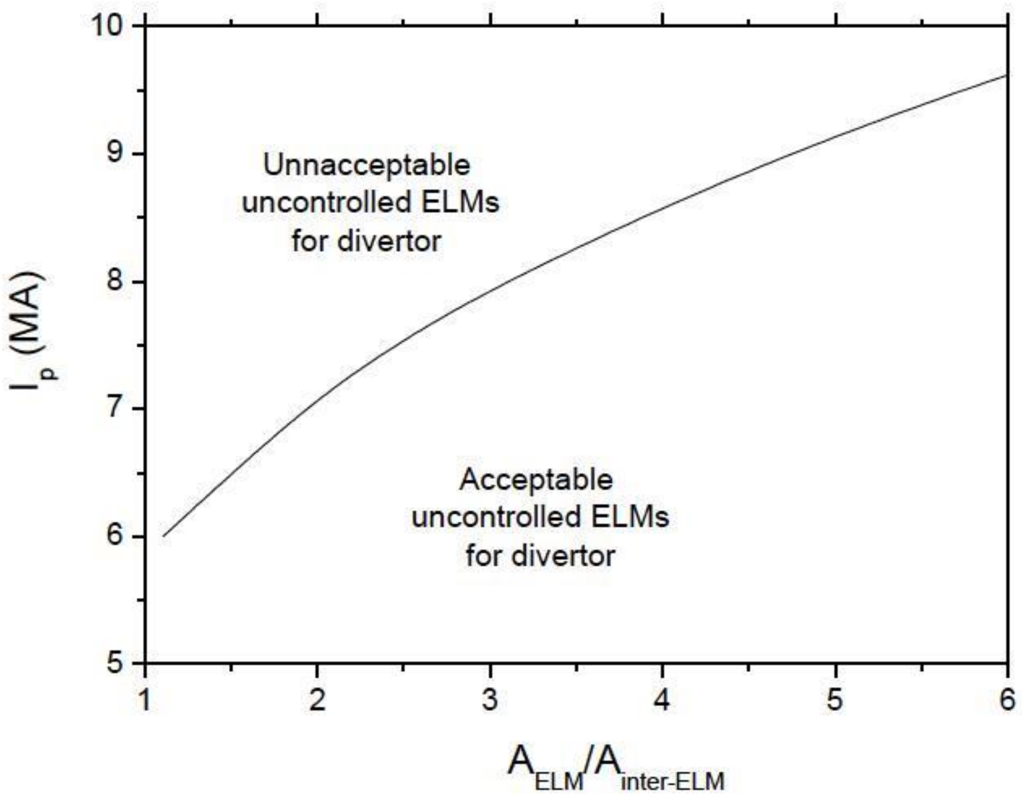


- Number of striations, i.e. ELM filaments, observed on the outer divertor target increases from 3 – 5 to 10 – 15 during the ELM rise time

- A_{wet} significantly increases compared to inter-ELM value, typically by factor 3-4

S. Devaux, JNM 2011

Acceptable ELMs for various I_p for ITER are predicted



A. Loarte, NF 2014

- A_{wet} increase by up to a factor of 6 has been observed in JET
- I_p is key parameter for pedestal pressure, therefore ELM energy loss
- Necessary A_{wet} increase for a range of I_p to avoid divertor damage by ELMs

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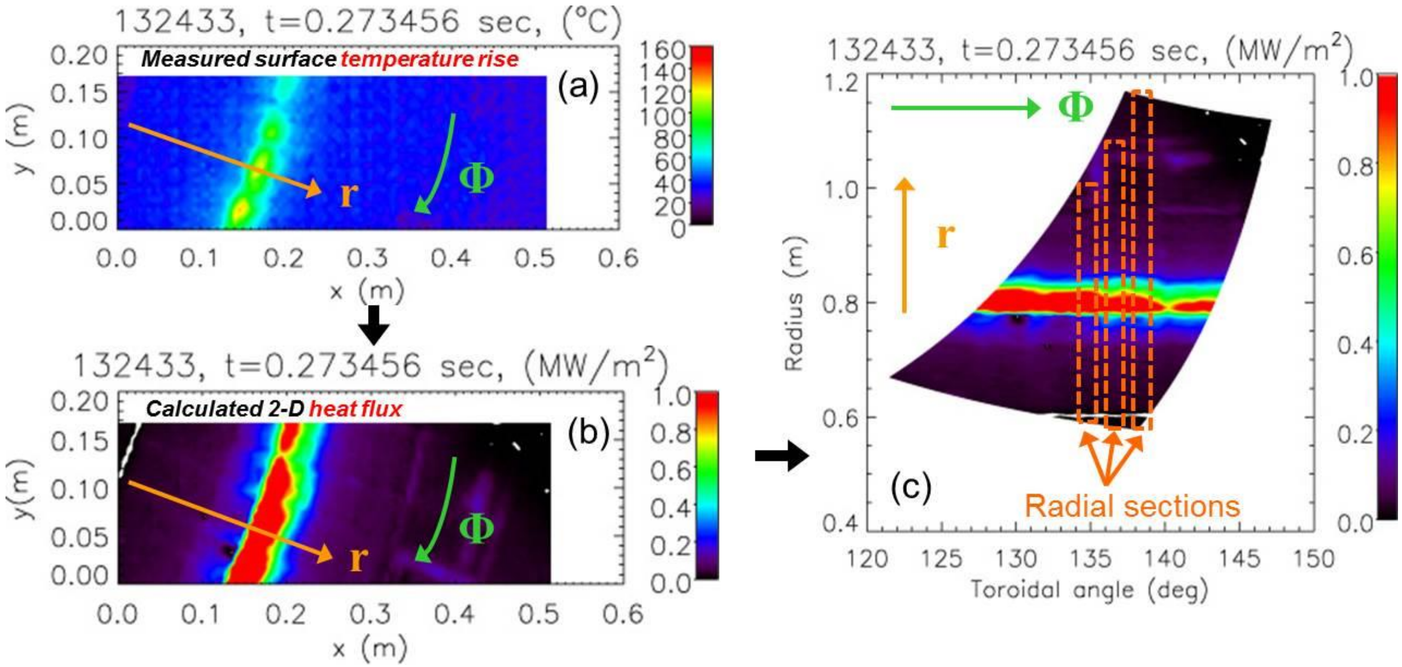
NSTX: multiple radial heat flux profiles are averaged for data analysis

Outer divertor in LSN



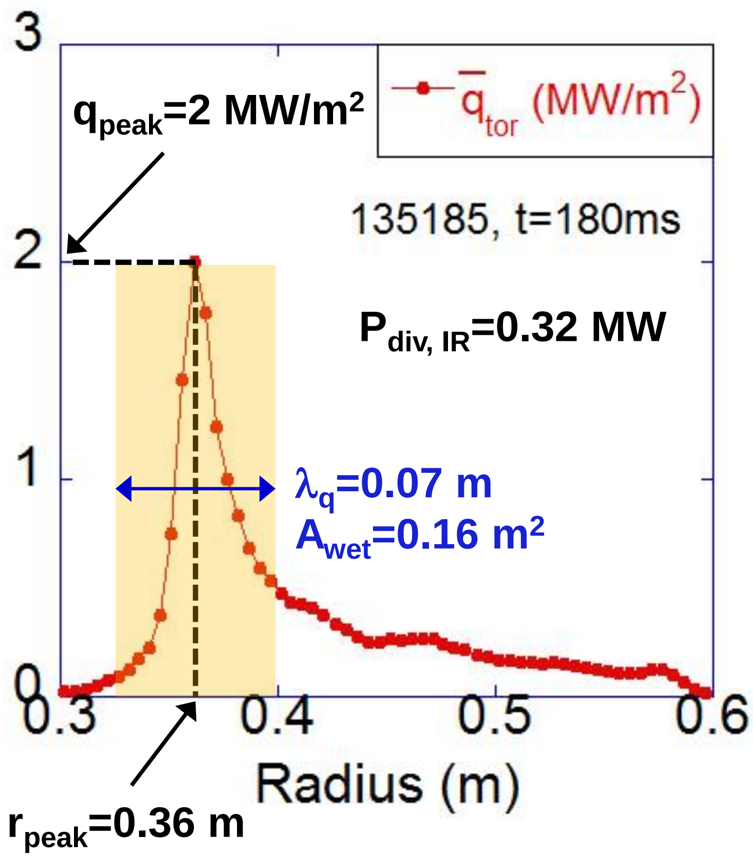
- 2-D surface temperature data from IR camera are used for heat flux calc.

- Heat flux data in (x, y) plane is re-mapped to the (r, Φ) plane and all radial heat flux profiles are combined to create an average profile

$$\bar{q}_{peak,tor} = \sum \left(q_{peak,rad} \right) / N_{rad} \qquad \bar{\lambda}_{q,tor} = \sum \left(\lambda_{q,rad} \right) / N_{rad}$$

Peak heat flux and heat flux width are determined by total power and wetted area

Average radial heat flux profile



- Total deposited power to divertor:

$$P_{div,IR} = \int 2\pi r \bar{q}_{tor}(r) dr$$

- Wetted area

$$A_{wet} = P_{div,IR} / \bar{q}_{peak,tor}$$

- Integral heat flux width

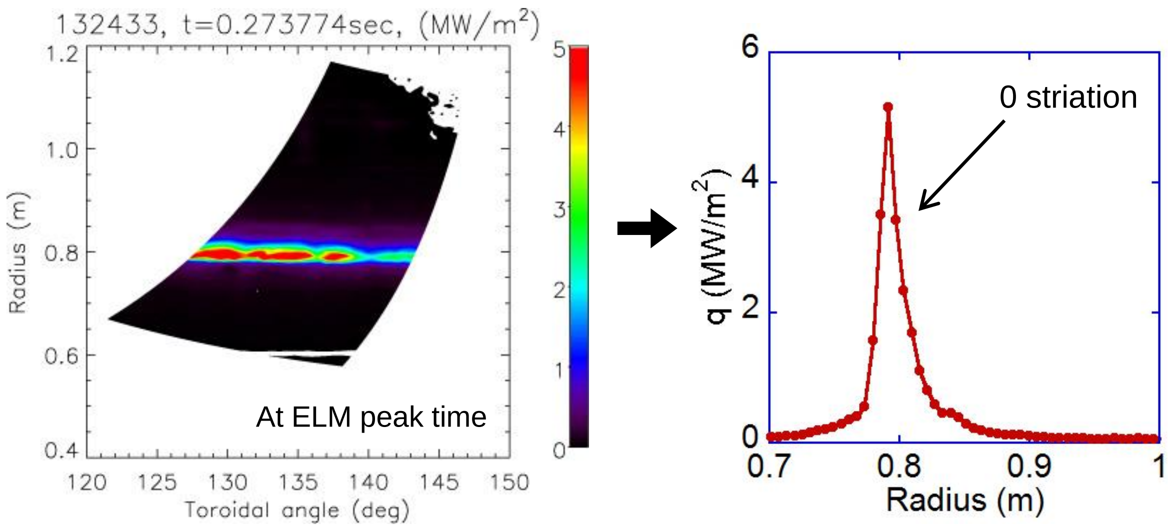
$$\bar{\lambda}^{\mathrm{int}}_{q,tor} = P_{div,IR} / 2\pi r_{peak} \bar{q}_{peak,tor}$$
$$= A_{wet} / 2\pi r_{peak}$$

- Total deposited energy to divertor

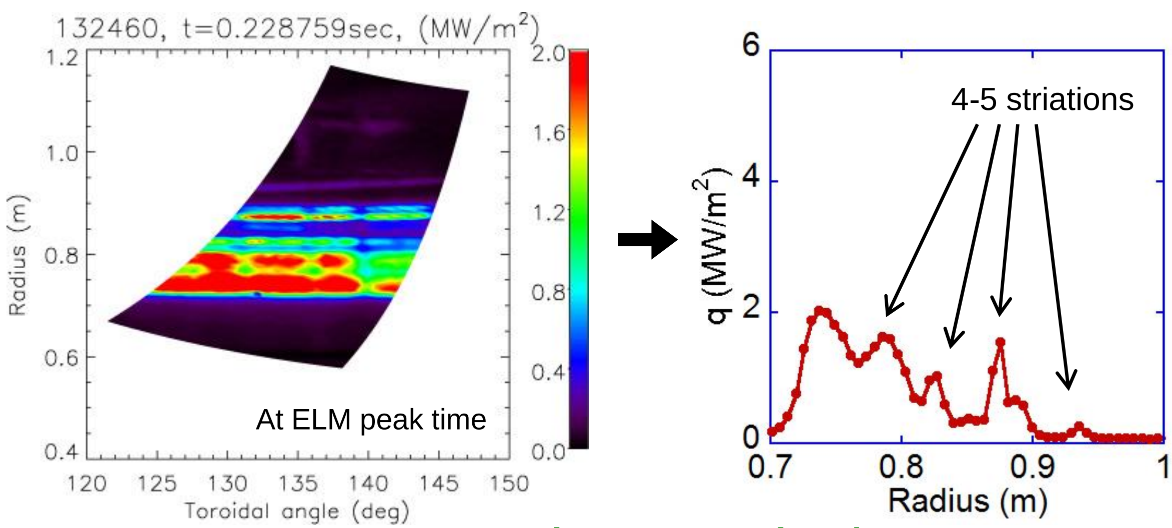
$$W_{div,IR} = \int P_{div,IR} dt$$

Temporal evolution and dependence on the ELM size of $P_{div,IR}$ and A_{wet}

Example of heat flux profiles with 0 and 4-5 ELM striations show opposite heat deposition pattern in NSTX



- An ELM with no striations leads to a very peaked heat flux profile with high (> 5MW/m^2) peak heat flux



- 4-5 ELM striations spread heat over a larger area, reducing the peak heat flux (~ 2MW/m^2)

J-W. Ahn, NF 2014 (Nov)

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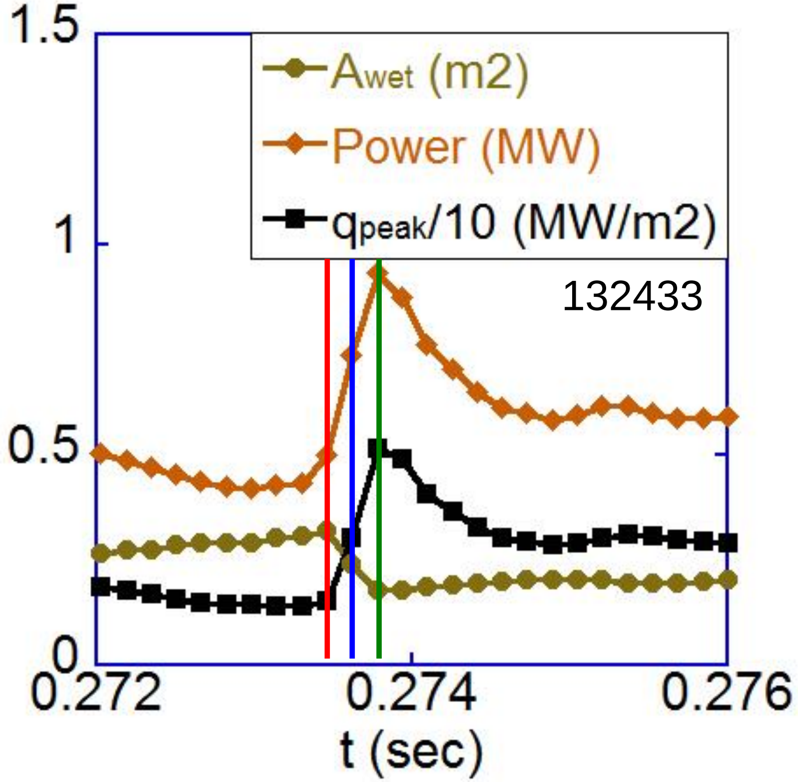
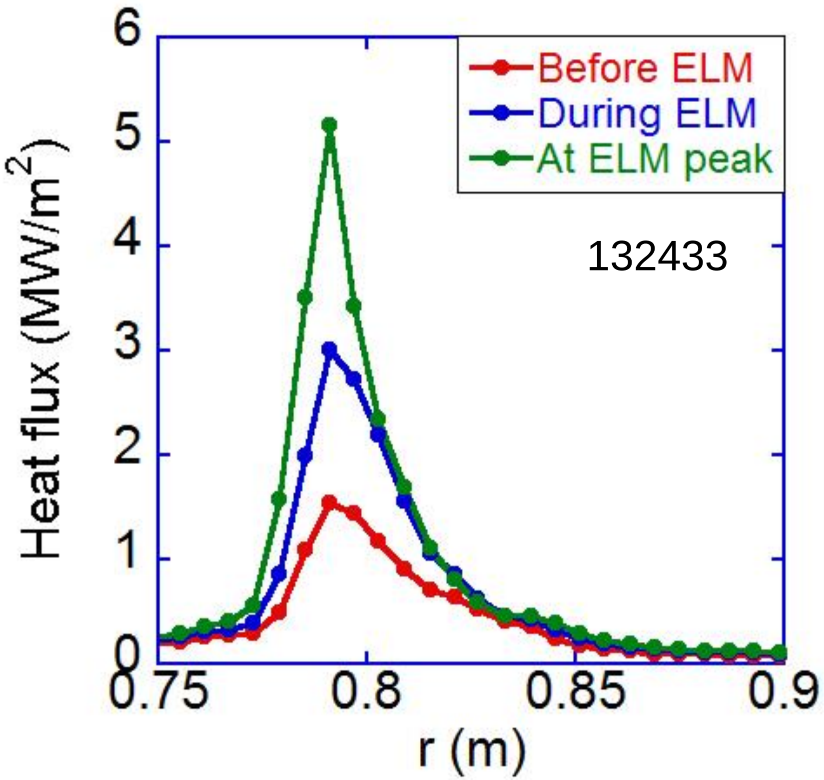
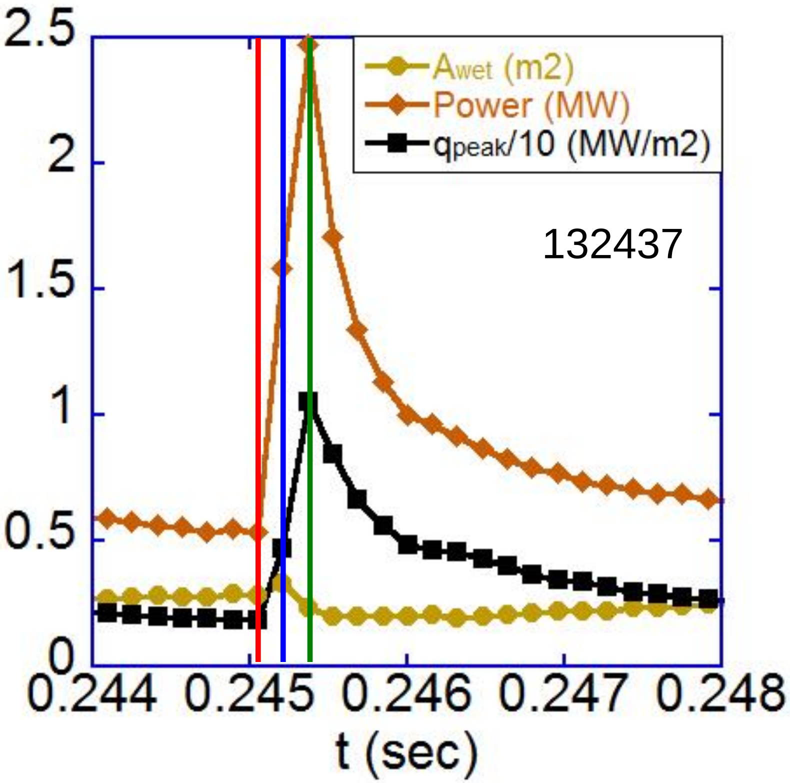
ELM heat flux profile with 0 striation – A_{wet} decreases most significantly

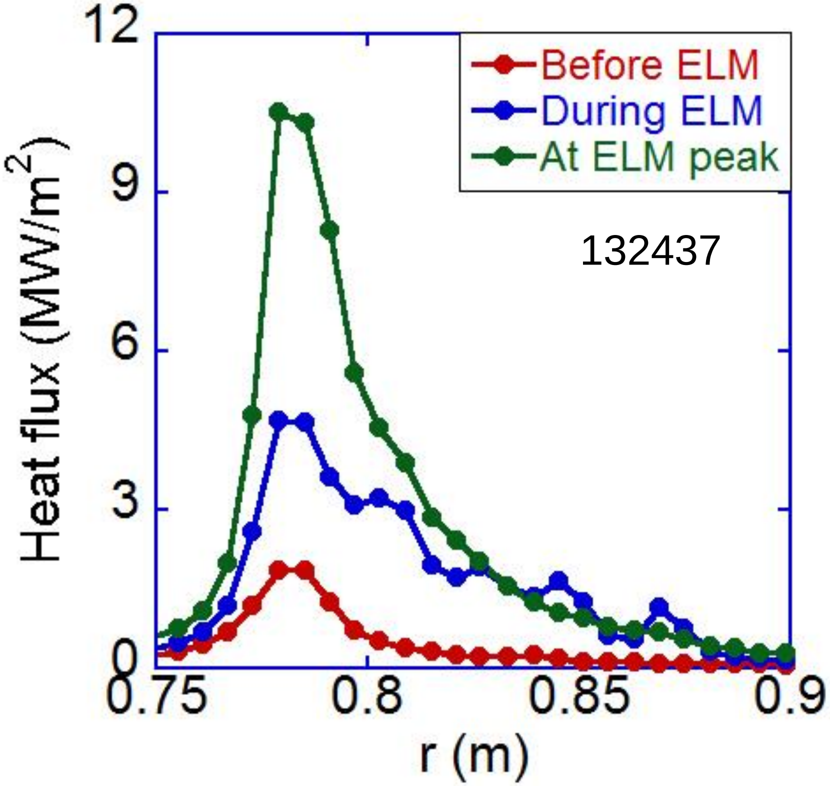




- No striation seen during the whole ELM rise time
- A_{wet} decrease is generally largest, up to ~40 – 50%
- q_{peak} keeps rising, A_{wet} continues to decrease during the ELM rise time

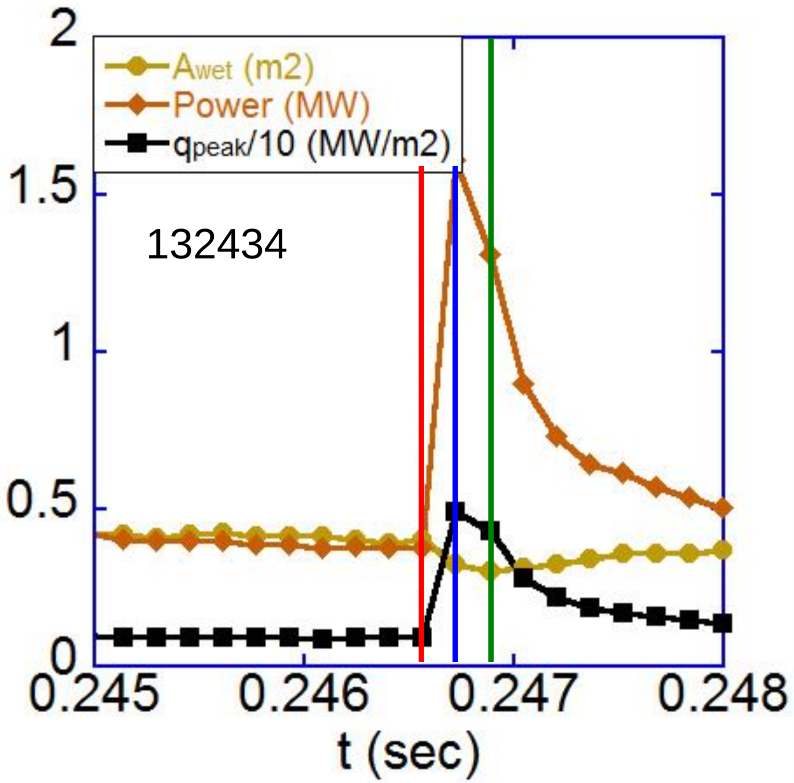
ELM heat flux profile with 3 striations – A_{wet} begins to rise

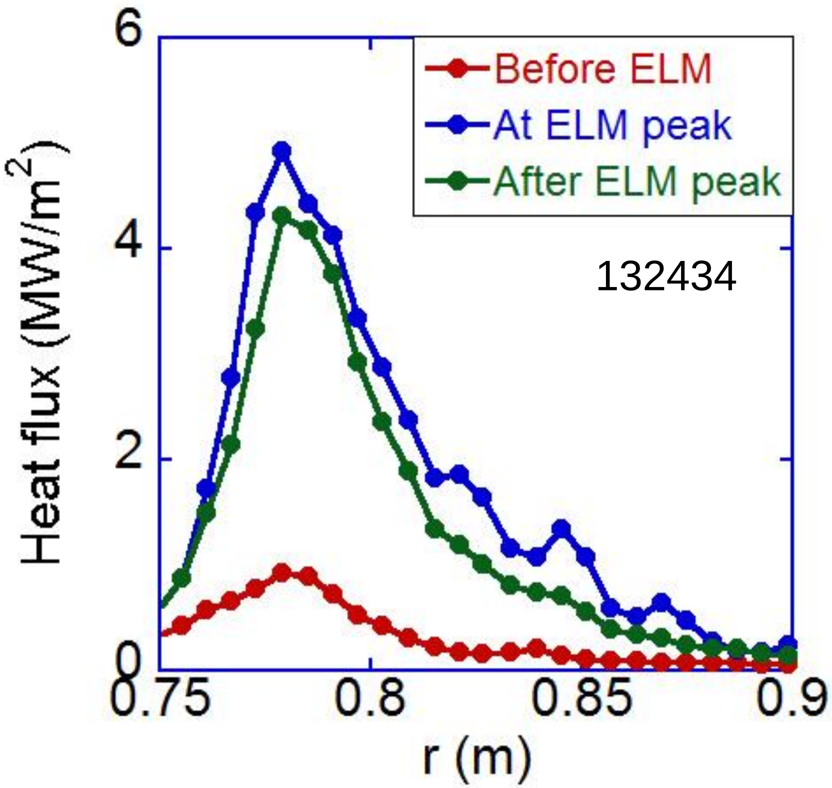




- 3 – 4 filaments slightly raises A_{wet} but at a later stage striations disappear and A_{wet} decreases while power goes up
- Generally, A_{wet} can either increase or decrease for 3 striations

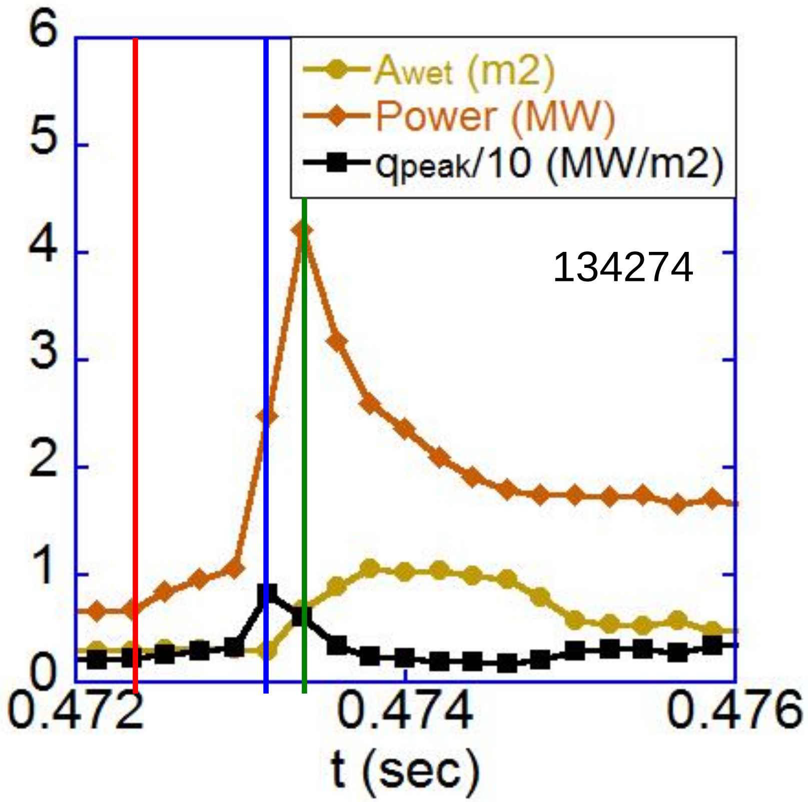
ELM heat flux profile with 3 striations that reduces A_{wet}

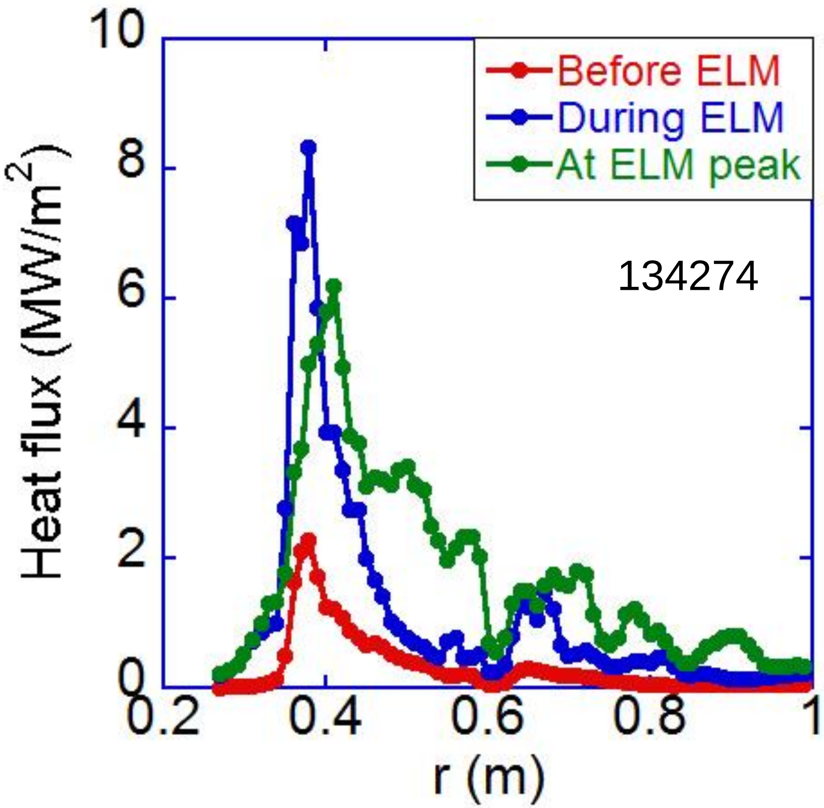




- Three filaments are observed but A_{wet} decreases in this case → q_{peak} remains rather constant after peak power deposition

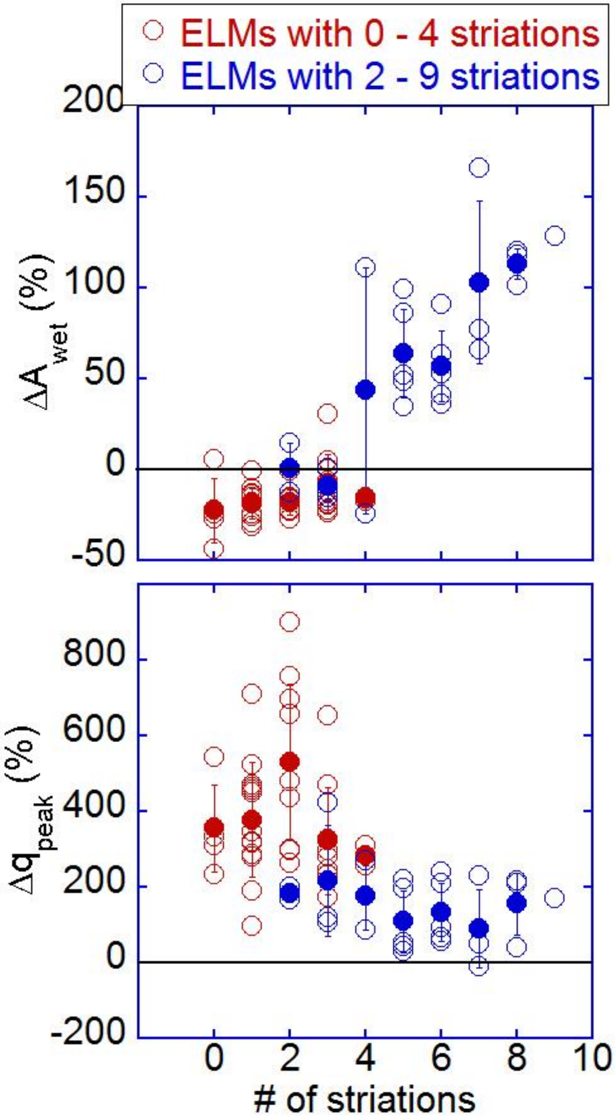
ELM heat flux profile with 9 – 10 striations – A_{wet} increases and q_{peak} decreases

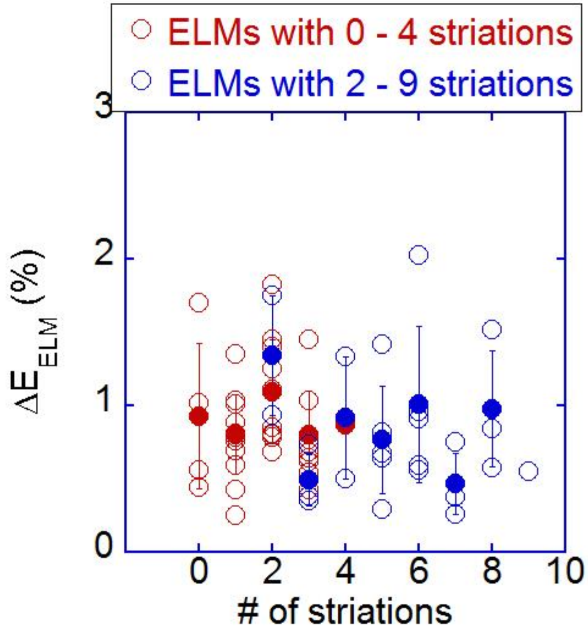




- Only a few striations in the far SOL at initial stage of ELM rise → A_{wet} slightly decreases and q_{peak} reaches its maximum
- Afterwards, 9 – 10 filaments appear and broaden the profile by a factor of ~2 → q_{peak} decreases even with rising ELM power

A_{wet} increases while ELM size remains constant and q_{peak} decreases with the number of observed striations



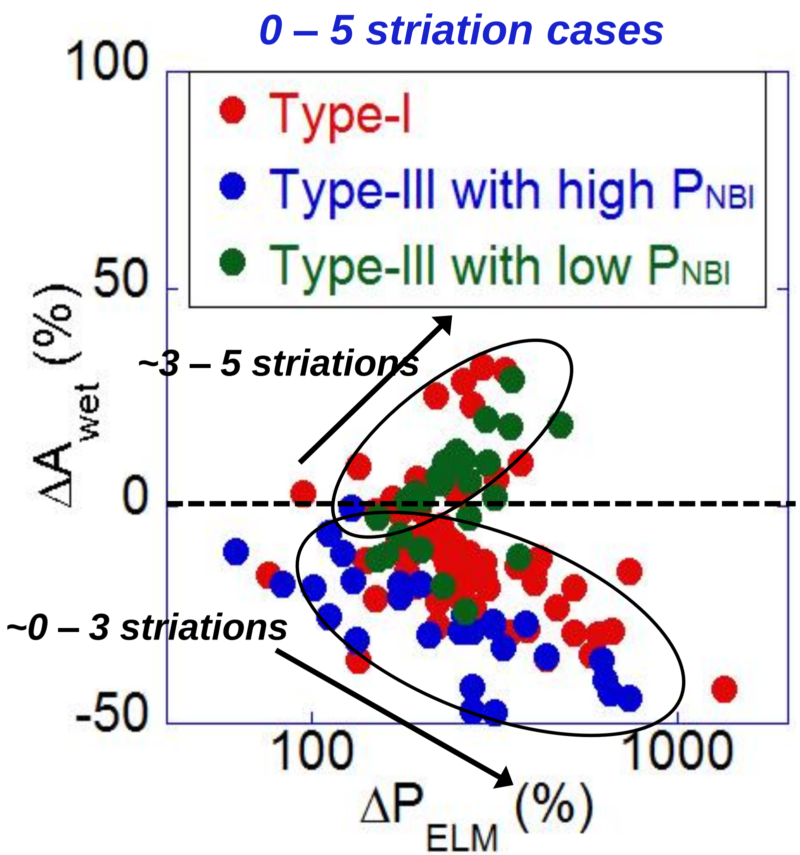


J-W. Ahn
NF 2014 (Nov)

- Two groups of ELM data
  - 0 – 4 striations for weaker shaping (κ~1.9, δ~0.5)
  - 2 – 9 striations for stronger shaping (κ~2.5, δ~0.75)

- A_{wet} increases with the # of striations but the ELM size (energy ejected by an ELM, measured by IR camera) is independent of the # of filaments → reduction of q_{peak}

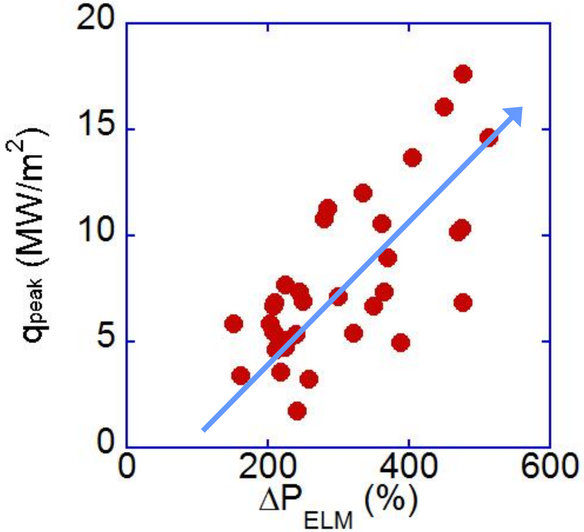
Dependence of A_{wet} on ELM size shows both favorable and unfavorable trends depending on filament numbers

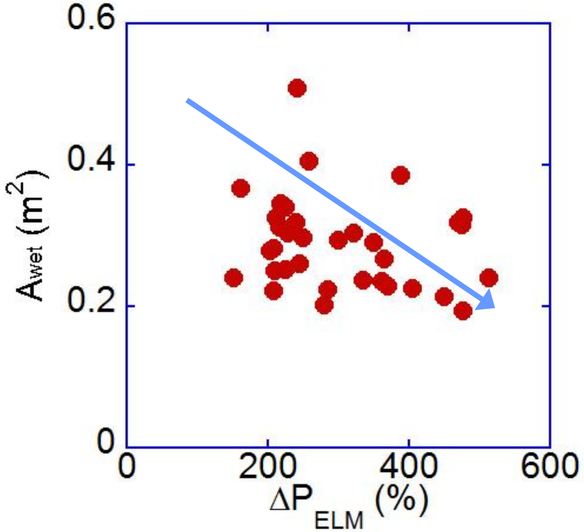


- Type-I and type-III ELMs show similar trend:
  - A_{wet} (therefore λ_q) decreases or increases during the ELM, depending on filament structures
  - The size of change becomes bigger with the size of ELM power → A_{wet} decrease or increase becomes larger for larger ELMs
- Larger ELM size gives bigger impact on expansion and contraction of A_{wet}

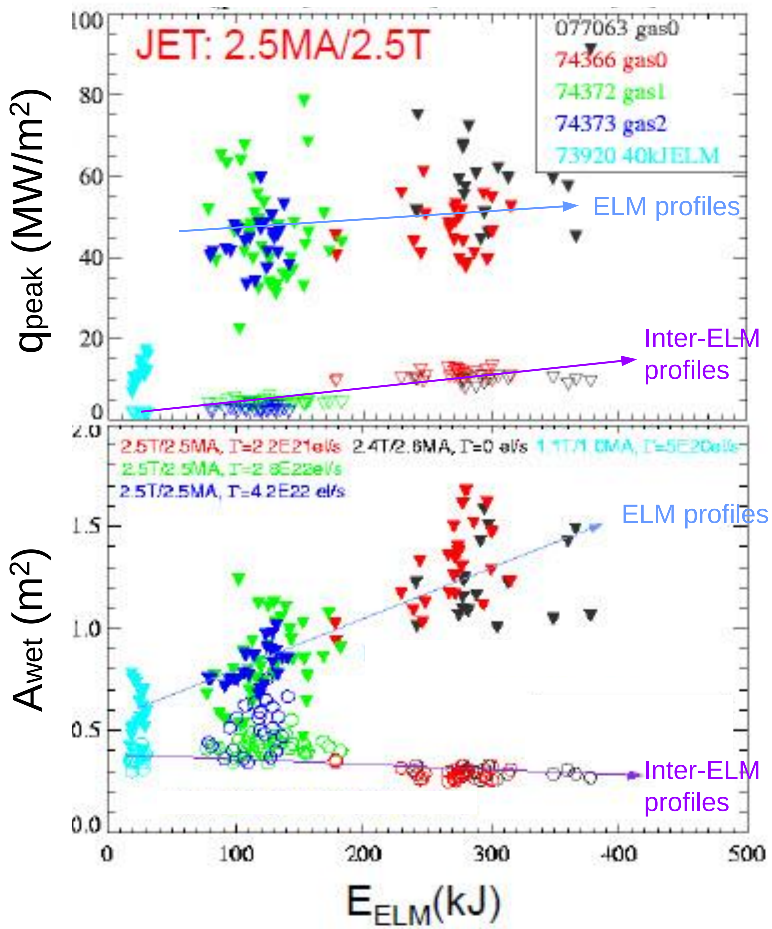
NSTX ELMs with 0 – 4 striations: A_{wet} decrease leads to q_{peak} increase with increasing ELM size for type-I ELMs

NSTX, type-I





JET, type-I

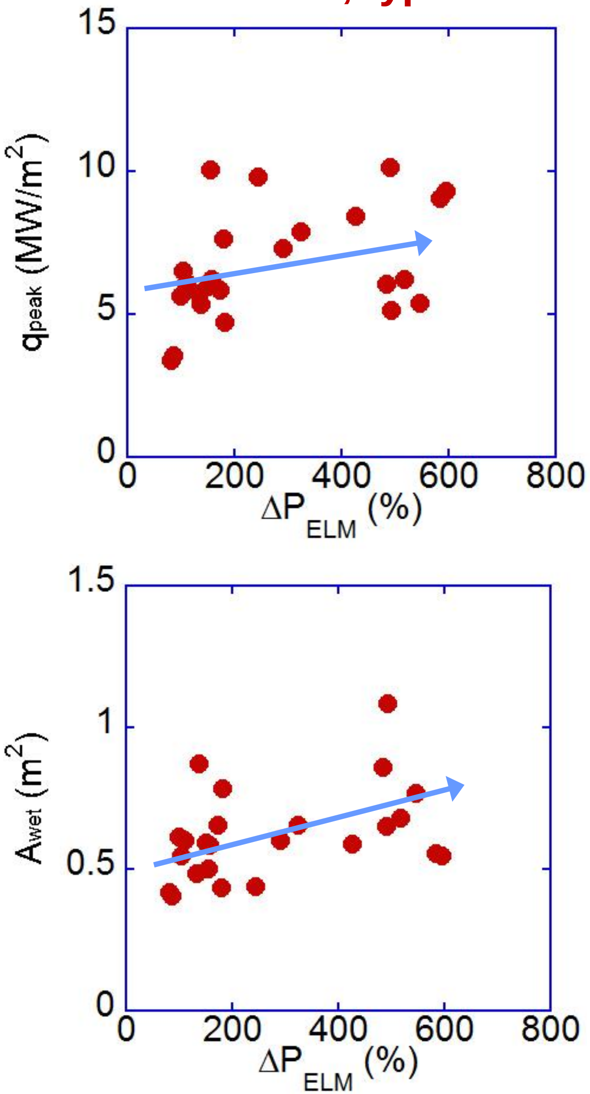


T. Eich, JNM 2011

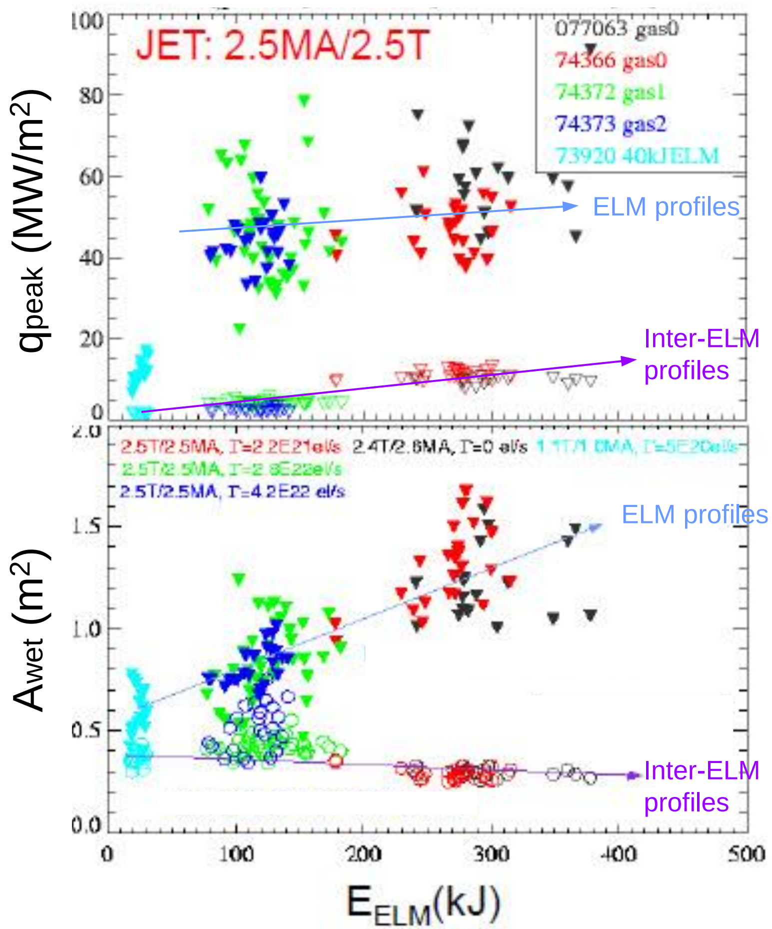
- NSTX: A_{wet} decreases with ELM power → q_{peak} increases
- JET : A_{wet} increases with ELM energy loss → q_{peak} constant

NSTX ELMs with 2 – 9 striations: A_{wet} increases and q_{peak} slightly rises with increasing ELM size for type-I ELMs

NSTX, type-I



JET, type-I



T. Eich, JNM 2011

- Moderate increase of A_{wet} leads to slight increase or constant q_{peak}.
- This trend is similar to the observation at JET and is more favorable

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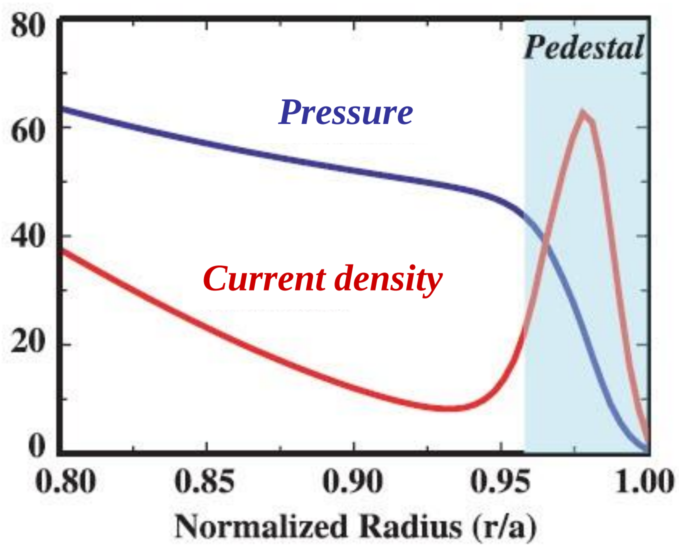
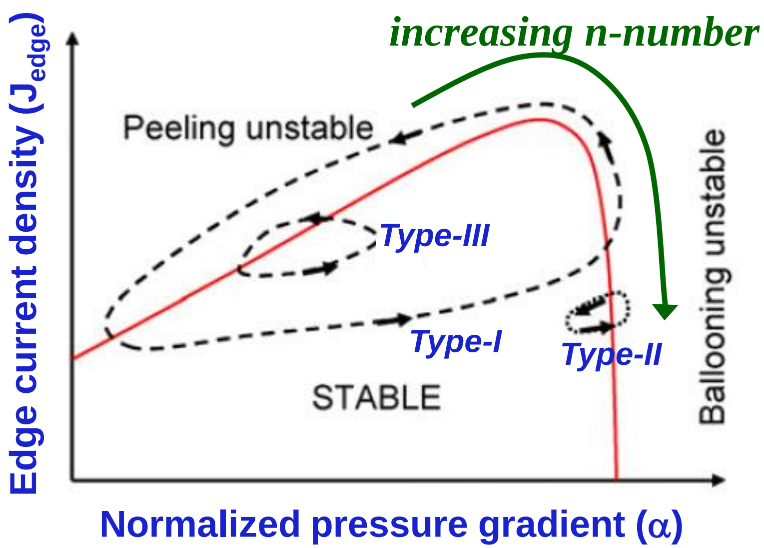
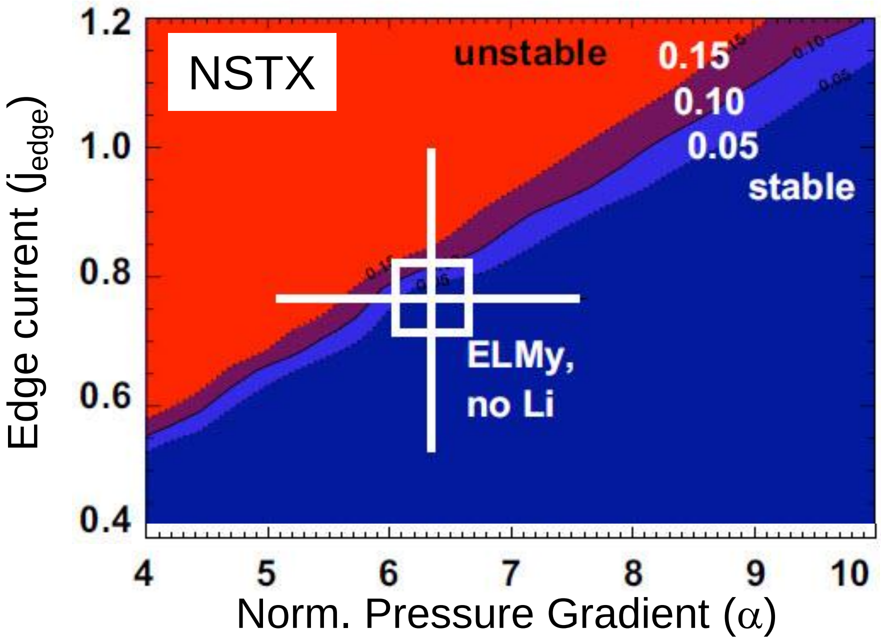
ELMs can be explained by ideal MHD stability theory, with different toroidal mode number for different regime



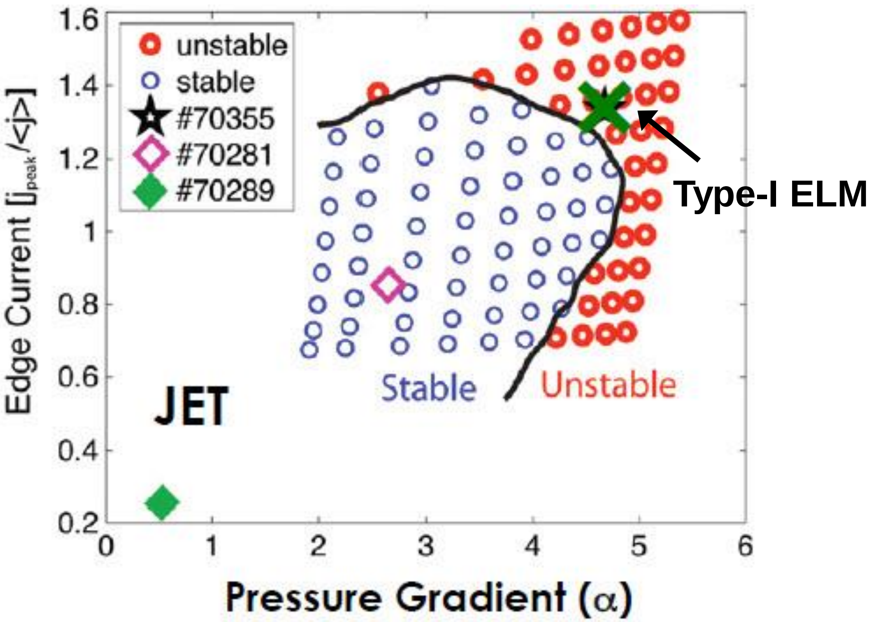


- Several types of ELMs are envisioned in the framework of ideal MHD theory
  - Edge (pedestal) current density (J_{edge})
    → Peeling instability
  - Pressure gradient (p'_{edge})
    → Ballooning instability
  - Bootstrap current (J_{bs}) links J_{edge} and p'_{edge}
- Toroidal mode number (n) increases from peeling to the ballooning side

NSTX type-I ELMs are against kink/peeling boundary with lower toroidal mode number n



R. Maingi (PRL 2009), D.P. Boyle (PPCF 2011)

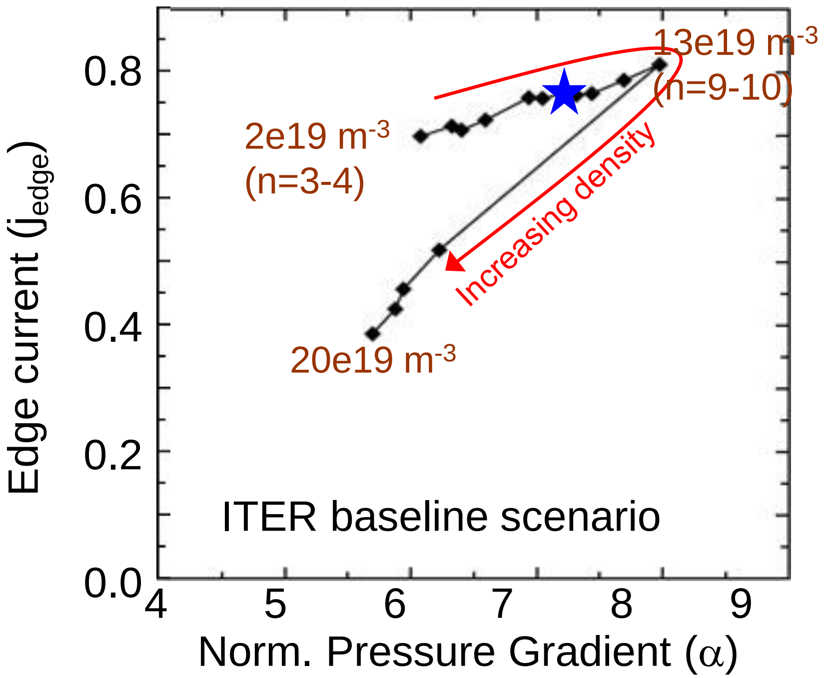


S. Saarelma (PPCF 2009)

- ELMs in many tokamaks have peeling-ballooning nature (n=10 – 20)
- Stability analysis shows NSTX is most unstable for low n numbers (n=1 – 5)
- ELITE calculation: NSTX ELMs are on the peeling side → low n-number is consistent with smaller number of ELM filaments in heat flux profile

EPED model predicts ITER ELMs to be against peeling boundary with low n-number like in NSTX

EPED modeling as a function of $n_{e,ped}$



P.B. Snyder, NF 2011

- Stability analysis shows that ITER pedestal will be against current-driven kink/peeling modes due to low collisionality and shaping
- Predicted n~3 – 10, closer to NSTX → ELM profile broadening might not be as effective as in JET

Important to better determine where ITER will sit on stability regime to estimate n-number, plus need some non-linear ELM calculations for the evolution of filament numbers

Conclusions

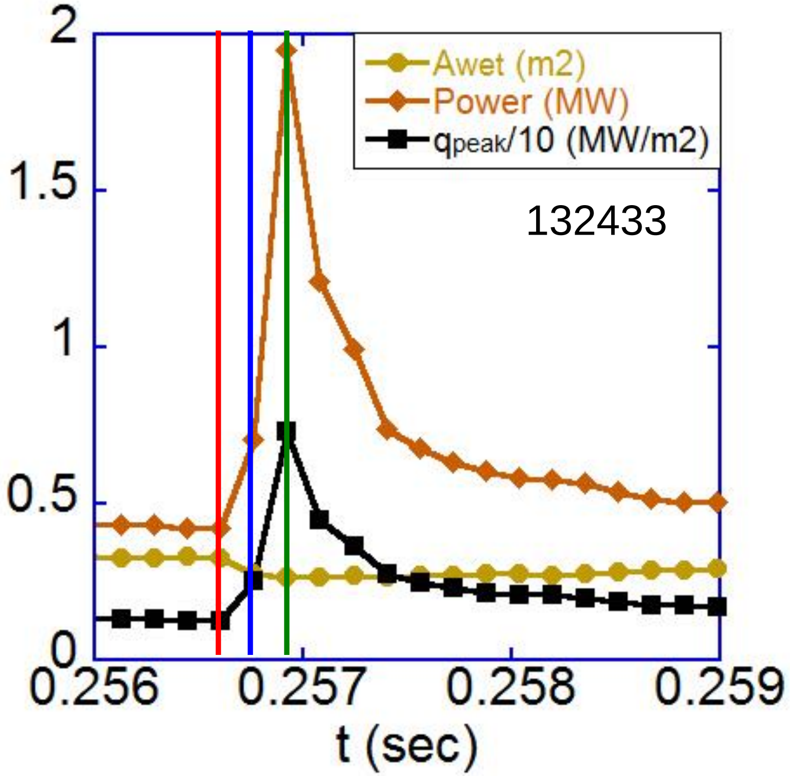
- ELM filament structure determines A_{wet} change and the # of striations can be used as a good metric; low # (0 – 3) generally reduces A_{wet} and higher # (> 3) increases it

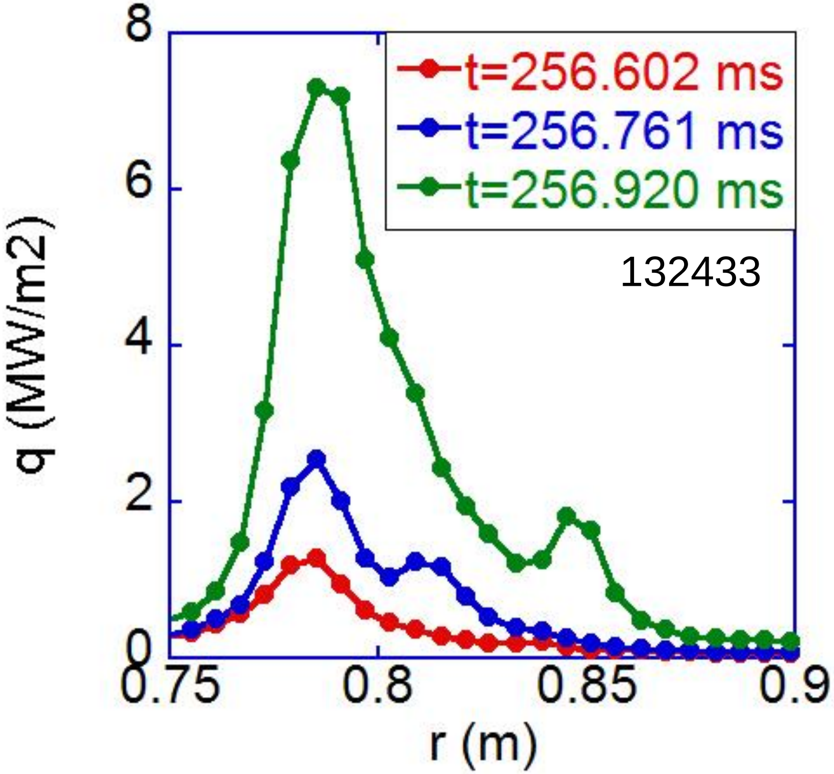
- For ELMs with low mode number, A_{wet} decrease leads to q_{peak} increase with increasing ELM size. For higher mode number, A_{wet} slightly increases and q_{peak} remains rather constant.

- ITER ELMs are predicted to have peeling nature, therefore low n ELMs could produce unfavorable trend → Need detailed study of stability analysis and the requirements for ELM mitigation

Back-up Slides

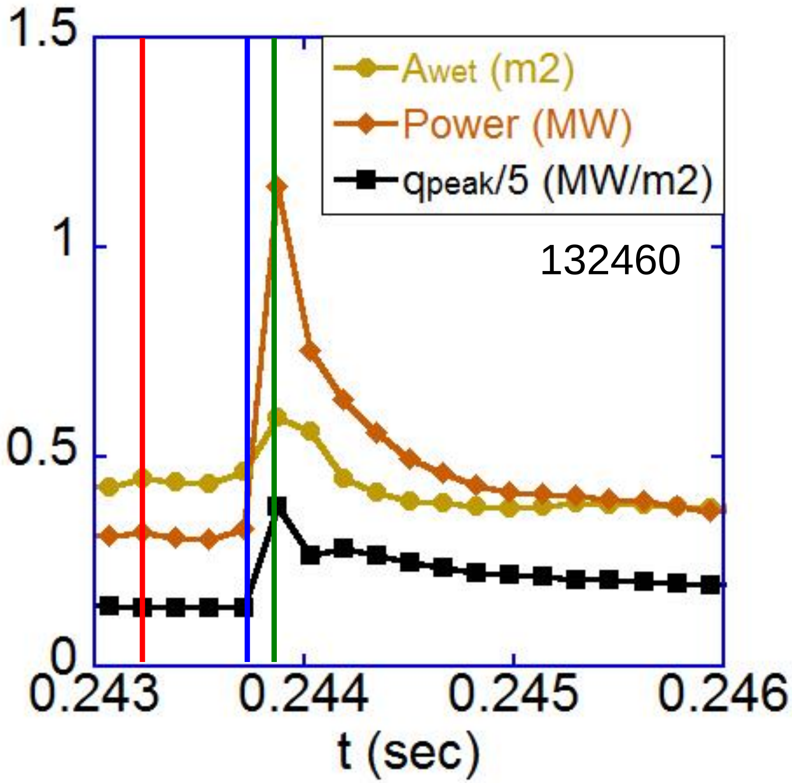
ELM heat flux profile with 1 striation - A_{wet} decreases most of the time

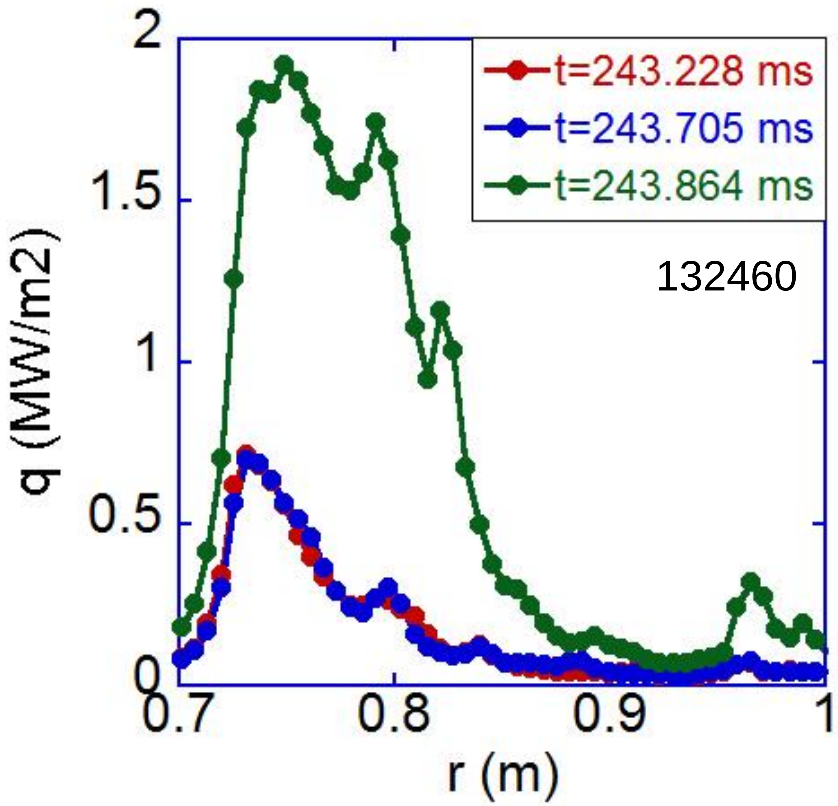




- A clear filament appears during the ELM rise time but it is not enough to keep A_{wet} from decreasing
- Heat flux also keeps going up while ELM power goes up

ELM heat flux profile with 5 striations to increase A_{wet}





- Filaments clearly increases A_{wet} and this keeps q_{peak} increase rather modest even with rapid power increase