NSTX-U

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Impact of ELM filaments on divertor heat flux dynamics in NSTX and its implication for ITER

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J-W Ahn[1] OAK RIDGE National Laboratory

K.F. Gan[2], R. Maingi[3], T.K. Gray[1], A.G. McLean[4],J.M. Canik[1], J.D. Lore[1], V.A. Soukhanovskii[4], and the NSTX Research Team

[1]ORNL, [2]ASIPP, [3]PPPL, [4]LLNL

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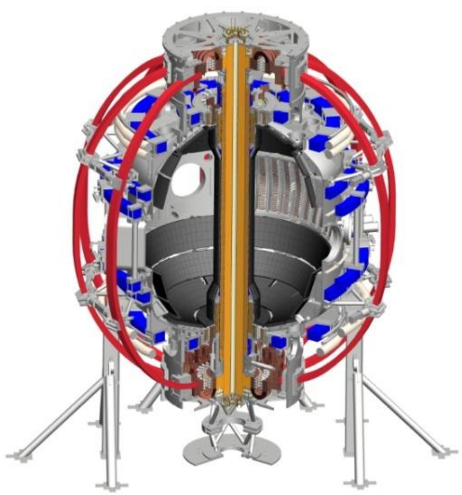

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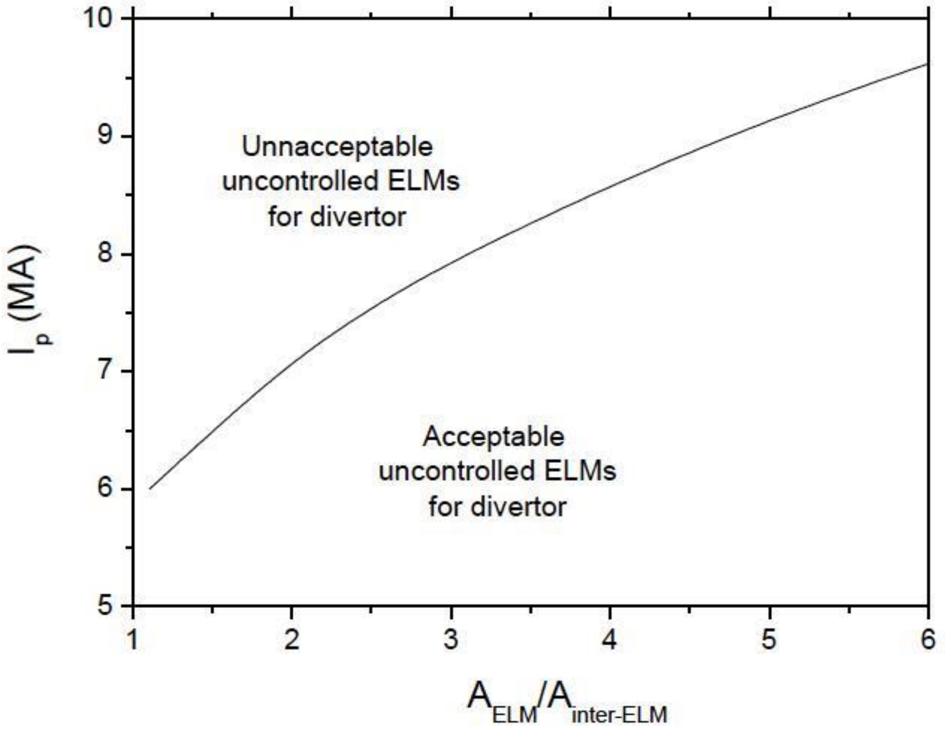
Motivation

- ELM heat flux profile characterization is important for ITER to determine requirement of ELM control system performance
- Relationship of wetted area (A_{wet}) and ELM size directly impacts peak heat flux (q_{peak})
- Larger A_{wet} allows larger total ELM energy loss (ΔW_{ELM}) to be acceptable, however uncertainty in A_{wet} remains unresolved yet
- Present prediction for ITER is based on JET/AUG data that shows rather constant q_{peak}, irrespective of ELM size, due to increased A_{wet}

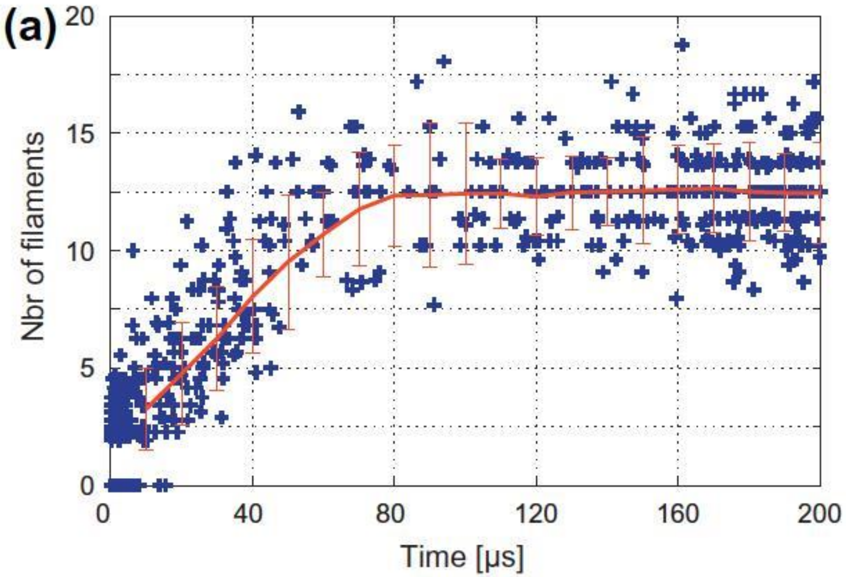
Acceptable ELMs for various I_p for ITER are predicted

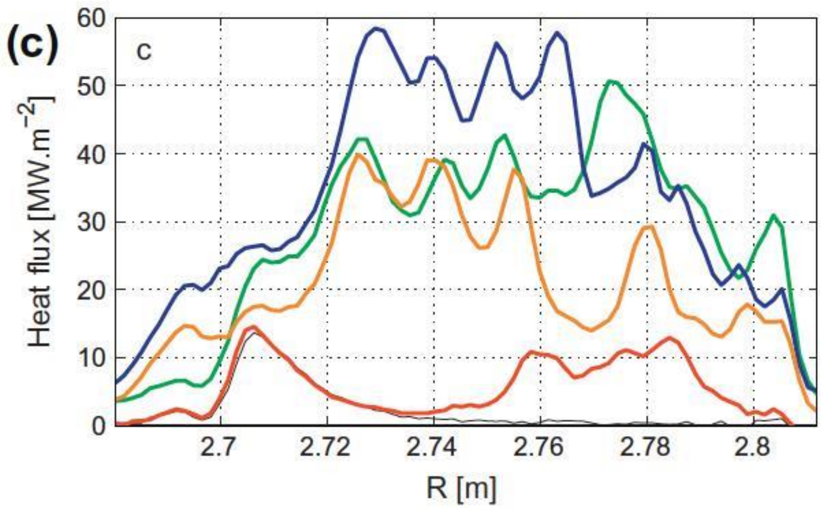


Loarte, NF 2014

- A_{wet} increase by up to a factor of 6 has been observed in JET and ASDEX-U
- I_p is key parameter for pedestal pressure, therefore ELM energy loss

JET: many filaments during the ELM broadens heat flux profile and raise A_{wet}



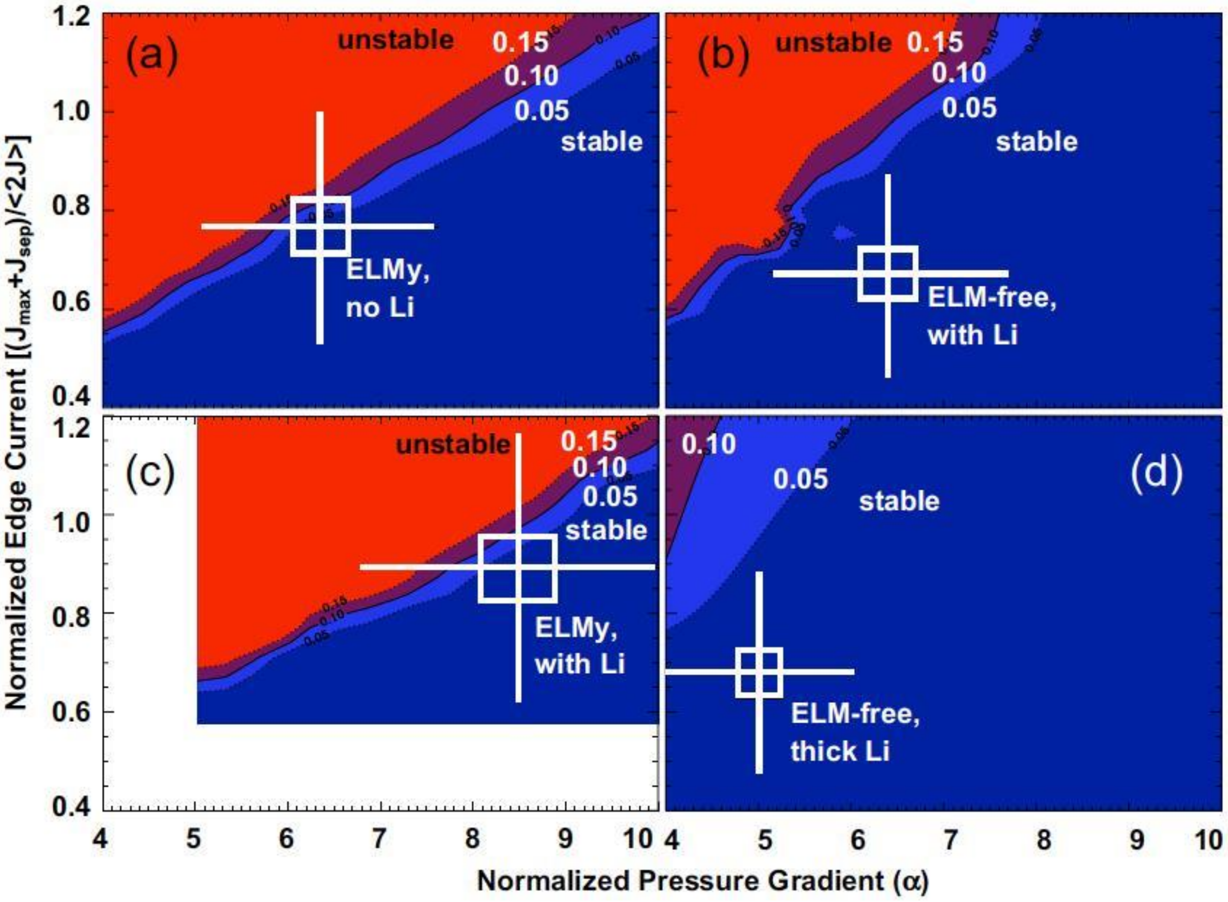


- Number of striations, i.e. ELM filaments, observed on the outer divertor target increase from 3 – 5 to 10 – 15 during the ELM rise time

- A_{wet} significantly increases compared to inter-ELM value

Devaux, JNM 2011

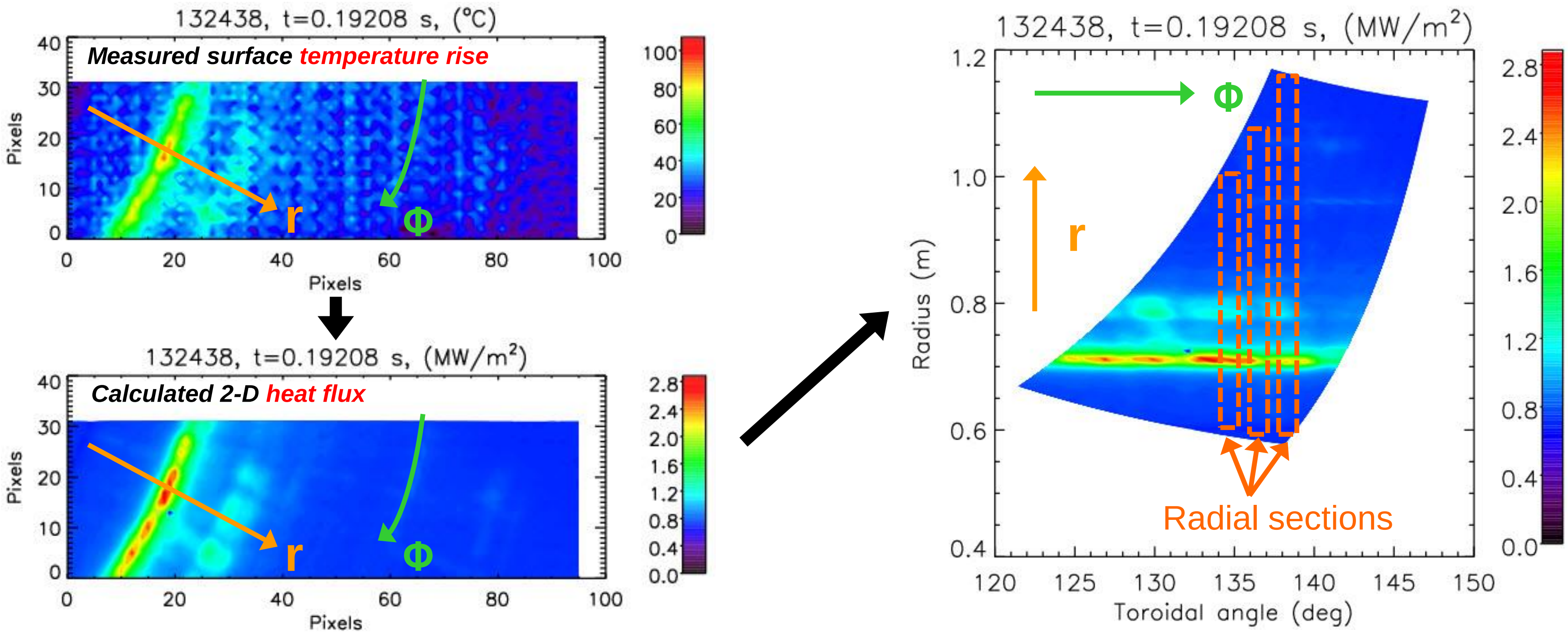
NSTX ELMs are against king/peeling boundary with lower toroidal mode number n



Boyle, PPCF 2011

- ELMs in other tokamaks have peeling-ballooning nature, i.e. n=10 - 20
- Stability analysis shows NSTX is most unstable for low n numbers (n=3 – 5)
- ELITE shows NSTX ELMs are on peeling side

Multiple radial heat flux profiles are averaged for data analysis

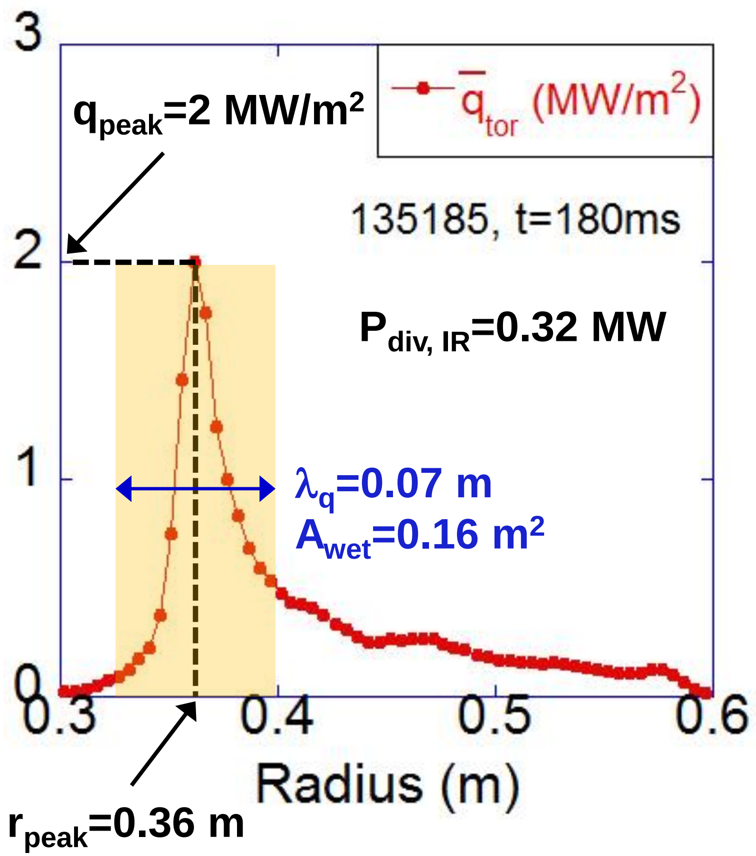


- 2-D surface temperature data from IR camera are used for heat flux calc.
- Heat flux data in (x, y) plane is re-mapped to the (r, Φ) plane and all radial heat flux profiles are combined to create an average profile

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

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:

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

- Wetted area

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

- Integral heat flux width

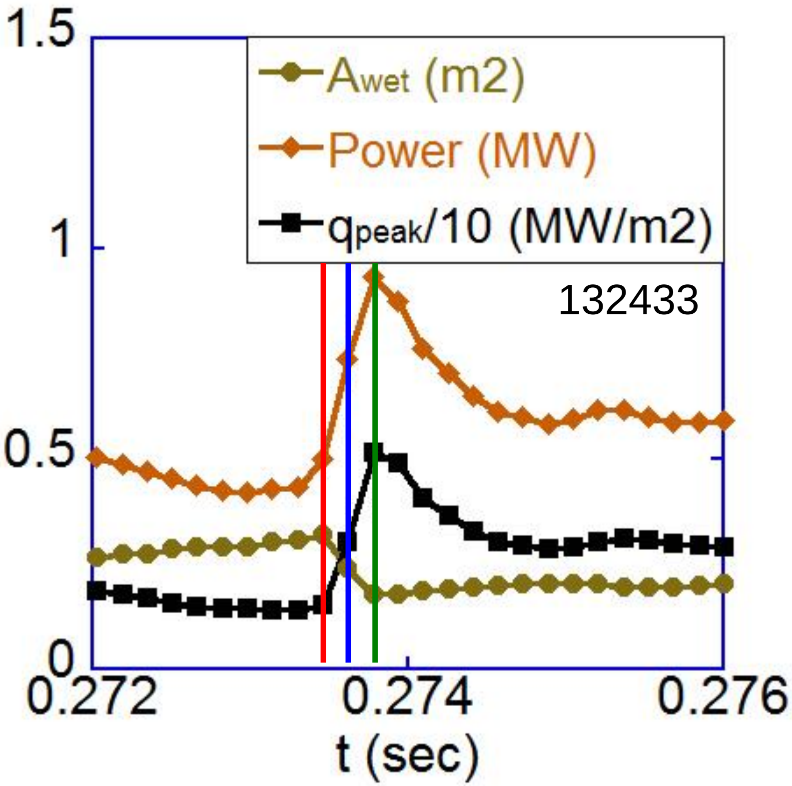
$$\overline{\lambda}^{int}_{q,tor} = P_{div,IR} / 2\pi r_{peak} \overline{q}_{peak,tor}$$
$$= A_{wet} / 2\pi r_{peak}$$

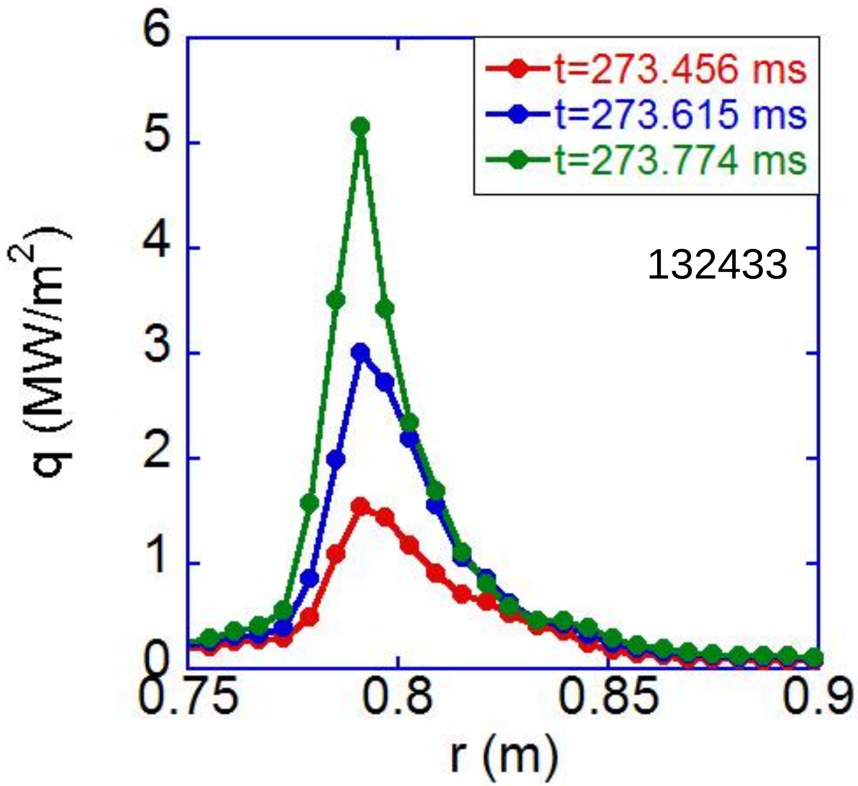
- Total deposited energy to divertor

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

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

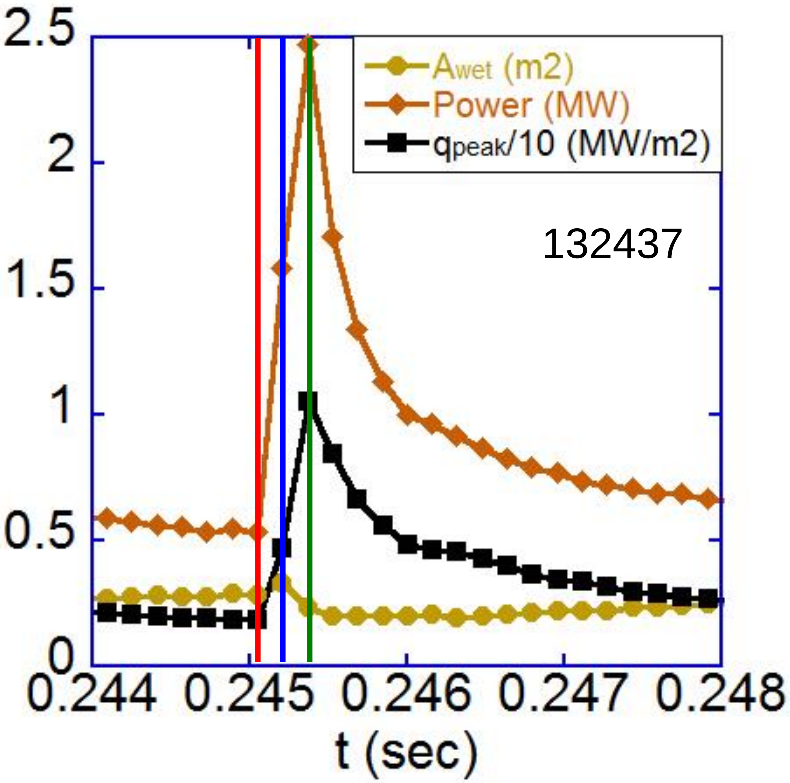
ELM heat flux profile with no striation – A_{wet} decreases most significantly

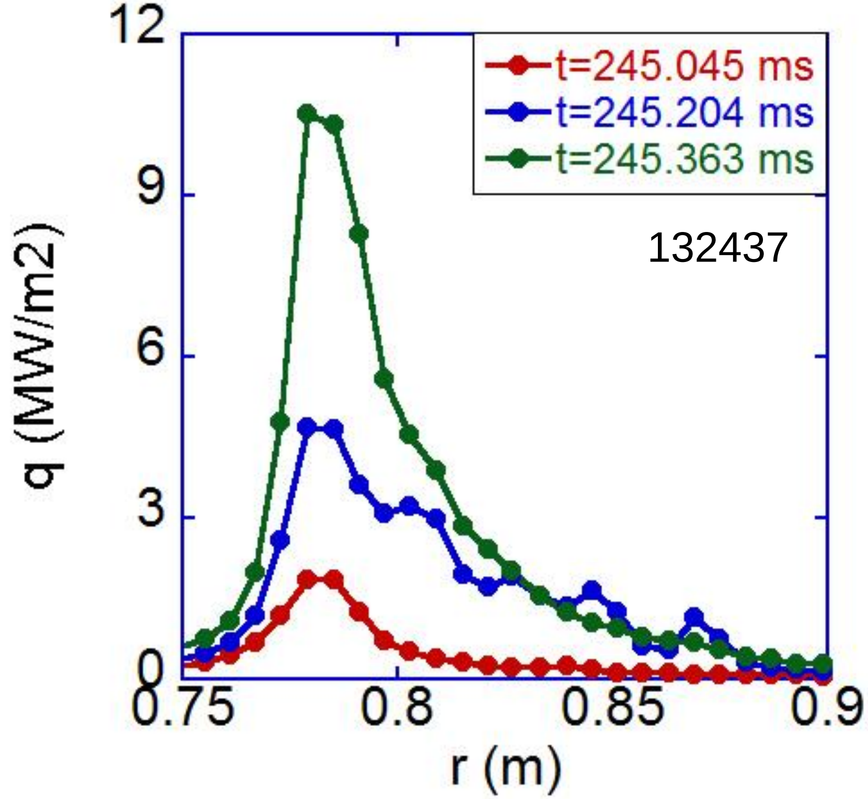




- No striation seen during the whole ELM rise time
- A_{wet} decrease is generally largest, up to ~40 – 50%
- q_{peak} keeps rising, A_{wet} continues to decrease during the ELM rise time

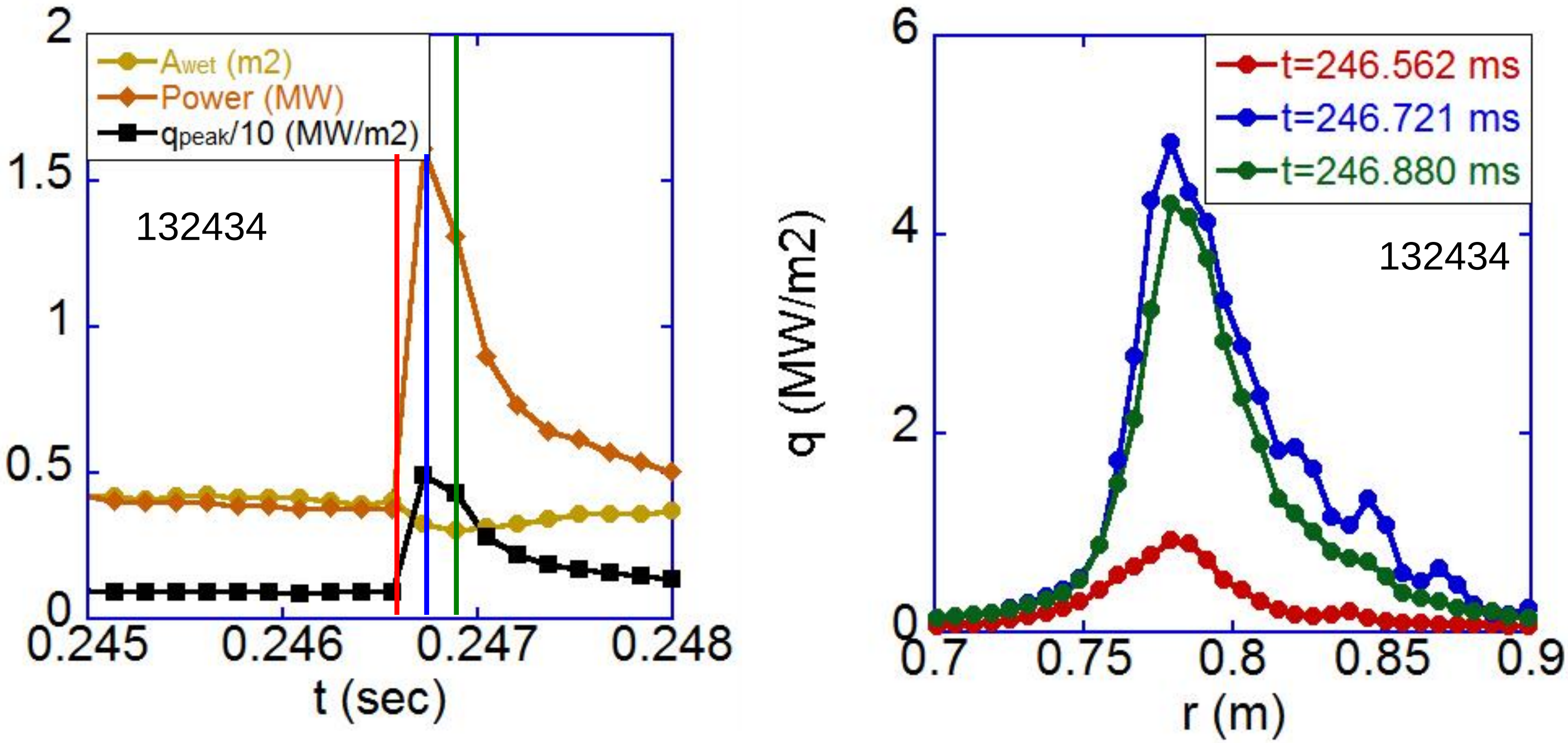
ELM heat flux profile with three striations – A_{wet} begins to rise





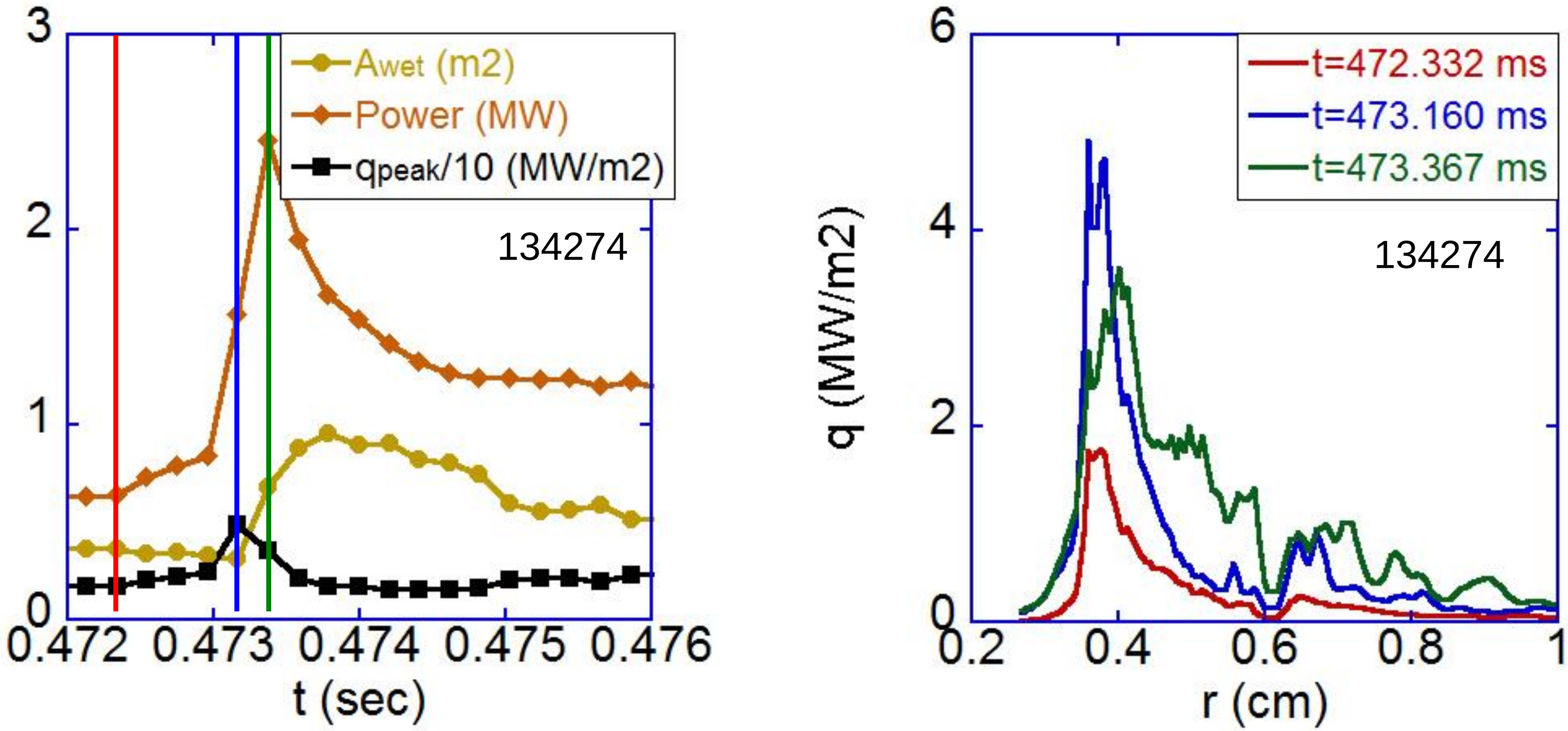
- 3 – 4 filaments slightly raises A_{wet} but at a later stage filaments disappear and A_{wet} decreases while power goes up
- This results in rapid q_{peak} increase

ELM heat flux profile with three 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

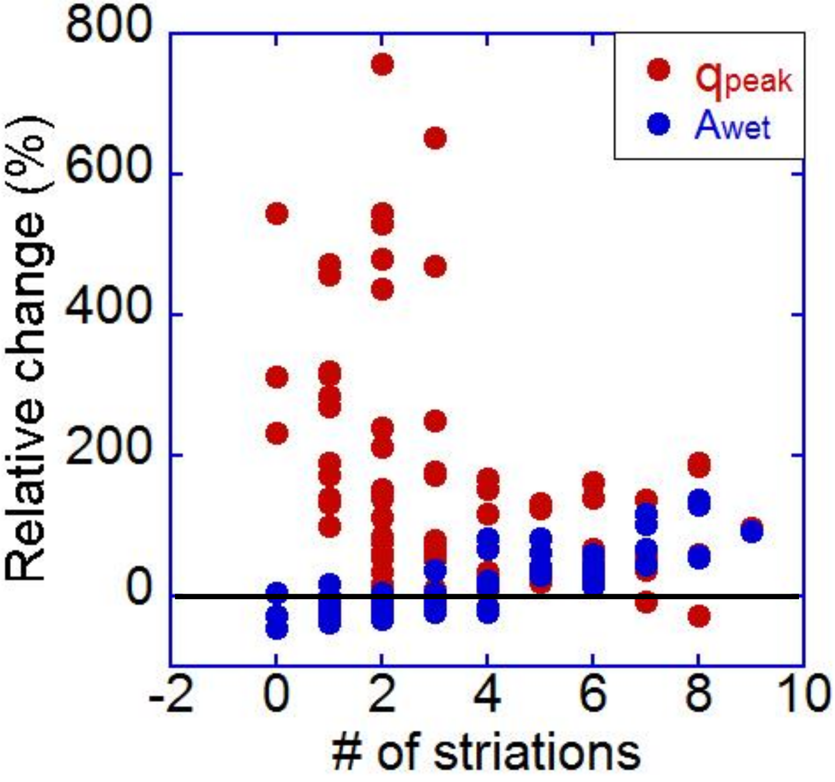
ELM heat flux profile with ten striations



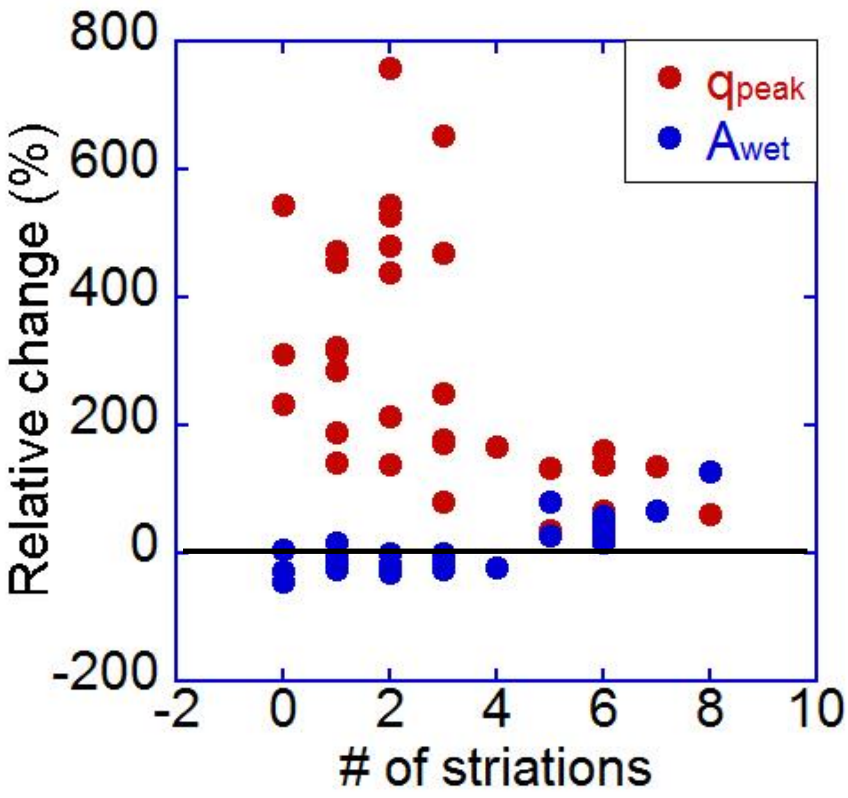
- Only 2- 3 filaments at initial stage of ELM rise time → A_{wet} slightly decreases and q_{peak} reaches its maximum
- Afterwards, 9 – 10 filaments appear and broaden the profile by a factor of ~2 → q_{peak} decreases even with rising ELM power

A_{wet} increases with the number of observed striations but q_{peak} decrease not obvious for n~4 and higher

During the ELM

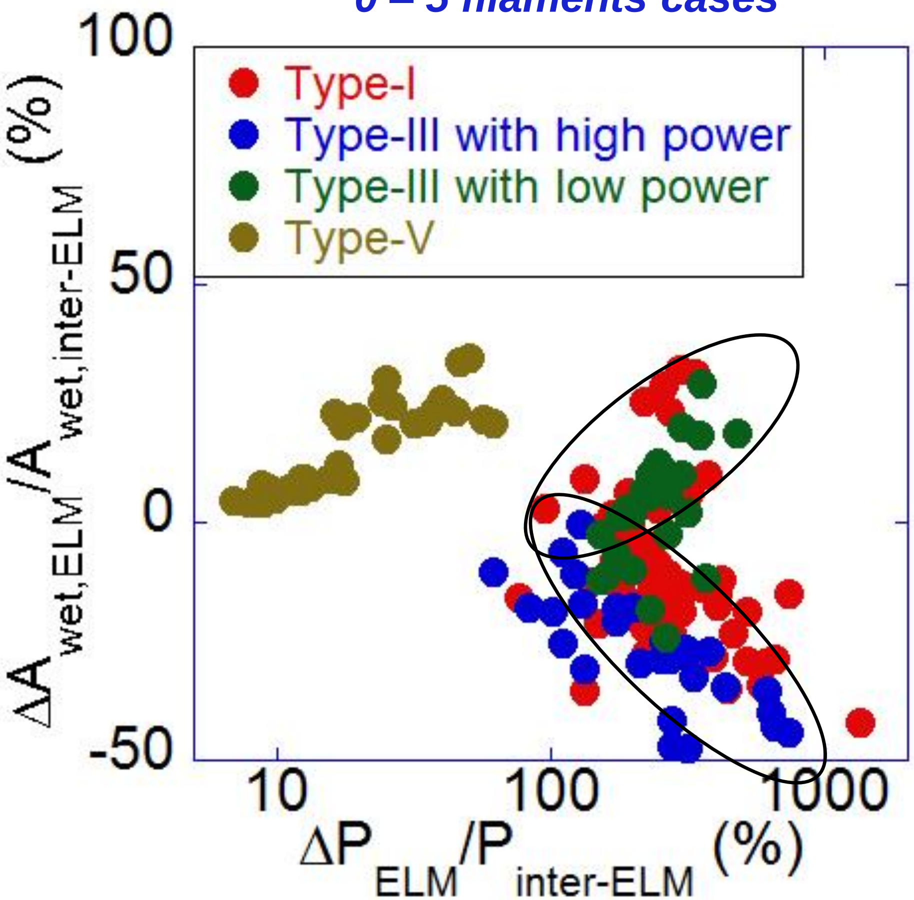


At ELM peak time



- Due to the fact that ELM power increases with # of filaments

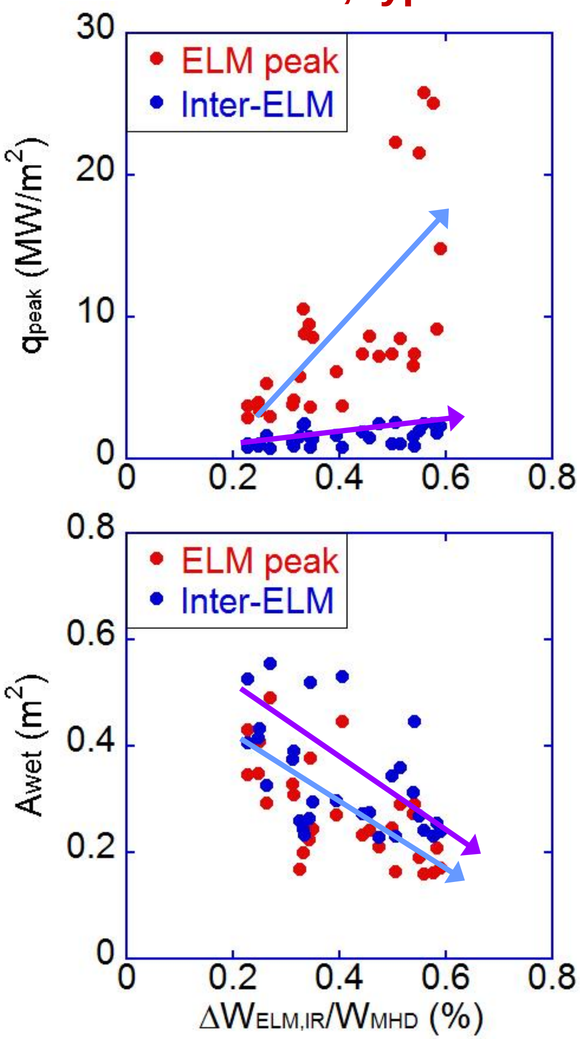
Dependence of A_{wet} on ELM size shows both favorable and unfavorable trends depending on filament numbers



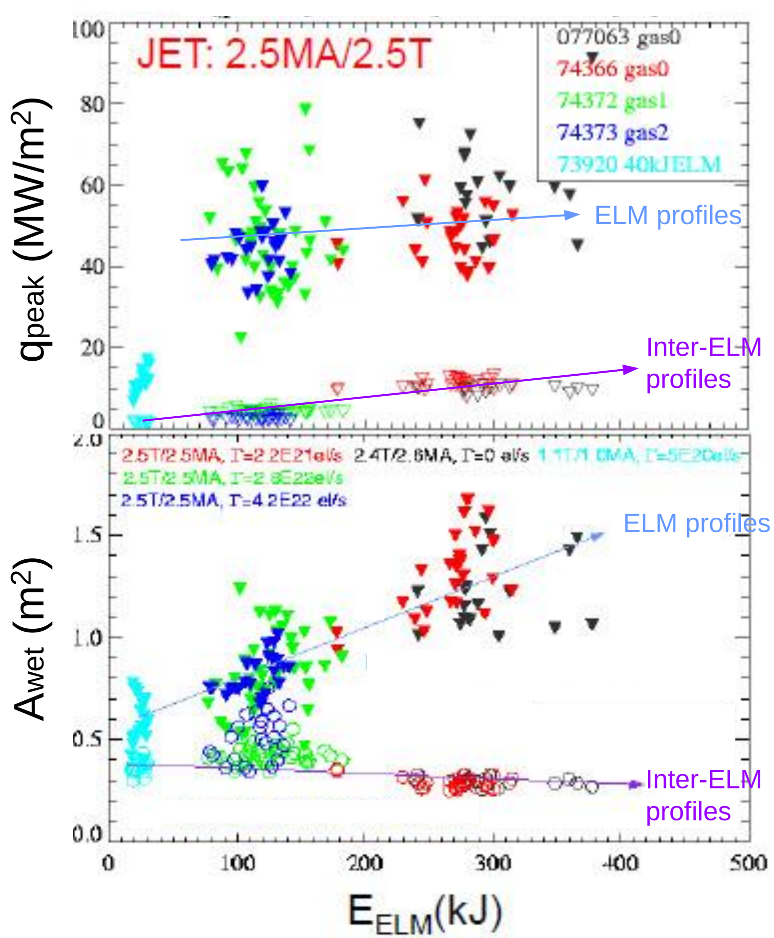
- Type-I and type-III ELMs show similar trend:
  - A_{wet} (therefore λ_q) decreases or increases during the ELM, depending on filament structures
  - The size of change becomes bigger with the size of ELM power → A_{wet} decrease or increase becomes larger for larger ELMs
- Type-V ELMs:
  - Shows favorable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

NSTX ELMs with 0 – 3 filaments: A_{wet} decrease leads to q_{peak} increase with increasing ELM size for type-I ELMs

NSTX, type-I



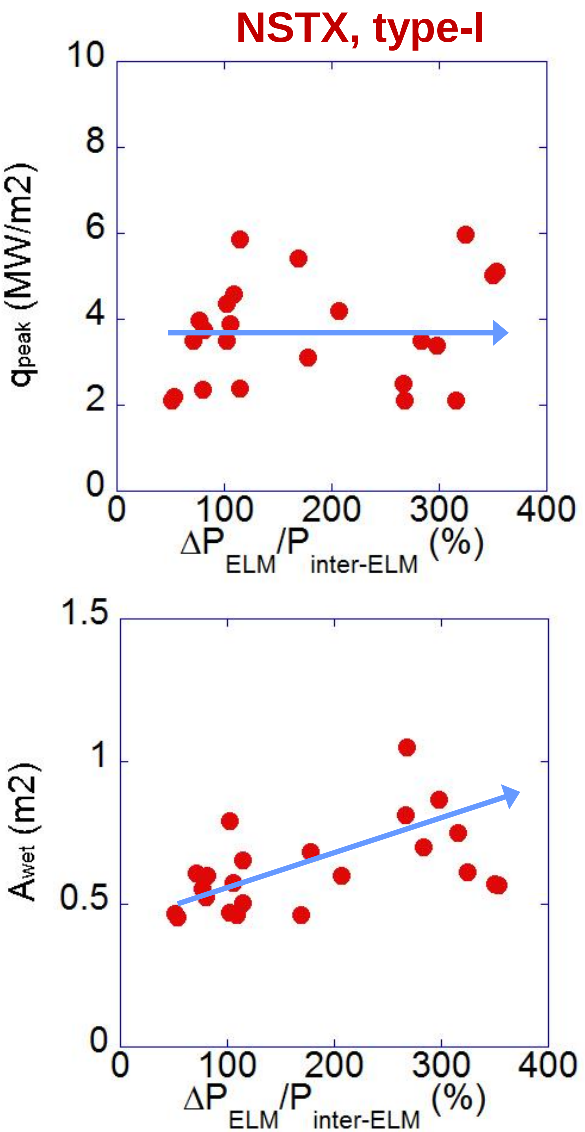
JET, type-I

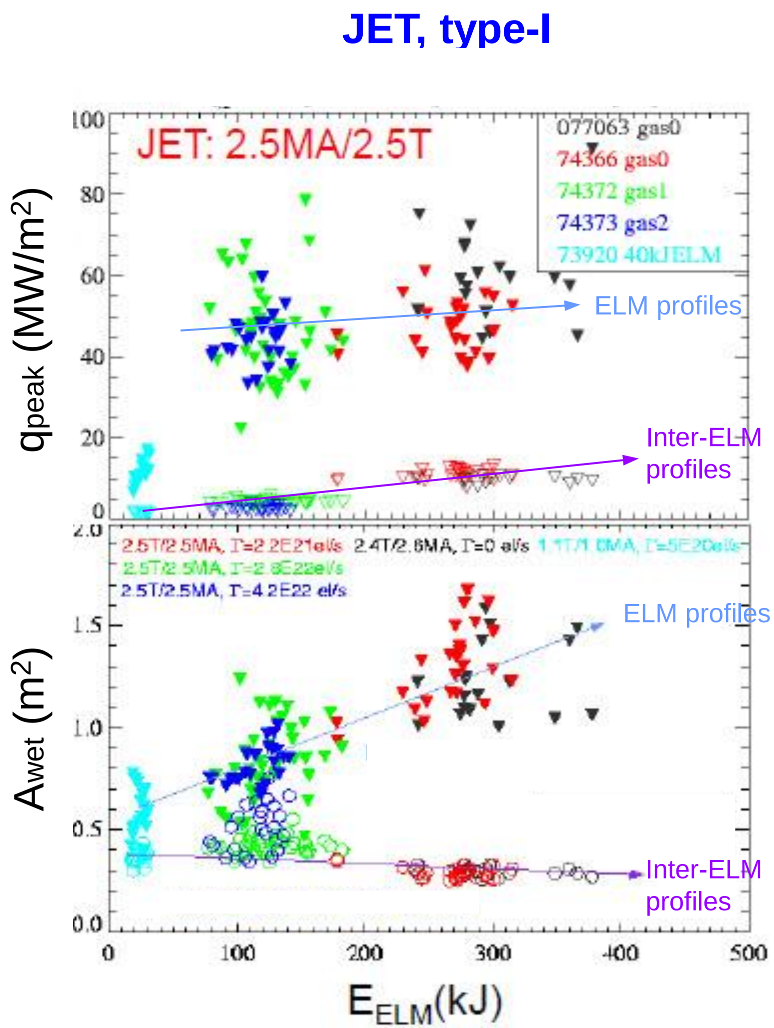


Eich, JNM 2011

- NSTX: A_{wet} decreases with ELM energy loss → q_{peak} increases
- JET [1]: A_{wet} increases with ELM energy loss → q_{peak} constant
- Both machines show A_{wet}↓ and q_{peak}↑ for inter-ELM profiles

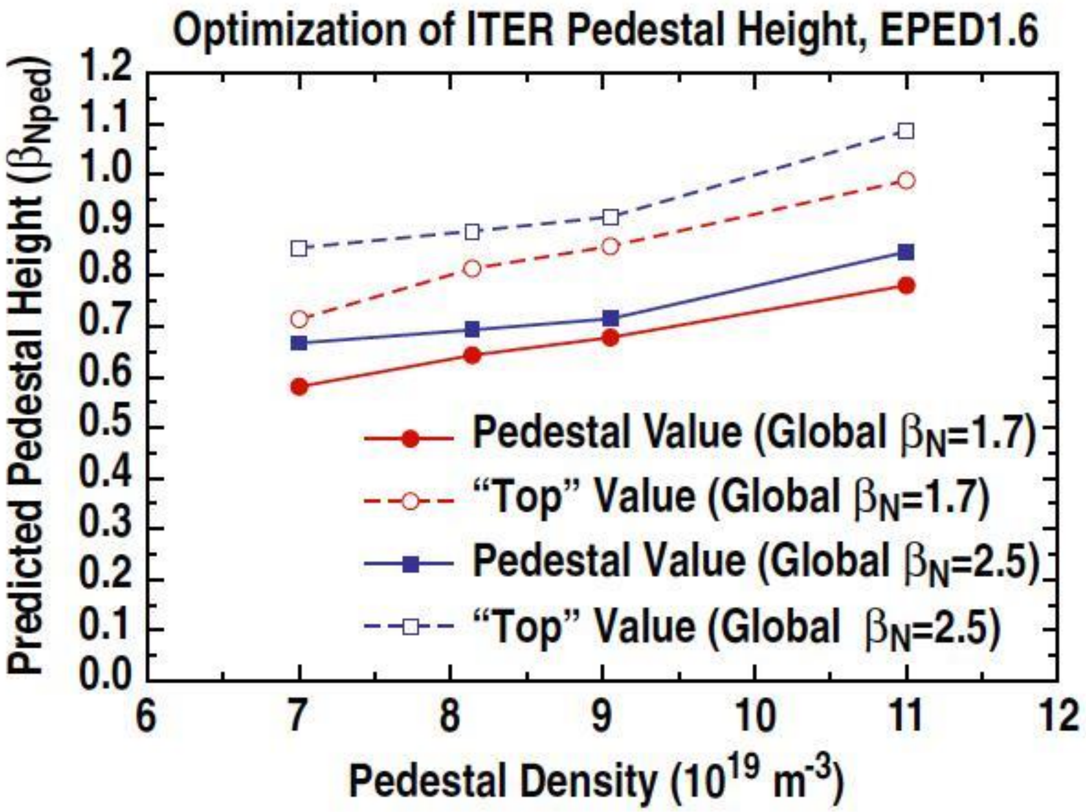
NSTX ELMs with 2 – 9 filaments: A_{wet} increase leads to constant q_{peak} with increasing ELM size for type-I ELMs





- This trend is similar to the observation at JET

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



Snyder, NF 2011

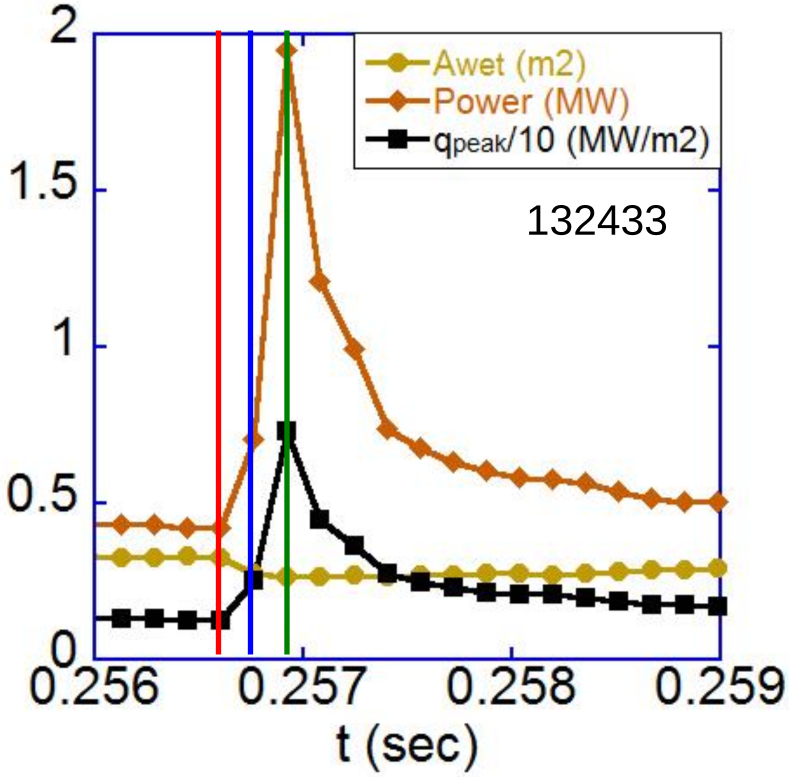
- Stability of ITER pedestal is limited by current-driven kink/peeling modes due to low collisionality and shaping
- Predicted n~3 – 10, similar to NSTX → ELM profile broadening might not be as effective as JET

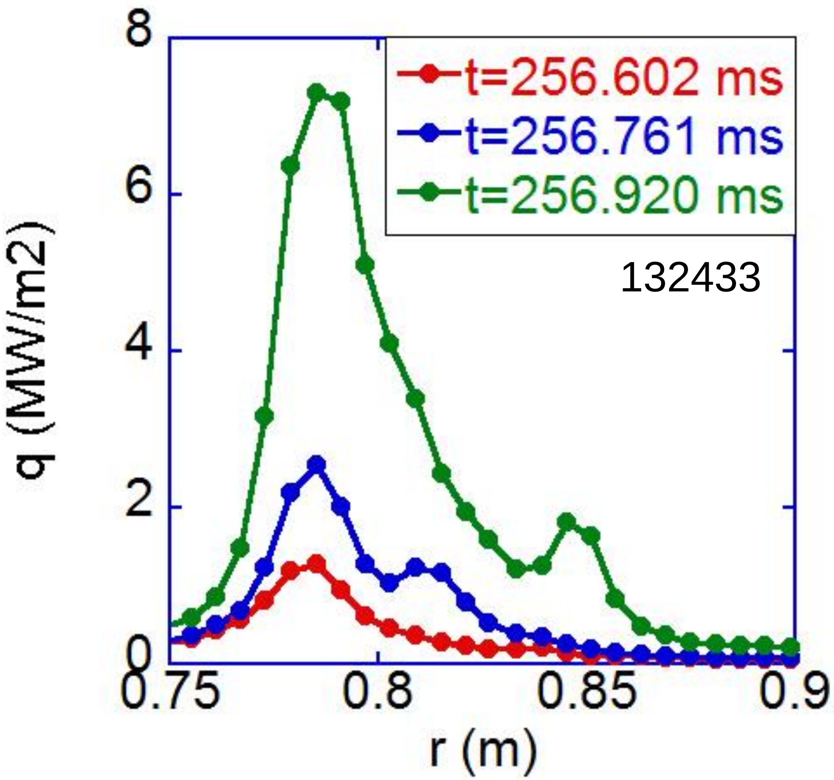
Conclusions

- ELM filament structure determines A_{wet} change and its mode number can be used as a good figure of merit; low n (0 – 3) general reduces A_{wet} and higher n (> 3) increases it
- The size of A_{wet} change is proportional to the size of ELM for both increase and decrease cases
- For ELMs with low mode number, A_{wet} decrease leads to q_{peak} increase with increasing ELM size. For higher mode number, A_{wet} increases and q_{peak} remains constant.
- ITER ELMs are predicted to have peeling nature, therefore low n ELMs could be dangerous

Back-up Slides

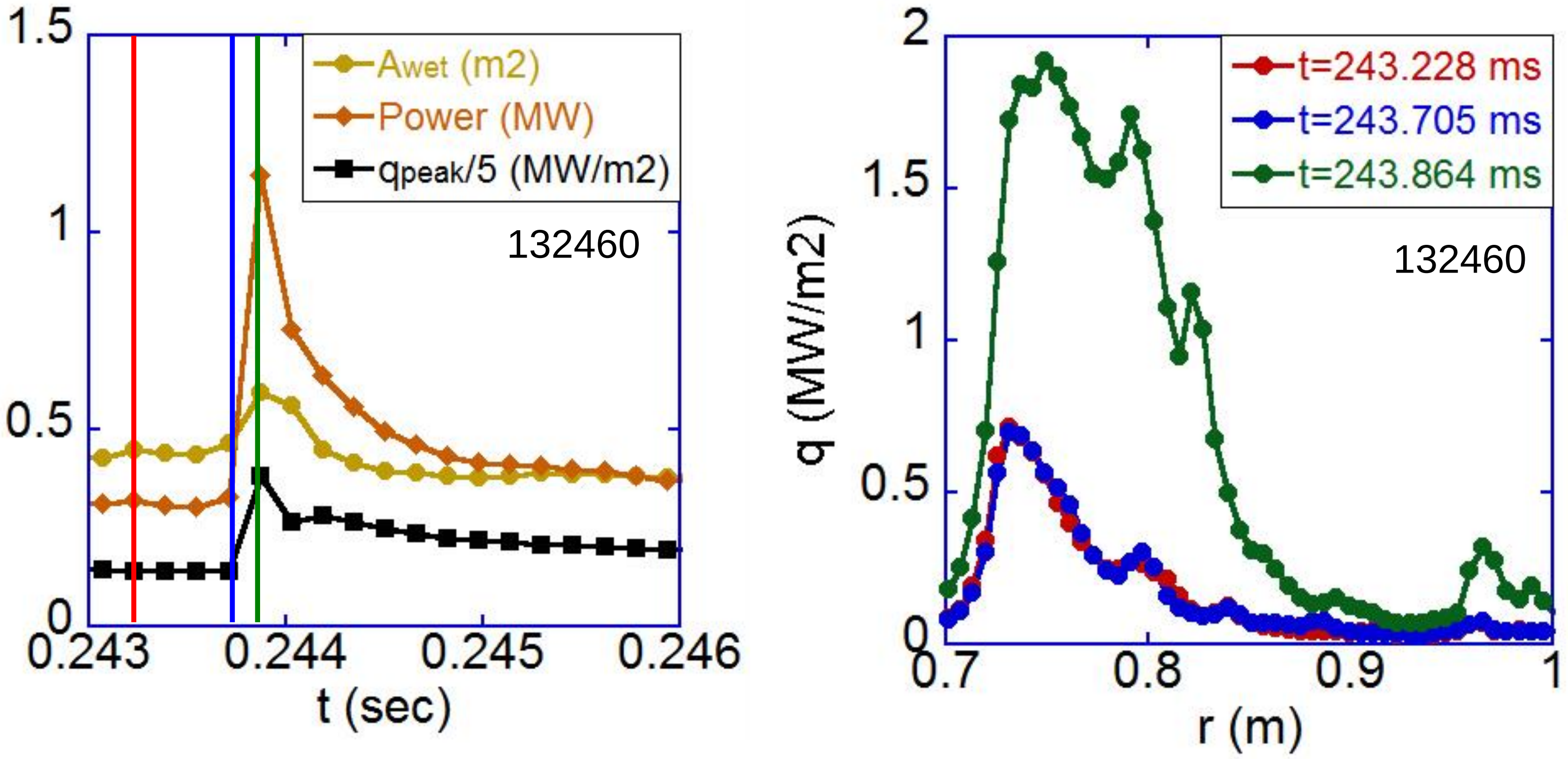
ELM heat flux profile with one striation - A_{wet} decreases most of the time





- 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 five striations



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