NSTX-U

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Toroidal asymmetry of 2-D divertor heat flux profiles during the ELM and 3-D field application in NSTX

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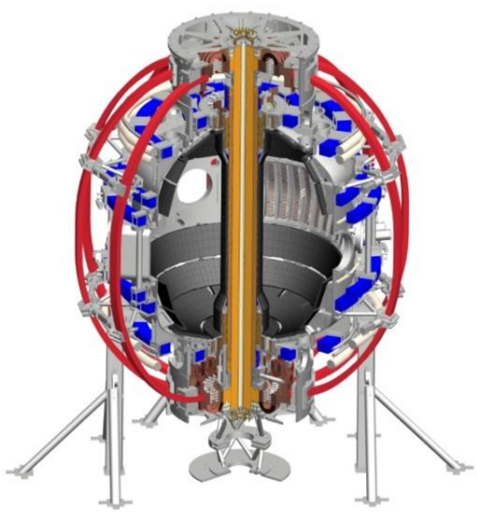

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Motivation

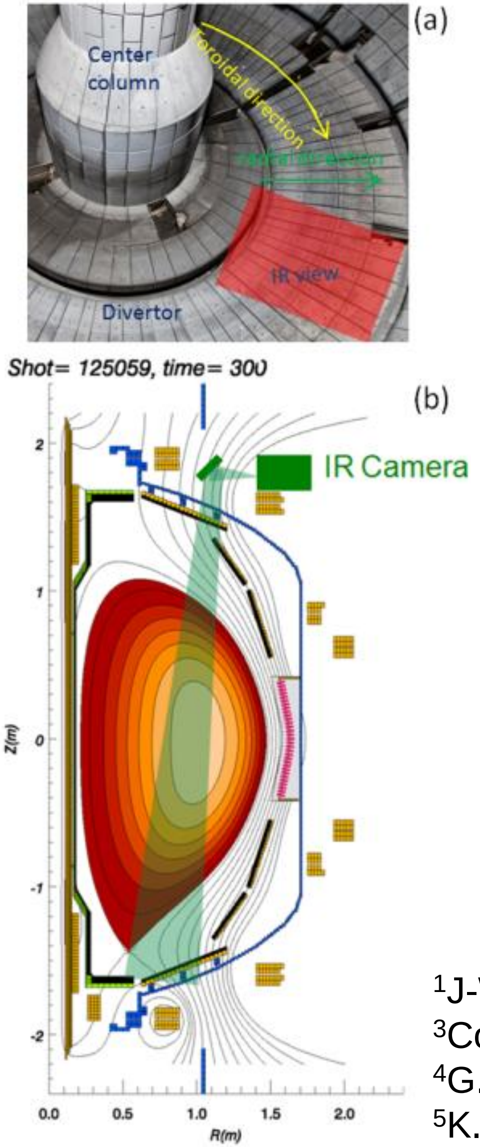
- Toroidally asymmetric heat flux deposition is often observed in various physical phenomena, e.g. ELMs, MHD events, application of 3-D magnetic perturbations, etc

  → can be harmful to the maintenance of divertor tiles as the design is usually based on the assumption of 2-D axisymmetry

- 1-D heat flux profiles in the radial direction at one toroidal location have been widely used in the divertor heat flux study → A full 2-D profile is necessary to study toroidally asymmetric heat deposition

- Conventional heat conduction codes are only able to produce 1-D radial heat flux profiles → need to develop a novel methodology for 2-D heat flux profiles

IR camera diagnostics for heat flux measurement



- Divertor surface temperature is monitored by fast IR camera

- Single band (8-12 μm) fast IR camera in 2009[1]
  - Spatial resolution: 1.7 mm
  - Temporal resolution: 1.6 – 6.3 kHz

- Dual band (4-6μm and 7-10 μm) IR adapter in 2010[2]
  - For lithiated PFC surface, 1.6kHz frame speed

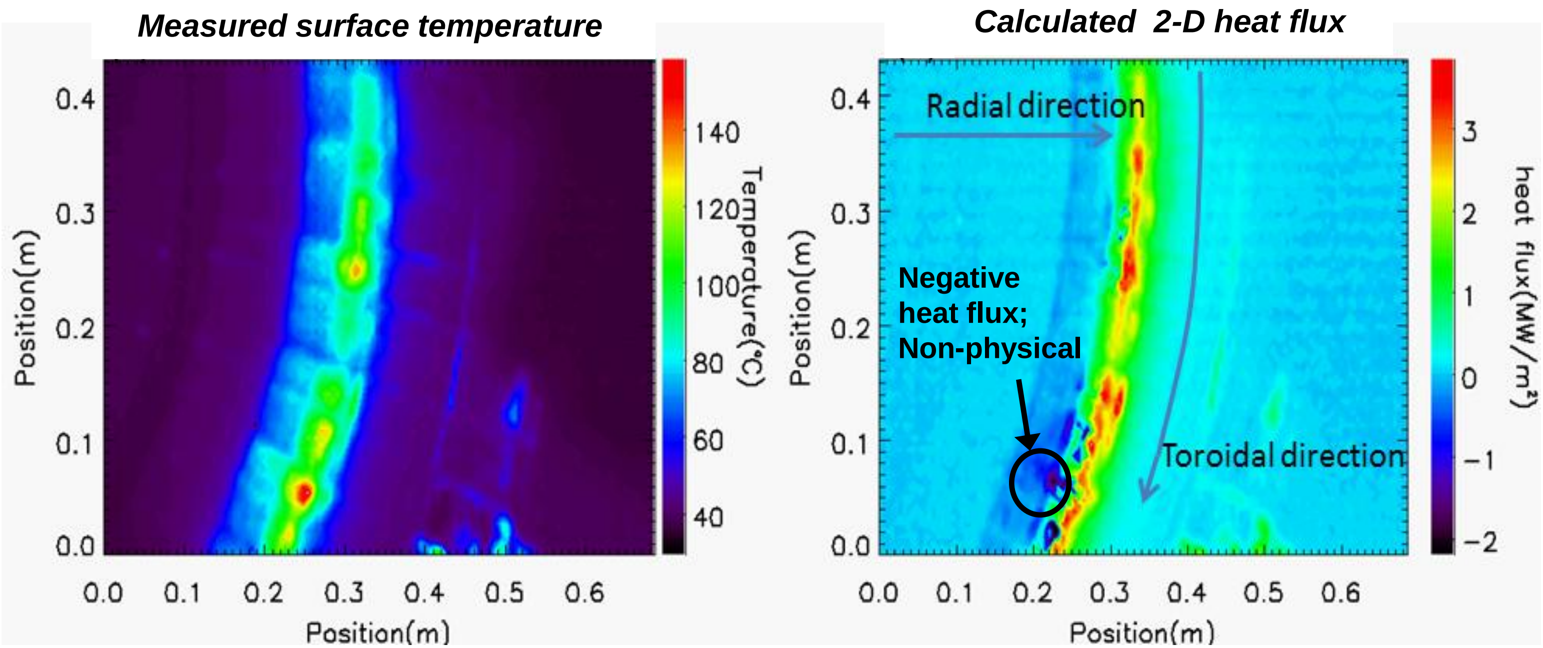
- Heat flux calculation from the measured surface temperature
  - 1-D radial heat flux profile from THEODOR[3]
  - 2-D (r, Φ) heat flux profile from TACO[4], improved to incorporate thin surface layer effect[5]

[1]J-W. Ahn, RSI 81 (2010), 023501, [2]A.G. McLean, RSI 83 (2012), 053706
[3]Collaboration with IPP Garching, A. Hermann
[4]G. Castle, COMPASS Note 97.16, UKAEA Fusion (1997)
[5]K.F. Gan, submitted to RSI (2012)

TACO calculates 2-D heat flux distribution at divertor surface

$$Q_{xy}(t_j) = \frac{k\delta}{2\chi\Delta\tau}\frac{(T_{xy}(t_j)-T_{xy}(t_0))}{C_o} - \sum_{\ell=1}^{j-1} Q_{xy}(t_{j-\ell})\frac{C_l}{C_0}$$

Surface heat flux



K.F. Gan, submitted to RSI (2012)

- 2-D heat flux data in (x,y) plane are obtained from TACO
- Toroidally non-axisymmetric 2-D heat flux data are particuarly important during the ELMs and 3-D fields application

Implementation of heat transmission coefficient in TACO alleviates negative heat flux problem

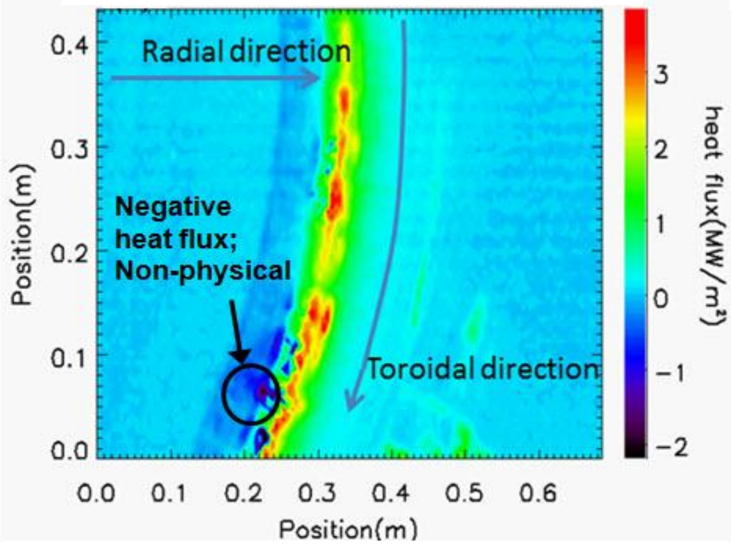
$$\alpha = k_{layer} / d \quad \longrightarrow \quad T_{surface} = T_{measured} - \frac{q_s}{\alpha}$$

α: Heat transmission coefficient[1]
k_{layer}: surface layer thermal conductivity,
d: surface layer thickness

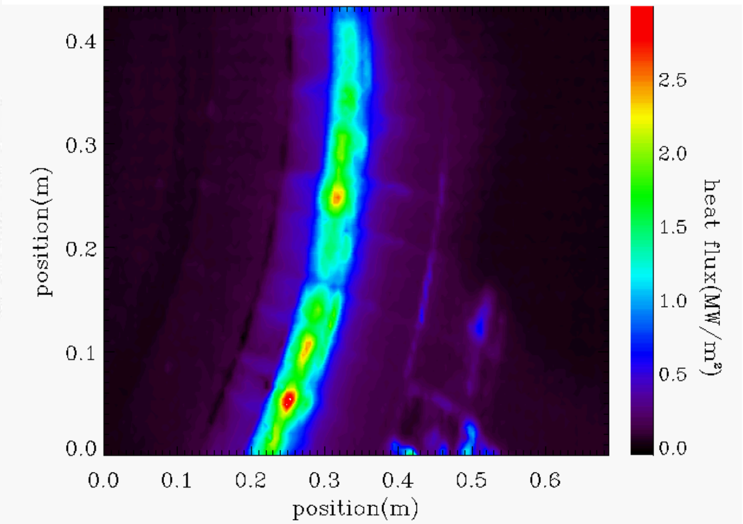
$$Q_{xy}(t_j) = \left(\frac{T_{xy}(t_j) - T_{xy}(t_0)}{C_o} - \sum_{\ell=1}^{j-1} Q_{xy}(t_{j-\ell}) \frac{C_\ell}{C_0} \right) \Big/ \left(1 + \frac{k\delta}{2\chi\Delta\tau C_0 \alpha} \right)$$

Surface heat flux with α incorporated in heat conduction equation

Calculated 2-D heat flux with no α



Calculated 2-D heat flux with $\alpha = 60$ ($kWm^{-2}K^{-1}$)



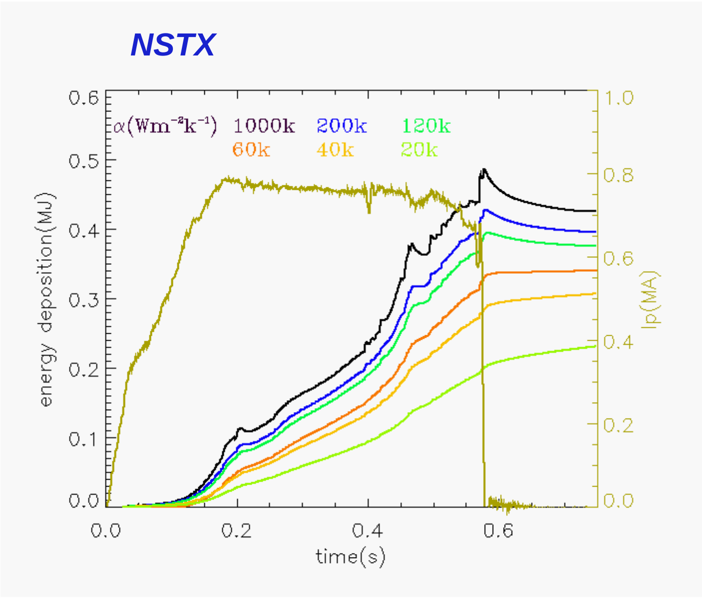
- With α implemented in the heat conduction equation, negative heat flux problem is alleviated[1,2]. This also lowers the computed peak heat flux

[1] A. Herrmann, PPCF (1995)

International collaboration on THEODOR with IPP-Garching

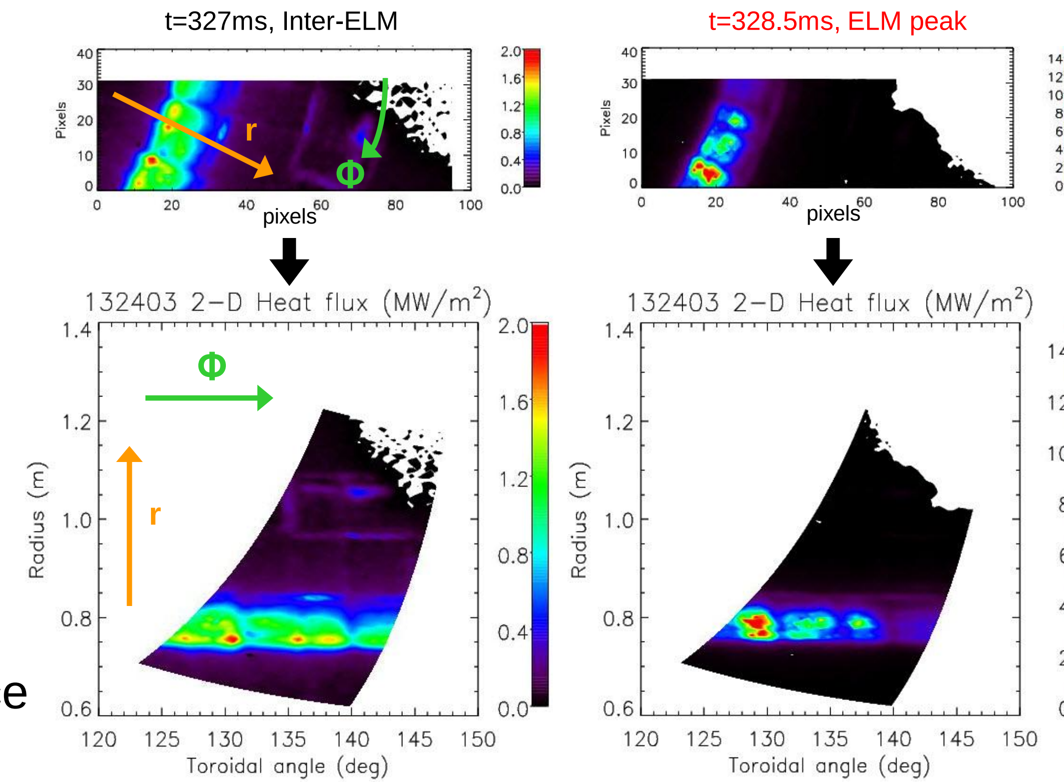
[2] K.F. Gan, submitted to RSI (2012)

The calculated 2-D heat flux profiles are re-mapped to (r, Φ) plane with the choice of α value from the energy conservation



- The α value makes a large influence on the heat flux calculation, and different values lead to very different results

- In NSTX, an α value is chosen such that the deposited energy remains constant after the discharge



- The calculated 2-D heat flux profile in (x, y) plane is re-mapped to the (r, Φ) plane.

  → useful in the study of non-axisymmetric heat flux deposition

Degree of Asymmetry (DoA) is defined to quantify asymmetric heat deposition onto divertor

$$DoA(q_{peak}) = \sigma_{qpeak} / \bar{q}_{peak,2D}$$

$$DoA(\lambda_q) = \sigma_{\lambda q} / \bar{\lambda}_{q,2D}$$

- Define DoA (Degree of Asymmetry) for peak heat flux (q_{peak}) and heat flux width (λ_q)
  - q_{peak} and λ_q is obtained for each radial array of data
  - σ_{peak} and $\sigma_{\lambda q}$ are the standard deviation of q_{peak} and λ_q over the data in the toroidal direction
  - σ_{peak} and $\sigma_{\lambda q}$ are normalized to the 2-D mean values of q_{peak} and λ_q

$$\bar{q}_{peak,2D} = \sum (q_{peak}) / N$$

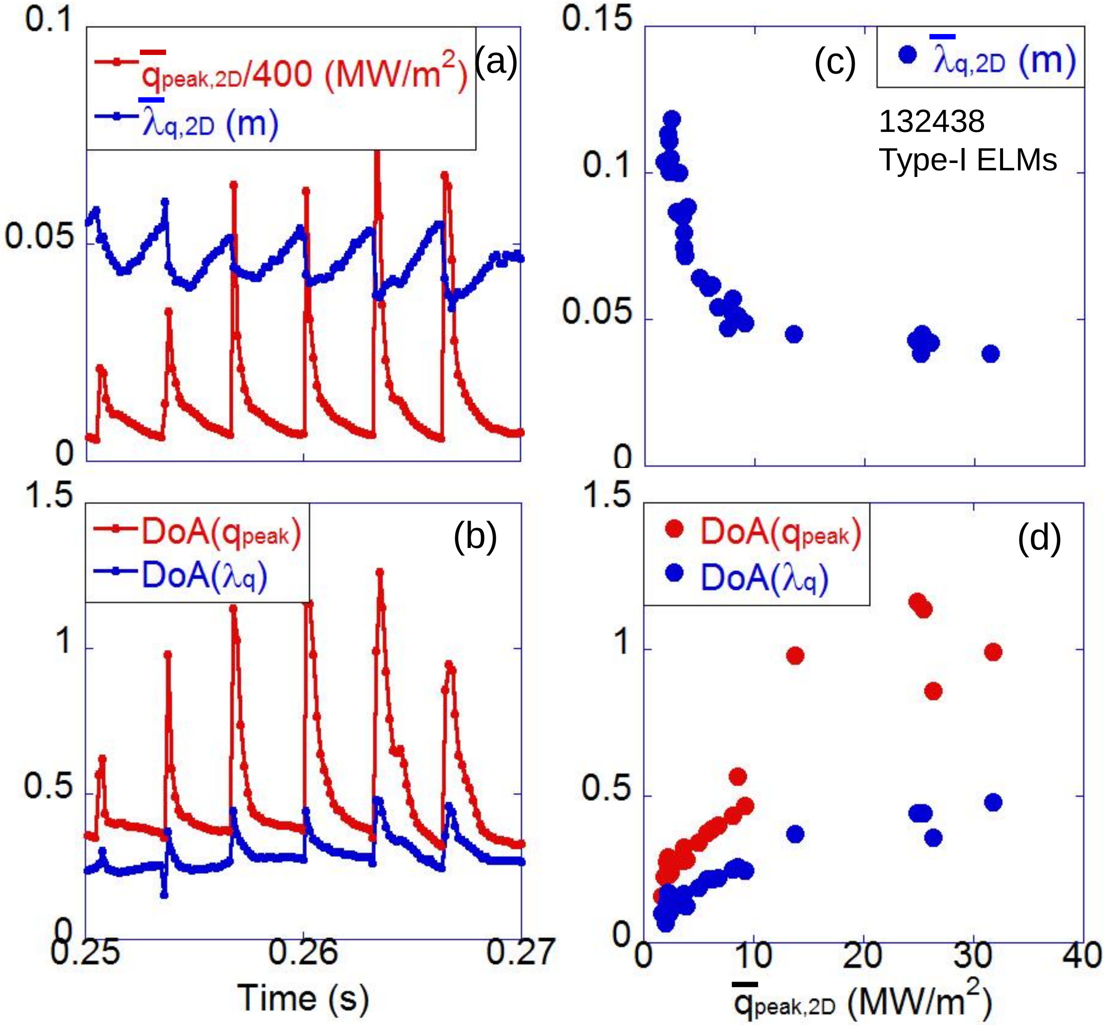
$$\bar{\lambda}_{q,2D} = \sum (\lambda_q) / N$$

- Define mean value of q_{peak} and λ_q, each to represent the 2-D plane
  - N is the total number of toroidal arrays
  - $\bar{q}_{peak,2D}$ and $\bar{\lambda}_{q,2D}$ are the mean values of q_{peak} and λ_q along the toroidal direction. This represents the whole 2D plane viewed by the IR camera at each time slice

Degree of Asymmetries increase with rising peak heat flux for ELMs – type-I ELMs

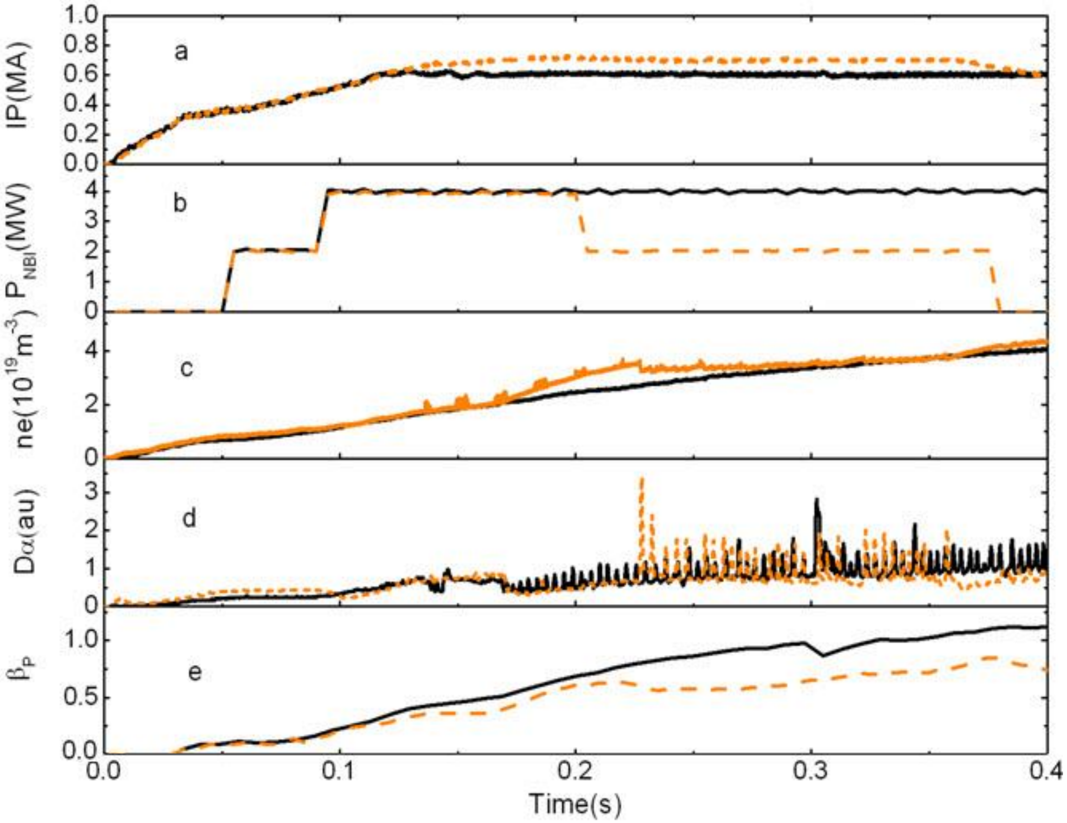
Temporal evolution for t=0.25 – 0.27 s

At ELM peak times for t=0.2 – 0.27 s



- The 2-D mean value of heat flux width drops during the ELM rise time → inverse relation between λ_q and q_{peak}, contrary to some observations in other tokamaks
- Toroidal asymmetries (DoA) increase during the ELM for both λ_q and q_{peak}
- DoA(q_{peak}) is always higher than DoA(λ_q) by a factor 2-3. Both DoAs increase with increasing q_{peak}

Distinction between type-III ELMs – high and low β_p



[1]K.F. Gan, submitted to NF (2012)

- 132401

  I_p=600kA, P_{NBI}=4MW → High β_p

- 132460

  I_p=700kA, P_{NBI}=2MW → Low β_p

- Inverse relation between q_{peak} and λ_q was revealed for type-III ELMs with high β_p, but the opposite relation is observed for low β_p type-III ELMs[1]

- The poloidal beta (β_p) has been chosen as a global parameter to represent the pedestal performance

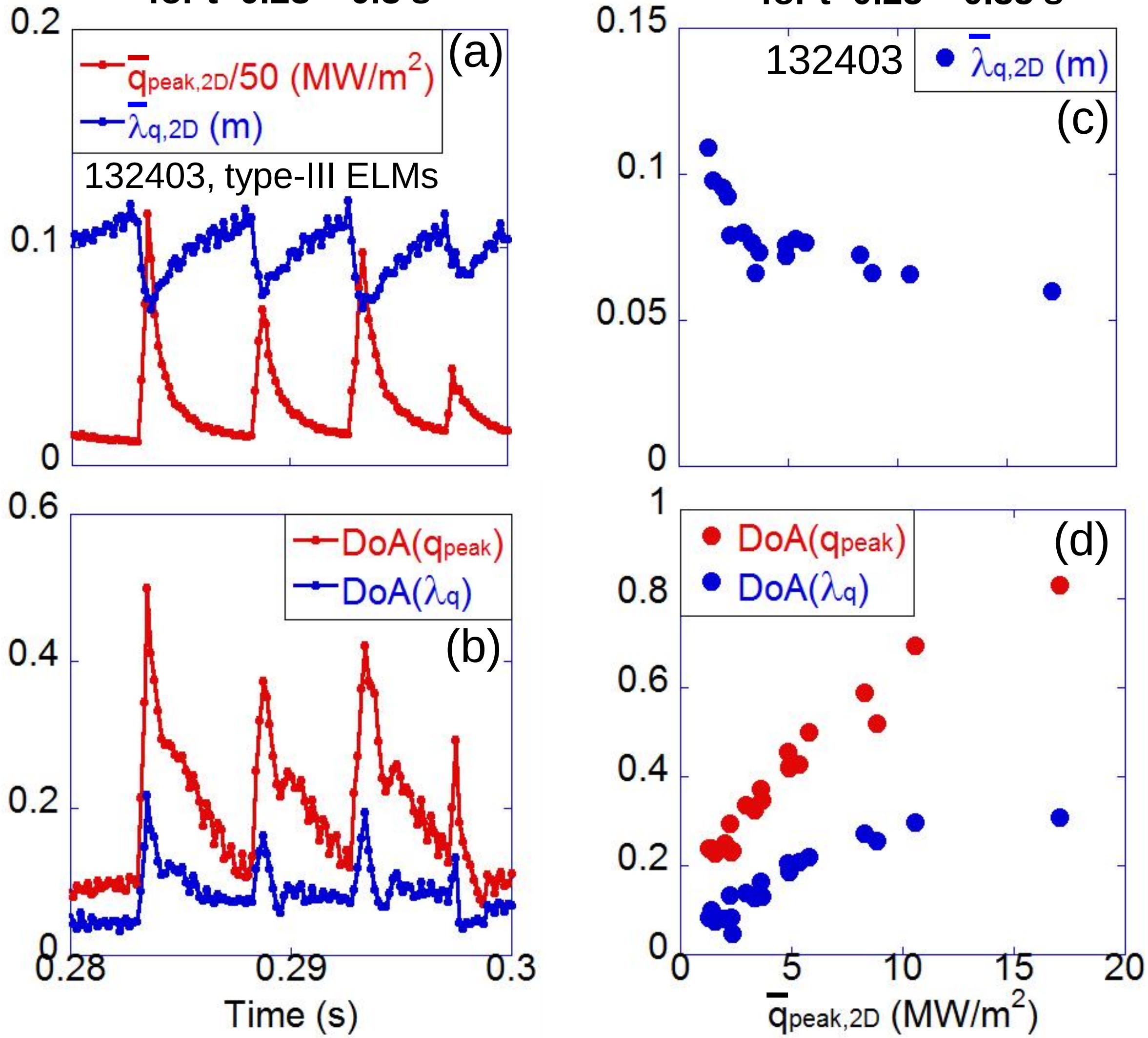
  → Other variables such as pedestal T_e, n_e and the pedestal υ_e* might better represent the pedestal

  → Work in progress

Degree of Asymmetries increase with rising peak heat flux for ELMs – type-III ELMs with high β_p

Temporal evolution for t=0.28 – 0.3 s

At ELM peak times for t=0.25 – 0.35 s

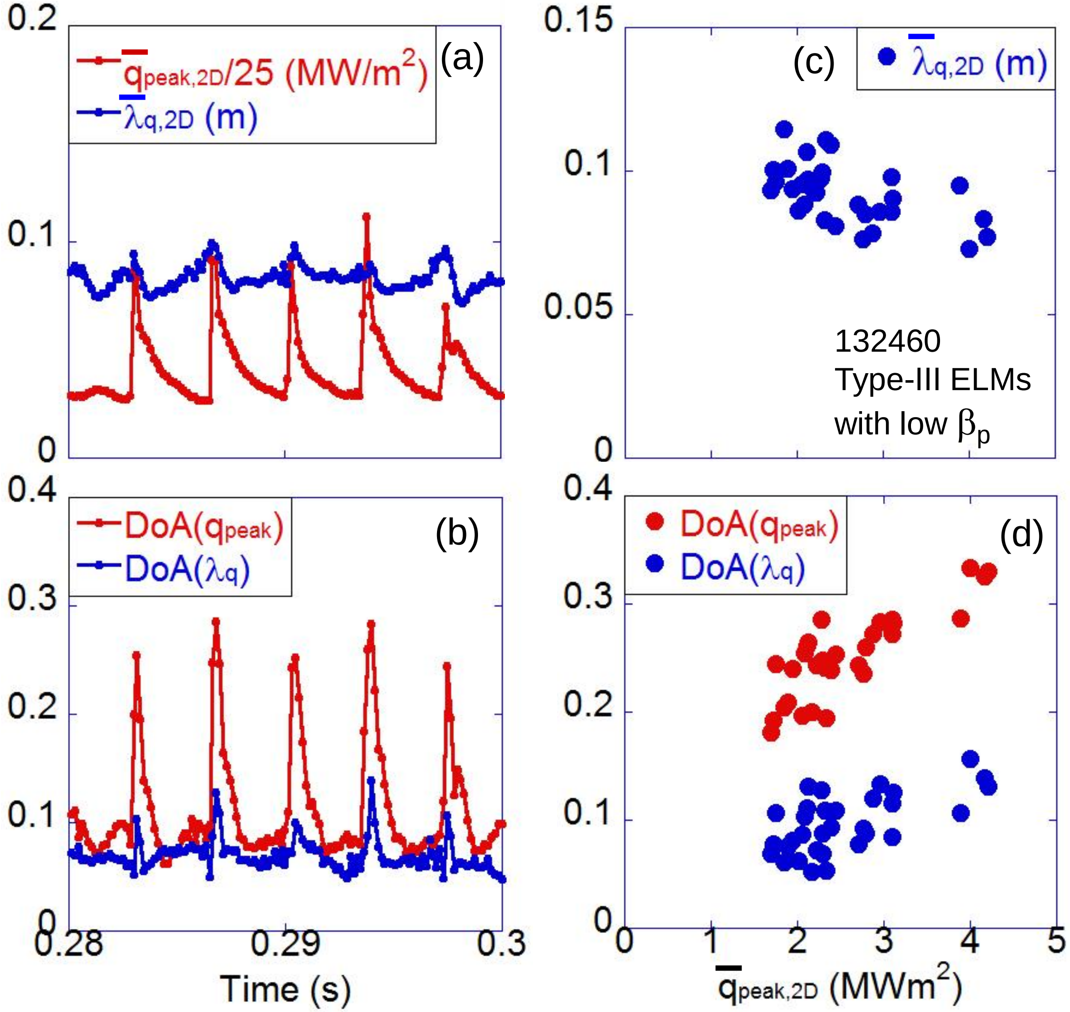


- Similar behaviors to type-I ELMs are observed
  - → $\bar{\lambda}_{q,2D}$ ↓ during the ELM
  - → Inverse relation b.t.w. $\bar{\lambda}_{q,2D}$ and $\bar{q}_{peak,2D}$ at ELM peak times
- Toroidal asymmetries (DoA) increase again during the ELM
- Both DoAs increase with increasing q_{peak} but the rate of increase seems to saturate at higher q_{peak}

λ_q during the ELM increases but still decreases with increasing q_{peak} at ELM peak times – type-III ELMs with low β_p

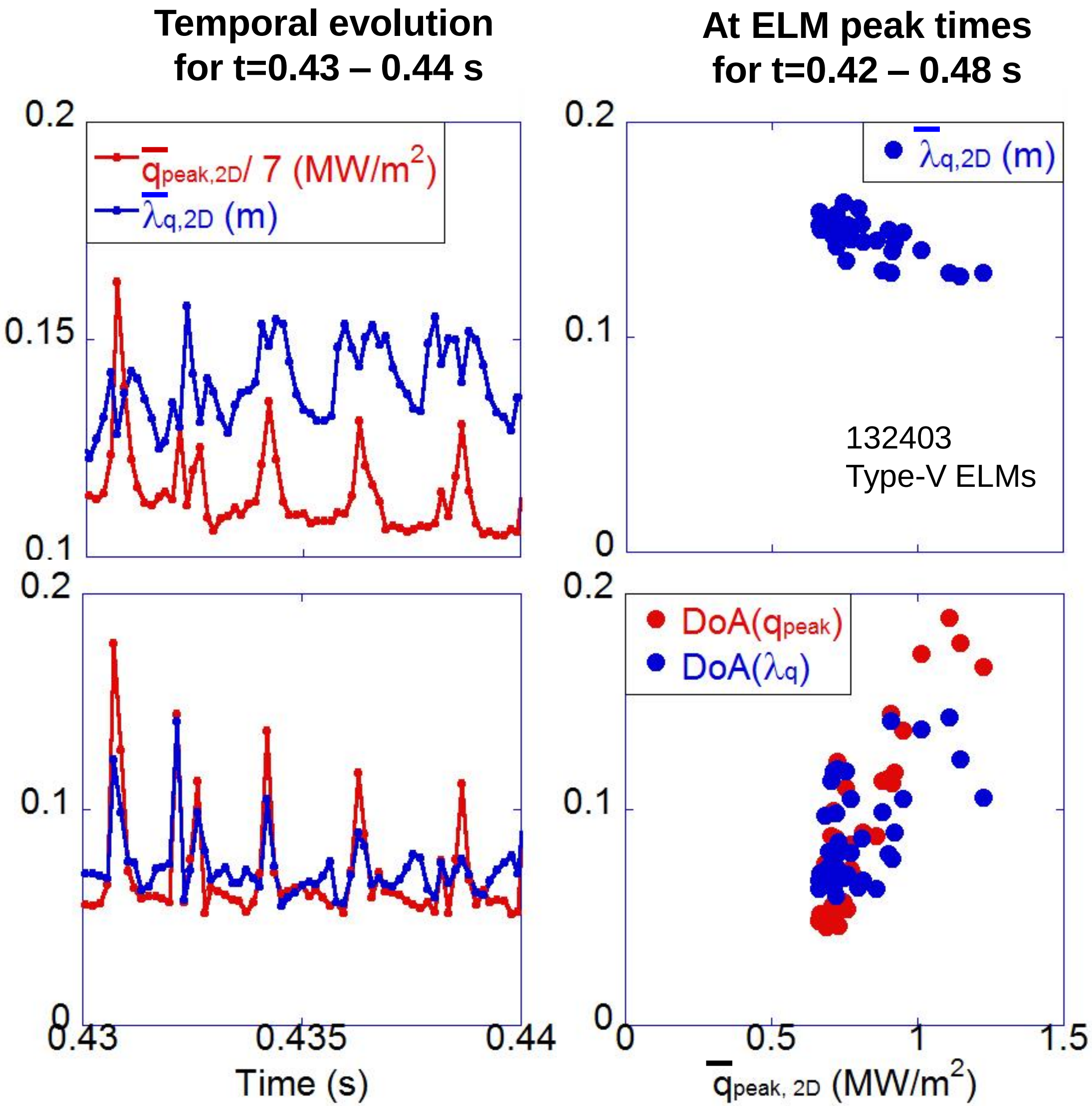
Temporal evolution for t=0.28 – 0.3 s

At ELM peak times for t=0.24 – 0.35 s



- The 2-D mean value of heat flux width increases during the ELM rise time → the opposite trend to type-III ELMs with high β_p
- However, heat flux width at ELM peak times still decreases with increasing peak heat flux
- Similar temporal behavior of the two DoAs; increase during the ELM for both λ_q and q_{peak}
- DoA(q_{peak}) is also higher than DoA(λ_q). The absolute value of both DoA is much smaller than the high β_p case

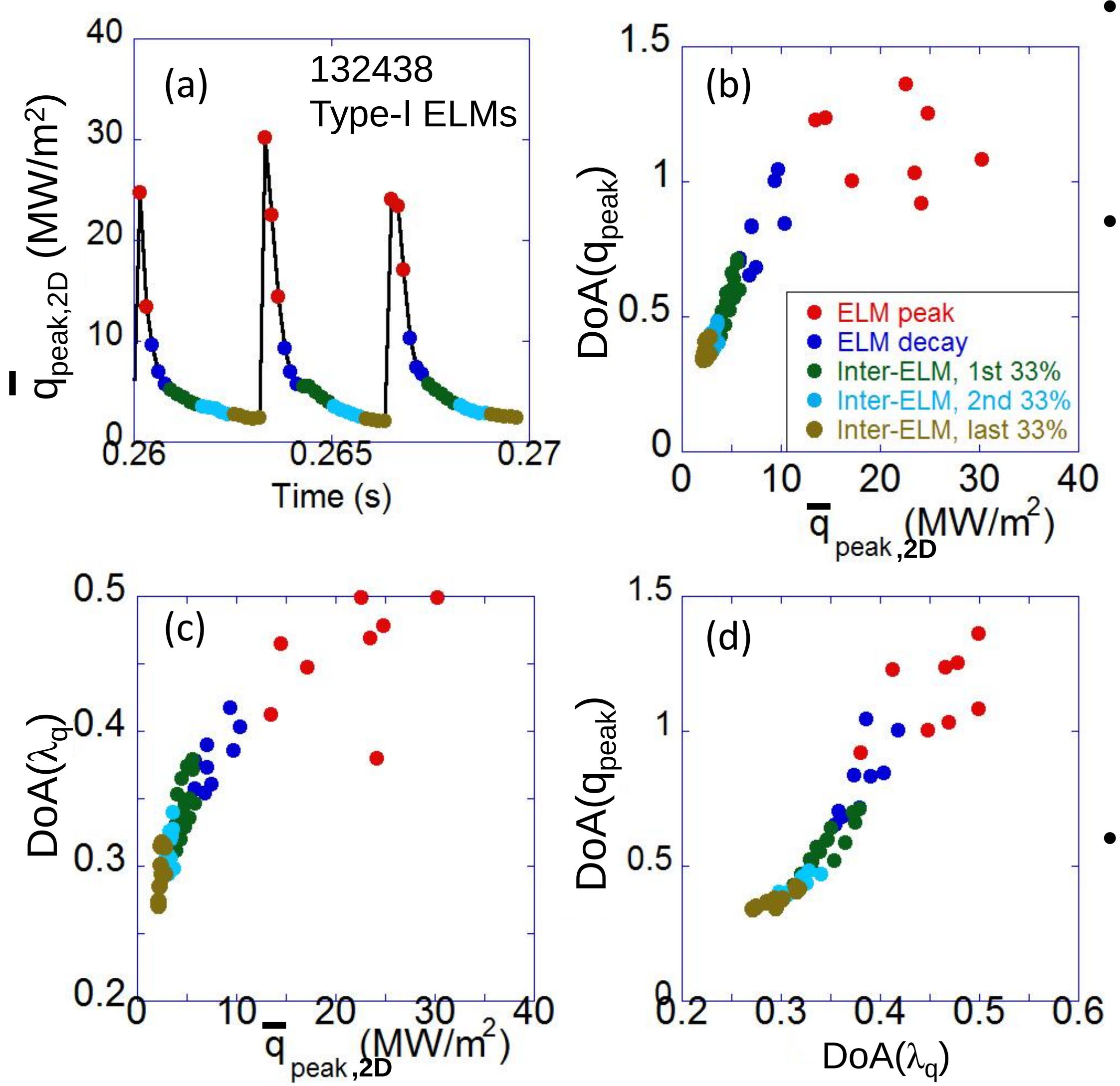
λ_q during the ELM increases and the Degree of Asymmetry for q_{peak} and λ_q is similar – type-V ELMs



- Type-V ELM is a small ELM regime identified in NSTX[1]
- Heat flux width increases during the ELM, similar to type-III ELMs with low β_p
- Both toroidal asymmetries increase during the ELM
- The level of DoA(q_{peak}) and DoA(λ_q) is similar, contrary to all other types of ELMs

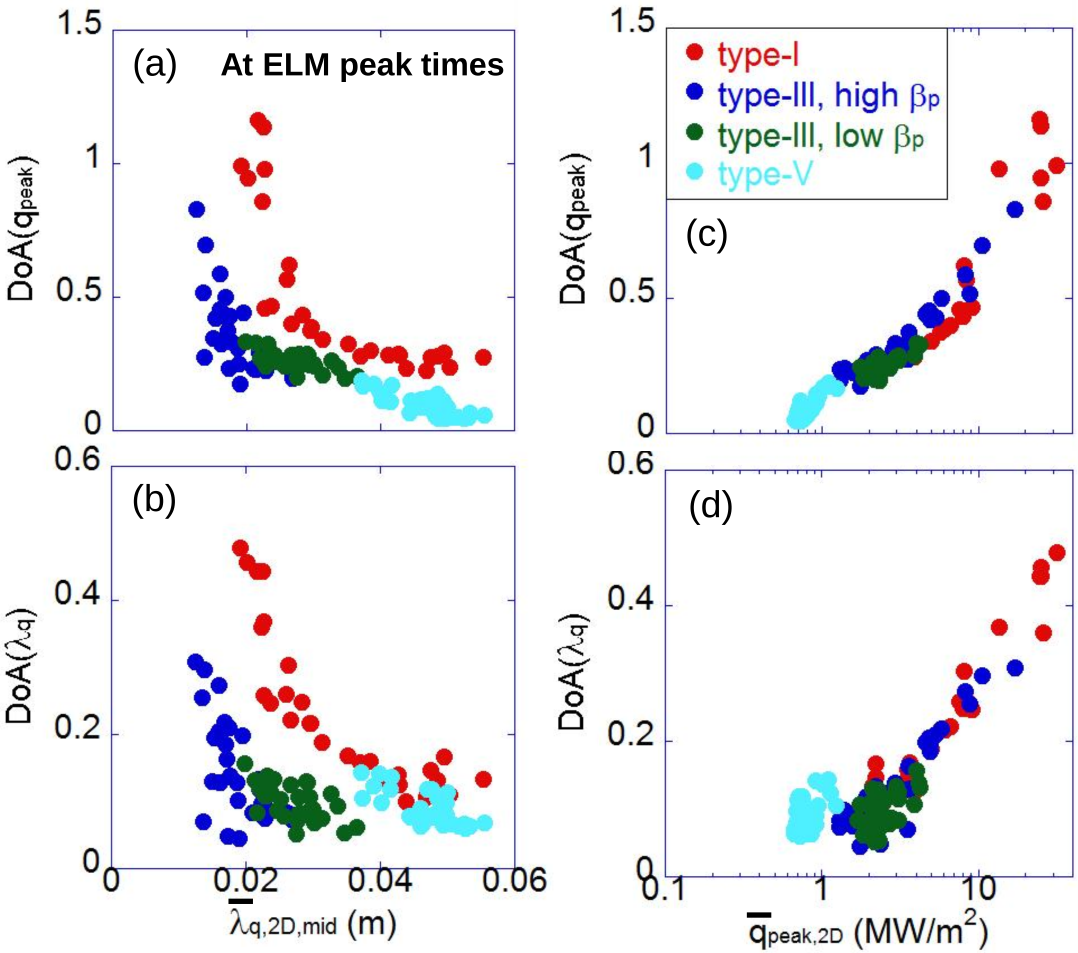
[1]R. Maingi, Nucl. Fusion 45 (2005) 264

Behavior of toroidal asymmetries during the ELM cycle for type-I ELMs



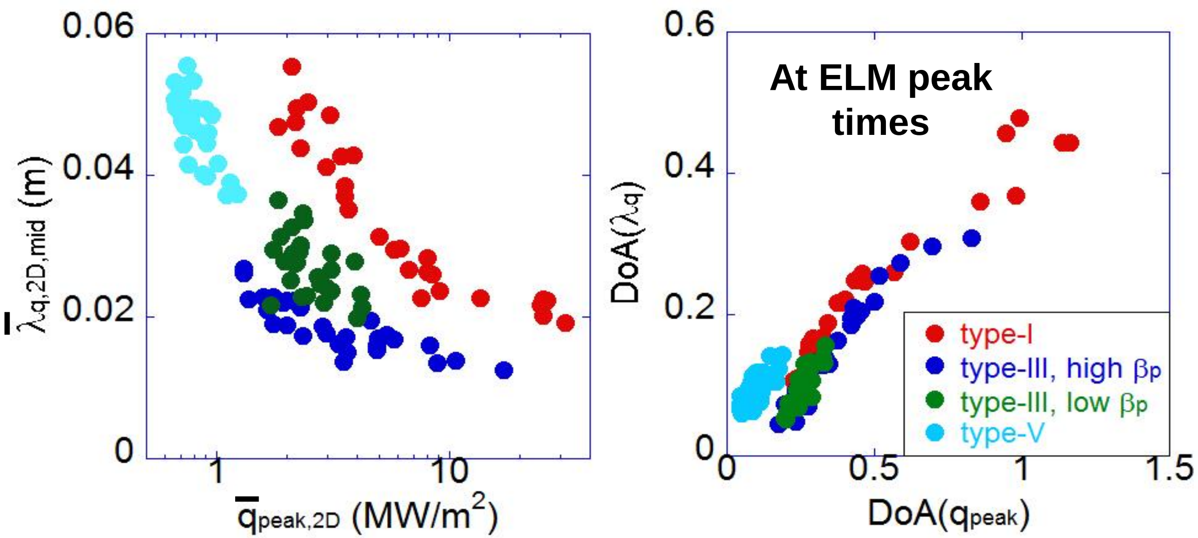
- Both DoA(q_{peak}) and DoA(λ_q) become largest at the ELM peak times
- Both DoA values increase with increasing q_{peak} and therefore the degree of asymmetric heat deposition is highest at the ELM peak times, while it becomes lower toward the later stage of the inter-ELM period → higher q_{peak} leads to higher degree of asymmetric q_{peak} and λ_q
- The correlation between DoA(q_{peak}) and DoA(λ_q) is the strongest at the ELM peak times and becomes weaker later in the ELM cycle.

Dependence of toroidal asymmetries on peak heat flux and mid-plane heat flux width for all ELM types



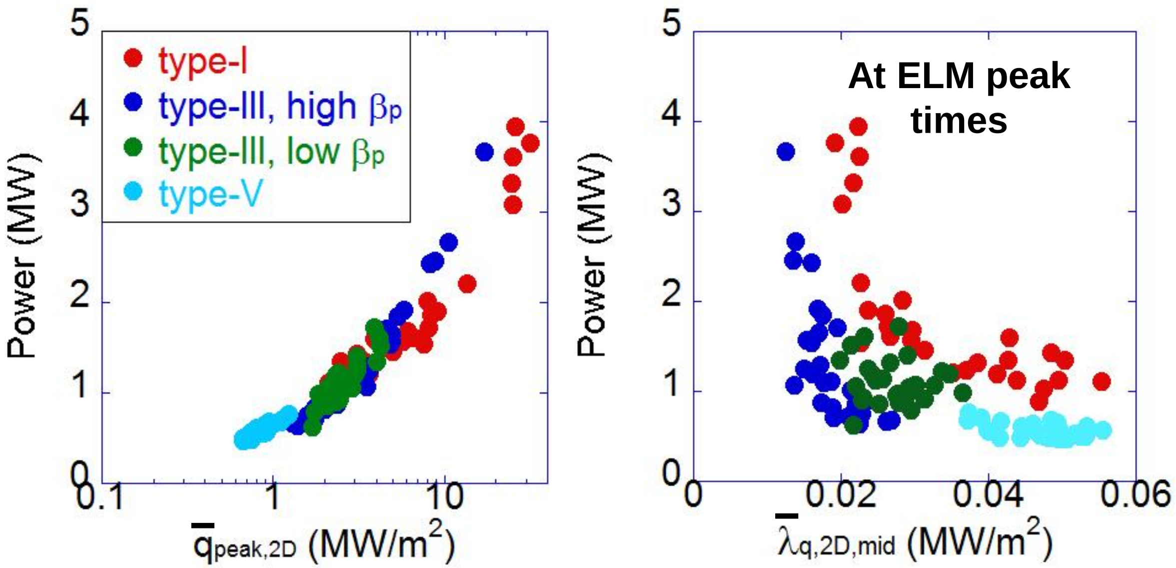
- Comparison of the two DoAs as a function of peak heat flux and heat flux width for all ELM types → Mid-plane heat flux width ($\bar{\lambda}_{q,2D,mid}$) is used, taking account of the flux expansion
- As a function of $\bar{\lambda}_{q,2D,mid}$: DoAs rapidly decrease with increasing $\bar{\lambda}_{q,2D,mid}$ for low $\bar{\lambda}_{q,2D,mid}$ (≤ 2–2.5 cm) values, but then the rate of decrease significantly slows down or saturates for $\bar{\lambda}_{q,2D,mid}$>2–2.5cm.
- As a function of $\bar{q}_{peak,2D}$: both DoAs increase with increasing q_{peak}, type-V ELMs have relatively higher DoAs

Correlation between peak heat flux and heat flux width and between the two degrees of asymmetry – all ELM types



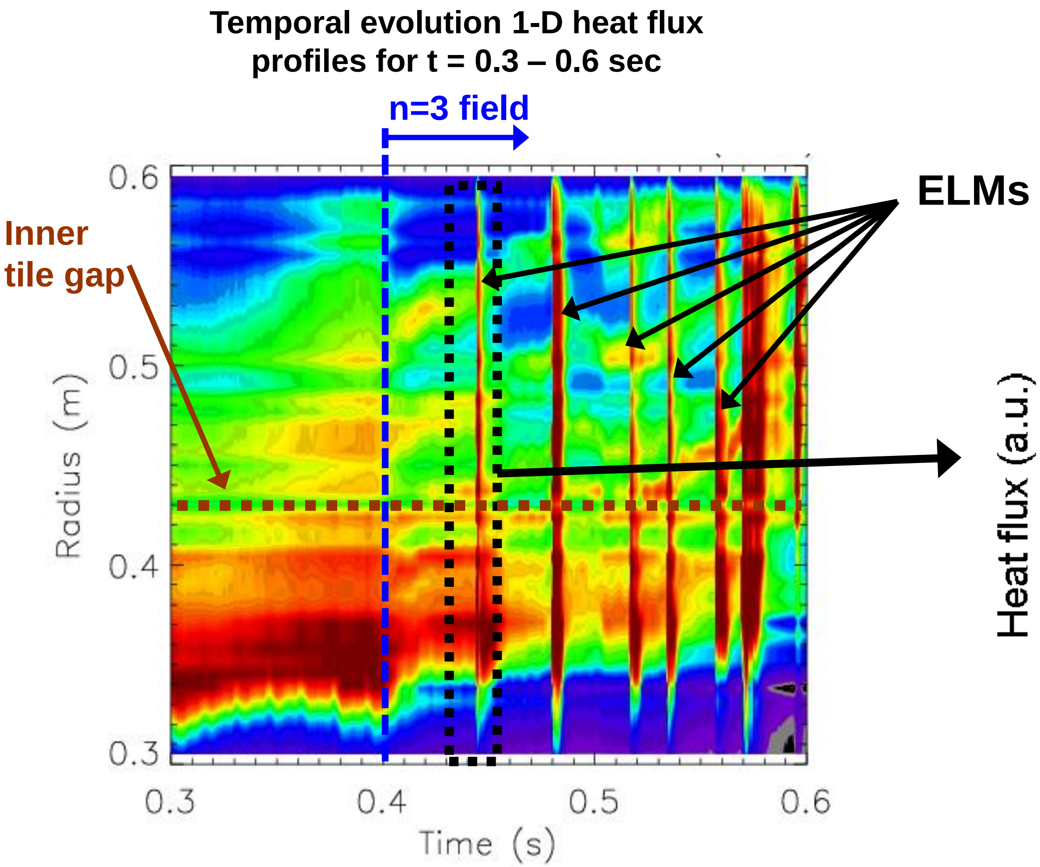
- Inverse relationship between heat flux width and peak heat flux is observed generally for all ELM types → not favorable for the extrapolation to the future machine
- Type-V ELMs exhibit the most desired characteristics, *i.e*. the lowest peak heat flux and the largest heat flux width
- The two degrees of asymmetry are found to have positive dependence on each other for all ELM types

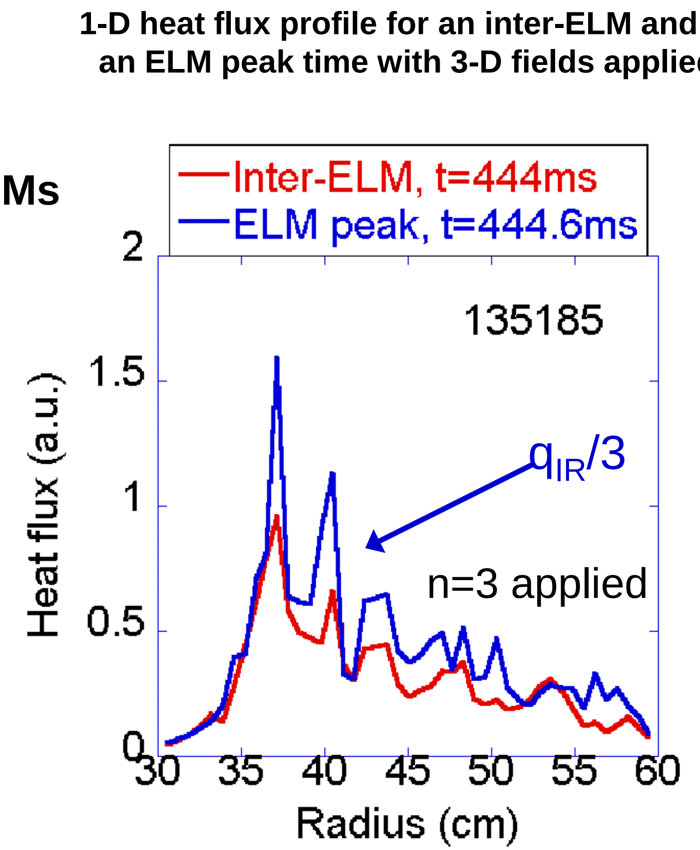
Dependence of ELM power on peak heat flux and mid-plane heat flux width – all ELM types



- The total power deposited onto the divertor surface is another important parameter of interest → its dependence on peak heat flux and heat flux width
- The ELM power is a strong function of peak heat flux, forming a consistent trend through all ELM types
- The dependence of power on the mid-plane heat flux width is rather flat for a significant portion of the whole range of heat flux width, except for type-I and high β_p type-III (strong negative dependence at low $\bar{\lambda}_{q,2D,mid}$)

Heat flux from ELMs triggered by n=3 fields follows imposed field structure

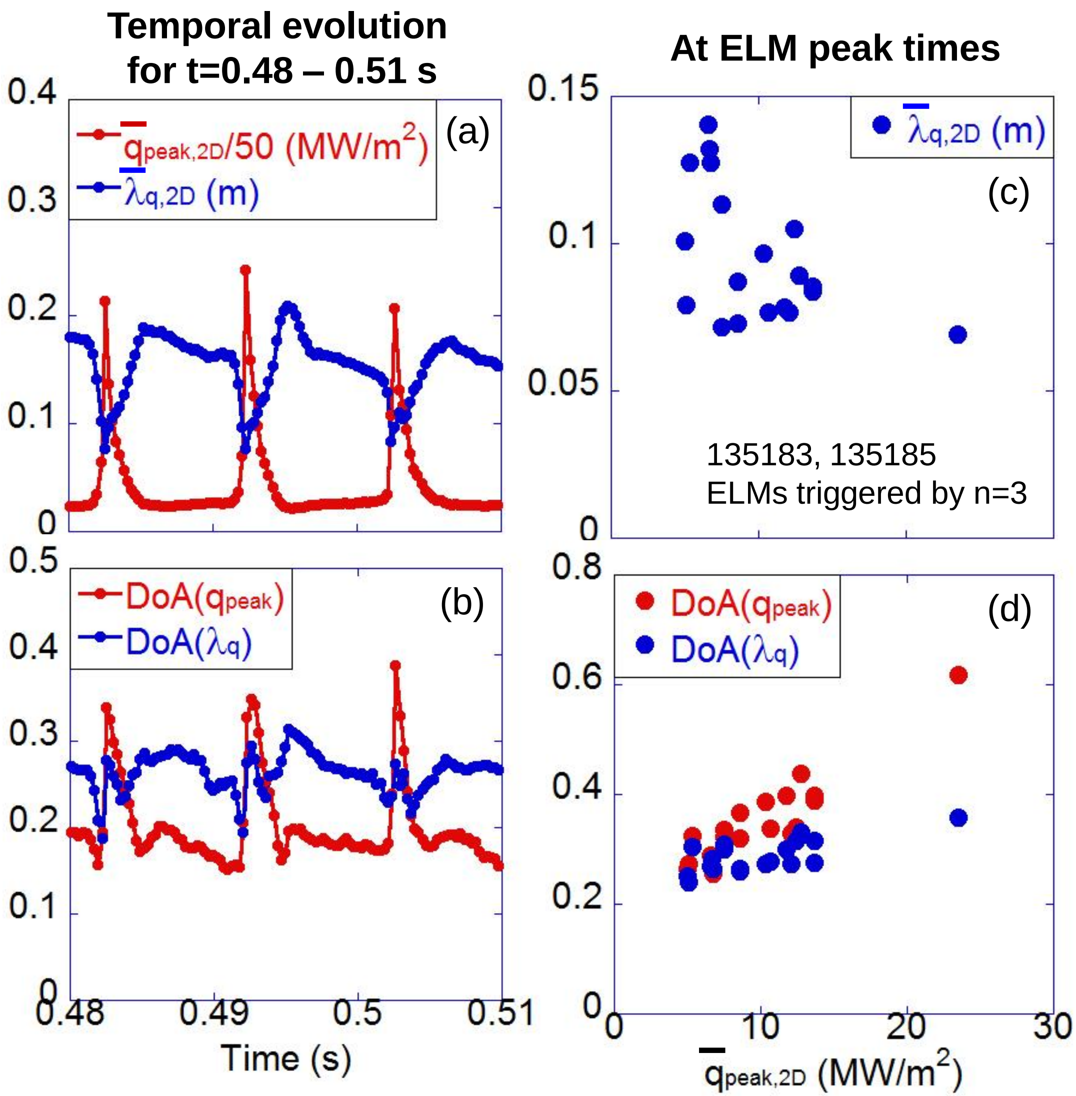




- Striations in the heat flux profile appear in the same locations as before the ELM
- 3-D field (n=3) triggered ELMs in NSTX are phase-locked to the externally applied perturbation structure[1] (also seen in DIII-D[2])

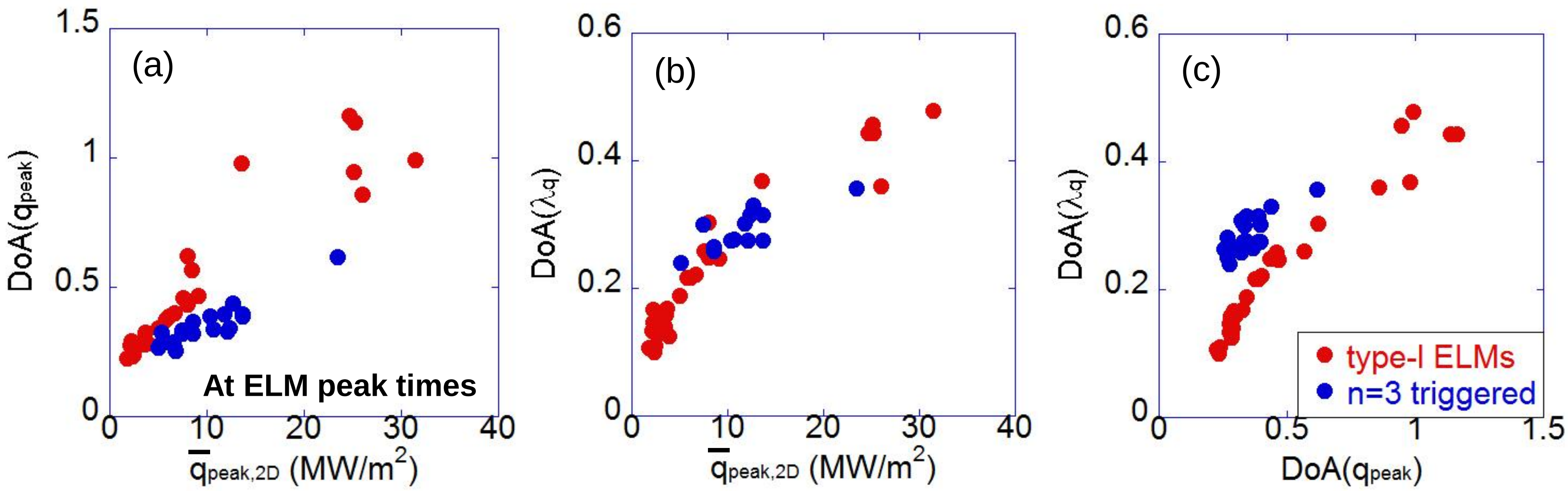
[1]J-W. Ahn, JNM 415 (2011), S918 [2]M. Jakubowski, NF 49 (2009), 095013

Behavior of Degree of Asymmetries is not the same as the naturally occurring type-I ELMs – 3-D field triggered ELMs



- Important to examine the characteristics of 2-D heat flux deposition for the triggered ELMs
- The heat flux width drops dramatically by 40-60 % during the ELM
- λ_q continues to decrease slowly for a significant fraction of the inter-ELM period → opposite to all types of naturally occurring ELMs
- The increase of DoA(λ_q) due to the ELM is very weak compared to the inter-ELM level, while DoA(q_{peak}) shows a clear spike for each ELM

Comparison of toroidal asymmetries between naturally occurring type-I ELMs and 3-D field triggered ELMs



- Both for DoA(q_{peak}) and DoA(λ_q), the dependence on peak heat flux is noticeably weaker for the triggered ELMs than for the type-I ELMs

- Correlation between DoA(q_{peak}) and DoA(λ_q) shows that the variation of DoA(λ_q) is significantly weaker than that of DoA(q_{peak})

  → May provide an insight into the mechanism of 3-D field ELM triggering

  → Any relation to the observed phase lock of heat flux profile to the 3-D fields?

Summary and Conclusions

- Implementation of TACO with the incorporation of surface layer effect enables easier study of 2-D heat flux distribution and the toroidal asymmetry of heat flux profiles via remapping of data from (x, y) to the (r, Φ) plane
- The Degree of Asymmetry (DoA) was defined for q_{peak} and λ_q to quantify how asymmetrically (in the toroidal direction) these two parameters are distributed, as well as the definition of mean value of q_{peak} and λ_q for the 2-D plane
- During the ELM, λ_q decreases for type-I and high β_p type-III ELMs but increases for low β_p type-III and type-V ELMs. At ELM peak times, λ_q tends to decrease as q_{peak} increases
- Both DoAs, as well as the correlation between the two DoAs, increase with increasing peak heat flux and therefore are highest at the ELM peak times
- $\lambda_{q,mid}$ variation has no significant impact on DoAs except for low $\lambda_{q,mid}$ (~2cm)
- Similar level of DoA(q_{peak}) and DoA(λ_q) are observed for Type-V ELMs
- 3-D field triggered ELMs have lower level of toroidal asymmetries compared to naturally occurring type-I ELMs. The range of DoA(λ_q) is particularly narrower → Any relation to the observed 'phase lock' of heat flux profile to the 3-D fields?