NSTX-U

Supported by U.S. DEPARTMENT OF ENERGY Office of Science

Evaluation of 2-D heat flux profiles and its application to the divertor physics study in NSTX

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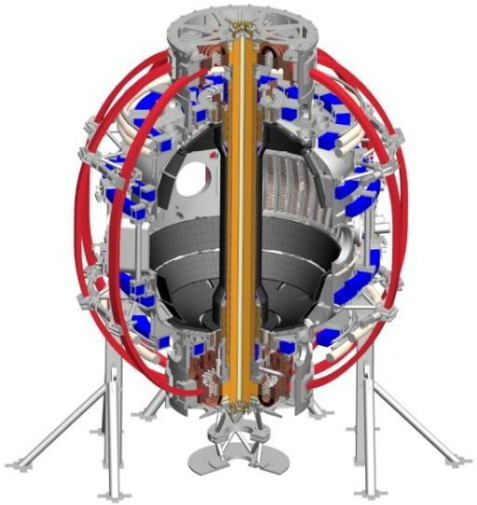

Motivation

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

  → can be harmful to the integrity of divertor tiles because the design is usually based on the assumption of axisymmetry

- Need to quantify the toroidal asymmetry in heat flux (and extrapolate it to the future machine if possible)

  → 2-D profile is necessary to study toroidally asymmetric heat deposition

  → Explore connection with upstream and/or global parameters

- Conventional heat conduction codes typically produce 1-D radial heat flux profiles

  → implemented a 2-D heat flux code including surface layer effects

Outline

- Evaluation of 2-D heat flux profiles by TACO with effect of thin surface layer incorporated
- Estimation of toroidal asymmetry from 2-D profiles
- Examples of application
  - Toroidal asymmetry in heat flux during ELMs
  - Toroidal asymmetry in heat flux by error fields
- Caveats and future work

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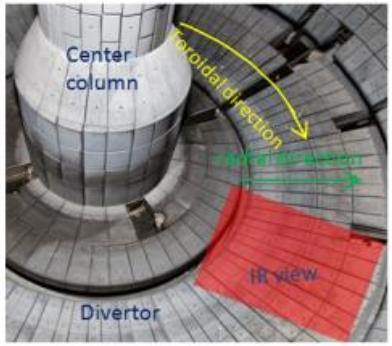
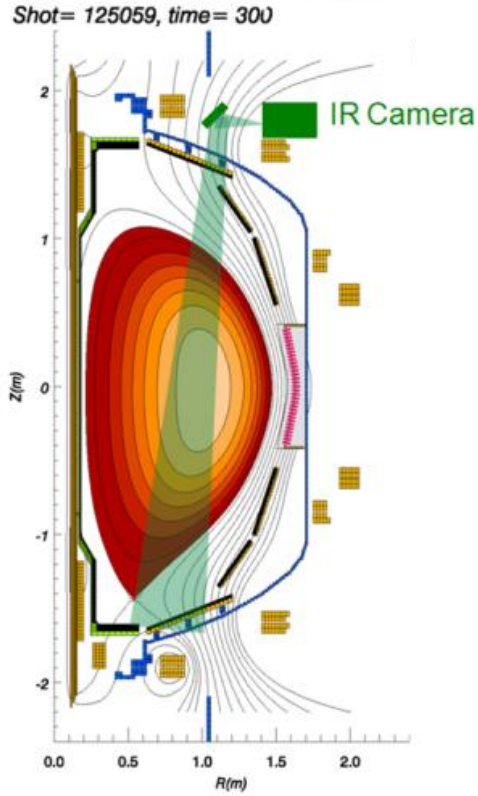
IR camera diagnostics for heat flux measurement





- Lower divertor surface temperature is monitored by fast IR camera
  - Long wavelength: 8-12 μm
  - Spatial resolution: ~7 mm
  - Frame speed: up to 6.3 kHz

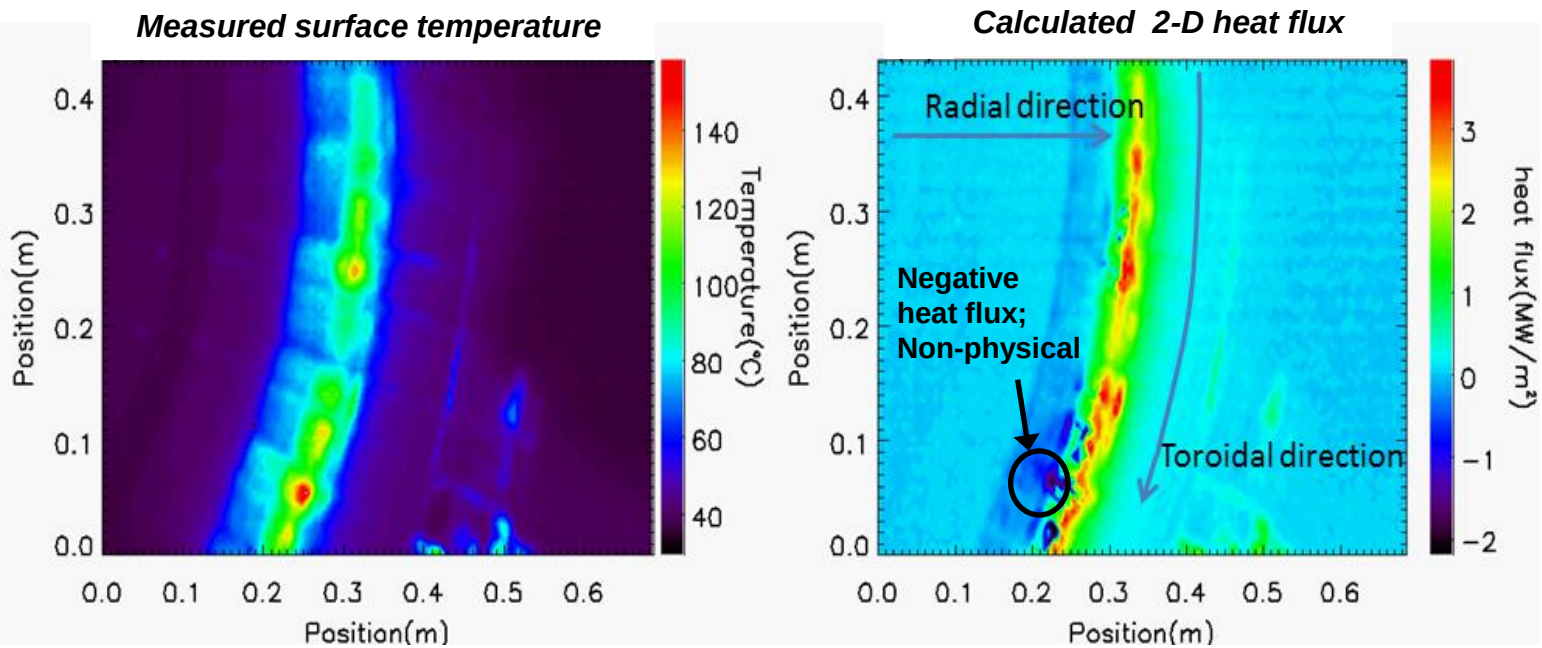
- Heat flux calculation from the measured surface temperature
  - 2-D heat flux profile (TACO[1] code) enables investigation of spatial structure of heat flux profile

[1] In collaboration with Culham, UK

TACO calculates 2-D heat flux distribution at divertor surface

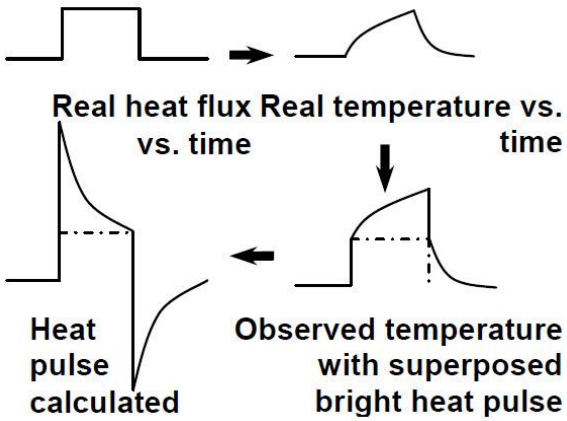
$$Q_{xy}(t_j) = \frac{k\delta}{2\chi\Delta\tau}\frac{(T_{xy}(t_j)-T_{xy}(t_0))}{C_o} - \sum_{\ell=1}^{j-1} Q_{xy}(t_{j-\ell})\frac{C_l}{C_0}$$

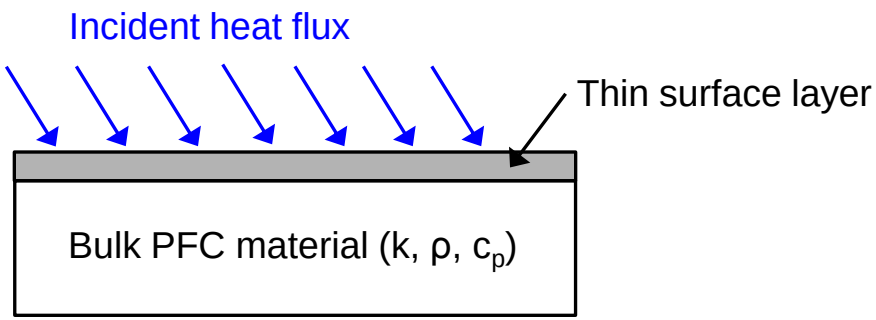
Surface heat flux



- 2-D heat flux data in (x, y) coordinates are obtained from TACO

The effect of thin surface layer on heat flux calculation





- Thin layer of hydrocarbon composite often forms on the surface of PFC material
- Low thermal conductivity with poor thermal contact with the PFC substrate underneath

  → IR emission is much brighter when a heat pulse hits the surface than it should be w/o thin layer → interpreted as much higher temperature rise than real → Excessively high heat flux computed to explain this ΔT_{surf}
- Also, the surface layer makes the drop of surface IR emission excessively rapid after the heat pulse

  → interpreted as a rapid T_{surf} drop → Solution of heat conduction equation yields negative heat flux to accommodate this temperature change

Implementation of heat transmission coefficient for surface layer alleviates negative heat flux problem

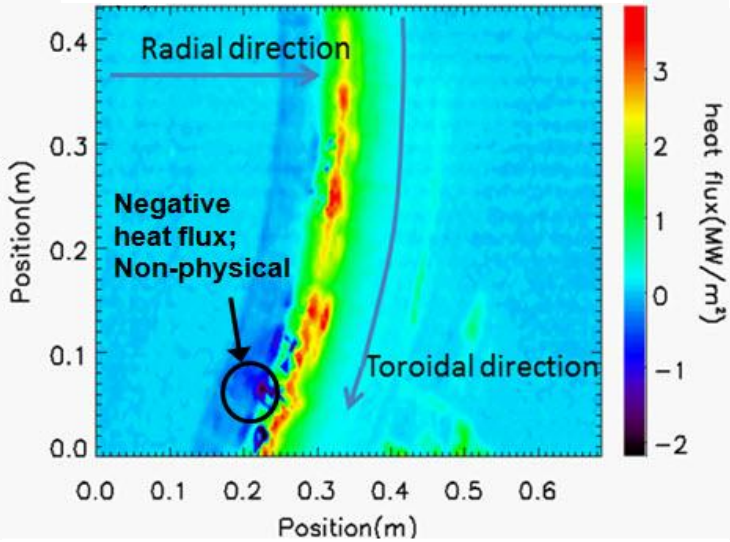
$$\alpha = k_{layer} / d \longrightarrow T_{bulk} = T_{measured} - \frac{q_s}{\alpha}$$

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

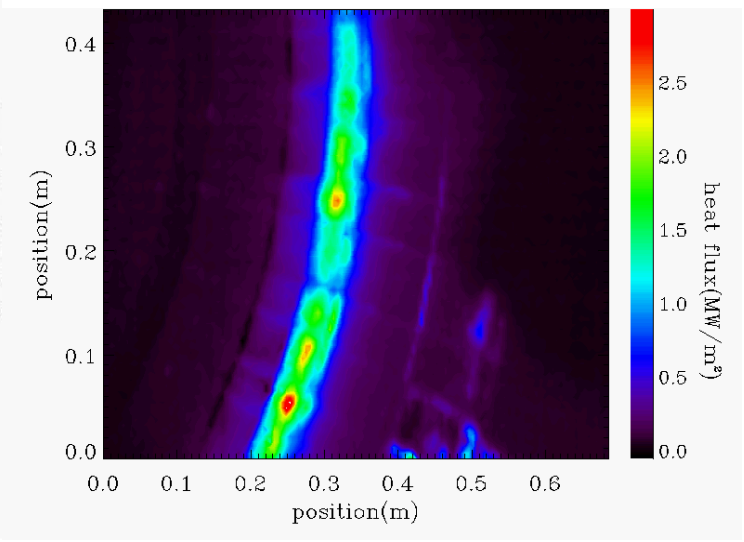
$$Q_{xy}(t_j) = \left(\frac{T_{xy}(t_j) - T_{xy}(t_0)}{C_o} - \sum_{\ell=1}^{j-1} Q_{xy}(t_{j-\ell}) \frac{C_\ell}{C_0} \right) \Big/ \left(1 + \frac{k\delta}{2\chi\Delta\tau C_0 \alpha} \right)$$

Surface heat flux with α incorporated in heat conduction equation[2]

Calculated 2-D heat flux with no α



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



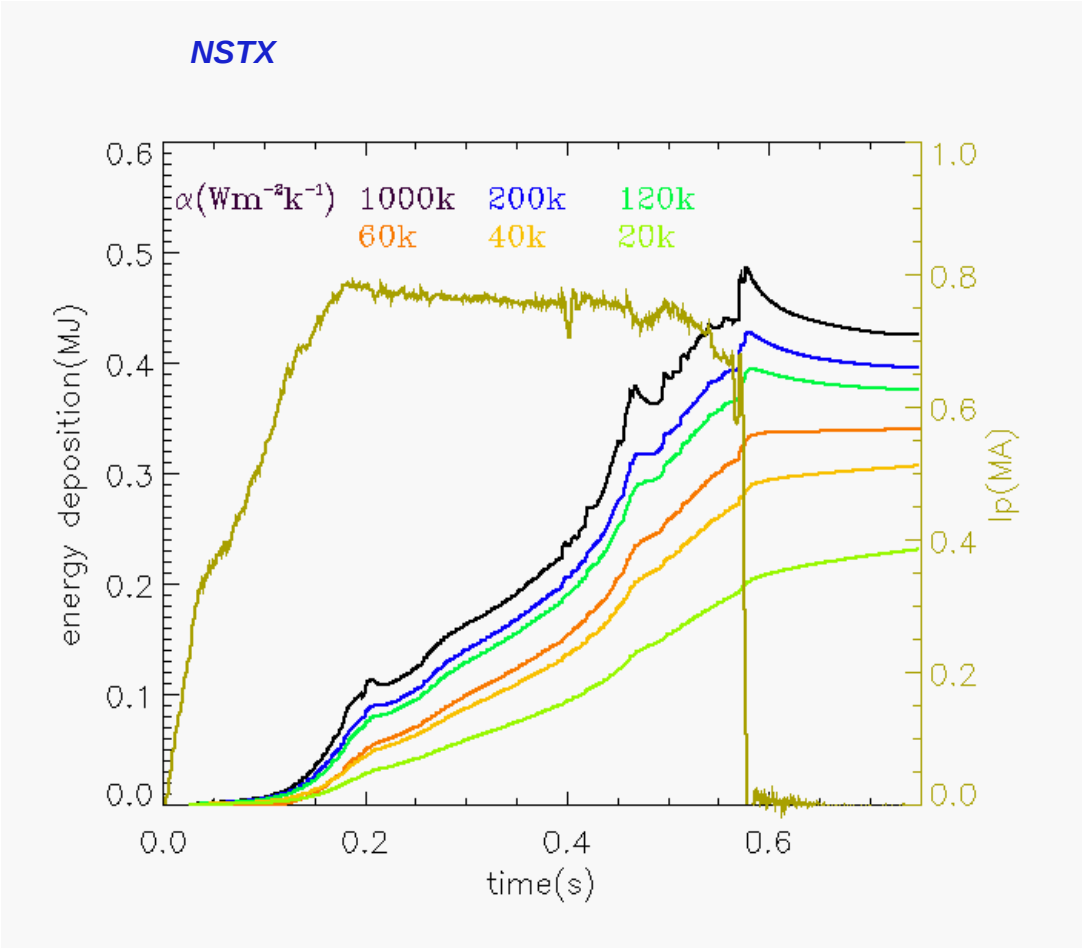
- Assume there is an excess temperature at the surface proportional to the incident heat flux, $T_{surf} - T_{bulk} = q_{surf}/\alpha$. If no surface layer, $\alpha \rightarrow \infty$ and $T_{bulk} \rightarrow T_{surf}$

[1] A. Herrmann, PPCF (1995)

International collaboration with IPP-Garching

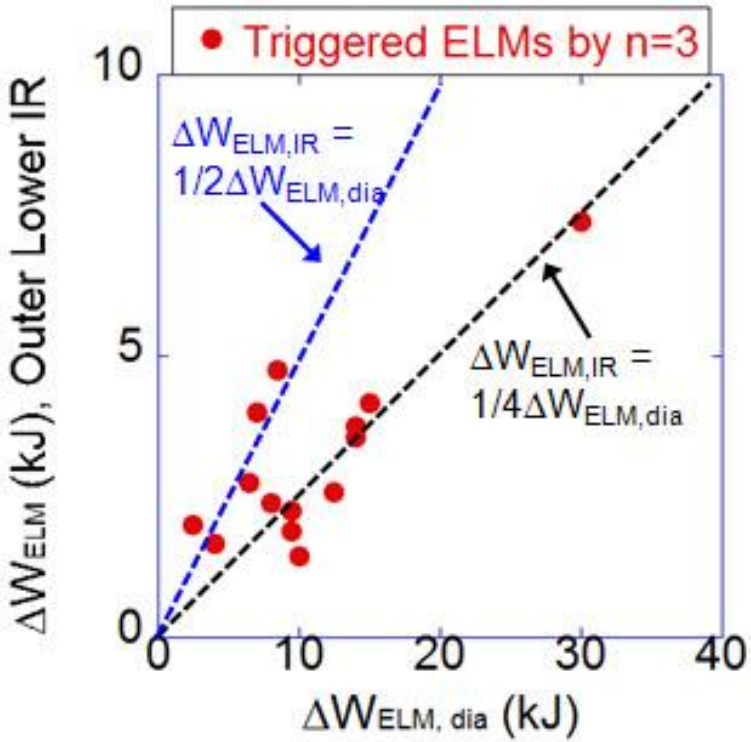
[2] K.F. Gan, J-W. Ahn, accepted to RSI (2013)

Choice of α value is made by comparing time traces of deposited energy from different α



- The α value makes a large influence on the heat flux calculation, and different values lead to very different results
- Several ways to choose α have been used in different machines
- In NSTX, we choose the α value that keeps the deposited energy constant after the discharge

Measured ELM energy loss accounts for 25 – 50% of stored energy loss for the chosen α value



- Data for ELMs triggered by n=3 magnetic perturbations, α=40k used
- $\Delta W_{ELM,IR}$ measured for outer lower divertor

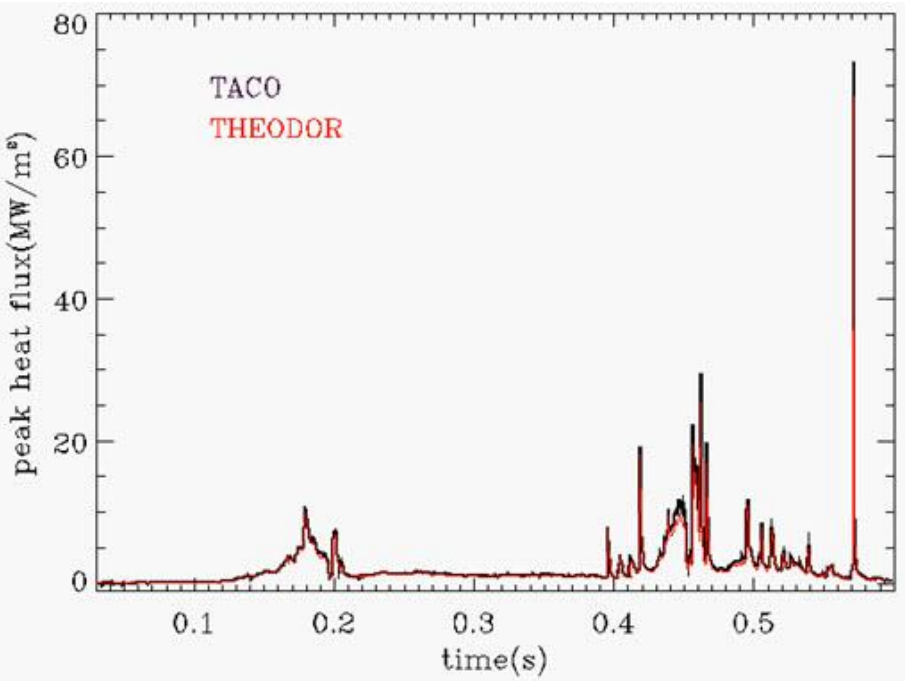
  → majority of data distributed between 1/4$\Delta W_{ELM,dia}$ and 1/2$\Delta W_{ELM,dia}$
- $\Delta W_{ELM,IR}$ for both inner and outer divertors are found to be 0.4 – 0.7$\Delta W_{ELM,dia}$ in JET[1]

  → NSTX data seem in right ballpark

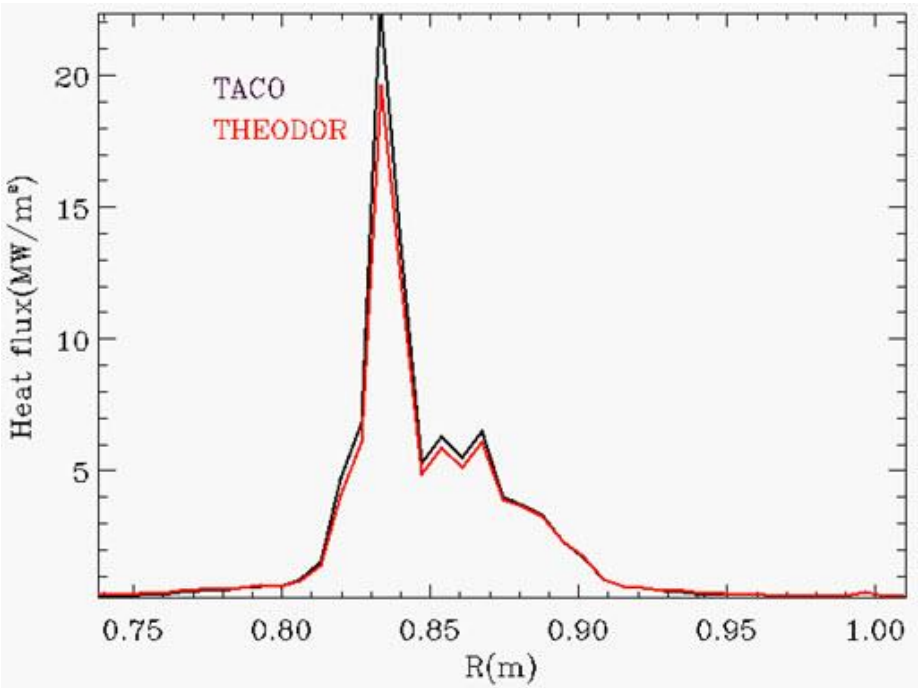
[1]Eich, PPCF 2007

Comparison of new TACO calculation and THEODOR with same α value

Peak heat flux evolution



Heat flux profile



- Comparison of 1-D radial profile results from TACO to those from THEODOR
  → Good agreement for both the temporal evolution of peak heat flux and the spatial heat flux profile at a specific time slice

K.F. Gan, J-W. Ahn, accepted to RSI (2013)

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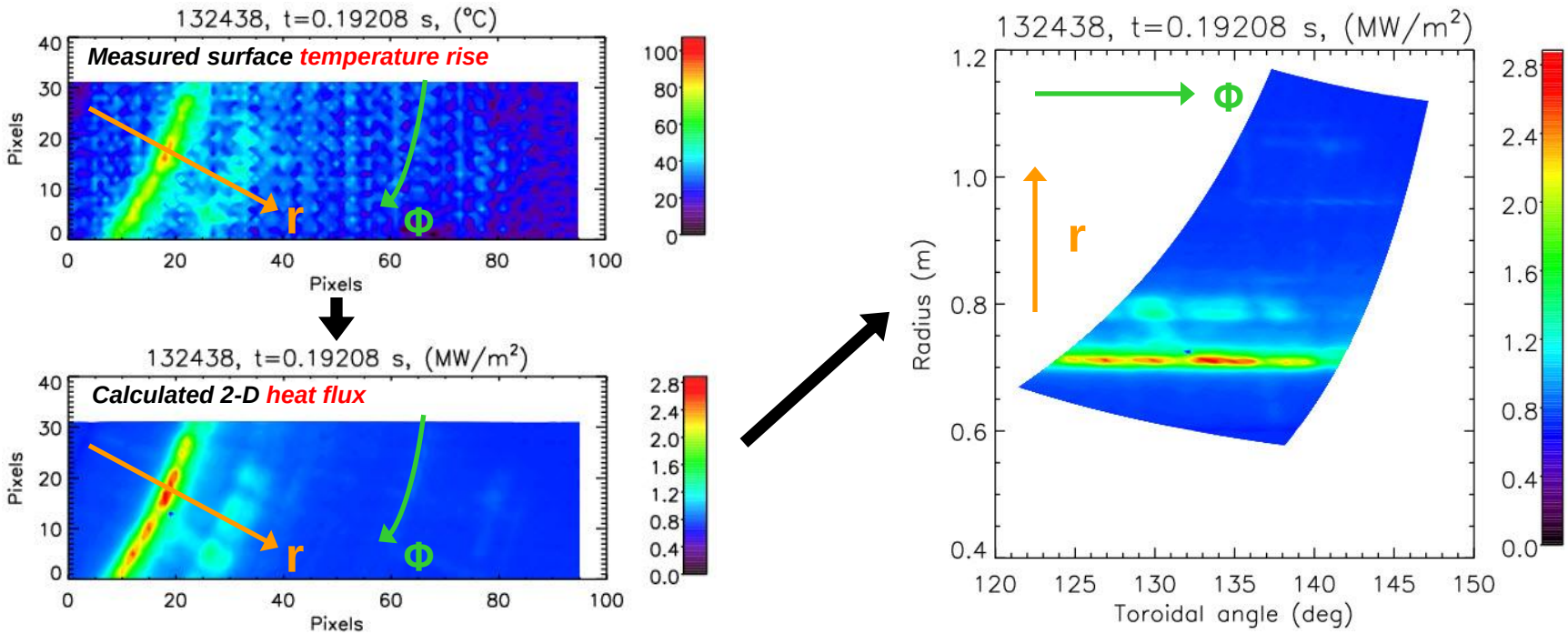
  - Toroidal asymmetry in heat flux by error fields
- Caveats and future work

Obtained 2-D Heat flux profiles are re-mapped from (x, y) to (r, Φ) plane



- TACO calculates 2-D heat flux profiles in (x,y) coordinates
- 2-D heat flux profile in (x, y) plane is re-mapped to the (r, Φ) plane
  → useful technique in the study of toroidally non-axisymmetric heat flux deposition
  → particularly important during the ELMs and 3-D fields application

Several figure of merits can be defined for the toroidal asymmetry in heat flux for the 2-D plane

- Toroidal peaking factor (PF) of peak heat flux (q_{peak}):

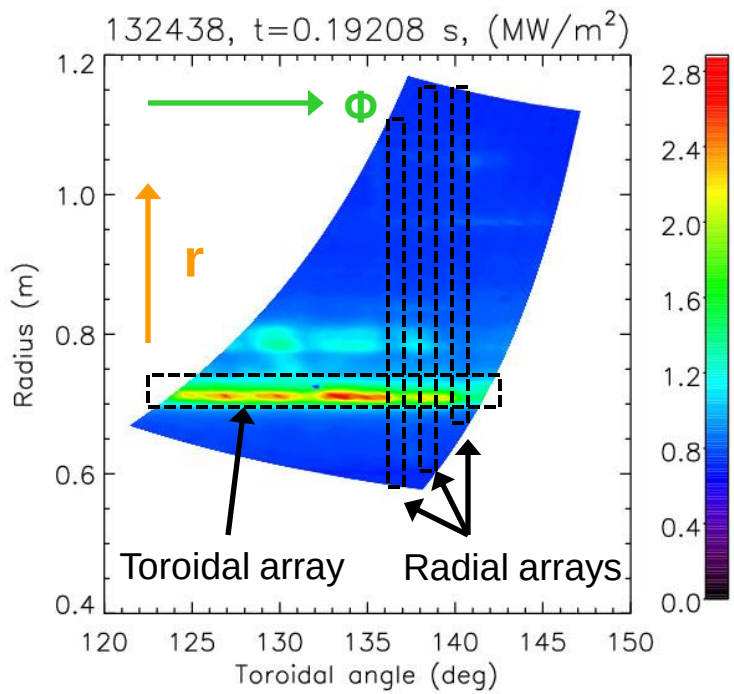
  $PF(q_{peak}) = max(q_{peak})/mean(q_{peak})$
- Toroidal degree of asymmetry (ε_{DA}) for q_{peak} and λ_q

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

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

  - q_{peak} and λ_q obtained for each radial array of data
  - σ_{qpeak} 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

J-W. Ahn, accepted to JNM (2013)



- ε_{DA} for overall 2-D heat flux

$$\varepsilon_{DA}(q) = \Sigma(\sigma_q / \bar{q}_{1D,toroidal}) / N$$

  - σ_q is the standard deviation of heat flux (q) for each toroidal array, is then normalized to the mean value, and is finally averaged over the whole 2-D plane

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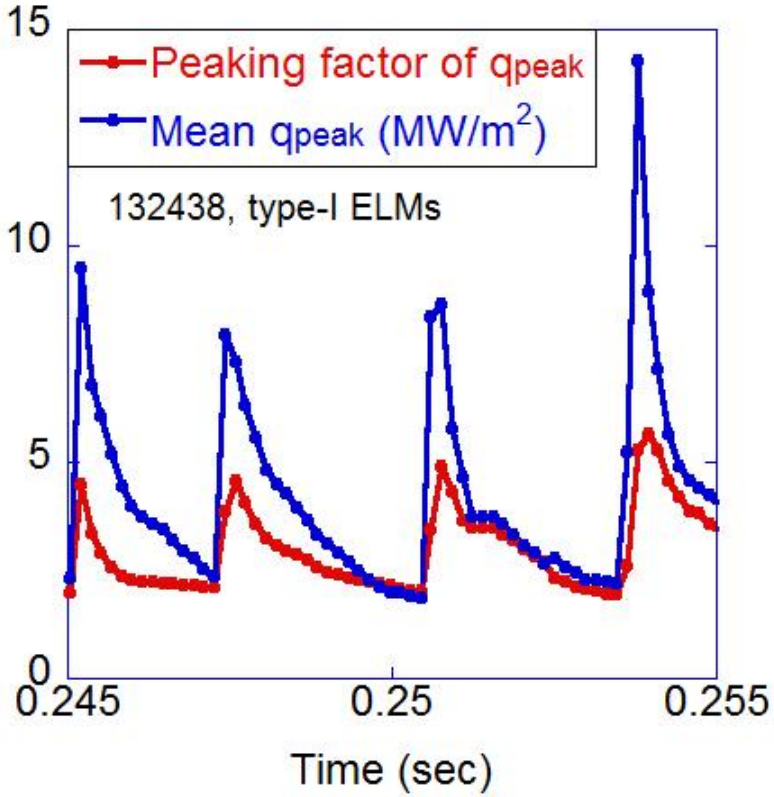
Toroidal peaking factor increases as the peak heat flux rises during the ELM

- Peaking factor goes up during the ELM

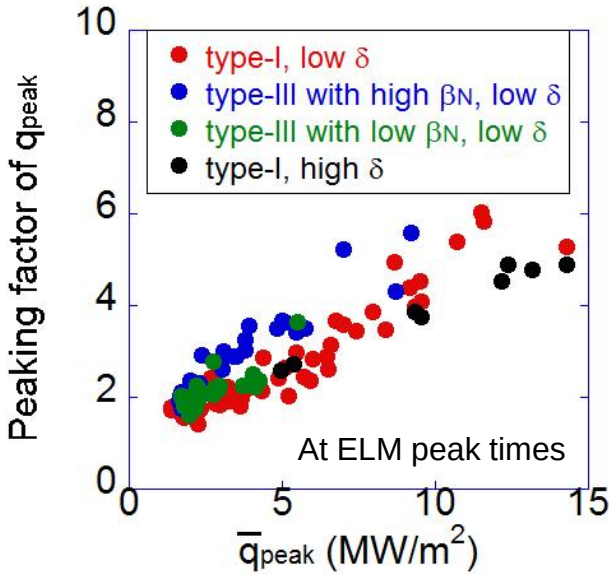
→Toroidal distribution of peak heat flux becomes rapidly asymmetric during the ELM



J-W. Ahn, APS 2012

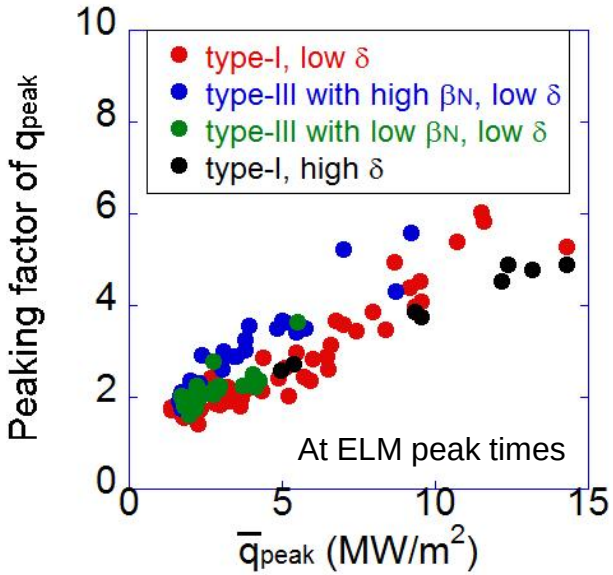
Peaking factor at ELM peak times is strongly dependent on peak heat flux and is independent of ELM types

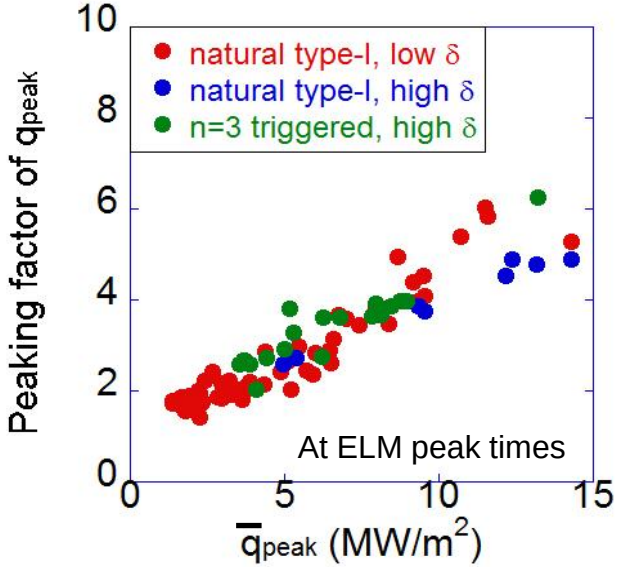
- Peaking factor at ELM peak times increases with increasing q_{peak} for all ELM types
- Data for different ELM types align well → independent of ELM types



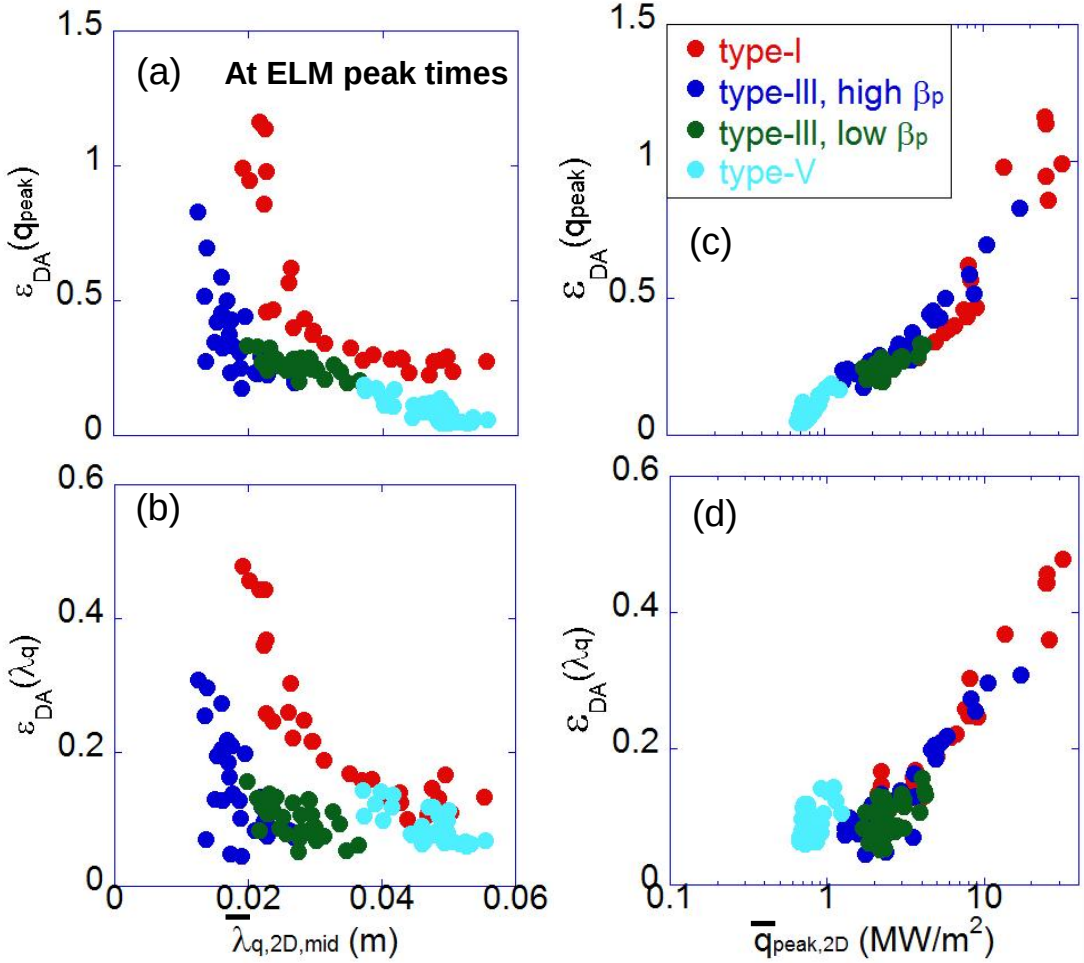
Peaking factor at ELM peak times is strongly dependent on peak heat flux and is independent of ELM types

- Peaking factor at ELM peak times increases with increasing q_{peak} for all ELM types
- Data for different ELM types align well → independent of ELM types
- Data for triggered ELMs are well aligned with the natural type-I ELMs
  → The dependence of toroidal peaking factor on the peak heat flux is common





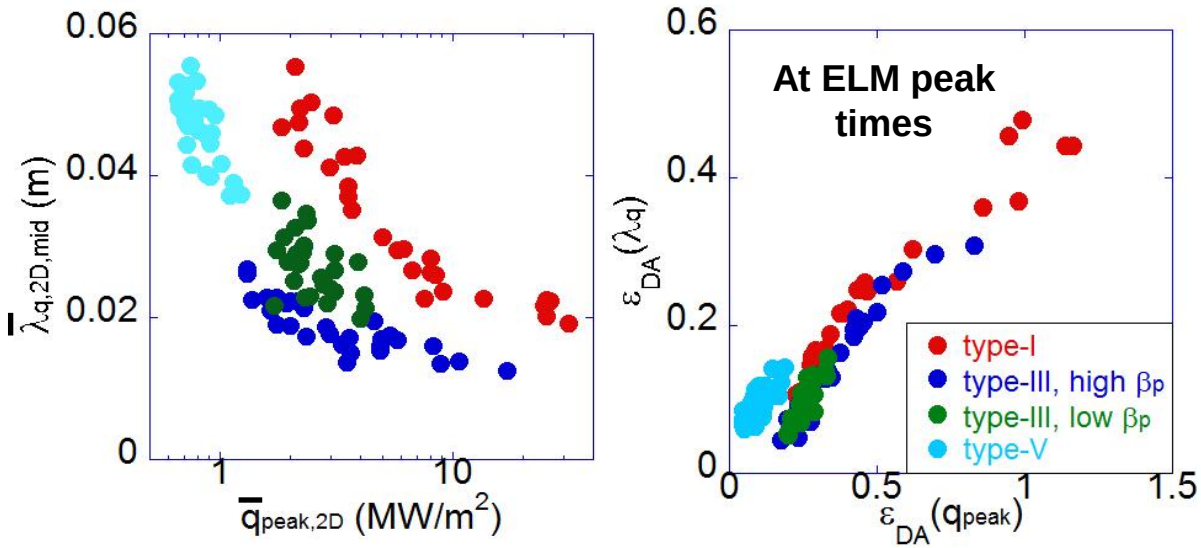
Dependence of toroidal asymmetries on peak heat flux and mid-plane heat flux width for all ELM types



J-W. Ahn, IAEA 2012

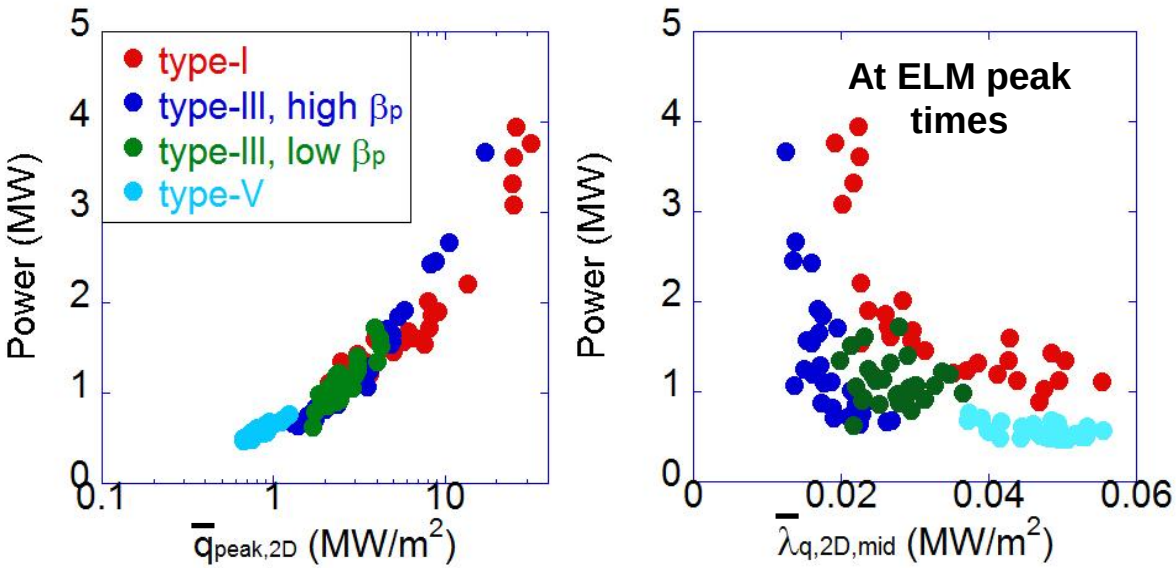
- Comparison of the two ε_{DA}s as a function of peak heat flux and heat flux width for all ELM types → Mid-plane heat flux width ($\bar{\lambda}_{q,2D,mid}$) is used, taking account of the flux expansion
- As a function of $\bar{\lambda}_{q,2D,mid}$: ε_{DA}s rapidly decrease with increasing $\bar{\lambda}_{q,2D,mid}$ 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 ε_{DA}s increase with increasing q_{peak}, type-V ELMs have relatively higher $\varepsilon_{DA}(\lambda_q)$

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



- Inverse relationship between $\bar{\lambda}_{q,2D,mid}$ and $\bar{q}_{peak,2D}$ 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 ε_{DA}s 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 IR power 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 $\bar{\lambda}_{q,2D,mid}$)

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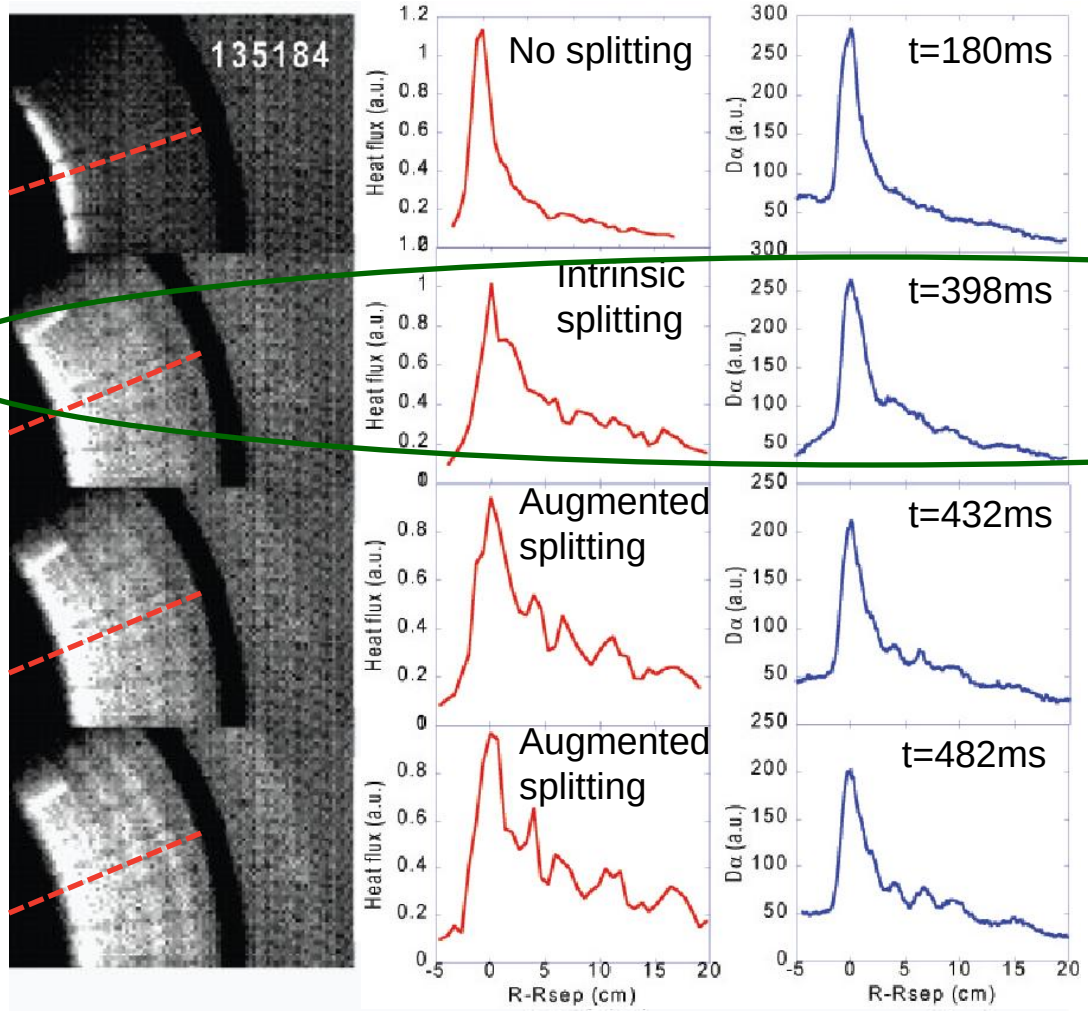
Divertor profile is modified by intrinsic and applied 3-D magnetic perturbations

Raw IR image **Heat flux profile** **D_α profile**



At earlier time slice

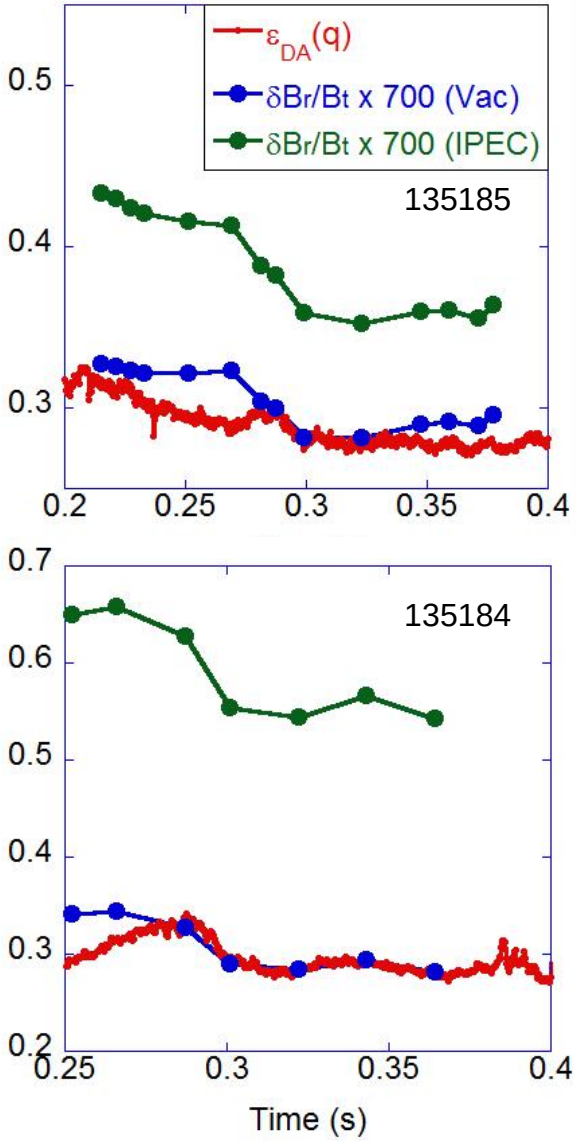
2ms before 3-D field application

32ms after 3-D field application

82ms after 3-D field application

J-W. Ahn, Nucl. Fusion (2010), 045010

Asymmetry in heat flux can be used as an indicative to the internally arisen 3-D effects such as from error fields



- Three primary sources of intrinsic error fields are considered
  - n=3 and n=1 from PF5 coil, n=1 from OH coil
- $\delta B_r/B_t$ estimation both from vacuum and with ideal plasma response (IPEC) calculations
- Agreement between $\varepsilon_{DA}(q)$ and $\delta B_r/B_t$ is reasonably good
- IPEC provides consistently higher perturbation fields than vacuum, although the trend of time trace is similar to the result from vacuum calc.

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Caveats for the study of toroidal asymmetry in heat flux

- Irregular (i.e. spatially varying) PFC surface layers could affect the measurement because only a constant heat transmission coefficient is being used for the solution of heat conduction equation
  - Could be a problem locally but probably not a dominant factor overall because the α treatment is for the whole 2-D plane observed

- Tile misalignments and gaps can add artificial toroidal asymmetry
- Intrinsic error fields produce baseline toroidal asymmetry

} Can produce baseline toroidal asymmetry irrespective of physics

Future work for TACO development

- Extension of TACO from semi-infinite to finite thickness geometry

  → necessary for long pulse plasmas in NSTX-U, KSTAR, etc

- Modeling of thermal response of liquid lithium for NSTX-U

- Account for the IR reflection effects for metallic PFCs (eg, by ray tracing, etc)

- More complicated situations in the future (eg, actively cooled PFCs, etc)

Future work for physics investigation

- Implementation of wide angle IR camera to cover nearly full (r,Φ) → significant advantage for 3-D physics study
- Simultaneous achievement of high speed for ELM resolution, if possible
- 3-D Modeling of non-linear evolution of ELMs (eg, by JOREK) to compare transient divertor flux to the measurement
- Explore link of 2-D divertor flux distribution to the pedestal conditions including ELM control experiments

Summary and Conclusions

- 2-D heat flux profiles are computed with the TACO heat flux code, enabling to study toroidal asymmetries for steady and transient heat flux profiles

- Several figure of merits for the toroidal asymmetry in heat flux profile have been defined – each one suitable for different asymmetry characteristics

  → Asymmetry increases during the ELM

  → Strong positive dependence on peak heat flux regardless of ELM types (3-D field triggered ELMs also follow the same trend and the asymmetry data are well aligned with naturally occurring type-I ELMs)

  → Temporal evolution of heat flux asymmetry caused by intrinsic strike point splitting agrees reasonably well with the calculated magnetic perturbation by error fields