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Cross diagnostics measurements of heat load profiles on the lower tungsten divertor of WEST in L-mode experiments

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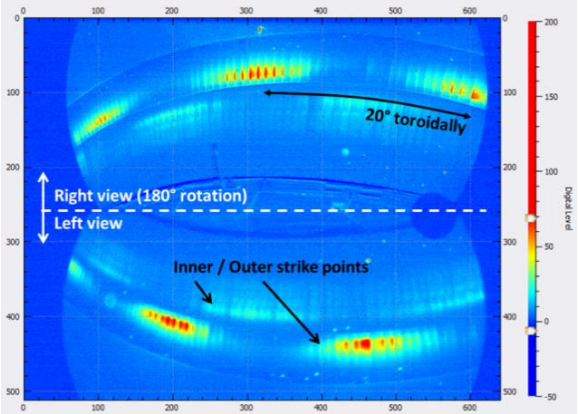
Summary

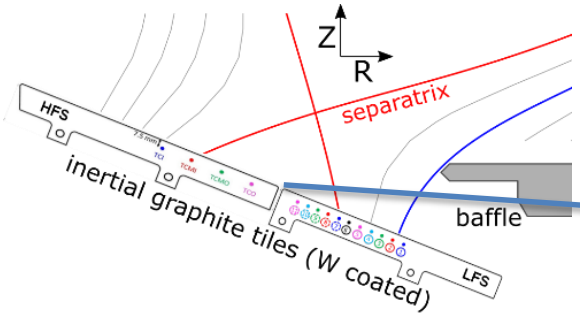
	slides
WEST: full metallic tokamak + extensive set of diagnostics for heat load measurement on lower divertor tungsten tiles (tungsten coated uncooled graphite tiles)	**3**
• Flush mounted Langmuir probes, **not discussed here**	
• High resolution arrays of embedded thermal sensors (TC & FBG)	**4**
• Infra-red (IR) thermography	**5-7**
Results overview:	
IR challenged by inhomogeneous & low surface emissivity of W tiles $(\epsilon \approx 0.1)$	**6**
Toroidal heat load modulation → consistent with incidence angle modulation by ripple	**8**
IR and embedded sensors → consistent peak heat flux and integrated tile energy	**9-10**
L-mode scenarios with $P_{add} = 4$MW → up to 6MW/m2 on the divertor targets	
Target heat channel width (λ_q^t) depends linearly on magnetic flux expansion	**11**
Remaining issue: λ_q^t from IR about 3 times lower than λ_q^t from embedded sensors	**11-12**

Inside view of WEST

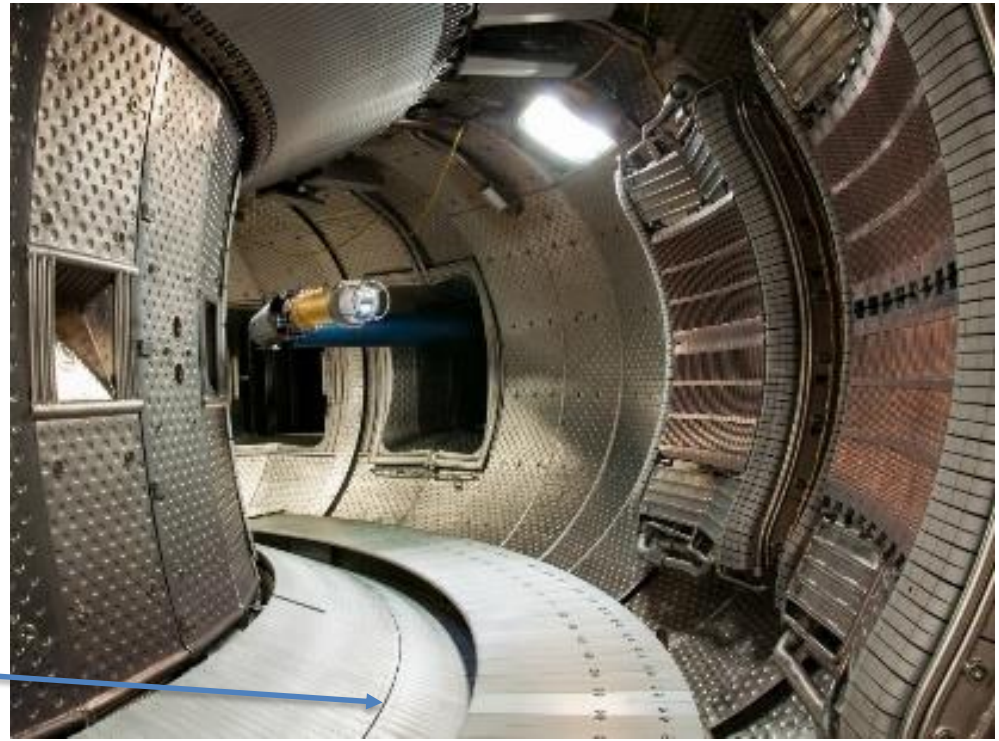
Lower divertor infra-red thermography



Thermocouples / FBG



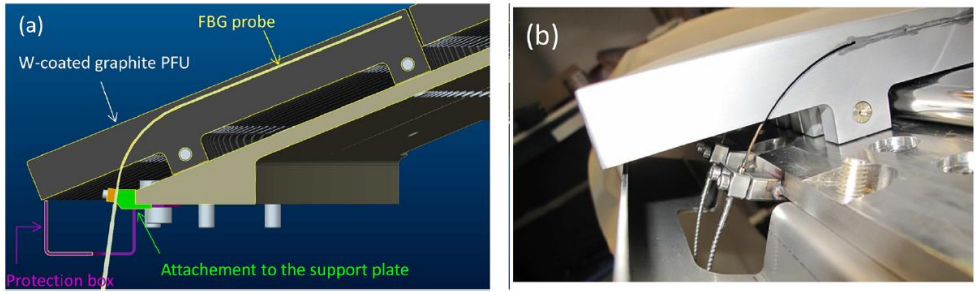
Inside of WEST tokamak (with the articulated inspection arm)

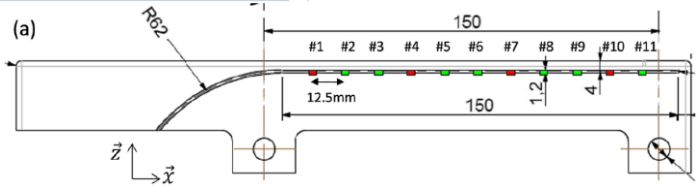


Thermal sensors embedded a few mm from tile surface allow inversion of deposited heat flux

Fiber Bragg Gratings: 12.5mm spatial resolution

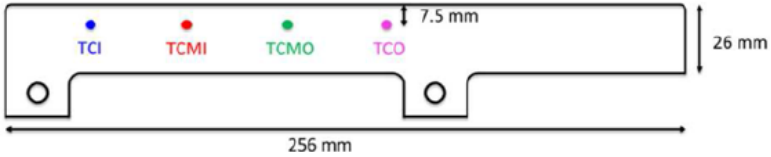
[Y. Corre FED 2018]





Thermocouples: 37.5 mm spatial resolution

[J. Gaspar JoP 2016]



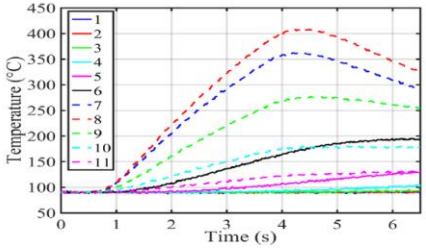
- Absolute bulk temperature measurements
- Consistency between TC & FBG
- Data inverted into deposited heat flux profiles:

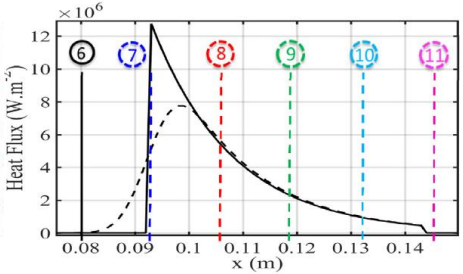
[J. Gaspar NME 2017]

- assuming a "Wagner" shape

$$q(s) = \frac{q_0}{2} \cdot \exp\left(\left(\frac{S^t}{2\lambda_q^t}\right)^2 - \frac{s - s_0}{\lambda_q^t}\right) \cdot \mathrm{erfc}\left(\frac{S^t}{2\lambda_q^t} - \frac{s - s_0}{S^t}\right) + q_{bg}$$

- s_0, λ_q^t & S^t constant in time
- q_0 & q_{bg} time dependant





Infra-red thermography of tiles equipped with thermocouples

- Absolutely calibrated infra-red endoscopes (top ports) looking at lower divertor

  [X. Courtois FED 2019]
- Effective Black body T° profiles extracted along tiles equipped with thermocouples (for emissivity calibration)
- Spatial resolution ≈ 2.7mm

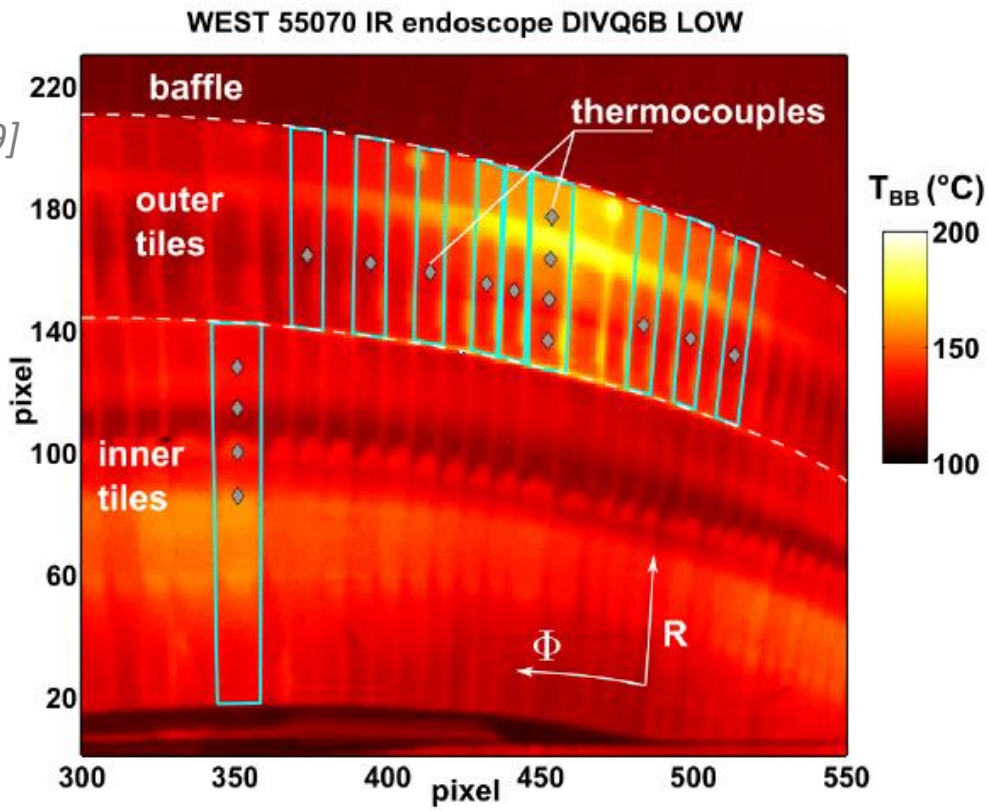
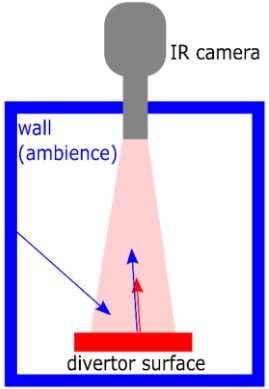


Figure 1: infra-red view of a section of the lower divertor prior to a plasma pulse, following a session of divertor loading. The colormap represents the calibrated effective black body temperature. The pattern exhibits a toroidal modulation (along Φ) due to plasma loading modulated by magnetic ripple, and radial modulations (along R) consequent from varying surface emissivity. Light blue rectangles delimit tiles that are equipped with thermocouples, and along which treatments are performed. Tiles equipped with 4 thermocouples sits at toroidal locations where magnetic ripple produces the maximum deposited heat flux.

Surface emissivity profiles estimated from pre-pulse conditions → show strong inhomogeneity & low values around strike points

Insitu methodology to estimate emissivity profiles from IR & embedded TC:

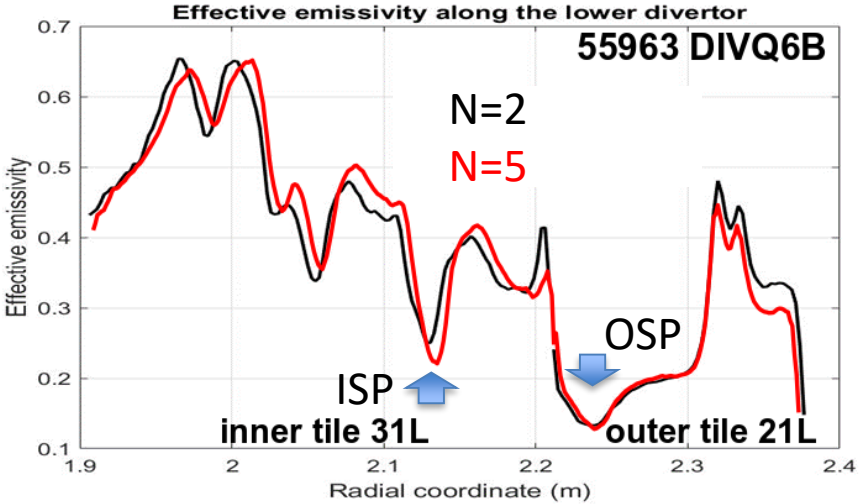
- Luminance model $L_{planck}(T_{IR}) = \epsilon L_{planck}(T_{true}) + (1-\epsilon)\epsilon_{amb} L_{planck}(T_{wall})$
- In the pre-pulse phase: tile temperature is uniform and different than wall temperature
- True tile temperature measured by thermocouples
- From N consecutive pre-pulse phases (T increments)
  → Best fit of emissivity values from IR ad TC data



Important Results:

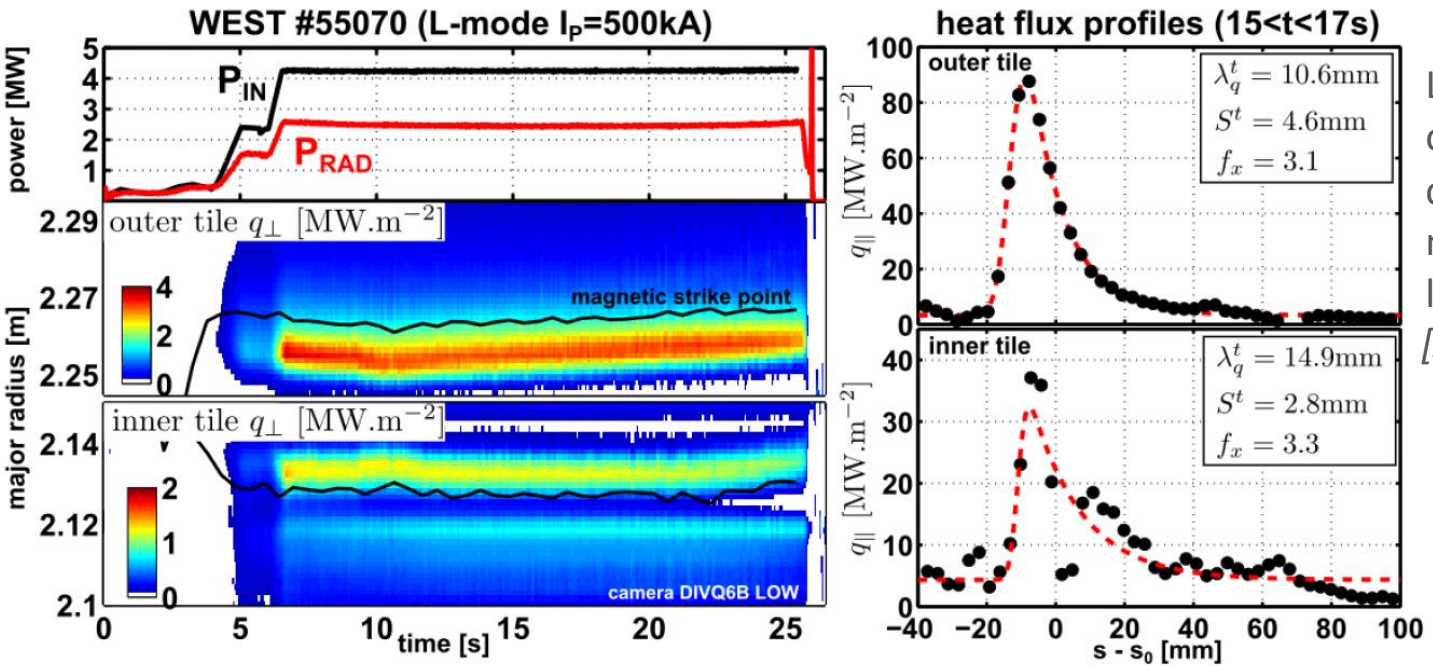
- Emissivity varies strongly across the divertor surface
- Very low ($\epsilon \approx 0.1$) around the main outer strike point
- Varies across campaigns (possibly related to deposits)

[J. Gaspar this conference Poster session 3 n°66]



Corrected IR data inverted with TEDDY (equivalent to THEODOR)

- Thermal inversion with TEDDY *[N. Fedorczak Phys.Script. 2020]*
- Outer target profiles well fitted with a “Wagner” shape.
- Fit less robust for the inner target (multiple peaks related to ExB flows?)



L-mode scenario
outer target $\lambda_q \approx 3.4$mm
consistent with multi-machines L-mode scaling law
[A. Scarabosio JNM 2013]

Heat flux pattern toroidally modulated by the incidence angle (magnetic ripple)

Finite magnetic ripple in WEST (~1%)

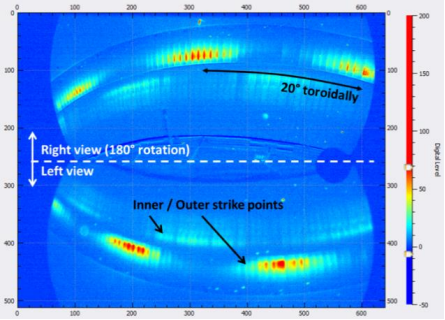
→ The magnetic field incidence angle on the divertor surface is toroidally modulated

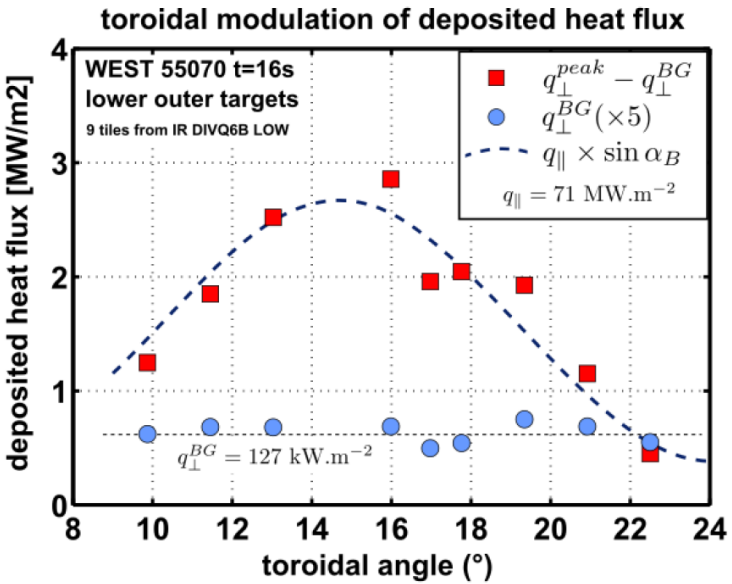
Toroidal modulations of IR estimated heat flux at outer target consistent with:

- geometrical projection of a toroidally uniform parallel heat flux
- plus a toroidally uniform background* much weaker than peak heat flux (one order of magnitude)

(background value ~2 times larger than radiative flux estimated from bolometry inversion)

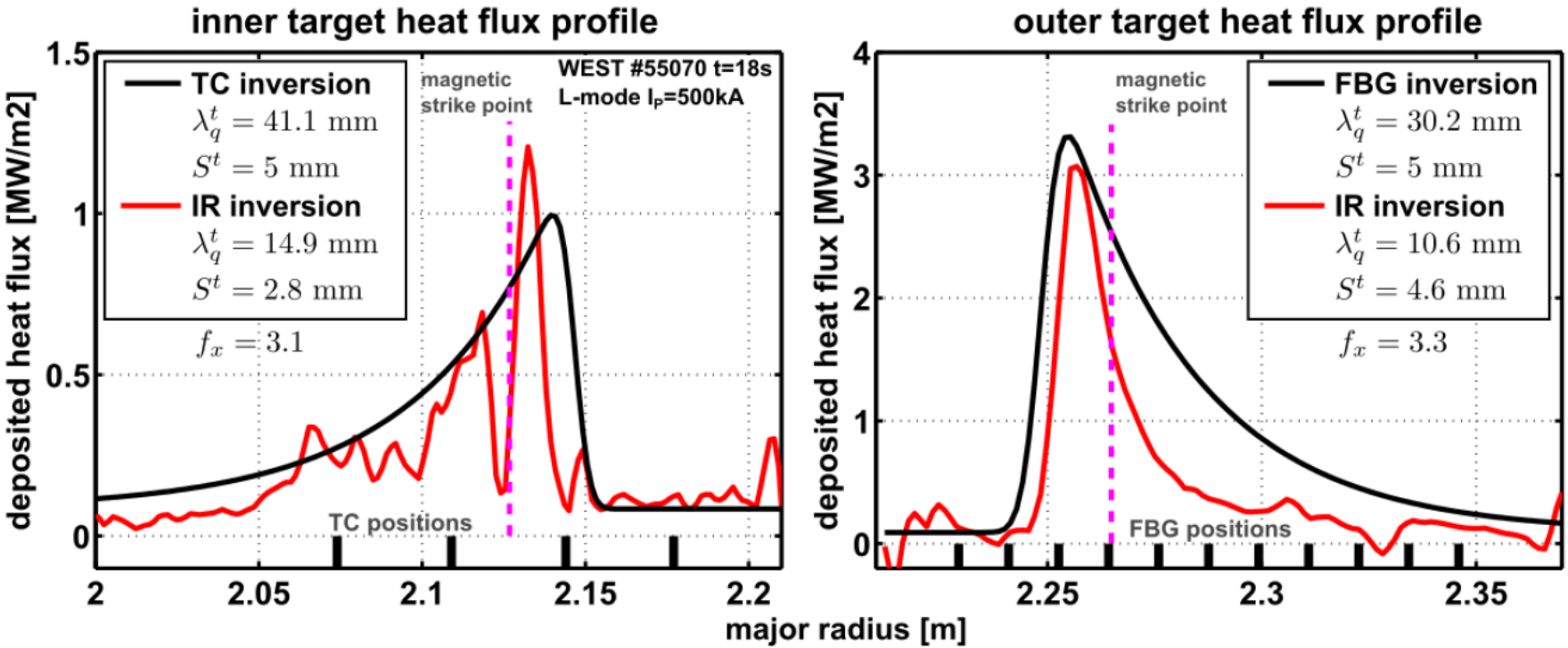
→ Validates the common assumption that deposited heat flux is dominated by the projection of a parallel heat flux





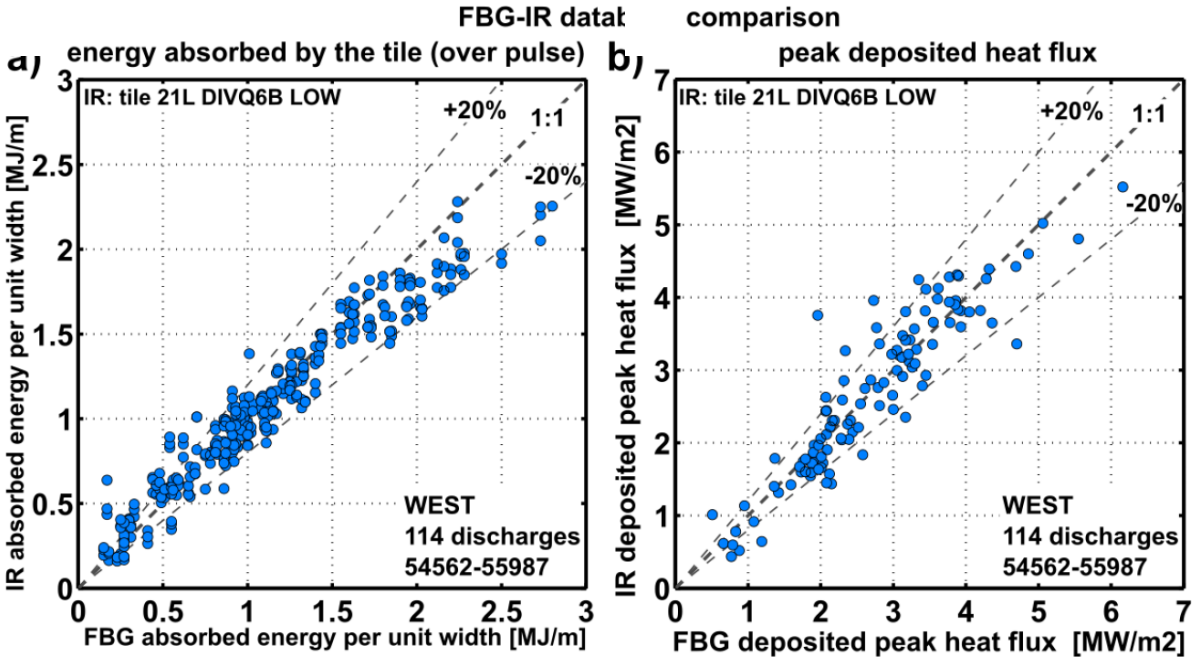
IR & FBG estimated heat flux profiles agree reasonably well

- Heat flux profiles estimated at the maximum ripple modulation
- Good agreement on peak amplitude and position, less on profile width



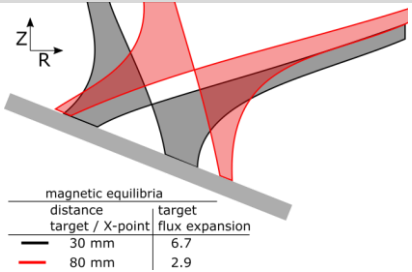
IR & FBG agree well on estimated peak and integrated heat flux

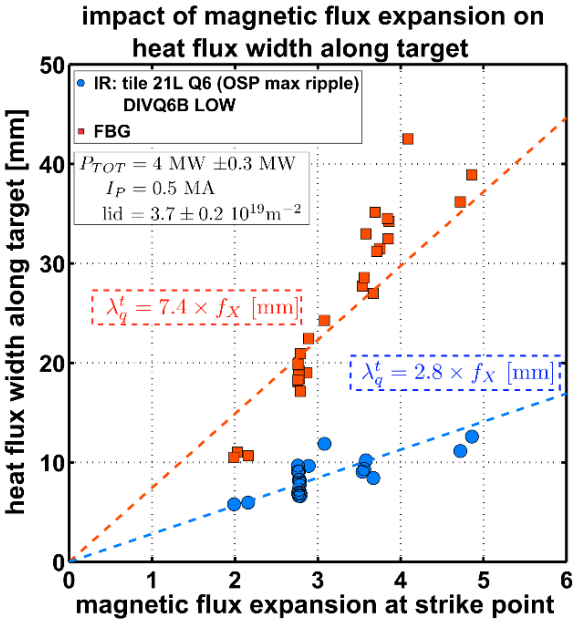
- Data base of more than 100 L-mode discharges with stable (>4s) heating phases
- Consider only outer target (inner profile shape not understood)
- Local peak heat flux well matched by the 2 diagnostics (20% scatter)
- Integrated tile energy also well matched ($E \equiv \int \int q_{\perp} ds dt$ integral along tile length & time)



IR & FBG estimated target heat flux width λ_q^t vary linearly with magnetic flux expansion

- Consider stable L-mode heated plasma scenario
- Magnetic flux expansion at target (f_X) varied by changing the X-point height wrt divertor surface.
- Outer target heat flux width λ_q^t estimated by "Wagner" fit of experimental profiles from IR & FBG
- Good linearity of λ_q^t function of f_X
  → Validates the common normalization $\lambda_q \equiv \lambda_q^t / f_X$





Important observations:

- λ_q from IR is about 3 times lower than from FBG in scenarios
  $\lambda_q^{IR} \approx 2.8$mm & $\lambda_q^{FBG} \approx 7.4$mm
- For this WEST scenario, multi-machine scaling laws predict
  $\lambda_q \approx 2.9 - 3.7$ mm L-mode database [A. Scarabosio JNM 2013]
  $\lambda_q \approx 1.1 - 3.7$ mm H-mode database [T. Eich NF 2013]

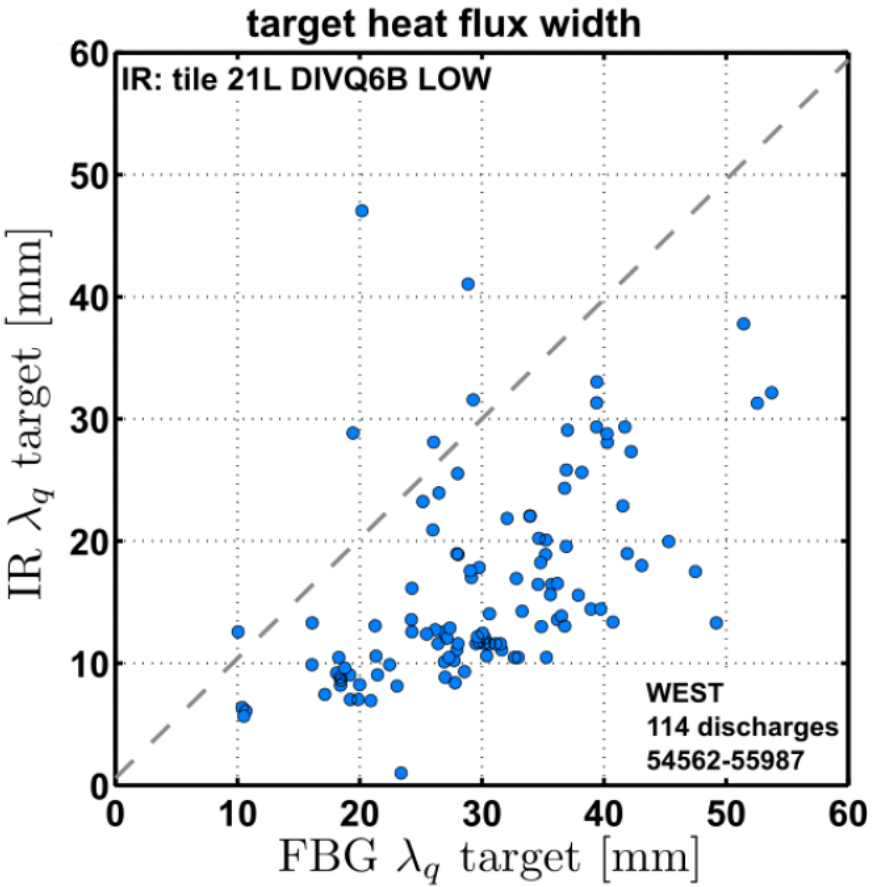
IR & FBG estimated target heat flux width λ_q^t indeed disagree on large database

- Data base of more than 100 L-mode discharges with stable (>4s) heating phases
- Strong dispersion found in the comparison between λ_q^t from IR & FBG
- Statistically $\lambda_q^{FBG} \approx 3\lambda_q^{IR}$

But peak heat flux and integral are well matched

→ Different profile widths compensated by different background heat fluxes from IR & FBG

→ This could suggest a systematic error in the treatment of IR reflections (self-reflections)
Still under investigation



Conclusions

- Heat flux deposited profiles routinely measured by embedded thermal sensors (FBG & TC), IR thermography and flush mounted Langmuir probes
- WEST experiments validate commonly accepted geometrical assumptions:
  - Target heat flux width varies linearly with magnetic flux expansion, allowing to define a remapped channel heat flux width $\lambda_q \equiv \lambda_q^t / f_X$
  - Toroidal deposited heat flux modulation is consistent with the magnetic projection of a parallel heat flux + homogeneous background (radiation & neutrals)

  → **Key steps to prepare WEST scenarios for ITER grade PFU testing**
- FBG & IR estimated peak heat flux and flux integral agree quantitatively
- Heat flux channel widths from IR are about 3X lower than estimated from FBG

  → This could suggest an inappropriate treatment of IR reflections in metallic wall
- Comparison with Langmuir probes ongoing