Infrared measurements of divertor heat loads on MAST

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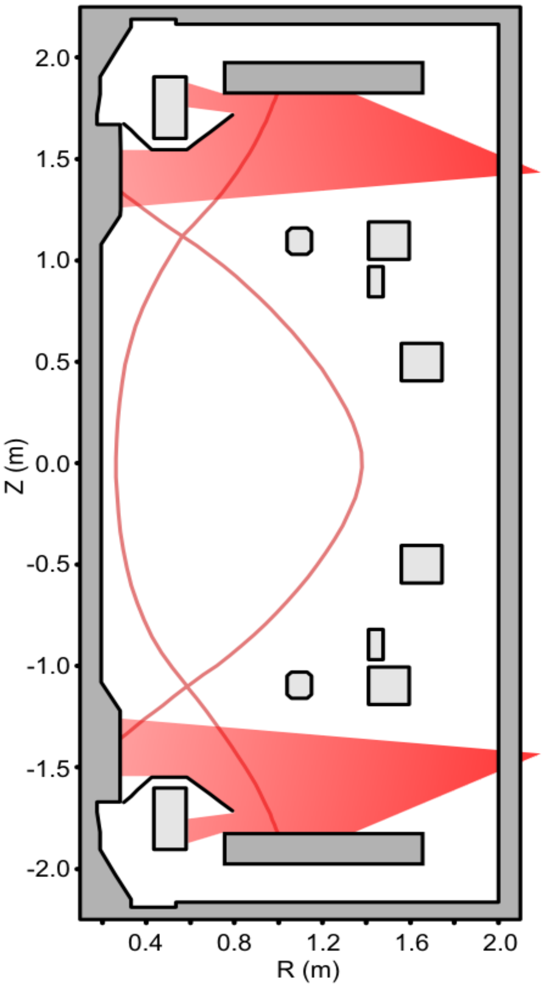
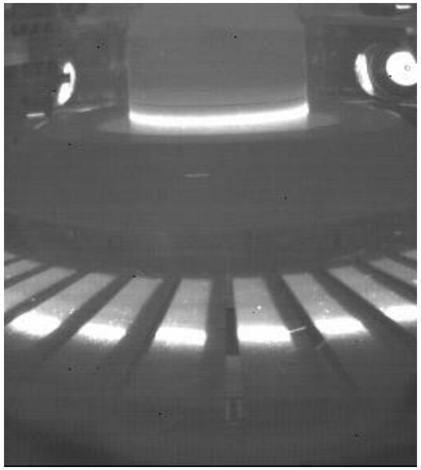
Motivation

- **Target power loads are a concern for future machines**
- **Challenge in spherical tokamaks due to the smaller area for power deposition**
- **Recent work has focussed on a number of areas concerning heat loads**
  - SOL widths: Predictions for ITER based on new scalings are narrow
  - Filaments: How much power falls outside the main strike point?
  - ELMs: Power loads in future devices too high, need to mitigate
- **MAST-U ideally placed to investigate control of divertor power loadings**
  - Super-X divertor
    - Enhanced radiation, larger area for power deposition
  - Investigation of power loads requires extensive IR coverage

Infrared thermography on MAST

- **Routine IR coverage across the upper and lower divertor**
- **Lower divertor: Medium wavelength camera (MWIR)**
  - Filtered to 4.5 – 5.0 µm range
  - Up to 10 kHz possible, typically operated at 5 kHz
- **Upper divertor: Long wavelength camera (LWIR)**
  - 7.6 – 9.0 µm range
  - Up to 20 kHz possible, typically operated at 7.5 kHz
- **Field of view of cameras covers the inner and outer strike points**
  - Allows energy balance to be performed





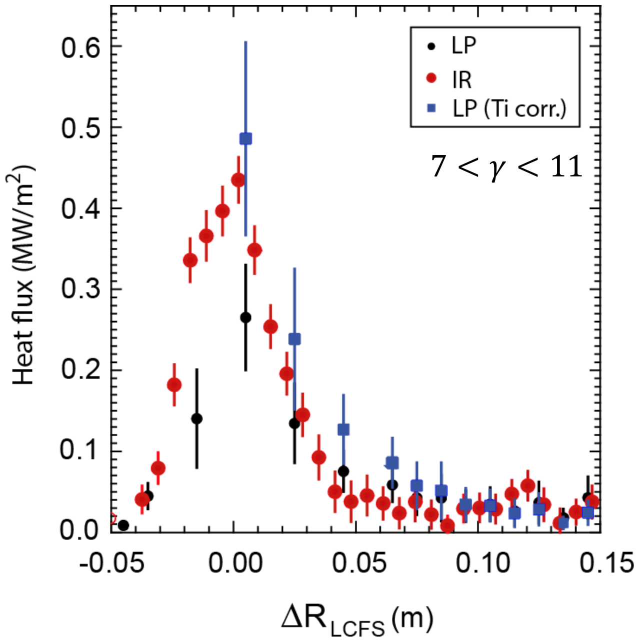
Example IR camera view on MAST

Infrared thermography on MAST

- **Power balance: Use to determine the effect of surface layers**
  - Compare total energy to divertor with energy leaving plasma by integrating;

$$P_{SOL}=P_{NBI}^{ABS} + P_{ohmic} - P_{rad} - dW/dt$$

- **Langmuir probes can be used to determine the power to the divertor**
  - T_i affects the calculated power; use a retarding field energy analyser[a] to measure T_i
  - Accounting for the ratio of T_i/T_e gives good agreement with the IR



[a]Elmore et al J. Nuc. Mater. 438 (2013) S1212

SOL fall off lengths

- **Target power fall off lengths characterised by the fit by Eich***
  - Exponential fall off in the SOL convoluted by a Gaussian for PFR diffusion

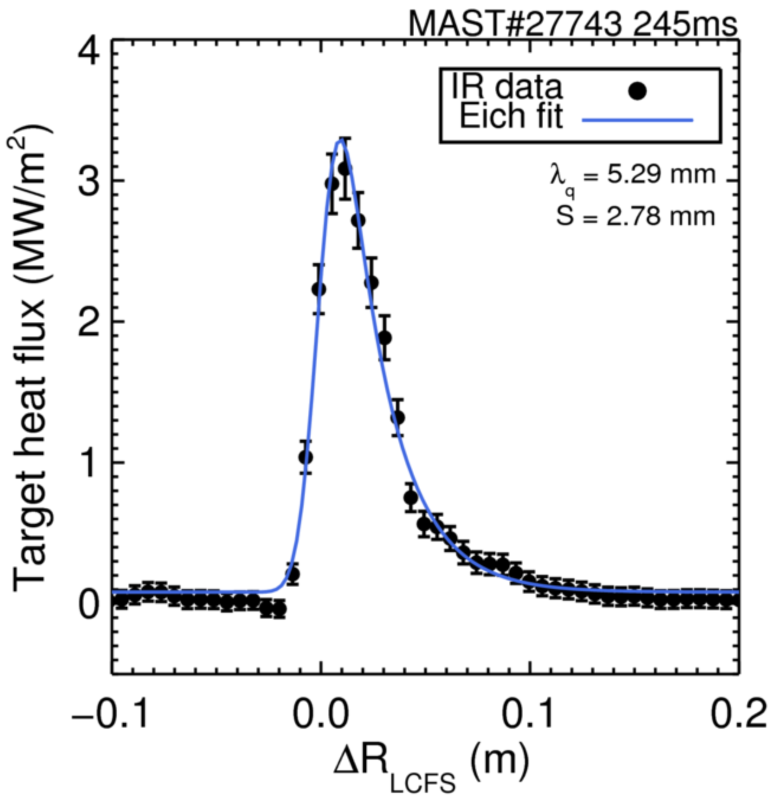
$$q(\bar{s}) = \frac{q_0}{2} exp\left[\left(\frac{S}{2\lambda_q}\right)^2 - \frac{(\bar{s})}{\lambda_q . f_x}\right] . erfc\left(\frac{S}{2\lambda_q} - \frac{\bar{s}}{S . f_x}\right) + q_{bg}$$

$$\bar{s} = \mathrm{R} - \mathrm{R}_0$$

- **MAST profiles well fitted by this form**

- **Investigate the scaling of the heat flux width on MAST**
  - Determine if the MAST data are consistent with scalings suggesting:

$$\lambda_q^{ITER} \sim 1\ \mathrm{mm}$$



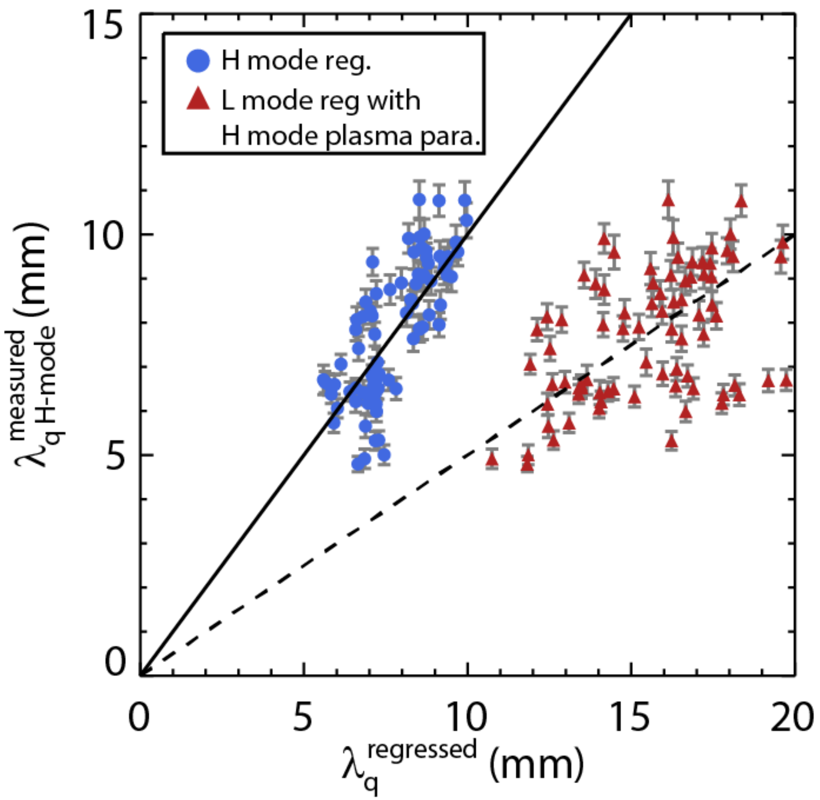
* Eich et al PRL 2011

SOL fall off lengths

- **Regression performed with major plasma parameters in both L and H mode**

$$\lambda_q^{H\,mode}[mm] = 4.03(\pm 0.14) I_p^{-0.75(\pm 0.23)} P_{SOL}^{0.24(\pm 0.08)} n_e^{line\;0.14(\pm 0.19)}$$ [1]

$$\lambda_q^{L\,mode}[mm] = 7.00(\pm 0.21) I_p^{-1.06(\pm 0.07)} P_{SOL}^{0.03(\pm 0.02)} n_e^{line\;0.59(\pm 0.04)}$$ [2]



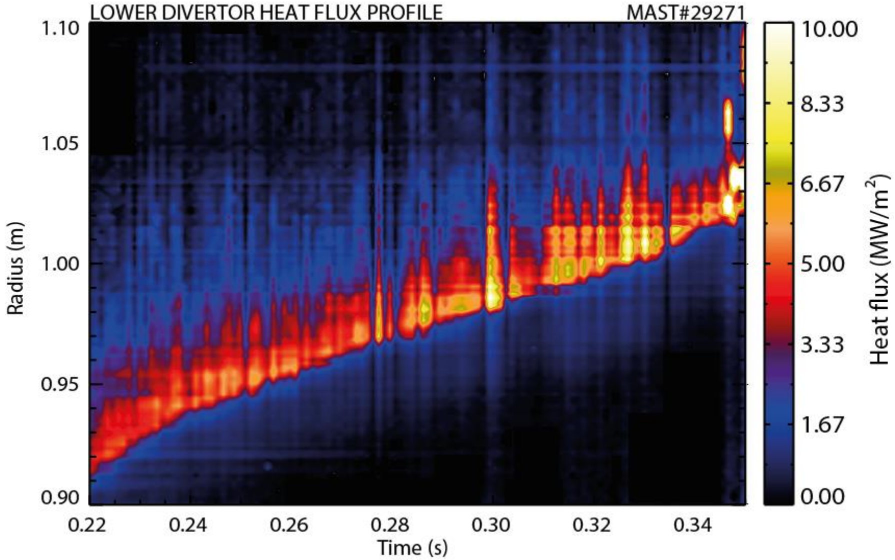
- **Major scaling parameter: I_p**
  - Sign consistent with NSTX: $I_p^{-1.6(\pm 0.1)}$ [Gray et al JNM 415 (2011) S360-4]
  - Scalings differ in density exponent
    - I_p correlated with density
- **Regression constant double between scalings**
  - L mode widths twice H mode
  - Supported by data from JET/AUG [Scarabosio JNM (2013) S426-430]
- **H mode scaling fits well with multi-machine regression including NSTX** [Eich NF 53 (2013) 093031]

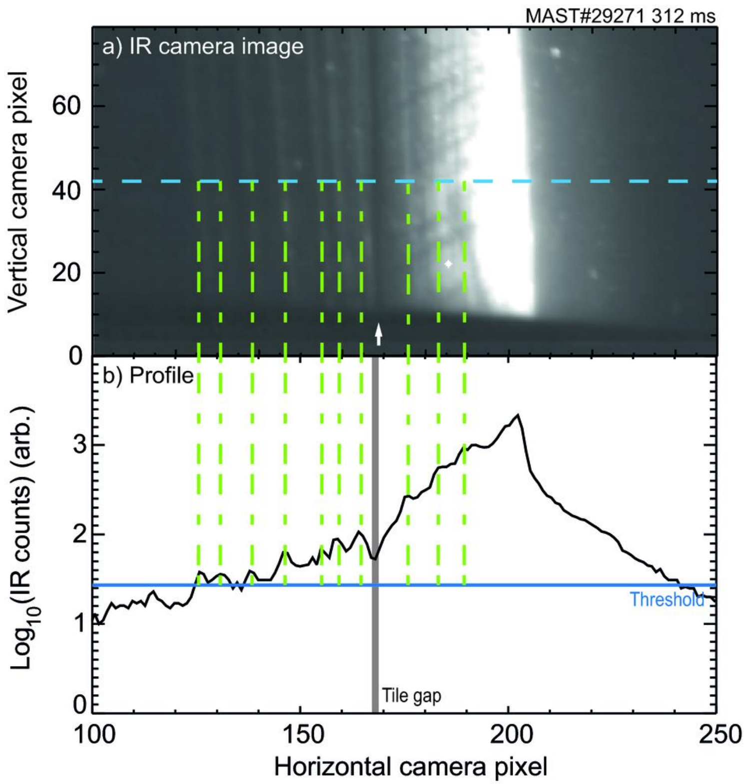
[1] Thornton et al PPCF 56 (2014) 055008
[2] Elmore et al, in prep

Filament measurements

- **Filament heat fluxes can extend beyond the footprint defined by λ_q**
  - Power is deposited in regions beyond the divertor
  - MAST-U has a close fitting wall onto which this power can fall

- **IR data show the filamentary nature of the power to the target**
  - Filaments in the raw data can be correlated with peaks in the profiles





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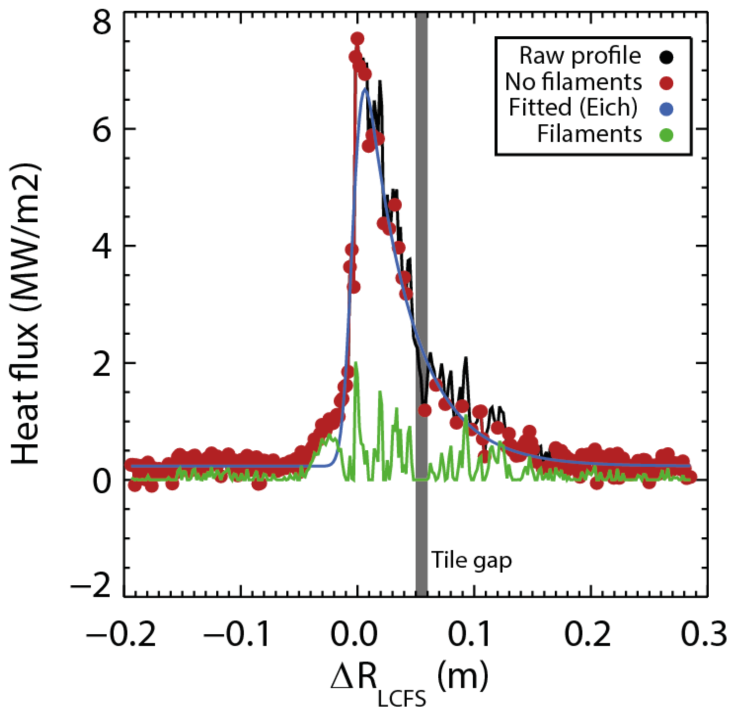
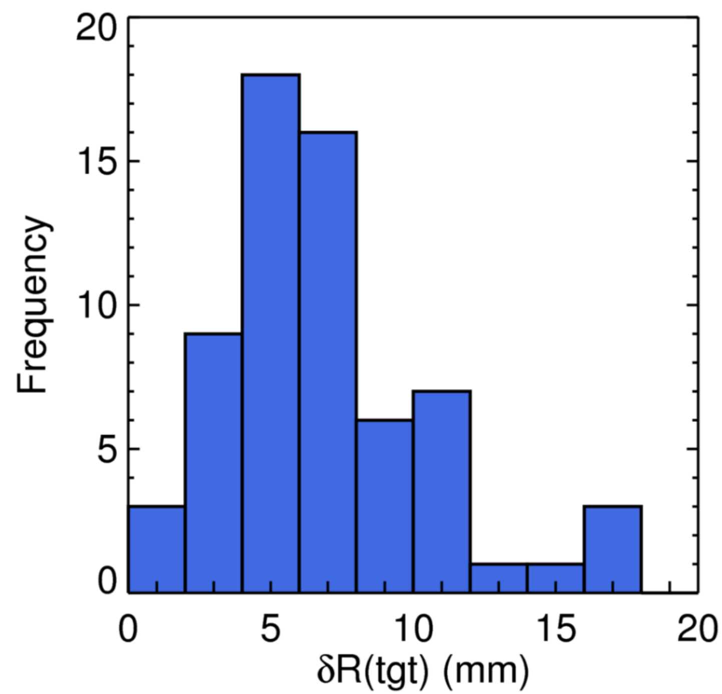
Filament measurements

- **Determine the filament size from the peaks seen in the IR data**
  - Identify the location of the peaks via background subtraction
  - Fit the peaks with a Gaussian to characterise the width
- **Filament radial sizes at the target are of the order 5 mm**
  - Filaments are separated by approximately 15 mm at the target
- **Power carried to the outer divertor is small but dominated by isolated filaments**





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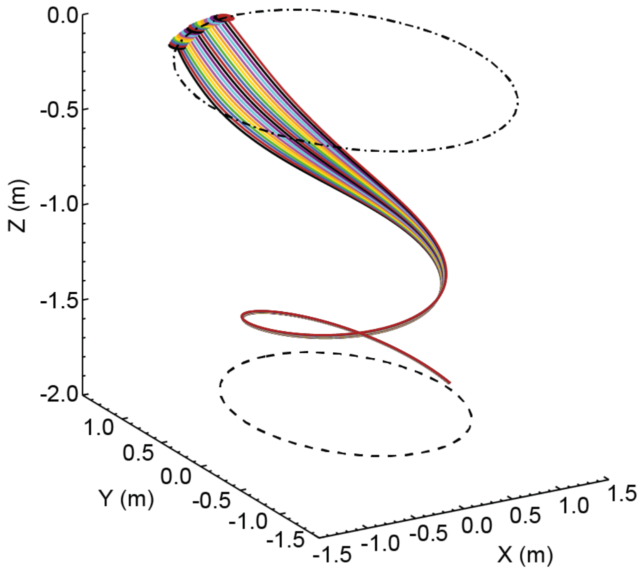
Filament measurements

- **Visible imaging of the filaments in MAST is performed at the midplane**
- **Relate the target filament size and the midplane filament size**
  - Field line tracing: toroidal extent at the midplane manifested as radial extent at the target



$$\delta\phi_{mid} = \frac{R_{mid}}{R_{tgt}F}\left[R_{tgt}\frac{d\phi_{tgt}}{dR_{mid}}\right]\delta R_{tgt}$$

Thornton et al PPCF 57 (2015) 115010

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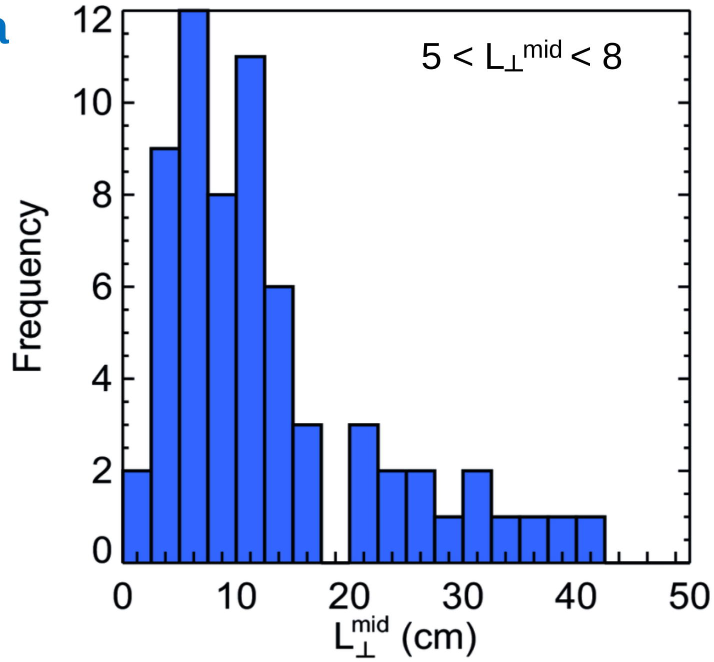
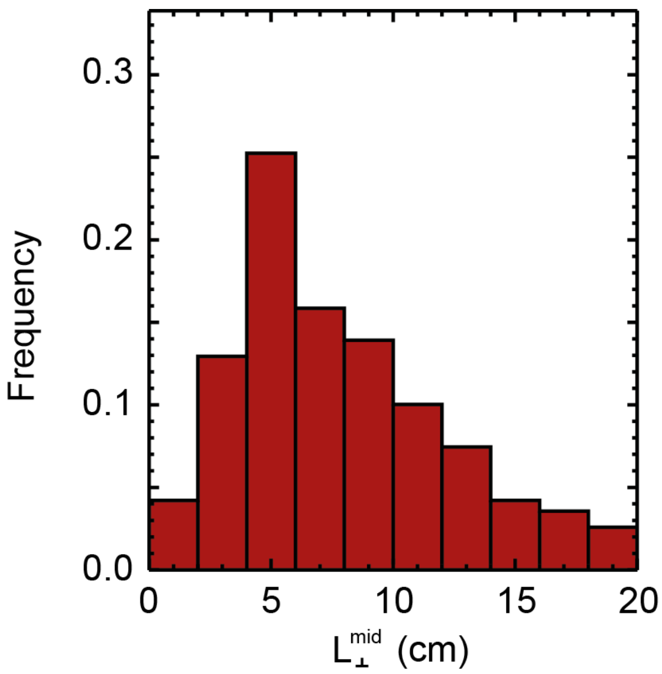
- **Relate the target filament size and the midplane filament size**
  - Field line tracing: toroidal extent at the midplane manifested as radial extent at the target
- **Directly compare the size at the midplane from two different diagnostics**
  - IR data: toroidal size 5 – 8 cm

IR data



Visible data



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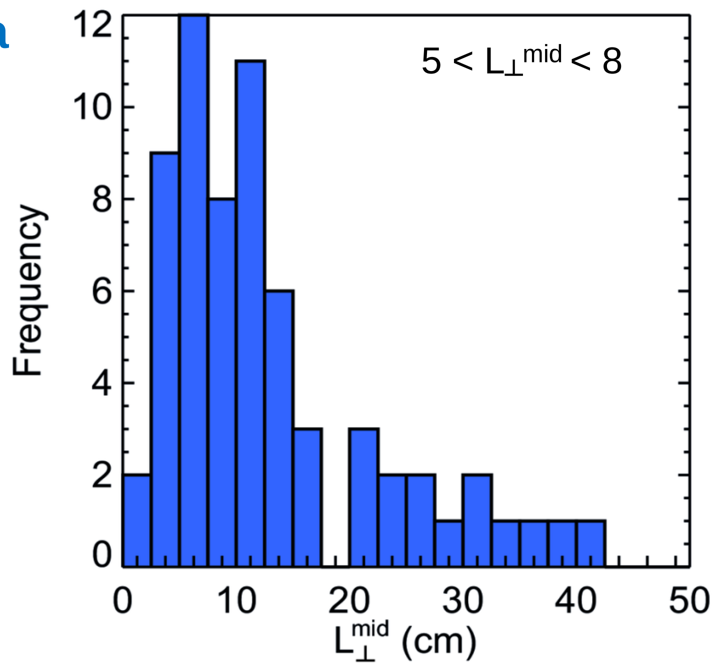
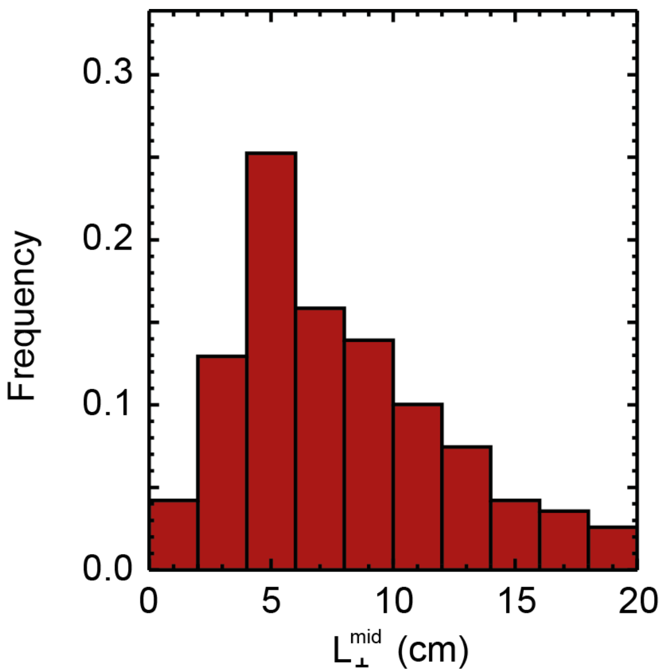
- **Directly compare the size at the midplane from two different diagnostics**
  - IR data: toroidal size 5 – 8 cm
  - Visible data: toroidal size ~ 5 cm

IR data



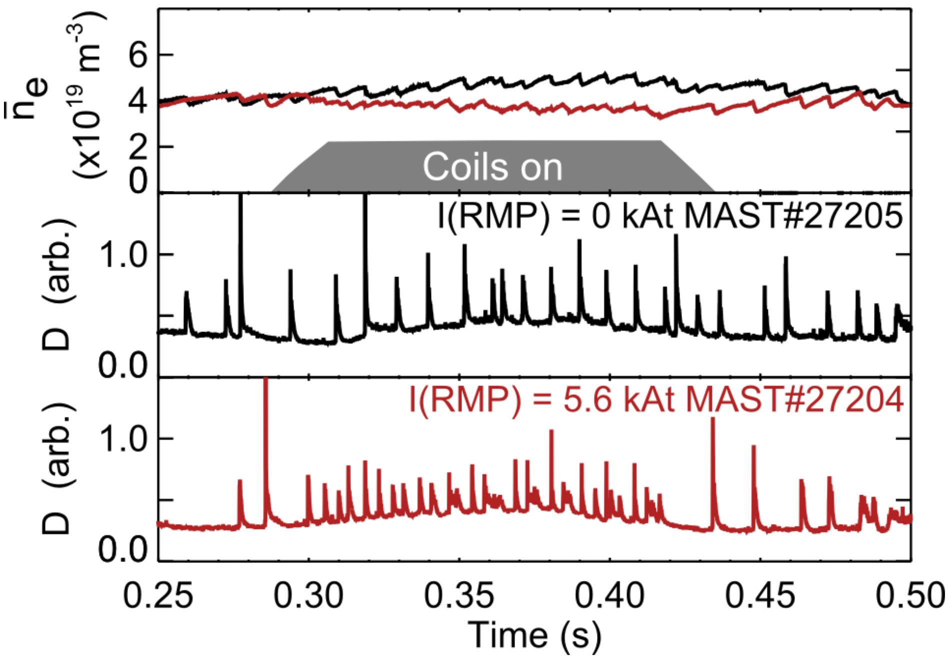
Visible data



Thornton et al PPCF 57 (2015) 115010

ELM divertor heat loads

- **Control of the ELM heat flux is a key issue for ITER**
  - Investigation of ELM control via resonant magnetic perturbations has been performed on MAST*
- **Mitigation has been achieved using RMP fields**
  - Mitigation is effective using RMPs with a range of toroidal mode numbers



* Kirk et al NF 2015

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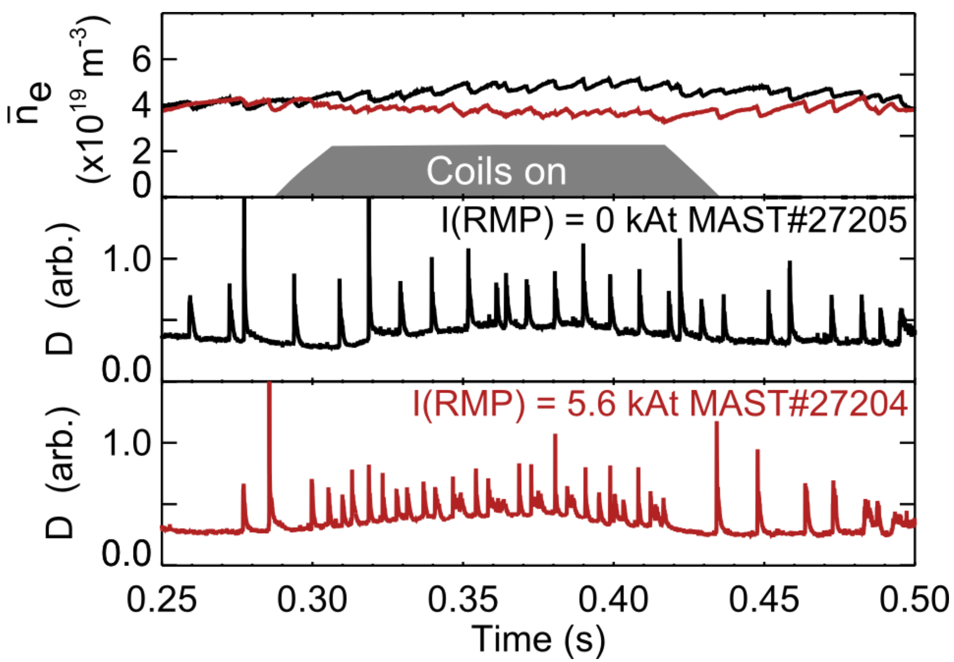
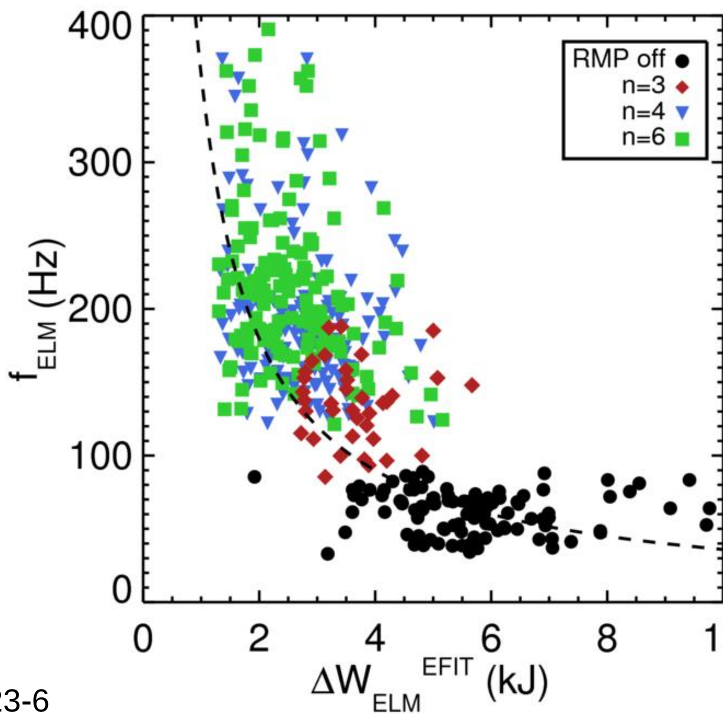
- **Mitigation has been achieved using RMP fields⁺**
  - Mitigation is effective using RMPs with a range of toroidal mode numbers
  - An increase in the ELM frequency and decrease in the ELM energy is seen

$$\Delta W_{ELM} * f_{ELM} \sim \text{constant}$$





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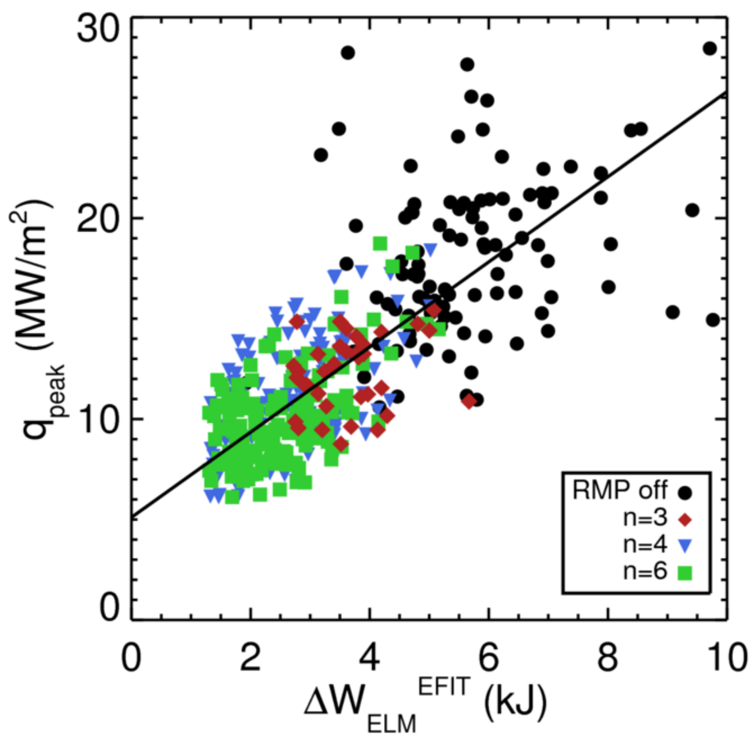
⁺Thornton et al J. Nuc. Mater. 2015 463 723-6

ELM divertor heat loads

- **Reduction in the ELM energy generates a reduction in the peak heat flux**
  - Results show a halving of the ELM energy, halves the peak heat flux
  - Change in wetted area could explain non-zero offset seen in data



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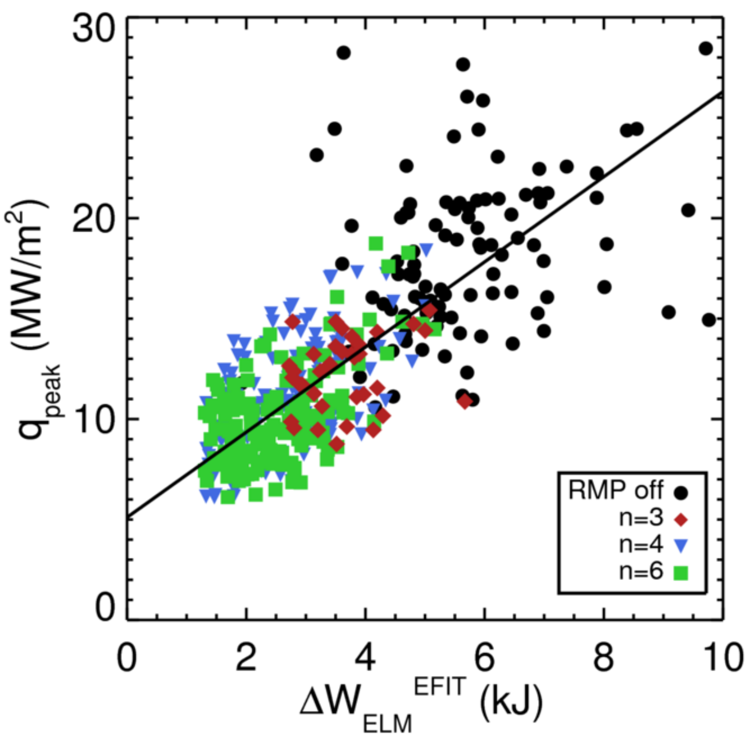
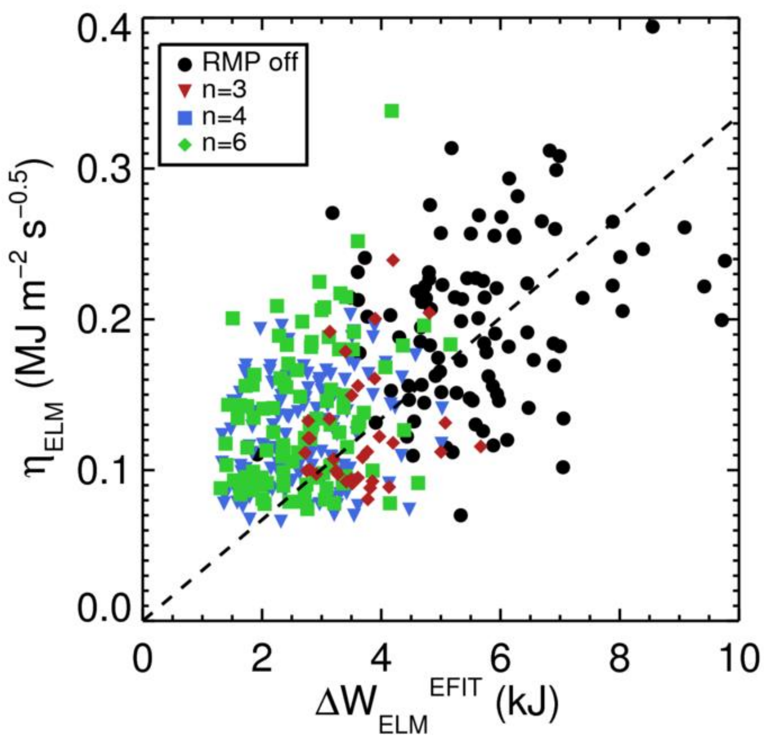
  - Change in wetted area could explain non-zero offset seen in data
- **Energy impact factor accounts for change in wetted area and duration**

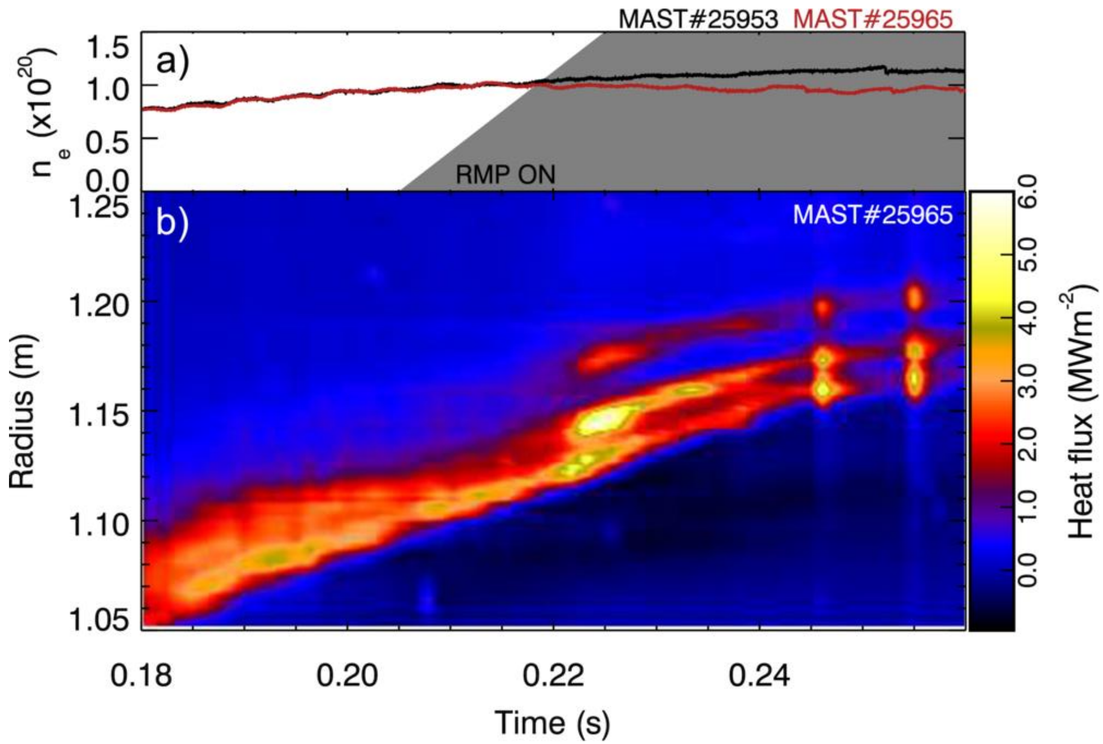
$$\eta_{ELM} = \frac{E_{ELM}}{A_{wetted}\sqrt{t_{ELM}}}$$





Strike point splitting

- **Application of RMP seen to generate splitting of the strike point**
  - Application of n=3 RMP causes strike point splitting
    - Onset of splitting occurs when other effects seen (density pump out, increase in ELM frequency)
  - Concern in future devices that the splitting of the strike point could lead to uneven erosion of the divertor
    - Increases heat loads

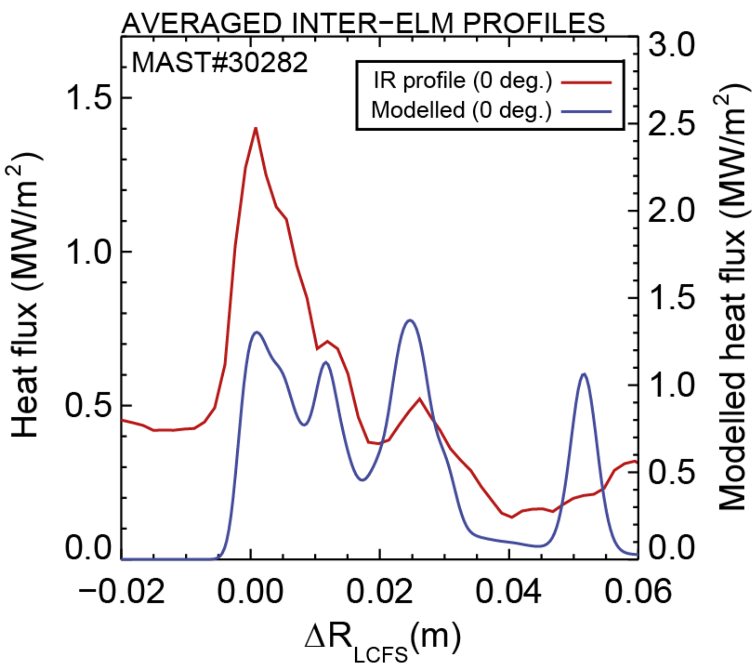


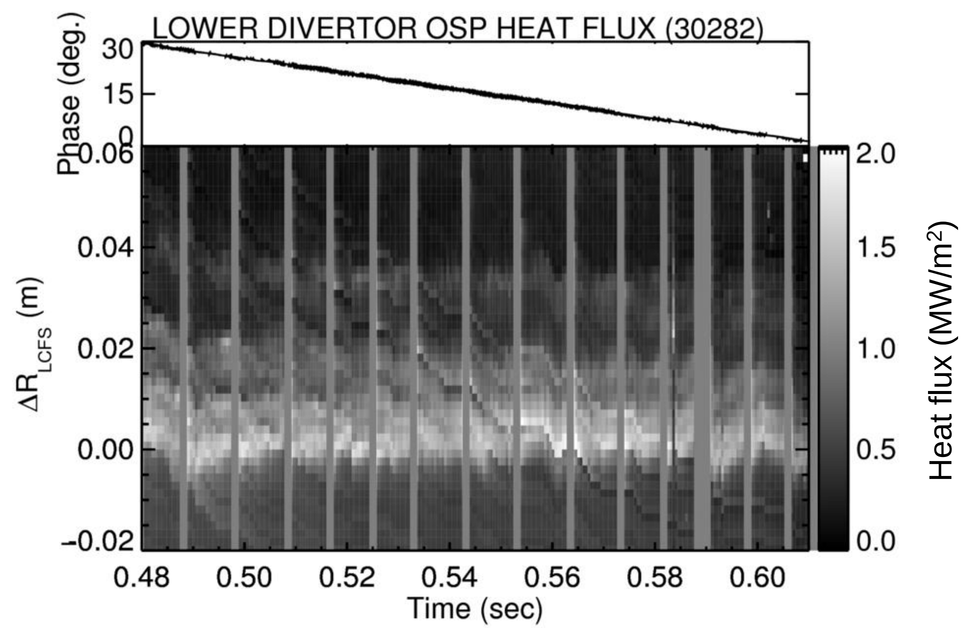
- **Apply a rotating RMP field to move the splitting**
  - Performed in MAST

Thornton et al Nucl. Fusion 54 (2014) 064011

Strike point splitting

- **Measurements of the splitting agree well with vacuum modelling**
- **Rotation of the RMP field gives rise to motion of the strike point splitting**
  - Rotation of 30° performed, giving a motion of the splitting of order 1 cm across the tile
  - The level of mitigation is unaffected by the rotation





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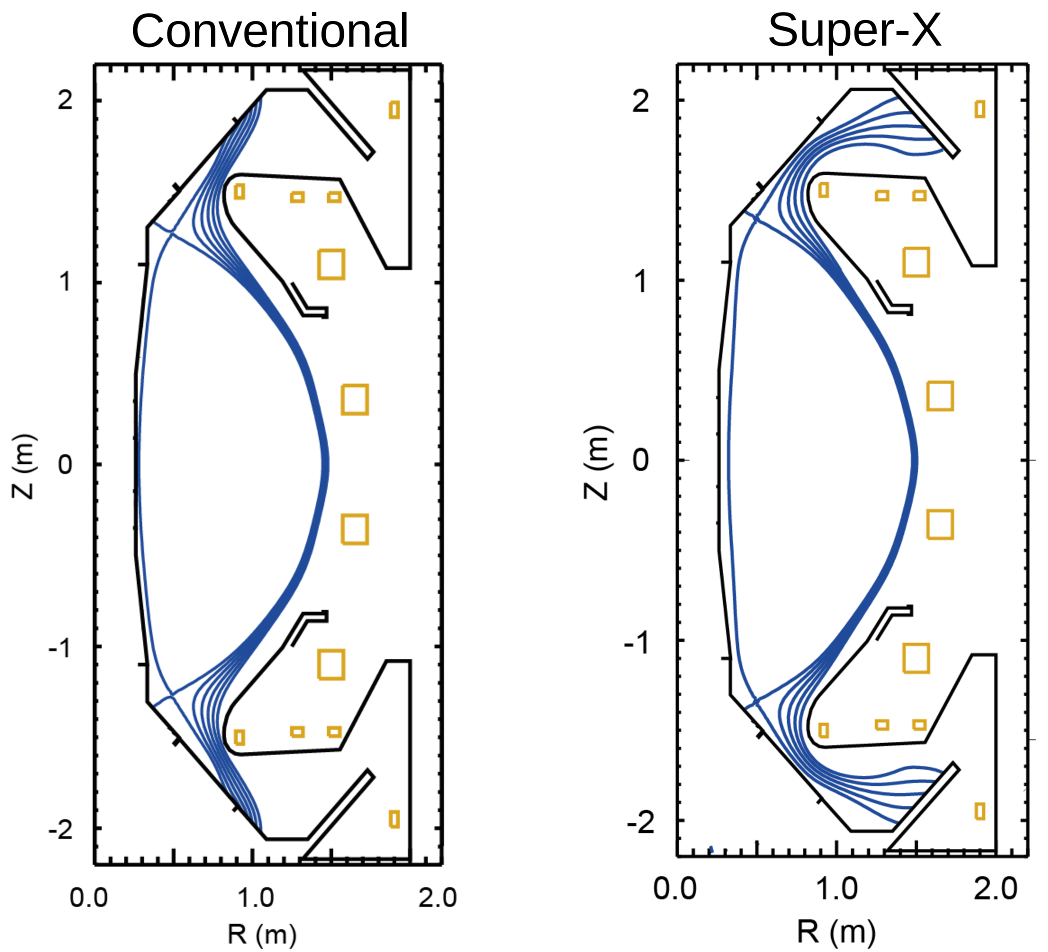
MAST-U IR diagnostics

- **MAST-U allows a wide range of different divertor configurations: conventional, Super-X and snowflake**
  - Many regions where the power load to the target needs to be monitored

- **For IR coverage to monitor the strike points require;**
  - Re-entrant port at the midplane to view the inner strike point and wide angle view
  - Coverage in both upper and lower divertor chambers



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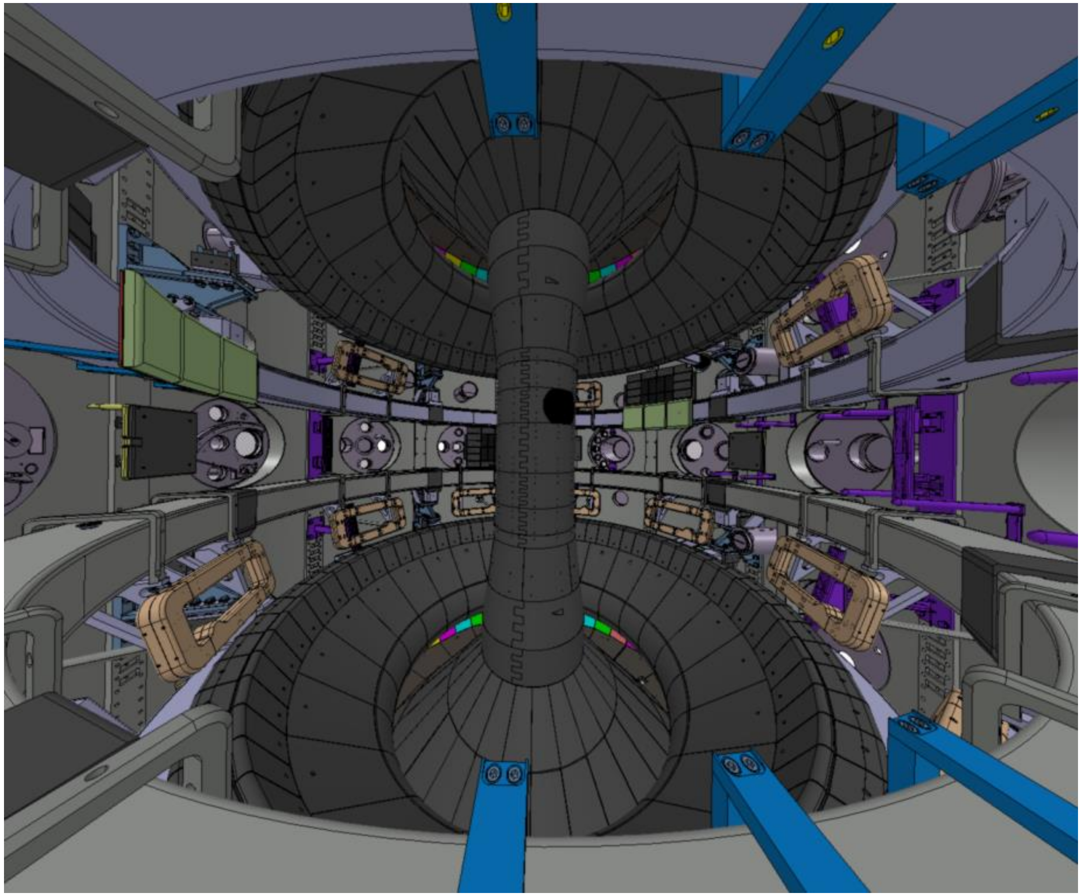

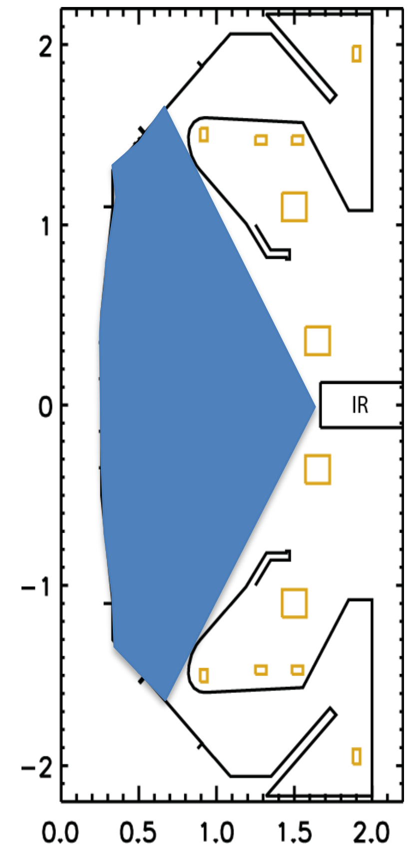

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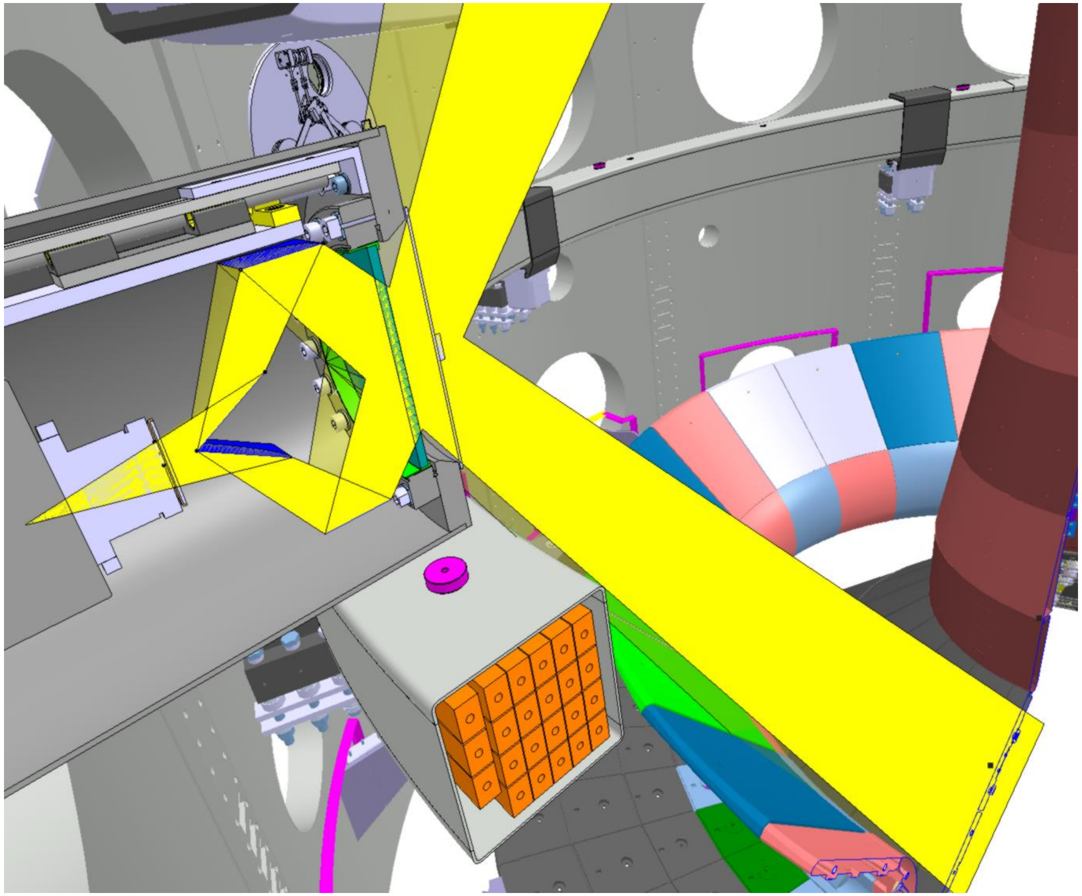

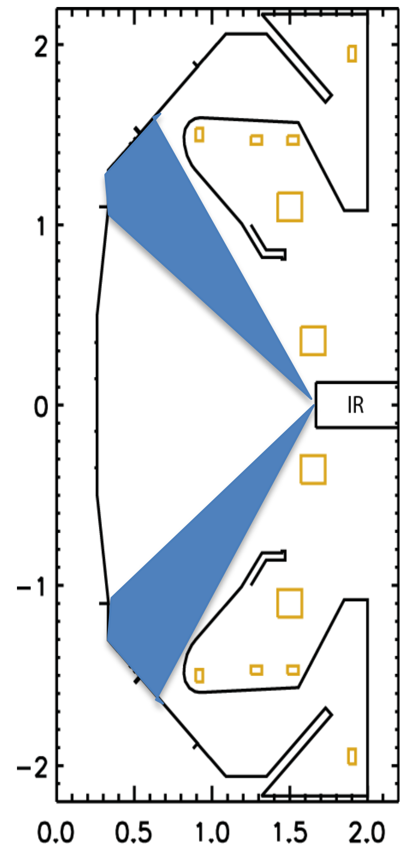

MAST-U IR diagnostics

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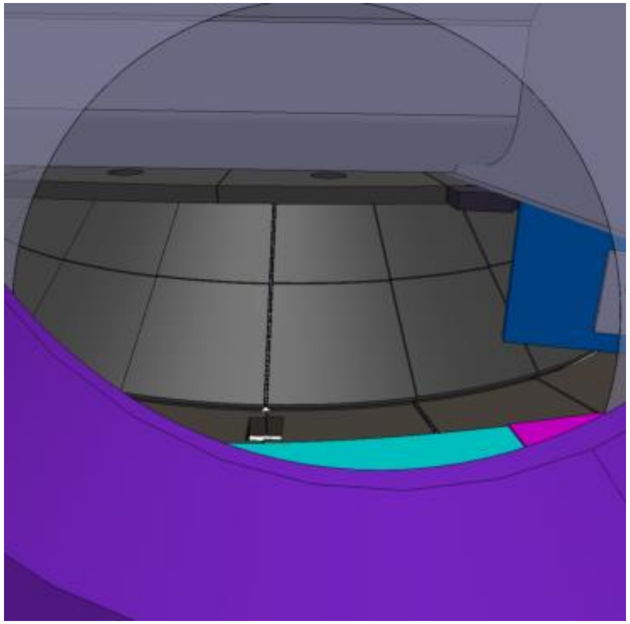
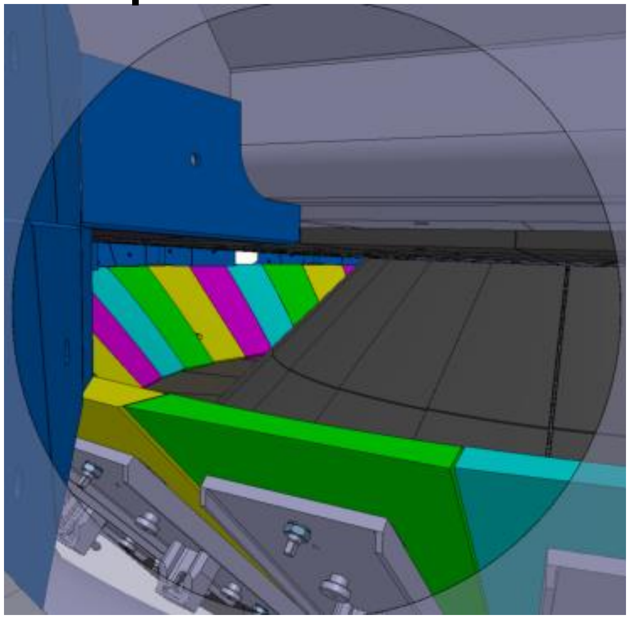
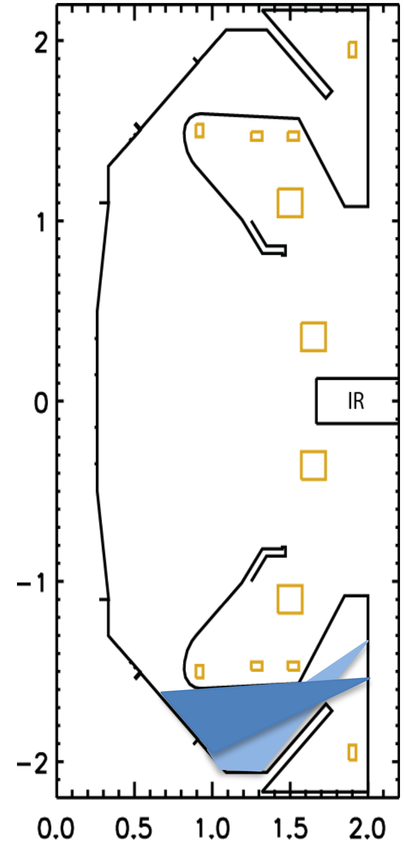
  - Many regions where the power load to the target needs to be monitored
    - Outer target for the conventional divertor: ~3 mm/pixel
    - Outer target for the Super X divertor: ~2-10mm /pixel

Conventional outer divertor



Super-X divertor view





J Harrison and K Hawkins

Summary

- **IR thermography has been extensively used on MAST, permitting study of;**
  - **SOL widths:**
    - Support the results of conventional devices predicting $\lambda_q^{ITER} \sim$ 1mm
    - Further work required to better understand the power spreading
  - **Filaments:**
    - Measurements of the width at the divertor are consistent with the upstream width
    - Power carried to the outer divertor is small but dominated by isolated filaments
  - **ELM mitigation**
    - ELM mitigation yields a 50% reduction in the peak power load
    - RMP generate strike point splitting
    - Rotation of RMP fields gives rise to motion of the splitting & spreading of power load
- **MAST-U has extensive IR views to investigate the effect of the Super-X divertor**
  - Wide range of views required to provide full coverage of configurations