Infrared measurements of divertor heat loads on MAST

AJ Thornton, S Elmore, G Fishpool, A Kirk, YQ Liu and the MAST team

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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:
  \[
P_{\text{SOL}} = P_{\text{NBI}}^{\text{ABS}} + P_{\text{ohmic}} - P_{\text{rad}} - \frac{\text{d}W}{\text{d}t}
\]

- **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

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

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

\[ \bar{s} = R - R_0 \]

- 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:

\[ \lambda_q^{ITER} \sim 1 \text{ mm} \]

* Eich et al PRL 2011
The major scaling parameter is $I_p$.

- 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]
Filament measurements

• Filament heat fluxes can extend beyond the footprint defined by $\lambda_q$
  – 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
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
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

\[ \delta \phi_{mid} = \frac{R_{mid}}{R_{tgt}} F \left[ R_{tgt} \frac{d\phi_{tgt}}{dR_{mid}} \right] \delta R_{tgt} \]
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
- Directly compare the size at the midplane from two different diagnostics
  - IR data: toroidal size 5 – 8 cm

Thornton et al PPCF 57 (2015) 115010
Filament measurements

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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
  - Visible data: toroidal size ~ 5 cm
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

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ELM divertor heat loads

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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

\[ \Delta W_{ELM} \times f_{ELM} \sim \text{constant} \]

* Kirk et al NF 2015
+ 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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- Energy impact factor accounts for change in wetted area and duration

\[
\eta_{ELM} = \frac{E_{ELM}}{A_{wetted} \sqrt{t_{ELM}}}
\]
• 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
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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    - 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
Summary

- IR thermography has been extensively used on MAST, permitting study of:
  - SOL widths:
    - Support the results of conventional devices predicting $\lambda_q^{ITER} \sim 1$mm
    - 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