Outer divertor target heat fluxes during resonant magnetic perturbation induced ELM suppressed regimes in KSTAR

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• Summary
Introduction to div. IRTV measurement

- KSTAR divertor IRTV consists of the vacuum cassette + optics (periscope) + IR camera
- Sapphire viewport / ZnSe and CaF$_2$ lenses are used
- Standard optics provides the 18° solid angle and 1.2 mm/pixel resolution

<table>
<thead>
<tr>
<th>Model</th>
<th>FLIR SC6101</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detector type</td>
<td>InSb (Indium Antimonide)</td>
</tr>
<tr>
<td>Spectral Range</td>
<td>3.0 ~ 5.0 μm</td>
</tr>
<tr>
<td>Resolution</td>
<td>640 × 512</td>
</tr>
<tr>
<td>Detector Pitch</td>
<td>25 μm</td>
</tr>
<tr>
<td>Integration time</td>
<td>10 μsec to 687 sec</td>
</tr>
<tr>
<td>Max Frame Rate (@ Min Window)</td>
<td>35.112 kHz (64 × 4) (9.009) kHz (640x4)</td>
</tr>
<tr>
<td>Full frame rate</td>
<td>125 Hz</td>
</tr>
<tr>
<td>Temperature range</td>
<td>up to 1500 °C</td>
</tr>
</tbody>
</table>
Since 2015 campaign, **add-on 3X zoom lens** has been applied for the divertor IRTV, providing 3 times higher spatial resolution of ~ **0.4 mm/pixel** than standard lens

Sample image taken with **standard lens**
Spatial resolution ~ **1.2 mm/pixel** along the tile

Sample image taken with **3X zoom lens**
Spatial resolution ~ **0.4 mm/pixel** along the tile
Heat flux reconstruction code (NANTHELOT*) has been developed

\[
\frac{\partial}{\partial x} \left( \kappa \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left( \kappa \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left( \kappa \frac{\partial T}{\partial z} \right) = \rho C_p \frac{\partial T}{\partial t}, \quad q_\perp = -\kappa \frac{\partial T}{\partial x} \quad \text{at surface}
\]

- Finite Volume Method is applied to solve the heat diffusion equation
- 1D ~ 3D solutions can be chosen
- Both explicit and implicit are available
- Temperature-dependent thermal properties are considered
- Surface layer effect can be compensated
- Benchmarked against THEODORE [Herrmann PPCF 37 17 (1995)]

measured by div. IRTV

*C. S. Kang RSI 87 083508 (2016)
Introduction to div. IRTV measurement

For the study of the outer heat flux profile, the striking point is actively controlled to be located on the central divertor target tile.
The measurement of the ELM heat load has been achieved with fast IR camera acquisition frequency of ~ 9 kHz (integration time of 100 μs) on KSTAR

KSTAR #16237 (I_p = 600 kA, B_T = 2.3 T, P_{NBI} = 4.0 MW)
The measurement of the ELM heat load has been achieved with fast IR camera acquisition frequency of $\sim 9$ kHz (integration time of 100 $\mu$s) on KSTAR.

$\tau_{IR} \sim 440$ $\mu$s $\dagger$

$\tau_{||} \sim 220$ $\mu$s $\ast$

$\tau_{IR}$ : ELM rising time measured by IRTV  

$\tau_{||} \equiv 2\pi q_{95}R/\sqrt{(T_i + T_e)/m_i}$ : ion parallel connection time

$\dagger$  

$\ast$
3D heat flux profile during RMP-ELM suppression regime

KSTAR In-vessel Control Coils (IVCC): Top/Mid/Bot
H.K. Kim et al, FED (2009)

n = 1, +90 phasing

\( n = 2 \)
In 2017, the longest sustainment of RMP-ELM suppression regime of 34 secs was achieved on KSTAR.
The heat flux profile measurement result represents the effects of 3D RMPs on the divertor heat load.

The striation pattern observed on the target tile is different according to the phase of RMPs (rotating RMPs).
The main 3D structure feature follows the field line tracing calculation† although details of the calculation can be slightly different according to plasma response models† K. Kim PoP 24 052506 (2017)

The measurement time can be regarded as the toroidal angle

† K. Kim PoP 24 052506 (2017)
Dynamics of the heat flux profile during RMPs

Sometimes, it was observed that the striking point splitting is much clearer during the ELM suppression regime while the heat flux profile becomes very sharp with larger peak heat load.
Dynamics of the heat flux profile during RMPs

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Dynamics of the heat flux profile during RMPs

KSTAR #15656

\( D_\alpha \) [a.u.]

\( q_\perp \) [MW/m²]

\( n=2 \) RMPs

\( \text{Ltile-Lsep [mm]} \)
Dynamics of the heat flux profile during RMPs

KSTAR #19032

$I_p$ [kA]

$I_{IVCC}$ [kA]

$max(q_{\text{perp}})$ [MW/m$^2$]

$W_{\text{tot}}$ [kJ]

$D_\alpha$ [a.u.]

Time [sec]

$\Phi = +45$

$\Phi = +90$

$\Phi = +135$

$\Phi = +180$

$\Phi = +45$

$\Phi = +90$

$\Phi = +135$

$\Phi = +180$
Dynamics of the heat flux profile during RMPs

The recent measurement result implies that higher peak heat flux in ELM-supp. regime than those in the w/o RMP and ELM-mitigation regimes is a *global phenomenon*. But, the physical mechanism for this phenomenon is still under investigation.

\[ A_{\text{wet}} = \frac{\int q_\perp dS_{\text{div}}}{\max(q_\perp) - q_{BG}} \]

The figure shows the dynamics of the heat flux profile during RMPs, with various suppression angles and times.
Summary

• The divertor IRTV has been applied to investigate the non-axisymmetric outer divertor target heat flux profile in the presence of the external resonant magnetic perturbations in KSTAR.

• It has been realized that the non-axisymmetric outer divertor target heat flux pattern during RMP-ELM suppression regime agrees well with the expectation of field line tracing calculation although there are some differences in details, which are under investigation.

• In KSTAR, it was sometimes observed that peak heat flux in ELM-suppression regime becomes higher than those in the w/o RMP and ELM-mitigation regimes regardless of the toroidal phase of RMPs.

• But, how this observation relates with plasma operation scenario or machine circumstances should be investigated comprehensively considering plasma transport, plasma response to external RMPs as well as SOL power balance.