Divertor heat & particle flux study in the EAST superconducting tokamak

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Outline

1. Introduction
2. Heat flux diagnostics on EAST
3. Divertor power loads for various ELMs
4. Active control of divertor heat flux
5. Scaling of divertor power footprint width
6. Summary and discussion
Introduction

- ELMs are quasi-periodic MHD instabilities occurring at H-mode edge pedestal, transient releasing particles & energy into SOL → divertor and other PFCs.

- ITER is envisaged to operate in ELMy H-mode in order to control the plasma density and impurity levels, and the intolerable heat load during giant ELMs is the main issue concerned.

- A number of ELM types have been classified, chiefly type-III around the L-H threshold and type-I when higher additional power is inputted. Small ELMs, EDA & QH-mode w/ good confinement are of special interest to the fusion community.

- A systematic study on the divertor power load for various ELMs obtained in EAST is of significant importance to ITER. Active control of divertor heat load is a must!
Introduction (ctd.)

Particle and power deposition widths characterize the impacted target area and thus the power loads onto divertor targets.

The inter-ELM SOL power width scaling has been studied on US and EU tokamaks very recently, showing good agreement with the heuristic drift-model proposed by Goldston, in both magnitude and scaling.

The notable finding is the strong inverse scaling with $I_p$ (thus $B_p$ and $q_{95}$), which leads to $\lambda_q \sim 1\text{mm}$ when extrapolated to ITER!

Scaling of SOL width in RF-heated Type III ELMy H-mode plasmas has been performed on EAST, in DN, LSN, USN divertor configurations. The plasma current ranges from $I_p = 0.3\text{MA}$ to $0.8\text{MA}$.

Experimental Advanced Superconducting Tokamak

- Major radius: $R_0 = 1.9$ m
-Minus radius: $a = 0.5$ m
-Plasma duration: $t=1000$ s
-Plasma current: $I_p = 1$ MA
-Toroidal field: $B_T = 3.5$ T
-Triangularity: $\delta = 0.3-0.65$
-Single/Double Null configuration

- Commenced operation on 26 Sept. 2006
- First H mode on 7 Nov. 2010. 23:16
-H-mode duration over 30s on 28 May 2012. 22:22
-Divertor operation over 400s on 21 June 2012. 21:26
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EAST diagnostics – divertor LP arrays

- Parameters to be measured:
  \( n_t \), \( T_t \), \( V_f \), particle & heat flux…
- Spatial resolution:
  15mm@inboard, 10mm@outboard
- Time resolution: 0.2ms in 2010, 0.02ms in 2012
- Power supplier: DC 200V, 3A/10A

The bird-view of EAST tokamak and the region with divertor probes

The poloidal layout of divertor triple probe arrays

The real picture of upper outboard (UO) divertor probes
EAST diagnostics – divertor LP arrays

◆ Particle flux: \( \Gamma_{ion} = n_t C_{st} = j_s / e \)

\[
\Gamma_{ion}[m^{-2} s^{-1}] = 6.24 \times 10^{22} j_s [Accm^{-2}]
\]

◆ Parallel heat flux: \( q_{//} = \gamma n_t T_t C_{st} = \gamma T_t j_s / e, \quad \gamma \sim 7 \)

\[
\left( T_i = T_e, C_{st} = \sqrt{2T_t / m_i} \right)
\]

◆ Target heat flux: \( q_t = q_{//} \sin \theta \)

◆ Time integrated energy load on divertor targets:

\[
\Delta W_{div} = \int_{t_1}^{t_2} \int_{s_a}^{s_b} 2\pi R_{div} q_t (R_{div}, s, t) ds dt, \quad \Delta W_{div}^{ELM} = \sum_{i=1}^{4} \Delta W_{div, i}^{ELM}
\]

◆ Simple exponential fittings to the particle/power profiles in the SOL were performed to obtain the mid-plane widths: \( \lambda_{js} \) and \( \lambda_q \)

\[
j_s = A_{js} \exp \left[ - (R - R_{max}) / \lambda_{js} \right], \quad q_{//} = A_q \exp \left[ - (R - R_{max}) / \lambda_q \right]
\]

[L. Wang et al., NF 52, 063024 (2012) & L. Wang et al., NF 53, 073028 (2013)]
EAST diagnostics – IR camera

- **Parameters to be measured:**
  - Divertor surface temperature,
  - Target heat flux
- **Temporal resolution:** 20ms
  (too low to resolve ELMs)
- **Spatial resolution:** 6mm/pixel

*The system setup of EAST divertor IR camera in 2012*

[K. F. Gan et al., JNM 438, S364 (2013)]

Top (up) and real (low) view-field of IR camera
EAST diagnostics – LFS reciprocating LPs

- Two reciprocating LPs
- Toroidally separated by 89°
- Parameters to be measured: SOL ne, Te, pe, $\phi_p$, $\Gamma$, $v_\parallel$ and coherence
- Sampling rate: 2 MHz

[W. Zhang et al., RSI 81, 113501(2010)]

A specifically designed multi-tip probe head
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Type I ELMs were obtained in LSN with LHCD + ICRH. About a dozen of coherent Type I ELMs were selected in both of the two characteristic pulses: shaded ELMs in #41200, all plotted in #42556.

- The ELMs in #42556 are pure Type I, while that in #41200 are mixed Type I and small ELMs.

- A profound loss of the plasma stored energy can be observed when Type I ELMs were produced.

- The peak heat flux of Type I ELMs on divertor target for #41200 & #42556 are ~12 & ~8MWm⁻², respectively.

- The repetition frequencies of Type I ELMs in #41200 & #42556 are \( f_{\text{ELM}} \approx 20 & \approx 10 \text{ Hz} \), respectively.

#41200: \( I_p = 0.4\text{MA}, \ n_e/n_G \approx 0.47, \ \delta = 0.38, \ P_{\text{heat}} \approx 1.55\text{MW} \);

#42556: \( I_p = 0.3\text{MA}, \ n_e/n_G \approx 0.47, \ \delta = 0.41, \ P_{\text{heat}} \approx 1.45\text{MW} \).
Type-I ELM power load, Pedestal energy loss

Characteristics of divertor power load and peak heat flux for a Type I ELM.

- Pedestal energy loss: ~ 8.5%
- Divertor power load: ~ 5%
- Most of Type I ELM ejected power is deposited on the outboard divertor

ELM energy loss and the subsequent heat load on divertor targets for the two groups of coherent Type I ELMs in #41200 and #42556.
The LO target endures most of the ELM ejected particles

Ion saturation current density at divertor targets  

\( \Gamma_{ion} = \frac{j_s}{e} \)

Contours of \( j_s \) at UI (a), UO (b), LI (c) and LO (d) divertor targets for a typical Type I ELMy H-mode. The traces shown in the bottom panels (e, f) are the divertor \( D_a \) emission.
Compound ELMs in EAST

- Compound ELMs are characterized by an initial ELM spike followed by a number of small ELMs in the $D_\alpha$ and $I_{sat}$ signatures.

- In EAST, compound ELMs were observed in DN with LHCD+ICRH.

- The time scale of a compound ELM is a few ms.

- The plasma stored energy loss is $\sim 4.5\%$ for a compound ELM in #41164.

- The peak heat flux on divertor for compound ELMs is between that of Type I and Type III.

- #41164: $I_p=0.4\text{MA}$, $n_e/n_G\sim0.55$, $\delta=0.46$ (DN), $P_{\text{heat}}\sim1.3\text{MW}$;

Time evolution of the plasma stored energy, divertor $D_w$ ion saturation current, LO peak heat flux, and the contour of $j_s$ distribution at LO target for compound ELMs.
Compound ELMs also favor the outboard divertor, consistent with the ballooning like transport in the LFS.

The ELM power load on divertor targets is approximate to the loss of the plasma stored energy (both ~ 5%), which is attributed to the time scale of compound ELMs.

For a compound ELM, the pedestal energy was intermittently released in a few ms. During the intervals between adjacent ELM spikes of a compound ELM, the plasma stored energy increases slightly as well. Therefore, the divertor power load temporally integrated over the ELM duration time ($\Delta W_{\text{div}}$) for compound ELMs is comparable to or larger than the observed $\Delta W_{\text{dia}}$. 
Characteristic difference between ELM filaments and compound ELMs

Statistically, the interval time between adjacent ELM filaments is 150-250μs, much less than that between adjacent ELM spikes of a compound ELM.

ELM filaments observed in the ion saturation current of LO#10 divertor triple LPs, also shown is the time evolution of divertor $D_\alpha$ emission.
Type-III ELMs in EAST

- Type III ELMs are the most common ELMs observed around the L-H threshold power, in both DN and SN, in a wide density range, favoring the outboard divertor as well.

→ Type III ELM power load: 1-2%; Peak heat flux: ~2MWm⁻²; no $W_{\text{dia}}$ loss was observed.
The very small ELMy H-mode regime was achieved with LHCD+ICRH.

High triangularity: The very small ELMs $\rightarrow$ Type I ELMs when $\delta$ was reduced to $\sim 0.4$.

High density: $n_e/n_G = 0.5 - 0.6$

High repetition frequency: $f_{\text{small ELMs}} = 0.8-1.5\text{kHz}$

Low peak heat flux: $< 1\text{MWm}^{-2}$ as a whole

No change of the plasma stored energy during the cycle of a very small ELM was observed.

The power load on target plates due to such a very small ELM is too low to be distinguished out by divertor LP measurements.

The very small ELMy regime may provide a potential scenario for ITER.

#38293: $I_p=0.4\text{MA}, q_{95}=4.5, P_{\text{heat}}\sim 1.7\text{MW}$.
The very small ELMs are type-II like

- Operation space of Type II ELMs: high $\delta$, high $\kappa$, high $n_e$, and high $q_{95}$
- Confinement of Type II ELMs: $H_{98}$ being 10% less than Type I ELMs
- Unique feature of Type II ELMs: w/ broadband MHD mode

(30±10kHz@ASDEX-Upgrade; 10-40kHz@JET)

Time-frequency spectrum of Mirnov magnetic signal.
Achieved long pulse H-mode over 30s with small ELMs to minimize transient heat load.

- Predominantly small ELMs with $H_{98} \sim 0.9$, between Type I and Type III ELMy H-modes.
- Target heat load is largely below 2 MW/m².
- The accompanied QCM provides quasi-continuous particle and heat exhaust.

J. Li, H.Y. Guo, B.N. Wan et al., 2013 Nature Phys. (Accepted)
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Edge magnetic topology change by LHCD

Helical Radiation Belts (current sheet)

Y. Liang et al., PRL 110, 235002 (2013)
Strong mitigation of ELMs with LHCD

- ICRF-dominated + 10Hz LHW modulation (LHW-off: 50ms $\sim \frac{1}{2}\tau_E$)
- $H_{98}=0.8$; $W_{dia}|_L \rightarrow H$: 50 $\rightarrow$ 100kJ
- LHW off: $f_{ELM} \sim 150$Hz
- LHW on: ELMs disappear or sporadically appear w/ $f_{ELM} \sim 600$Hz
- Peak particle flux: ↓ by 2-4
- $W_{dia}$ varied slightly: within $\pm 5\%$
- A quick reduction of $\Gamma_{i,div}$ during inter-ELM can be seen when LHW was switched off, indicating the LHW power was absorbed not only in the core plasma but also deposited in SOL.
Flexible boundary control with LHCD

- The long pulse H-mode was achieved with dominant LHCD, with additional ICRH.
- LHCD induces drives n=1 helical currents at edge, leading to 3D distortion of magnetic topology, similar to RMP.
- LHCD appears to be effective at controlling ELMs over a broad range q_{95}, in contrast to fixed RMP coils.
SHF can be actively controlled by changing edge plasma density

- Striated Heat Flux (SHF) region in the far-SOL can be actively controlled with SMBI.
- SMBI significantly enhancing SHF, while reducing peak heat fluxes near strike point.
- Achieving similar results with conventional gas puff or Ar seeding.
SHF can be actively controlled by changing edge particle fluxes

- For SHF: $q_{\text{SHF}} \sim \Gamma_i T_{\text{ped}}$, $T_{\text{ped}} \sim 350$ eV
  $\Rightarrow q_{\text{SHF}}$ increases with $\Gamma_i$.

- At OSP: $q_{\text{OSP}} \sim \Gamma_i T_{\text{div}}$, $T_{\text{div}} \sim \Gamma_i^{-1}$,
  $\Rightarrow q_{\text{div}}^{\text{OSP}}$ remains similar.

- This is a unique physics feature of ergodized plasma edge obtained by application of LHCD, allowing control of the ratio of $q_{\text{SHF}}/q_{\text{OSP}}$, thus divertor power deposition area via control of divertor plasma conditions.

J. Li, H.Y. Guo, B.N. Wan et al., 2013 Nature Phys. (Accepted)
This, coupled with conventional Radiative Divertor, opens a new avenue for heat control.

- Reduce peak heat load by impurity radiation.
- Change heat flux distribution by varying divertor plasma conditions.

This physics effect provides an additional knob for the control of the stationary divertor power load, beyond or in addition to the achievement of highly radiating divertor conditions, which may be of interest for future fusion devices such as ITER.
Achieved Long Pulse Divertor Operation over 400s by control of SS heat load

- Active water cooling with cryo-pumping.
- Divertor configuration varied betw. LSN-DN-USN periodically to minimize heat load accumulation.

B. N. Wan et al., NF 53, 104006 (2013)
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Divertor heat load for various ELMs currently achieved in EAST

- Present Type I ELMs in EAST lead to a peak heat load of \(~10\text{MW/m}^2\), with a loss of \(~8\%\) plasma energy.

- In contrast, peak heat load is below 2 MW/m\(^2\) for Type II-like, small ELMs, observed in long pulse H-modes.

- Divertor heat load in the next campaign will be a great challenge, with > 20 MW H&CD power.

<table>
<thead>
<tr>
<th>ELM type</th>
<th>(\Delta W_{\text{dia}}/W_{\text{dia}})</th>
<th>(\Delta W_{\text{div}}/W_{\text{dia}})</th>
<th>(q_{\text{peak}}) (MW m(^{-2}))</th>
<th>(H_{98}(y,2))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type I</td>
<td>8%</td>
<td>5%</td>
<td>(~10)</td>
<td>(~1)</td>
</tr>
<tr>
<td>Compound</td>
<td>4.5%</td>
<td>5% (in a few ms)</td>
<td>3–5</td>
<td>(~1)</td>
</tr>
<tr>
<td>Small Type III</td>
<td>Undetected</td>
<td>1–2%</td>
<td>2</td>
<td>0.5–0.8</td>
</tr>
<tr>
<td>Type-II like</td>
<td>Too small to be measured</td>
<td></td>
<td>&lt;1</td>
<td>0.8–0.85</td>
</tr>
</tbody>
</table>

L. Wang et al., Nucl. Fusion 53, 073028 (2013)
Many new and exciting physics results have been obtained with the following key findings:

- LHCD leads to edge plasma ergodization, mitigating ELM transient heat load and broadening the divertor footprint.

- The combination of LHCD & SMBI allows control of steady-state divertor heat flux distribution by regulating divertor plasma conditions, which needs to be further extended on EAST.

- Achieved ELM pacing at nearly 100% accuracy using lithium granule injection.

EAST is being upgraded with ITER-like W mono-block divertor and more than 20 MW CW H&CD, offering an exciting opportunity and great challenge for long pulse divertor studies.
Scaling of divertor power footprint width

- Three diagnostics independently demonstrate the inverse $I_p$ (Bp) scaling of SOL width. The scaling with $q_{95}$ is linear. Moreover, it is shown the inverse $I_p$ scaling is independent of plasma configuration.

\[
\lambda_{q,IR}^{EAST} = \lambda_{q,div-LPs}^{EAST} / 1.3 = 1.15 B_{p,omp}^{-1.25}, \quad \text{RF-heated}
\]

\[
\lambda_{q,IR}^{\text{multi-machines}} = (0.63 \pm 0.08) B_{p,omp}^{-1.19 \pm 0.08}, \quad \text{only C-Mod was RF-heated}
\]

- IR results shown good agreement with Eich-fit & Makowski model, with $S=2.3-4.6$ mm, $S/\lambda_q=0.31-0.48$ & $S/\lambda_{int}=0.21-0.33$ at $I_p=0.3-0.8$MA.

- Identified the relation between integral & fall-off widths in EAST, which may be of significant reference to ITER.

\[
\lambda_{int}^{EAST} = 1.39 \lambda_q^{EAST} + (0.97 \pm 0.35) \text{ mm}, \quad \lambda_{int}^{\text{JET}} = 1.26 \lambda_q^{\text{JET}} + (0.94 \pm 0.32) \text{ mm}
\]

\[
\lambda_{int}^{\text{AUG}} = 1.34 \lambda_q^{\text{AUG}} + (1.78 \pm 0.58) \text{ mm}, \quad \lambda_{int}^{\text{MAST}} = 1.41 \lambda_q^{\text{MAST}} + (3.7 \pm 0.5) \text{ mm}
\]

- The regression coefficient of Bp in EAST shows good agreement with multi-machine scaling, while the amplitude is about twice the multi-machine results. Lower injected power? Type III ELMs? RF Heating dominated plasma?
Thank you for your attention!
Comments and suggestions are appreciated.

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