Elimination of the Non-Axisymmetric inter-ELM Heat Flux Generated by Resonant Magnetic Perturbations in Detached Divertor Conditions

&

Assessment of Divertor Heat Load with and without External Magnetic Perturbation

B. Sieglin¹, A.R. Briesemeister²

¹ Max Planck Institute for Plasma Physics, Boltzmannstr. 2, 85748 Garching, Germany
² Oak Ridge National Laboratory, Oak Ridge, TN, USA

26th IAEA Fusion Energy Conference, 17-22 October 2016
Elimination of the Non-Axisymmetric inter-ELM Heat Flux Generated by Resonant Magnetic Perturbations in Detached Divertor Conditions

by
A.R. Briesemeister

with:
J.W. Ahn, I. Bykov, J.M. Canik, M.E. Fenstermacher, N. Ferraro, H. Frerichs,
C.J. Lasnier, J.D. Lore, A.W. Leonard, M.A. Makowski, A.G. McLean,
W.H. Meyer, O. Schmitz, M.W. Shafer, E.A. Unterberg, H.Q. Wang,
J.G. Watkins

Oak Ridge National Laboratory, Oak Ridge, TN, USA
Lawrence Livermore National Laboratory, Livermore, CA, USA
University of Wisconsin-Madison, Madison, WI, USA
General Atomics, San Diego, CA, USA
Sandia National Laboratories, Albuquerque, NM, USA
Princeton Plasma Physics Laboratory, Princeton, NJ, USA

Presented at the
26th IAEA Fusion Energy Conference
October 17th-22nd 2016
Assessment of Divertor Heat Load with and without External Magnetic Perturbation

B. Sieglin¹, T. Eich¹, M. Faitsch¹, A. Herrmann¹, A. Kirk², A. Scarabosio¹, W. Suttrop¹, A. Thornton², JET contributors*, the EUROFusion MST1 Team† and the ASDEX Upgrade Team¹

¹ Max Planck Institute for Plasma Physics, Boltzmannstr. 2, 85748 Garching, Germany
² CCFE, Culham Science Centre, Oxfordshire OX14 3DB, United Kingdom
* EUROfusion Consortium, JET, Culham Science Centre, Abingdon, OX14 3DB, UK
† See the author list of “Overview of progress in European Medium Sized Tokamaks towards an integrated plasma-edge/wall solution” by H. Meyer et al., to be published in Nuclear Fusion Special issue: overview and summary reports from the 26th Fusion Energy Conference (Kyoto, Japan, 17-22 October 2016)

26th IAEA Fusion Energy Conference, 17-22 October 2016

* See the author list of “Overview of the JET results in support to ITER” by X. Litaudon et al. to be published in Nuclear Fusion Special issue: overview and summary reports from the 26th Fusion Energy Conference (Kyoto, Japan, 17-22 October 2016)
Overview

• Introduction

• L-Mode and Inter-ELM H-Mode divertor heat load

• Divertor electron temperature and density distribution

• Divertor ELM deposited energy density

• Conclusions
Axisymmetric Divertor Heat Load

- Axisymmetric target heat load profile is quantified by power fall-off length $\lambda_q$ and by divertor broadening $S$.

- $S$ is increasing with decreasing divertor electron temperature.

$$ S \propto l_{div} \sqrt{\frac{\chi_\perp}{\chi_\parallel}} \propto T_e^{-5/4} n_e^{1/2} $$

- $\lambda_q$ in L-Mode described by the same parametric dependence as in H-Mode, but with about twice the absolute size.

$$ \lambda_{q,H-Mode} = 0.73 \pm 0.38 B_{tor}^{-0.78\pm0.25} q_{cyl}^{+1.07\pm0.07} P_{SOL}^{+0.10\pm0.11} R^{+0.02\pm0.2} $$

$$ \lambda_{q,L-Mode} = 1.45 \pm 0.13 B_{tor}^{-0.78} q_{cyl}^{+1.20\pm0.27} P_{SOL}^{-0.14\pm0.05} $$
Magnetic Perturbation

- DIII-D and ASDEX Upgrade are equipped with two rows of saddle coils.

**DIII-D**
- 12 coils
- n=1,2,3 (n=1,2 rotatable)
- Coil current 7 kAt

**ASDEX Upgrade**
- 16 coils
- n=1,2,3,4 (n=1,2,3 rotatable)
- Coil current 6.5 kAt
Overview

- Introduction

- **L-Mode and Inter-ELM H-Mode divertor heat load**
  - Divertor electron temperature and density distribution
  - Divertor ELM deposited energy density

- Conclusions
Heat Flux with Magnetic Perturbation (MP)

- L-Mode with slow rigid rotation of external magnetic preturbation to measure the 2D heat flux pattern on the divertor target.
- Non axisymmetric heat flux pattern in the presence of MP
- Averaged heat flux described by same model as unperturbed heat flux
• Experiments with n=2 perturbation in resonant, non-resonant, upper and lower coil only configuration.

\[ \lambda_q \] and \[ S \] are the same within the uncertainty for the toroidal averaged heat flux profile compared to the reference without MP.

⇒ MP does not change perpendicular heat transport significantly!
Heat Flux Peaking due to MP (Experiment)

- MP induces local increase of heat flux compared to axisymmetric profile without MP.
- Highest heat flux with MP close to the peak position without MP.
- Relative variation increases away from the separatrix.
- Characteristic reduced with increasing density.
Discharges focused on achieving the high density divertor conditions needed for detachment in H-mode

This work focuses on inter-ELM divertor conditions

RMPs reduced average ELM energy by 30%

Even Coil Parity n=3 (resonant):
- Top and bottom coil pairs have $\delta b_r$ in same direction, typically used for ELM suppression
- $B_T = 1.9 \, T$, $q_{95} = 3.5$
- I-coil current = 4 kAt

- This work focuses on inter-ELM divertor conditions
- RMPs reduced average ELM energy by 30%
Heat flux splitting measured in attached conditions eliminated in strongly detached conditions

- Gas puffing used to create matching core density profiles
- Heat flux measured between ELMs using infrared imaging
Overview

- Introduction
- L-Mode and Inter-ELM H-Mode divertor heat load
- **Divertor electron temperature and density distribution**
- Divertor ELM deposited energy density
- Conclusions
At moderate densities perturbations appear in the electron temperature in the divertor.

- A secondary region of elevated electron temperature measured 7 cm away from primary strike point
  - $T_e=20$ eV in secondary peak
  - $T_e=10$ eV around peak
- Without RMPs no such structure is seen
Electron density shows less pronounced structure than electron temperature.

- Electron density also shows structure which do not follow the flux surfaces calculated assuming axisymmetry.
  - A region of elevated density is seen on the target just inside the region where elevated electron temperature is seen.
RMP induced perturbations peel away from the floor as density is increased.

- Consistent with reduction of heat flux structure as density is increased.
- Suggests that reduction in heat flux is likely caused by detachment of the lobe structures, rather than changes in the magnetic structure.
Langmuir probes also show clear secondary peak only in lower density case.

- Secondary peaks are at different radial locations
- At higher density there is not clear secondary peak

\[ J_{sat} (\text{Amps/cm}^2) \]

Distance from OSP (mm)

- Langmuir probes are at toroidal position=172.5°, divertor Thomson scattering is at 120°
  - Secondary peaks are at different radial locations
- \( J_{sat} \) shows that higher density case is in high recycling regime
EMC3-Eirene modeling also shows $T_e$ structures move away from the floor as density increases.

- Non-axisymmetric structures in the electron temperature reach the target at lower densities simulations.
- Higher density cases show that electron temperature drops before reaching the target.
- Same magnetic configuration was used at all densities.
Simulations show $T_e$ reduction across the profile as the core density is raised.

- At low densities $T_e$ within the lobes can be equal to or greater than $T_e$ at the primary strike outer point.
- As density is raised $T_e$ profile is smoothed.
- No recombination in simulations $\rightarrow$ No detachment.

Inter-ELM H-Mode
Peaking at High Density

- Characteristic of 2D pattern is reduced with increasing density.

**Measurement**

\[ \frac{n}{n_{GW}} = 0.1 \]

\[ \frac{n}{n_{GW}} = 0.3 \]

**ASDEX Upgrade**

**Modelling**

\[ S = 0.29 \text{ mm} \]

\[ S = 0.85 \text{ mm} \]
Peaking at High Density

- Increasing $S$ is thought to be the reason for the reduced characteristic.
- Heat flux modelling using vacuum field approach with field line tracing and experiment are in agreement.

Toroidal Peaking

\[ \sigma_{tor}(s) = \frac{\max(q(s))}{\langle q(s) \rangle} \]

$s$: Poloidal target coordinate.

- Reduction of toroidal peaking of the heat flux is described by the simple model.
Overview

• Introduction

• L-Mode and Inter-ELM H-Mode divertor heat load

• Divertor electron temperature and density distribution

• Divertor ELM deposited energy density

• Conclusions
ELM Energy Density

- External magnetic perturbation is studied for ELM mitigation.
- Reduction of ELM deposited energy density is often observed to be correlated with reduction of the pedestal pressure and stored energy of the plasma.
ELM Energy Density

- Semi empirical model describes the ELM deposited energy in dependence of the pedestal pressure. Model gives lower and upper boundaries (3:1).

\[ \varepsilon_\parallel \approx K \, 6\pi \, p_{e,ped} \, R_{Geo} \, q_{cyl} \quad [K=1-3] \]

- Available data (JET, MAST, AUG) lies within the model boundaries.

- ELMs with and without magnetic perturbation are described by the model, within the scatter of the available data.

- **Proposal:** Assessment of ELM peak energy density reduction needs to correct for the pedestal pressure loss due to pump out.
Conclusions

• Power fall-off length in L-Mode described by the same parametric dependence as in H-Mode, but with factor 2 in absolute size.

• 2D heat flux pattern with magnetic perturbation
  • L-Mode perpendicular heat transport is unaffected by magnetic perturbation.
  • Characteristic of 2D structure is reduce with increasing density, observed in DIII-D and ASDEX Upgrade.
  • Both EMC3-Eirene simulations as well as simple modelling reproduces reduced characteristic with increasing density / divertor broadening.
  • No change in magnetic structure required to describe the observed decrease of the 2D characteristic.

• ELM deposited energy density is correlated to the pedestal pressure, which needs to be accounted for in the assessment of ELM mitigation.

“This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.”