

S. Elmore, S.Y. Allan, G. Fishpool, A. Kirk, M. Kočan, P. Tamain,
A.J. Thornton and the MAST Team

Scrape-off Layer Ion Temperature Measurements at the Divertor Target During Type III ELMs in MAST Measured by RFEA

Enquiries about copyright and reproduction should in the first instance be addressed to the Culham Publications Officer, Culham Centre for Fusion Energy (CCFE), Library, Culham Science Centre, Abingdon, Oxfordshire, OX14 3DB, UK. The United Kingdom Atomic Energy Authority is the copyright holder.

Scrape-off Layer Ion Temperature Measurements at the Divertor Target During Type III ELMs in MAST Measured by RFEA

S. Elmore^{1*}, S.Y. Allan¹, G. Fishpool¹, A. Kirk¹, M. Kočan², P. Tamain³,
A.J. Thornton¹ and the MAST Team¹

¹*CCFE, Culham Science Centre, Abingdon, Oxon, OX14 3DB, UK*

²*ITER organization, Route de Vinon sur Verdon, 13115 St Paul-lez-Durance, France*

³*Association Euratom-CEA, CEA/DSM/IRFM, CEA-Cadarache,
F-13108 St Paul-lez-Durance Cedex, France.*

The following article was subsequently published in Plasma-Surface Interactions 21. Proceedings of the 21st International Conference on Plasma-Surface Interactions in Controlled Fusion Devices, Kanazawa, Japan. May 26-30, 2014. Journal of Nuclear Materials, Vol.463, August 2015, pp.889-892
Further reproduction distribution of this paper is subject to the journal publication rules.

Scrape-off layer ion temperature measurements at the divertor target during type III ELMs in MAST measured by RFEA

S. Elmore^{a*}, S. Y. Allan^a, G. Fishpool^a, A. Kirk^a, M. Koan^b, P. Tamain^c, A. J. Thornton^a and the MAST Team^a

^aCCFE, Culham Science Centre, Abingdon, Oxon, OX14 3DB, UK

^bITER organization, Route de Vinon sur Verdon, 13115 St Paul-lez-Durance, France

^cAssociation Euratom-CEA, CEA/DSM/IRFM, CEA-Cadarache, F-13108 St Paul-lez-Durance Cedex, France.

Abstract

Edge-localised modes (ELMs) can carry significant fractions of their energy as far as main chamber plasma-facing components in divertor tokamaks. Since in future devices (e.g. ITER, DEMO) these energies could cause issues for material lifetime and impurity production, the energy and temperature of ions in ELMs needs to be investigated. In MAST, novel divertor measurements of T_i during ELMs have been made using the divertor retarding field energy analyser (RFEA) probe. These measurements have shown instantaneous ion energy distributions corresponding to an effective T_i at 5cm from the strike point at the target that can be as high as 60 eV and that this decreases with time after the ELM start. This is consistent with the hottest, fastest ions arriving at the target first by parallel transport, followed by the lower end of the ion energy distribution. This analysis will form a basis for future data analysis of fast swept measurements of ion distributions in ELMs.

PACS: 52.55 Fa, 52.55 Rk, 52.70 Ds

PSI-20 keywords: ELMs, Divertor plasma, MAST, Probes

***Corresponding author address: EURATOM/CCFE Fusion Association, Culham Science Centre, Abingdon, Oxon, OX14 3DB, UK**

***Corresponding author E-mail: Sarah.Elmore@ccfe.ac.uk**

Presenting author: Sarah Elmore

Presenting author e-mail: Sarah.Elmore@ccfe.ac.uk

1. Introduction

Measurements in JET have shown edge-localised modes (ELMs) to carry significant fractions of their energy to first wall materials [1]. This could be a dominant source of thermal loading and impurity sputtering in future devices such as ITER and DEMO [2]. Measurements of the ion temperature (T_i) and energy have been attempted in a number of present tokamaks such as JET [1], ASDEX-Upgrade [2, 3] and MAST [4] at the midplane using retarding field energy analyser (RFEA) probes, however, previously no measurements have been made at the divertor target in a tokamak. Using the divertor RFEA installed in MAST in 2012 [5], the ion energy distribution can be investigated at the outer divertor of MAST during ELM events. Two different measurement techniques have been attempted; a slow-swept method which can give information about the average ELM at a fixed point relative to the divertor strike point, as used in AUG [3]; and a fast-swept method which attempts to analyse the ion distribution on timescales shorter than the time taken for all ions in an ELM to arrive at the divertor. The fast swept measurements, although interesting and novel, prove to be more challenging to analyse due to capacitive effects in the probe which are comparable to the current signal measured.

In this paper the slow swept data will be studied in detail in an attempt to interrogate the time history of ions arriving at the outer divertor as a result of type-III ELM events. These type of ELMs are less dangerous than type-I ELMs, which were previously measured in JET [1], and have a higher frequency which higher statistical measurements. An average ion temperature can be determined from the slow swept data for a set of similar ELMs at a fixed position relative to the strike point. Further information of the time history of the ion energies can be determined by ‘box-carring’ the signals in 50 μ s time intervals, provided the signals from the ELMs are aligned in time.

2. Experimental setup

Ion temperature measurements were made at the outer divertor target of MAST during ELMs using the divertor RFEA probe [5]. Measurements of type III ELMs resulting from a double null plasma with plasma current of $I_p = 600$ kA and neutral beam heating power of $P_{\text{NBI}} = 1.8$ MW were made during ELMy H-mode periods, during which the position of the strike point relative to the divertor RFEA was fixed at two radial positions, accurate to ± 0.5 cm from infra-red (IR) measurements.

The RFEA is operated in the slow swept mode, where it is assumed that during the lifetime of an ELM event, the voltage on the discriminating grid (grid 1) is approximately constant. The voltage is swept from 0 V to ~ 300 V at 40 Hz. This is similar to the method used in the AUG RFEA ELM measurements [2, 3]. The slit plate was held at a constant voltage of -200 V in order to repel electrons and measure the saturation current density, j_{sat} . Grid 2, used for suppression of secondary electrons, was held at a constant voltage of -300 V. See figure 1 for a diagram of the RFEA setup. The effective temperature of the ion energy distribution during an ELM can be determined by comparing the slit plate and collector currents during ELMs at various grid 1 voltages. The average collector current during an ELM is defined as [3]:

$$\langle I_c \rangle_{E1} = \Delta t_{E1}^{-1} \int_{\Delta t_{E1}} I_c dt \quad (1)$$

Where t_{ELM} is the duration of the ELM signal, defined by the time that j_{sat} on the RFEA slit plate is greater than $0.1 * (j_{\text{sat}}^{\text{peakELM}} - j_{\text{sat}}^{\text{inter-ELM}}) + j_{\text{sat}}^{\text{inter-ELM}}$, and I_c is the measured current at the collector plate.

It is assumed that during the measurements, ELM events enhance the steady state plasma at the RFEA probe and therefore the measurements are a combination of inter-ELM and ELM ions. In order to calculate T_i for purely the ELM ions, the steady state ion current arriving at the collector plate due to the scrape-off layer (SOL) plasma has been removed before $\langle I_c \rangle_{E1}$ is

calculated. The background ion current, I_{BKGD} , of ions resulting from steady state SOL plasma can be estimated for the specific radial location of the measurements using steady state data obtained in the same plasma scenario [6]. Using the measured inter-ELM T_e , T_i and j_{sat} profiles, I_{BKGD} can be determined for a particular distance of from the strike point at the target ($R_{\text{LCFS}}^{\text{tgt}}$) using an assumed transmission through the probe, $T_r \sim A_s \tau_{\text{opt}}^3$, where A_s is the slit area, τ is the estimated transmission through the probe slit, and τ_{opt} is the optical transmission through the grids. Using the following steady state equation I_{BKGD} can be calculated for the particular constant applied grid voltage (V_g) during the ELM.

$$\begin{aligned} I_B &= A_s \xi_r \xi_o^3, & V_g < 2.7T_e \\ I_B &= A_s \xi_r \xi_o^3 j_s \exp\left(\frac{-(V_g - 2.7T_e)}{T_i}\right), & V_g \geq 2.7T_e \end{aligned} \quad (2)$$

I_{BKGD} is subtracted from I_c to give I_{CELM} before integrating using equation 1. For the radius ranges used in this analysis inter-ELM $T_i = 13.5 - 16$ eV, $T_e = 7.5 - 8$ eV and $j_{\text{sat}} = 0.7 - 1.3$ kAm⁻².

To remove any biasing effect on the collector measurements resulting from variation in the flux across ELM events, the collector current, I_c for an ELM is normalized to j_{sat} . The time averaged j_{sat} , $\langle j_s \rangle_{\text{EI}}$, is calculated in the same way as equation 1. By comparing the ratio of the slit plate and collector currents for a set of similar ELMs at a fixed $R_{\text{LCFS}}^{\text{tgt}}$, T_i can be determined using the following:

$$\frac{\langle I_c \rangle_{\text{EI}}}{\langle j_s \rangle_{\text{EI}}} = T_r \exp\left(\frac{-(V_g - V_s)}{T_i}\right) + C \quad (3)$$

T_r can be estimated from probe dimensions. However in this analysis it will be a fitted parameter along with V_s , the sheath voltage, which is defined as $V_s = 2.7T_e$ [3], T_i , and C , which accounts for any offsets in the current signals.

It is possible to interrogate the evolution of the ion distribution arriving at the divertor RFEA in time by analyzing separate time cuts through t_{ELM} rather than calculating T_i for the time-averaged ELM. First the ELMs must be aligned in time so that the time windows analysed are comparable for all ELMs. The alignment is done by finding the leading edge of the ELMs on the slit plate j_{sat} signal. The leading edge is defined as the point at which j_{sat} signal reaches $0.5*(j_{\text{sat}}^{\text{peakELM}} + j_{\text{sat}}^{\text{inter-ELM}})$; this time is labelled t_{ELM} . Once all ELMs at a fixed $R_{\text{LCFS}}^{\text{tgt}}$ are aligned, the currents are divided into $50 \mu\text{s}$ windows starting at t_{ELM} until $t_{\text{ELM}} + 300 \mu\text{s}$, see figure 2 for an example j_{sat} signal with time window cuts shown. These windows become t_{ELM} in equation 1 and the ratio of $\langle I_{\text{c}} \rangle_{\text{E1}} / \langle j_{\text{s}} \rangle_{\text{E1}}$ as a function of $t-t_{\text{ELM}}$ from t_{ELM} to $t_{\text{ELM}} + 300 \mu\text{s}$ can be constructed. This allows, for each $50 \mu\text{s}$ time window, the normalised current ratio to be plotted against grid 1 voltage for the set of ELMs and therefore T_i , V_s and t_0 to be determined as a function of $t-t_{\text{ELM}}$.

3. ELM T_i measurements

A set of similar type III ELMs have been measured at $R_{\text{LCFS}}^{\text{tgt}} \sim 5 \text{ cm}$ and $R_{\text{LCFS}}^{\text{tgt}} \sim 7 \text{ cm}$, where $\lambda_q^{\text{t}} \sim 3 \text{ cm}$ as measured by IR. Similar ELMs to be analysed as a set have been determined by requiring the j_{sat} signals, normalized to the largest peak signal, to fit within a pre-determined shape of the rise and fall as a function of time. Figure 3 shows the chosen ELMs for each radial position, where the red dotted lines display the upper limit on normalized j_{sat} ; the green dotted lines display the lower limit on j_{sat} ; and the blue dotted lines require that maximum peaks are above a minimum fraction of the largest ELM and that they occur within a range of time following the time defined as t_{ELM} . If it is assumed that any variations in the j_{sat} signal with time are caused by changes in density and not in temperature, then determining the inferred T_i using the ratio of $\langle I_{\text{c}} \rangle_{\text{E1}}$ to $\langle j_{\text{s}} \rangle_{\text{E1}}$ will remove any effects due to j_{sat} magnitude variations.

For each 50 μs time window the ratio of integrated currents, $\langle I_c \rangle_{EL} / \langle J_s \rangle_{EI}$, is plotted against voltage, V_g , and using equation 2, T_i , V_s and T_r can be determined; see figure 4 for a characteristic for the time window $0 \mu\text{s} > t_{ELM} > 50 \mu\text{s}$, at $R_{LCFS}^{tgt} \sim 5 \text{ cm}$.

Using the fitted parameters from the characteristics, T_i , V_s and T_r can be plotted as a function of time through the ‘average’ type III ELM in this particular MAST plasma scenario, see figure 5, measured at $R_{LCFS}^{tgt} \sim 5 \text{ cm}$ and $R_{LCFS}^{tgt} \sim 7 \text{ cm}$. Peak T_i is measured at t_{ELM} , where t_{ELM} is half the time of the rise on j_{sat} , of $T_i \sim 64 \text{ eV}$ at $R_{LCFS}^{tgt} \sim 5 \text{ cm}$ and $T_i \sim 27 \text{ eV}$ at $R_{LCFS}^{tgt} \sim 7 \text{ cm}$. Figure 5 shows T_i reduces with time after the ELM start, t_{ELM} , with the hottest ions measured closest to the divertor strike point for $t - t_{ELM} < 100 \mu\text{s}$. Both sets of ELMs show a similar reduced T_i after $t - t_{ELM} \sim 100 \mu\text{s}$. This suggests that most hot ions arrive at the target before $t_{ELM} + 100 \mu\text{s}$, which is consistent with estimated parallel transport times for ELM ions. The difference in T_i for the two measurement positions also suggests less hot ions reach the divertor target at larger distances from the strike point and although temperatures $\sim 60 \text{ eV}$ are measured at $R_{LCFS}^{tgt} \sim 5 \text{ cm}$, these reduce considerably a few cm further from the strike point.

V_s , which is proportional to T_e , shows a slight initial peak at t_{ELM} . Since $V_s \sim 2.7T_e$, we measure $T_i \sim 3.8T_e$ at t_{ELM} at $R_{LCFS}^{tgt} \sim 5 \text{ cm}$ and $T_i \sim 1.5T_e$ at t_{ELM} at $R_{LCFS}^{tgt} \sim 7 \text{ cm}$. This shows a reduction in both T_i and T_i/T_e with distance from the strike point at the target. V_s has a slight tendency to reduce after t_{ELM} , and settles at a relatively constant value for both radial positions of $V_s \sim 40 \text{ V}$ at R_{LCFS}^{tgt} over the following 300 μs .

It can be seen that T_r remains relatively constant, on average, as would be expected, since it is largely determined by the geometry of the RFEA probe. The values estimated from the fitted data correspond to $\tau_r \sim 0.2 - 0.4$; which spans the range of estimated values calculated from Ko an’s model [7] using the dimensions of the MAST divertor RFEA probe; $\tau_r \sim 0.2 - 0.3$. It is expected that value of τ_r could be larger than those theoretically calculated since the attenuation

of the MAST RFEA protective housing could mean the theoretical current transmitted is an underestimation. Values for τ estimated experimentally from the divertor RFEA probe on MAST [5] show values in the range $\tau \sim 0.3 - 0.8$, therefore incorporating the transmission estimated here from the fitted characteristics.

4. Summary

Slow swept data analysis of type III ELMs has been exploited to gain understanding of the evolution of T_i and V_s through an ELM arriving at the target. This information will provide a basis for which to compare fast swept RFEA ELM data to be analysed in the near future. Both T_i and V_s are seen to reduce through time which is consistent with the model of hot ions draining from the ELM faster than the cooler ions. It has also been shown that at larger R_{LCFS}^{tgt} , T_i^{ELM} reduces; consistent with hot ions being lost at smaller R. The transmission through the probe is consistent with that expected from theoretical predictions for the dimensions of the MAST divertor RFEA. Further analysis will tackle type I and type III ELMs measured by the fast swept method, for which this work will allow valuable comparison. Future kinetic modelling will be used along with these measurements in order to investigate the loss process in ELMs.

Acknowledgements

This work was part-funded by the RCUK Energy Programme [grant number EP/I501045] and by the European Union's Horizon 2020 research and innovation programme. To obtain further information on the data and models underlying this paper please contact PublicationsManager@ccfe.ac.uk. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

References

- [1] R. A. Pitts, et al., Nucl. Fusion **46** (2006) 82-98
- [2] M. Kočan, et al., Nucl. Fusion **52** (2012) 023016
- [3] M. Kočan, et al., Plasma Phys. Control. Fusion **53** (2011) 065002
- [4] P. Tamain, et al., J. Nucl. Mater. **415** (2011) S1139-S1142
- [5] S. Elmore, et al., Plasma Phys. Control. Fusion **54** (2012) 065001
- [6] S. Elmore, et al., J. Nucl. Mater. **438** (2013) S1212-S1215
- [7] M. Kočan, et al., Rev. Sci. Instrum. **79** (2008) 073502

Figure captions

Figure 1. Schematic of RFEA module in operation and cross-section of divertor RFEA in the MAST lower outer divertor target.

Figure 2. Typical normalised j_{sat} signal during an ELM, aligned to t_{ELM} . Red lines indicate cuts in time used for boxcar time dependant analysis. All time intervals are $t_{\text{ELM}} = 50 \mu\text{s}$.

Figure 3. Set of similar ELMs which fit within the constrained window for (a) $R_{\text{LCFS}}^{\text{tgt}} \sim 5 \text{ cm}$ and (b) $R_{\text{LCFS}}^{\text{tgt}} \sim 7 \text{ cm}$. Red dotted lines display the upper limit on normalized j_{sat} ; green dotted lines display the lower limit on j_{sat} ; and blue dotted lines require that maximum peaks are above a minimum fraction of the largest ELM and occur within a range of time following the time defined as t_{ELM} .

Figure 4. Example fitted characteristic of $\langle J_{\text{c}} \rangle_{\text{E1}} / \langle j_{\text{s}} \rangle_{\text{E1}}$ vs V_{g} for $t_{\text{ELM}} < t < t_{\text{ELM}} + 50 \mu\text{s}$ at $R_{\text{LCFS}}^{\text{tgt}} \sim 5 \text{ cm}$.

Figure 5. Time dependant results of T_{i} , V_{s} and T_{r} for similar type III ELMs at $R_{\text{LCFS}}^{\text{tgt}} \sim 5 \text{ cm}$ and $R_{\text{LCFS}}^{\text{tgt}} \sim 7 \text{ cm}$. Also shown are the theoretical prediction and the experimental estimate of t_0 for the MAST divertor RFEA.

Figures

Figure 1

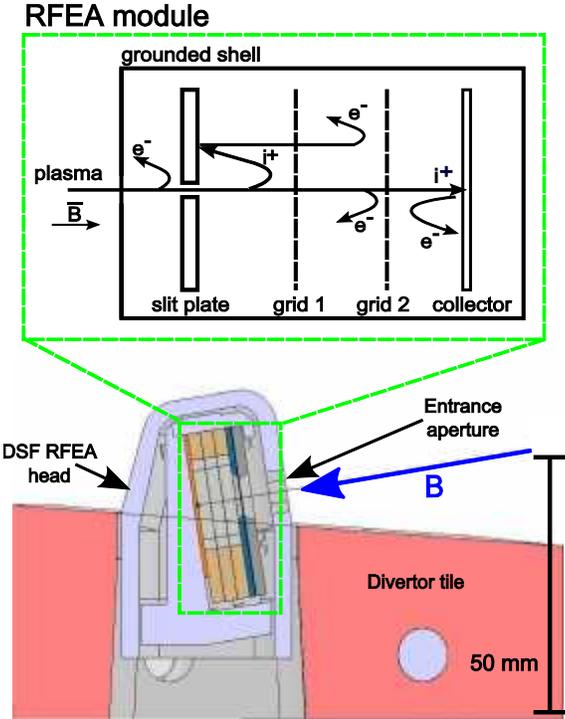


Figure 2

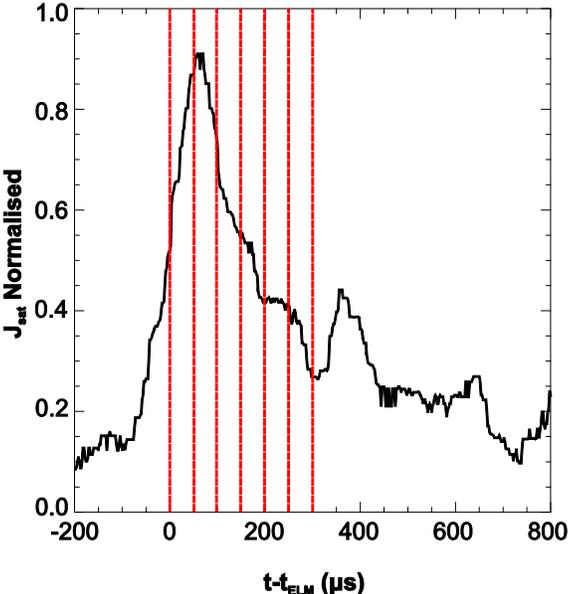


Figure 3

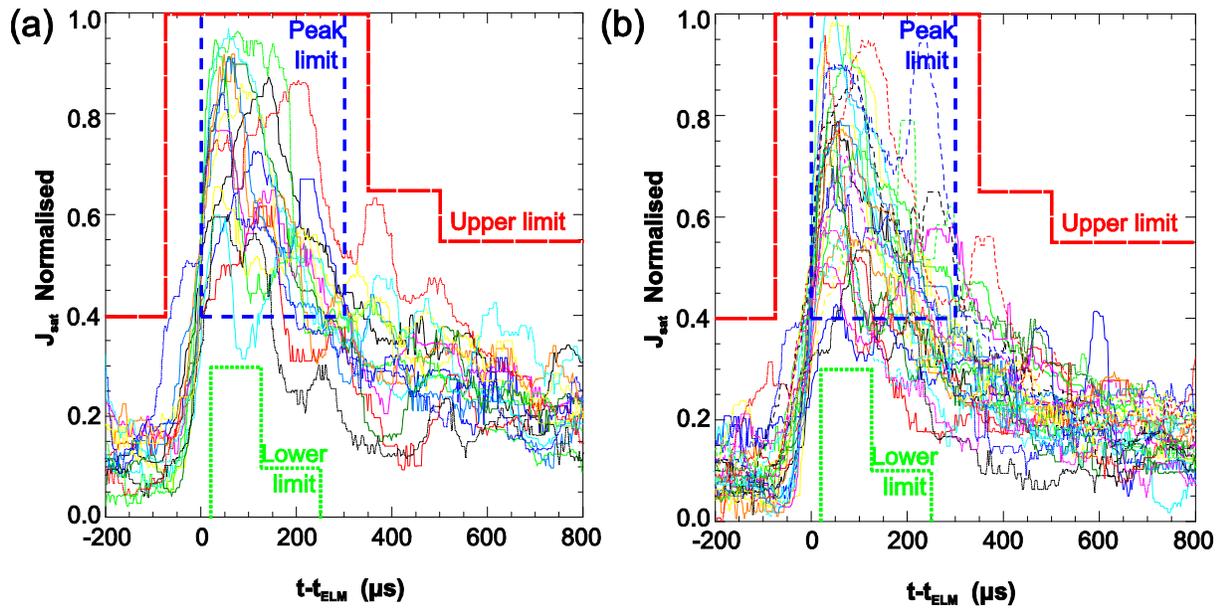


Figure 4

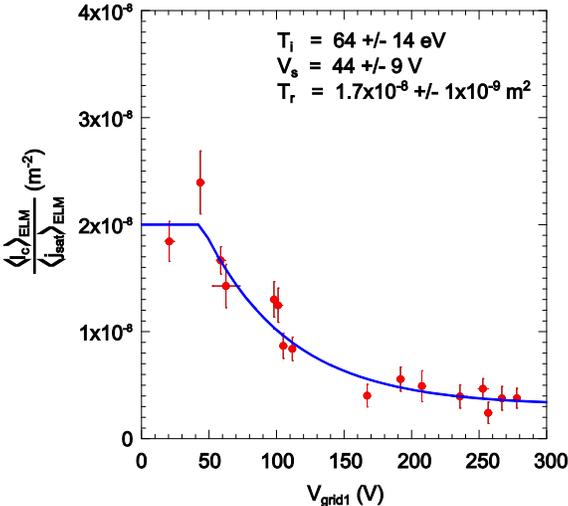


Figure 5

