27th EPS Conference on Contr. Fusion and Plasma Phys. Budapest, 12-16 June 2000 ECA Vol. **24B** *(2000) 1577 -1580*

Divertor Power Loading Studies in the MAST tokamak

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1. Introduction

The SOL plasma parameters and power loadings in double-null (DND) ST geometry were measured and analysed for the first time on START [1], where several unusual features were observed, including strong in-out/up-down power asymmetries and significant SOL currents. However, interpretation of the data was complicated by a blanket of high neutral density surrounding the START plasma (a result of the fuelling scheme, fully open divertor geometry and large vessel to plasma volume ratio), which was believed to give rise to large charge exchange losses from the SOL.

The larger successor to START, the Mega Ampere Spherical Tokamak (MAST) at Culham, has now been successfully commissioned and obtained first tokamak plasma in December 1999. The present plasma performance [2] already includes over 1 MA plasma current, significant ion heating from NBI auxiliary heating, densities up to 1.8x$n_{Greenwald}$ and H-mode operation (the main operating parameters are summarised in Table 1). Preliminary investigations of plasma conditions (including power loading) at each of the four strike points in MAST have been undertaken for a number of Ohmic DND plasmas, with flat top plasma currents of about 500 kA and $\bar{n}_e$ of around $1x10^{19}m^{-3}$. The results are presented together with initial data indicating that, as expected from modelling [3], neutral densities in the MAST vessel are substantially lower than in START, much reducing the uncertainties introduced by large charge exchange losses.

Operating Parameters	**Design Range**	**Shot 2321**
Major radius, R (m)	0.7 – 0.85	0.82
Minor radius, a (m)	0.5 – 0.65	0.57
Plasma current, I_p (MA)	≤ 2	0.44
Aspect ratio, A	≥ 1.3	1.44
B-field on axis, B_0 (T)	≤ 0.6	0.4
P_{AUX} (MW)	≤ 6.5	0
Pulse length (s)	≤ 5	0.15
n_e ($\times 10^{19}$ m^{-3})	1 – 18	~1

Table 1. Main operating parameters of MAST. Parameters for shot 2321 at time 144 ms are given on the right hand column as well as the general parameter ranges on left.

2. Experimental setup

MAST is well equipped with arrays of high spatial resolution, swept Langmuir probes covering all four strike point regions at the same toroidal location (Fig. 1). The inboard strike points (ISP) presently fall on the ~40 cm diameter centre column. This is protected by graphite tiles in which there are 212 flush-mounted probes spaced 3mm apart and arranged in two arrays covering the upper and lower ISP regions. The outboard strike points (OSP) fall on a series of radial graphite ribs, two of which (one upper and one lower) are installed with arrays of 90 flush-mounted probes, spaced

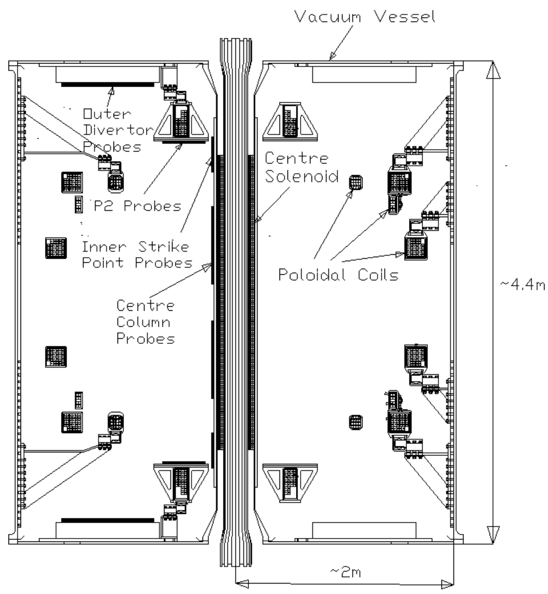

Fig. 1. A schematic view of the MAST Langmuir probe arrays, 576 probes in all

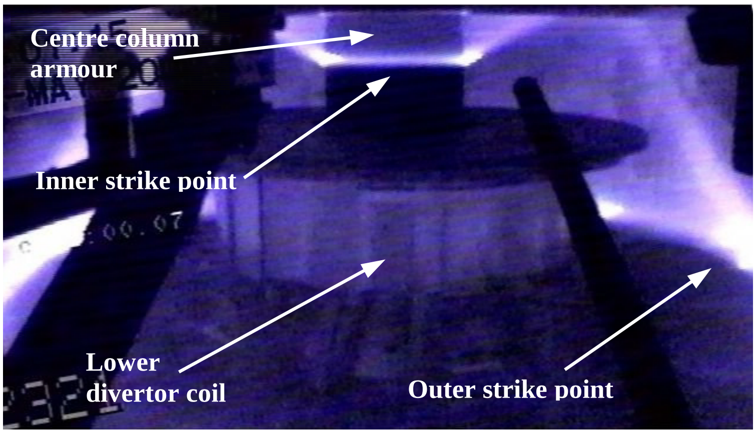

Fig. 2. Visible light image for shot 2321 (Ohmic only), showing lower inner and outer strike points at time 140 ms.

10mm apart.

Data were analysed for the period after the formation of a clear DND configuration (Fig.2), with the inboard separatrix well separated from the centre column. Care was taken to select data from well-established plasmas, with low levels of MHD activity, and for which good-quality data was available at all 4 strike points simultaneously.

3. Results

3.1 *Target parameter results*

Fig. 3 shows the target profiles of ion saturation current (I_{sat}), electron temperature (T_e), electron density (n_e) and electron pressure (p_e) across the upper ISP for shot 2321. Except for T_e (the analysis of which is subject to the largest uncertainties), the profiles are characterised by a well defined peak corresponding to the separatrix location and a clear exponential fall-off in the SOL. Similar sets of data were obtained for each of the other 3 strike points.

The target profile data are summarised in Table 2 together with estimates of the experimental uncertainties for this preliminary analysis. Unlike START observations [4], there is only weak evidence within experimental uncertainties for up/down asymmetries in target parameters. However, clear asymmetries are observed between the inboard and outboard temperature and density scale lengths, which are around an order of magnitude larger on the outboard side as a result of the strong poloidal flux expansion characteristic of the ST. This effect is also observed in measurements of the separatrix density, which are substantially lower on the outboard side.

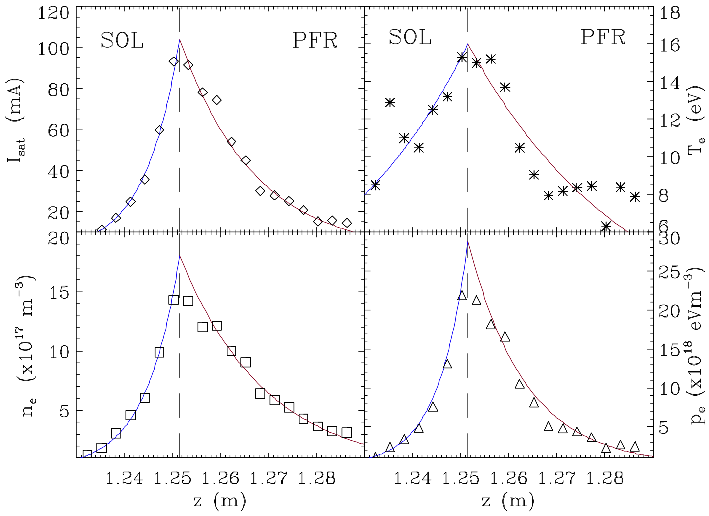

Fig. 3. Target plasma parameter profiles across the upper ISP at time 144 ms for shot 2321. Peak I_{sat} is regarded as the separatrix location.

One more interesting observation relates to the temperature and density decay lengths at the targets. At three of the four strike points, the ratio $\lambda_{Te}^{SOL} : \lambda_{ne}^{SOL}$ lies between ~5-8. This is higher than usually encountered in conventional aspect ratio devices and perhaps indicative of a significant difference between heat and particle diffusivities in the ST SOL and/or low recycling conditions at the targets. The ratio at the lower OSP is just 2.5 for reasons which remain to be understood. To this end, work is on-going to implement Onion-Skin method

Parameter	Strike Point Location	
	Upper	
	Inboard	Outboard
T_e^{sep} (eV)	16±5	17±8
n_e^{sep} (x 10^{17}m^{-3})	18±3	3.2±1
λ_{Te}^{SOL} (cm)	3.1±0.9	43±21
λ_{ne}^{SOL} (cm)	0.71±0.1	5.7±1.7
	Lower	
	Inboard	Outboard
T_e^{sep} (eV)	16±8	20±10
n_e^{sep} (x 10^{17}m^{-3})	13±4	2.0±0.6
λ_{Te}^{SOL} (cm)	4.4±2.2	27±14
λ_{ne}^{SOL} (cm)	0.76±0.23	11±3.4

Table 2. Summary of the target profile data for shot 2321 at time 144ms.

(OSM) [5] analysis for the MAST SOL, and to supplement target probe data with upstream measurements from reciprocating probe and helium line ratio diagnostics.

Rather more speculative, given the preliminary nature of the data, is an estimate of the SOL collisionality, which is often characterised in terms of the quantity $\nu^*=L_{//}/\lambda_{ee}$, where $L_{//}$ is the parallel connection length and λ_{ee}, the electron-electron mean free path. Only a rough estimation of the collisionality is currently possible due to uncertainties in the evaluation of $L_{//}$. However, typical measured values of target density (~2.5×10^{17}m^{-3}) and temperature (~20eV) at the outboard strike points, combined with $L_{//}$ of around 50m (scaled from START data), indicate that the outboard SOL is marginally collisional (ν^*~7) for the Ohmic shot considered. A higher density (1.5×10^{18}m^{-3}) and slightly lower temperature (~16eV) at the inner strike points, together with $L_{//}$ of around 40 m, suggests that the inner SOL is collisional in nature (ν^*~50).

Parameter	Strike Point Location	
	Upper	
	Inboard	Outboard
q^{sep} (MWm^{-2})	1.05±0.2	0.20±0.06
λ_q^{SOL} (cm)	0.53±0.1	4.8±1.4
Power (kW)	21±4	137±41
	Lower	
	Inboard	Outboard
q^{sep} (MWm^{-2})	1.05±0.3	0.18±0.05
λ_q^{SOL} (cm)	0.61±0.2	6.6±2
Power (kW)	23±7	118±35

Table. 3. Summary of the power flow results for shot 2321 at time 144ms

3.2 *Power to the target plates*

Estimates of power flow to the strike points are summarised in Table 3. The peak heat flux density (q^{sep}) shows a significant in/out asymmetry at both upper and lower targets, with the inboard tiles subject to ~5 times higher values (~1MWm^{-2}) than the outboard ones, but with a strike point width nearly 10 times as narrow. The total power flow to each target was estimated by integrating across both the SOL and private flux region (PFR) heat flux density profiles and assuming toroidal symmetry. The power flowing to the outboard divertor targets is typically ~5-7 times higher than that to the inboard side (~130kW), while the total power flowing to each of the upper and lower targets is approximately the same (~150kW), giving a grand total of ~300kW.

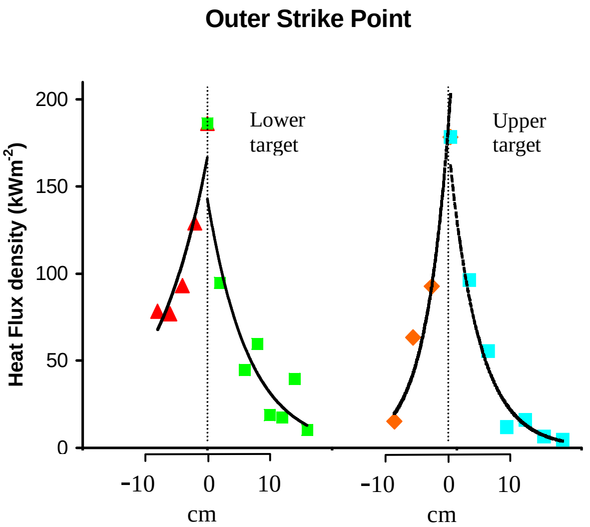

Fig. 4. Heat flux density profiles on the outboard side for shot 2321 at time 144ms.

Fig. 4 shows the heat flux density profiles on the outboard side at both upper and lower targets with fitted exponential fall-off curves. No marked difference between upper and lower profiles was observed (apart from a shift in the radial position, resulting from a vertical displacement of the core plasma). The heat flux density width, λ_q, in the SOL at the inner strike points is typically around 5mm (and wider than 1 cm in the private flux region), whilst that at the outer strike points exceeds ~5cm (and ~4-6 cm in the PFR). This gives a value of ~1.5 cm for the inner total strike point width and ~10 cm for the outer width (a result of strong outboard flux expansion in the ST).

4. Discussion

Making the assumption that the plasma was in steady state and taking the core radiated power fraction from bolometry to be ~40%, the net SOL input power is estimated at P_{SOL}~450kW for shot 2321. The measured target power load of ~300kW thus represents ~2/3 of the power entering the SOL. This value may be contrasted with results from START, in which typically only ~1/3 of P_{SOL} arrived at the divertor tiles [1]. This difference may be explained by a reduced level of charge exchange collisions in the MAST SOL compared to START, a result of much lower neutral density in the MAST vessel and thus plasma edge. Measurements of the neutral density in MAST indicate a reduction by a factor ~50 compared to START (Fig. 4), due to substantially higher particle confinement times and longer pulse lengths which allow plasma refuelling to evolve beyond the initial gas-puff stage.

A useful ratio is that of the outboard to inboard total power efflux. At ~6.5, this ratio is significantly in excess of the geometric ratio of outer to inner separatrix surface area which, for a typical DND equilibrium, is around 3. This is similar to observations from START [1] and indicates that geometric effects in the ST are augmented by increased transport at the outboard side, perhaps resulting from steep gradients in flux surface parameters (arising from a large Shafranov shift in the ST). This effect has significant implications for the design of future ST power plant scale devices by directing the bulk of power to the outboard side, where the larger strike point radius and high flux expansion ameliorate target power loading.

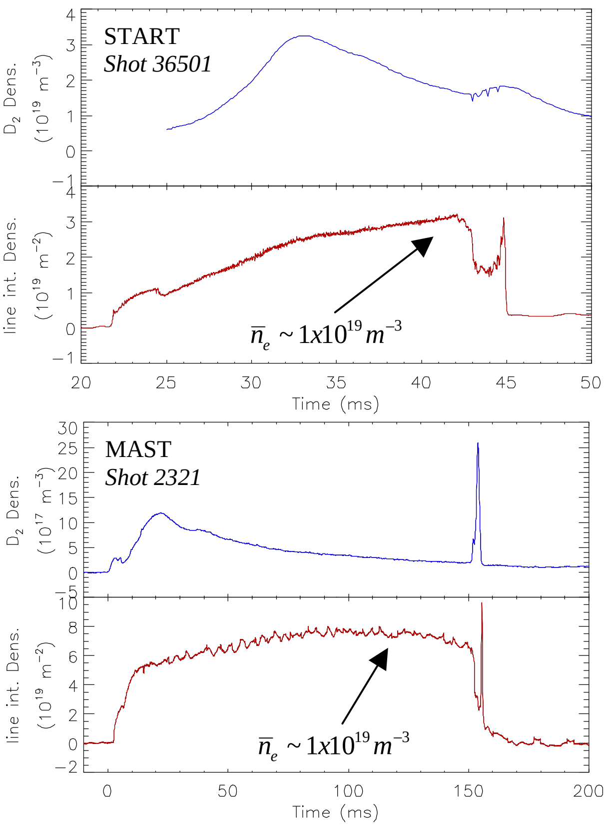

Fig. 5. Vessel neutral (blue) and plasma (red) densities for typical START (upper 2 traces) and MAST (lower 2 traces) plasmas

Acknowledgements

This work is jointly funded by the UK Department of Trade and Industry and Euratom. J-W. Ahn would like to acknowledge financial support from the British Council.

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