ELSEVIER

Journal of Nuclear Materials 266–269 (1999) 1040–1044

journal of nuclear materials

Asymmetries in the divertor power loading in START

K.M. Morel [a,*], G.F. Counsell [b], P. Helander [b]

[a] *Imperial College of Science, Technology and Medicine, London, SW7 2BZ, UK*

[b] *UKAEA Fusion, Culham Science Centre, Abingdon, (UKAEA/Euratom Fusion Association) Oxfordshire, OX14 3DB, UK*

Abstract

Langmuir probe measurements from the divertor strike points for a series of very similar, highly up-down magnetically *symmetric* double-null divertor discharges are presented. These show a strong in–out electron density (n_e) asymmetry, as well as up-down asymmetries in the electron temperature (T_e), the power density scale length (λ_q) and n_e, on the inboard side. These up-down asymmetries seem to be due to particle drift effects and not due to an imbalance in the magnetic *X*-points. It is estimated that only about 35% of the power that enters the scrape-off layer (SOL) reaches the divertor tiles. There is a high neutral density in the START SOL and it is conjectured that the bulk of this missing power is lost through charge exchange, or elastic collisions, of the ions with these neutrals as they flow towards the divertor tiles. The highest power density (q), of about 4–8 MW/m^2, is found to be at the upper *outboard* strike point, not the inboard, because the major radii of the inboard and outboard strike points is similar and n_e is much higher on the outboard side.

Keywords: Power loading; Start; Divertor; Langmuir probe; Neutral particle

1. Introduction

Power loadings on material surfaces are of particular importance for the design of divertors in high power, long pulse length tokamaks. This is also true for low aspect ratio machines, such as MAST (the new Mega-Amp Spherical Tokamak currently being built at Culham), where the smaller area over which the power is deposited may give rise to a higher power density than on an equivalent size conventional tokamak.

The Small Tight Aspect Ratio Tokamak (START) has just completed a successful seven year operational lifetime, during which it has achieved a number of significant results. These include the recent world record value for toroidally averaged β of ~40%, which was aided by approximately 1 MW of neutral beam injected power from the 30 kV beam (on loan from Oak Ridge National Laboratory). Some of the main operating parameters are summarized in Table 1. The power loading to each of the four strike points in this device has been investigated for a number of reproducible double null divertor (DND) plasmas, with peak plasma currents of around 200 kA, $\bar{n}_e$ of about 2.5×10^{19} m^{-3} and toroidal field pointing clockwise when viewed from above (i.e. ion ∇B drift directed towards the lower divertor).

2. Experimental procedures

On START, flush-mounted Langmuir probes arrays are located in the divertor tiles (Fig. 1). There are 29 such probes in the vertical face of each tile, and 16 in the horizontal, each with a geometric surface area of 15 mm^2. These are all at one toroidal location and give a spatial resolution of 3 mm.

Two sets of electronics are available to drive these probes, operated as single Langmuir probes, one of which offsets each of the applied voltage sweeps to local floating potential (V_f) in a novel way. V_f is measured inter-sweep, held on a sample-and-hold unit and then fed back as a DC offset onto the next sweep, ensuring that the voltage sweep is optimally located to maximize the signal to noise ratio.

The short pulse length on START ($\leqslant$ 50 ms) means that probes have to be swept relatively quickly (sweep

* Corresponding author. E-mail: keith.morel@ukaea.org.uk

0022-3115/99/$ – see front matter
PII: S0022-3115(98)00851-4

Table 1
Some of the main operating parameters of START

Major radius, R (m)	0.25–0.35
Minor radius, a (m)	0.19–0.29
Plasma current, I_p (kA)	100–300
Aspect ratio, A (dimensionless)	1.3–1.4
Magnetic field on axis, B_0 (T)	0.15–0.35
Injected neutral beam power (MW)	$\leqslant 1$
Pulse length (ms)	30–50
Dimensionless edge collisionality, ν^*	0.30–4.8
$\bar{n}_e(\times 10^{19}\ m^{-3})$	1–10

durations of 50 and 100 μs), in order to obtain good temporal resolution. This means care must be taken when fitting exponentials in order to obtain T_e, because of degraded signal to noise ratios. (Note: in the exponential fit, only the region from ion saturation to just beyond floating potential was used in order to avoid distortion of the characteristic resulting from the suppression of electron current [1].)

Up to 20 of these probes can be swept at any one time, so it was not possible to cover all four strike points with good spatial resolution in a single shot. Thus, a series of 20 very similar plasmas was run, half with measurements taken at the inboard strike points and the other half with outboard measurements. Only data taken from after the formation of a clear DND configuration, with the inboard separatrix well separated from the center column, were used.

All these restrictions meant that a complete picture of the power loading to all four strike points was only available between 44 and 46 ms, which is after peak plasma current.

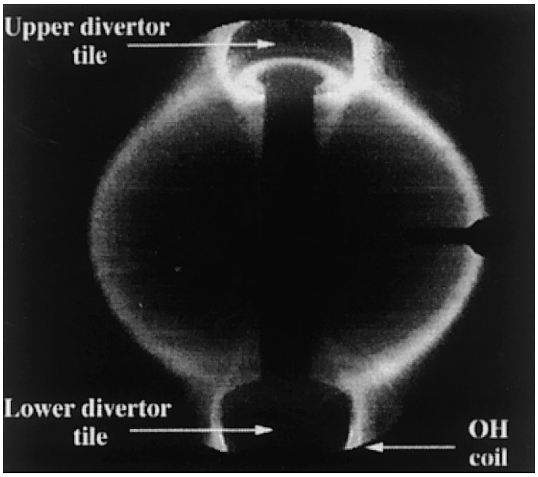
The power density (q) to each probe was calculated using $q = \delta\ J_{sat} T_e$, where the sheath power transmission factor (δ) was taken as 7, which assumes the electron and ion temperatures (T_i) are equal and no secondary electron emission. The ion saturation current density (J_{sat}) was taken as the ion saturation current (I_{sat}) divided by the full geometric area of the probe, rather than its projection onto the field line, since the ion gyro-radius is large compared to the probe dimensions (even at low T_i).

The power density scale length and separatrix value (q^{sep}) were then derived from exponential fits to the profiles (Fig. 2), where the separatrix was identified from the peak in the ion saturation current.

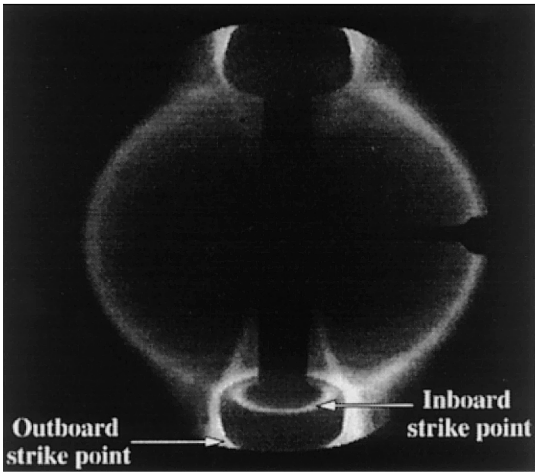
The power to each strike point was then determined by integrating over the total surface area of the strike point assuming an exponential profile for the power density:

$$P = \int_0^\infty 2\pi R q^{sep} e^{-x/\lambda_q}\ dx + \int_0^\infty 2\pi R q^{sep} e^{-x/\lambda_q^{PFR}}\ dx = 2\pi R q^{sep}\left(\lambda_q + \lambda_q^{PFR}\right), \quad (1)$$

where P is the power in SOL and private flux region (PFR) in strike point region, R the radius of separatrix at target, x the radial or vertical coordinate (radial for inboard strike point, vertical for outboard), λ_q the power density scale length and q^{sep} the power density at the separatrix.



Shot : 35016



Shot : 35018

Fig. 1. (A) Visible light image for shot 35016, showing the locations of the upper and lower divertor tiles and one of the Poloidal Field coils - the so called ‘Ohmic Heating’ or OH coil and (B) visible light image for shot 35018, showing the inboard and outboard strike points (the outboard strike point is partially hidden by the OH coil). The toroidal field is in the ‘anticlockwise’ direction for shot 35016 and ‘clockwise’ for shot 35018. Note the switch, from top to bottom, of the bright region near the X-point on the inboard side.

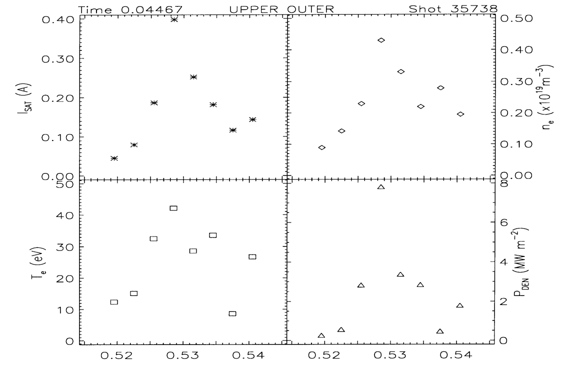


Fig. 2. Profiles across the upper outboard strike point. The SOL is on the right-hand side of the peak I_{sat}.

3. Results

3.1. Probe measurements

The results are summarized in Table 2. They show up–down asymmetries in the electron temperature and power density scale length, as well as in the electron density on the inboard side.

The distribution of the power between the outboard and inboard sides exceeds the ratio of the plasma outboard to inboard surface areas. In addition, there is a marked in–out density asymmetry seen at both tiles.

The total power flowing to each of the divertor tiles is approximately the same (~80 kW), where on the outboard side the effect of the higher upper strike point temperature is more or less offset by its smaller scale length. This is also true to some extent on the inboard side, but here the up–down density asymmetry leads to slightly more power flowing to the lower tile.

Table 2
Summary of divertor probe results for shots 35732–35750 (which have the $E \times B$ drift directed towards the upper tile on the inboard side) between times 44–46 ms, quoted with standard deviations

Parameter	Strike point location	
	Inboard	Outboard
Upper		
n_e^{sep} ($\times 10^{18}$ m^{-3})	0.45 ± 0.05	2.6 ± 0.5
T_e^{sep} (eV)	40 ± 10	39 ± 9
λ_q (cm)	0.7 ± 0.3	0.6 ± 0.2
q^{sep} (MW m^{-2})	1.3 ± 0.6	6 ± 2
Power (kW)	9 ± 2	70 ± 20
Lower		
n_e^{sep} ($\times 10^{18}$ m^{-3})	0.8 ± 0.1	2.4 ± 0.4
T_e^{sep} (eV)	20 ± 4	25 ± 6
λ_q (cm)	1.1 ± 0.3	1.2 ± 0.2
q^{sep} (MW m^{-2})	0.9 ± 0.2	3 ± 1
Power (kW)	15 ± 4	60 ± 20

The power flowing into the SOL can be estimated as

$$P_{SOL} \approx P_{VI} - \frac{d}{dt} W_{MAG} + P_{BEAM}^{abs} - \frac{d}{dt} W_{KIN} - P_{RAD}, \qquad (2)$$

where P_{SOL} is the power flowing into SOL, W_{MAG} the energy stored in the magnetic field, $P_{VI} - dW_{MAG}/dt$ the net ohmic heating power, W_{KIN} the kinetic energy of the plasma, P_{BEAM}^{abs} the absorbed beam power and P_{RAD} the radiated power from confined region.

The average value of P_{SOL} is 460 ± 40 kW for this dataset, which means that only about 35% of the power entering the SOL arrives at the divertor tiles. Some of this missing power might be accounted for by losses due to the high SOL neutral density in START.

3.2. Neutral densities in the START edge

One of the unique features of START is its small ratio of plasma volume to vessel volume. (In START this is about 7%, whereas in the conventional geometry COMPASS-D, this ratio is about 50%.) This means that START is refueled primarily from the gas reservoir surrounding the plasma.

There are two separate measurements of the neutral density in START. Firstly, a standard Bayert–Alpert ion gauge, fitted with a photon dump and a magnetic shield, which is mounted on the top of the vessel and connected to fast response drive and acquisition electronics. This gives a density in the range $(0.5 - 2.0) \times 10^{19}$ m^{-3} for D_2 molecules some 50 cm from the edge of the plasma, depending on the plasma density and wall conditioning regime. This is comparable to the volume averaged plasma density of $(1 - 8) \times 10^{19}$ m^{-3}.

Secondly, the atomic neutral density just inside the confined plasma region is deduced from tomographic inversion of a linear CCD based D_α array, which is situated on the midplane. This suggests a density of D atoms of 5×10^{16} m^{-3}.

The molecular neutral density drops sharply towards the separatrix as the D_2 molecules dissociate (mainly through electron impact), leading to a strong source of energetic D atoms in the SOL. A simple balance of particle efflux from the plasma against refueling (Fig. 3) indicates that the density of these atoms at the separatrix is of the order 1×10^{17} m^{-3}, which is not inconsistent with the D_α array.

The dominant ion energy loss processes in the SOL are elastic collisions with both deuterium atoms and molecules, and charge exchange between the ions and deuterium atoms. The total cross-section for these processes is about 2×10^{-18} m^2. This gives a mean free path of <0.5 m, which is less than the distance the ions travel along the SOL to the divertor tiles ($L_\parallel \sim 5$ m) and therefore provides a mechanism for the loss of ion

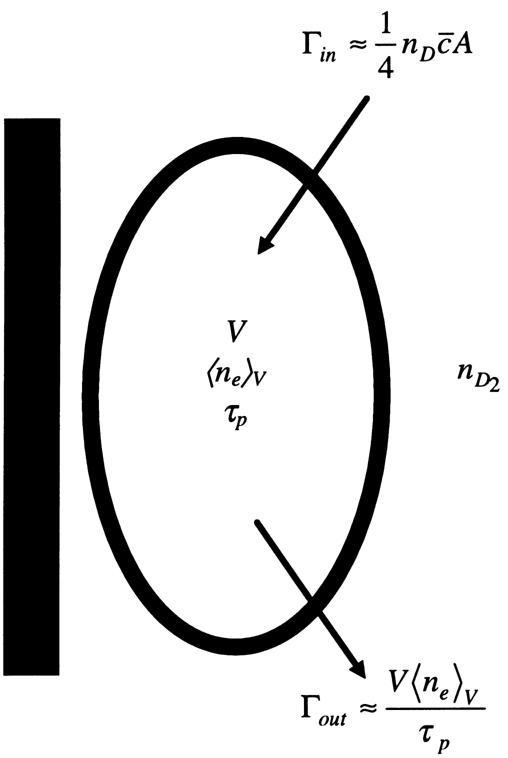


Fig. 3. 0D plasma refueling model. In steady state, $\Gamma_{in} - \Gamma_{out}$, which for the typical confinement time on START of 5 ms and an energy of 4 eV (dissociation energy) gives $n_D \sim 1 \times 10^{17}$ m^{-3}.

energy in the SOL. Unfortunately, there are no measurements of the ion temperature in the SOL on START. However, the ion and electron temperatures in the confined plasma are approximately equal [2] and so in the absence of any further measurements, it seems reasonable to assume that the ions carry about 50% of the power entering the SOL. The loss of such a percentage of the power entering the SOL, as the plasma flows towards the divertor tiles, is not inconsistent with the measurement of the power reaching those tiles, given the experimental uncertainties.

4. Discussion

In summary, up–down asymmetries in the electron temperature, the power scale length and the inboard electron density are observed in the START divertors. These could be caused by either of two effects. First, if the magnetic field is asymmetric, the *X*-points may not be on the same magnetic flux surface. There are then not one, but two, separatrices. The inner separatrix would presumably be hotter than the outer one and there would be a corresponding difference in the plasma parameters between the two divertors [3]. However, magnetic reconstruction suggests that the separation of the separatrices at the mid-plane is small in comparison with the SOL width. Moreover, there is experimental indication that the up–down asymmetry is reversed if the direction of the toroidal magnetic field is changed. This is particularly clear on the CCD camera viewing the plasma, where the brightest visible emission on the inboard side reverses with the toroidal field between the upper and lower divertors (Fig. 1). This is supported by a more limited divertor probe dataset (not presented here) that suggests the inboard density asymmetry also reverses when the toroidal field direction is reversed.

It is therefore more plausible that the up–down asymmetries are caused by particle drifts. Cohen and Ryutov [4] have demonstrated that, in a rectilinear model of the SOL with isothermal field lines, the density is higher at the target plate towards which the $E \times B$ drift is directed. Chankin and Stangeby reach a similar conclusion in Ref. [5]. If the electrostatic potential is assumed to follow the temperature, as expected from the sheath boundary condition, this would predict the highest electron densities to be at the lower outboard and upper inboard strike points, respectively, for the data in Table 2. This is clearly not observed in these START plasmas.

The analysis in [4] neglects any curvature or variation in the magnetic field, but it can be shown that the sign of the up–down asymmetry caused by the $E \times B$ drift should not be sensitive to geometrical effects. However, in a curved magnetic field, the magnetic drifts could also be important, and in START the parallel temperature gradients could play a role, as the electron temperature is observed to have an up–down asymmetry.

Turning now to the in–out electron density asymmetry, this is probably not caused by particle drifts. However, the cross-field particle transport coefficient, $D_\perp$, may vary poloidally in such a way so as to increase the flow of particles into the outboard SOL. (For instance, the classical diffusion coefficient, $D_\perp \propto B^{-2}$ and Bohm like diffusion obeys $D_\perp \propto B^{-1}$). Alternatively, geometrical effects, such as the ratio of the areas the inboard and outboard SOLs have in contact with the bulk plasma combined with the Shafranov shift enhancing diffusive processes into the outboard SOL, may provide an explanation.

5. Summary

The highest power density occurs at the upper outboard strike point, which is substantially thinner than its lower counterpart, and is of the order of 4–8 MW/m^2 between 44 and 46 ms. It occurs at the *outboard,* rather than the inboard, strike point because the major radii of the two strike points are similar (about 0.174 and 0.130

m, respectively) but the electron density is much higher on the outboard side.

It is important to understand these asymmetries since an evenly distributed power loading is desirable. It seems that the up–down asymmetries are due to particle drift effects and work is continuing in an effort to quantify this.

The high SOL neutral density in START is believed to reduce the power loading on the divertor tiles by removing energy from the ion population, through charge exchange or elastic collisions.

The total power reaching the divertor tiles is about the same and distributed between the outboard and inboard sides in a ratio that exceeds the ratio of the outboard to inboard plasma surface areas (which for these plasmas at the time of the measurements was about 3.6 to 1). This is encouraging for the next generation of spherical tokamaks, such as MAST.

Acknowledgements

The authors would like to thank Marcus Price for help in generating the photographic images, and Richard Martin and Mike Walsh for help with the EFIT equilibrium reconstructions and power accounting.

This work is jointly funded by the Department of Trade and Industry and Euratom. One of the authors (KMM) would like to acknowledge both the EPSRC and Culham for financial support. The loan of neutral beam equipment from ORNL and the US DOE is also acknowledged, as is the provision of EFIT by General Atomics.

References

[1] J.A. Tagle et al., Plasma Phys. Contr. Fusion 29 (1986) 297.
[2] P.G. Carolan, Plasma Phys. Reports 24 (1998) 206.
[3] R. Marchand et al., Nucl. Fusion 35 (1995) 297.
[4] R.H. Cohen, D.D. Ryutov, Comments Plasma Phys. Contr. Fusion 16 (1995) 255.
[5] A.V. Chankin, P.C. Stangeby, Plasma Phys. Contr. Fusion 38 (1996) 1879.