Methane screening in JET reverse field experiments

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Abstract

JET plasmas with reverse magnetic field feature a different SOL flow than those with normal field. The observed carbon fuelling efficiency from injecting methane gas was similar in reverse and normal field. EDGE2D modeling used an externally applied force to create the SOL flows, without specifying the origin of the force. The resulting flow agreed reasonably with the experimental values between the separatrix and 4 cm mid-plane depth in the SOL. The effect of the flow on the calculated carbon screening was 5–15% higher carbon fuelling efficiency for the low flow velocity with reverse field.
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1. Introduction

Methane screening experiments [1] have been used to benchmark the effectiveness of the SOL and divertor at preventing impurities from contaminating the plasma core. The carbon fuelling efficiency is measured when a known amount of carbon is injected. That information is used to infer the contamination by intrinsic carbon sources, and to constrain code calculations about the fuelling efficiency. These same codes can be used to infer the carbon contamination in other machines [2] and other plasma conditions.

One unresolved aspect was the impact of SOL flows on the carbon fuelling efficiency. Large SOL flows have been observed in JET [3] and other devices [4,5]. The magnitude of the observed flows is presently not understood [3,6,7]. Consequently, the flows cannot be introduced into the models on a first-principles basis. The effect of the experimental flows on the SOL and the carbon fuelling is therefore unknown. Recent JET reverse magnetic field experiments [8] allowed methane screening experiments with changed SOL flow. This paper documents and models the SOL flow influence on the screening.

The experimental screening was unchanged when the fields were reversed while the SOL flows at the machine

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top reduced from a Mach number of 0.5 to near stagnation. The screening was modeled using EDGE2D/NIMBUS [9] where the flow was created by external forces acting upon the deuterium (and optionally upon the carbon) in the SOL. The required force was different for the forward and reverse field cases. The effect of the larger flow was to reduce the calculated carbon fuelling efficiency by about 5–15% indicating only a weak screening dependence on the SOL Mach number.

2. Experiment

A reciprocating Mach probe [3] measured the SOL flow at the vessel top. Both field directions have Mach numbers of about 0.2 at the separatrix, but differ at distances greater than 0.5 cm into the SOL [8] (Fig. 1). Normal field plasmas have peak Mach numbers of 0.5. Reverse field plasmas have a near stagnation point.

The reverse field screening experiments reproduced normal field JET L-Mode discharges [1]. However, the Gas Box Divertor (Mk II GB) was used for the normal field experiments, and the Septum Replacement Divertor (Mk II GB SRP) was used for the reverse field experiments. Since the Gas Box carbon screening was insensitive to the divertor configuration [1], the different divertor configuration is assumed to not influence the results. Since the carbon originates in the main chamber and is non-recycling, the divertor geometry is unlikely to influence the screening.
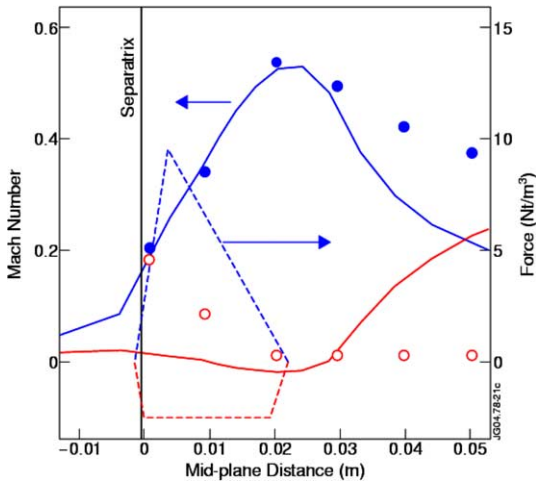

Fig. 1. The experimental [8] (points) and EDGE2D (solid lines) Mach number for JET L-Mode plasmas are plotted as a function of the mid-plane SOL depth. The dashed lines are the external deuterium forces with no force acting on the carbon (Table 1). The solid circles indicates normal field and the open circles is reverse field operation.
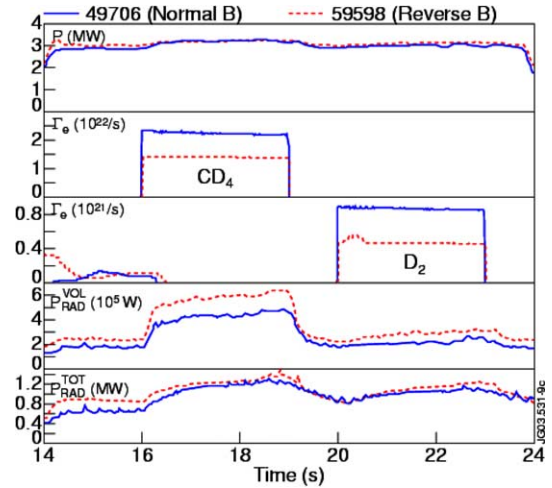

Fig. 2. Time evolution of the applied power, P, the electron injection rates, Γ, of CD_4 and D_2, and the power radiated, P_{RAD}, from the core and the total for normal (solid line) and reverse (dashed line) field plasmas.

Deuterated methane was puffed at the horizontal mid-plane for about 3 s. A separate deuterium injection phase followed which produced a reference plasma condition of the same density but without the methane (Fig. 2). The carbon content difference between 18 s and 22 s indicated the core carbon content due to the injected methane. The shot pair 49706 and 59598 had the same core density (Figs. 2, 3 and Table 1). The methane injection rate was about 30% higher in the normal field case. This difference occurred since the reverse field had increased wall fuelling causing higher density than the normal field plasmas with the same methane injection rate. To compare plasmas at the same core density, the reverse field plasma had lower methane injection rate than the normal field plasma. The density and visible Bremsstrahung emission were similar both during the methane injection and the deuterium injection reference phase (Fig. 3).

The raw data in Fig. 3 indicates that the Z_{eff} and the charge exchange measured core carbon content increase were both larger in the normal field case in proportion to the difference in the methane injected rate. Thus the carbon fuelling efficiency was similar for normal and reverse field. The carbon fuelling efficiency [1] is defined as $FE = \Delta N_C / (\Gamma_C \tau_p^*)$.

3. Results

The L-Mode screening for methane injected at the horizontal mid-plane was similar in reverse and normal field. The carbon screening was insensitive to the SOL flow change in Fig. 1. The density and applied power
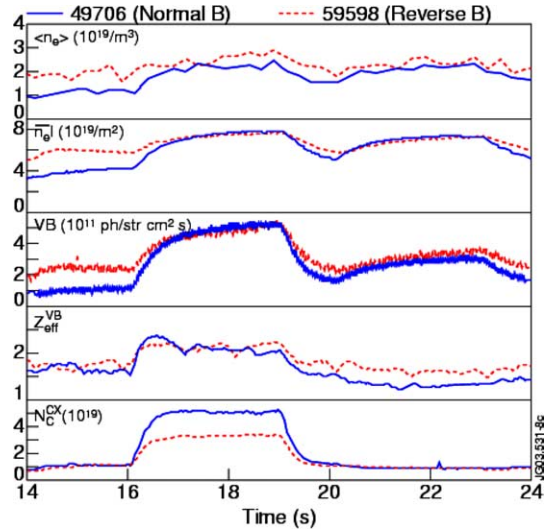
Fig. 3. Time evolution of the volume averaged electron density, $\langle n_e \rangle$, the line-averaged electron density $n_e l$, visible Bremsstrahlung intensity, VB, the VB deduced Z_{eff}, and the charge exchange deduced total carbon content N_C^{CX} in the core for normal (solid line) and reverse (dashed line) field.
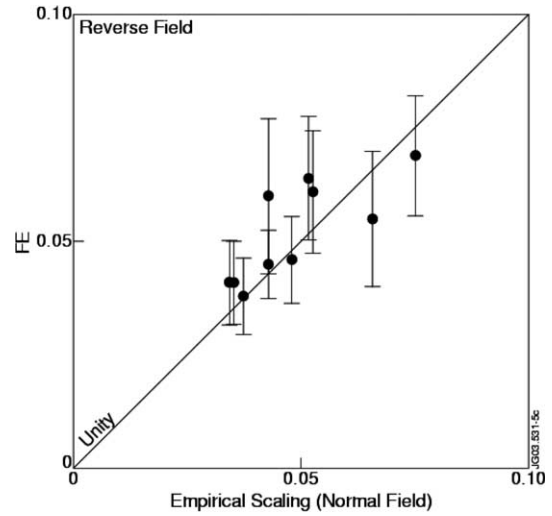

Fig. 4. The experimental carbon fuelling efficiency, FE, for the reverse field L-Mode plasmas plotted against the normal field empirical scaling [1]. The error bars arises primarily from the differencing of the Z_{eff} values (Fig. 3).

were varied for the reverse field plasmas. For methane injected at the horizontal mid-plane, the reverse field screening also fit the normal field regression [1] (Fig. 4). The Z_{eff} differencing uncertainties [1] were similar for both field directions and dominate the error bars in Fig. 4. Normal field plasmas (Eq. (5) of [1]) had decreased carbon fuelling efficiency at higher density and lower energy confinement. The reverse field data showed the same trends as the normal field data, with less variation on the achieved density, due to the higher wall source, and more variation in the applied power, due to the lack of an H-Mode.

The poloidal variation of the carbon fuelling efficiency was obtained by puffing the methane from other gas injection valves (Fig. 5). The poloidal variation of the carbon fuelling efficiency was similar but not identical to the distribution observed with normal field. Compared to normal field operation, the divertor was better screened and the top of the device worse screened.

4. Modeling

Two plasmas with similar density and energy confinement were chosen for experimental comparison (Table 1) and EDGE2D modeling. EDGE2D/NIMBUS models

Table 1
Experimental and EDGE2D simulation results compared for the normal field and reverse field cases

| Field | Experiment | | EDGE 2D | | | |
| | 49706 | 59598 | D force | | D + C force | |
	Normal	Reverse	Normal	Reverse	Normal	Reverse
M (at 2 cm)	.57	.02	0.52	−.02	.53	−.02
D+ force (Nt/m³)	–	–	9	−3	9	−3
C force (Nt/m³)	–	–	0	0	1.0	−.9
$\langle n_e \rangle$ (10^{19}/m³)	2.4	2.5	–	–	–	–
n_{SEP} (10^{19}/m³)	–	–	.8	.86	.85	.85
n_{2CM} (10^{19}/m³)	–	–	.28	.4	.28	.4
Γ_C (10^{21}/s)	2.2	1.38	1.5	1.5	1.5	1.5
τ_E (s)	.5	.5	.67	.67	.67	.67
FE (%)	5.6	4.6	5.25	5.53	4.76	5.33

The volume averaged density was used to match the experimental shots, while the separatrix density was used to match the models. For JET L-Mode plasmas the separatrix density is often about 1/3 of the volume averaged density.
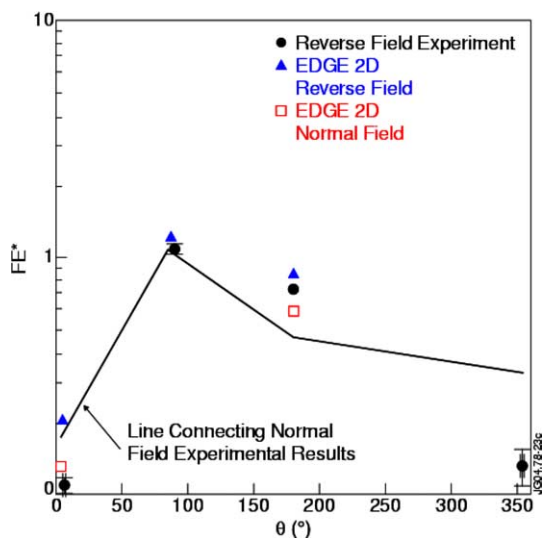
Fig. 5. The carbon fuelling efficiency, FE*, normalized to the normal field scaling (Eq. (5) of [1]) is plotted against the poloidal angle of methane injection. The line connects the normal field experimental results.

the JET SOL using fluid equations with a Monte Carlo treatment of the deuterium and carbon neutrals [9]. Carbon was only introduced into these simulations as 0.36 eV injected carbon neutrals [1] simulating the carbon from the methane. The carbon cross field diffusion coefficient is unknown and was treated as a free parameter, being adjusted until the normal field models agreed with the normal field experiments [1,2]. Essentially, the errors introduced by modeling atomic carbon rather than molecular methane as well as other measurement errors (of SOL parameters), result in a different modeled carbon diffusion coefficient than reality. However, the effect of the SOL flow on the screening is separated from these assumptions and measurement errors because the same carbon diffusion coefficient is applied to the reverse field models, and the comparison of normal with reversed field screening experiments and models isolate the effect of the SOL flows.

The known forces in the fluid modeling cannot account for the observed flows [3]. Therefore, an external force was applied to create the SOL flows. The force was applied parallel to the field lines, from below the horizontal mid-plane to the vessel top, and from the separatrix to a 2 cm mid-plane SOL depth (Fig. 1). A peak force acting on the deuteron ions of +9 Nt/m^3 for normal field, and −3 Nt/m^3 for the reverse field was required to account for the SOL flow. The externally applied force is about twice as large as the sum of the parallel thermal force, the frictional force between the deuterium and the carbon, and the $E \times B$ and diamagnetic forces that make up the Pfirsch–Schluter current.

All these forces are included in the EDGE2D calculation.

The resulting flow agreed reasonably with the experimental values between the separatrix and 4 cm mid-plane depth in the SOL at the location where it was measured near the vessel top (Fig. 1). The flow in the entire SOL is complicated, and measurement in just one location is not adequate to constrain the calculations. In this paper, a minimum poloidal extent was used to achieve agreement with the Mach probe measurements. The effects of a more extended poloidal force have not yet been studied.

In some models, the force was only applied to the deuterium. On these runs, the carbon experiences the applied force through the frictional coupling to the deuterons. On other runs, an external force was applied to the carbon as well. That force was distributed over the charge states according to their relative density. A force on each carbon equal to the force on each deuteron, caused a further 10% reduction in the normal field carbon fuelling efficiency, but did not change the reversed field fuelling efficiency (Table 1). The forces quoted in Table 1 are the total force integrated over the species density.

The carbon fuelling efficiency was 5–15% higher in the reverse field simulation (Table 1), which is less than the error bars in Fig. 4. Consequently, the modeling indicates little change in the predicted carbon fuelling efficiency in spite of the considerable change in the SOL flow pattern (Fig. 1). The result is plausible since the carbon contamination is a consequence of the carbon content in the main chamber SOL (Fig. 15 of [2]), and that content is determined by the carbon escape into the divertor, or the carbon flow velocity at the divertor entrance. EDGE2D calculated the escape velocity to be relatively unchanged by the application of the external force (Fig. 6).

The location of the carbon injection was varied in separate code runs. The carbon fuelling efficiency changed in a manner similar to the experimental data (Fig. 5). The reverse field simulations had systematically higher carbon fuelling efficiency at both the divertor and the machine top.

The higher flow velocity (normal field) was calculated to modify the SOL electron density profile, causing a steeper density gradient (Table 1). The normal field deuterium gas injection rate was required to be 30% higher to achieve the same separatrix density. The SOL density profile changed is quantified in Table 1 by the density 2 cm from the mid-plane separatrix. That density was 30% lower with the higher SOL flow. The code runs were matched to the separatrix density. The SOL density profile influences the location of carbon ionization, and with the higher flow having a thinner SOL, the carbon is ionized closer to the separatrix, so the flow effect on screening includes also a change in the carbon ionization location.
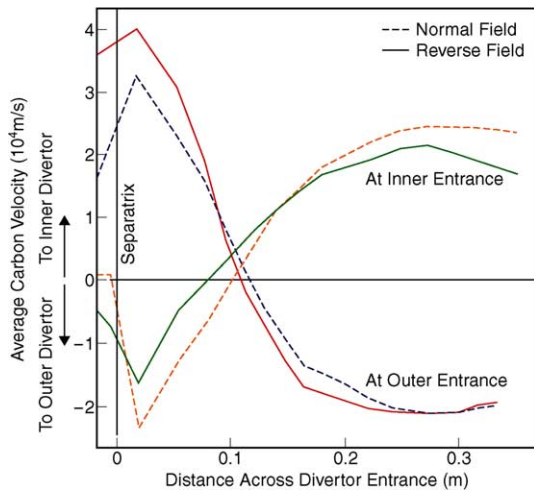
Fig. 6. The EDGE2D calculated carbon velocity (averaged over all charge states) plotted verses the distance along the inner or outer divertor entrance. Due to the thermal force, the carbon close to the separatrix moves from the divertor into the main chamber at both divertors. The main chamber SOL flow did not significantly changed the carbon velocity at the inner and outer divertor entrances.

5. Conclusion

The JET reverse field experiments indicated that carbon screening was not changed by the JET SOL flow changes. The experimental results differ from previous DIII-D H-Mode experiments [10]. We attribute that difference to the difference in plasma regimes since the JET results are in L-Mode.

The JET results were modeled by EDGE2D indicating that little change in the screening might occur since the carbon escape velocity into the divertor is unchanged. A force acting upon the carbon equal to the deuterium force only modestly changed the screening.

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