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Scrape off layer modelling studies for SST-I

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Abstract

SOL modelling results for SST-1 (SST Team, Proceedings of the 16th IEEE/NPSS Symposium on Fusion Engineering, Champaign, IL, vol. II, 1995, p. 481) show a sheath limited flow regime. This is due to the low edge densities required by lower hybrid current drive (LHCD), coupled with high power input per unit volume. Coupled plasma–neutral transport studies using B2-Eirene [R. Schneider et al., J. Nucl. Mater. 196–198 (1992) 810] show significantly high charge exchange losses and radiated power from the core. It also shows that the heat flux to the inner divertor is higher than that to the outer divertor due to thinner inner SOL widths. The Monte-Carlo neutral transport code DEGAS [D. Heifitz et al., J. Comput. Phys. 46 (1982) 309] was used to optimise the baffle plate geometry and it was seen that a configuration where the baffle plate shields the main plasma from the divertor strike point results in reduced backflow of neutrals. The divertor erosion code DIVER (M. Warrier et al., SST Divertor Modelling Report, 1996–1997) was used to predict a steady state operating temperature for the SST divertor plate lying in the range 750–1000°C for which the erosion will be minimum. © 1999 Elsevier Science B.V. All rights reserved.

Keywords: B2/EIRENE; Erosion of graphite; Edge modelling

1. Introduction

The Superconducting Steady State Tokamak (SST-1) is designed for double null operation, having a major radius 1.1 m, minor radius 0.20 m, ellipticity $\kappa \sim 1.7$–1.9, safety factor $q_{sep} \sim 5$–6, plasma current of 250 kAmps, for a power input of 1 MW and having a pulse duration of 1000 s with an LHCD. LHCD requires fairly low average densities (1×10^{19} m^{-3}). The power input per unit volume is fairly high (0.8 MW m^{-3}). The low densities coupled with the high power per unit volume results in high edge temperatures and large neutral backflow from the divertor region to the main plasma. Divertor plate erosion is also a concern for a machine having 1000 s shots.

The scrape off layer of SST has been modelled using the simple two-point Barr model [1,2] which has energy balance in the SOL and takes into consideration the magnetic geometry effects, the 1-D steady state plasma transport code ZEPHYR [3] which solves the plasma transport equations given a neutral density profile as an input, and the 2-D code B2.5 [4] which solves the plasma transport equations on a conformally mapped magnetic geometry with a simple self-consistent neutral model. DEGAS was run on a plasma background input from the results of ZEPHYR and B2.5 for various probable baffle geometries. A steady state particle balance model [5] considering gas puff efficiency, divertor chamber recycling, etc. was used to interpret the DEGAS results from the viewpoint of pumping requirement and plasma density control. The plasma–neutral transport coupled codes B2-Eirene with multi-species impurity transport and realistic magnetic geometry with the provision of treating inclined divertor plates and first wall components were as used to get more realistic plasma parameter values for the design. It must be mentioned that B2-EIRENE incorporates flux limits to handle the cases with long mean-free-path for binary collisions and is therefore applicable to SST-1 SOL. A divertor erosion code DIVER which compares well with the PISCES

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experimental results [6] was used to estimate the worst case erosion yields and the optimum divertor plate steady state operating temperature.

Section 2 contains the plasma transport results for SST-1 from models having approximate neutral transport. Section 3 contains the baffle plate optimization using the Monte-Carlo neutral transport code DEGAS and a 0-D steady state particle balance model. Section 4 contains the results from B2-EIRENE for a range of edge densities and transport coefficients for SST-1 and comparisons with an unrealistically high edge density case to bring out the advantages of operating at higher densities from a good divertor operation point of view. Section 5 contains the results from the divertor erosion code DIVER for SST-1. Section 6 consists of the conclusions.

2. SOL plasma transport modelling

For modelling the SST-1 double null, a worst case in:out asymmetry of 1:4 and an up:down assymetry of 1.2:1 was assumed and only the outer, up SOL leg was modelled since maximum power is exhausted in this leg. It is assumed that 20% of the input power of 1 MW is radiated from the core.

In the Barr model, parameter scans were carried out over the fraction of radiated power in the SOL ($F_{\mathrm{rad}} = 0.2$–0.8), density at the separatrix midplane ($n_{\mathrm{sep}} = 0.5 \times 10^{19}$–$1.5 \times 10^{19}$ m^{-3}), perpendicular thermal conductivity ($\chi_{\perp} = 1$–4 m^2 s^{-1}) and the ratio of the plasma pressure at the divertor plate to that at the separatrix midplane ($\omega = 0.5$–0.1). The Barr model yields high separatrix and divertor plate temperatures with very small SOL widths for power flow at the midplane and a worst case peak heat flux of 5 MW m^{-2} [7]. When unrealistically high edge densities of 1.5×10^{19} m^{-3} are used with 80% power loss in the SOL, high recycling solutions are obtained. Comparison of SST-1 parameters with the results of Barr model for ITER and DIII-D indicate that the smaller edge density and magnetic geometry factor for SST-1 results in thin SOL widths for SST-1.

The 1-D code ZEPHYR assumes steady state, quasi neutrality and no current flow in the SOL. It takes into consideration ionization, charge exchange and hydrogen radiation losses in the SOL. It solves the continuity equation, the ion and electron momentum equations summed up and the ion and electron energy equations seperately from the seperatrix mid-plane to the sheath edge at the divertor plate along the magnetic field lines. The neutral particle density profile is specified as

$$n^0(z) = n^0_{\mathrm{bg}} + n^0(0)\,\mathrm{e}^{-z/\lambda_0}, \tag{1}$$

where n^0 is the neutral density, λ_0 the neutral density fall off length, n_{bg} the constant neutral background density and z is directed away from the divertor plate toward the seperatrix mid-plane. For SST-1 peak neutral densities corresponding to 0.3–3 Torr, with λ_0 varying from 0.3 to 1.0 m were used. Plasma temperature was varied in the range 200–500 eV at the separatrix midplane as predicted by Barr model. ZEPHYR yields sheath limited flows with high average energy fluxes of 1.5 MW m^{-2} on the divertor plates. Values for divertor chamber recycling, defined as $R = (\Gamma_{\mathrm{p}} - \Gamma_x)/\Gamma_{\mathrm{p}}$, where Γ_{p} is the ion flux at the divertor plate and Γ_x is the ion flux entering the divertor chamber, greater than 0.9 are obtained when the divertor neutral densities correspond to values greater than 1 m torr with a λ_0 of 1 m for plasma edge densities of 0.5×10^{19} m^{-3} [7]. For such cases the ratio of plasma pressure at the plate to that at the seperatrix midplane can be greater than 0.5 and even 1.0 with the driver for particle flux being the parallel viscosity term in the momentum equation. At higher edge plasma densities this effect is seen at higher divertor chamber recycling. Flux limits have not yet been implemented in ZEPHYR and this effect may disappear when it is done.

The neutral transport model in B2.5 is not valid for low density machines like SST-1. The neutral gas is governed by an equation that is of Navier–Stokes form along the magnetic field and of diffusive form across the field [8]. The 2D multifluid code B2.5 was used to model SST-1 for a wide range of edge temperatures and densities for two cases differentiated by the neutral transport coefficients used, one standard and the other five times smaller. The code produced low density everywhere, with properties almost constant along the field lines onto the target and neutrals spread over a large volume. High recycling solutions were obtained only at unreasonably high edge densities (2×10^{19} m^{-3}) on reducing the input power by a factor of 4. Runs with low transport coefficients for neutrals gave a high recycling divertor for an edge density of 2×10^{19} m^{-3}, but not for the expected edge density of 0.5×10^{19} m^{-3}. Therefore, B2.5 runs indicate that good divertor conditions (high density, low power, well trapped neutrals) are unlikely for SST-1 parameters and one must baffle the divertor so that neutrals do not get into the main plasma. B2.5 results also indicate subcentimeter SOL widths for power flow at the separatrix midplane.

3. Neutral transport modelling

A 0-D steady state particle balance model has been used to relate the number of particles flowing back to the core per second from the divertor chamber and the number of particles being pumped out per second in terms of the number of particles coming out of the core per second N_{c} [5]. The model considers the efficiency ϵ of neutrals puffed and reflecting from the first wall to penetrate the SOL and the divertor chamber recycling.

The following relations were obtained:

$$n_{bf} = \frac{f_{bf}}{f_{bf} + f_p\epsilon}, \qquad (2)$$

$$n_p = \frac{f_p}{f_{bf} + f_p\epsilon}, \qquad (3)$$

where n_{bf} is the fraction of N_c that flows back to the core and n_p the fraction of N_c that is pumped out. f_p is the fraction of the neutral particles from the divertor plate that gets pumped out and f_{bf} the fraction of the neutral particles from the divertor plate that flows back to the core.

The objective of our study was to position a baffle for SST-1 that: (a) keeps pumping requirements within bounds; and (b) reduces backflow of neutrals and impurities to the core. The Monte-Carlo neutral transport code DEGAS was used to solve neutral particle motion for a variety of baffle shapes for fixed plasma backgrounds.

The main emphasis in design is on choosing the optimum solution among a variety of possible options on the basis of relative performance. To this end, details of the plasma were considered less important and a set of representative plasma profiles for high density (low temperature) and low density (high temperature) were generated and used for DEGAS runs. Typical plasma parameters on the separatrix as seen in ZEPHYR and B2.5 runs were used.

The two main configurations (Fig. 1) were (a) slot and (b) throat cases. In the first case, the baffle was kept close to and along the outer divertor plate to form a narrow slot. A horizontal reflector plate on the inboard side and the auxilliary baffle on the outboard side were used to direct the flow of neutrals coming out of the slot to the pumps. This configuration resulted in rather high backflow because the neutrals coming off the outer divertor plate got reflected towards the core plasma rather than towards the pumping ports. Also, the slot plasma was not dense enough to provide high recycling to curb neutral backflow. Therefore the baffle was terminated below the strike point in case (b) and the reflector plate connected from the inner baffle tip to the pumping port to reflect particles toward the pump. This resulted in lower backflow. In this configuration, variation of throat size (narrow and wide) was studied and the reflector plate was removed to assess its role.

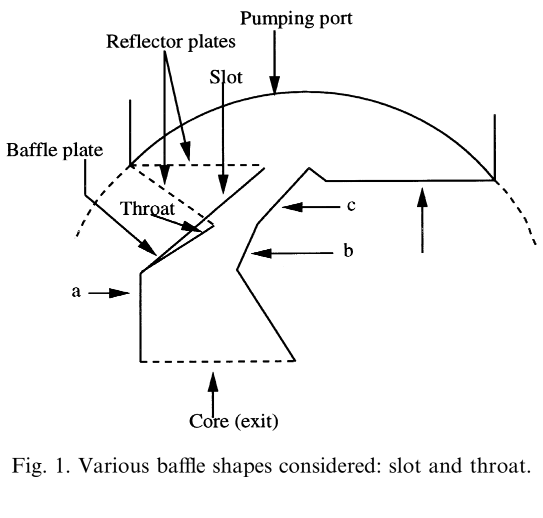

Fig. 1. Various baffle shapes considered: slot and throat.

It was required to impose a steady state pumping speed of 30 k l/s, as a practical constraint for SST. In order to do this, the pump was modelled as a very rough absorbing wall. The absorbance was varied iteratively to fix the pumping speed to ≈30 k l/s. Neutrals were assumed to have come only through one channel viz., recycling at the divertor plate. Since the probability of leakage to the main plasma and to the pump depends to a great extent on the location of the source of neutrals, three locations marked by ‘a’, ‘b’ and ‘c’ were studied (Fig. 1). The location ‘a’ corresponds to the inner divertor plate and ‘b’ and ‘c’ correspond to the outer divertor plate with the seperatrix strike point lying on ‘c’. The neutral particle source ratio of inner:outer divertor plates was taken as 1:4. The core plasma region was modelled as an exit, with a correction being applied to account for the charge exchange neutrals entering the divertor from the core. The fuelling efficiency was taken as 30% while interpreting the DEGAS results using the steady state particle balance model.

The fractions f_p and f_{bf} obtained from DEGAS were used to calculate n_p and n_{bf} using the 0-D model after correction was applied to account for the charge exchange neutrals emerging from the core. It is seen that the narrow throat (2.6 cm) baffle with strike point above the throat gives least backflow and is best suited from a pumping point of view. It was found that keeping the strike point closer to the pump duct and using the baffle to shield it from the main plasma yields a higher n_p and lower n_{bf}. Also, using a reflector plate improves things further.

4. Coupled plasma–neutral transport modelling

B2-EIRENE runs for SST-1 were carried out for a range of edge densities (0.5×10^{19}–5.0×10^{19} m^{-3}) and perpendicular transport coefficients ($\chi_\perp$ varying in the range 0.3–2 m^2 s^{-1} and $D_\perp$ varying in the range 1–4 m^2 s^{-1}). Carbon sputtered from the wall in all its ionized states and as neutrals was included. A real magnetic equilibrium with the narrow throat baffle plate configuration and the standard baffle plate configuration was used (Fig. 2). The total power of 1 MW was distributed between the inner and outer regions by the ratios of the inner:outer scrape off areas.

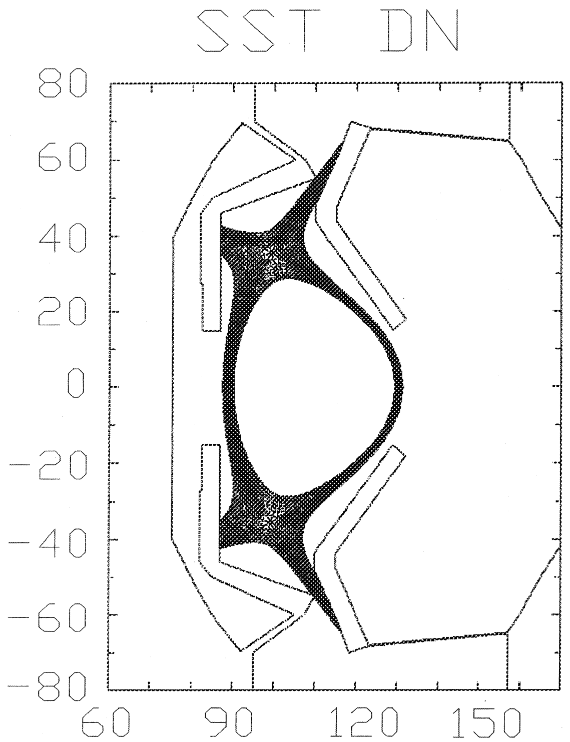

Fig. 2. Mesh and first wall used by B2-EIRENE.

B2-EIRENE shows SOL temperatures >200 eV and a relatively transparent SOL with a sheath limited flow for the edge densities expected in SST-1. The total charge exchange energy loss for the 1×10^{19} m^{-3} case was 0.15 MW and for the 5×10^{19} m^{-3} case was 0.19 MW. The small core region included in the mesh (Fig. 2) contributed twice the amount of charge exchange energy loss in the low density case as in the high density case. The small core region also radiated more power in the low density case, though the total power radiated in the SOL was much larger (0.390 MW) in the high density case as compared to the low density case (0.104 MW). This implies that the energy confinement degrades and the heat flux to the divertor plates increase at low density operation. This is due to better shielding of the main plasma from impurities in the high edge density cases. In both cases it is seen that carbon sources from the first wall is negligible w.r.t that from the outer divertor plate, but comparable to that from the inner divertor plate.

B2-EIRENE also shows thinner SOL widths for the inboard side as compared with the outboard side. This is due to the parallel flow velocities being larger in the inboard side. This difference decreases at higher densities and also when higher values for the transport coefficients are used. The difference in parallel flow velocities could be due to higher recycling in the well baffled outer side as compared to the recycling at the inner open divertor region [9]. A higher Z_{eff} at the innboard side was observed and this is explained by thinner SOL widths for H^+, rather than any impurity clumping at the inboard side. Flow reversal for carbon from the x-points to the inner and outer mid-planes is observed in both cases with a large reverse flow area in the low density case. No flow reversal is observed for hydrogen in any case.

It is seen that the inner divertor plate has a higher heat flux than the outer divertor plates (Fig. 3). The reasons for this are: (a) inner SOL widths are smaller than the outer SOL widths; and (b) the inner divertor plates have a smaller poloidal inclination than the outer divertor plates. It is also seen that the narrow throat baffle succeeds in shielding the main plasma from the outer divertor source.

5. Divertor plate erosion modelling

SST-1 divertor is being designed to use graphite as the divertor tile material. Divertor erosion studies for SST-1 were done in order to determine (a) the divertor plate life time and (b) the plate temperature for which erosion is minimum. The code DIVER was developed to calculate erosion. It uses empirical formulae for all plasma–surface interactions and contains physical and chemical sputtering, radiation enhanced sublimation, thermal evaporation and backscattering.

A steady state 0-D particle balance model (Fig. 4) was used to model erosion. Let $\Gamma_{\mathrm{c}}^{\mathrm{out}}$ represent the net outflux of carbon from the target. Let $\Gamma_{\mathrm{c}}^{\mathrm{ret}}$ be the incident carbon flux on the target which is a fraction f_{r} of $\Gamma_{\mathrm{c}}^{\mathrm{out}}$. $\Gamma_{\mathrm{c}}^{\mathrm{out}}$ has contributions from the incident hydrogen flux (Γ_{h}) and $\Gamma_{\mathrm{c}}^{\mathrm{ret}}$.

$$\Gamma_{\mathrm{c}}^{\mathrm{out}} = Y_{\mathrm{h}}\Gamma_{\mathrm{h}} + Y_{\mathrm{c}}\Gamma_{\mathrm{c}}^{\mathrm{ret}}, \tag{4}$$

$$\Gamma_{\mathrm{c}}^{\mathrm{ret}} = (Y_{\mathrm{h}}\Gamma_{\mathrm{h}} + Y_{\mathrm{c}}\Gamma_{\mathrm{c}}^{\mathrm{ret}})f_{\mathrm{r}}. \tag{5}$$

Note that carbon fluxes from other divertor plates can be included by adjusting the value of f_{r}.

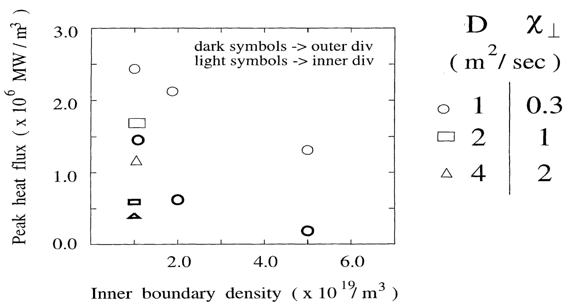

Fig. 3. Peak heat flux from B2-EIRENE.

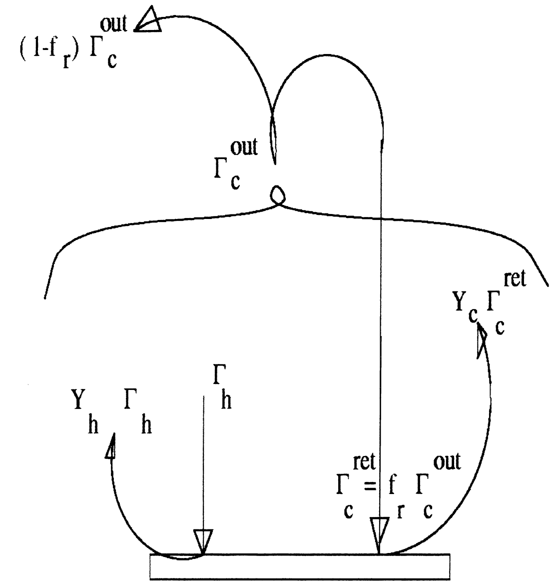

Fig. 4. Carbon balance at target to model gross erosion.

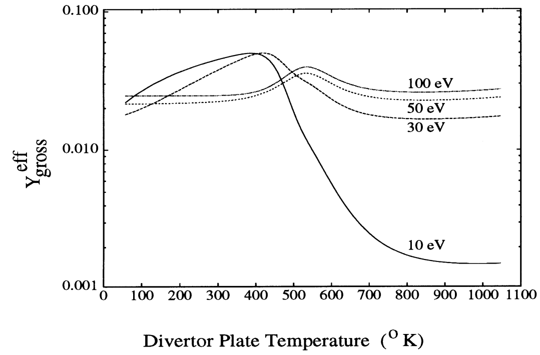

Fig. 5. Gross effective erosion yields.

Using the above equations the gross (without redeposition) and net erosion yield of carbon release are given by

$$Y^{\mathrm{eff}}_{\mathrm{gross}} = \frac{Y_{\mathrm{h}}}{1 - Y_{\mathrm{c}} f_{\mathrm{r}}}, \tag{6}$$

$$Y^{\mathrm{eff}}_{\mathrm{net}} = \frac{Y_{\mathrm{h}}(1 - f_{\mathrm{r}})}{1 - Y_{\mathrm{c}} f_{\mathrm{r}}}, \tag{7}$$

where Y_{h} is the sputtering yield for hydrogen incident on graphite, Y_{c} the sputtering yield for carbon incident on graphite, $Y^{\mathrm{eff}}_{\mathrm{gross}}$ the effective gross sputtering yield, and $Y^{\mathrm{eff}}_{\mathrm{net}}$ the effective net sputtering yield.

The results of the code match with those from the PISCES experiment within a factor of 3. The main mismatch of results was for the effective gross sputtering yields at target temperatures below 350°C where athermal chemical erosion dominates for incident particle energies of 100 eV. There was no difference in the yields from the DIVER results whereas the PISCES results showed a flux dependence. This was because the athermal chemical sputtering formulae used [10] does not contain flux dependence. This can be rectified by using an appropriate flux dependence for athermal chemical sputtering.

The code DIVER was run for various plasma temperatures at the divertor plates and the effective gross sputtering yields were plotted as a function of plate temperature (Fig. 5).

It is seen that for SST-1 conditions, the divertor plate must be kept between 750°C and 1000°C for minimum erosion. Below 300°C the effective yield is lower, but it is difficult to maintain such low temperatures in a steady state for the heat fluxes expected in SST. The main erosion mechanism for SST for a plate temperature of 850°C will then be physical sputtering and for typical particle fluxes of 1×10^{23} the erosion rate is 0.03 mm per 1000 s shot.

6. Conclusion

The results from SOL modelling for SST-1 show that due to low average density SST-1 will have sheath limited flows in the SOL with low divertor chamber recycling and small SOL widths. The power loading on the divertor plates is not a problem as long as confinement is not good (Fig. 3). The narrow throat baffle keeps the backflow within bounds and also satisfies the pumping requirements. For SST-1 a divertor plate temperature in the range 750–1000°C will yield minimum erosion. The gross erosion rates for SST-1 seem to be high and the effect of redeposition has to be studied. It is speculated that athermal chemical sputtering is flux dependent.

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