ENHANCED PARTICLE FLUX CONTROL IN A TOKAMAK WITH A RESONANT HELICAL DIVERTOR

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1. INTRODUCTION

A series of experiments designed to demonstrate the efficacy of the Resonant Helical Divertor /1/ (RHD) concept in a tokamak have been completed. These proof-of-principle experiments utilized a small scoop limiter and a simple modular coil set /2/ to produce an $m = 7$, $n = 2$ RHD configuration for controlling the particle efflux and edge refueling rate in the Texas Experimental Tokamak (TEXT). The coils were designed to generate a quasi-ergodic edge layer using a few modes. Nevertheless at small perturbation levels intact islands are produced. See Fig. 1 for the relative positions of the perturbation coils and the scoop limiter module. A description of the movable scoop limiter, the diagnostics used for analyzing the RHD performance, and the TEXT island topology have been given in a previous paper /3/. Typical TEXT RHD parameters are $\bar{n}_e \approx 2 - 3 \times 10^{13}$ cm^{-3}, with an ohmic plasma current (I_p) between 230 kA and 295 kA depending on r_ℓ. The results, for scoop limiter minor radii (r_ℓ), between 20 cm and the primary TEXT limiter at $r = a = 26$ cm ($R_o = 1.0$ meter) clearly demonstrate greater flux control than had been expected for this simple RHD geometry. Conditions necessary for optimal particle collection are: the scoop limiter at the o-point of a 7/2 magnetic island, a 4 kA current in the coils producing islands of ~ 1.0 cm full width, and helium discharges at high toroidal magnetic field ($B_T = 2.8T$). The neutral density (n_o) within the scoop limiter head is increased by up to 500% and recycling on the front scoop face can be reduced as much as 80%. Under optimal collection conditions the central electron density ($\bar{n}_e$) is reduced by 20% indicating enhanced global particle control. Experimental results and implications of cross-field particle diffusion are presented. A comparison of RHD efficiencies in hydrogen and helium discharges is discussed.

The RHD concept was proposed in 1977 after experiments in Pulsator /4/ suggested that magnetic islands could be resonantly driven with external coils and used to guide plasma flux into a collection aperture. This is conceptually similar to the poloidal divertor but with the advantage that resonant helical magnetic islands may be driven using relatively modest currents in a simple external coil. Operational advantages of the RHD approach include an ability to adjust the flux collection efficiency on a short time scale for feedback control during a discharge and dynamic island shielding of sensitive material collector components. An ideal RHD configuration may be capable of providing plasma unloading efficiencies from 10%, a typical value for conventional pump limiters, up to values approaching 100%, which are expected with full poloidal divertors.

Demonstration experiments on TEXT have produced better than expected particle flux control results. The relatively small poloidal and radial extent of the magnetic islands, shown to scale in Fig. 1, restrict the size of the limiter head and neutralization plate which means

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that particles must make many toroidal circuits before transiting an island and striking the neutralizer. In high cross-field diffusion dominated discharges the full benefit of coherent island RHD flux control mechanisms are lost to local effects which dominate near the limiter. Extreme radial diffusion washes out the island effects completely. In this limit the RHD concept has little or no useful purpose in terms of flux control. Although the TEXT configuration is somewhat less than ideal with its small radial island widths and closely spaced multiple mode resonances, (see Fig. 1), the experiments demonstrate very large improvements in the scoop collection efficiency during RHD operation. The increase in efficiency is so dramatic that additional mechanisms must be invoked to explain the rapid circulation of particles around the islands. The case shown in Fig. 1 implies that particles must make about 10 toroidal circuits in order to travel from the inner 7/2 island separatrix to the outer separatrix where they will be collected by the limiter. This corresponds to a toroidal transit length of ~60 meters or roughly a 1 ms transit time. In TEXT $D_r \approx 10^4$ cm^2/sec gives an average radial diffusive velocity $\langle v_r \rangle_{diff} = \langle \Delta r \rangle_{diff}/t$ =3 cm/ms. Thus radial diffusion carries particles across the primary resonant islands faster than it takes them to make a normal island circuit assuming only parallel flow. The effective rate of circulation can be increased if the island o-points are at a different potential than the separatrix. 50 V/cm radial island electric fields have been observed on CSTN-11 /5/ with externally imposed magnetic islands and would provide a sufficient $\mathbf{E}\times\mathbf{B}$ island circulation velocity to compensate for the effect of radial diffusion and explain the large efficiency increases which are observed with the TEXT RHD.

2. FLUX CONTROL RESULTS FROM THE RHD DEMONSTRATION ON TEXT

In the demonstration experiments on TEXT a measure of the effectiveness of the RHD is obtained from neutral density measurements behind the scoop limiter head. During the steady state RHD period, a parallel particle flux $\Gamma_{\parallel} \propto n_i v_{\parallel}$ enters the scoop aperture, hits the neutralizer and is collected for measurement as neutral gas in the scoop chamber. When the helical current is pulsed (typically with a pulse length of several hundred milliseconds) any neutral density change in the scoop chamber reflects a change in $\Gamma_{\parallel}$.

The typical data signature of interest is a drop in the recycling light on the limiter face with a corresponding rise in the scoop chamber neutral density as $q_\ell \left(\equiv q_{cyl}\left[1+\frac{\epsilon^2}{2}\gamma\right]\right)$, the safety factor on the scoop limiter face, nears 7/2. Here $\epsilon = r_\ell/R_o$ and $\gamma = 2(\Lambda-1)+(\Lambda-1)^2+3$ account for the reduced plasma size and toroidal effects with $\Lambda = \beta_p + \ell i/2$. These signatures are consistently observed with 20 cm $\leq r_\ell \leq$ 24 cm and with the helical coil current (I_H^-) phased to produce a fundamental $m/n = 7/2$ island o-point on the limiter head. Figure 2 shows the neutral density time response. Figure 2(a) shows n_o^H for a hydrogen discharge with $r_\ell = 24$ cm while 2(b) shows n_o^{He} for a helium discharge with $r_\ell = 22$ cm. As q_ℓ increases through 3.3, n_o^H goes up by approximately a factor of two. $\delta n_o(q_\ell)$ is clearly a resonant phenomenon. Given a plasma density of $\bar{n}_e = 4 \times 10^{13}\ cm^{-3}$ this increase in scoop neutrals corresponds to roughly 2.5% of the total plasma ions. A reduction in the recycling source at the face of the scoop limiter accounts for an additional loss of fueling. Although the exact nature of this change in recycling is complex we expect that an increase in recycling takes place inside the scoop chamber as flux is diverted away from the face into the aperture.

The combined effect of enhanced particle flux collection with loss of limiter face refueling are shown in Fig. 3. A multi-chord FIR laser interferometer is used to obtain plasma density profiles, $n_e(r)$, just prior to the I_H^- pulse (*i.e.*, at $t = 300$ ms), and at four subsequent times during the I_H^- pulse. Figure 3(a) shows the n_e profiles during the RHD pulse at t = 345 ms, 465 ms, 390 ms, and 428 ms respectively. Shown in Fig. 3(b) are the time evolution of $\bar{n}_e$ and the H_α light from the scoop limiter face. These results are from a hydrogen discharge which had a n_o^H response similar to that shown in Fig. 2(a). A $n_e(r)$ profile modification occurs as the scoop collection efficiency is increased and the scoop limiter recycling begins to drop. This causes a decrease in n_{eo}, the central electron density, with relatively little change in the shape of the $n_e(r)$ profile. One-quarter of 20% reduction in n_{eo} is accounted for with the increased flux collection of the scoop limiter while the remainder is due to a drop in the limiter face recycling and a reduction in the particle confinement time due to a partial ergodization of the edge /6/.

3. COMPARISON OF RHD EFFICIENCY IN HYDROGEN AN HELIUM DISCHARGES

RHD induced neutral density increases in the scoop limiter chamber are observed for both hydrogen and helium discharges. Typically the increase in the scoop efficiency is more pronounced for helium, in some cases a 500% increase is observed. The best results in hydrogen are limited to slightly better than 100%. Figure 2(b) shows a typical RHD induced n_o^{He} increase. This may be compared with the results shown in Fig. 2(a) for hydrogen. Figure 2(a) shows data for $I_H^- = 3$ kA while Fig. 2(b) $I_H^- = 5$ kA. Allowing for differences in r_ℓ in these two cases and the perturbation field intensity decay typical of our $m = 7$ coils there remains a slight difference between the optimal I_H^- for hydrogen and that for helium discharges. The difference in I_H^- may be related to a difference in the radial diffusion coefficients (D_r) for hydrogen and helium.

As yet data on the radial diffusion coefficients (D_r), scrapeoff layer widths (λ_n), and particle confinement times (τ_p) for these two species is incomplete. Relatively complete electron temperature profiles have been measured and measurements of τ_p in hydrogen and deuterium have been regularly obtained. These τ_p measurements indicate a $m^{1/2}$ /7/ scaling suggesting that a factor of two increase in τ_p from hydrogen to helium may be reasonable. All the data now support a model which indicates that the flux steering capacity of the RHD configuration depends strongly on D_r.

4. CONCLUSION

The effectiveness of the RHD concept for enhanced particle flux control has been demonstrated on TEXT. Different RHD efficiencies have been found for hydrogen and helium discharges. These differences are believed to be related to the diffusion coefficient, D_r, as well as variations in other discharge parameters. Correlations with other parameters are being investigated both experimentally and with numerical particle transport simulations. Enhanced island circulation velocity due to radial electric fields in the island and $\mathbf{E}\times\mathbf{B}$ drift can explain the better than expected efficiency of the RHD on TEXT. The full potential of the RHD awaits demonstration on a large auxiliary heated tokamak using an optimized perturbation coil to generate coherent islands of width ~0.1 a.

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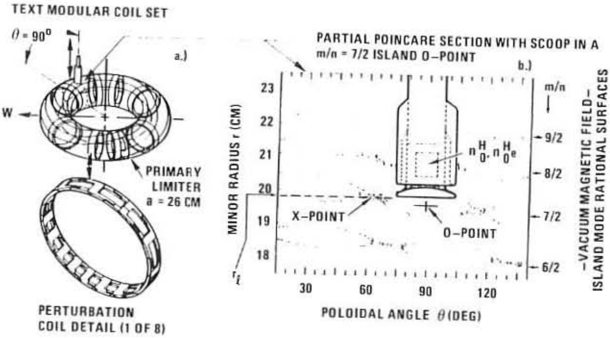
Fig. 1.

a.) Relative positions of the RHD perturbation coils and movable scoop limiter. b.) Partial Poincaré section showing the magnetic island topology with the scoop head positioned in the $\theta = 90^0$, m/n = 7/2 island o-point.



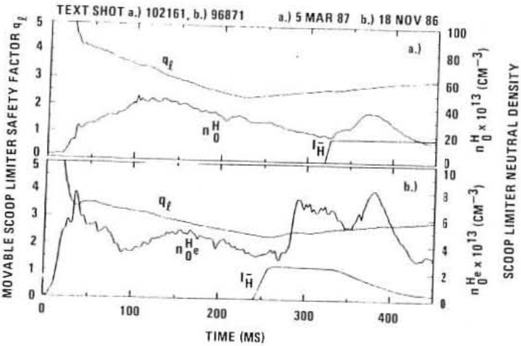


Fig. 2.

a.) Time evolution of the scoop neutral density n_0^H in hydrogen. b.) Time evolution of n_0^He for similar conditions as a.) but in helium. Note the larger δn_0^He but lower ambient n_0^He value.

Fig. 3.

a.) Density profile n_e (r) at five times during the discharge as indicated by the arrows from b.).
b.) Time evolution of $\bar{n}_e$ and the scoop H_α with $I_{\bar{H}}$ = 5 kA in hydrogen.