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THE PLT ROTATING PUMPED LIMITER

By

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JULY 1984

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PREPARED FOR THE U.S. DEPARTMENT OF ENERGY,
UNDER CONTRACT DE-AC02-76-CHO-3073.

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The PLT Rotating Pumped Limiter

DE84 017070

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ABSTRACT

A limiter with a specially contoured front face and the ability to rotate during tokamak discharges has been installed in a PLT pump duct. These features have been selected to handle the unique particle removal and heat load requirements of ICRF heating and lower-hybrid current-drive experiments. The limiter has been conditioned and commissioned in an ion-beam test stand by irradiation with 1 MW power, 200 ms duration beams of 40 keV hydrogen ions. Operation in PLT during ohmic discharges has proven the ability of the limiter to reduce localized heating caused by energetic electron bombardment and to remove about 2% of the ions lost to the PLT walls and limiters.

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1. Introduction

The heat loads generated in present-day tokamaks place stringent requirements on their limiters. They may be expected to receive power loadings in excess of 10^4 W/cm² and a total deposited energy greater than 10^5 J. The temporal and spatial variation of the power depend on the particular experiment. In PLT, high-power RF experiments have been in progress for several years. Recently, two plasma-materials interactions have been discovered which are peculiar to RF heated plasmas. During ICRF heating in the H⁺ 2nd harmonic and H⁺ minority regimes, fast-ion loss to the edge has been discovered.¹ Small carbon probes placed in this region have experienced enhanced erosion attributed to synergistic interaction involving both the bulk plasma and the energetic ions.² During LHCD (lower hybrid current drive) experiments, small (~ 1 cm²) incandescent hot spots, attributed to energetic electron impact, have been observed on the limiters.³ These result in a carbon influx which quenches the current drive. Both of these effects are detrimental and have motivated a reevaluation of the PLT limiter arrangement.

With this impetus, several other desirable capabilities of limiters were considered. Particle control in PLT had been accomplished via Ti gettering and discharge cleaning. Both were difficult to implement and harsh on the machine components. The success of pumped limiters⁴ in decreasing recycling has been established, and the possibility of an improved energy confinement time, as brought about in diverted⁵ and expanded boundary⁶ tokamaks, was considered.

It was concluded that a limiter should be built which would handle high power fluxes, prevent the evolution of hot spots, and bring about a degree of particle control. A limiter design which satisfies the above is shown in Fig. 1. Rotation of the limiter spreads out any highly localized heat load. The

large pump duct acts as a gas ballast and provides a high conductance from the limiter to the pump. The detailed design considerations and testing program for the limiter are discussed in Section II, and the initial results obtained during operation in PLT are presented in Section III.

II. Design, Instrumentation, and Testing

The limiter shape was chosen to be a figure of revolution. It is different from previous limiters in that it is neither simply concave nor convex. The physical basis for this shape is that the power scrape-off distance λ_p depends inversely^{7,8} on the parallel velocity, $v_{\parallel}$, of impacting particles. Runaway electrons have $\lambda_p \leq 1$ mm, energetic ions have $\lambda_p \approx 3$ mm, and bulk plasma has $\lambda_p = 10$ mm. With a limiter shape as shown in Fig. 2, the runaway electrons impact the limiter between the center and edge of the front face. By rotating the limiter, about 30 cm of circumference are available for handling the heat deposited by runaway electrons. Energetic ions should impact on the flat portion of the front face, and bulk plasma deposits about 1/4 of its power on the front face and the rest on the back. Thus the "leading edge" of the limiter is different for each species.

From the relation $\Gamma_p = \Gamma_{nh}E$, where Γ_p is the power flux, Γ_{nh} is the particle flux, and E is the average particle energy, one readily sees that the front face of the limiter receives the power loading and the rear face the particle loading.

ATJ graphite was chosen as the material for the limiter. The bases of this decision follow:

1. Carbon has low z .
2. Good results have been previously achieved with graphite limiters.

3. We judge chemical sputtering to be unimportant due to the several Franck Condon dissociation⁹ steps, each "reflecting" CH_n back to the wall.
4. Excellent thermal properties.
5. Ease of manufacture.

One major change in the preparation of this limiter was in its conditioning. Subsequent to its machining and vacuum bake at 1100°C , it was mounted on its water-cooled support and placed in an ion-beam line. There it was irradiated head-on, by fifty-five, 200 ms duration, 1 MW hydrogen ion beam shots. The beam diameter was about 12 cm. The peak limiter surface temperature rose beyond 2000°C and the bulk achieved $T > 600^\circ\text{C}$. During the beam shots the limiter face sparkled with hundreds of hot spots, presumably due to crystallites having poor thermal contact. The frequency of the sparkling was nearly the same in the last beam shot as it was in the first.

The limiter is rotated by means of a shaft connected to a hollow ferrofluidic feedthrough located at the end of the pump duct. A vespel bushing, on a spider assembly located near the limiter, acts as the second bearing support for the shaft. The hollow shaft allows water cooling tubes and electrical wiring to be brought to the limiter. A stepping motor drives the shaft at speeds up to 2 RPS, the limit being due to the motor torque.

A segmented graphite collar (fixed at a tokamak minor radius of $r=42$ cm) surrounds the limiter to restrict gas conductance back into the tokamak. The limiter is movable in and out of the tokamak via a bellows assembly at the ferrofluidic feedthrough. With the limiter fully retracted to $r=45$ cm, the conductance back into the machine for D_2 is 400 ℓ/s , and the conductance down the pump is 720 ℓ/s at $0.1 < P < 1 \mu$. Pressures are measured by a Shultz Phelps gage

which has been calibrated against a capacitance manometer. Both gages are located 2 m from the vacuum vessel at the far end of the pump duct. The time constant of the Shultz Phelps gage is ~ 1 ms.

The collection efficiency of the limiter has been modelled with a 2-d ballistic calculation. For a 2 cm flux scrape-off distance, the amount of ion flux "trapped" by the limiter/collar arrangement is 50% of that incident for a limiter position 5 cm beyond the collar, $r_0 \approx r_c - r_L$.

The limiter temperature is measured in two ways. There are 9 W5%Re/W26% Re thermocouples embedded in the limiter by use of a graphite adhesive, Graphi-bond 551-R. The thermocouples are ~ 4 mm below the limiter front surface and located at the perimeter, half-perimeter, and center. Their response time, calibrated during the hydrogen ion beam irradiation run, is about 100 ms. The surface temperature is monitored with an Inframetrics infrared camera, which has a framing rate of $\sim (30 \text{ ms})^{-1}$. The camera views the limiter face at $\sim 30^\circ$ from the normal through a ZnSe window 3.5 m away.

We have modelled the limiter thermal response using a finite element, 3-d code. The main finding is that the limiter can handle $\sim 2 \text{ kW/cm}^2$ for ~ 1 sec before the limiter surface temperature exceeds $\sim 2000^\circ\text{C}$. This corresponds to about 1 MW distributed uniformly over the limiter's front and back face. Thus a single limiter of this type should be able to handle a sizeable fraction of the power loading planned for PLT through 1985, but it is not adequate for long pulse (10 sec) experiments.

III. Operation on PLT

With the IR camera, video recordings have been made during ohmic plasmas with $6 \times 10^{12} < \bar{n}_e < 4 \times 10^{13} \text{ cm}^{-3}$. A general feature, seen previously with probes^{10,11} and more recently in limiter studies,¹² is an asymmetric deposition of power. More power is deposited on the "ion-drift" side than on the electron drift side. The pattern of the power deposition, shown in Fig. 3a, is for high density operation, and Fig. 3b shows the pattern for low density operation. The predicted effect of runaway electron bombardment is seen by the higher power loading at smaller limiter circumference. The hot areas at smaller limiter circumference frequently reach their highest temperatures at discharge initiation and termination, when the single turn loop voltage is highest - another sign of runaway bombardment. The higher temperature in the midplane is due to the larger radius of curvature of the plasma in the toroidal versus the poloidal direction.

The hot areas have been spread out by rotating the limiter. The peak temperature has dropped about a factor of two. A larger improvement is expected for the localized hot spots generated in lower hybrid experiments. At present we cannot quote absolute power fluxes as derived from the IR camera data because of a lack of in situ calibration.

The pressure rise in the pump duct is shown in Fig. 4 for two 500 kA discharges with $\bar{n}_e \approx 1 \times 10^{13} \text{ cm}^{-3}$. The limiter radius was 40 cm. In one discharge the valve to the pump was opened and for the other it was closed. In both cases the pressure in the duct is seen to rise throughout the discharge. As the density in the main plasma begins to fall at 700 ms, the pressure in the duct rises more steeply. For densities above $\bar{n}_e = 1 \times 10^{13} \text{ cm}^{-3}$, the pressure in the pump duct continues to rise for discharges of 1 sec duration.

We have measured the pressure in the duct as a function of limiter position for fixed plasma position. Using $t = 600$ ms as a fiducial point, we show the pressures in the duct in Fig. 5 for five different plasma densities. Because of limits set on the allowable limiter position (to protect RF components) this experimental scan only covers $39 \leq r_L \leq 41$ cm. Up to 10 reproducible discharges were run at each limiter position, density, and valve setting. The recorded pressures varied less than 10%. Based on the ballistic modelling, for constant plasma behavior and $\lambda = 2$ cm, a fall-off in pressure is not expected until $r_L \sim 7$ cm. The observed behavior is consistent with this.

The particle removal rate is readily calculated from the pump speed and the duct pressure. However the fraction of the ions which leave the plasma and are removed by the pump can only be estimated in a most rudimentary way because the particle confinement time is not well-known. Based on LENS measurements¹³ of charge exchange neutral efflux, the particle confinement time at $n_e = 1 \times 10^{13} \text{ cm}^{-3}$ is 30 ms. With the limiter at 40 cm and the valve open, the particle removal rate is .32 Tl/s of D_2 . An assumption here is that the gas in the duct is room temperature D_2 . The tokamak particle-loss rate is $\langle n_e \rangle v_{pLT}/\tau = 10^{21} \text{ D}^+/\text{s}$. Therefore the pumped particles represent 2% of those lost. If τ_p scales as n_e , as τ_E supposedly does, then the percentage pumped does increase with density up to about 3% for $r_L = 39$ cm and $n_e = 3 \times 10^{13} \text{ cm}^{-3}$.

IV. Summary

A limiter has been built to handle the heat loads and particle control requirements of RF experiments in PLT. It has been conditioned and commissioned in an ion beam test stand. Initial results on PLT during ohmic heating experiments do confirm the ability of the limiter to distribute the heat load by

rotating during the tokamak discharge. Estimates of particle removal indicate that ~2% of those ions lost from the plasma are removed by the pump.

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Figure Captions

1. Schematic of the rotating pump limiter in PLT. The limiter, mounted on the end of a water cooled shaft, enters the vacuum vessel through an outside midplane port. A 36 cm diameter pump duct surrounds the assembly.
2. Cross section of the graphite limiter blade. The indentation causes the tangency point of the last closed flux surface to be halfway out on the limiter front face. The different scrape-off scale lengths of each species result in the power loading on the front face and particle loading (by the bulk plasma) on the rear face. The holes in the graphite limiter are for bolts and Langmuir probes.
3. Isotherms showing power loading on the limiter front face during (a) medium, $\bar{n}_e \sim 3 \times 10^{13} \text{ cm}^{-3}$, and (b) low density, $\bar{n}_e \approx 6 \times 10^{12} \text{ cm}^{-3}$ ohmic operation. The isotherms are approximate due to lack of in situ calibration.
4. Time evolution of the electron density and pump duct pressure. Higher pressure results when the valve to the pump is closed.
5. Density and limiter position dependence of the pump duct pressure measured at 600 ms during discharge of 1 second duration. Measurements were made with the pump valve open and closed.

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Fig. 1

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PLT ROTATING LIMITER CROSS SECTION

Fig. 2

#84X0758

Fig. 3

Fig. 4

Fig. 5