DESIGNS FOR A TFTR FULL-POWER PUMPED LIMITER

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PPPL--2365
DE87 003073

ABSTRACT

A pumped-limiter system which would provide increased particle control and enhance the performance of full-power discharges is being considered for TFTR. The system consists of two toroidal belts located near the Zirconium-Aluminum (ZrAl) getter panels. The limiter blades would be made of carbon/carbon composite in order to have a very thin profile, allowing a large fraction of the scrape-off flux to be pumped. Simulations of the plasma scrape-off and neutral transport indicate that the limiter pumping should reduce the recycling coefficient by 10-25%. Simulations of central plasma processes indicate that the lowered recycling could increase Q_{fusion} by more than 100%. This paper discusses the designs and the performance predictions for the system. Further details will be given elsewhere [1].

1. INTRODUCTION

A pumped-limiter system is being considered for full-power TFTR operation. The primary goals of this system are to achieve significant particle exhaust rates and to explore the possibility of improved energy confinement. Other goals are to enlarge the range of major and minor radii available for plasmas, to limit plasmas during ion cyclotron resonance heating (ICRH), and to allow limiter biasing.

The enhanced confinement regime, recently obtained in TFTR, results from conditioning the limiters to lower the recycling coefficient and the density limit. These discharges, and those limited by the PDX scoop [2], indicate that limiter pumping could improve energy confinement. Plasma simulations indicate that the density control resulting from a lowering of the recycling coefficient could increase the fusion power ratio Q_{fusion} for DT plasmas. Also, this might help achieve the enhanced confinement regime and the energetic-ion mode at higher plasma current, help shape the plasma profile, and help facilitate pellet injection.

Simulations of the plasma edge and neutral transport indicate that two requirements are needed for a pumped limiter to achieve a large reduction (>10%) of the recycling coefficient. The pumped limiter must be the main recycling source. This means it must be able to withstand most of the scrape-off power. Also, the limiter blade must have a thin profile, with the entire blade being close to the last closed-flux surface. If the profile thickness is comparable to the ion-flux scrape-off length, than a large portion of the scrape-off flux can flow behind the blade to the neutralizer and be pumped.

In TFTR, the neutral-beam injection (NBI) pulse length will remain sufficiently short (2 sec), so that a large area limiter might not require water cooling. If the limiter does not need water tubes or backing plates, it could have a very thin profile. To withstand full-power TFTR pulses, a double toroidal belt system, having a limiter surface area of 25 m^2, is being considered. The system would consist of twenty limiter blades located over the ZrAl getter panels which are outboard, above and below the midplane. This location has the advantages of using the existing pumping system, of locating plasmas close to the ICRF antenna, and of minimizing interferences with existing diagnostics. Neutralizers would be positioned behind the limiter blades, and scrape-off flux striking them would be emitted towards the getter panels. Skirts could be used to confine particles beneath the blades, further enhancing the efficiency.

In order to withstand high heat loads and to be strong enough not to require backing plates, the limiter blades would be made of carbon/carbon composite. This would allow the profile of the limiter blades to be about 2 cm, allowing a large pumping efficiency. Several additional features would result from making the blades of carbon/carbon composite. They would be light weight and have relatively simple attachments, so they would be easy to install or remove. Also during DT operation, carbon/carbon composites will not become as radioactive as would limiters containing more metal, like graphite limiters mounted on large backing plates. Not requiring water tubes would make it easier to include the capability of biasing the limiter blades.

The full-power pumped limiter has not been approved or funded, but it is being considered as an option. Shields for the ICRF antenna are being designed for TFTR using carbon/carbon composite. They may have the capability of pumping, in which case they would function as a low-power pumped-limiter prototype.

2. MODELING TFTR PLASMAS AND LIMITER PUMPING

2.1. TFTR plasmas

The particle recycling coefficient R is not known, but it is believed to usually be close to one for discharges formed on both the inner and movable limiters. The effective particle confinement-time $\tau_p^* = \tau_p/(1-R)$ is several seconds for poorly conditioned limiters, but can be lowered to ~0.25 sec with extensive limiter conditioning. This results in the enhanced confinement regime. The implication is that this limiter conditioning reduces R to a value considerably less than one.

The BALDUR code [3] was used to investigate effects in DT plasmas of density control. These simulations show that lowering R has several advantages: it makes the density profiles more peaked, leading to better beam penetration and to higher ion temperatures because the coupling between ions and electrons is reduced in the periphery.

During full-power NBI, a large amount of D^0 will be injected. To optimize the DT mix in the simulation, a tritium pellet and a large amount of T_2 gas were injected. These sources along with recycling from the limiter and walls determine the density. Lower R means that less D and T will be recycled, and thus less T_2 needs to be injected to maintain an optimal DT mix.

The BALDUR simulations were for DT plasmas with 27 MW of NBI, 7 MW of ICRF heating, and T_2 pellet fueling. The particle transport model was calibrated by simulating actual D_2 pellet plasmas. The recycling coefficient was varied, and at each value the T_2 gas fueling rate was adjusted to maximize the peak fusion power ratio Q_{fusion}. The electron density at large minor radius decreases with decreasing R, the central electron temperature increases, and the ion temperature increases substantially at all radii. The values of Q_{fusion}, shown in fig.1, rise rapidly at the start of the heating pulse for all choices of R, but later they level off if R is close to one and continue to rise for lower R. This indicates that reduced recycling would be especially advantageous for long heating pulses.

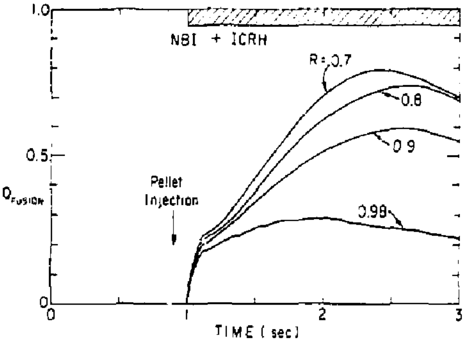

Fig. 1. BALDUR Simulations of full-power DT plasmas with different values for R.

2.2. <u>Scrape-off profiles</u>

The pumping efficiency ε of the limiter is the ratio of the number of ions pumped to the number entering the scrape-off from the last closed-flux surface. The pumping reduces R by ε. A characterization of the scrape-off layer is needed in order to estimate the pumping efficiency. The ion-flux profile determines how much flux hits the limiter blades and how much flows behind to the neutralizers. Most of the flux to the blades will not be pumped. The limiter geometry and the density and temperature profiles determine how many of the neutrals emitted by the neutralizer will enter the pumps.

The scrape-off lengths are expected to be relatively small (~1 cm) for discharges limited by toroidal limiters. Ionization effects may play a significant role in the scrape-off, so when neutrals are pumped the scrape-off profiles will change. If the effect is to lower the scrape-off lengths, then the pumping efficiency will be reduced.

A one-dimensional edge model [4] was used to simulate edge conditions in TFTR. The neutralizer was assumed to intercept flux at a distance δ between 2 and 10 cm from the last closed-flux surface. A fraction f_{pump} of the ions which flow to the neutralizer was assumed to be pumped, and the rest was returned to the scrape-off region. This fraction was varied while the transport coefficients were held fixed to simulate the effects of pumping on the scrape-off profiles.

The calculated profiles of the electron density, the electron temperature, and the neutral density are given in fig. 2. As f_{pump} rises from 0, the n_e profile drops rapidly and the temperature rises, becoming step-like. The neutral density at the minor radius of the neutralizer decreases also. This simulation suggests that pumping will change the scrape-off region substantially. As f_{pump} increases, the ion flux to the limiter and neutralizer, the fraction of this flux hitting the neutralizer, and the flux to the vacuum vessel wall decrease. The pumping efficiency does not rise linearly with f_{pump} due to the change in the scrape-off.

2.3. Neutral transport

Plasma profiles such as those in fig. 2 were used with the DEGAS code [5] to evaluate the pumping efficiencies of different limiter designs. The DEGAS code computes neutral transport in three dimensions using Monte Carlo methods. The code includes a detailed description of the neutral plasma interactions for both atoms and molecules, as well as a detailed wall reflection model. The limiter blades and neutralizers were modeled as rough carbon for which the reflection coefficient is close to zero. The vacuum vessel was modeled as smooth stainless steel.

Also, a two-dimensional plasma fluid model (PLANET) [6], which directly incorporates DEGAS, was used to model the TFTR scrape-off plasma and pumping efficiencies.

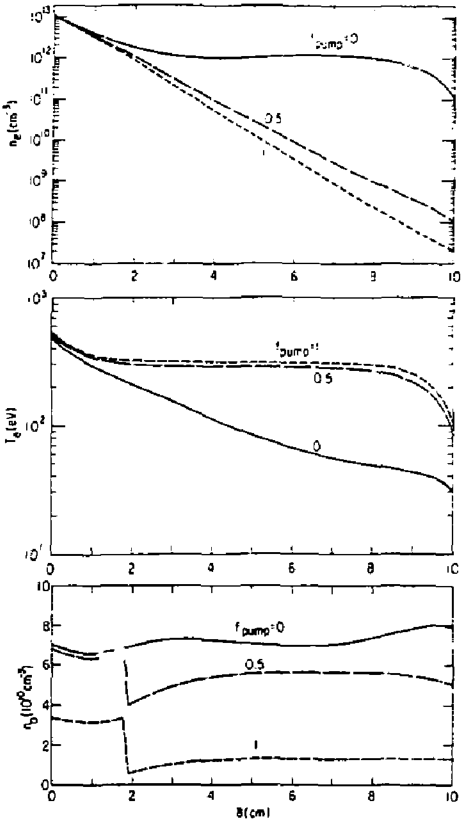

Fig. 2. Simulation of scrape-off profiles.

3. PUMPED LIMITER CONFIGURATION

The TFTR surface pumping system with all of the 36 ZrAl getter panels activated would have a pumping speed of 5×10^5 liters/sec. For comparison, the turbo pump system has a pumping speed of 7×10^3 liters/sec. The surface pumping system has helped TFTR achieve low base pressures, but has not had a measurable effect on plasma performance. The DEGAS calculations show that the pumping efficiency of these getter panels is presently very small (<1%) since the major recycling sources, the movable and inner limiters, are too far from them. The movable limiter will eventually be removed from TFTR since it can not withstand the higher NBI heat loads becoming available.

A plan view of one of the belts formed by the pumped-limiter blades and of the getter panels is shown in fig. 3. An elevation view showing the limiter blades in the vacuum vessel and several compatible plasmas is shown in fig. 4. The biggest standard inner plasma which can be formed with the inner limiter without contacting the movable limiters is 15 cm from the planned pumped limiter position and 25 cm from the getter panels. The other plasmas could only be formed with the movable limiter removed.

The standard pumped plasma, shown in fig. 4, is positioned to maximize the pumping ratio. The plasma is sufficiently far from the inner limiter that the recycling would occur mainly on the pumped limiter. The hybrid pumped plasma is a large inner limiter plasma whose edge is 2 cm from the pumped limiter and 12 cm from the getter panels. Most of the limiter recycling would occur on the inner limiter, so the pumping efficiency is calculated to be relatively low. The outboard pumped plasma is formed on the surface of the ICRF antenna shields. Since the area of the shields is relatively small, not much beam power could be injected into these plasmas.

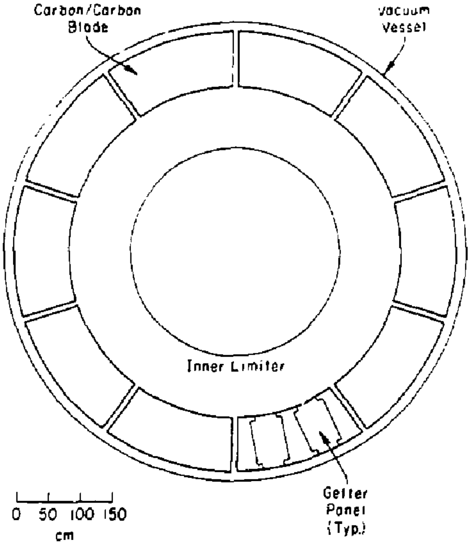

Fig. 3. Plan view of TFTR showing the inner and pumped limiters and the getters.

Two generic limiter designs are being investigated. One has transverse (rib) neutralizers located at each getter panel location. The other has an axisymmetric (spine) neutralizer. Slices through these two designs are shown in fig. 5. To increase the pumping ratio, skirts could be added along the sides of the getters to confine neutrals near the panels.

4. DESIGN CONSIDERATIONS

In the preliminary design of the limiter blades, sheets of carbon/carbon composite 6 mm thick would be used. These can withstand high temperatures (up to 2700 C), but the ports in which they would be mounted cannot withstand high temperatures or temperature gradients. The limiter blades would be thermally isolated from the mounting brackets with sliding mounts. These brackets may require water cooling. If the blades do not need to be water cooled, they could be electrically isolated from the vacuum vessel. This would allow the blades to be biased or to be

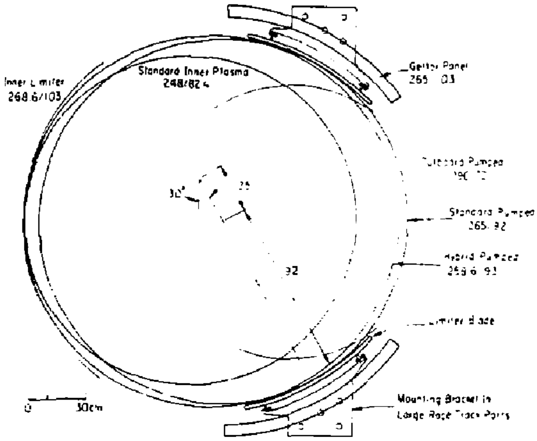

Fig. 4. Sketch of limiters, getter panels, mounts, and compatible plasmas. Major and minor radii and limiter radius are in cm.

grounded through a resistance that can be varied.

The electrical conductivity of ordinary carbon carbon composites is about 10[illegible] lower than that of the Inconel used for the backing plate of the inner limiter. Consequently, the eddy current forces will be much lower and appear manageable. Results of the disruption eddy current induced loads and stresses show that the maximum induced shear is 12 MPa if the blade is not stiffened and can be lowered to 3 MPa if toroidal stiffeners are used.

Outgassing tests of carbon/carbon composites are being conducted. Preliminary results indicate that the outgassing is less than that of ATJ or POCO graphite. It may be possible to condition the blades in TFTR using the getter panel heating system to heat the blades radiatively. The getter panels can be kept at 400 C for long times.

The surface area of the limiter blades is larger than that of the inner limiter, so the system should be able to withstand the full power. The heat flux is expected to be 50 W/cm^2 on the front surface and 500 W/cm^2 on the leading edge. This will cause the limiter to come to an equilibrium temperature of 175 C between discharges and to heat to a peak of 900 C.

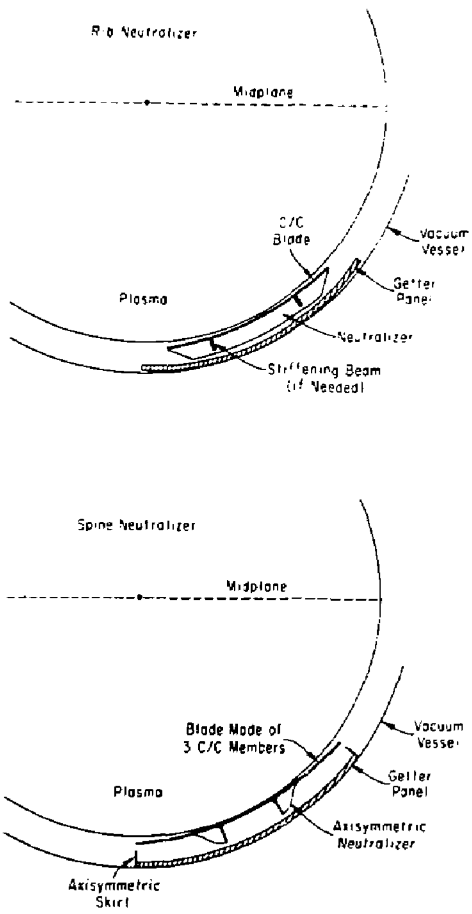

Fig. 5. Details of two alternative designs for the neutralizers.

Several aspects make the heat load different for these limiters. The heating from escaping hot ions will be larger on the pumped limiter. Also, the toroidal field ripple is larger on the pumped-limiter blades. The toroidal field ripple at the proposed limiter location is ±2 mm. This affects the heat and particle flow to the limiter. If the toroidal field ripple is determined to cause excessive heat on the edge of the blades, or to reduce the particle pumping too much, the blade design can be altered to compensate.

5. PUMPING PERFORMANCE

The pumping efficiency ϵ depends strongly on the ion-flux scrape-off. If this is exponential with a particle-flux scrape-off length of λ_f = 1.5 cm, then a calculated 26% of the particle flux will flow to the neutralizers under the pumped-limiter blades. The DEGAS code indicates that f_{pump} = 37% of the neutrals emitted from the rib-style neutralizer will be pumped instead of ionized in the scrape-off. This gives a lower bound for the pumping efficiency of ε = 26%×37% = 10%. The spine-style neutralizer, without skirts to trap neutrals, will have a lower f_{pump}, so ε = 3%.

Most of the neutralizer outflux which is not pumped is ionized in the scrape-off, and most of this will return to the neutralizer in a toroidal pumped limiter. Thus the DEGAS results, which do not return particles to the neutralizer, are lower limits for ε. An upper limit for ε is then 26% if λ_f remains 1.5 cm with pumping. A self-consistent PLANET-DEGAS calculation using a similar scrape-off plasma gives 13% for the pumping efficiency of the spine-style design.

6. SUMMARY

A pumped limiter can have a large pumping efficiency and lower the recycling coefficient significantly only if it is the main recycling source. Also, since the pumping ratio is proportional to the number of ions flowing to the neutralizer, and since the scrape-off lengths are expected to be small, the profile of the pumped limiter must be as thin as possible. In the design discused above, the use of carbon/carbon composite allows the thickness of the limiter blades to be 0.6 cm. This leads to a profile that is 2 cm thick. The pumping ratio for the pumped limiter is estimated to be 10-25%. This may significantly effect the energy confinement and Q_{fusion}.

*Other authors were J. Bialek, W. Blanchard, D. Brown, R. Hawryluk, D. Heifetz, D. Mikkelsen, D.K. Owens, M. Petravic, and M. Ulrickson from the Princeton Plasma Physics Laboratory, and A. Pontau and R. Watson from the Sandia National Laboratories, and H. Takatsu form the Japan Atomic Energy Research Institute at Naka-Machi.

7. ACKNOWLEDGEMENTS

This work was supported by U.S. Department of Energy Contract No. DE-AC02-76-CHO-3073.

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