MASTER**PUMP LIMITER STUDIES ON THE HELIOTRON-E DEVICE***D. L. HILLIS, P. K. MIODUSZEWSKI, R. A. ZUHR, R. E. CLAUSING,
F. W. BAITY, R. H. FOWLER, and J. A. ROME

Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831, USA

O. MOTOJIMA, T. MIZUUCHI, T. MUTOH, H. ZUSHI, A. IYOSHI, and K. UO

Plasma Physics Laboratory, Kyoto University, Uji, Japan

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ABSTRACT *

Particle control with pump limiters has been successfully demonstrated in a variety of tokamaks. This experiment has obtained, for the first time, experimental data on pump limiter operation in a heliotron configuration. A movable pump limiter module was installed on a horizontal midplane port of Heliotron-E. The limiter assembly consists of a TiC-coated graphite head with single-sided particle collection and active pumping. The location of the limiter is varied from near the vacuum vessel wall or up to 8 cm inside the last closed magnetic flux surface. This flexibility permits the study of a heliotron plasma that is limited either by the magnetic separatrix or by a material limiter. In the configuration investigated, only very low pressures are observed in the pump limiter when it is located outside the last closed flux surface, indicating that the scrape-off layer density is very low ($< 5 \times 10^{11} \text{ cm}^{-3}$). For limiter positions inside the last closed flux surface, pressures of 2-6 mTorr are observed (similar to comparable tokamak operation). Erosion patterns on the vacuum vessel, as well as hot spots on the limiter head, indicate that the particle flow out of the confined plasma exhibits complicated patterns.

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This suggests that for efficient particle collection in a stellarator, pump limiters must be matched to the particle flow patterns.

1. Introduction

Stellarator/heliotron [1–3] type devices offer an attractive alternative to tokamaks as fusion reactors because of their prospects for steady-state high-beta operation without plasma current, thus eliminating a major driving force for instabilities and the need for current drive. In long-pulse and steady-state devices (especially in D-T burning devices), it will be necessary to provide plasma density control and impurity removal schemes to optimize plasma performance. In a tokamak configuration, density (particle) control and some impurity control have been successfully demonstrated with pump limiters [4]. The main goal of these Heliotron-E pump limiter experiments is to obtain experimental data on particle flow and edge plasma properties during pump limiter operation for a stellarator configuration and make comparisons with current tokamak pump limiters.

2. Experimental details

2.1 The Heliotron-E device

The Heliotron-E device is a helical toroidal system that has an $\ell = 2$, $m = 19$ helical field with large rotational transform ι and shear [3]. The major radius of the device is 2.2 m, and the shape of the magnetic surfaces is elliptical with an elongation factor of 2 as shown in Fig. 1. The average minor radius of the plasma is about 0.2 m. Currentless hydrogen target plasmas are produced at a toroidal field of $B = 1.9$ T with electron-cyclotron heating (ECH) using, typically, 300 kW of rf power from three 53.2-GHz gyrotrons. Near the end of the 50-ms ECH pulse, neutral beam injection (NBI) of up to 3.4 MW of neutral hydrogen for 150 ms is injected into the ECH target plasma. In the latter part of the discharge,

the plasma is heated only by NBI. For these experiments, typical plasma parameters are $n_e \approx 2-8 \times 10^{13} \text{ cm}^{-3}$, $T_e \approx 700-1000 \text{ eV}$, and $T_i \approx 600-1000 \text{ eV}$ for 3.2 MW of NBI. All values of NBI power are given as power into the vacuum vessel. The NBI power absorbed by the plasma is generally only about 50% of the injected power due to a large amount of beam shinethrough. Gettering is used to cover 30-70% of the wall with titanium before the start of the experiments.

Another feature found in heliotron/stellarator-type devices is a magnetic divertor action. Fig. 1 also shows the last closed magnetic flux surface, which is located at $r = 28 \text{ cm}$. The crosshatched region shows the poloidal cross section of the Heliotron-E divertor region [5] along with indications of localized divertor traces on the vessel wall. For this crosshatched region the connection length of the field line between the plasma and the wall is greater than 5 m. For even larger $r > 31.5 \text{ cm}$ (outside the crosshatched region), the connection length is very short ($\leq 1 \text{ m}$) and the field lines are even more strongly diverted to the wall.

2.2 The pump limiter

To study pump limiter operation in a stellarator/heliotron-type configuration, a movable pump limiter module was installed on a horizontal midplane port of Heliotron-E. The experimental arrangement of the pump limiter module on Heliotron-E is shown in Fig. 1. The pump limiter has a stroke of 58 cm and permits the positioning of the limiter either near the vacuum vessel wall or up to 8 cm inside the last closed flux surface. This flexibility in positioning the pump limiter permits the study of either a heliotron plasma limited by the magnetic separatrix or of a heliotron plasma that is limited by a material limiter. The limiter assembly consists of a TiC-coated graphite head with single-sided particle collection, while the remainder of the structure is stainless steel. The size of the limiter is restricted to approximately 14.5 cm in diameter due to the size of the port holes

in the Heliotron-E vacuum vessel. The dimensions of the particle collection window in the pump limiter module are 2.5 cm in height (along major radius) and 10 cm in width. In order to avoid excessive heat loads, the leading edge of the limiter, which is also the leading edge of the pumping slot, is recessed 1.6 cm from the limiter tip (or plasma boundary).

Active pumping for the system is provided by a Zr/Al getter pump [6] that is located directly behind the limiter head. The nominal pumping speed for hydrogen is 2000 L/s for the nude cartridge used here, and in the pump limiter configuration, it is measured to be 1000 L/s for thermal particles due to conductance limitations. The pressure in the pump limiter chamber is measured with a Schütz-Phelps gauge. When the Zr/Al is not activated and pressure equilibrium is attained, the measured pressure corresponds to the actual pressure in the limiter chamber. Upon activation of the pump, a pressure gradient along the getter cartridge has to be accounted for, and the measured pressure has to be multiplied by a factor of 3 to give the pressure near the entrance slot of the pump limiter.

The locations of the limiter head and particle collection window are shown in Fig. 1 relative to the last closed flux surface of Heliotron-E. All limiter positions x are made with respect to the last closed flux surface. At $x = 0$ the limiter tip is just tangent to the last closed flux surface, whereas $x = 2$ cm corresponds to the limiter tip at 2 cm inside the last closed flux surface. Measurements of the scrape-off layer plasma electron temperature and density are provided by two double Langmuir probes located inside the throat of the pump limiter, while the total energy scraped off by the limiter head is measured by an imbedded thermocouple. The particle flux to the limiter is deduced by using a fast Schütz-Phelps ionization gauge (1-ms response time) to measure the pressure rise in the limiter chamber. The Schütz-Phelps gauge is located at the end of an extension tube that has a vacuum time constant of about 20 ms.

3. Experimental results

To study the effects of the limiter on the plasma particle flow and edge plasma properties, the limiter position x is varied from the vacuum vessel wall up to 8 cm inside the last closed flux surface both before and after activating the limiter pump. Figure 2 shows the pressure rise observed in the pump limiter as a function of the limiter position for a series of identical 3.2-MW NBI discharges for $n_e = 4 \times 10^{13} \text{ cm}^{-3}$ with the pumps activated (“pumps on”) and nonactivated (“pumps off”). Clearly, the activated pump has decreased the pressure observed in the limiter by about a factor of 5 over the unpumped case. Outside the last closed flux surface ($x < 0$) only small pressure buildups are observed in the pump limiter chamber, whereas the pressures increase very rapidly for $x > 0$. By placing the limiter head inside the last closed magnetic flux surface at $x = 0$, the plasma boundary is defined not by the magnetic separatrix, but by the TiC-coated graphite limiter head. In this mode of operation with $x > 0$, the Heliotron-E pump limiter behaves very similarly to a tokamak pump limiter. For the ISX-B tokamak with 1.0 MW of NBI and $n_e \approx 4 \times 10^{13} \text{ cm}^{-3}$, pressures of 2–3 mTorr were observed for a similar unpumped configuration (see Fig. 9 of Ref. [6]). For Heliotron-E a pressure of 3 mTorr is observed in the unpumped case at $x = 4 \text{ cm}$.

To investigate the differences in plasma parameters on Heliotron-E as the plasma is limited by the magnetic separatrix or the pump limiter, Fig. 3 shows the electron temperature T_e and the radiated power P_{rad} as the limiter position is changed. The quantity P_{rad} is the radiation loss of the plasma as measured by a calibrated bolometer. Both T_e and P_{rad} are essentially unaffected for $x < 4 \text{ cm}$; however, for $x > 4 \text{ cm}$ T_e begins to fall sharply and the radiated power increases. A similar behavior is also noted in n_e , T_i , and the plasma stored energy.

In Fig. 4 the effects of the pump limiter on the core plasma density are shown at a given gas flow rate, ϕ , and identical NBI fueling both before and after the

limiter pumps is activated. The data shown in Fig. 4 demonstrate quite clearly a density change between activated and nonactivated pumps when the limiter is located at $x = 4$ cm. For identical gas fueling rates, the plasma density decreases from about $5.7 \times 10^{13} \text{ cm}^{-3}$ to around $4.8 \times 10^{13} \text{ cm}^{-3}$ near the end of the plasma discharge. Typically, the plasma density after pumping is reduced by about 20% throughout the plasma discharge. If the limiter is positioned at $x = 2$ cm, a density decrease of only about 8% is observed between the activated and nonactivated cases, and for $x = -2$ cm no density reduction is observed. With the present limiter configuration, density control is demonstrated for limiter positions inside the last closed flux surface; however, for positions outside the last closed flux surface, no density control is observed, as is expected, due to the low pressures observed in the limiter chamber for $x < 0$.

To investigate the relationship between the edge plasma density of the scrape-off-layer, $n_e[SOL]$, and the pressure observed in the pump limiter, the average plasma density n_e is varied from $2 \times 10^{13} \text{ cm}^{-3}$ to $8 \times 10^{13} \text{ cm}^{-3}$ for 3.2 MW of NBI with the limiter located at $x = 4$ cm and the pump activated. Figure 5 shows the pressure observed in the pump limiter module as a function of $n_e[SOL]$. The edge plasma density is measured by a double Langmuir probe at the entrance to the pump limiter. Figure 5 shows that the pressure increases linearly with the scrape-off layer density. A linear dependence similar to that of Fig. 5 is also found if the pressure is plotted against the average plasma density n_e . The electron temperature of the scrape-off layer, as measured by the double Langmuir probe, is found to be $T_e \approx 16$ eV and is independent of n_e .

4. Discussion of results

To provide optimal pump limiter operation, large pressure buildup (1-10 mTorr) and high edge densities ($> 5 \times 10^{12} \text{ cm}^{-3}$) are necessary to efficiently remove par-

ticles from the plasma. To prevent impurity generation and gas recycling from the limiter head, it is desirable to locate the limiter outside the last closed flux surface in the separatrix or divertor region of Heliotron-E. In the divertor region, impurities and gas recycling from the limiter would be somewhat insulated from the plasma core. For limiter positions inside the last closed flux surface ($x > 0$) and an unpumped limiter, pressures of 1–6 mTorr are observed (see Fig. 2) and scrape-off layer densities indicate $n_e[SOL] \approx 0.2\text{--}1.3 \times 10^{13} \text{ cm}^{-3}$. These values are consistent with those found on the ISX tokamak [6] with a similar pump limiter configuration. For limiter positions near or outside the last closed flux surface ($x \leq 0$), pressures of only 0.2–0.5 mTorr are observed with correspondingly small scrape-off layer densities of $< 5 \times 10^{11} \text{ cm}^{-3}$. Unfortunately, for the conventional pump limiter configuration used here, the edge density is too low outside the last closed flux surface and therefore not effective for particle removal.

The data of Fig. 4 are best discussed by considering the global particle balance as discussed in Ref. [8]. In steady state the number of plasma particles is given by

$$N = \frac{\phi \tau_p}{1 - R}, \quad (1)$$

where R the global recycling coefficient, τ_p is the global particle confinement time, ϕ is the external fueling rate, and $N \approx n_e V_p$ is the total number of plasma particles contained in the plasma volume V_p . By introducing $\tau_p^* = \tau_p / (1 - R)$, then Eq. (1) can be rewritten as $\tau_p^* = N / \phi$. Both N and ϕ are determined experimentally, and τ_p^* is found to be 125 ms for $n_e \approx 5 \times 10^{13} \text{ cm}^{-3}$ and 3.2 MW of NBI. Unfortunately, τ_p is not known accurately for Heliotron-E, but τ_p is expected to be about $\tau_E \approx 10$ ms [5] as is found in many tokamaks of comparable size. If $\tau_p^* \approx 125$ ms and $\tau_p \approx 10\text{--}30$ ms, then a global recycling coefficient $R \approx 0.8\text{--}0.9$ results.

Equation (1) demonstrates that small changes in R produce significant changes in N , if R is about unity. A limiter with active pumping effectively reduces the recycling by a small amount ϵ , which results in a significant reduction in the particle

density. An estimate of the exhaust efficiency ϵ of the pump limiter can be obtained from the ratio of the measured densities with and without active pumping for the case shown in Fig. 4 by utilizing Eq. (1) with constant ϕ and τ_p and the relation [7], $N/N_0 = (1 - R)/(1 - R + \epsilon)$, where R is the recycling coefficient without pumping, N_0 is the number of plasma particles without pumping, and $(R - \epsilon)$ is the reduced global recycling due to the exhaust efficiency of the pump limiter. The observed density reduction as shown in Fig. 4 due to the active pumping is consistent with an exhaust efficiency of 2–4% with $R \approx 0.8$ –0.9.

During the pump limiter experiment, the plasma parameters remain essentially unchanged for $x < 4$ cm (see Fig. 3), but T_e , T_i , and n_e decrease dramatically for $x \geq 5$ cm. If the limiter is inserted beyond $x = 5$ cm, an appreciable increase in metallic impurities is observed in the plasma with an accompanying increase in P_{rad} (see Fig. 3). The metal impurity content of the plasma continues to increase as the limiter is inserted (T_e decreases) until finally the plasma discharge terminates at a limiter position of about 7.5 cm.

For Heliotron-E, particles are expected to leave the well-confined plasma and flow to the vessel wall in a complicated pattern that is defined by the magnetic field structure and divertor pattern (crosshatched region of Fig. 1). Direct evidence of this divertor action is seen as localized erosion [5] on the wall where these divertor traces are expected. Further evidence that plasma flow out of the divertor region is not isotropic is found on the TiC-coated graphite limiter head. A very localized burn pattern is found on the side of the limiter head, where substantial removal and melting of the limiter's TiC coating occurred. Although it is difficult to conclude when or where this damage occurred, the radial position and angle of the burn are consistent with magnetic calculations that follow field lines through the divertor region. These calculations indicate that the burn occurred at or near $x = -2$ cm and is due to a large particle flux flowing out of one of the divertor regions. To

produce the observed melting of the TiC coating, a heat flux of at least 8 kW/cm^2 is required. A rough estimate of the particle flux required to produce this heat flux is about 10^{20} particles per $\text{cm}^2\cdot\text{s}$. Some possibility exists that runaway electrons are produced during plasma breakdown or the magnetic field rampdown; however, no appreciable runaway electrons are observed during these experiments, and they are probably not responsible for the limiter burn pattern.

Pressure buildup and exhaust efficiency depend critically on the design and orientation of the limiter head. In these experiments a conventional pump limiter geometry (of the type used in tokamaks) is not optimized to take full advantage of the large particle flux flowing out of the Heliotron-E divertor region. Clearly, pump limiter/divertor designs that better match the stellarator particle flow pattern to the pump limiter structure are needed.

5. Summary

Particle control with a conventional pump limiter (as used on tokamaks) has been successfully demonstrated on Heliotron-E if the pump limiter is located inside the last closed magnetic flux surface. Estimates of the particle removal efficiency indicate that about 2-4% of the particles lost from the plasma are removed by the pump limiter. If the pump limiter is placed outside the last closed flux surface, little or no particle control is observed. For optimum performance of a pump limiter on a stellarator, the limiter structure should be removed from the well-confined plasma to reduce impurity generation and gas recycling from the limiter. This requires locating the pump limiter outside the last closed flux surface. For Heliotron-E, particles leave the well-confined plasma via a complicated divertor-like pattern that is given by the magnetic field structure. The conventional limiter geometry used in these experiments is not well suited for efficient particle exhaust in a stellarator if the limiter is not optimally located in the divertor region. For efficient particle

collection in a heliotron/stellarator-type device, the pump limiter must be matched to the particle flow patterns.

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Figure captions

- Fig. 1. Poloidal cross section of Heliotron-E with the last closed magnetic flux surface shown as well as the magnetic divertor region (crosshatched region). The movable pump limiter assembly is introduced through an outboard midplane port.
- Fig. 2. Measured pressure in the pump limiter module versus limiter position for 3.2 MW of NBI at $n_e \approx 4.0 \times 10^{13} \text{ cm}^{-3}$ before and after activation of the pumps. Limiter positions are measured relative to the last closed magnetic flux surface ($x = 0$) with negative limiter positions referring to positions outside the last closed flux surface.
- Fig. 3. Electron temperature as measured by electron cyclotron emission and P_{rad} , the radiated power, as measured by a calibrated bolometer shown as a function of the pump limiter position. The data are for 3.2 MW of NBI and a plasma density of $n_e \approx 4 \times 10^{13} \text{ cm}^{-3}$.
- Fig. 4. Electron density and gas puff program ϕ of two Heliotron-E discharges: before activation of the limiter pumps ("OFF") and after activation of the limiter pumps ("ON") with 3.2 MW of NBI and the limiter positioned 4 cm inside the last closed flux surface.
- Fig. 5. Measured pressure in the pump limiter module after activating the pumps as a function of the scrape-off layer density $n_e[SOL]$ as measured by a double Langmuir probe located at the entrance to the pump limiter.

Fig. 1

Fig. 2

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Fig. 3

Fig. 4

ORNL-DWG 86C-2289 FED

Fig. 5