port to our belief that the predicted transient effects could be measured.

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Efficacy of Passive-Limiter Pumping of Neutral Particles

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Experiments have been performed to measure the neutral pressure buildup behind the limiter as a function of plasma density and gas species. The results indicate that a passive mechanical limiter effectively removes from the vacuum vessel up to 20% of the atoms injected during a discharge. The feasibility of mechanical limiters removing the fusion-reaction helium ash, thus negating a major need for magnetic divertors, is discussed.

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To sustain a controlled, steady-state D-T burn, one must be capable of maintaining a fixed α-particle density. For typical ignition-size plasmas and plasma parameters, the steady-state conditions may be achieved if approximately 10% or more of the α particles are not recycled; in other words, if they are pumped away.[1,2] One possible way to do this is by using a passive mechanical limiter, comparable to those promoted by Schivell.[3]

Experiments to investigate the effectiveness of a passive-limiter pumping scheme were performed on the Alcator-*A* tokamak. The vacuum vessel has a major radius of 54 cm and a minor radius of 12.5 cm. The total volume of the torus and the diagnostic port extension tubes is 451 liters; plasma volume is ≈ 117 liters.

A single molybdenum limiter is inserted from the horizontal port as shown in Fig. 1. The limiter is electrically floating and isolated from the vacuum vessel. The toroidal thickness of the limiter is 1.1 cm with a poloidal extension of 205°. The limiter inner radius (plasma radius) is 10.4 cm and the outer radius is 12.2 cm.

At the limiter flange there are three port extension tubes. During tokamak operation the ex-

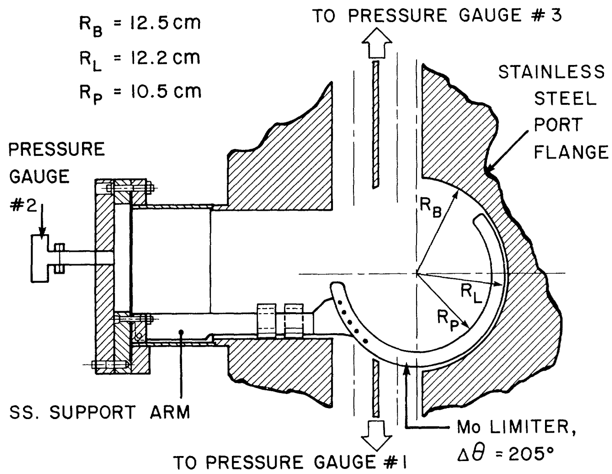

FIG. 1. Cutaway view in the poloidal plane of the Mo limiter and the port slots.

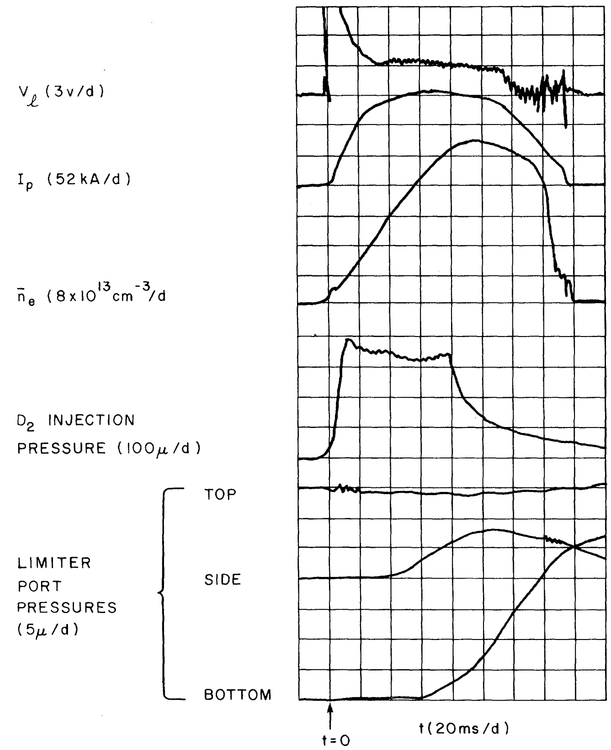

FIG. 2. Temporal evolution of a typical deuterium discharge for $B_T = 60$ kG. The bottom three traces are the signal outputs from the pressure gauges in the limiter volume top, side, and bottom, respectively. The fast neutral-gas valve is opened ≈ 5 ms before discharge initiation.

tension tubes are maintained at an average temperature of 30–40 °C. The top (volume 3) and the bottom (volume 1) have volumes of 13.3 and 13.7 liters, respectively. Each is connected to the main toroidal vacuum vessel via two rectangular slots (approximately $5.9\times 1.3\times 20$ cm^3) as shown in Fig. 1. The horizontal port (volume 2) is much smaller, with a volume of 2.1 liters, and is connected to the vacuum vessel by a rectangular slot of dimensions $1.6\times 17\times 16.7$ cm^3. At the end of each of the volumes a fast-response absolute-pressure gauge, maintained at 20 °C, is mounted to measure the pressure increase in the three respective limiter port volumes. Each of the pressure gauges has a response of ≲ 5 ms with a pressure range of 10^{-5} to 1 Torr and an absolute error of $\lesssim 5.0\times 10^{-5}$ Torr. It should be noted that none of the three volumes have any external pumps or gas sources associated with them. During plasma operation the plasma density is increased by the injection of neutral gas through a fast piezoelectric valve from the top port, located 180° toroidally from the limiter.

Neutral-gas pressure measurements in the limiter port volumes were made during routine Ohmically heated plasma operation. Typical plasma parameters were $B_T = 60$ kG and peak plasma currents $130 \lesssim I_p \lesssim 200$ kA, with the plasma density and working gas as variables. Profiles and central values of n_e, T_e, and T_i are comparable to those reported elsewhere[4] for similar operating conditions.

The number of atoms in the vacuum vessel during plasma initiation $[(4-8)\times 10^{-5}$ Torr$]$ is 2–3 orders of magnitude below the number of atoms injected during the discharge to increase plasma density. Discharge duration is typically between 115 and 140 ms, with the slightly longer discharges occurring at the lower plasma densities.

Figure 2 shows a typical D_2 discharge evolution for peak line-average density of $\bar{n}_e = 4.3\times 10^{14}$ cm^{-3}. During the constant-pressure portion of the gas injection the plasma density increases approximately linearly in time, peaking about 10 ms after the valve turns off and gas in the injection volume continues to empty into the torus. The gas-injection volume is approximately 1600 cm^3 and the pressure waveform shown gives a gas-feed rate of 6×10^{20} molecules/s. Higher- and lower-density discharges were obtained by using the same pressure waveform and increasing or decreasing the injection pulse proportionately. After several high-density discharges, a constant density of $1\times 10^{14} \lesssim \bar{n}_e \lesssim 5.5\times 10^{14}$ cm^{-3} could be maintained with a throughput $\approx 1\times 10^{20}$ molecules/s for the duration of the constant-current phase of the discharge. The bottom three traces in Fig. 2 are the outputs for the three pressure gauges, 3, 2, and 1, respectively. There is no pressure rise in the top port, volume 3, until well after the discharge has terminated. This is presumably due to the desorption of some of the working gas for the cold walls. It should also be noted that no portion of the limiter is directly in front of the access slots to volume 3. The pressure trace from volume 2, the side port, shows a small linear increase with density for $\bar{n}_e \lesssim 2\times 10^{14}$ cm^{-3}. For higher density, the pressure increases more rapidly, with a temporal behavior similar to the remaining density rise but with a 10–15 ms time lag, which is the approximate response time of the port. Volume 1 shows a much larger pressure increase, peaking at ≈ 27 μm at about 180 ms. This much slower time response is reasonable, when the significantly larger volume of volume 1 (13.7 liters) and an associated slower response time of ≈ 100 ms due to the conductance of the connection between the large volume and the pressure gauge are taken into consideration.

Figure 3 shows the peak neutral pressure measured in volume 1 (limiter bottom port) as a function of line-average density for the three working gases of H_2, D_2, and He. The neutral-gas accumulation is small, increasing slowly with density for $\bar{n}_e \lesssim 2\times 10^{14}$ cm^{-3}. For high plasma density the slope of the port pressure versus the plasma density increases by a factor of 5–6, with port pressures as high as 29 μm having been measured in D_2 at $\bar{n}_e \approx 5.1\times 10^{14}$ cm^{-3}. It is worthwhile to note that these pressures are 1–2 orders of magnitude higher than the steady-state fill-gas pressure and are factors of 5–10 higher than the pressure rise measured from pulsing cold gas into the torus with no plasma. In addition, we have made pressure measurements at other no-limiter ports. The behavior has been similar to that measured in volume 3 above the limiter. In all cases we have found no pressure increases in nonlimiter ports until well after discharge termination, i.e., 200–300 ms later, and the pressure rises have been on the order of only 2–3 μm for the highest-density discharges. As stated previously, this is presumably due to the gradual desorption of some of the working gas that has been retained by the chamber wall during the plasma discharge.

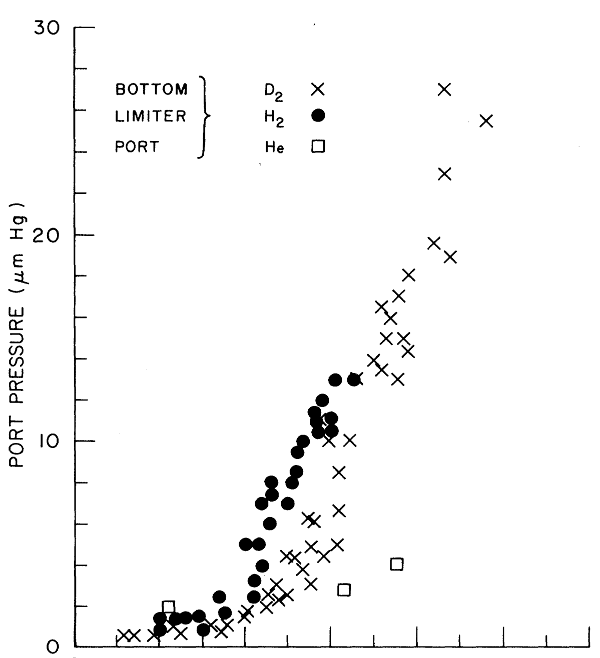

FIG. 3. Maximum gas pressure measured in the limiter bottom port as a function of peak line-average density and various gases. All measurements for $B_T = 60$ kG, $130 \leq I_p \leq 200$ kA.

The observation of large neutral pressure buildup in trapped volumes directly behind the mechanical limiter is not in itself surprising. If one has a relatively tenuous plasma in the limiter shadow, there may be large fluxes of charged particles to the limiter, where they become neutralized and scatter ballistically and/or recycle from the limiter to form a dense neutral cloud in the immediate vicinity of the limiter.

Measurements of the shadow-plasma properties in JFT-2 (JAERI fusion torus–2; Japan Atomic Energy Research Institute) indicate that as much as 80% of the charged-particle flux is to the limiter versus the wall.[5] Similar measurements[6] of the shadow plasma in the Alcator-*A* indicate that typically greater than 90% of the flux is incident on the limiter. Floating limiters, such as ours, should have a sheath potential, thereby accelerating the ions into the limiter. Thus the particle flux to the limiter is

$$\Gamma_{\parallel} = n_i \bar{V}_{si},$$

where $\bar{V}_{si} \simeq [(T_i + 3T_e)/m_i]^{1/2}$ is the ion sound speed. For incident ion energies of less than several hundred electronvolts, experimental data and computer calculations indicate that more than 50% of the incident ions are reflected.[7] Of those reflected (80–85)% come off as neutrals with an energy distribution peaked at the energy of the incident ions (for energies $\lesssim 2$ keV) and a cosine angular distribution.[7,8]

One can get a better feeling for the efficiency of particle removal by plotting the total fraction of injected atoms collected in the limiter bottom and side ports (volumes 1 and 2, respectively), as done in Fig. 4. These data were taken from D_2 discharges for $B_T = 60$ kG and $140 \lesssim I_p \lesssim 200$ kA. The differences between the solid points and the circles reflect the effects of recycling of neutral gas from the wall to maintain plasma density. Circles represent discharges for which the number of injected atoms was increased from the previous discharge such that the peak plasma density was higher than the preceding discharges; the solid points are for discharges for which the number of injected atoms was decreased from the previous shot such that the peak density was lower than the preceding shot. We observe that for lower densities, e.g., $\bar{n}_e \lesssim 1\times 10^{14}$ cm^{-3}, only (3–4)% of the injected particles are "pumped" into the limiter ports. However, for line-average plasma densities above 2×10^{14} cm^{-3} the fraction of "pumped" particles increases with density, attaining a level of 20% for $\bar{n}_e \approx 5\times 10^{14}$ cm^{-3} in

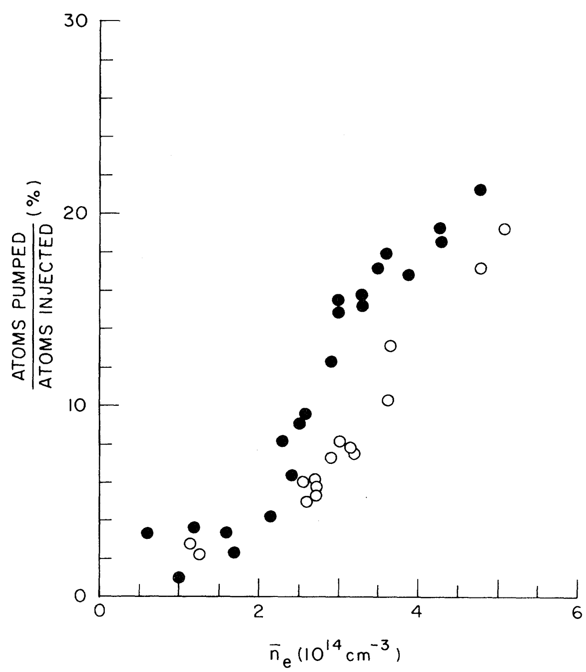

FIG. 4. The percentage of the injected atoms collected in the limiter side and bottom ports as a function of peak line-average density. $B_T = 60$ kG, $140 \leq I_p \leq 200$ kA, deuterium.

deuterium. The surface area of the limiter bottom and side apertures is only 1.5×10^{-3} of the total surface area of the toroidal vacuum-vessel wall. Comparing this number to the fraction of injected atoms actually deposited into the limiter ports, we find that the presence of the limiter has provided a "pumping" enhancement of 20–200 for the density ranges investigated.

Another way to quantify the "pumping" efficiency is to compare the measured flux of particles entering the limiter side and bottom trapped volumes to the average flux of particles leaving the plasma volume, as deduced from the global particle-confinement time.[9] Over the density range investigated with D_2 (1.5–10.5)% of the particle flux from the plasma edge enters the limiter-port apertures. This also indicates a factor of 10–100 "pumping" enhancement over the strict surface-area ratio of the limiter-port apertures to the vacuum-vessel wall.

Since the data are limited for He discharges, one cannot make a precise quantitative statement as to the relative pumping efficiency between H or D and He. However, were we to plot port pressure versus $\bar{n}_i$ in Fig. 3, we would find that the He is pumped at least as well, if not better, than H or D for the same line-average ion density.

Ultimately the goal of a passive-limiter pumping scheme is to remove ~10% of the fusion-produced helium from the plasma edge to allow a sustained D-T burn in a reactor. If the helium concentration is uniform throughout the main plasma and limiter shadow, then our results would imply that from 4 to 20% of the helium, as well as the fuel gas, could be adequately removed by a mechanical-limiter pumping scheme. Any dependence on the spatial distribution of the He would also be a limitation of a magnetic divertor as well.

Thus, we feel that the results presented here warrant new and additional consideration of the use of mechanical limiters instead of divertors in the next generation of tokamaks. Depending on the design of the limiter and the associated pumping port access to the limiter, a sufficient portion of the neutralized He could be removed.

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Production of Large-Amplitude Cyclotron Waves on an Intense Relativistic-Electron Beam for Collective Ion Acceleration

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Large-amplitude, low–phase-velocity, axisymmetric electron cyclotron waves have been excited and propagated more than 10 wavelengths on an intense relativistic-electron beam transported along a magnetic field inside a cylindrical vacuum waveguide. Measurements of wavelength and azimuthal symmetry have been accomplished. Wave-phase-velocity control, essential for collective ion acceleration, has been demonstrated by spatially varying the magnetic field strength. From measured wave quantities, on-axis accelerating fields of 10 MV/m are inferred.

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Among the proposed[1] methods of collective ion acceleration is the autoresonant-accelerator concept[2] which employs an axisymmetric slow cyclotron wave impressed on a very intense electron beam. In this scheme the ions are initially trapped by the wave potential in a high–magnetic-field, low–phase-velocity region and then accelerated as the phase velocity is increased by flaring the magnetic field. In this paper, the excitation, propagation, and identification of this mode on a high-power electron beam are reported. The azimuthal-mode number and wavelength of this mode have been measured. In addition, control of the wave phase velocity by spatial variation of the guide–magnetic-field strength has been demonstrated. These waves have been generated at levels of interest for collective ion acceleration.

The experimental setup is shown in Fig. 1. The 2.25-MV, 20-kA pulsed electron beam is produced in a vacuum diode employing a 5-cm-diam hemispherical cold cathode and a planar anode with a 6-cm-diam aperture through which the beam is extracted. The diode is immersed in a 2.5-kG axial magnetic field. Experimental measurements are made during an 80-ns time window when the diode voltage is constant to within 5%.

The electron beam is propagated along a guide magnetic field interior to a 7.6-cm-diam conducting drift tube which is evacuated to 10^{-6} Torr. Beam propagation has been studied with use of total collecting and multiport Faraday cups,[3] magnetic-field probes, wall charge collectors, and collimated x-ray detectors and has been found to be well behaved. In particular, the radial current-density profile has been measured to be uniform with a diameter of 5.0 cm.

The antenna used to launch the waves is located approximately 1 m from the diode, and consists of a resonant (239 MHz) half-wavelength coaxial

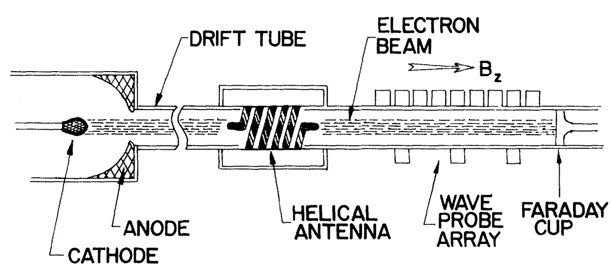

FIG. 1. Cross-sectional view of experimental arrangement.