RESISTIVE DIFFUSION OF CESIUM PLASMA IN A STELLARATOR*

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We have continued our investigations on particle losses from cesium plasmas in the Wendelstein stellarator. At the Culham Conference we reported on measurements[1] obtained in a stellarator magnetic field with helical windings of type $l=2$.[2] We found particle-loss rates to be much less than the anomalously high "pump-out" losses usually encountered in stellarators.[3] Moreover, the relationship observed between ion input flux and the resultant particle density distribution was in agreement with calculations which assumed resistive diffusion across the magnetic confining field and recombination on the insulating surfaces of the supports of the plasma source, the latter constituting the predominant loss process.[4]

In recent experiments, which will be described in this Letter, surface recombination losses within the plasma volume were made negligibly small by minimizing the surfaces of the supports of the plasma source. In this way we have been able to show the radial transport of the plasma to be governed by resistive diffusion.

Our machine has a race-track shape with an axial length of 319 cm and a tube diameter of 5 cm. The main magnetic field can be pulsed up to 15 kG for about one second; the $l=2$ helical windings yield a maximum angle of rotational transform of 0.4π at a main field strength of 11 kG. A small correction field transverse to the magnetic axis can be applied from two pairs of auxiliary windings which encircle the machine. The plasma is produced by contact ionization on a hot tantalum sphere, 5 mm in diameter, which is hung from a thin (25 μm in diameter) tungsten wire. The emitting sphere is heated by bombardment with a beam of energetic electrons from a gun outside the plasma volume. This electron beam is switched off during the time of the experiment and the emitting sphere is allowed to assume its floating potential. The total ion input flux is determined from the ion saturation current drawn when a voltage is applied between the emitting sphere and the vacuum vessel with no magnetic field present. Two small cylindrical electrostatic probes (50 μm diam, 5 mm length) —one located close to the emitting sphere ("near probe"), the other one half-way around the machine ("distant probe")—are situated at the axis of the plasma volume. They are biased negatively with respect to the emitting sphere, and the plasma density is determined from the measured probe current. An annular particle detector which defines the cross section of the plasma volume by its open area is situated near the position of the distant probe. Particles which have left the so-defined plasma volume can be detected by this detector if they move along the magnetic field lines toward its surface. With these measuring devices we obtained the following results:

(1) With fixed magnetic field and for a typical ion input flux of 10^{12} sec^{-1} we found the resultant plasma density to be nearly independent of the temperature of the emitting sphere between 1800 and 2200°K. Beyond these limits the density dropped sharply. This behavior could be explained in terms of plasma production and interaction with the surface of the emitting sphere.

(2) Since the particle density determined by the probes depends strongly on the correction fields, we adjusted them for maximum probe signal. This adjustment was made keeping all other parameters constant. Reversal of all magnetic fields left the plasma properties unchanged. If the emitting sphere was displaced, the correction fields had to be readjusted. This resulted in a displacement of the magnetic axis which was apparently the same as that of the sphere. The temperature of the emitting sphere and the correction fields are adjusted in the following as described above.

(3) The measured output signal of the annular detector represents about 25% of the ion input flux to the machine. If we estimate that about the same fraction of the input flux is lost on the insensitive area of the annular detector, we can account for the rest of the input flux as being lost on the probes and their shafts as well as by recombination on the source. This means that approximately all particles which have left the plasma volume hit the annular detector. This excludes the existence of a large radial plasma transport velocity.

(4) Moving the probes to their maximum sig-

nal positions and correcting for the difference in sensitive areas, we found that the signal of the distant probe was only slightly smaller than that of the probe near the emitting sphere. If the losses had been due to pump-out, the associated high radial plasma flux would have caused a rapid decay of the particle density in the axial direction away from the source (see Fig. 1).

(5) Simultaneous observation of the central particle density, n_0, and of the flux to the annular detector, Φ_R, yielded a relation that allowed a quantitative check on the diffusion mechanism governing the radial plasma transport. For resistive diffusion one would expect

$$\Phi_{re} = C_1 \frac{n_0^2}{B^2}\left(1 + \frac{4\pi^2}{\iota^2}\right);$$

if pump-out losses were dominant, the result would be

$$\Phi_B = C_2 \frac{n_0}{B},$$

where C_1 and C_2 are coefficients which include plasma temperature and geometrical dimensions, and which take into consideration that only a fraction of the radial plasma flux will be measured by the annular particle detector.

The quantities n_0 and Φ_R have been measured in three different types of experiments: (a) B and ι were varied to the limits of our power supply; (b) ι was changed keeping all other parameters constant (Fig. 2); (c) the ion input flux was varied leaving the magnetic fields unchanged (Fig. 3).

In Figs. 2 and 3 two curves are drawn to represent the connection between n_0 and Φ_R as calculated from the two loss processes mentioned above. For both cases axial uniformity of the radial particle density distribution was assumed, although in case of pump-out losses a large axial gradient of particle density would be expected. Furthermore, it is taken into account that the annular particle detector —due to its particular geometry—measures only about one-half of the flux arriving on its surface. The experimental results show agreement with the curves for resistive diffusion and disagree with those for pump-out losses in the range of experimental parameters investigated, except for the deviations from the theoretical curve in Fig. 2. These deviations could be interpreted as an indication of incomplete plasma thermal equilibrium when the radial

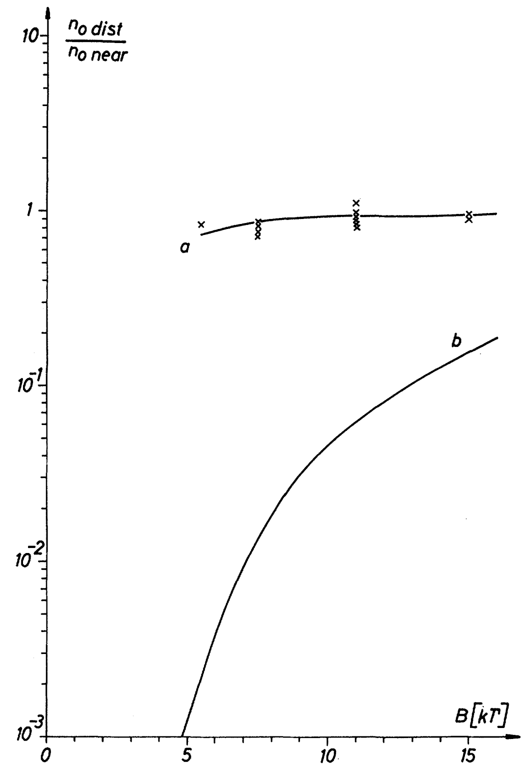

FIG. 1. Ratio of probe signals—distant probe to near probe—versus main magnetic field. Crosses indicate experimental values. Solid curves represent calculated ratios of densities at the two probe positions: curve (a), assuming resistive diffusion; curve (b), pump-our losses.

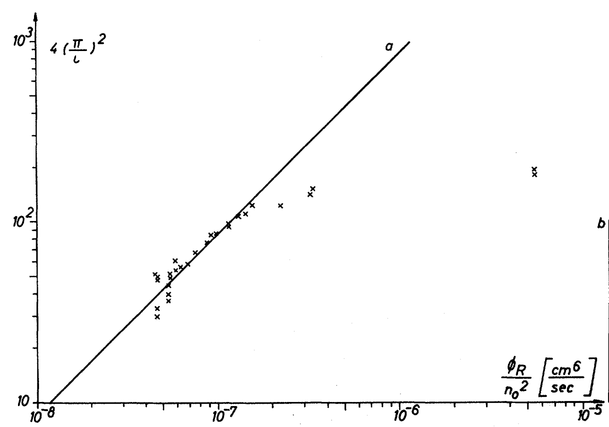

FIG. 2. Total signal of the particle detector related to the central particle density versus $4(\pi/\iota)^2$ for $B = 11$ kG. ι is the angle of rotational transform, n_0 was determined from the probe current. Experimental values are indicated by crosses. Curve (a) represents the calculated relationship assuming resistive diffusion. Curve (b) shows the calculated ratio of Φ_R and n_0^2 if pump-out losses were operative, n_0 having the average value found in this particular experiment.

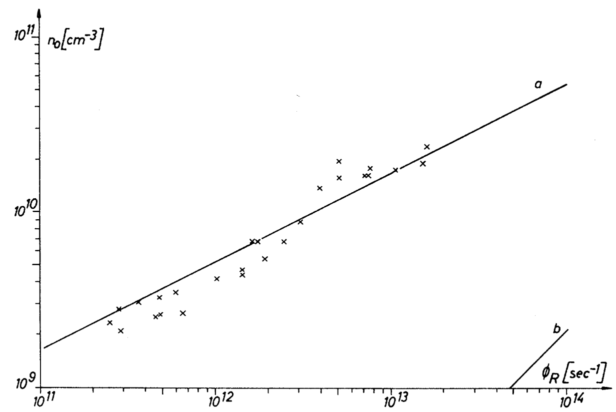

FIG. 3. Relationship between central particle density and flux of diffusing particles for $B = 11$ kG and $\iota = 0.3\pi$. Crosses indicate measured values determined from probe current and particle detector, respectively. Curve (a) is calculated assuming resistive diffusion, curve (b), from pump-out losses.

losses become excessively large for too small values of ι.

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[1]D. Eckhartt, G. v. Gierke, and G. Grieger, in Proceedings of a Conference on Plasma Physics and Controlled Nuclear Fusion Research, Culham, England, 1965 (International Atomic Energy Agency, Vienna, 1966), Vol. II, p. 719.

[2]L. Spitzer, Jr., Phys. Fluids $\underline{1}$, 253 (1958).

[3]W. Stodiek, R. A. Ellis, Jr., and J. G. Gorman, Nucl. Fusion, Suppl., Pt. I, 193 (1963).

[4]It should be kept in mind that the coefficient of resistive diffusion has to be multiplied by $(1+4\pi^2/\iota^2)$, where ι is the angle of rotational transform,[2] so as to allow for the power required to drive the secondary currents in a plasma of finite conductivity [D. Pfirsch and A. Schlüter, Max-Planck-Institut für Physik und Astrophysik Report No. MPI-PA 7/62, 1962 (unpublished); D. Eckhartt and G. Grieger, Max-Planck-Institut für Physik und Astrophysik Report No. MPI-PA 29/64, 1964 (unpublished)].

PHASE TRANSITION IN A LATTICE GAS WITH EXTENDED HARD CORE

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Phase transitions in lattice models of "hard molecules" (i.e., molecules occupying one lattice site and excluding other molecules from certain neighboring sites) have been investigated by several authors. For planar square and triangular lattices occupied by molecules with an exclusion core covering first-neighboring sites only, the situation seems clear as a result of recent works of Gaunt and Fisher,[1] Runnels and Combs,[2] and Ree and Chesnut[3,4]: Both cases most likely exhibit a second-order continuous transition (with a horizontal inflection in the pressure-versus-density curve). Little work has been devoted to more extended hard cores. For the square lattice, Bellemans and Nigam[5,6] worked out the cases of hard-square molecules with exclusion ranges extending up to second- and third-neighboring sites, respectively. Using different techniques (low- and high-density series, matrix method, generalized Bethe approximation) they concluded that first-order and even second-order continuous transitions are excluded in the first case,

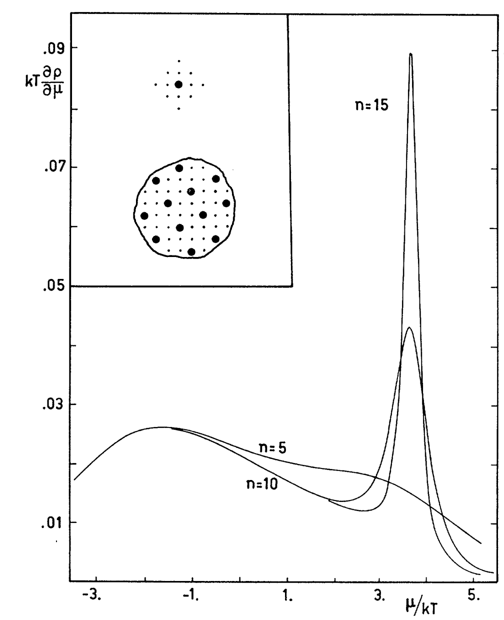

FIG. 1. Plot of $kT\partial\rho/\partial\mu$ vs μ/kT for $n=5$, 10, and 15. The upper left part of the figure shows the exclusion neighborhood of a molecule and the close-packing configuration.