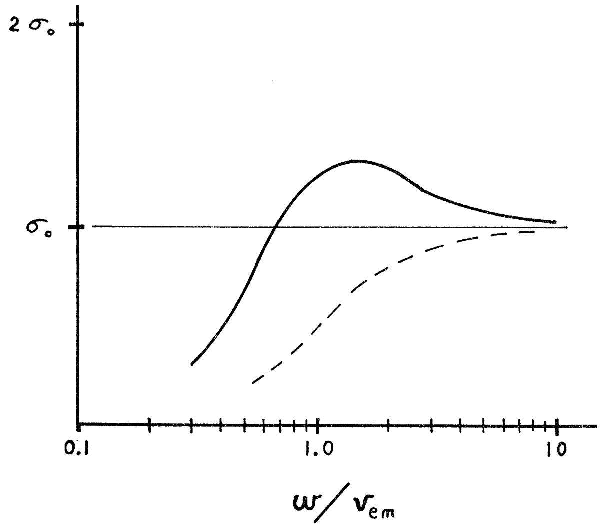

FIG. 1. The frequency dependence of the scattering cross section. Solid line: complete theory, Eq. (13). Dashed line: electron-electron correlations only, Eq. (14).

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Production of a Very Quiescent Plasma in "Skipping" Magnetic Fields

A. Goede, G. J. Brakenhoff, H. J. Hopman, and P. Massmann

Association EURATOM-FOM, FOM-Instituut voor Atoom- en Molecuulfysica, Amsterdam, The Netherlands

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A very quiescent helium plasma, with density fluctuations of *less* than *0.2%*, is produced by applying the stabilizing field of permanent magnets. The steady-state plasma column created in this field, which is of the *average* minimum-B type, not only proves to be extremely quiescent but also has a homogeneous density distribution in the axial direction ($\Delta n/n\Delta z \approx 2\times10^{-3}$ cm^{-1}). The plasma has a density of 5×10^{10} cm^{-3}; the electron temperature is about 7 eV.

A very effective way to suppress the low-frequency density fluctuations in a mirror-confined plasma is the formation of a Joffe-type minimum-B field. As we have previously reported,[1] the same field configuration can be produced simply by replacing the Joffe bars by strips of permanent magnets along the plasma column. The use of strips of permanent magnets resulted in a reduction of the density fluctuations in a steady-state plasma column from 10% or more, without stabilization, to values below 0.5%. The application of permanent magnets is cheap and has proved to be very convenient in producing minimum-B traps.

A major drawback inherent to minimum-B fields is that the field lines diverge outwards from the axis of the trap. In our experiment, where we have a long cylindrical plasma column, most of the field lines intersect the wall before passing through the axial magnetic mirrors. This causes plasma loss along the field lines to the vessel wall. We observed that the plasma density falls off strongly along the axis away from the plasma source. A nearly exponential density decrease with an e-folding length of about 12 cm was measured.[2]

In order to remove the axial density gradient, we have to avoid the diverging field lines. We accomplished this by *reversing the polarity* of the permanent magnets every 15 cm along each strip. Then an outwardly curving field line is periodically bent back towards the axis of the plasma column. In this way we get in the center of the column a much larger region from where the field lines do not touch the vessel wall, unless they have passed through the axial mirror. In this Letter we report that the large axial density gradient can indeed be removed by this modification of the magnetic field, while the stabilizing properties are retained. The plasma is produced with an electron cyclotron resonance discharge (ECR discharge), in which the microwave energy is coupled into the plasma by means of a Lisitano antenna.[3]

Similar to this idea to bend back the diverging field lines of a minimum-B field is the field configuration in the Decca IIB experiment.[4,5] Here the field lines are returned to the axis outside the magnetic mirrors, while the plasma finds itself in the minimum-B region. Besides the fact that the field is generated by currents, the difference between this field configuration and ours is that in our case the bending back of the field lines takes place seven times in the region between the mirrors. Our plasma is therefore confined in a field that has the minimum-B property only on the average, in which case the function $\int_{z_1}^{z_2} dl/B$ is decreasing with radius. The integral has to be evaluated along a field line. In Furth's book[6] it is shown that the combination of an alternating multipole field with a homogeneous field does have the average minimum-B property.

Suppression of the low-frequency instabilities in comparable plasmas produced with a Lisitano antenna has been tried already in other ways. Brown *et al.*[7] used a form of feedback stabilization by a rapid control of the rf power input. Lisitano, DeDionigi, and Fontanesi[8] stabilized the plasma by means of a second antenna, which adjusts the radial temperature profile of the plasma. Neither scheme is an effective as minimum-B stabilization. Their fluctuation levels are minimally about 1%.

Field configuration in skipping magnetic fields.—The skipping field is a superposition of a mirror field, with a homogeneous middle section, and a hexapole field created by strips of permanent magnets. The six strips are parallel to the main field, but the magnets have a magnetization that is predominantly in the radial direction. Along each strip the polarity is reversed every 15 cm. A sketch of the arrangement with the permanent magnets along the plasma column, together with a flux tube, is shown in Fig. 1. We call this type of field a "skipping field" because of the periodic polarity changes in axial direction.

The field has a threefold rotational symmetry around the axis. The cross section of a flux tube resembles a three-pointed star, which rotates over $\pi/3$ rad every 15 cm. At the ECR condition the field strength in the homogeneous part of the main field is about 900 G. The transverse field produced by the permanent magnets increases quadratically with radius. At $r = 2.5$ cm the strength is 300 G, which results in a well depth $|B_{r=2.5}/B_{r=0}| = 1.05$ at that radius. The main field consists of a homogeneous part ($\pm\frac{1}{2}\%$) with a length of 60 cm and with mirrors (ratio 1.8) whose field maxima lie 120 cm apart. The length of the magnetized strips is 120 cm; the internal diameter of the structure is 7 cm, and it is mounted coaxially with the coils producing the main

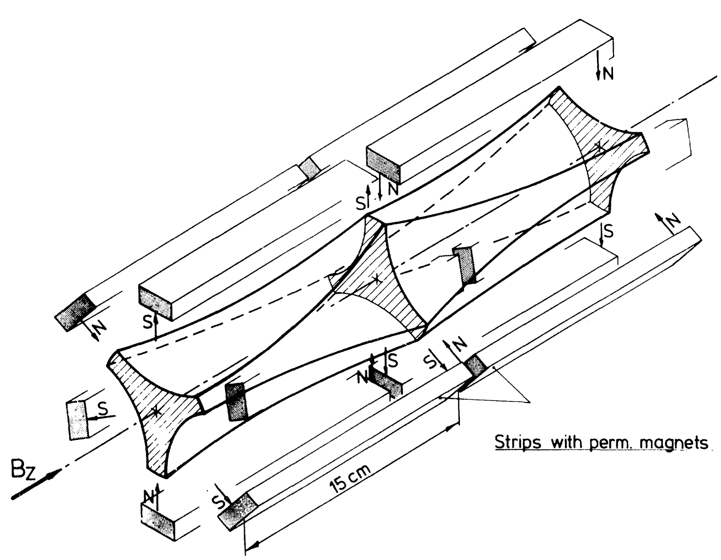

FIG. 1. Sketch of a section of the flux tube in the "skipping" B field. The field is generated by adding to a magnetic mirror field the transverse field of permanent magnets. Their polarity is periodically changed along the strip.

field. No measurements were done in different geometries.

Plasma properties.—The introduction of the "skipping" field affects the plasma properties in a twofold manner. Firstly, while the plasma is produced at electron cyclotron resonance, the different $\vec{B}(\vec{r})$ dependence changes strongly the coupling of the rf power into the plasma. Secondly, the skipping field influences the properties of the created plasma, such as fluctuation level and axial and radial density profiles. We give a phenomenological discussion of the coupling conditions and the plasma properties at a typical discharge condition.

We use helium gas with a pressure of 3.5×10^{-3} Torr and an rf power source of 60 W at a fixed frequency $\omega_{rf}/2\pi = 2.45$ GHz. We monitor both the microwave energy sent to the antenna as well as the energy reflected back. The difference between these is called the absorbed power P_{abs}. The Lisitano antenna, 10 cm in length, has axial slots and is positioned at the end of the homogeneous section in the axial field.

The plasma can be produced at field strengths around or below the resonant B-field value. The interval has a width of 15%. In Fig. 2 we give as a function of the B_z-field strength the absorbed microwave power, the ion saturation current, and its fluctuation level. The latter were measured with a Langmuir probe, situated in the middle of the homogeneous axial field section. The uncertainty in the absolute value of the B_z field is within 2%. We have expressed it in terms of the corresponding electron cyclotron frequency $\omega_{ce} = eB_z/m_e$. The B-field interval can be divided roughly into three regions.

I. $0.85 < \omega_{ce}/\omega_{rf} < 0.90$. In this region the power absorbed by the plasma is very low. About 5 W of the 64.5 W is coupled in. The plasma density is 4.5×10^{10} cm^{-3} at the center of the column. The fluctuation level in this region can be as low as 0.2%, at $\omega_{ce}/\omega_{rf} = 0.85$. The density gradient along the axis, $\Delta n/n\Delta z$, is less than 2×10^{-3} cm^{-1} over 50 cm. In Fig. 3 we show the radial profiles of the density, electron temperature, and plasma potential determined by Langmuir-probe measurements. The absolute value of the density is obtained from the measured dispersion

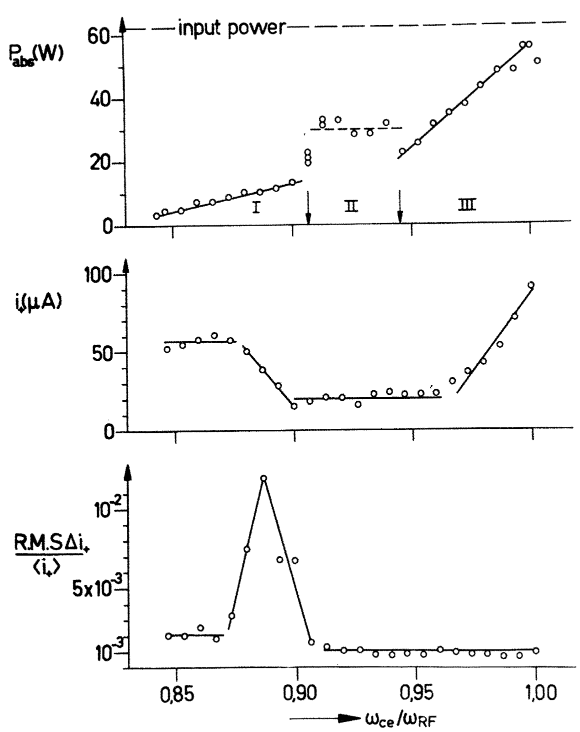

FIG. 2. Absorbed microwave power, ion saturation current, and the fluctuations in the ion saturation current are shown as a function of the B_z-field value, expressed in ω_{ce}/ω_{rf}.

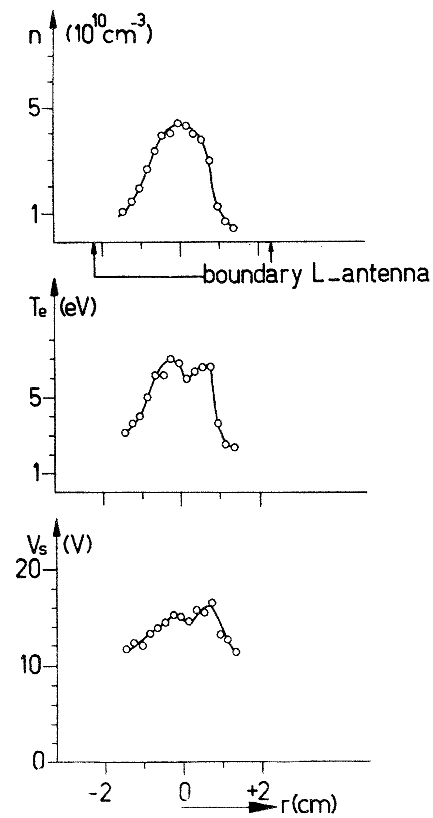

FIG. 3. Radial distributions of plasma density, electron temperature, and space potential are shown at a typical discharge condition: He gas at a pressure of 3.5×10^{-3} Torr, rf power 60 W, magnetic field value such that $\omega_{ce}/\omega_{rf} = 0.85$.

characteristic of the longitudinal electrostatic plasma wave.[9] Remarkable in this case is that the column has shrunk to a half-width of 2 cm, in contrast to regions II and III where the internal diameter of the antenna (4.5 cm) determines the boundary of the column.

II. $0.90 < \omega_{ce}/\omega_{rf} < 0.95$. The discharge can be started only in this region. About half of the input power is absorbed. The density is relatively low and the fluctuation level is lower than 0.2%.

III. $0.95 < \omega_{ce}/\omega_{rf} < 1.00$. In this region the absorbed power and the plasma density increase strongly with B_z. Up to 90% of the power is radiated into the plasma. The fluctuation level is 0.1%. Here we observe an axial inhomogeneity in the density distribution. At about 15 cm in front of the microwave source, the density has a maximum that is twice as large as the average value. Possibly plasma creation takes place primarily outside the source. Measurements by Lisitano, Fontanesi, and Bernabei[10] support this assumption. Their interferometer measurements on cyclotron waves excited by the antenna indicate that the waves first propagate along the column before they dissipate their energy by ionizing the gas.

The most important effect of the introduction of the skipping field is the quiescent state of the plasma. However, in contrast to the stabilization by the Joffe-type field there are in the frequency spectrum of the ion saturation current nearly always some instability peaks present between 5 and 40 kHz. These instabilities occur in localized areas and their frequency and amplitude vary as a function of B. At the transition of region I to region II of the B-field interval, at $\omega_{ce}/\omega_{rf} = 0.88$, the relatively high fluctuation level of 1.2% is found. This is due to a very coherent oscillation, with a frequency of 15 kHz.

Conclusion.—A remarkably quiescent plasma with an axially homogeneous density distribution is produced in an average minimum-B field configuration by an electron cyclotron resonance discharge. The plasma is more quiescent than the well-known alkali plasmas, while much higher electron temperatures (≈ 7 eV) can be reached and no restriction on the gas species exists. This should make the plasma very suitable for steady-state investigation of fundamental plasma properties, such as wave propagation and instabilities. However, the field geometry, which is of the average minimum-B type, will complicate theoretical analysis of these plasmas.

On the other hand, the field geometry is interesting because these types of complex magnetic fields are encountered in pulsed fusion experiments. The field geometry is essentially intermediate between a stellarator and a multipole configuration. Therefore, the special configuration described here can be used for the investigation under steady-state conditions of loss mechanisms related to the geometry of magnetic fields.[11]

The use of permanent magnets is limited to moderate field strengths and coercive forces (in our case they withstand axial fields up to 2.5 kG). They create, however, in a simple way complex static field configurations and can serve as cheap pilot experiments for devices operating with current-carrying conductors.

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