PARAMETRIC INSTABILITY OF A TOROIDAL HIGH-FREQUENCY DISCHARGE IN A MAGNETIC FIELD

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Submitted September 25, 1970

Zh. Eksp. Teor. Fiz. **60**, 1621–1626 (May, 1971)

The results are reported of experiments on a high-frequency discharge excited in a toroidal chamber in the presence of a magnetic field. The magnetohydrodynamic instability observed in these experiments takes the form of a parametric instability of the hf current in the longitudinal magnetic field. The experimental results are compared with calculations for an ideal magnetohydrodynamic model.

EXPERIMENTS with a toroidal discharge[1] have shown that, when the Shafranov-Kruskal criterion is violated, the stability of the quasiconstant current can be substantially improved by superimposing on the discharge an hf current with an angular frequency ω of the order of 10^7. This result enables us, among other things, to evaluate the possibility of using high-frequency methods in this frequency range to improve the stability and additional heating of plasma in toroidal traps in the Tokamak series.

Experiments performed recently were designed to elucidate the stabilization mechanism and to investigate the stability of the toroidal discharge both in the case of two components of the longitudinal current (quasiconstant and hf current) and in the case of a single hf current.

The principle of dynamic stabilization[2] was considered as a possible stabilization mechanism. The conclusion of Bobyrev and Fedyanin[3] that dynamic current stabilization of long-wave perturbation is possible would appear to provide a basis for this. The calculations reported in[4] for a single hf current in a longitudinal magnetic field and for the case of an hf and quasiconstant current have shown that the best stabilization conditions are achieved for the case of the single hf current. It follows that when the possibilities of dynamic stabilization are investigated, the case of a single hf current is of the greatest interest. In the present paper we discuss the results of a study of the hf current stability. The stability of a two-component discharge with an hf and a quasiconstant current will be considered in a separate publication.

The experiments were carried out on the Toloskop installation described in[1] in which a toroidal quartz discharge chamber (without internal diaphragms) is surrounded by a copper envelope with a minor radius $b = 3.75$ cm. The main chamber has a major radius of $R = 30$ cm and a minor radius of $a = 3$ cm. The copper envelope has a single transverse slot through which hf voltage exciting the high-frequency current in the plasma can be introduced (amplitude up to 10 kA, frequency 1.1 MHz, pulse length about 250 μsec). In addition, there is a single longitudinal slot which enables us to use the envelope as a single-turn solenoid for producing the quasiconstant magnetic field (up to 10 kOe). Let us consider some of the measured parameters of the plasma column for the following typical conditions: hf current amplitude 4 kA, magnetic field 1.5 kOe, initial hydrogen pressure 10^{-3} Torr. Figure 1d shows the hf current pulse. Figures 1a and 1b can be used to estimate the plasma density n as a function of time during the hf current pulse. Figure 1b shows the intensity of the radiation in the continuum at a wavelength of about 5700 Å in a band of about 50 Å. This range was chosen after preliminary photography of the spectrum after preliminary photography of the spectrum between 4000 and 7000 Å, using the ISP-51 spectrograph. The absence of line emission against the continuum background within the 50 Å band centered on 5700 Å enabled us to use it to determine the plasma density. A photomultiplier was used for a time sweep of the spectral region defined by the slit.

It is well known that the intensity of the continuum is proportional to $n^2T_e^{-1/2}$ and, in practice, the photomultiplier signal represents the time dependence of the density. This signal can be calibrated at the time of cutoff of the signal from the 2.26 mm interferometer as the plasma decays. The estimated density on the flat part of the hf pulse gives a value of 2×10^{14} cm^{-3}. The reflected 2.26-mm signal shown in Fig. 1c and the signal from the magnetic probe in Fig. 1e indicate that the plasma column exhibits oscillations (Fig. 1f shows the rectified magnetic probe signal illustrating the oscillations in the envelope of the hf signal from the magnetic probe which appear in Fig. 1e as a 10–20% modulation). A rough estimate of the fundamental frequency of these oscillations using the oscillograms in Figs. 1e and 1f gives a figure of about $\frac{1}{2}\omega$. Figures 1g and 1h show the low-frequency component of the diamagnetic probe signal and the intensity of the H_β line (sweep time in Figs. 1a–d is 500 μsec and in Figs. 1f–h it is 200 μsec). It is clear from these oscillograms that the plasma parameters show no appreciable variation after a period of a few μsec following the interaction of the high-frequency current, i.e., the stationary state is reached. At this time $n(T_e + T_i) \approx 8 \times 10^{14}$ and the plasma is highly ionized.

It is noted in[1] that the measured plasma diamagnetism, i.e., the quantity $n(T_e + T_i)$, increases linearly with increasing magnetic field H_z, but only up to a certain critical value (~ 1000 Oe), and then this increase essentially stops. It is shown in[5] that at this value of the magnetic field the current column begins to exhibit

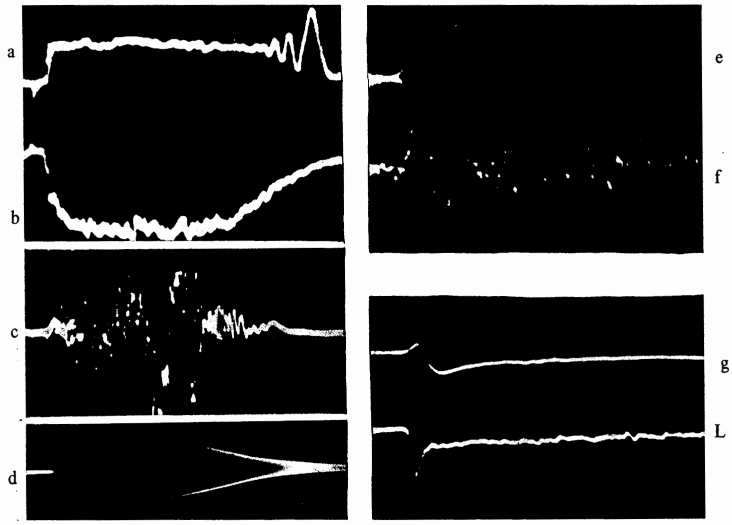

FIG. 1. a–Output of the 2.26-mm interferometer, b–intensity of the continuum between 5700 and 5750Å, c–reflected 2.26-mm signal, d–signal of the Rogowski loop measuring the current in the plasma, e–magnetic probe output, f–rectified magnetic probe output, g–low-frequency component of the diamagnetic probe, h–H_β. Time scale a–d 500 μsec, e–h 200 μsec.

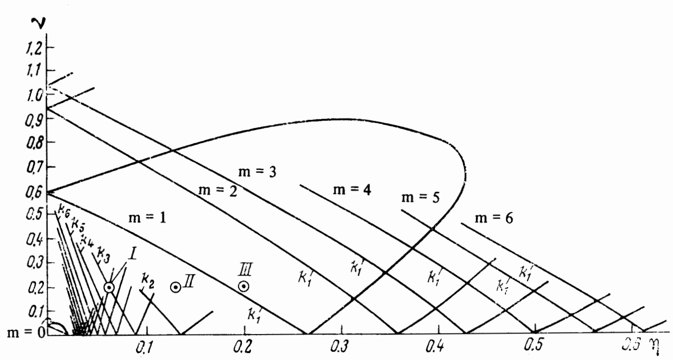

FIG. 2. Calculated boundaries of the instability regions: $\nu \equiv H_\varphi$, $\eta \equiv H_z$.

oscillations at a frequency equal to half the current frequency. The instability occurs in a broad range of fields (in our experiment up to 7000 Oe; no measurements were carried out at higher fields) and for initial neutral gas pressures in the chamber between 5×10^{-4} and 5×10^{-2} Torr. By analogy with[3,4] we calculated the regions of hf current instability for the parameters of the Toloskop installation and these calculations differed from those in[3,4] by the fact that the effect of the conducting envelope was taken into account. The calculations were performed for perturbations of the form

$$\xi(r) \sin(\tfrac{1}{2}n\omega t - \sigma) \exp i(m\varphi + kz + \gamma_n t)$$

using the coordinates

$$\nu = \frac{1}{\omega a}\frac{H_\varphi}{\sqrt{4\pi\rho}} \qquad \eta = \frac{1}{\omega R}\frac{H_z}{\sqrt{4\pi\rho}}$$

where H_φ is the field due to the current on the boundary of a plasma column of radius a.

Figure 2 shows the results of the calculation of the boundaries of the instability regions for n = 1, where parametric oscillations at frequency $\frac{1}{2}\omega$ should occur. Instability regions for a set of k_s are shown for m = 1 (the subscript s increases toward short-wave perturbations beginning with s = 1 which corresponds to long-wave perturbations). For m = 2, 3, ... the figure shows the boundaries of the instability regions only for the long-wave perturbation (k_1). For short-wave perturbations, the limits shift toward lower values of η by analogy with m = 1. The figure does not show the boundaries of the short-wave regions for m > 1 and not all regions for n > 1 are indicated. Bearing this in mind, we may conclude that for the ideal magnetohydrodynamic model of the plasma column the entire $\nu - \eta$ plane is covered with regions of parametric instability.

Let us consider in greater detail our experimental results on hf current instabilities. As indicated in[6], the instability was investigated by correlational processing of the results of measurements of oscillations in the position of the center of the hf current column. These oscillations were measured with pairs of magnetic probes connected in opposition and mounted at diametrically opposite points on the minor circle of the torus in the gap between the quartz chamber and the copper envelope. It is well known that the output of differential point probes depends not only on the axial component of the shift of the current column but also on the perpendicular component. The use of such probes complicates the analysis of measurement results. In our experiments we used probes similar to those described in[7]. They were in the form of two half-circles with a continuous winding. The winding density varied sinusoidally along the minor circle of the torus. It can be shown that when the two halves are connected in opposition the probe output is a measure of the axial shift along a line passing through points of maximum winding density.

In the field of the hf current column, whose center oscillates, the probe measures the amplitude-modulated hf signal. As already noted, analysis of these signals shows that they are amplitude-modulated at a frequency of about $\omega\frac{1}{2} = \omega/2$. The frequency $\omega\frac{1}{2}$ is more clearly defined when H_z = 1–2 kOe. To obtain more detailed information on the modulating signal we used a rectifying system in which the signal from each half-probe was detected separately, and the two were then subtracted using a differential amplifier. The detectors were connected in parallel and their loads were in the form of a filter with a cutoff just below ω. The output of the differential amplifier was proportional to the shift of the center of the current column and had both a constant and a variable component. Narrow-band filters were placed at the output of the differential amplifier in the case of

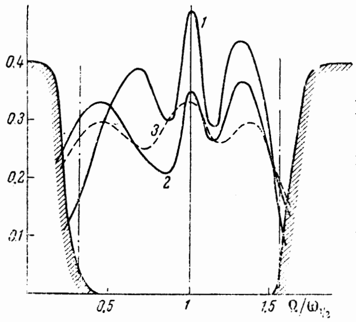

FIG. 3. Noise spectrum of the hf discharge (relative units) obtained by correlation analysis of magnetic probe output: 1—H_z = 1.5 kOe, 2—H_z = 4 kOe, 3—H_z = 6 kOe; $\Omega = \omega\frac{1}{2}$—frequency of paramagnetic instability.

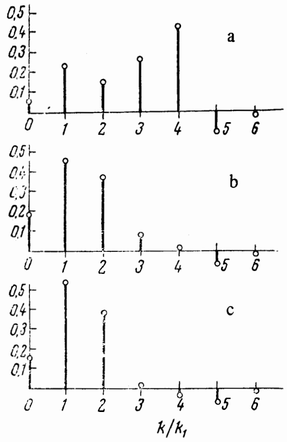

FIG. 4. Spectrum of spatial harmonics of the instabilities (relative units) with $\Omega = \omega\frac{1}{2}$ for different fields H_z: a—1 kOe, b—2 kOe, c—3 kOe.

fast oscillations of the center of the current column. The output signals were analyzed with the correlation receiver described in[6]. Correlation coefficients were obtained with a relative variance of 20%, and were used to construct self- and mutual-correlation functions (for probes distributed at different angular distances on the major circle of the torus).

Figure 3 shows the results of a Fourier analysis of the self-correlation functions for an hf current amplitude of 4 kA. The fields were H_z = 1.5, 4, and 6 kOe for curves 1, 2, and 3, respectively, and the initial pressure was 10^{-3} Torr. The figure also shows the passband of the filter (shaded). The vertical dot-dash lines define the region of reliable results of our analysis. It can be seen that the spectrum of instability frequencies Ω has three peaks of which the central peak corresponds to $\Omega = \omega\frac{1}{2}$.

When the frequency spectrum is investigated it must be remembered that the instability which we are studying has a nonstationary character, so that if we assume that the plasma column is excited at the parametric frequency then, clearly, it may come into contact with the chamber walls after a few oscillations. At the same time, the instability amplitude should vary with time, and this additional amplitude modulation, whose frequency is less than the parametric frequency, should lead to the appearance of side bands in the spectrum. These ideas seem good enough to explain the presence of the two relatively symmetric side peaks in the frequency spectrum of the instability.

Measurements of the mutual correlation coefficients have shown that the perturbations have the form of a standing wave along the major circle of the torus. This conclusion follows from the fact that the maximum on the mutual correlation function found experimentally corresponds to zero delay for any angular separation between the probes. Our measurements have also shown that in one cross section of the torus there is no mutual correlation between the outputs of probes recording displacements in mutually perpendicular directions.

Figure 4 shows the results of a Fourier analysis of the mutual correlation functions obtained by using the narrow-band filter at the output of the differential amplifier with a passband of about $\frac{1}{2}\omega$ (passband at the 0.7—100 kHz level). The use of the narrow-band filter was forced on us by the fact that the analysis of the spectrum of characteristic wavelengths of the perturbations using broad-band filters (with the low-frequency cutoff at 100 kHz) showed that the zeroth component of the spectrum of spatial harmonics has an appreciable magnitude. The significance of this component will require additional discussion. However, it seems quite likely that the factors which determine its presence are short-period interactions between the plasma column (looked upon as an elastic ring) and the chamber wall, field inhomogeneities in the chamber (for example, those determined by the transverse slot in the copper envelope), and other agents unconnected with the parametric nature of the instabilities.

It is clear from Fig. 4 that as H_z decreases the instability shifts toward shorter wavelengths. Using the known and measured parameters of the plasma column (a, R, ω, H_z, $I_{\sim\,max}$, n), we can calculate ν and η corresponding to the experimental region in Fig. 2, and compare the instability wavelength data obtained after correlational analysis with the corresponding wavelengths of parametric instabilities.

It is clear from Fig. 4a (H_z = 1 kOe, point I in Fig. 2), Fig. 4b (2 kOe, point II in Fig. 2), and Fig. 4c (3 kOe, point III in Fig. 2) that there is good agreement between experiment and calculation. It is interesting to note that, as H_z decreases, the spectrum of spatial harmonics of the instability increases.

Our studies thus lead to the conclusion that the toroidal plasma column with an hf current in a longitudinal magnetic field is unstable under our experimental conditions, and that this instability has the parametric character.

We are indebted to V. F. Shanskiĭ for suggesting these measurements and for his help in the infrared, and to A. B. Berezin and B. V. Lyublin for help with the spectrometric measurements. We acknowledge the major contribution of V. L. Luk'yanov to the preparation of the 2-mm interferometer and of L. V. Duev in the preparation of the experiments. We are also greatly indebted to M. L. Levin, V. D. Shafranov, L. V. Dubov, S. M. Osovets, and M. G. Nikulin for valuable discussions.

[1] I. M. Roĭfe and M. A. Vasilevskiĭ, Plasma Physics and Controlled Nuclear Fusion Research, IAEA, Vienna, Vol. 2, 1969, p. 477.

[2] S. M. Osovets, Zh. Eksp. Teor. Fiz. 39, 311 (1960) [Sov. Phys.-JETP 12, 221 (1961)].

[3] N. A. Bobyrev and O. I. Fedyanin, Zh. Tekh. Fiz. 33,

1187 (1963) [Sov. Phys.-Tech. Phys. 8, 887 (1964)].
[4] M. G. Nikulin, Zh. Tekh. Fiz. 39, 2144 (1969) [Sov. Phys.-Tech. Phys. 14, 1618 (1970)].
[5] M. A. Vasilevskiĭ, I. M. Roĭfe, and E. V. Seredenko, Paper at Second Conference on Closed Systems, Dubná, 1969.
[6] M. A. Vasilevskiĭ, I. M. Roĭfe, V. A. Rodichkin, G. A. Serebrenyĭ, and A. M. Timonin, Paper A-4 at the Conference on Plasma Diagnostics, Sukhumi, 1970.
[7] A. Haberstich and P. R. Forman, LA-4075-MS, 1968, p. 18.

Translated by S. Chomet
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