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Abstract

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PHYSICS

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MAGNETIC SURFACES AND PLASMA CONFINEMENT

BY HELICAL FIELDS IN A STELLARATOR

WITH EXTERNAL INJECTION

(Presented by Academician L. A. Artsimovich, 23 IX 1964)

1. Studies of the behavior of plasma in helical magnetic fields in devices that have received the name stellarator have been carried out for more than 10 years (see, for example, ([1–3])). The main attention in these works was concentrated on ohmic heating of plasma created by a current. However, until now the stabilizing action of helical windings on currentless plasma had not been investigated, experimental studies of the existence of closed magnetic surfaces had not been carried out, and external injection of plasma had not been performed. All these questions were studied by us on a closed toroidal device with a two-pass helical field. The existence of magnetic surfaces in the absence of strong resonant perturbations was shown; the influence of resonant perturbations was investigated; plasma injection into the trap was carried out; and the stabilizing action of helical windings on currentless plasma was demonstrated.

2. The vacuum chamber of the device (major diameter 1200 mm, minor diameter 100 mm) is made of nonmagnetic stainless steel 2 mm thick. Around the chamber, along its entire length, there is placed a longitudinal-field winding and a winding creating a two-pass helical field. The magnetic fields are time-dependent. The rise time of the fields to the maximum value is 2.7 msec, and the decay time constant is 7 msec. The maximum value of the longitudinal field is 10,000 oersted. The parameter ε, equal to the ratio of the magnitude of the fundamental harmonic of the helical field to the magnitude of the longitudinal field, can be varied smoothly within the range $0.71 \div 0.33$. The pitch angle of the helical winding is $\sim 45°$. The

Fig. 1. Cross sections of magnetic surfaces at different values of the parameter ε. $a - \varepsilon = 0.40$; $b - \varepsilon = 0.37$; $c - \varepsilon = 0.39$.

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windings are powered from a capacitor bank (stored energy 450 kJ). The chamber is equipped with a number of ports used for pumping, plasma injection, and diagnostics.

3. As is known, in stellarator fields, in the absence of strong perturbations, there should exist closed magnetic surfaces formed by a field line as a result of the transformation of the rotation upon its multiple passage around the torus. At a certain value of the rotational transform angle, the field lines of a given surface close upon themselves after some number of turns. Under these conditions, the presence of perturbing fields may lead to a resonant (the spatial structure of the perturbation coincides with the structure of the unperturbed surface) distortion of the surfaces, in particular to their splitting, the formation of rosettes, and, in the case of very strong perturbations, to complete destruction. To verify the fact of the existence of the surfaces, their shape, and to investigate resonances, detailed measurements were undertaken. The measurements were made with the aid of a pulsed (pulse duration ~ 3 μsec) electron gun and a small probe measuring 3×3 mm^{2}*, which intercepted the electron beam at some

* It could be assumed that, with such dimensions of the probe, one may neglect the size of the Larmor radius of the electrons, which was $6 \cdot 10^{-2}$ mm, and consider that the electrons move exactly along the magnetic field lines.

turn after its injection. The coordinates of the probe in which it registered the electrons for a given gun coordinate determine the shape and coordinates of the magnetic surfaces, while the moment at which the signal appeared at the probe determines the number of turns made by the beam. The coordinates and the number of turns make it possible to determine the mean angle of the rotational transform. With the aid of a signal electrode, the lifetime of the electrons on the given magnetic surface was recorded. In the absence of resonances the electron beam made more than 200 turns, its lifetime being determined by electron losses at the gun.

Fig. 1. Cross sections of magnetic surfaces at different values of the parameter ε.
$a - \varepsilon = 0.40$; $b - \varepsilon = 0.37$; $c - \varepsilon = 0.39$.

Figure 1 gives, by way of example, magnetic surfaces at different values of ε, measured with the aid of a probe. In Fig. 1a two unperturbed magnetic surfaces are shown for $\varepsilon = 0.40$; in Fig. 1b an example is given of a resonant perturbation at a second-order resonance and the outer unperturbed surface; and in Fig. 1c the inner unperturbed surface and a third-order resonance are shown. At a first-order resonance (when the line of force closes after one turn), strong destruction of an entire group of magnetic surfaces was observed. As a result of the measurements it was established that, when a transverse magnetic field of intensity 40 Oe (1.3% of the magnitude of the longitudinal field) is applied along the entire length of the torus, the surface is displaced by 1.2 cm, in good agreement with the calculation.

Thus, the magnetic measurements confirmed the theoretical concepts developed in works (4–6) concerning the existence of magnetic surfaces and the influence of perturbations in resonant and nonresonant cases.

4. Among the main questions arising in the study of a stellarator with external injection are such questions as the introduction of plasma into the volume of the vacuum chamber, the process of filling the chamber, and the influence of the helical magnetic field on the distribution of plasma in the chamber cross section and on its confinement time. To obtain preliminary results on these basic questions, the following injection method was used in the installation. In one of the cross-sectional planes of the vacuum chamber, four spark plasma injectors were installed, which operated simultaneously for 0.4 μsec. When several injectors operated simultaneously, the plasma jets interacted with one another in such a way that the plasma spread mainly along the magnetic field. Measurements of the plasma density and of its radial distribution were made with a double probe. The guns operated after an adjustable time interval following the beginning of the magnetic-field cycle. Usually the delay time was 500–800 μsec, which corresponded to injection into a field of 1500–2700 Oe*.

* During these measurements the maximum value of the longitudinal field was 5000 Oe.

The investigations carried out on the effectiveness of the plasma-injection method, based on the principle of interaction of plasma jets, showed that when two diametrically arranged guns are operated, the plasma density increases not by a factor of two but by a factor of 4 relative to the value of the density at the same instant of time and at the same place, but with one gun operating. Analysis of oscillograms of the current to a probe showed that the time required for establishment of a stationary density distribution over the chamber cross section* is in agreement with estimates and is of the order of R/v_{T}, where R is the major radius of the chamber and v_{T} is the ion thermal velocity.

Figure 2 gives plots of the instantaneous plasma distributions over the chamber cross section at different times after injection. Figure 2A shows the distribution in the presence of a helical field, and Fig. 2B the distribution for injection into a toroidal field ($\varepsilon = 0$). Comparison of the two distributions makes it possible to establish a substantial influence of the helical field. Indeed, if, in the presence of a helical field, the maximum value of the plasma density 80 μsec after injection is $1.2 \cdot 10^{11}$ cm^{-3}, then in the toroidal field the density is equal to $6 \cdot 10^{10}$ cm^{-3}. The time constants for the decay of the plasma density in the first case are

~ 700 μsec, and in the second no more than 200 μsec. Finally, in the presence of the helical field the plasma is separated from the walls and the distribution is symmetric with respect to the axis, whereas in the toroidal field the plasma touches the outer wall and the distribution is asymmetric.

Fig. 2. Density distribution along the diameter of the chamber for various times after injection. $T_e = 20$ eV. A –helical field, $\varepsilon = 0.39$; B –longitudinal field, $\varepsilon = 0$. a $-\Delta\tau = 80$ μsec, b –120 μsec, v –400 μsec, g –700 μsec.

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* Apparently, the plasma lifetime obtained from probe measurements is underestimated. One of the reasons reducing the lifetime is particle losses to the probe.

Note: Figure translations are in progress. See original paper for figures.