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Letters to the Editor

TRAPPING AND CONTAINMENT OF A TURBULENTLY HEATED PLASMA IN A MIRROR SYSTEM

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THE most difficult problem is experimental investigations of plasma containment in mirror systems is probably that of producing a hot plasma and trapping it. For instance, in the work of Post et al [1] the plasma was produced by the complicated method of multistage compression.

We have recently proposed and described a method of plasma heating (called turbulence heating) that allows rapid (approximately 10^{-7} sec) heating of plasma electrons to temperatures of the order of a kilovolt or higher. [2,3]

We describe experiments below in which the turbulence heating technique has been used to obtain a plasma with hot electrons in a magnetic mirror machine ("probkotron"). The distance between the mirrors is 60 cm. The stationary magnetic field varies from 0 to 1000 Oe; the mirror ratio is 5. A diagram of the experiment is shown in Fig. 1. A hydrogen plasma from a hydrogen-saturated titanium injector 1, which gives a cold plasma jet (T_e approximately 5 eV) with densities $2-5 \times 10^{13}$ cm^{-3}, is injected along the axis of the probkotron in a quartz tube 3, 3.6 cm in diameter, in which the pressure is 10^{-6} mm Hg. Turbulent heating of the plasma in the probkotron is realized by means of the low-Q oscillation circuit 4. A detailed description of the circuit and its operation can be found in [3]. The maximum amplitude of the radio-frequency magnetic field $H_\sim$ inside the circuit is 1200 Oe in the absence of plasma. The constant magnetic field is produced by coils 5 and the magnetic mirror field by coils 6. The plasma density is estimated by cutoff of 8 mm signals 7.

An idea of the plasma containment time in the probkotron can be obtained from the variation in plasma density and the emission of the He II 4686 Å line.

The efficiency of turbulent heating is reduced as the ratio $(H_0^2 + H_\sim^2)/H_\sim^2$ increases. On the other hand, for good plasma containment it is desirable

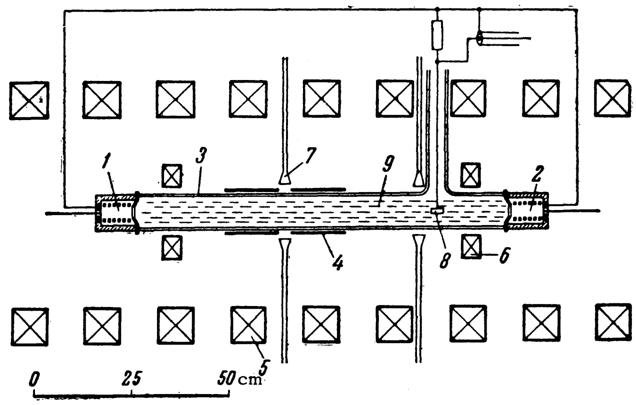

FIG. 1. Diagram of the experiment. 1, 2) plasma guns with hydrogen-saturated titanium electrodes, 3) quartz tube 3.6 cm in diameter, 4) radio-frequency circuit producing a magnetic field up to 1200 Oe at a frequency of 10 Mc, 5) coil for producing constant magnetic field, 6) mirror coils, 7) 8-mm measurement signal, 8) probe for measuring ion temperature, 9) plasma region from which light reaches the photoelectric monochromator.

to operate at high magnetic fields. In the experiment described here the constant magnetic field is approximately equal to the peak value of the variable field $H_0 \approx H_\sim$. Under these conditions, as a result of turbulent heating a unit volume of plasma can absorb approximately half of $H_\sim^2/8\pi$. Hence, the gas pressure nT_e of the heated plasma filling the probkotron should be comparable with the magnetic pressure $H_0^2/8\pi$.

In these experiments we measure the plasma containment time in the probkotron as a function of the delay in switching on the radio-frequency circuit with respect to the initiation of injection. The injector pulse is approximately 3—4 μsec in length. The density of the plasma filling the working volume changes in the course of time. At long delays, (greater than 5—10 μsec) the plasma density falls off with time. The containment time for a probkotron plasma containing hot electrons is taken to be the time required for the intensity of the He II line to be reduced by a factor of 2. In Fig. 2 we show typical oscillograms of the emission of the He II with the mirrors on and with the mirrors off. The intense emission of the line appears at the instant the radio-frequency electron-heating circuit is turned on. The results of an analysis of a large number of measurements of containment time are given in Fig. 3.

At a particle density of approximately 1.7×10^{13} cm^{-3} the plasma containment time in the probkotron is $t_c = 9.5$ μsec. If we substitute these values in the expression for the time required for plasma to escape from the probkotron by virtue of Coulomb collisions [4]

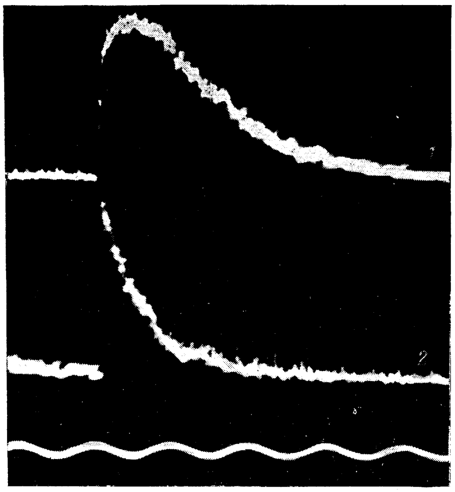

FIG. 2. Oscillograms showing the emission of the He II 4686 Å line (curve 1) with mirrors and (curve 2) without mirrors. Curve 2 is taken with a gain 3 times greater than curve No. 1. The period of the calibration signal is 10 μsec. The emission appears after the operation of the radio-frequency circuit (4, Fig. 1). The strength of the constant magnetic field H_0 = 600 Oe, the alternating field $H_\sim$ = 1200 Oe.

$$t_c = \sqrt{m}\,(|\ln\alpha| - 0.6)\,T^{3/2}/6.1\,le^4 n$$

(where e and m are the mass and charge of the electron, n is the plasma density, α is the mirror ratio and l is the Coulomb logarithm) we find that the experimentally determined value of t_c corresponds to an electron temperature T_e of approximately 420—650 eV. This temperature is in agreement with an estimate made on the basis of energy considerations. In turbulent heating we have $T_e \approx 0.5\,\xi H^2/8\pi n$ where $\xi = 0.5$ is a geometric factor given by the ratio of circuit length to the distance between mirrors. With a plasma density of 1.7

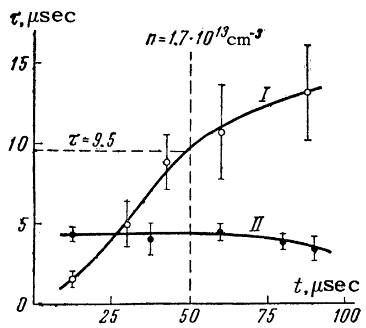

FIG. 3. The time τ for the emission of the He II line to be reduced by a factor of 2 as a function of the delay time t of the circuit with respect to the gun; with mirrors (curve 1) and without mirrors (curve 2). At a delay of 50 μsec the plasma density measured by cutoff of a signal at λ = 8 mm is found to be 1.7×10^{13} cm^{-3}. Under these conditions the containment time is 9.5 μsec. The strength of the constant magnetic field H_0 = 600 Oe, the strength of the alternating field $H_\sim$ = 1200 Oe.

$\times 10^{13}$ cm^{-3} and $H_\sim = 1.2 \times 10^3$ Oe the temperature T_e is approximately 530 eV.

The question arises as to why plasma loss due to a convective instability is not observed in the experiments. The time required for a convective instability to develop in the probkotron is of order $(MrL/T_e)^{1/2}$ (L is a length of the apparatus and r is the plasma radius); in the present experiments this quantity is 5×10^{-7} sec.

It is evident that the absence of anomalous loss is not due to the fact that the convective instability is inhibited as a consequence of the finite ion Larmor radius r_H or the fact that the lines of force are frozen in the ends of the apparatus. The first factor stabilizes the convective instability if $(r_H/r)^2 \gtrsim T_e r/T_i L$, a condition that is not satisfied in these experiments ($T_i \sim 5$ eV, $T_e \sim 500$ eV, $r_H/r \sim 0.3$, $r/L \sim 1/50$).

The force lines of the magnetic field are frozen in the metal discs at the end of the tube (injector elements). This freezing-in effect stabilizes the instability if $\pi^2 r/L \gtrsim 4\pi n T_e/H^2$ that is to say, if $\beta = 8\pi p/H^2 \lesssim 1/3$. For a fixed field of 600 Oe, a plasma density of 1.7×10^{13}, and an electron temperature t_e of approximately 500 eV (estimated from the containment time) the calculated value of β is approximately unity. It might be assumed that because of an instability the plasma pressure would fall to a value corresponding to stability in a time of 1 μsec. However, it is difficult to reconcile this assumption with the experimental results since the 8-mm density measurements show that there is no noticeable change in density during this time. If we assume that the temperature falls by a factor of 3—5 the remaining stable plasma should escape from the mirror by virtue of collisions in a time 5—10 times shorter than that indicated by the measurements.

Thus, the experiment indicates that the plasma is more stable than would be expected from theoretical estimates. The measured containment time for the plasma with hot electrons is approximately equal to the loss time calculated on the basis of Coulomb collisions. These experiments also furnish additional proof that the turbulence-heating technique is capable of heating electrons to high temperatures.

We wish to thank S. N. Popov for providing the plasma guns.

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PHOTOPRODUCTION OF NEUTRAL PIONS ON HYDROGEN AND DEUTERIUM AT LOW ANGLES

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THE previously described [1] experiments on the measurement of the ratio of the cross sections of the processes

$$\gamma + d \to \begin{cases} d + \pi^0 \\ n + p + \pi^0 \end{cases}, \qquad \gamma + p = p + \pi_0$$

in the near-threshold energy region were continued in the region of meson emission angles $\theta_\pi \sim 0°$.

Unlike the preceding experiments, we measured directly the differential cross section of these processes. The neutral pions were registered by the two decay gamma quanta using ordinary gamma telescopes, connected in a coincidence circuit. The efficiency of the telescopes was determined in a monochromatic high-energy photon beam [2]. The absolute measurements of the bremsstrahlung intensity were made with a quantometer [3].

The differential cross sections for the mean values of the primary photon energies κ and for the meson emission angle θ_π were determined as the ratio of the measured yield $Y(\alpha, \theta_1, \kappa)$ to the function determining the probability of registering the neutral pion. The latter is connected with the kinematics of the process, the characteristics of the apparatus and of the bremsstrahlung beam, and with the geometry of the experiment. Thus,

$$\frac{d\sigma}{d\Omega}(\bar{\varkappa}, \bar{\theta}_\pi) = Y(\alpha, \theta_1, \varkappa) \Big/ n \int_{\varkappa_{thr}}^{\varkappa_{max}} \int_{\Omega_\pi} N(\varkappa, \Omega_\pi) f(\varkappa)\, d\Omega_\pi\, d\varkappa; \quad (1)$$

here α and θ_1 are the angles which define the position of the telescopes, n is the number of nuclei per square centimeter of target, $f(\kappa)$ the bremsstrahlung spectrum, κ_{max} the maximum energy in the bremsstrahlung spectrum, κ_{thr} is the photon energy corresponding to the neutral-pion photoproduction threshold, and $N(\kappa, \Omega_\pi)$ the probability of registering a neutral pion emitted in a unit solid angle at an angle from θ to $\theta + \Delta\theta$ and produced by a photon with energy from κ to $\kappa + \Delta\kappa$. The average values of the energy κ and the cosine of the angle θ_π, to which the cross section pertained were calculated from the formulas

$$\bar{\varkappa} = \int_{\Omega_\pi} \varkappa N(\varkappa, \Omega_\pi)\, d\Omega_\pi \Big/ \int_{\Omega_\pi} N(\varkappa, \Omega_\pi)\, d\Omega_\pi,$$

$$\overline{\cos\theta_\pi} = \int_{\varkappa_{thr}}^{\varkappa_{max}} \cos\theta_\pi N(\varkappa, \Omega_\pi) f(\varkappa)\, d\varkappa \Big/ \int_{\varkappa_{thr}}^{\varkappa_{max}} N(\varkappa, \Omega_\pi) f(\varkappa)\, d\varkappa. \quad (2)$$

The integrals in the denominators of (1) and (2) determine, respectively, the probability of registration and the functions of the energy and angular resolution in the given experiment. These integrals are calculated analytically and by the Monte Carlo method on an electronic computer.

Table I lists the measured differential photoproduction cross sections of neutral pions on hydrogen and deuterium in the laboratory system. Only the statistical errors are indicated.

The measurement of the differential cross section for the angle $\theta_\pi \approx 90°$ was carried out by way of a control experiment. The cross section obtained therein for hydrogen agrees well with the results of other authors [4,5]. At the same time, the cross section for hydrogen in the angle region $\theta_\pi \sim 0°$, and also the ratio of the cross sections at angles close to 15° and 90° for $\kappa \approx 220$ MeV (second and fourth lines of the first column of Table I), clearly contradict the data obtained by Vasil'kov, Govorkov, and Gol'danskiĭ on the basis of an analysis of the experiment [4]. Our results

Table I. Differential cross sections for the photoproduction of neutral pions on hydrogen and deuterium

$\bar{\varkappa}$, MeV	$(d\sigma/d\Omega)_p$	$(d\sigma/d\Omega)_d$	$\overline{\cos\theta_\pi}$
	in 10^{-30} cm²/sr·photon·nucleus		
190	1.6 ± 0.2	5.0 ± 0.3	0.938
224	6.3 ± 0.3	15.3 ± 0.4	0.966
207	—	10.7 ± 0.4	0.063
218	5.5 ± 0.2	—	0.002