STABILITY OF A TURBULENTLY HEATED PLASMA DURING ADIABATIC COMPRESSION

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A turbulently heated plasma was compressed adiabatically by a magnetic field having a peak value 9 kOe and a half-period 2.5 msec. The plasma was found to be stable during both compression and expansion throughout the observation time ~2 msec. The electron temperature based on bremsstrahlung from within the plasma was ~30 keV at a density of ~2 $\times 10^{13}$ cm^{-3}. The upper limit of plasma drift velocity across the magnetic field was 2 m/sec.

1. INTRODUCTION

IN earlier work [1-5] we have shown that a strong electromagnetic wave propagating in a collision-free plasma across a magnetic field transfers irreversibly up to 30% of its energy to the plasma within a distance of the order of a wavelength. This dissipation of the wave energy (turbulent heating) is associated with the development of flow instability in the wave and raises the plasma temperature to

$$T_e + T_i = \xi H_{\sim}^2 / 8\pi k n, \quad (1)$$

when the condition

$$r \geqslant u_A / 4\nu, \quad (2)$$

is fulfilled, where T_e and T_i are the electron and ion temperatures after the wave has passed, $H_{\sim}$ is the magnetic field intensity of the wave, k is Boltzmann's constant, n is the number of charged particles per unit volume, ξ is an experimentally measured coefficient depending on $H_{\sim}/H$ and equal to ~0.3 for $H_{\sim} \approx H$, [1-5] H is the constant magnetic field, r is the plasma column radius, u_A is the Alfvén velocity, and ν is the frequency of the field $H_{\sim}$.

The experimental conditions govern the distribution of the energy received from the electromagnetic wave between the plasma electrons and ions after heating. [5] In the present work only the electron temperature was measured.

We note that (1) pertains to a plasma which is collision-free, at least during a time of the order of the $H_{\sim}$ oscillation period. However, following the passage of the wave the plasma in the trap remains collision-free during a considerably longer time, thus enabling continued heating of the plasma by adiabatic compression in a slowly increasing magnetic field H. [6] Adiabatic compression can occur successfully only when the plasma in the trap is sufficiently stable.

We describe here experiments on the adiabatic compression of a turbulently heated plasma, and investigate its stability, diffusion across a magnetic field, and bremsstrahlung.

2. EXPERIMENT

The experimental layout is sketched in Fig. 1. The magnetic field $H = H_m \sin \Omega t$ for adiabatic compression of the plasma was generated by a solenoid 7, 95 cm long and 30 cm in diameter,

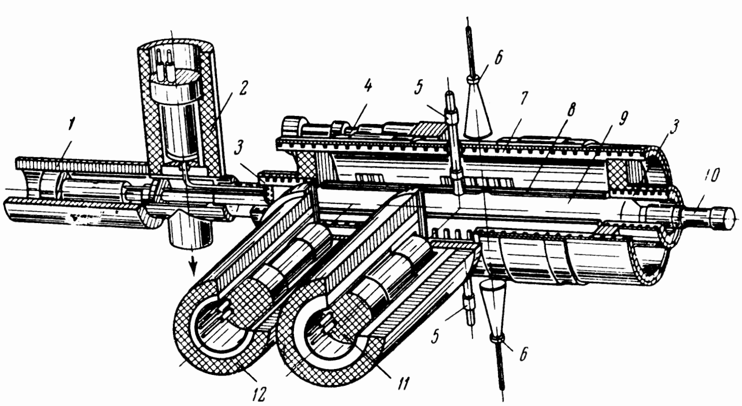

FIG. 1. Experimental apparatus. 1 – longitudinal x-ray probe along magnetic axis, 2 – longitudinal x-ray probe 1.5 cm from magnetic axis, 3 – coils producing the magnetic mirrors, 4 – monochromator with photomultiplier, 5 – ion probes, 6 – microwave probes, 7 – coil generating magnetic field for adiabatic compression, 8 – high-frequency shock circuit, 9 – vacuum chamber, 10 – plasma injector, 11 – scintillation counter with collimator, 12 – scintillation counter (monitor)

energized by a capacitor bank rated 0.014 F. The magnetic field rise time to maximum varied in the range 0.7—1.27 msec, and the field amplitude reached $H_m = 0.9 \times 10^4$ Oe. The mirror ratio was 2.

While H was in the interval $500 \leq H \leq 1500$ Oe, cold plasma having a concentration (1—5) $\times 10^{12}$ cm^{-3} from the plasma injector 10 made of titanium disks saturated with hydrogen or deuterium passed through the adjacent magnetic mirror into the glass chamber 9, which was 100 cm long and 8 cm in diameter. A strong cylindrical electromagnetic wave was then generated in the plasma by means of a low-Q shock circuit 8;[5] the amplitude of the hf magnetic wave was 600 Oe, with frequency $\nu = 10^7$ cps.

The plasma temperature rose sharply following the operation of the shock circuit, and adiabatic compression of the hot plasma was initiated. To measure the electron temperature we used the x-ray probe 1 and a CsI(Tl) crystal 0.5 cm in diameter with interchangeable 10—100μ aluminum foils; the probe was placed behind the magnetic mirror. This probe detected the bremsstrahlung from electrons passing behind the mirror and striking the aluminum foils covering the probe crystal. An identical probe 2, adjacent to probe 1, was displaced 1.5 cm from the chamber axis towards its wall. Probes 1 and 2 were used to observe the movement of the plasma boundary during adiabatic compression. The plasma concentration was evaluated from the cutoff of the 0.8-cm microwave signal and from the deexcitation time of the H_β line registered by the monochromator 4.

At one side, facing the middle of the mirror system, are located spectrometric scintillation counters 11 and 12 with 1000 and 400 cm^3 NaI(Tl) crystals, used to investigate the hard (40 keV upward) x rays emitted by the plasma through the 2-mm glass wall of the chamber. One of the counters (11) was equipped with a lead collimator for registering radiation from a selected small plasma volume located either on the axis of the plasma column or at the chamber wall. The second counter (12) was used to monitor the plasma radiation. Both counters were located 50 cm from the plasma, were equipped with lead diaphragms, and were sufficiently sensitive to register individual x-ray quanta on an oscillograph. The counters were calibrated for the range 30—110 keV by means of 49-keV radiation from a Cd^{161} compound, and for the range above 100 keV by means of 660-keV γ radiation from Cs^{137}. The counters provided 20% energy resolution.

Two identical probes were placed opposite each other in the central portion of the vacuum chamber 7 mm inside the interior wall. Each probe consisted of a collecting electrode 7 mm in diameter and a stainless steel electrostatic shield. The side of the shield facing the plasma was screened with a copper grid and was installed parallel to the magnetic lines of force. The distance between the collecting electrode and the grid varied from 0.5 to 10 mm in the different experiments. The shield was grounded on the plasma gun. The collecting electrode was struck mainly by ions moving with a Larmor radius exceeding that of the electrons. Special experiments showed that the electric fields of the plasma did not affect these probes 5.

3. RESULTS

We ascertained, first of all, that the magnetic compression of hydrogen plasma injected into the mirror system without shock heating could under no conditions result in an x-ray signal in a probe having the sensitivity of our probe 1. This presents no contradiction with the experimental results obtained by Post,[7,8] because in our measurements the adiabatic compression rate was almost one order of magnitude smaller than in [7]; therefore only an extremely small part (apparently < 1%) of the cold plasma was compressed by the field and no plasma bremsstrahlung was registered. With shock heating of the plasma, probe 1 continually registered powerful x radiation during a large part of the magnetic half-period. At the instant of greatest plasma compression the hardness of the radiation reached 8—10 keV, as measured by absorption in foils, with the magnetic compression factor $\alpha \approx 15$; therefore the initial electron temperature under adiabatic compression was $T_{e0} = 0.5—0.7$ keV. Measurements of the initial hydrogen plasma density before compression gave $n_0 = (2—5) \times 10^{12}$ cm^{-3}, but the microwave technique showed that in most instances soon after compression began the plasma density was at least 1.7×10^{13} cm^{-3}, which was maintained during most of the half-period of the compressing magnetic field. In the absence of a shock but with all other conditions unchanged, the plasma concentration was insufficient to cut off the 0.8-cm wavelength signal.

Figure 2 shows typical oscillograms of signals from probe 1 placed along the vacuum chamber axis. Figure 3a shows the signal from probe 2, 1.5 cm from the axis, and Fig. 3b shows the cutoff of the 0.8-cm wavelength signal.

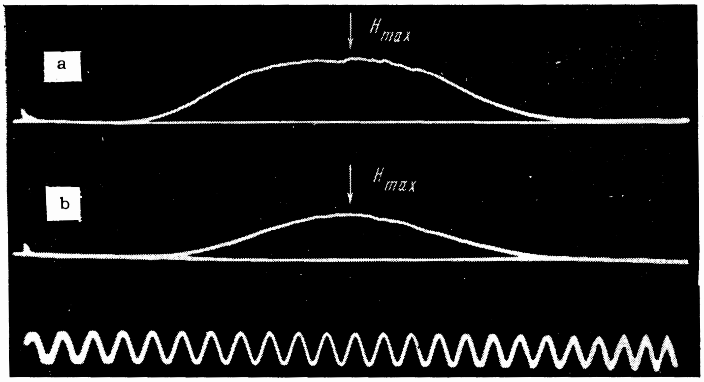

FIG. 2. Oscillograms of CsI(Tl) crystal luminescence induced by electron bremsstrahlung in aluminum foil of different thicknesses: a – 20 μ, b – 40 μ, Here and subsequently the sinusoidal period is 0.1 msec. The arrow indicates the magnetic field peak. The X-ray probe 1 is located along the axis of the vacuum tube containing the hydrogen plasma.

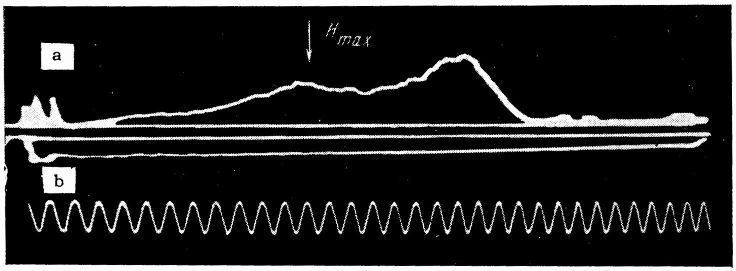

FIG. 3. Oscillograms of CsI(Tl) crystal luminescence induced by electron bremsstrahlung in 40-μ aluminum foil, and cutoff of 0.8-cm wavelength signal. The x-ray probe 2 was located 1.5 cm from the axis of the vacuum tube containing the hydrogen plasma.

Figure 4 is a photograph of luminescence from a thin CsI(Tl) crystal disk placed at the center of a magnetic mirror perpendicular to the pyrotron axis and covered with 20-μ aluminum foil on the side facing the plasma. This figure gives an idea of the relative diameters of the plasma cylinder and chamber in the middle of the trap. The chamber wall is shown with a correction for plasma compression in the mirror.

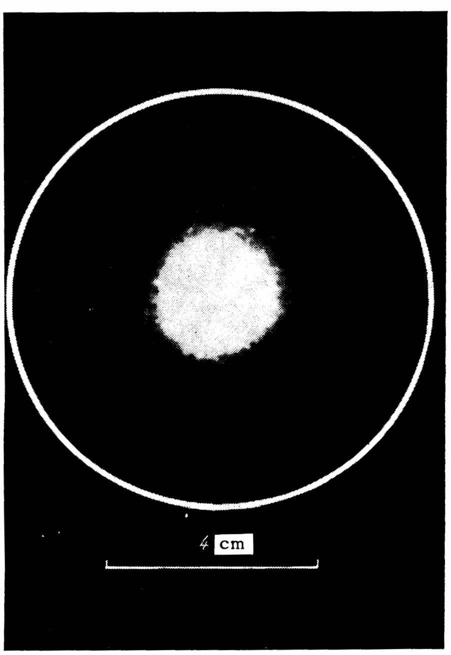

FIG. 4. Static photograph of luminescence in a thin disk of CsI(Tl) crystal located in a magnetic mirror and covered with 20-μ aluminum foil. The chamber wall is represented with a correction for compression of the hydrogen plasma in the mirror.

X-ray bremsstrahlung from the volume of the plasma was also investigated. To prove that the radiation originated in the volume, counter 11 was collimated and its readings were compared with those of counter 12, which served as a monitor. The number of bremsstrahlung quanta from the central region of the chamber was 15 times greater than from the region near the wall (when the collimator was located 3 cm above the axis of the system, the chamber radius being 4 cm).

Figure 5 is an oscillogram of the relatively soft x rays ($\sim$50 keV) from deuterium plasma when counter 11, equipped with a lead diaphragm, was shielded from the plasma by the chamber wall (2 mm of glass) and 1 mm of aluminum. This figure was used to plot the x-ray spectrum (Fig. 6) for two time intervals: a) $0 \le t \le 300$ μsec and b) $300 \le t \le 600$ μsec, when the magnetic field varied approximately linearly with time. The slope of the semilogarithmic spectrum in Fig. 7 corresponds to the electron temperature $\sim$30 keV.

Since the scintillation counter 12, which registered individual quanta, had a large aperture and was therefore highly sensitive to x rays from the chamber, we easily detected hard radiation (above 20 keV) during adiabatic compression of the deuterium plasma without shock heating. This radiation resulted from the adiabatic compression and containment of a small fraction of the high-energy electrons in the injected plasma. Since the plasma

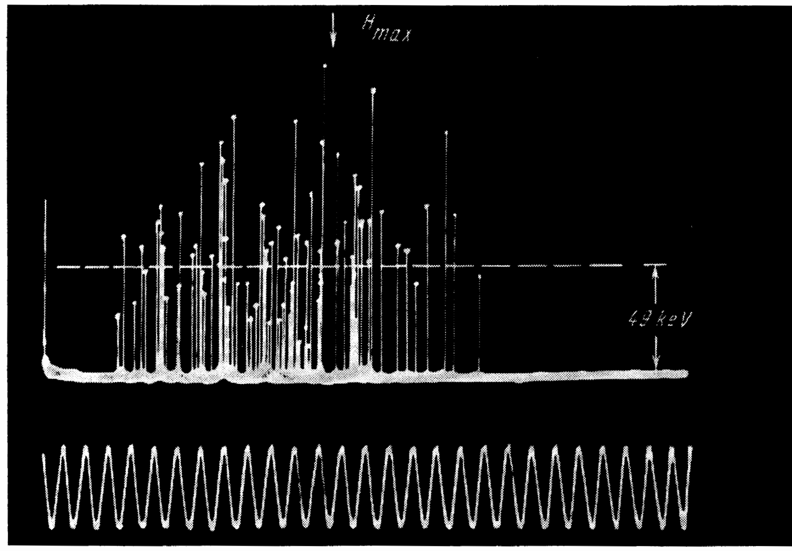

FIG. 5. Oscillogram of x rays from deuterium plasma, registered by scintillation counter 11 and a NaI(Tl) crystal. 49-keV γ rays from a Gd^{161} source were used to calibrate the radiation.

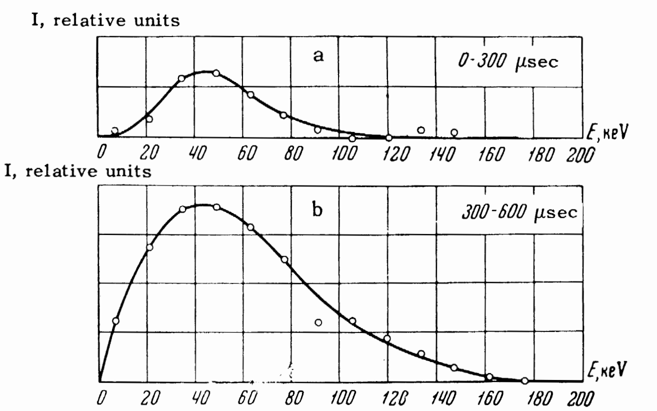

FIG. 6. Bremsstrahlung spectrum from deuterium plasma for two time intervals during magnetic compression: a) 0 – 300 μsec, b) 300 – 600 μsec. The spectrum represents the average of many measurements with counter 11. The sharp drop at low energies corresponds to x-ray absorption in the glass vacuum chamber wall and in 1 mm of aluminum covering counter 11, which exhibited 20% energy resolution.

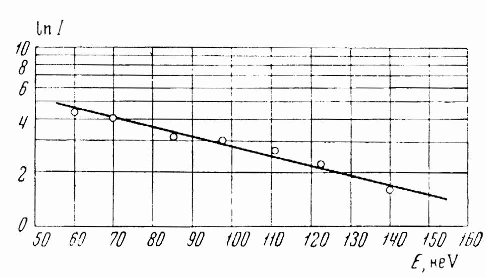

FIG. 7. Semilogarithmic spectrum of deuterium plasma bremsstrahlung during the time interval 300 – 600 μsec. The slope of the straight line corresponds to an electron temperature of 30 keV. This graph is based on oscillograms obtained with counter 11.

gun was operated with only a short lag after the quasi-static magnetic field began to increase, the compression factor for the hot-electron component of the plasma reached 50. It can therefore be assumed that before compression began the plasma could have contained electrons having energies of from one to several thousand electron volts. Electrons with these energies could be captured in the trap because the plasma gun was close to the midplane of the mirror; therefore the discharge current of the gun continued to flow through the plasma jet even when the plasma was moving inside the trap. The magnetic field of a bunch could be another cause of plasma capture.

It was interesting, independently of the foregoing, to determine how the high-energy electron content is increased by turbulent heating. For this purpose comparative measurements were made of the energy spectrum and intensity of plasma bremsstrahlung with and without shock heating.

Figure 8 shows typical oscillograms of radiation with and without turbulent heating. The difference lies in the fact that in the case of turbulent heating the crystal was covered with a lead diaphragm that reduced the flux reaching it by a factor of 50. When the oscillograms in Fig. 8,a and b, are compared it is seen that turbulent heating greatly enhances the intensity (by a factor of more than 50) and hardness of the bremsstrahlung.

4. DISCUSSION OF EXPERIMENTAL RESULTS

We shall first consider to what extent our measurements furnish evidence for adiabatic compression of a turbulently heated plasma. It is entirely obvious that we observed an increase of plasma electron energy with a growing magnetic field and a reduction with a decreasing field. This can be seen from the oscillograms in Fig. 2 which

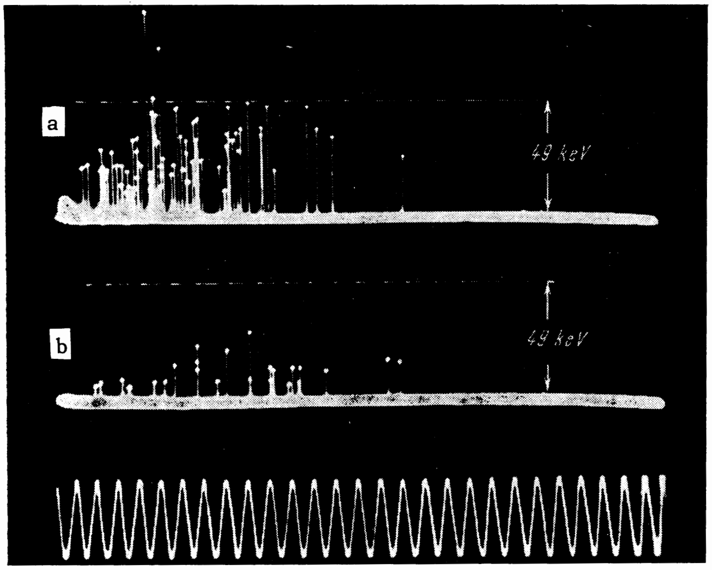

FIG. 8. Oscillograms of x rays from adiabatically compressed deuterium plasma: a – with turbulent heating, counter 11 being covered by a lead diaphragm; b – without turbulent heating, and with an unshielded crystal.

demonstrate with certainty the increased hardness of bremsstrahlung emitted by electrons leaving the mirror during the magnetic compression of the plasma. It is easily shown that the time dependence of the signal from probe 1 cannot be attributed to an increasing number of electrons leaving the pyrotron, but is associated with the exponential attenuation of bremsstrahlung in the absorber and the relatively slight variation of plasma density during adiabatic compression. For the same reason the oscillograms for probe 1 with filters of different thicknesses do not resemble each other (Fig. 2, a and b).

Adiabatic compression of the plasma is indicated by the symmetry of the curves about the magnetic field maximum (Fig. 2). With any appreciable escape of plasma from the trap or with cooling of the plasma during compression and expansion we could hardly expect symmetry in the readings from probe 1 about the magnetic field peak. We therefore have sufficient reason to claim that adiabatic compression was observed in our experiment. It must be remembered, however, that this conclusion is based on the measurement of bremsstrahlung in the region of a few keV. Obviously, the conditions for adiabatic compression might not be fulfilled in the case of electrons possessing low energies following turbulent heating. These electrons escape from the trap quickly without being registered by probe 1.

We shall estimate roughly the electron energy for which the conditions of adiabatic compression are fulfilled following turbulent heating. For these electrons the time required for escape from the trap must obviously be greater than the time required to double their energy as a result of magnetic compression. If t_0 is the instant of turbulent heating, then the magnetic field at this instant is $H_0 = H_m \sin \Omega t_0$, and the time t when the field H_0 has been doubled will be given by $t = 2t_0$ if $t_0 \ll 2\pi/\Omega$. For the time of electron containment in the trap because of Coulomb collisions we have

$$\tau \approx 10^9\, T_0^{3/2}/n \text{ sec} \tag{3}$$

(with T_0 given in keV); hence $T_0^{3/2} \geq 2 \times 10^{-9}\, nt_0$.

In our experiments $n \approx (2–5) \times 10^{12}$ cm^{-3} and $t_0 \approx (3–5) \times 10^{-5}$ sec; therefore, for the maximum values $n = 5 \times 10^{12}$ cm^{-3} and $t_0 = 4 \times 10^{-5}$ sec the initial electron energy for containment in the trap during adiabatic compression must be $T_0 \geq 0.34$ keV. This value of T_0 can be compared with the calculated temperature following turbulent heating. According to (1), taking $T_e \gg T_i$, $n = 5 \times 10^{12}$ cm^{-3}, $H_\sim = 6 \times 10^2$ Oe, and $\xi = 0.3$, we obtain $T_e \approx 0.6$ keV $> T_0$. It can thus be considered that a large part of the entire plasma prepared by turbulent heating was compressed adiabatically in the experiment.

It is interesting to note that the foregoing calculated initial temperature $T_e = 0.6$ keV with the compression factor $\alpha = 18$ gives a final temperature ~ 11 keV following compression; this is of the same order as the hydrogen plasma temperature measured by probe 1. Variation, from experiment to experiment, of the initial plasma density and of the instant of heating can, of course, greatly affect both the initial and final temperatures and even the electron energy distribution following compression, which can differ appreciably from the distribution obtained with turbulent heating.[5]

We must now point out that the readings of probe 1 depend on its distance from the axis of the magnetic trap. A comparison between Figs. 2 and 3 indicates that the symmetry of the curve in Fig. 2 is destroyed when the probe is shifted radially from the center; the oscillogram now exhibits a minimum. The experiment showed that with increasing distance of probe 1 from the magnetic axis the minimum of the curve in Fig. 3 approaches the start of the sweep, and the second peak becomes higher than the first. These effects are easily accounted for by motion of the outer plasma boundary during compression of the column by the magnetic field. Indeed, electrons which as a result of Coulomb collisions travel behind the mirror move within the latter practically along the same lines of force as in the trap, because the Larmor radius of the electrons is not greater than 0.1 cm. Therefore the probe registers electrons leaving the plasma layer which at a given instant is located on the magnetic lines passing through the probe. Thus if the probe is located somewhat closer to the axis of the trap than the outer plasma boundary, at some time after the initiation of compression the probe readings will drop to a minimum but will increase again during the expansion phase of the plasma column (Fig. 3).

The different heights of the peaks in Fig. 3 can be accounted for by increased escape of electrons from the lateral surface of the plasma through the mirror due to increased charged particle concentration in the thin surface layer of the plasma. This increase is associated with the ionization of neutrals proceeding from the walls into the interior. It can easily be shown that with $n \approx 2 \times 10^{13}$ cm^{-3} and about 1 keV electron temperature neutrals cannot penetrate more than 0.1—0.3 cm into the plasma. Neutrals pass into the plasma from the walls during the entire time of magnetic field rise and decline; therefore the plasma surface layer concentration increases to a limit at which equilibrium is established between the entrance and departure of particles through the mirrors and diffusion across the magnetic field. Therefore during the plasma compression phase the charged particle concentration must be smaller than during the expansion phase. This leads to a large escape of plasma through the mirrors during expansion, as is clearly shown by Fig. 3.

Finally, adiabatic compression is represented graphically by the oscillogram of scintillation counter 11 in Fig. 5 and by the curves in Fig. 6 for the short-wave bremsstrahlung spectrum of deuterium plasma. The emission spectra drop sharply at low energies because of absorption in the filter, but decrease slowly at high energies. The number of hard quanta increases with magnetic compression, as is to be expected for adiabatic compression.

Let us consider the bremsstrahlung spectrum of deuterium plasma in Fig. 6. This spectrum cannot be ascribed to emission by monoenergetic electrons. We know that in this case the intensity in a portion of the spectrum would be inversely proportional to the quantal energy, in sharp contrast with the measurements. However, if the energy distribution of the plasma electrons is Maxwellian (or nearly so), the slope of the straight line representing the logarithmic radiation intensity ($\ln I$) as a function of ϵ has the value ϵ/T. Figure 7 shows this dependence, based on the oscillograms from counter 11 for the time interval 300—600 μsec. The electron temperature $T_e \approx 30$ keV determined thereby is much higher for the deuterium plasma than the temperature determined for the hydrogen plasma from the bremsstrahlung of electrons escaping through the mirror. This result can be accounted for in two ways:

1) Mainly colder electrons leave the trap; their energy distribution should show a shift in the lower energy direction, while the hotter electrons remain in the trap.

2) In the case of turbulent heating the maximum attainable electron temperature is proportional to the ion mass, and will therefore be higher for deuterium plasma than for hydrogen plasma.

The measured electron temperature appears to be completely accounted for by the foregoing reasoning. We shall show that energy considerations confirm the possibility of strong plasma heating. For deuterium plasma condition (2) is fulfilled with plasma concentrations $n \geq 10^{12}$ cm^{-3}. Therefore, assuming $n = 12^{12}$ cm^{-3}, we obtain the initial electron temperature $T_e \approx 3$ keV, following turbulent heating, at $t = 5 \times 10^{-5}$ sec; at $t \approx 0.5$ msec this becomes ≈ 30 keV, which does not conflict with experiment. The value $n \approx 10^{12}$ cm^{-3} assumed here lies within the limits of n in the different experiments resulting from different working voltages and from injector instability.

Figure 4 illustrates the existence of a hot plasma filament in the pyrotron, located exactly along the magnetic axis of the system, at least in the mirrors. Since the CsI(Tl) crystal in this experiment was covered with 20-μ aluminum foil, the photographs show the plasma boundaries only at the time when compression had raised the electron temperature to at least 5 keV, when the filament radius should be about 1.5 cm.

From Figs. 2, 4, and 5, in conjunction with the fact that the 0.8-cm wavelength signal was cut off during the entire period of plasma compression and expansion, it follows that in our experiments the plasma filament was contained stably on the mirror-system axis. We were unable to register disintegration of the filament and the appearance of a plasma sheath at the wall, as was observed by Post[8] in a low-density plasma ($n \sim 10^{11}$ cm^{-3}) with high compression factors ($\alpha \sim 10^3$). The x-ray signals from probe 1, which are shown in Fig. 2, undoubtedly indicate high plasma stability during the entire period of compression and expansion. As already mentioned, in Fig. 2 the symmetry of the curve about the magnetic field maximum is especially interesting. If during compression and expansion plasma leaves the trap to an appreciable degree because of Coulomb collisions, anomalous diffusion, or any other reasons, the signal from the x-ray probe should not be symmetric about the magnetic field maximum. The signal from probe 1 actually exhibits some asymmetry, which can be attributed to plasma escape through the mirrors and across the magnetic field. We can thus estimate roughly the upper limit of plasma drift velocity $v_\perp$ across the magnetic field if we assume that the asymmetry of the x-ray curve results only from this cause. From oscillograms similar to those in Fig. 2 we obtain $v_\perp \leq 2 \times 10^2$ cm/sec. The actual value of $v_\perp$ is evidently much smaller; therefore the plasma escapes from the trap mainly through the mirrors, rather than across the magnetic field. This is also indicated by an estimate of the plasma containment time considering only the Coulomb collisions. Thus from (3) we can estimate the order of magnitude of the containment time of plasma electrons. If for the region of maximum compression of a hydrogen plasma we assume $T_e = 10$ keV and $n \approx 2 \times 10^{13}$ cm^{-3}, we have $\tau \approx 1.5$ msec. Since this is comparable with the period 2.5 msec of the magnetic field, plasma can escape through a magnetic mirror.

The plasma instability in our experiments is probably associated with the fact that the hot plasma is very dense and that the residual vacuum is about 10^{-6} mm Hg. The operation of the gun further impairs the vacuum. Therefore through ionization of the residual gas by hot electrons, outside the mirrors there existed a cold plasma which provided electrical contact of the hot plasma contained in the pyrotron with the metal parts of the injector at the end of the vessel. Under such conditions a current of particles drifting in an inhomogeneous magnetic field and causing flute instability can establish a closed circuit through the cold plasma and metal. Of course, the efficiency of this process depends on the plasma concentration and temperature between the mirror and the metal and on the condition of the metal surface. For the calculations that follow it was assumed that a good electrical contact exists between the cold plasma and the metal.

We shall now calculate the cold plasma density required to stabilize the flute instability. Radial displacement of the magnetic force tube with the plasma destroys the axial symmetry of the plasma. Therefore as a result of the azimuthal (φ) drift of particles in an inhomogeneous magnetic field a displaced force tube will be charged at the rate

$$\frac{\partial q}{dt} = -\int_{-L}^{L} \frac{e}{r} \frac{\partial n'}{\partial \varphi} (v_{0i} - v_{0e})\, ds(l)\, dl \approx ip \frac{c^2 (T_e + T_i)}{rH^2 \omega} \frac{dn_0}{dr} E_\varphi S, \qquad (4)$$

where q is the space charge of the tube, 2L is the distance between the mirrors, S is the cross section of the tube, $v_{0i,e}$ is the azimuthal drift velocity of particles in the pyrotron,

$$\mathbf{v}_{0i,e} \approx cT_{i,e}[\mathbf{H}\nabla H] / eH^3, \quad n' = i(cE_\varphi / \omega H)(dn_0 / dr) \qquad (5)$$

is the perturbation of plasma density, p and ω are the azimuthal number and frequency of the perturbation. If a cold plasma of concentration n_1 occupies the space between a mirror and the metal end plate these charges can be removed either completely or partially by currents flowing along the magnetic field through the cold plasma and through the metal. Consequently, for complete charge neutralization and for stability the cold plasma must be able to send a current larger than $\partial q/\partial t$ through the cross section of the given force tube.

In a cold plasma the current density along a line of force is related to the projection $E_{||}$ of the electric field on the force line as follows: $j_{||} = -e^2 n_1 E_{||}/i\omega m$. We neglect the effect of collisions on the current; this can be justified under our experimental conditions. Indeed, if it is assumed that the density of a cold plasma is three orders smaller than that of a hot plasma, i.e., $n_1 \sim 10^{10}$, and the cold plasma electron temperature is ~ 1 eV, the mean free electron path is $\sim 10^3$ cm, which very much exceeds the distance between the mirror and end metal ($l \sim 10$ cm). $E_{||}$ can afterwards be represented simply by E_φ, assuming an irrotational (curl E = 0) perturbed electric field outside the mirrors. In this case $E_{\parallel} \approx rE\varphi/pl$. The required condition of plasma stability $j_{\parallel}S > \partial q/\partial t$ can then be put into the form

$$\frac{n_1}{n_0} \gtrsim \frac{m}{M}\frac{\rho_H^2}{r^2}p^2\frac{l}{n_0}\frac{dn_0}{dr}, \quad \rho_H^2 = \frac{(T_e+T_i)Mc^2}{e^2H^2}. \qquad (6)$$

Since adiabatic compression does not change the value of ρ_H^2/r^2, this inequality is satisfied with increasing ease as the degree of compression is reduced. In our experiments at the instant of maximum compression $r < 2$ cm, $\rho_H < 1$ cm, and $l \sim 10$ cm. Therefore for stability of the perturbation $p = 1$ we require $n_1/n_0 \gtrsim m/M$. This condition is fulfilled in a vacuum not as good as 10^{-6} mm Hg and hot plasma concentration $n_0 \sim 10^{13}$.

The rotation of a turbulently heated plasma during adiabatic compression has been observed. In the present experiment readings were obtained simultaneously from probes 5 and 1. Figure 9 shows oscillograms of signals from ion probes 5; the plasma evidently rotates with a period ~ 100 μsec. Figures 9 and 2 indicate that this rotation does not result in anomalous plasma drift across the magnetic field. Spikes on the oscillograms of the current to probes 5 can be associated, for example, with the scattering of energetic ions on inhomogeneities of the cold plasma surrounding the hot plasma and rotating with the velocity $cEr/H \sim 10^6$ cm/sec. This would require a radial electric field ~ 100 V/cm in the plasma, which is entirely possible with $T_e \sim 10$ keV.

5. CONCLUSIONS

1. Turbulent heating in conjunction with adiabatic compression is an effective method of producing a dense high-temperature plasma with a relatively small compression factor.

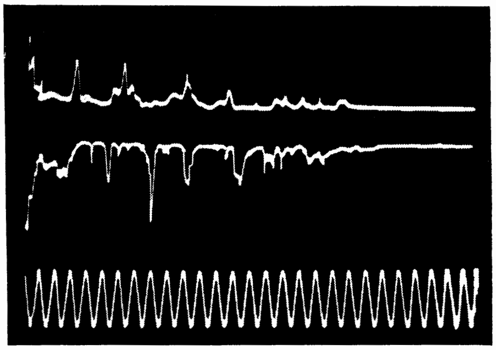

FIG. 9. Oscillograms from two ion probes 5 at the middle of the vacuum vessel. The periodicity of the peaks and their time discrepancy lead to information regarding the rotation of the plasma.

2. The experiments indicated complete stability of a dense high-temperature plasma in a mirror-system during ~ 2 msec. The hot plasma occupies a cylindrical volume that is coaxial with the magnetic field in the trap.

The stability of the plasma conflicts with the elementary theory of interchange instability in a mirror system, and probably results from the cold plasma that serves as a contact between the hot plasma and the ends of the trap. The amount of cold plasma obtained through ionization of the residual neutral gas by fast electrons appears to be sufficient to bring about stabilization.

3. The upper limit of hydrogen plasma velocity across the magnetic field is 2 m/sec, within experimental accuracy, for $T_e \approx 10$ keV and $n \approx 2 \times 10^{13}$ cm^{-3}.

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