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ACCELERATING AND CAPTURING ELECTRONS IN A MAGNETIC TRAP DURING ELECTRIC BREAKDOWN

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A number of preliminary experiments are described for injecting and compressing plasma bunches in a magnetic mirror trap. For high magnetic compression (initial magnetic field strength $H_{0z} = 50-100$ Oe, final magnetic field amplitude $\tilde{H}_{\max} = 12-15$ kOe) of a relatively rarefied plasma ($n_{e0} \approx 2 \times 10^{12}$ cm^{-3}), x-radiation with an energy of about 10 keV is observed to emerge from the trap. In special experiments, whose descriptions make up the bulk of this article, the plasma is magnetically compressed after a longitudinal current (along the lines of force of the magnetic field) with an amplitude up to 10 kA is passed through the plasma. In this case, during the time that the pulsed magnetic field was sustained (~300 μsec), hard x-radiation was observed ($W \approx 40$ keV) for weak magnetic compression ($H_{0e} = 1000-2000$ Oe, $\tilde{H}_{\max} = 5-10$ kOe). This radiation is completely absent at small magnetic compression factors when no longitudinal current is excited in the plasma. Magnetic probes were used to measure plasma heating caused by passing a longitudinal current through it. It was shown that the plasma was not heated essentially when a longitudinal current was passed through it and the observed x-radiation from the trap was due to accelerating and capturing a small number of fast electrons at the beginning of plasma-column breakdown. The concentration of fast electrons causing the observed hard x-radiation is less than 0.1–1% of the electron density in the cold dense plasma inside and outside the mirror trap.

THIS article describes experiments for injecting a plasma into a magnetic mirror and subsequently compressing it by an increasing magnetic field.

X-radiation from the trap, due to adiabatically heating the plasma electronic component, was observed in these experiments, which were similar to those of Perkins and Post[1] and Bariau et al.[2] However, the most experiments were performed for those conditions when breakdown of the plasma column in the longitudinal direction (the current was excited along the lines of force of the magnetic field) was initiated at the same time that the plasma was compressed. The experimental conditions were similar to those of Babykin et al.[3] for turbulent plasma heating. The sharp increase in the intensity of x-radiation from the trap observed in this series of experiments, may be due to the additional heating of a certain portion of plasma electrons as a result of the longitudinal current.

To ascertain the effectiveness of plasma heating and the number of fast electrons which are responsible for the hard x-radiation from the trap, we measured the plasma pressure with magnetic probes and performed experiments for different energy inputs to the plasma.

The experiments described were performed on the "Aspa"[1)] device, which constitutes a magnetic mirror intended for investigating thermonuclear fusion. Figure 1 shows a diagram of this device. It consists of a large solenoid (diameter 1 m, length 4 m) in which a quasistationary magnetic field with a strength up to 3 kOe and half period ~ 0.1 sec is created. A cylindrical vacuum chamber made of separate sections of stainless steel and glass is placed along the solenoid axis. The diameter of the glass section is 10 cm and its length is 1.5 m. A coaxial plasma injector was placed at one end of the chamber. Deuterium was used as the working gas in most of the experiments. Two coils producing a pulsed magnetic field of mirror configuration were placed over the glass tube. The coil spacing was 20 cm, the mirror ratio 1:2, the maximum field in the mirrors 25 kOe, the field rise time 40 μsec, and the field decay time 300 μsec.

In addition to these pulsed field coils, another pair of coils was placed over the glass tube and was connected in separate experiments in series with the basic solenoid circuit and created in the

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[1)] The term "Aspa" is an acronym for "adiabatic plasma compression."

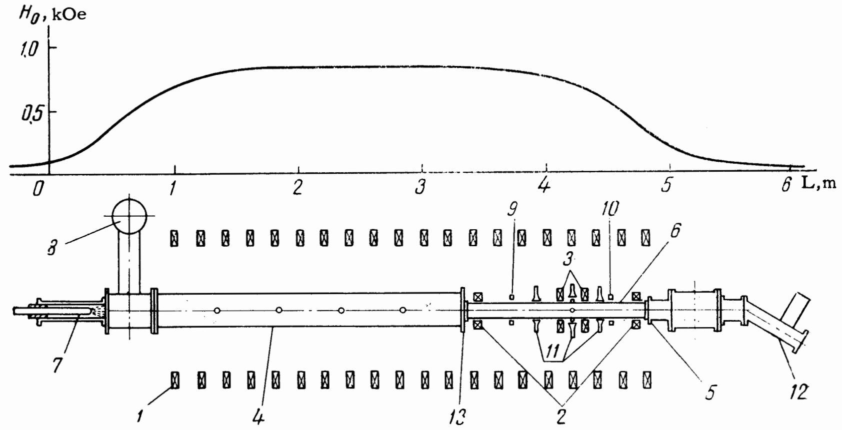

FIG. 1. Diagram of the "Aspa" device: 1 – master magnetic field solenoid; 2 – static magnetic trap coil; 3 – pulsed magnetic field coils (dynamic trap); 4 – metallic vacuum chamber; 5 – end flange on glass tube; 6 – glass tube; 7 – Marshall coaxial injector; 8 – vacuum oil-vapor diffusion pump; 9 – coil used to measure plasma diamagnetic field; 10 – Rogowski loop; 11 – microwave interferometer horns ($\lambda = 2.3$ mm); 12 – mass spectrometer; 13 – front end flange on glass tube. A graph of the master magnetic field strength at the solenoid axis is shown above ($V_{mas} = 800$ V, $C_{mas} = 1.5 \cdot 10^4$ μF).

glass-chamber region a quasistationary mirror field with mirror ratio 1:2. The mirrors were about 1.3 m apart.

The voltage from the capacitor bank could be applied to the metallic flanges at the ends of the glass tube to produce a longitudinal current with an amplitude up to 10 kA through the plasma injected into the glass chamber of the device. The switching time sequence for the basic units of the device was as follows: the quasistationary master magnetic field (H_{0Z}) with a strength of 50 to 2000 Oe was initially switched; at its maximum (40 msec) the Marshall coaxial injector began operating. The plasma jet was fed from the injector to the glass chamber, where the plasma was adiabatically compressed (20–60 μsec after the injector began operating). The longitudinal current jet to additionally preheat the injected plasma could be excited in the plasma simultaneously with application of the pulsed magnetic field compressing the plasma.

The initial density of the injected plasma in the region where the plasma was adiabatically compressed was 3×10^{12} to 5×10^{13} cm^{-3} in the majority of experiments described below and was measured with a microwave interferometer ($\lambda = 2.3$ mm). The initial quasistationary magnetic field varied from 100 to 800 Oe and the amplitude of the pulsed magnetic field compressing the plasma in the mirrors was constant and equal to 25 kOe in all experiments. The temperature of the injected plasma was estimated using magnetic probes and found to be 5 eV. Upon compressing the plasma adiabatically, hard x-radiation ($W > 20$ keV) from the mirror trap region was registered.

The soft x-radiation was naturally filtered out in most experiments by the glass wall of the chamber (3 mm thick) and by the shielding aluminum jacket (0.5 mm thick) on the NaI crystal. When simple adiabatic plasma compression was studied without longitudinal current, relatively soft x-radiation was registered (NaI crystal with beryllium foil, window in glass chamber covered with 20 μ mylar film), whose energy was roughly estimated by using aluminum filters at 5–10 keV.

Following strong adiabatic compression of the rarefied plasma ($H_{final}/H_{0Z} \approx 100$, $n_{e0} \le 10^{12}$ cm^{-3}, $T_{e0} \approx 5$ eV), soft ($W \approx 10$ keV) x rays were detected (Fig. 2), which emerged from the region where the plasma was compressed during the entire time when the pulsed magnetic field was maintained (~ 300 μsec). When longitudinal breakdown was produced ($C_{br} = 2\mu$F, $V_{br} = 2.5$ kV) at the same time as the pulsed magnetic field in the plasma ($n_{c0} = 10^{12} - 5 \times 10^{13}$ cm^{-3}, $T_{e0} \approx 5$ eV), a strong increase in intensity and hardness ($W > 20$ keV) of the x-radiation from the trap was observed, in complete agreement with the work of Babykin et al.[3] This x-radiation was registered even for very small magnetic compression factors $H_{final}/H_0 \lesssim 10$ during the entire lifetime of the strong pulsed field (i.e., 300 μsec).

We enumerate below the results of the basic experiments showing that the hard x-rays observed are due to the partial capture and heating of a small amount of fast "runaway" electrons during the adiabatic compression in the magnetic trap. These electrons are accelerated during the electric breakdown ("starter" x-radiation in a toroidal discharge, "starter" x-radiation in the Marshall gun, etc.). A characteristic feature of the experiments described is that such a breakdown of the ionized gas was initiated in the trap with mirror configuration of the magnetic field.

During the gas breakdown a small amount of the accelerated electrons may be captured by the trap and exist within it for a long time, determined essentially by the energy of these electrons and by

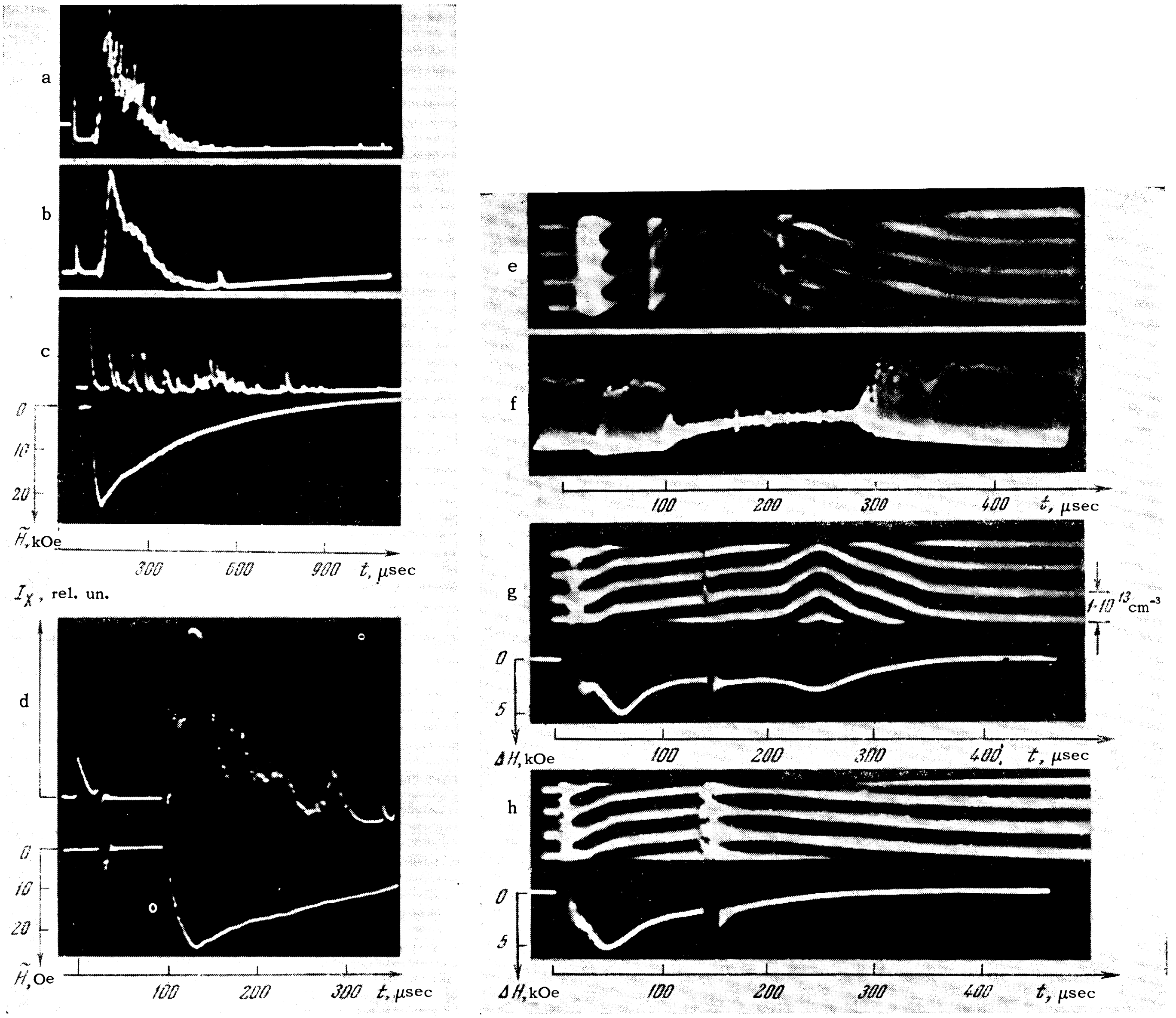

FIG. 2. a — x-rays from the plasma upon simple adiabatic compression, $\tilde{H}$ — pulsed magnetic field strength. $H_0 = 150$ Oe, $H_{final} = 12$ kOe, $R_{mir} = 1:2$, $n_{e0} \leqslant 2 \times 10^{12}$ cm^{-3}, $W_X = 10$ kV, working gas — deuterium; b — x-rays upon compressing a plasma with initiated breakdown. $H_0 = 560$ Oe, $H_{final} = 12$ kOe, $n_{e0} = 5 \times 10^{12}$ cm^{-3}, $W_X \geqslant 25$ kV, $C_{br} = 2$ μF, $V_{br} = 2.5$ kV; c — x-rays of Marshall-gun starter electrons captured in the trap. $H_0 = 720$ Oe, $H_{final} = 12$ kOe; d — x-rays upon plasma compression with initiated breakdown $H_0 = 720$ Oe, $H_{final} = 12$ kOe, $n_{e0} \approx 1 \times 10^{13}$ cm^{-3}, $W_X = 15$ kV, $C_{br} = 0.01$ μF, $V_{br} = 7$ kV; e — interference pattern ($\lambda = 2.3$ mm) of the density of a cold deuterium plasma ahead of the magnetic trap; f — cutoff of microwave signal ($\lambda = 2.3$ mm) when a longitudinal current is passed through the plasma, $C_{br} = 168$ μF, $V_{br} = 3$ kV, $I_{br} = 20$ kA, $H_0 = 560$ Oe, $n_{e0} \approx 1 \times 10^{13}$ cm^{-3} working gas — deuterium; g — oscillograms of the density and diamagnetic signal ΔH of the deuterium plasma jet. $H_0 = 720$ Oe, $n_{e0} \approx 10^{13}$ cm^{-3}, $T_{e0} \approx 3$ eV, $V_{br} = 0$; h — oscillograms of density and diamagnetic signal ΔH of the deuterium jet when a longitudinal current passes through the plasma. $H_0 = 720$ Oe, $n_{e0} \approx 10^{13}$ cm^{-3}, $T_{e0} \approx 3$ eV, $C_{br} = 0.1$ μF, $V_{br} = 7$ kV.

the plasma density, in spite of the fact that a main cold plasma with $T_{e0} \approx 5$ eV and $n_{e0} \approx 10^{13}$ cm^{-3} is present in the trap.

The following experimental facts support this conclusion.

1. The increase in the intensity and hardness of the x-radiation upon compression of a plasma heated by the direct-discharge current cannot be attributed to the preheating of the entire plasma, since magnetic probes do not show any significant increase in plasma jet temperature when a longitudinal current is passed through it. The diamagnetic signals observed in the experiments are responsible for the 10–15 eV increase in total plasma column temperature or the accumulation of a small number of hot 10–15 keV electrons in the plasma

(with a concentration less than 0.1–1% of the plasma-electron density).

2. During the entire adiabatic compression of the cold plasma jet, a dense low-temperature plasma is accumulated before the trap, (its duration, as measured by a 2-mm interferometer, is about 400 μsec, $n_e \approx 5 \times 10^{13}\,\mathrm{cm}^{-3}$, $T_e = 5$ eV), constituting a stopped tail section of the jet, enriched by a large amount of impurities and recombining at the walls of the glass chamber and inside the volume (continuous glow of the D_β line and of impurity atoms C I, C II, O I, etc. are observed). This dense cold plasma is continually in contact with the plasma in the trap but nevertheless does not affect the hard x-rays emerging from the trap for 200–300 μsec.

3. Control experiments with various values of capacitance discharged into the plasma jet and exciting a longitudinal current in the plasma showed the following: a) at a very low capacitor energy ($C_{br} = 0.01\,\mu$F, $V_{br} = 8$ kV, capacitance of the supply cables to the flanges $C_{cable} = 0.03\,\mu$F), which even under the most optimistic estimates barely suffices to heat all the plasma jet electrons by 1–2 eV ($N_{tot} \approx 10^{18}$ particles), stable hard x-radiation is observed for the entire lifetime of the pulsed magnetic field at small magnetic compression factors ($H_{final}/H_{0z} \approx 15$); b) for a high capacitor-bank energy ($C_{br} = 150\,\mu$F, $V_{br} = 3$ kV) and for small magnetic compression factors, hard x-radiation is also seen to exist for a long time; however, the density of the low-temperature plasma jet exceeds $2 \times 10^{14}\,\mathrm{cm}^{-3}$ for 200–300 μsec (owing to stronger gas desorption from the wall and its subsequent ionization).

4. When the pulsed magnetic field and the Marshall source are simultaneously switched on, starter electrons accelerated at the instant of breakdown in the Marshall gun are directly captured in the trap and exist there for a long time ($\sim$300 μsec) as observed by the hard x-ray bremsstrahlung. In these experiments no longitudinal current was excited, and accordingly $V_{br} = 0$. Naturally, these electrons have no relation to the x-rays observed upon compressing the plasma and initiating a longitudinal discharge, since both the plasma compression and the longitudinal-current excitation usually take place 30–200 μsec after the coaxial source begins to operate, when no accelerated electrons enter the magnetic trap from the Marshall gun.

5. When the longitudinal current and pulsed compression coils are switched on simultaneously, the intensity and duration of the hard x-rays do not depend on which part of the plasma jet is compressed (head, middle, or tail).

6. When the instants of initiating the breakdown in the jet in a uniform magnetic field and of the switching on of the pulsed magnetic field creating the mirror configuration of the magnetic field and subsequently compressing the plasma are more than 4–5 μsec apart, no hard x-rays are observed from the trap.

7. Control experiments were performed with jets of weakly-ionized argon (the Marshall source was fed from a cylinder with technical argon). This experiment was performed with the aim of explaining the function of impurities in the plasma during observed heating of the electronic component and capture of the fast electrons. The experiments showed that when longitudinal breakdown is excited in the argon plasma jet at the same time that the pulsed magnetic field compressing the argon plasma is switched on, long-lived ($\sim$300 μsec) hard x-rays are also observed.

The experiments performed make it possible to state that under the conditions described in this article (which are similar to the experimental conditions of Babykin et al.,[3, 4] a situation is perfectly feasible in which a dense cold plasma situated inside and outside the magnetic trap is basically only a medium in which various processes develop for dissipating the energy of a small group of electrons (with energies of 3.0 kV or more), confined and heated during compression in the magnetic trap.

We note that this article completely ignores the problem of the mechanism whereby the accelerated electron are captured in the trap. Apparently one of the most probable mechanisms for capturing electrons accelerated during the first stages of breakdown is the interaction of a beam of accelerated "runaway" electrons with the plasma,[5] although in principle other mechanisms for the appearance of a small amount of fast electrons in the trap are not excluded.[6] Thus, we can state that the hard x-rays observed from the trap are associated with the partial capture of a small amount of accelerated "starter" electrons or the heating of a small fraction of plasma electrons upon interaction of a beam of "starter" electrons with the plasma. We can characterize the efficacy of this capture by the fraction of fast electrons situated in the trap and corresponding to the observed hard x-ray radiation. The concentration of electrons with an energy $W \gtrsim 30$–40 keV is less than 0.1–1% of the density of cold plasma electrons in the magnetic trap.

At present, àn article is being prepared which is more detailed and represents more completely the experimental data. This article will be read at the Culham Conference on Plasma Physics.

In conclusion, the author takes the opportunity to express his appreciation to Academician I. K. Kikoin for his continuous interest.

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