SHOCK HEATING OF PLASMA IN A RAPIDLY INCREASING MAGNETIC FIELD

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The experimental excitation of intense collisionless shock waves ($M \geq 5$) with subsequent plasma compression by the magnetic field of a shock coil is described. A magnetic plug > 20 kOe is produced in $\approx 100 \times 10^{-9}$ sec by a current generator, a long line with 250-kV water insulation and a characteristic impedance of 1 Ω. At an initial deuterium-plasma density of $\approx 2 \times 10^{14}$ cm^{-3}, shock waves with a front width of $\approx 20c/\omega_{0e}$ and a velocity of $\approx 5 \times 10^7$ cm/sec are recorded. The ion energy after the accumulation, determined from the neutron yield, turns out to be $\gtrsim 2$ keV. Axial shock waves excited by the plasma flow beneath the shock coil are observed.

1. Studies of plasma heating by collisionless shock waves [1, 2] have shown a satisfactory agreement between the final ion energy and the assumptions and results of both the simplified "free-particle" model [3, 20] and the modified "snowball" theory of Sagdeev [4]. For θ-pinch systems, in which a magnetic plug is produced by the discharge of a capacitor bank into a single-turn coil, the final average transverse ion energy E_{r0} and the characteristic time t_c of the rapid-compression stage are for both models

$$E_{r0} \sim \frac{V}{R\sqrt{n}}\frac{1}{1+\lambda}, \quad t_c{}^2 \sim \frac{RlL_k\sqrt{n}}{V} \qquad \left(\lambda = \frac{L_a}{L_k}\right) \tag{1.1}$$
$$t_c \ll t_f = {}^1/_2\pi\sqrt{LC}$$

Here V is the voltage across the capacitor bank, R is the coil radius, n is the initial plasma density, λ is a ratio, L_a is the parasitic inductance, L_k is the coil inductance, l is the coil length, C is the bank capacitance, L is the total circuit inductance, and t_f is the rise time of the magnetic field. These expressions hold for a magnetic plug of infinitesimal thickness Δ. This is the reason for the identical dependences of the average energy and plasma compression time on the coil voltage and the linear charged particle density in both models.

Figure 1 shows experimental results obtained in 1966-1968 in experiments involving shock heating of a plasma (see Sec. 2 below and [5-15, 21]). For each of these studies, the directional energies E_{r0} calculated from Eq. (1.1) are plotted along the abscissa. The experimental points are along the ordinate. For comparison, the solid lines in this figure show the theoretical particle energies with an account of the possible dissipation of the directional energy. Five cases were treated:

1) where there is no dissipation

$$E_{r0} = E_r \qquad \text{(curve 1)}$$

2) where all the energy is in the random transverse and longitudinal motion,

$$E_{r0} = T_{i\perp} + {}^1/_2 T_{i\parallel}, \qquad T_{i\perp} = T_{i\parallel} = 0.67 E_{r0} E_{r0} \quad \text{(curve 2)}$$

3) where some of the energy corresponds to random motion,

$$E_{r0} = E_r + T_{i\perp} + {}^1/_2 T_{i\parallel}, \qquad E_r = T_{i\perp} = T_{i\parallel} = 0.4 E_{r0} \quad \text{(curve 3)}$$

Novosibirsk. Translated from Zhurnal Prikladnoi Mekhaniki i Teknicheskoi Fiziki, Vol. 11, No. 2, pp. 28–38, March-April, 1970. Original article submitted July 14, 1969.

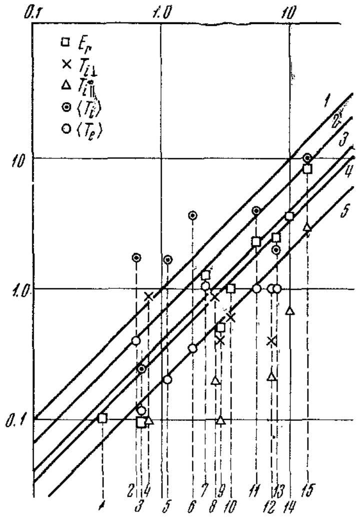

Fig. 1

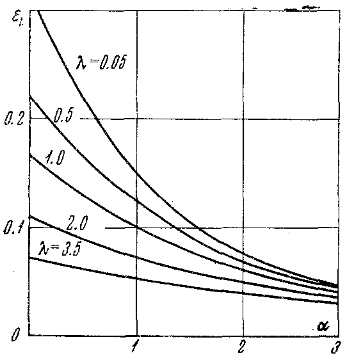

Fig. 2

Fig. 1. Comparison of theoretical and experimental energies of the plasma particles. The Mach numbers and references corresponding to the numbers at the bottom of the figure are: 1) 3 [5]; 2) 3 [6]; 3) 3 [7]; 4) 10 [8]; 5) [9]; 6) 3 [10]; 7) 3 [11]; 8) 2.6 [12]; 9) 10 [13]; 10) 5 [14]; 11) 3 [15]; 12) 3 [7]; 13) 5 (this study); 14) 3 [14]; 15) 4 [21].

Fig. 2. Calculated radial dependence of ε_l for various values of α and λ.

4) where electron heating is taken into account in a total energy redistribution,

$$E_{r0} = T_{i\perp} + T_{e\perp} + {}^1/_2 T_{i\parallel} + {}^1/_2 T_{e\parallel}$$

$$T_{i\perp} = T_{e\perp} = T_{i\parallel} = T_{e\parallel} = 0.33 E_{r0} \quad \text{(curve 4)}$$

5) where electron heating is taken into account in a partial energy redistribution,

$$E_{r0} = E_r + T_{i\perp} + T_{e\perp} + {}^1/_2 T_{i\parallel} + {}^1/_2 T_{e\parallel}$$

$$E_r = T_{i\perp} = T_{e\perp} = T_{i\parallel} = T_{e\parallel} = 0.2 E_{r0} \quad \text{(curve 5).}$$

Here E_r is the energy transverse to the magnetic field, $T_\perp$ and $T_\parallel$ are the random-motion temperatures in the transverse and longitudinal directions, $\langle T \rangle$ is the mean temperature at the end of the compression, and i and e correspond to ions and electrons. The best energy-transformation conditions for nuclear fusion are those corresponding to curves 4 and 5. As Fig. 1 shows, the available experimental data on the redistribution of directed compression energy in a θ-pinch generally differ from those of the optimum cases 4 and 5. The basic difference is that the directional energy E_r is almost always greater than the calculated values, while the longitudinal temperature $T_\parallel$ is always lower than the calculated values.

It follows from the Sagdeev theory [4] that when $M > 3$ the shock-wave front is governed by the ion viscosity and must have a characteristic dimension $\Delta \approx c/\omega_{0i}$ (ω_{0i} is the ion plasma frequency). In most experiments, we have $\Delta \approx$ 1-3 cm, and Δ makes up a significant part of the transverse dimension of the chamber. Apparently, it is just this finite width of the magnetic-perturbation front which disrupts the steady state of the propagating waves, resulting in a decrease in the threshold value of the longitudinal ion temperature and an incomplete randomization of the directed motion.

For $M < 3$, the condition for a steady-state shock wave was satisfied in most of the experiments, and the results of [7, 11, 15] are in satisfactory agreement with the Sagdeev results [4], showing a predominant heating of the electronic component of the plasma under these conditions. The greatest discrepancy between experiment and calculation is therefore observed when the critical Mach number is exceeded.

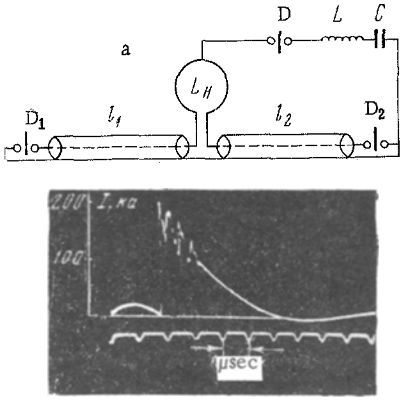

Fig. 3. a) Schematic diagram of the long-line current generator; b) oscillogram of the current I (in kA) in the coil.

The condition for a steady-state shock wave at large Mach numbers incorporates two physical aspects. The first is that the magnetic plug be infinitesimally thin:

$$\Delta \ll R \tag{1.2}$$

The second requirement is that the magnetic plug must be produced during a time less than the time required for a shock wave to propagate to the axis of the compression coil:

$$t_f \lesssim t_c \approx R/Mv_0 \tag{1.3}$$

where v_0 is the sound velocity in the unperturbed plasma.

This treatment thus shows that when conditions (1.2) and (1.3) hold, the energy of the plasma particles will increase with increasing voltage V of the current source.

To satisfy Eq. (1.2), we must start from the fact that the Sagdeev theory and experiment directly indicate an expansion of the wave front to $\Delta \approx c/\omega_{0i}$ as the Mach number increases. Satisfaction of the second condition (1.3), although of fundamental importance, is of a more technical than physical nature, related directly to the parameters of the power systems available. For typical experimental conditions, the compression time is of the order of $t_c \approx 10^{-7}$ sec. Equation (1.3) means that the current rise time in the coil must satisfy

$$t_f \lesssim 10^{-7} \text{ sec},$$

which is quite a strict technical requirement and which can be satisfied by decreasing the capacitance of the magnetic field oscillator [see (1.1)] and by increasing the oscillator working voltage V to several hundred kilovolts.

An apparatus with a brief magnetic field rise time t_f must transfer energy to the plasma highly efficiently. The efficiency η of a θ-pinch system satisfies the proportionality

$$\eta \sim (t_c/t_f)^2 \tag{1.4}$$

and is of the order of unity for $t_f \approx t_c$. For a high-energy storage bank, and thus for large t_f, the efficiency is low, $\approx 10^{-3}$.

It should be noted here that an increase in the magnetic field after the compression of the plasma cylinder should cause an adiabatic heating of the plasma. However, this stage itself has a low efficiency, not to mention several of the associated disadvantages (instability of the plasma with respect to penetration of the magnetic field into it during the shock heating, etc.). Figure 1 shows the maximum ion temperatures obtained by adiabatic compression in megajoule insulations [6, 9, 10]. It is not difficult to see that in insulations of lower energy (having $\approx$ 10kJ) but having a higher working voltage ($V \approx$ 200-300 kV) and a low magnetic-field rise time $t_f \approx 10^{-7}$ sec, the ion temperatures achieved exceed the ion energies at the end of adiabatic compression in megajoule insulations (see Fig. 1 and [15, 20, 21]).

The best storage devices for producing a cylindrical magnetic plug during a time of the order of 10^{-7} sec are evidently long-line systems, which can be used at high voltages. The current rise time in this case is given by

$$t_f \sim L_k/Z$$

where Z is the characteristic impedance of the line. As was shown by Vitovitsky [22], t_f may now be reduced to $\approx 10^{-8}$ sec at $Z \approx 1\ \Omega$. The steady-state condition (1.3) may thus be easily satisfied in this manner. The working voltage of a long line can be easily increased to $\approx$ 1000 kV, more than an order of magnitude greater than that of the best capacitor banks.

The equation describing the motion of a magnetic plug in the "free particle" model for a system with a long line is

$$\frac{d}{d\tau}\{[\lambda + 1 - y^2]\, y^{\cdot}\} = 1 - \alpha y^{\cdot} \tag{1.5}$$

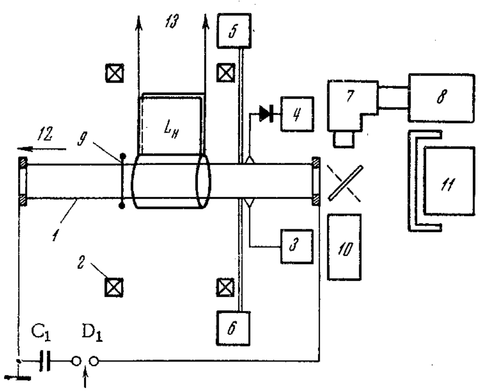

Fig. 4. Block diagram of the apparatus.

where

$$y^{\cdot} = |dy/d\tau|, \qquad \tau = t/t_c, \qquad y = a/R$$
$$\alpha = 2Zt_c/L_k = t_c/t_f \tag{1.6}$$

t_c is the characteristic compression time [from (1.1)], L_k is the inductance of the compression coil, and t is the time. The mean ion energy E at the end of the shock compression is

$$E = \frac{4m_i R^2 \varepsilon_l}{t_c^2} \qquad \left(\varepsilon_l = \int\limits_1^0 y^{\cdot 2} y\,dy\right) \tag{1.7}$$

or, when (1.6) is taken into account,

$$E = \frac{4m_i R^2}{t_f} \frac{\varepsilon_l}{\alpha^2} \tag{1.8}$$

Here m_i is the ion mass and ε_l is a dimensionless parameter proportional to the mean ion energy.

The parameter ε_l was calculated as a function of λ and α through a numerical solution of Eq. (1.7) in the approximation $t_c < t^*$ (t^* is the time required for the wave to pass along the line); the results are shown in Fig. 2. For $\lambda \ll 1$, the $\varepsilon_l(\alpha)$ dependence for $\alpha \gtrsim 1$ can be approximated by

$$\varepsilon_l \sim \alpha^{-1} \tag{1.9}$$

Substitution of Eq. (1.9) into (1.8) yields

$$E \sim \frac{4m_i R^2}{t_f^2} \frac{1}{\alpha^3} \tag{1.10}$$

Equation (1.10) shows that α must be reduced in order to increase the particle energy E for given t_f and R. However, the least permissible α satisfying condition (1.3) for steady-state shock waves is

$$\alpha \approx 1 \tag{1.11}$$

Using Eqs. (1.6), (1.9), and (1.11), we can write the efficiency

$$\eta = 2\varepsilon_l \alpha^2 L_k / L_l$$

as

$$\eta \approx t_c / t^* \tag{1.12}$$

where L_l is the inductance of the long line and t^* is the time required to pass along the line. For a flat line, this time is

$$t^* = \frac{8\pi W}{c\sqrt{\varepsilon}E^{*2}hd} \tag{1.13}$$

Here W is the energy stored in the long line, ε is the dielectric constant, E^* is the electric field intensity, and h and d are the line width and thickness. A simple estimate shows that an energy source with $W \approx 10$ kJ, a flat line with $\varepsilon \approx 100$ and $E^* \approx 10^6$ V/cm, connected to a single-turn coil $R \approx 5$ cm in radius, can heat a plasma with a density of 10^{14} cm^{-3} to thermonuclear temperatures.

2. The current generator, shown schematically in Fig. 3a, was used in experiments on shock heating of plasma in a rapidly increasing magnetic field. The generator is a 250-kV long line l_1, l_2, filled with water as a dielectric. Water is used because of its high dielectric constant, $\varepsilon \approx 80$, which permits the use of the comparativley small characteristic impedance $Z \approx 1$ ohm for a total system capacitance of $C \approx 0.2$ μF.

The generator load in these experiments is a single-turn coil (the shock coil) L_H, 7 cm in diameter and 10 cm long, connected to a gap in the high-voltage electrode in the middle of the line. The coil is insulated by a polyethylene film and by water. The line is charged to its maximum voltage in 2 μsec by means of a Marx oscillator (L, C, D in Fig. 3a). Two microseconds after the start of the charging, discharger D_1 is triggered externally and a 250-kV, 250-ka wave with a rise time of $\approx 50 \times 10^{-9}$ sec passes through the load, reaching discharger D_2, which is also short-circuited at this time. The oscillogram in Fig. 3b illustrates this line charging, the passage of the current wave through the load, and the result of the subsequent short-circuiting of discharger D_2.

The magnetic field at the coil axis increases during a time $t_f \approx 100 \cdot 10^{-9}$ sec to a maximum value of $H^* \approx 20$ kOe, than decreases, in correspondence with the current shape in the line, to $0.1\ H^*$ over a time of $\approx 4\ \mu$sec.

Figure 4 shows a block diagram of the experimental apparatus (arrow 12 indicates the direction of the pump, and arrow 13 indicates the direction of the current generator). The deuterium plasma was ionized and heated beforehand by a Z-pinch discharge (C_1 and D_1 in Fig. 4) in a glass chamber (1) 6 cm in diameter and 100 cm long, in a quasisteady-state magnetic field $H_0 = 0\text{–}1$ kOe (2 in Fig. 4).

The density n and electron temperature T_e of the preliminary plasma (working-pressure range of $p \approx 2\text{–}14$ mtorr) were determined by the following methods: 1) the density n was determined by microwave (3) probing at a wavelength of 0.4 cm; 2) the density n and the temperature T_e were determined from the attenuation of a beam of fast (10-keV) neutral hydrogen and helium atoms (5 and 6) [16]; 3) the density n was determined by an optical method – the Stark broadening of the D_β line (7 and 8);4) the quantity nT was determined with a diamagnetic probe (9). Figure 5 shows the time dependence of the density of the prelimenary plasma.

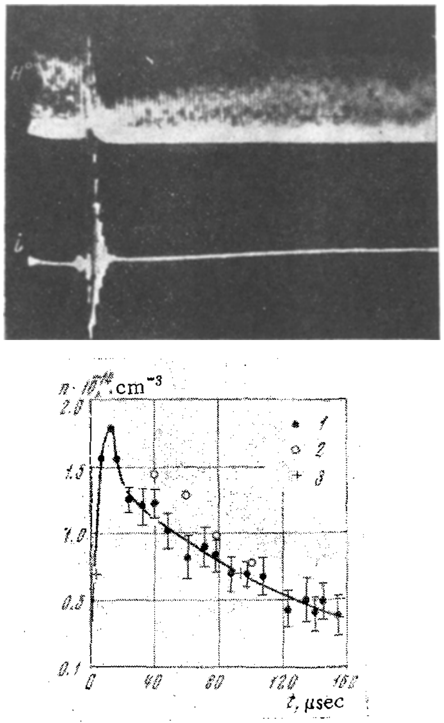

Fig. 5. Time dependence of the density of the preliminary plasma: 1) data from probing with beam H^0; 2) data from broadening of D_β Balmer line; 3) data from microwave probing; H_0) oscillogram of the attenuation of a beam of neutral hydrogen atoms; i) discharge current; V = 30 kV, $H_0 = 1$ kOe, and p = 3.3 mtorr. The discharge period is 2 μsec.

The transverse plasma-filament dimension, required for the calculation of nT for the plasma from the diamagnetic signals and for calculating the attenuation of the neutral beams, was determined by photography of a transverse aperture by an image converter (10). The shock-wave structure was studied and its velocity and the heating efficiency were measured at high Mach numbers by means of two magnetic probes 3 mm in diameter placed r = 0.5 cm and r = 2.5 cm from the chamber axis in the central plane of the coil and by high-speed photography by the image converter (10) and x-ray and neutron spectrometers* (11).

Figure 6 shows oscillograms from the two magnetic probes illustrating the shaping of the shock-wave front for "forward" (Fig. 6a) and "reverse" (Fig. 6b) polarities of the initial magnetic field $H_0 = 1$ kOe with $n = 2 \times 10^{14}$ cm^{-3}. These results show that the threshold Mach number in these experiments is

$$M = \frac{u}{v_{A0}} \approx 5,$$

where

$$v_{A0} = \frac{H_0}{\sqrt{4\pi n m_i}} \approx 10^7 \text{ cm/sec}$$

is the Alfven velocity in the unperturbed plasma, and u is the shock-wave velocity. As the shock wave arrives at the chamber axis, the alternating magnetic field H^* in the coil reaches 12 kOe. The significantly nonsteady-state nature of the wave shaping, due to the small transverse dimension of the chamber, hinders extraction of information about the width of the wave front.

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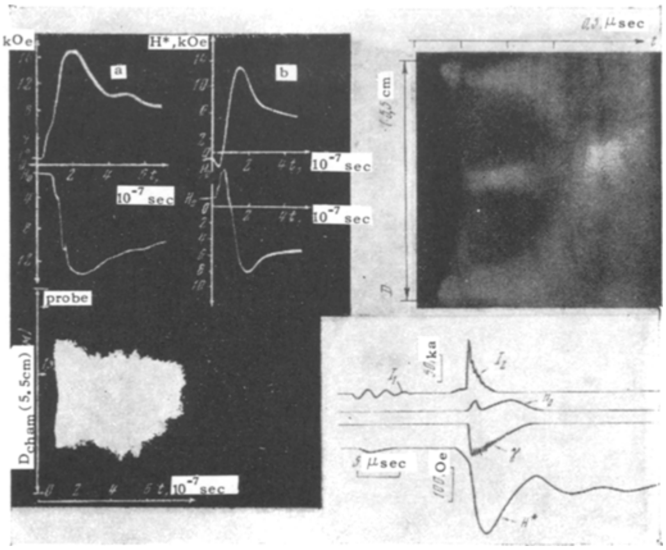
*The neutron spectrometer was developed by A. G. Ponomarenko and V. N. Stibunov, our collegues at the Institute of Nuclear Physics, Siberian Branch, AS USSR.



Figs. 6 and 7

Fig. 6. Shaping of the radial shock wave: a) $H^*\uparrow\uparrow H_0$. Below) Evolution of the luminous transverse dimension of the plasma obtained by the image converter; b) $\hat{H}^*\downarrow\uparrow \hat{H}_0$.

Fig. 7. Neutron and x-ray emission of the plasma upon passage of the shock wave: I_1) preliminary ionization current; I_2) current in shock coil; n^0) neutrons; γ) x-radiation; H^*) signal from magnetic probe 10 cm from coil. Above) photograph of transverse aperture beneath the shock wave, $H^*\uparrow\uparrow H_0$, $H_0 = 1$ kOe, $n = 2 \times 10^{14}$ cm^{-3}.

Some information can be found about the instant at which the wave passes through the peripheral probe. Under the assumption that the shock wave velocity is

$$u = \frac{H_0 + H^*}{2\sqrt{4\pi n m_i}}$$

we find from the oscillogram in Fig. 6 that the front width is ≈ 0.6 cm. Since the Mach number at this time is ≈ 3, this result is in agreement with the data of [2, 17, 18], in which the front width for M > 3 satisfied $\Delta \gg 10\, c/\omega_{0e}$. The probe near the chamber axis (r = 0.5 cm) detected a front of double structure with a less steep leading edge and a characteristic dimension of $\Delta \approx 20 c/\omega_{0e}$.

The shock-wave velocity, determined from the indications of the magnetic probes and the high-speed photography by the image converter tube of a transverse aperture in the coil, turned out to be ≈ 5×10^7 cm/sec, which corresponds to a Mach number of ≈ 5.

We also see from Fig. 6 that with the "backward" polarity of the initial field ($H^*\downarrow\uparrow H_0$), the shock wave intersecting the probe r = 0.5 cm from the axis has an amplitude of ≈ 5 kOe. These data can be used to evaluate the final dimension of the plasma filament, which is required to determine the ion energy from the neutron yield at the cumulation time.

The total number of neutrons detected at this time ($\Delta t \approx 10^{-6}$ sec) by a spectrometer operating in the single-pulse mode (calibrated with a neutron generator) turned out to be ≈ 10^7. Hence, we find the temperature of the deuterium ions to be ≥ 2 keV. The results of the electron-temperature measurements are still being treated; preliminary data obtained with a two-channel x-ray spectrometer yield $T_e \lesssim 1$ keV.

Figure 7 shows the neutron and x-ray emissions of the plasma upon passage of the shock wave ($H^*\uparrow\uparrow \bar{H}_0$) . The reason for the suppression of the second neutron peak has not yet been established; at this point we can suggest that it is due to an interaction of the heated plasma coming from beneath the coil with the preliminary plasma, which acts as target at the front of the shock wave propagating in the axial direction.

The plasma flow parallel to the magnetic field after the cumulation of the wave beneath the coil was studied. The image-converter study through the transverse aperture (Fig. 7) shows that the plasma filament was ≈ 1 cm in size at maximum compression, in agreement with the probe indications for the case $H^* \downarrow\uparrow H_0$.

Since the magnetic field in the shock coil was not of a corkscrew configuration, the heated plasma could freely flow in the axial direction. Figure 8 shows oscillograms of signals from a magnetic probe 10 cm from the edge of the shock coil; they show that the supersonic motion of the hot plasma $v \geq 2v_{A0}$ generates a magnetic perturbation having the form of a shock wave [19]. An estimate of the front width of this perturbation yields $\Delta \approx 5$ cm, equal to the transverse dimension of the chamber. This circumstance apparently placed an upper limit on the magnetic field excited.

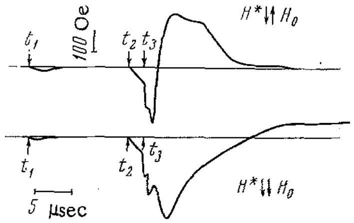


Fig. 8. Formation of a longitudinal shock wave: t_1) instant at which the preionization current is turned on; t_2, t_3) times at which the charging and operation of the lone are begun; $H_0 = 1$ kOe, $n = 2 \times 10^{14}$ cm^{-3}.

3. These results thus show that, in agreement with theory [4] for high Mach numbers, a shock wave forms in a collision with plasma, with a characteristic magnetic-perturbation front of $\Delta \approx 20c/\omega_{0e}$.

Because of the large value of $\lambda \approx 3.5$ in these experiments, it was not possible to use all the advantages of the energy storage device used, a long line with a low characteristic impedance. However, the plasma parameters acheived at the end of compression ($n \approx 2 \times 10^{14}$ cm^{-3}, $T_i \approx 2$ keV, $T_e \lesssim 1$ keV) (Fig. 1) show a satisfactory agreement between experimental and calculated ion energies.

A simple calculation shows that the actual efficiency of the system reaches $\eta \approx 1\%$ in this case for an initial stored energy of ≈ 2 kJ. It would be quite a simple matter to obtain in the very near future a ratio $L_a/l_k = \lambda \ll 1$, which should lead to an increase of η to 5% and an increase in the ion energy to $\gtrsim 10$ keV at $n = 2 \times 10^{14}$ cm^{-3}. To obtain ion energies of ≈ 10 keV during the first stage of rapid compression with ordinary θ-pinch devices with a capacitive storage bank, it would be necessary to have an initial stored energy of $\approx 10^6$ J.

We can conclude that there is a real possibility of using a superfast θ-pinch with a high-voltage line as a storage device for efficient plasma heating to thermonuclear temperatures during a time of $\approx 10^{-7}$ sec. Such a small time for transferring energy to the plasma ions and electrons from the external magnetic field is the basic reason for the optimism that no important macroscopic instabilities will develop during this time.

Further successful progress at ion energies in the range ≈ 10-100 keV will of course depend strongly on the extent to which the energy-dissipation mechanism at the front of superintense shock waves is understood and on the technological process toward producing high-voltage storage systems.

The authors thank G. I. Budker and R. Z. Sagdeev for formulating the problem, R. I. Soloukhin for interest in the study, and S. P. Shalamov for construction of the apparatus.

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