# Adiabatic compression of a toroidal plasma pinch by a magnetic field

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Adiabatic plasma compression was effected in a tokamak-type installation by rapidly increasing the toroidal field. The energy lifetime in the compressed plasma is four times longer than in ohmic heating. The compression is accompanied by an abrupt attenuation of the oscillations in the plasma.

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1. The installation "Tuman-2"[1] is a tokamak with a large radius $R = 40$ cm and with a diaphragm radius $a = 8$ cm. It is intended for the investigation of plasma compression following a rapid increase of the toroidal magnetic field.

The first experiments performed at low plasma parameters were described in[2]. The experiments described here were aimed at obtaining adiabatic heating and at a study of a compressed pinch at plasma parameters typical of tokamaks.

2. An improvement in the vacuum technology has made it possible to obtain a magnetohydrodynamically stable regime of ohmic heating. The largest current in the plasma for a stable regime was $I_p = 5$ kA at a toroidal magnetic field $H_{\theta_0} = 4$ kOe. This provides a stability margin $q(a) = 6$ at the edge of the diaphragm. The electron-temperature profile plotted on the basis of the spectral and laser measurements is well approximated by the parabola

$$T_e(r) = T_0[1 - (r^2/b^2)], \qquad b = 5\text{ cm}. \tag{1}$$

The profile is noticeably narrower than the opening in the diaphragm. It appears that this explains why $I_p = 5$ kA is the limit for $H_{\theta_0} = 4$ kOe. The laser measurements were performed at the center of the discharge chamber and yielded, with ohmic heating, an electron temperature $T_0 = 100–150$ eV. The temperature of the hydrogen ions, determined from the spectrum of the charge-exchange atoms, amounts to $T_i = 30$ eV.[3] The electron concentration at the center of the chamber, measured with a microwave interferometer ($\lambda = 4$ mm) and with a laser, amounts to $n_e = (6–8) \times 10^{12}$ cm$^{-3}$.

A calculation of the energy lifetime of the plasma and of the ratio of the gaskinetic pressure to the pressure of the toroidal magnetic field yields respectively $\tau_E = 150–200$ μsec and $\beta_I = 0.6$.

3. The compression was effected in the stationary stage of the discharge (Fig. 1). The toroidal field increased within 125 μsec from the initial value $H_{\theta_0} = 4$ kOe to the maximum value $H_{\theta_c} = 12$ kOe (the compression coefficient was $\alpha = H_{\theta_c}/H_{\theta_0} = 3$). The system of the toroidal-field coils was then short-circuited (clamping), and the field decreased with an approximate time constant 2 msec ($H_\theta$ is Fig. 1). The plasma current was maintained constant in this case ($I_p$ in Fig. 1). Special programming of the transverse field made it possible to retain the plasma pinch near the center of the chamber during the course of the compression.

An inductive spike appears on the voltage $U_p$ (Fig. 1), due to the decrease of the radius $a$. An analysis of the behavior $U_p$ during compression shows that the narrowing of the current-carrying channel corresponds to the condition of the "freezing-in" of the plasma in the magnetic field: $a^2(t) \sim [H_\theta(t)]^{-1}$.

Curve 2 of Fig. 2 shows the ratio of the plasma con-

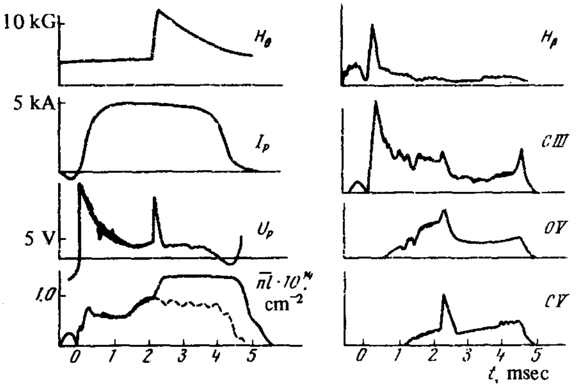

FIG. 1.

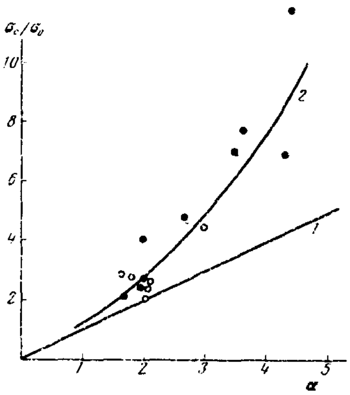

FIG. 2. □—$I_p$ = 1.8 kA, ●—$I_p$ = 3.6 kA, ○—$I_p$ = 5 kA.

ductivity before compression ($\sigma_0$) and immediately after compression ($\sigma_c$) at different values of $\alpha$. Curve 1 of the same figure shows the variation of $\sigma_c/\sigma_0$ corresponding to the adiabatic law ($\sigma_c/\sigma_0 = \alpha$). We see that $\sigma_c/\sigma_0$ is always larger than $\alpha$, indicating additional heating of the plasma in excess of the adiabatic heating. Thus, at $\alpha = 3$, the temperature $T_\sigma$ calculated from the conductivity is increased by a factor $T_{\sigma_c}/T_{\sigma 0} \approx 3$ ($T_c/T_0 = \alpha^{2/3} = 2$ for adiabatic heating). Another estimate of the temperature in the course of compression was based on the "burning-out" time of the spectral line of the ion $C_V$ in the central part of the compressed pinch ($C_V$ in Fig. 1). An estimate using the data of[4] yields $T \gtrsim 300$ eV. Laser measurements of the electron temperature were performed at the instant of the maximum compression and 300 μsec later, during clamping, at the center of the chamber and at a point shifted 2 cm away from its equatorial plane. These measurements have shown, first, that the radial profile of $T_e$ becomes narrower. Second, it turns out that the center of the compressed plasma pinch is shifted away from the equatorial plane of the chamber. Thus, measurements at different points of space in ohmic heating yield practically the same values of $T_e$, whereas in the case of compression the temperature at the center of the chamber is $T_e = 110 \pm 20$ eV as against $190 \pm 30$ eV 2 cm away from the center. The largest temperature, $T_e = 280 \pm 45$ eV, was obtained during clamping at the shifted point. We assume that in this measurement the center of the plasma pinch was closest to the point of observation of the scattered laser light. Measurements of the conductivity and spectral measurements point to an increase of $T_e$ after the instant of maximum compression. The ion temperature in the contracted pinch was $T_i \approx 55$ eV.[3]

The curve marked $\bar{n}l$ in Fig. 1 is an oscillogram of an interferometry signal. Its variation during compression is close to that calculated under the "frozen-in" condition. The absence of a noticeable decrease of $\bar{n}l$ with decreasing $H_\theta$ during clamping indicates that the particles accumulate in the compressed pinch, and consequently that their lifetime is increased.

The plasma parameters attained as a result of the compression stay at a stationary level for a long time ($\approx 1$ msec), owing to the current flowing through the plasma. Calculation of the energy lifetime from the experimental data yields $\tau_E = 600-800$ μsec. For the compressed pinch we obtain $\beta_I = 1.5$.

Tuman-2

| | Ohmic heating | Compression |
|---|---|---|
| $H_\theta$, kG | 4 | 12 |
| $I_p$, kA | 5 | 5 |
| $U_p$, V | 4 | 3 |
| $\bar{T}_\sigma$, eV | 50 | 150 |
| $T_e$, eV | 110 | 300 |
| $T_i$, eV | 30 | 55 |
| $\bar{n}_e$, $10^{13}$ cm$^{-3}$ | 0.5 | ~1.5 |
| $\beta_I$ | 0.6 | 1.6 |
| $\tau_E$, μsec | 150 | 600 |
| $\tau \sim a^2 H_\phi$, μsec | 180 | 100 |

4. The table compares the values of the most important parameters in ohmic heating and in compression. We list below the principal results of the present paper:

a) The ohmic-heating regime is typical of tokamaks. In particular, $\tau_E$ in ohmic heating agrees with an experimental relation that is well known for tokamaks[5]:

$$\tau_E = 3.6 \cdot 10^{-8} a^2 H_\phi. \tag{2}$$

b) The change of plasma concentration with increasing toroidal field corresponds to the condition of the plasma being "frozen-in" into the magnetic field.

c) The heating upon compression is due mainly to the adiabatic effect. Release of Joule heat due to the current flow in the plasma may explain the heating in excess of the adiabatic heating.

d) The oscillations in plasma become strongly damped upon compression.

e) The thermalization of the plasma improves, $\tau_E$ increases fourfold over the ohmic heating. It is important that the value of $\tau_E$ for the compressed pinch is much larger than the value given by (2). The improvement of the thermal insulation in compression is apparently due to "detachment" of the plasma from the diaphragms, in agreement with the calculation results.[7]

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