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EFFECTIVENESS OF THE "THETA-PINCH-WITH-LINER" TYPE OF THERMONUCLEAR SYSTEM

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This work examines the influence of the compressibility of the liner substance on the effectiveness of a "theta-pinch-with-liner" system. Numerical calculations with respect to the dynamics of liner compression are conducted. The results of the calculations are approximated by estimation equations.

One of the trends in creating a pulsed thermonuclear reactor is heating of plasma via compression of a theta-pinch together with a thermoinsulating magnetic field by an accelerated metallic jacket (liner). Plasma confinement in the terminal state during the time required according to Lawson takes place due to liner inertia. The basic principles for creating such a thermonuclear reactor are described in [1-3]. We shall not deal with problems of creating the required power engineering and problems of stability, but shall only discuss the limitations on the full energy of the system due to energy losses during compression and confinement.

Calculations are presently being conducted to determine energy losses to radiation and thermal conductivity in the direction of and at right angles to the thermoinsulating magnetic field both in the process of compression and in the terminal state [4-7]. It follows from the results of these calculations that the plasma compression may be considered adiabatic in satisfying the conditions set for the geometry and parameters of the system. In particular, due to the losses along the system's axis, the following condition holds for the length of the system:

$$nL \geqslant 6.10^{22}\ cm^{-2} \qquad (1)$$

which exceeds $nL = 4 \cdot 10^{22}\ cm^{-2}$ necessary for braking of α particles. It was shown in [4] that for closed-end systems, when the criterion $nL > 4 \cdot 10^{22}\ cm^{-2}$ is satisfied, there exists a stationary distribution of temperature along the length of the system; it is such that the power of nuclear energy release completely compensates for the heat loss to thermal conductivity and volumetric radiation. Therefore, the variant of a closed-end reactor is preferable since a self-sustaining reaction is possible when the necessary confinement is provided in this type of reactor.

In satisfying these conditions it turns out that the effectiveness of such an idealized model is strongly dependent on the coefficient of energy transfer from the liner to the plasma η_p since as a result of the compressibility of the liner material at $P > 10^6$ atm a portion of the energy expended on acceleration of the liner remains in the liner itself in the form of potential energy during its compression.

It is apparent that η_p may be close to unity only in the case of a "thin" liner, when the cross-section of the liner is much less than the cross-section of the plasma in the terminal state, and correspondingly, when the potential liner compression energy is small at shut-down.

This is possible only if the plasma pressure is much less than $\rho_0 v_0^2$, which leads to systems with low densities since the system's radius is inversely proportional to density, and this leads to very high liner energy

$$Q_0 \sim 3 n \kappa T \pi \frac{(n\tau)^2}{\rho_0^2 v_0^2} 8 \kappa^2 T^2 \tag{2}$$

on the order of 10^7-10^5 MJ for liner velocities of 10^5-10^6 cm/sec, respectively, at $(n\tau) \sim 10^{15}$ $cm^{-2}\cdot sec$. In the opposite case $P \approx \rho_0 v_0^2$, although the coefficient of energy transfer from liner to plasma decreases to 0.5, the total energy of the system is lowered to 10^6-10^2 MJ for the very same conditions. The relation of liner cross-section to plasma cross-section proves to be on the order of 3-10 for pressure $P > 10^6$ atm, when compressibility is substantial. Thus, for pulsed reactors based on the concept of direct theta-pinch by the liner, closed-end systems with a totality of energy in the plasma on the order of the initial energy density in the liner are the most advantageous and realistic from the standpoint of creating the necessary energetics.

Calculations dealing with determination of the dependence of system full energy on the efficiency of energy transfer from liner to plasma and selection of optimum η_p to decrease Q_0 are presented below. We decided on a unidimensional statement of the equation of liner dynamics with the introduction of artificial viscosity to account for the resulting shock waves within the liner during braking, the equation of plasma energy balance, in which allowances were made for controlling loss to radiation and thermal conductivity along the system's axis, and the equation of D-T reaction kinetics. The equation for cold compression of the liner was taken in model form

$$P = P_0 \left[\left(\frac{\rho}{\rho_0} \right)^m - 1 \right] \qquad (3)$$

where P_0 and m were selected so that the experimental results in the pressure range $P \leqslant 1$ M atm and Thomas-Fermi-Dirak calculations at 10^6 atm $< P < 10^8$ atm [8-10] were approximated with satisfactory accuracy.

From the results of the calculations it follows that the dependence of the full energy of the liner on efficiency η_p has the form:

$$Q_0 \sim \eta_p^{-1} (1 - \eta_p)^{-\frac{2m}{m-1}} \qquad (4)$$

which is minimal at $\eta_p = \frac{m-1}{2m}$. With this optimum efficiency, the relation of liner cross-section to plasma cross-section in the terminal state is approximately 3/2(m+1).

In this case the dynamics of liner compression at shut-down becomes substantial, since the pressure equalization time along the liner is comparable to the effective confinement time. There are movement regimes: a) when the degree of burn-up is small, and b) when burn-up is so great that the contribution of plasma self-heating by α particles becomes substantial and plasma heating by compression is necessary only for "ignition" of the self-sustaining reaction during liner dispersion.

In the first case, of relatively little interest for thermonuclear power plants, but interesting with respect to a physical reactor with $(n\tau) \sim 10^{14}$ and, correspondly, with a burn-up coefficient $\xi \leqslant 1\%$, the following pattern is observed. At first, the internal boundary of the liner stops, and, naturally, the maximum temperature and pressure correspond to this moment in time. Then, over a certain period the internal boundary scarcely moves until pressure becomes equalized throughout the whole volume of the liner – a pressure wave ascends with the current along the bombarding layers of the liner (Fig. 1). After pressure equalization and shut-down of the entire liner for time $t = h/v_s$ (h is the thickness of the compresses liner, v_s is the speed of sound) unloading begins, and the external layers of the liner are accelerated back. From this it follows that $P(t)$ and $T(t)$ are asymmetric in time, since plasma pressure increases with a characteristic time $t_1 = r/v_0$ (r is the final radius of the plasma) and decreases with time $t_2 = h/v_s$, Fig. 2. The kinetic energy of the liner remains finite at "shut-down."

At high degrees of burn-up $\xi \geqslant 5\%$, "ignition" of the reaction takes place and the incipient self-heating leads to further 2-3-fold pressure and temperature increments (Fig. 3). Such an explosive pressure increment creates a shock wave in the liner, which so strongly compresses the liner matter that after this wave passes through the liner its movement is described as the movement of an infinitely thin jacket, Fig. 4. Heating takes place for a period longer than the characteristic confinement time, since at $\xi > 1\%$ the energy of the α particles absorbed in the plasma exceeds the energy of ignition.

However, all of the energy of the α particles does not go to plasma heating in the sense of increasing the temperature: a significant part of it goes to accelerating the liner. Therefore, P(t) becomes more symmetric. Since the velocity of the shock wave and the velocity of the matter beyond its front are about equal to the initial velocity of the liner, plasma compression and liner dispersion take place with an equal characteristic time t_l. The basic liner compression takes place as the pressure in the plasma drops, and temperature drops more slowly due to the self-heating.

We shall give the equations approximating the numerical results:

$$Q_0 = 11.3 \frac{T^3 P_0^{\frac{2}{m-1}} \nu^2}{q^2 \rho_0^{\frac{2m}{m-1}} V_0^{\frac{4m}{m-1}}} \frac{(n\tau)^2}{(n\tau)_0^2} \quad Gg^*$$

$$P = 0.11 \cdot 10^6 \frac{\rho_0^{\frac{m}{m-1}} V_0^{\frac{2m}{m-1}}}{P_0^{\frac{1}{m-1}}} \quad atm$$

$$L = 1.78 \cdot 10^4 \frac{T P_0^{\frac{1}{m-1}}}{\rho_0^{\frac{m}{m-1}} V_0^{\frac{2m}{m-1}}} \quad cm$$

$$\tau = 21 \frac{T P_0^{\frac{1}{m-1}} \nu}{\rho_0^{\frac{m}{m-1}} V_0^{\frac{2m}{m-1}}} \frac{(n\tau)}{(n\tau)_0} \quad \mu sec$$

$$h = 2.1 \frac{T P_0^{\frac{1}{m-1}} \nu}{q \rho_0^{\frac{m}{m-1}} V_0^{\frac{m+1}{m-1}}} \frac{(n\tau)}{(n\tau)_0} \quad cm$$

where v_0, ρ_0 are the initial velocity and density of the liner (10^5 cm/sec and 10 g/cm^3), respectively; $(n\tau)/(n\tau)_0$ is the relation of energy released as the result of the reaction to that imparted to the plasma; $(n\tau)_0 = f(T)$, $n\tau(T = 10\ \text{keV}) = 7\cdot10^{13}\ \text{cm}^{-3}$ sec. The value of $q \quad 1$ characterizes the effectiveness of confinement, $v(\xi < 5\%) \approx 1$, $v(\xi \approx 10\%) \approx 0.5$.

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References

1. Ye. P. Velikhov, Zh. Teor. Fiz., 43, (2), 429 (1973).
2. S. G. Alikhanov, et al., Report at the 3rd Conf. on Phenomena in Ionized Gases, Belgrad, 1963.
3. J. P. Boris, et al., Proc. of the 6th European Conf. on Controlled Fusion and Plasma Phys., Moscow, 30 July - 4 August, 1973.
4. S. G. Alikhanov, I. K. Konkashbaev, and P. Z. Chebotaev, Nucl. Fusion, 1 (1970).
5. S. G. Alikhanov and I. K. Konkashbaev, Nucl. Fusion (1974).
6. P. Z. Chebotaev, et al., Proc. of the 6th European Conf. on Controlled Fusion and Plasma Phys., Moscow, 30 July - 4 August, 1973.
7. J. P. Boris, et al., Proc. of 5th European Conf. on Controlled Fusion and Plasma Phys., Grenoble, France, 21-25 August, 1972.
8. A. I. Voropinov, et al., UFN 100, 2 (1970).
9. N. N. Kalitkin, ZhETF 38, 2534 (1960).
10. Ya. B. Zel'dovich and Yu. P. Rayzer, Physics of Shock Waves and High-Temperature Hydrodynamic Phenomena [in Russian], Nauka, Moscow, 1966.

NOMENCLATURE

n - final plasma density

T - final plasma temperature

r - final plasma radius

P - pressure

P_0 - constant characterizing the compressibility of the liner matter

t - time

t_1, t_2 - characteristic times

τ - confinement time

ρ_0 - initial density of liner

ρ - density of liner

v_0 - initial velocity of liner

v_s - velocity of liner

h - final thickness of liner

L - length of system

m - index of "adiabatics" of cold compression

η_p - coefficient of energy transfer from liner to plasma

Q_0 - initial kinetic energy of liner

K - Boltzmann constant

π - relation of circumference to its radius

$(n\tau)$ - Lawson parameter

q - coefficient characterizing effectiveness of confinement

$\nu(\xi)$ - coefficient characterizing effectiveness of self-heating

n_α - density of α particles

n_e - electron density

$\xi = 2n_\alpha/n_e$ - degree of burn-up

FIGURE CAPTIONS

Fig. 1. Distribution of pressure P and velocity v when liner is shut-down.

v_0 = 10 km/sec; $(n\tau)$ = 1 without self-heating.

Fig. 2. Time dependence of pressure P, temperature T, and degree of burn-up $\xi = 2n_\alpha/n_e$.

Solid lines - with self-heating

Dotted lines - without self-heating

Fig. 3. Same as for Fig. 2

Fig. 4. Same as for Fig. 1, but with self-heating.

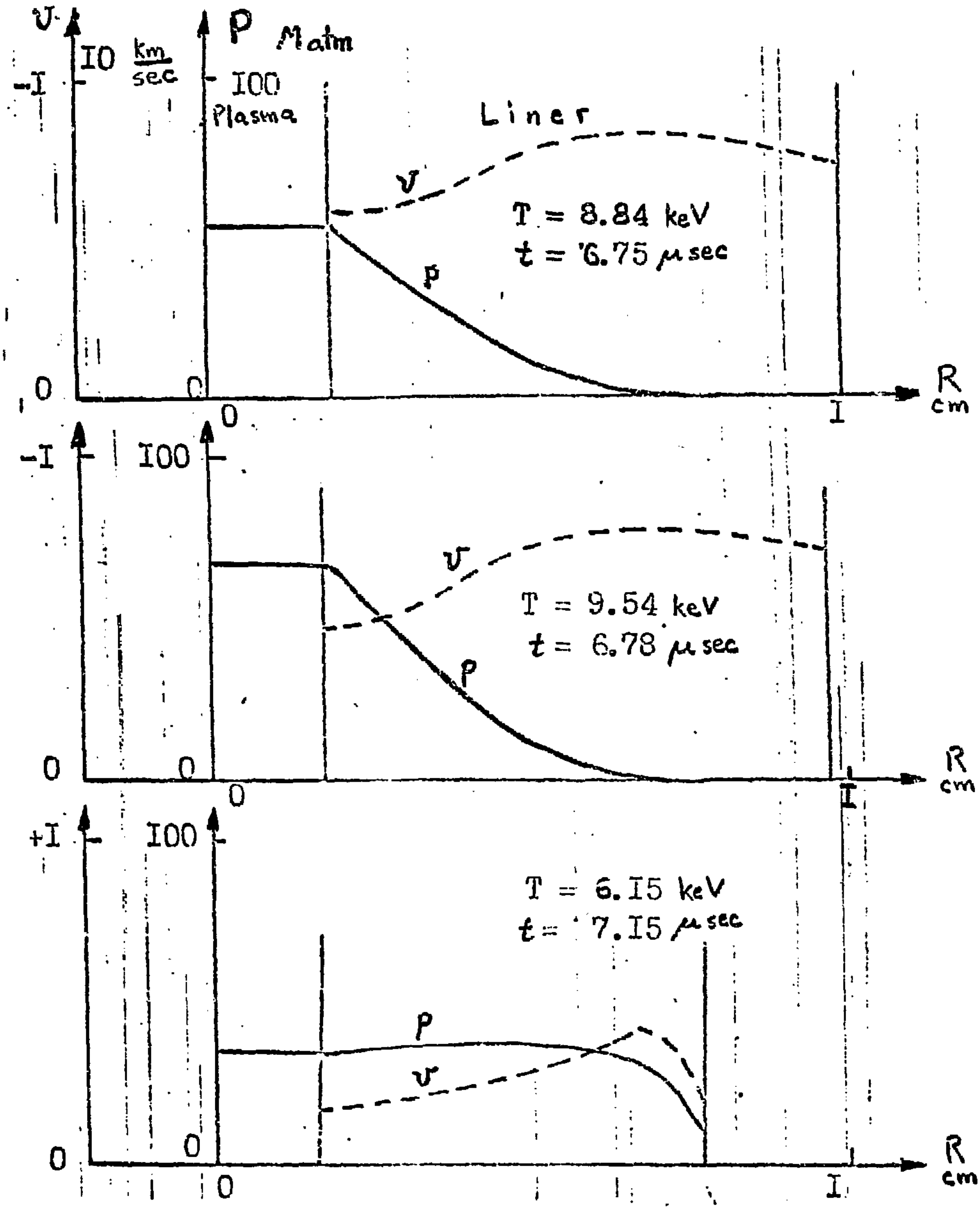

Fig. 1

Distribution of pressure P and velocity v when liner is shut-down.
v_0 = 10 km/sec, $(n\tau)$ = 1 without self-heating

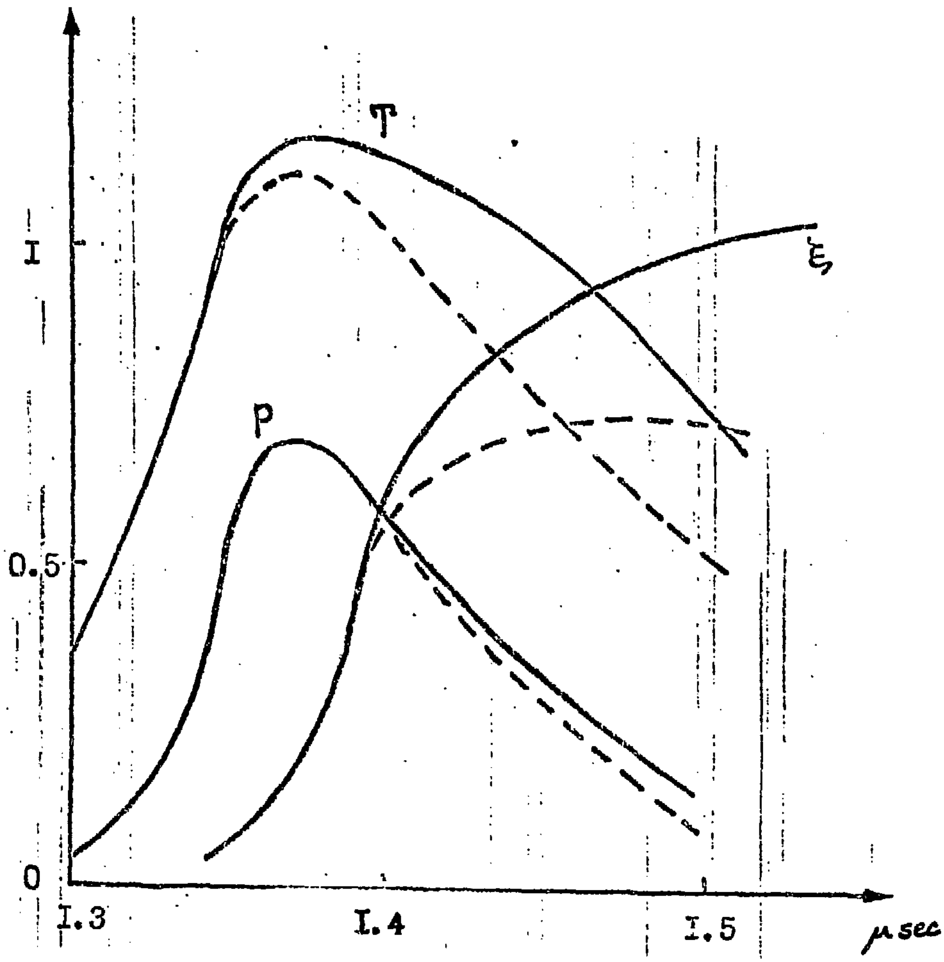

Fig. 2

Time dependence of pressure P, temperature T, and degree of burn-up $\xi = 2n_\alpha/n_e$.

Solid lines - with self-heating

Dotted lines - without self-heating

T in 10 keV, P in 100 Matm, ξ in %

v_0 = 10 km/sec, $(n\tau) = 1$.

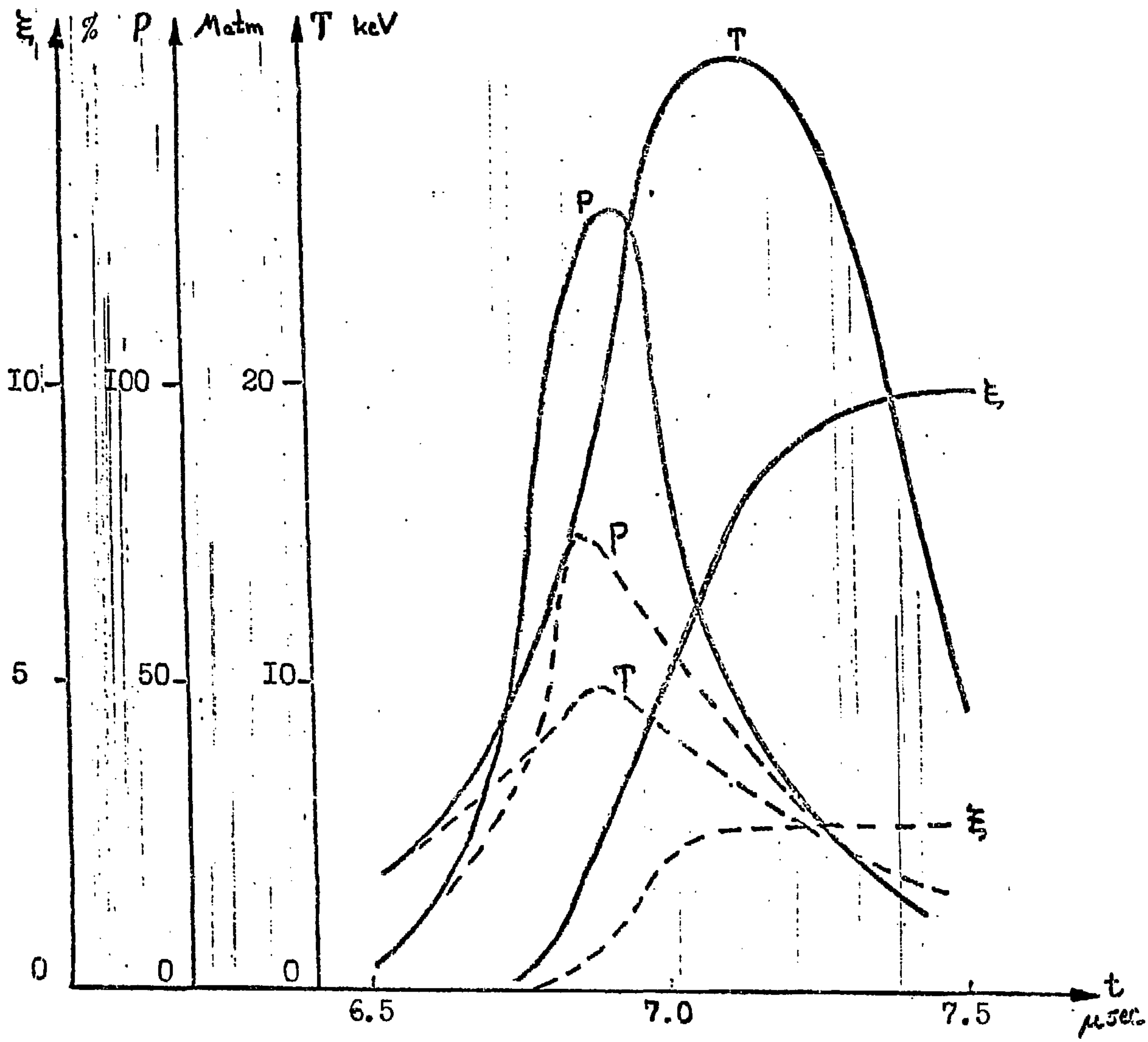

Fig. 3

Time dependence of pressure P, temperature T, and degree of burn-up $\xi = 2n_\alpha/n_e$.

Solid lines - with self-heating

Dotted lines - without self-heating

v_0 = 10 km/sec, $(n\tau)$ = 10.

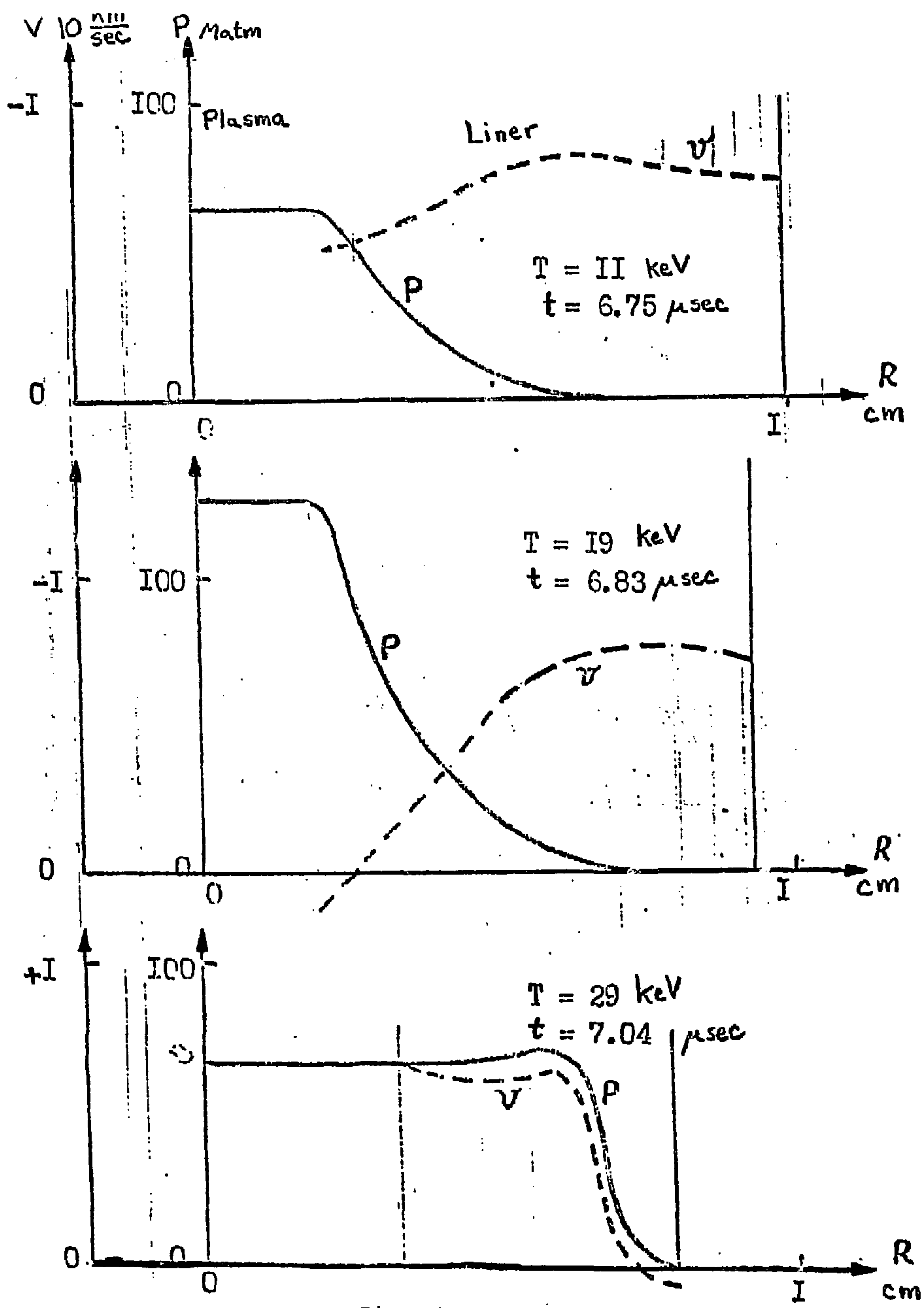

Fig. 4

Distribution of pressure P and velocity v when liner is shut-down

v_0 = 10 km/sec, $(n\tau)$ = 10 with self-heating