THE PLASMA FOCUS AND THERMONUCLEAR FUSION*

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Present-day notions concerning the effects involved in a plasma focus are reviewed, the efficiency of various energy transmission channels in the device is analyzed, and some ideas relating to the possible extrapolation to larger devices are indicated.

In an investigation of linear discharges toward the end of the 1950's N. V. Filippov in Moscow attempted to cope with the main shortcoming of high-power Z-pinch (namely, secondary breakdown when energy is transmitted too rapidly into the plasma) by changing over to experimental enclosures having the configuration shown in Fig. 1a. Here, as the current sheath rounds the corner of the center electrode, the insulator no longer "sees" the discharge, a situation that should prevent secondary breakdowns. What actually happened was not only the elimination of secondary breakdowns, but also the emission of a very intense neutron radiation from the small dense plasma zone situated near the center electrode. This zone was named the "plasma focus."

Shortly thereafter J. Mather discovered a similar phenomenon near the discharge opening of a plasma gun (Fig. 1b).

Many small groups subsequently devoted their efforts to research on this intriguing phenomenon, but difficulties, both experimental (small time and dimensional scales of the problem; exceedingly large density gradients) and theoretical (two-dimensional collapses; inapplicability of MHD theory); slowed progress enormously for about 10 years in understanding the processes involved in the plasma focus. To account for the neutron emission many models were proposed, which, depending on the predilections of the authors, were tied in with thermonuclear processes in moving or nonmoving plasmoids, with more or less complex beam–target interaction mechanisms, with effects having their origin in localized vortices, etc.

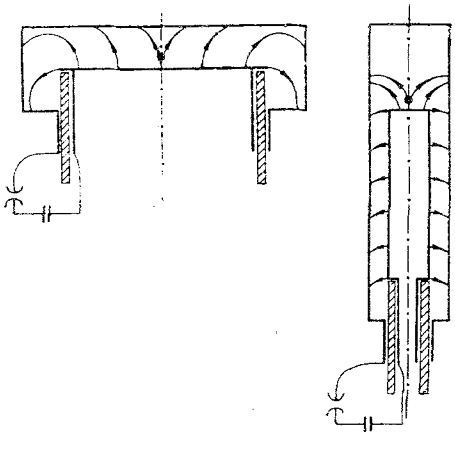

Fig. 1

In the last three years, however, the development of sophisticated diagnostic techniques (holographic interferometry, spatially and temporally resolved neutron measurements) along with substantial progress in international cooperation (with special reference to the Joint European Program for Plasma Focus Research) have revealed the existence of several different regimes (high and low pressures, clean and dirty discharges), and the situation is now perceived far more clearly. It has been established that the maximum neutron emission occurs after the compression maximum, the expansion of the plasma is accompanied by strong turbulent heating, and the devices of Mather and Filippov differ somewhat in the results they produce [1-3].

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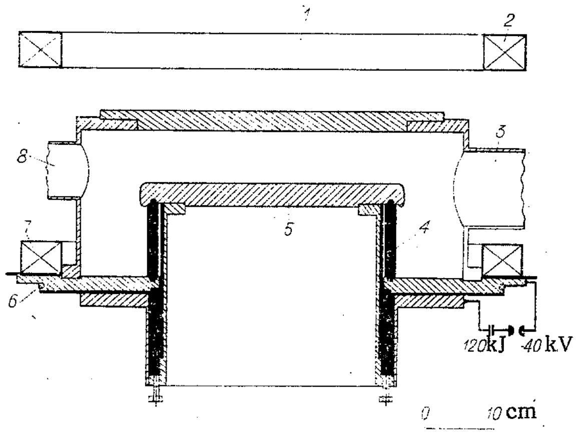

Fig. 2

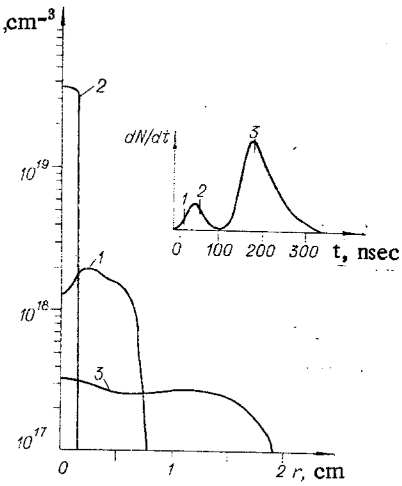

Fig. 3

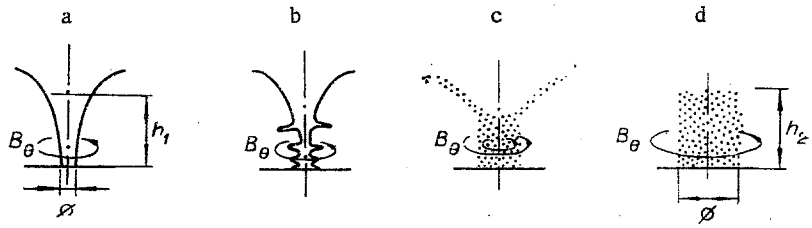

Fig. 4

For simplicity, and because the Filippov devices tend to be less capricious, in the present paper we consider the operation of these devices only (in the absence of impurities and at pressures corresponding to the maximum neutron yield, or high-pressure regime). All of the experimental results presented below refer to our machine at Frascati (Filippov type with a peak stored energy of 120 kJ and peak voltage of 40 kV); a schematic of the machine is given in Fig. 2: 1) neutron diagnostics plate; 2) magnetic field coil; 3) pump; 4) insulator; 5) neutron diagnostics plates; 6) Rogowski loop; 7) magnetic field coil; 8) neutron, optical, and x-ray measurements. The following operating conditions are typical: stored energy 74 kJ; voltage 32 kV; pressure 1.1 mm Hg; pure deuterium.

In writing the present paper we have striven more for clarity than for completeness, and the Literature Cited is therefore not meant to be exhaustive.

Neutron Emission Mechanism.

Neutrons are emitted by two separate pulses; the first, during which usually 10% of the total number of neutrons appears, occurs at the instant of maximum compression, whereas the second, containing $\sim$ 90% of the neutrons, occurs about 100 nsec later and lasts for approximately another 100 nsec (see Fig. 3, in which the linear density is $2.6 \cdot 10^{18}$ cm^{-1}). At the end of the "prehistoric" period (1971) the results of numerous indirect measurements had evolved into the model [4] depicted in Fig. 4.

At the compression maximum (Fig. 4a) one could attribute the miniscule neutron emission to thermonuclear reactions taking place in a relatively cold (about 1 keV) pinch plasma ($n \sim 2 \cdot 10^{19}$ cm^{-3}, $T_i \sim 1.6$ keV, $\varnothing \sim 4$ mm, $h_1 \sim 10$ mm). Then the plasma column is disturbed by an axisymmetrical macroscopic instability (Fig. 4b), the radial dimension of the plasma increases, the density decreases, and the magnetic field intermingles with the plasma; this so-called "dark pause" (Fig. 4c) is characterized by negligible neutron emission. During expansion, conditions are created for the inception of turbulent heating of one type or another, a large fraction of the magnetic energy is converted into heat, and a second strong

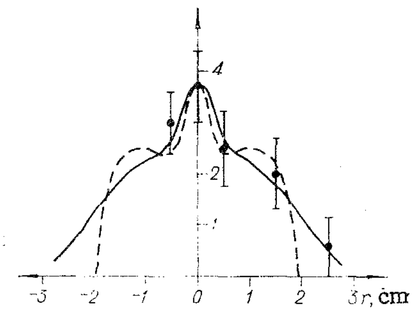

Fig. 5

neutron emission peak occurs due to thermonuclear reactions in the hot (5 to 10 keV) but not very dense plasma: $n \sim 10^{18}$, $T_i \sim 7$ KeV; $\varnothing \sim 15$ mm, $h_2 \sim 10$ mm (Fig. 4d).

At the time this model was proposed it was extremely speculative, because neither the density nor the temperature had actually beem measured. Without embarking on a critique of these early observations, it is interesting to note that even the very origin of the neutrons (thermonuclear or other) was an object of debate; advocates of the given model inferred from the anisotropy of the neutron emission and from the neutron energy spectra measured in different directions that approximately 80% of the neutrons had to be of thermonuclear origin [5], while others (see the discussion at the end of [5]) interpreted the same measurements as evidence of beam-target interaction as the neutron source.

Since that time direct measurements have been performed, demonstrating conclusively the qualitative correctness of the model in describing the effect, even though the numerical figures cited above must be somewhat modified. In the next section, as an example, we examine one of the best pulses (which is also one of the most difficult to explain) obtained at Frascati: $4.8 \cdot 10^{10}$ neutrons at an energy of 74 kJ stored in the capacitor bank.

Analysis of a Single Pulse.

In support of the foregoing discussion we use only reliable measurements:

a) The density obtained with spatial and temporal resolution by means of holographic interferometry [6] turns out at the time of peak neutron emission to be approximately $3 \cdot 10^{17}$ cm^{-3} in a volume with a diameter of 3.5 cm and height of 2 cm (see Fig. 3).

b) The absence of neutrons from the reaction (D, Li^7) in the discharge, with lithium bushings in both the anode and the cathode, indicates the absence of deuterons with energies greater than 300 keV (the energy at which the cross section for the corresponding reaction becomes appreciable).

c) Spatial and temporal scanning of the neutron emission shows that a considerable percentage of the neutrons (about 70%) appears in the volume indicated in [1]; the radial profile of the neutron emission coincides with the radial profile of the density squared; see Fig. 5, in which the solid curve corresponds to measurements of the neutron emission through a collimator with a diameter of 0.5 cm at a distance of 1 cm from the anode, and the dashed curve gives the result of calculations based on measurements of the density profile [on the assumption that T(r) = const].

d) The total current at peak neutron emission is approximately 800 kA; the duration of the second neutron peak is about 100 nsec.

First Hypothesis. The neutrons are of thermonuclear origin. The neutron yield N is given by the equation

$$N = \frac{1}{2} n^2 V \langle \sigma v \rangle \tau,$$

in which V is the volume, n is the density of electrons, and τ is the pulsewidth. Inasmuch as V, n, τ, and N are measured, this relation enables one to determine $\langle \sigma v \rangle$ and the temperature $T_i \simeq 9$ keV. Setting $T_e \simeq T_i$, as is indicated by measurements of the electron temperature in soft x radiation, we find the thermal energy of the plasma:

$$W_{th} = 3\, n\, k\, T\, V \simeq 20 \text{ kJ}$$

i.e., in the best shot up to 25% of the energy initially stored in the bank is transmitted to the hot plasma.

Electrical measurements [1] support such a rapid energy contribution in the interim

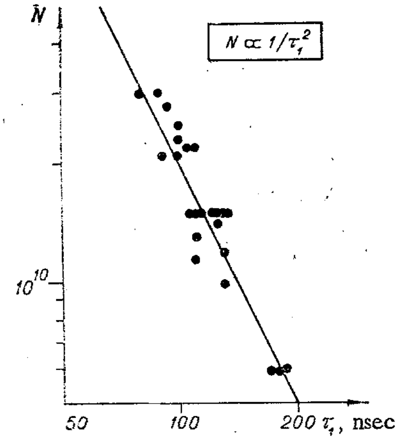

Fig. 6

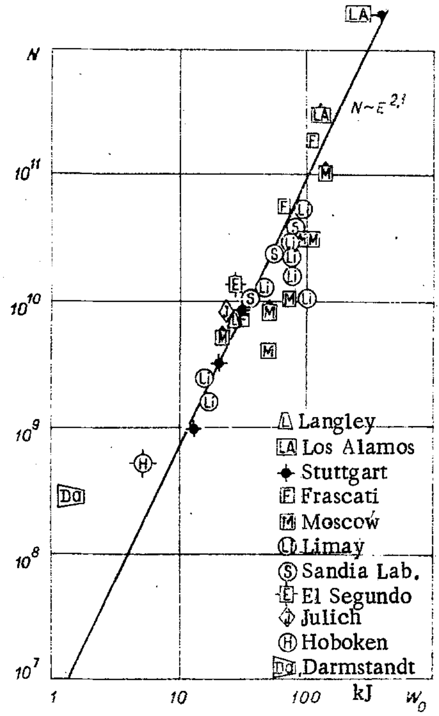

Fig. 7

between the first and second neutron emission peaks. The turbulent heating mechanism is vague, but it is definitely connected with the existence of high-intensity electron beams in the plasma [1, 3]. Apparently due to the disruption of the current sheath immediately after maximum compression the current in certain regions of the plasma column is carried entirely by escaping electrons, the majority of which lose energy in the plasma prior to impact with the anode; the hard x rays produced by the electrons that reach the electrode provide useful information [1], which, however, has not yet been systematically utilized.

The similarity in the radial distributions of the neutron emission and density squared suggests the absence of significant radial temperature gradients.

Second Hypothesis. The neutron emission mechanism is associated with beam–target interaction. Inasmuch as the density and volume of the target are known from facts a) and b) above, we can use the relation

$$N = n_p n_i V \langle \sigma v \rangle \tau,$$

in which n_p and n_i are the densities of the plasma and the ion beam, to find the density of the beam. We adopt the most favorable assumption with regard to the beam energy, taking it equal to 200 keV (it must be less than 300 keV!). Determining n_i, we find the total current in the ion beam:

$$I_i \simeq 3 \text{ MA}.$$

The energy carried by the ion beam is 60 kJ.

On comparing these figures with the total current through the plasma (0.8 MA) and with the total stored energy (74 kJ) we find clearly that a beam–target interaction mechanism cannot possibly account for the neutron emission.

Energy Estimates and Similarity Principles.

Proceeding from the notion that the majority of the neutrons in devices of the Filippov type are of thermonuclear origin and emanate from the turbulently heated plasma column, it is in our interest to examine the questions of whether it is possible to increase the neutron yield for a given stored energy and how the neutron yield varies as a function of the stored energy.

1. Denoting the efficiency of conversion of stored energy into heat by η_1, and the thermonuclear efficiency of the machine by η_2, we write the following expression for the energy $\eta_2 W_0$ released in thermonuclear reactions in an isothermal plasma with density n filling a cylindrical enclosure with radius r and height h:

$$\eta_2 W_0 \sim n^2 \langle \sigma v \rangle \pi r^2 h \tau \sim [3nkT\pi r^2 h]^2 \frac{\langle \sigma v \rangle}{T^2} \frac{\tau}{hr^2} \sim [\eta_1 W_0]^2 \frac{\langle \sigma v \rangle}{T^2} \frac{\tau}{hr^2},$$

where T and τ are the temperature and lifetime of the plasma. In a Filippov-type focus $r \simeq h$, and plasma confinement does not occur, either in the axial direction, where there is nothing to prevent efflux of the plasma away from the electrode, or in the radial direction (the Bennett condition is not satisfied, and the magnetic pressure is less than the plasma pressure). It is to be expected, then, that τ will be of the same order as the free-expansion period of the plasma, i.e., h/v_s (v_s is the speed of sound):

$$\tau = \alpha h / v_s,$$

where α is a coefficient characterizing plasma confinement (α cannot be much greater than unity). In this notation

$$\eta_2 \sim \alpha \frac{\eta_1^2}{r^2} \frac{\langle \sigma v \rangle}{T^{5/2}} W_0.$$

For both the D-D and the D-T reactions the function $\langle \sigma v \rangle / T^{5/2}$ has a broad maximum at T = 9 keV. As we showed in the preceding section, optimally improved devices are already capable of operating at this temperature. For them

$$\eta_2 \sim \alpha \frac{\eta_1^2}{r^2} W_0. \quad (1)$$

2. In existing devices α already attains large values (α = 5 at Frascati, since $\tau \simeq$ 100 nsec, $h \simeq 2$ cm, and $v_S \simeq 10^8$ cm/sec), but why this is so is rather difficult to comprehend; η_1 can attain 0.25 in the best shots.

It is evident from Eq. (1) that for a given energy W_0 stored in the bank the only reliable means of increasing the total efficiency η_2 is to diminish the radius r of the hot plasma. It has in fact been observed [4] that a device operating consistently under identical conditions exhibits a strong correlation between the number of neutrons and the delay time τ_1 between two neutron peaks (Fig. 6). If the plasma expands at a constant rate after maximum compression, then r is proportional to τ_1, and η_2 therefore varies as r^{-2}. In the present state of ignorance concerning the precise mechanism of turbulent heating it is not clear exactly what determines the radius r at which heating of the expanding plasma cylinder takes place. In the experiments to date the plasma radius at the instant of maximum compression is an order of magnitude smaller than the radius r (see Fig. 3), but the plasma is relatively cold at that time. The question of whether ways can be found to decrease r is left unresolved.

3. It has been observed experimentaly [7, 8] in the interval of W_0 from 5 to 400 kJ that for all optimized devices $\eta_2 \sim W_0^{1.1}$ (Fig. 7) and $\tau \simeq$ const. This means that $\alpha\eta_1^2/r^2 \simeq$ const and αh (or αr, whichever is smaller) is also constant.

These conclusions must be approached with caution, because most devices are of the Mather type, in which some doubt is cast on the thermonuclear origin of the neutrons. The similarity principles governing the quantities n, h, r, α, and η_1 are not yet known; their determination constitutes the prime objective of the megajoule plasma focus whose construction is being completed at Frascati. In any case, assuming that the quantity $\alpha\eta_1^2/r^2$ is constant, as known to be the case in the investigated energy range, and recognizing that the largest device is existence (the Los Alamos plasma focus with a total energy of 400 kJ and total neutron yield of $2 \cdot 10^{12}$ in pure deuterium) would yield a total efficiency $\eta_2 > 10^{-3}$

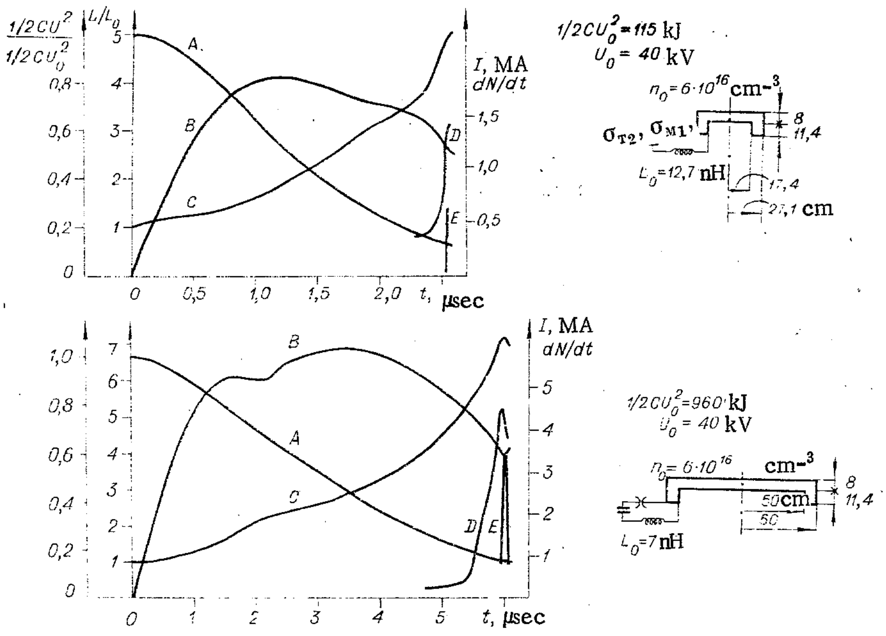

Fig. 8

in a D-T mixture, we can assert that the critical reactor ($\eta_2 = 1$) should perform at an energy level of the order of several hundred megajoules, which does not seem outrageously high.

Extrapolation to Larger Devices.

Assuming that the optimum device has been constructed for a given energy W_0 in the bank, how should the other fundamental parameters (radius R_0 and height H of the experimental chamber, density n_0 of the gas, charging voltage U_0) be selected as a function of W_0? It is required to find four relations between W_0, U_0, H, R, and n_0. We now show that two conditions must be satisfied, whereas an appreciable uncertainty exists with respect to the others.

1. The capacitor bank must completely discharge by the time maximum compression is reached. This requirement imposes the condition

$$\frac{W_0^2}{U_0^2 R_0^4 n_0} = \text{const.} \tag{2}$$

The heuristic proof of this relation entails a comparison of two independent estimates of the acceleration γ of the collapsing plasma sheath:

$$\gamma = \frac{\text{magnetic pressure}}{\text{mass per unit area}} \propto \frac{I^2/R_0^2}{n_0 R_0} \propto \frac{W_0}{L n_0 R_0^3}$$

and

$$\gamma = \frac{\text{distance}}{\text{time}} \propto \frac{R_0}{LC},$$

where L is the total inductance of the system, C is the capacity of the bank, and I is the current in the plasma.

2. The temperature of the plasma at the instant of maximum neutron yield is optimal (9 keV). The resulting condition (necessary, but not sufficient) is

$$\frac{W_0}{n_0 R_0^2 H} = \text{const.} \tag{3}$$

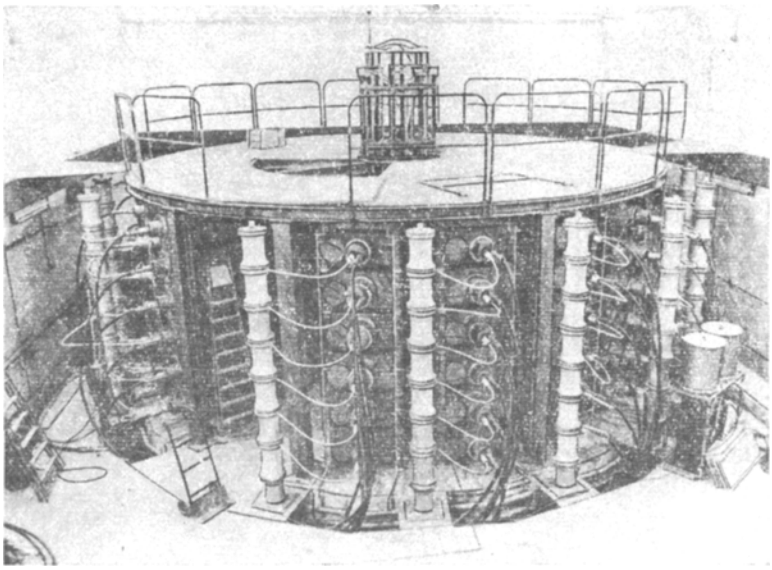

Fig. 9

Condition (3) implies that if the "raking" efficiency is constant, then the energy acquired by each particle in the pinch is also constant.

3. Besides these two necessary conditions, we must choose two other similarity criteria that would guarantee, for example:

a) a similarity condition for turbulent heating; while this condition is very essential, we cannot yet formulate the necessary requirement until the turbulent heating mechanism is more clearly understood;

b) an MHD similarity condition for dissipative processes [9]; the implication here is that the ratio of the mean free paths to the Larmor radius remains constant for both electrons and ions of the hot plasma, but, since MHD theory is invalid in the heating phase, the use of this condition is undesirable for the plasma focus;

c) a similarity condition for breakdown and voltage at the wall [4]; the obvious choice is the condition

$$\frac{W_0}{R_0^2} = \text{const}$$

in conjunction with

$$H = \text{const}.$$

These conditions combined with (2) and (3) yield the similarity principles

$$\begin{aligned} &R_0 \propto W_0^{1/2}; \\ &H = \text{const}; \; n_0 = \text{const}; \; U_0 = \text{const}. \end{aligned} \tag{4}$$

Here the total system inductance, which is proportional to H in the first approximation, remains constant, so that the current density and voltage on the insulator do not vary and thus leave invariant the Paschen condition for breakdown (Hn_0 = const, U_0 = const).

The megajoule machine being assembled at Frascati as part of the Joint European Program for Plasma Focus Research has been extrapolated from the existing 120-kJ machine at Frascati in accordance with the rules (4). The results of two-dimensional MHD calculations of plasma collapse in pure deuterium (Potter program in the Robouch modification) are summarized in Fig. 8: A) energy stored in capacitor; B) current; c) total circuit inductance; D) bremsstrahlung power (artibrary); E) neutron emission per unit time (arbitrary units); a) existing 115-kJ experimental device; b) 960-kJ machine in assembly. These calculations confirm that good similarity obtains between the machines up to maximum compression (at which time they lose validity). In practice, for technological reasons, the radius of the insulator was made equal to 40 cm, rather than 50 cm. Figure 9 gives an external view of the 960-kJ capacitor bank during electrical-engineering tests; the equivalent load substituted for the experimental chamber is seen in the upper part of the photograph. It is expected that 10^{13} neutrons will be generated in one pulse in operation with pure deuterium. This expectation is a large yield and will require effective shielding, which is to be provided by a building specially constructed for this purpose.

If the system of equations (4) were used to extrapolate existing machines to the level of a thermonuclear reactor, the stored energy (of order 1 GJ) would have to be released in more than 100 μsec. Then one could dispense with the capacitor bank and use instead a magnetic accumulator system supplied by, for example, a device of the Homopolar type.

We note in conclusion that substantial progress has been made in the last few years in our understanding of the plasma focus in devices of the Filippov type. The following basic problems must be dealt with in the immediate future:

1. Determine valid similarity principles up to the 1-MJ level, not only for the neutron emission, but also for the important parameters r, n, and τ.

2. Perform direct measurements of the ion temperature on the basis of laser scattering.

3. Explicate the turbulent heating mechanism.

It must be borne in mind with regard to longer-range plans that the excessive cost of pulsed energy necessarily restricts the extrapolation of high-speed systems to a thermonuclear reactor only when the heating efficiency is very high. The plasma focus has this important attribute, which in the author's opinion is also the principal justification for further work in this direction.

The European group, which comprises approximately 25 scientists working in Culham, Frascati, Julich, Limay, and Stuttgart, can with the advent of the new 1=MJ machine take an active part in the collaborative efforts in this area, working concurrently with other groups concentrated primarily in the United States (Livermore, etc.) and the USSR (I. V. Kurchatov Institute of Atomic Energy and Lebedev Physics Institute of the Academy of Sciences of the USSR).

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