Use of Super-Power Disk Explosive Magnetic Generators to Ignite a Target by Indirect Irradiation of Z Pinch with X-Rays

A.V.Ivanovsky

Russian Federal Nuclear Center – All-Russia Research Institute of Experimental Physics (RFNC-VNIIEF), Sarov, Russia

E-mail contact: ivanovsky@elph.vniief.ru

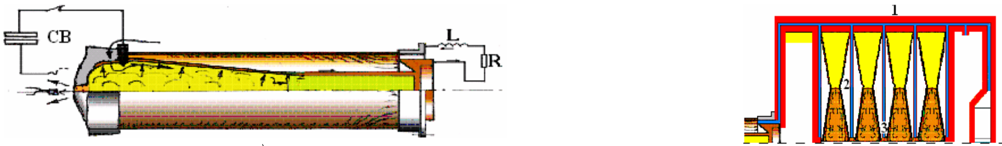
Abstract. In accordance with the existing concepts the X-radiation with the energy of 10 MJ should be generated by each Z pinch for the time of <5 ns in the scheme of a double-pinch vacuum hohlraum to ignite a thermonuclear target. Such parameters of X-radiation can be provided at the implosion of Z pinch by the current of ≥65 MA for the time of ~ 100 ns. Realization of such currents at the facilities on the basis of the capacitor banks is still a long way in the future. The Z machine (Sandia National Laboratories, USA), being the most powerful stationary facilities, realizes the implosion of the Z pinch at the current of 25 MA. At the same time the developed explosive technologies already allow obtaining and even exceeding the currents required for ignition. The super-power disk explosive magnetic generators (DEMG) can easily produce the currents of 300 MA for the time of ~10 μs. The application of the developed technologies of the foil electrically exploded current opening switches and of the explosive closing switches allows delivering the currents to 150 MA for the time of 1-2 μs to the load. The paper will consider a possibility of application of the second cascade of current pulse peaking on the basis of a low-inductive electrically exploded current opening switch in order to produce the current with the amplitude to 75 MA for the time of ~100 ns in the Z pinch. The paper will present the program of a step-by-step realization of such current source: a small class DEMG 250 mm in diameter, a middle class DEMG of 400 mm in diameter and, finally, a super-power DEMG 1000 mm in diameter producing the currents required for ignition.

1. Introduction

High energy density is required to realize thermonuclear ignition in the schemes with inertia confinement. The laser facilities that allow realizing the temperatures of X-radiation of 250-300 eV with relative ease are the most suitable tool for this. As of now, the laser facilities of the next generation have been designed: NIF has been constructed in USA (E_L~2 MJ), “Megajoule” is being constructed in France (E_L~2 MJ), there is a project of facility “UFL-900” in Russia (E_L~0.9 MJ).
Generation of the X-ray pulse with duration of ~5 ns with the energy of ~1.8 MJ on Z machine in Sandia National Laboratories (SNL, USA) [1] demonstrated that the electrophysical facilities provide an alternative possibility for a generation of high-power X-radiation. Due to higher, as compared with laser facilities, efficiency of usage of the electric energy of a capacitor bank (CB) they produce bigger amounts of X-radiation. So, the X-ray pulse of Z machine is close in energy to the pulse of the laser facility NIF. However, the energy density in the laser facilities is more then an order higher. Thus, the facilities an order more powerful than Z machine are required to realize thermonuclear ignition.
In accordance with the existing concepts the X-radiation with the energy level of no less than $2E_0$=20 MJ should be generated by two Z pinches (E_0~10 MJ in each) for the time $\tau \leq 5$ ns to achieve ignition threshold [2]. Such parameters can be provided at the implosion of Z pinch by the current of ~65 MA for the time of ~ 100 ns. To realize the above-specified conditions, the project of a stationary facility X has been developed at SNL; the BAIKAL facility is under construction in Russia.
It is possible that the simplest and the quickest answer to the question on feasibility of ignition can be given with the use of disk explosive magnetic generators (DEMG).

2. Current sources on the basis of EMG

In the result of natural selection over a period of five decades two designs possessing the highest reliability, stability of output parameters and fabrication simplicity were selected from several dozens of the considered and explored designs. They were the helical and disk EMG (HEMG and DEMG). These designs have not undergone any revolutionary changes from the time they came into being and, having passed a long way of evolutionary development, they have turned to a perfect tool for physical research.



a) b)

FIG. 1. Schematic diagram of operation: HEMG - a); DEMG – b).

In HEMG (Fig. 1.a) a deformable circuit is formed by the coaxially located coil and armature with an explosive charge. HE is initiates at the end. The initial magnetic flux is formed by a discharge of CB to the EMG circuit. HEMG produce the currents to ~35 MA in the load *L*=20-50 nH for the time of tens of microseconds.

In DEMG (Fig.1.b) the deformable circuit is formed by two conductors: the outer cylindrical (1) and the inner one made in the form of series-connected thin-walled copper disks (2). On the axis the disks are pairwise connected by copper cylindrical bridges (3). The space under the bridges is filled with HE. All charges in HEMG are initiated simultaneously. Under the effect of the explosion products the neighbor disks implode thus pushing the magnetic flux into the coaxial transmission line and the load. The HEMG is used to power the DEMG. The DEMG of POTOK family with dimensions of ∅ 1 m, 0.4 m and 0.25 m allow generating the currents to 300 MA for the time of 4-12 μs.

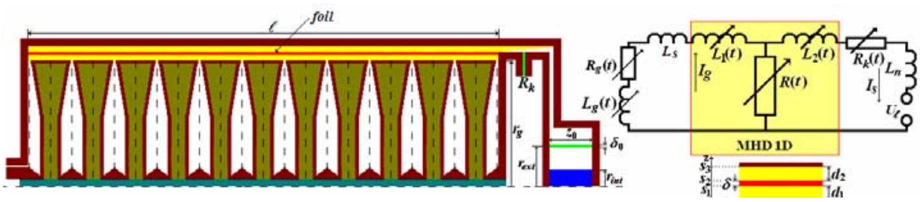


FIG. 2. Schematic diagram and electric diagram of the device on the basis of DEMG with FOS.

To reduce the time of energy delivery to DEMG, the electrically exploded (foil) current opening switches (FOS) are used (se Fig. 2).

The electric explosion of the foil is described by the equations of magnetic hydrodynamics [3]

$$\begin{cases} \dfrac{\partial}{\partial t}\left(\dfrac{1}{\rho}\right)=\dfrac{\partial u_z}{\partial s}, \quad \dfrac{\partial z}{\partial t}=u_z, \\ \dfrac{\partial u_z}{\partial t}=-\dfrac{\partial p}{\partial s}-j_y\dfrac{B_x}{\rho}, \\ \dfrac{\partial}{\partial t}\left(\dfrac{B_x}{\rho}\right)=\dfrac{\partial E_y^{'}}{\partial s}, \quad E_y^{'}=\dfrac{j_y}{\sigma}, \quad j_y=\dfrac{\rho}{\mu_0}\dfrac{\partial B_x}{\partial s}, \\ \dfrac{\partial \varepsilon_T}{\partial t}+p_T\dfrac{\partial u_z}{\partial s}=\dfrac{j_y E_y^{'}}{\rho}, \qquad s=\displaystyle\int_0^z \rho(z,t)\,dz, \end{cases} \tag{3}$$

where ρ, u_z are density and particle velocity; p is pressure; ε_T, p_T are thermal parts of specific energy and pressure; B_x, E'_y are components of magnetic and electric field in the frame related to plasma; j_y is current density.

The equations are solved in zone $0<s<s_3$ (see Fig.2). In zone $s_1 \le s \le s_2$ the EOS and copper conductivity should be used [4]. In the zone of dielectric the conductivity is equal to zero and the EOS in the Mie-Gruneisen form are used [5]

The equation for magnetic field is solved in the range $s_1<s<s_2$. Boundary conditions are determined through the currents in the circuits of the generator I_g and of the load I_s (Fig. 2).

$$B_x(s=s_1) = -\frac{\mu_0}{2\pi} \cdot \frac{I_g}{r_g}, \; B_x(s=s_2) = -\frac{\mu_0}{2\pi} \cdot \frac{I_s}{r_g}. \tag{4}$$

Currents I_g and I_s are determined from the equations for the circuits of the generator and of the load (ℓ_f is foil length)

$$\begin{gathered}\frac{\partial}{\partial t}\left\{\left[L_g(t)+L_s+\frac{\mu_0 \ell_f}{2\pi}\cdot\frac{z(s_1)-z_1(t=0)}{r_2}\right]\cdot I_g\right\}+R_g(t)\cdot I_g+E'_y(s=s_1)\cdot \ell_f=0,\; I_g\big|_{t=0}=I_0, \\ \frac{\partial}{\partial t}\left\{\left[L_1+\frac{\mu_0 \ell_f}{2\pi}\cdot\frac{z_2(t=0)-z_2(s_3)}{r_2}\right]I_s\right\}+R_k\cdot I_s-E'_y(s=s_2)\cdot \ell_f=0, \quad I_s\big|_{t=0}=0.\end{gathered} \tag{5}$$

The explosive switch K_1 operates when the voltage on the foil reaches the given value V^*, resistance dependence $R_k(t)$ is determined from the formula interpolating the experimental data [6].

To determine velocity v and the present location of the liner r, the equation of motion of the liner with mass m should be solved.

$$\begin{cases}\dfrac{dr}{dt}=v \\ \dfrac{dv}{dt}=-\dfrac{\mu_0}{4\pi}\cdot\dfrac{z_0}{mr}\cdot I_s^2\end{cases}, \; r\big|_{t=0}=r_{ext},\; v\big|_{t=0}=0. \tag{6}$$

Fig.3 gives comparison of the calculated and the experimental data [7] obtained with the use of the multiply tested device on the basis of DEMG ∅ 0.4 m delivering ~10 MJ of magnetic energy to the load for the time of ~1 μs. As is seen, the computational model describes well both the current pulses and the liner dynamics.

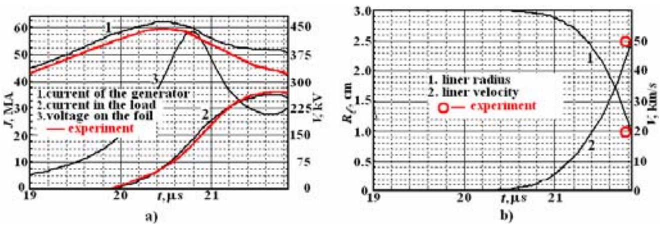


FIG. 3. Comparison of calculated and experimental: a) – currents; b) – liner dynamics.

The super-power DEMG produce ~40 MJ of electromagnetic energy per one disk element for the time of ~12 μs. The application of 15 elements will make it possible to realize the energy of ~600 MJ at the current of ~300 MA. The developed technology of the electrically exploded FOS allows delivering about a quarter of this energy (current of ~150 MA) to the load for the time of ~2 μs. Will further reduction of the current rise time to ~100 ns be possible?

Among the switches able to shape the current pulses of tens of MA for the time of ~100 ns the following should be noted: the electrically exploded switches, the plasma and the plasma-flow current opening switches. The electrically exploded current opening switches are the most extensively studied and the simplest ones.

3. Issues of high-power current pulses formation with the use of an electrical explosion of a conductor

A classical diagram of an electrically exploded FOS [7] is presented in Fig. 4. To get the current with the amplitude I_n~100 MA for the time of ~100 ns in the load of ~10 nH, it is necessary to generate the voltage V_n~10 MV. The electrical explosion is effective at the electric field intensity of 5-10 kV/cm. By this is meant that the foil length should be no less than $\ell \cong 10$ m. The existing technologies provide the strength of insulation above the foil not higher than 100 kV/mm. What this means is that the thickness of the dielectric should be no less than d=10 cm. The inductance of energy delivery to the load is determined from the ratio $L=\mu_0/2\pi\cdot\ell\cdot\ln(1+d/R)\cong 2$ nH/cm$\cdot\ell\cdot d/R\cong 100$ nH (R=2 m).

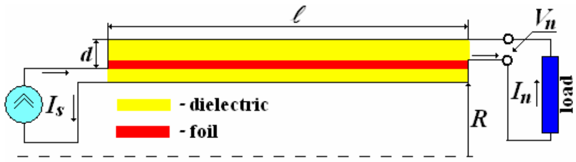


FIG. 4. Classical diagram of an electrically exploded current opening switch.

The energy that DEMG can deliver effectively to the load is no more than 20 nH. Due to this the application of the classical scheme of the electrically exploded FOS has low efficiency.
Work [8] describes a low-inductive electrically exploded current opening switch (LEEOS) in the form of a "snake" (Fig. 5). Subsequently it was proposed to use this switch together with DEMG to shape the current pulses of microsecond duration [9].
In this scheme the inductance above the foil is determined from $L=\mu_0/4\pi\cdot d/R\cdot(\ell/n+2\cdot d)$. At ℓ=100 m, d=10 cm, R=2 m and, for example, n=20 it is L=3.5 nH.

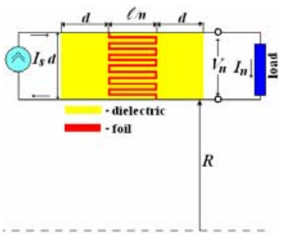


FIG. 5. Scheme of LEEOS.

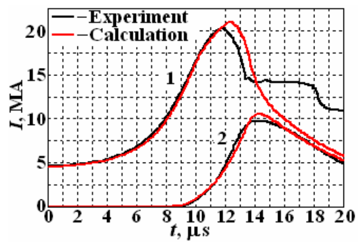


FIG. 6. Calculated and experimental currents vs. time: in DEMG circuit -1, in the load L_n=5 nH -2.

The efficiency of LEEOS is illustrated by Fig.6, where the calculated currents are compared with the currents recorded in the experiment with a 10-element DEMG ∅250 mm. in the experiment at n=4 the length of the foil was ℓ=20 cm, the thickness was δ=150 μm, the width was 66 cm.
To check a possibility of current peaking to ~100 ns, the calculations of the current formed in the load by the source on the basis of HEMG ∅240 mm were performed. The scheme of this source is presented in Fig. 7.

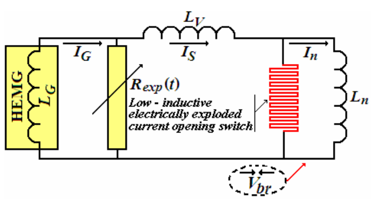
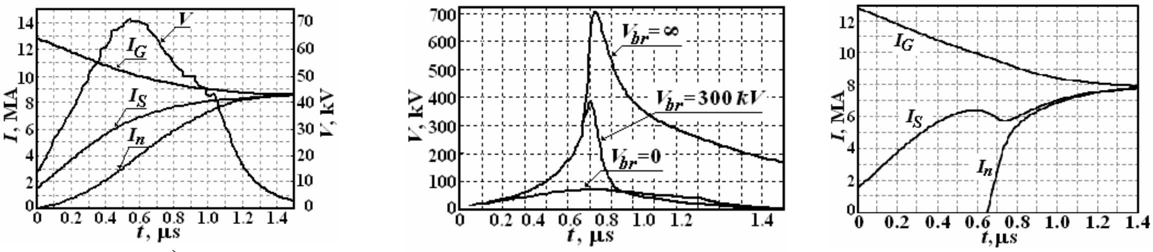


FIG. 7. Source of current on the basis of HEMG ∅240 mm and an explosive current opening switch.

Fig. 8a) shows the calculated time dependences of current and voltages on LEEOS (foil length is ℓ=0.6 m, thickness is δ=12 µm) during its operation with the current source from Fig. 8. The voltage on the foil is ~70 kV and no efficient current peaking is observed.



a) b) c)

FIG. 8. The calculated time dependences of currents in the load L_n=7.5 nH and of voltages on LEEOS: a) - without a discharger; b) – voltages at different V_{br}; c) – currents at V_{br}=300 kV.

On the other hand, with the open circuit "LEEOS – load" ($L_n=\infty$, Fig. 8a) the electrical explosion of the foil is effective, the voltage on it is as high as ~700 kV (Fig. 8b, $V_{br}=\infty$). Hence, it is necessary to "decouple" the LEEOS and the load at the stage of electrical explosion. This can be done by installing a discharger (in Fig. 7). The results of calculations with the discharger operating at the voltage V_{br}=300 kV are presented in Fig.8: the voltage on LEEOS is ~400 kV, the current in the load is 5 MA for 130 ns.
The vacuum low-inductive dischargers switching the current pulses at megavolt voltages for the time of <10 ns have been developed under BAIKAL program [10].

4. Sources of current on the basis of DEMG and of electrically exploded opening switches.

The scheme of the current source on the basis of DEMG for an implosion of Z pinch is presented in Fig. 9.

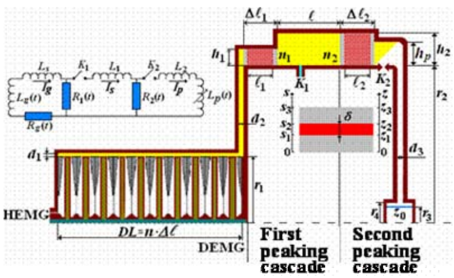


FIG. 9. Scheme of the current source on the basis of DEMG for Z pinch implosion.

In the result of electrical explosion of the foil in the first peaking cascade and operation of the explosive switch K_1 the magnetic energy goes to the circuit of the intermediate storage. The electrical explosion of the foil in the second cascade results in the operation of discharger K_2 and the energy is delivered to Z pinch via a through-pass dielectric.
The DEMG with flat disk elements [11,12], providing the maximum efficiency of HE energy conversion to the energy of magnetic field (20-25%), are used as the energy source. These DEMGs with three sizes of the disk elements: ∅250 mm with HE mass per a disk element of 0.9 kg/el; ∅400 mm with 3.3 kg/el; ∅1000 mm with 36 kg/el /13/ generate magnetic field energy per one element of E_{el}~1 MJ/el; ~4 MJ/el; ~40 MJ/el, respectively.
The effective generation of X-radiation is possible at the time of Z pinch implosion τ_{imp}≤120 ns. Constancy of τ_{imp} at the k-fold current rise $I'_p = k \cdot I_p$ can be provided due to an

increase of potential $V' = k \cdot V$ caused by an increase of the foil length $\ell' = k \cdot \ell'$. Herewith, the increase of inductances due to an increase of $h_i' = k \cdot h_i$ (i=1,2) is compensated by an increase of the foil location radius $r_2' = k \cdot r_2$ (see Fig. 9). The formulated scale parameters allow restricting to the calculations of the small class DEMG [12].

4.1 Disk EMG ∅250 mm

To describe the operation, it is necessary to know the inductances of the disk elements as a function of time $L_g(t)$ and the flux losses or resistance $R_g(t)$ as a function of time (see Fig. 9). Inductance as a function of time was taken from the gasdynamic calculations. The experiment was conducted to determine $R_g(t)$; the scheme of the experiment is given in Fig. 10.

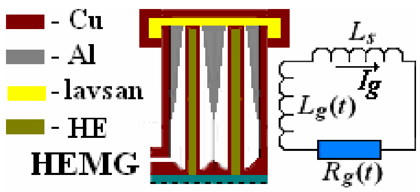


FIG. 10. Scheme of the model experiment with two disk elements ∅250 mm

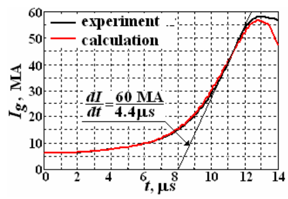


FIG. 11. Calculated (R_g=0.08·n mΩ) and experimental currents.

The analysis demonstrated that the generator operation can be rather well described with the resistance of a disk element constant in time R_g=0.08·n mΩ (see Fig. 11).

4.2. First cascade of current peaking

The electrical explosion of the foil is described by the equations (3) with boundary conditions (4-5).
The calculations were conducted for a 30-element DEMG ∅250 mm ($\Delta\ell$=3.3 cm). It was assumed that r_2=50 cm, L_s=10 nH, L_1=15 nH, V^*=100 kV, I_0=6.5 MA. Length and thickness of the foil were varied in the ranges: 80 cm≤ℓ_{f1}≤150 cm, 30 µs≤δ≤50 µm.
The maximum current and voltage on the foil are realized at δ=40 µm. Fig. 12 shows the solutions at ℓ_{f1} =100 cm, when the voltage is maximum.

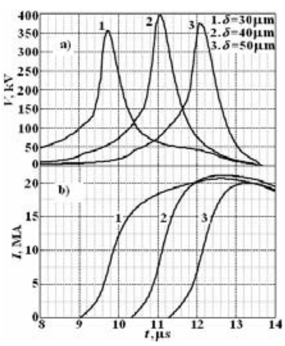


FIG 12. Calculated time dependences:
a) –voltage on the foil; b) –current in the load.

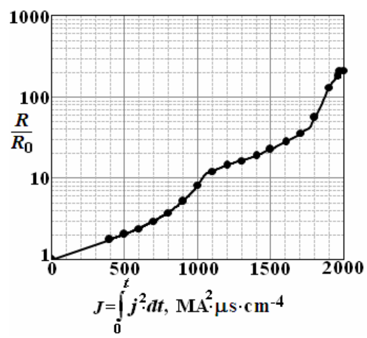


FIG. 13. Foil resistance as a function of current action integral at ℓ_{f1} =100 cm.

The inductance of the energy delivery to the foil L_s=10 nH can be provided at the following insulation thickness (see Fig. 9): d_1=3 mm; d_2=12 mm; h_1=10 cm (n_1=20,·ℓ_1=2.5 cm), $\Delta\ell_1$=6.9 cm. The strength of field in the dielectric does not exceed 60 kV/mm.
The foil resistance as a function of current action integral is presented in Fig. 13.

4.3. Second cascade of current peaking

The electric explosion of the foil is described by the equations (3). Currents I_s and I_p are determined from

$$\begin{cases} \frac{\partial}{\partial t}\left[(L_g(t)+L_s)\cdot I_g\right]+R_g(t)\cdot I_g+R_1(t)\cdot\left(I_g-I_s\right)=0, \\ \frac{\partial}{\partial t}\left(L_1\cdot I_s\right)+R_{K1}(t)\cdot I_s+E_y^{'}(s=s_1)\cdot\ell_{f2}=R_1(t)\cdot\left(I_g-I_s\right), \quad I_g\big|_{t=0}=I_0, \quad I_s\big|_{t=0}=0, \\ \frac{\partial}{\partial t}\left(L_2\cdot I_p\right)=E_y^{'}(s=s_2)\cdot\ell_{f2}, \quad I_p\big|_{t=0}=0. \end{cases} \qquad (7)$$

The length ℓ_2 and height of a "tooth" $\Delta h=h_2/n_2$ are determined by the developed technology $\ell_2/\Delta h=5$, i.e. $h_2=\ell_{f2}/10$. At the foil length ℓ_{f2}=2.5 m the inductance of LEEOS with regard for ℓ_2=7.5 cm will be ~3 nH. At h_p=8 cm the inductance of the dielectric-vacuum interface is ~2.4 nH. At d_3=0.5 cm, Z-pinch radius r_3=1.5 cm, height z_0=2 cm and r_4=2 cm the inductance of the vacuum supply of energy to Z pinch will be ~4.5 nH, and the total inductance will be L_2~10 nH.

When switching the current I_s~20 MA of the inductive storage L_1=15 nH (see Fig. 9) to the circuit of Z pinch with L_2=10 nH we should get the current $I_p \sim I_s \cdot L_1/(L_1+L_2)$ ~12 MA. To switch such current for the time Δt~120 ns, it is necessary to have the discharger breakdown voltage K_2 - $V_{br} \sim L_2 \cdot I_p/\Delta t$ ~1 MV.

Fig. 14 presents the voltage on the foil and the currents at ℓ_{f2}=2.5 m. The voltage is maximum and the time of current rise is minimum at the optimal thickness δ=10 µm.

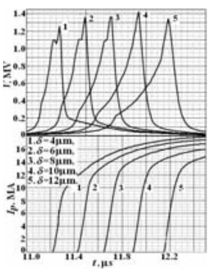


FIG. 14. Voltage and current as a function of time - ℓ_{f2}=2.5 m.

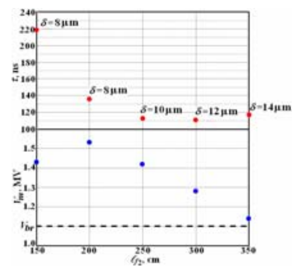


FIG. 15. Voltage and time of current rise to 12 MA at the optimal foil thicknesses.

Fig. 15 shows the optimal thicknesses and the corresponding voltages and current rise times as a function of foil length. The minimum rise time is observed at 2.5 m≤ℓ_{f2}≤3 m.

4.4. Z pinch implosion

Z pinch will be described by the equations (6). The initial conditions are: $r|_{t=0}$=1.5 cm; $v|_{t=0}$=0; z_0=2 cm.

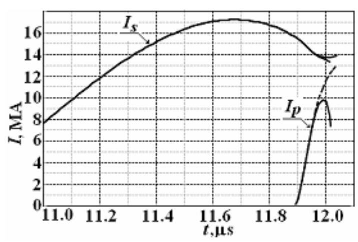


FIG. 16. Time dependences of currents of the source I_s and of Z pinch I_p at the liner mass m=3 mg.

In Fig. 16 one can see the time dependences of currents of implosion of Z pinch with mass *m*=3 mg. The source provided the implosion of Z-pinch at the current of ~10 MA for the time ~120 ns. At a 10-fold compression the velocity was ~500 km/s, the kinetic energy was ~360 kJ.

Mass of Z pinch *m*=3 mg is the optimal; it provides both high velocity and high kinetic energy of Z-pinch. Hence, the current source on the basis of a 30-element DEMG ∅250 mm and the system of the electrically exploded current opening switches transfers the kinetic energy of ~360 kJ to Z-pinch at a 10-fold implosion for the time of ~120 ns by the current with the amplitude ~10 MA.

5. Conclusion

The current source on the basis of a small-class DEMG can be created for the implosion of Z pinch for the time of ~120 ns at the current ~10 MA.

The parameters of recalculation of the characteristics of the small-class DEMG for the middle-class DEMG and for the super-power DEMG have been formulated. The analysis has demonstrated a possibility to realize implosion of Z pinches for the time of 120 ns with the use of the current sources on the basis of:

- a 30-element middle-class by the current I_m~25 MA;
- a 15-element super-power DEMG by the current I_m ~75 MA.

The parameters of the current source on the basis of a middle-class DEMG are close to the parameters of Z machine, and the source on the basis of a super-power DEMG will allow approaching the target ignition threshold [2].

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