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Energy efficiency of the High-Current Diode under the Blow-up Mode Evolution in the Anode

A. Adamenko¹, V. Novikov^{1,*}, V. Levchenko¹, V. Prokopenko^{1,2}, A. Shapoval^{1,2}, A. Pashchenko^{1,2}, V. Petukhov^{1,2}, I. Shapoval^{1,2}

¹Electrodynamics Laboratory “Proton – 21”, Kyiv, Ukraine

²National Science Centre “Kharkiv Institute of Physics and Technology”, Kharkiv, Ukraine

*Corresponding author

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energy flow,
mechanical deformation,
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ABSTRACT

The results of experimental studies of energy fluxes released during the diode target blow-up initiated by a high-current relativistic electron beam are presented in the paper. The energy of target explosion products required for realization of the observed diode structural elements deformation is being estimated. Measurements of the target explosion products parameters and finite-element modeling of the mechanical deformation of the cathode system elements show an energy release during the target explosion that far exceeds the energy input.

1. Introduction

Progress in solving inertial nuclear fusion problem in Proton-21 laboratory was made through the approach of self-organization and control of the evolution of complex systems using high-current relativistic diodes. The basic elements of the concept of controlled self-organizing fusion were published in a book edited by S. Adamenko et al [1] as well as in papers [2]-[10].

To date, since 1999, Proton-21 has accumulated a powerful database of the results experiments, some are described in [1] and [13]-[16], and the facilities themselves were protected by an international patent by S. Adamenko [11].

The first units developed in the laboratory (units of RVD type) were created on the basis of plasma opening switch. The units were the implementation of the duration of electron beam pulse in a diode reaching up to 40 nanoseconds, with the electron energy reaching up to 500 keV, and with the energy of electron beam during the pulse as high as hundreds of joules with the energy in primary capacitive storage up to 5 kJ.

As a result of the impact of an electron beam on the surface of the target anode, a nonlinear density wave is initiated and evolves in its body, moving from the surface to the optical center of the target with hyperbolic growth blow-up mode. In the central region of the target, the explosion of the target occurs and the products of its explosion are scattered in all directions with high velocities of about 10^6 cm/s or more.

Experiments were always accompanied by measurements, both in online and offline modes. In the online mode were measured:

- voltage and current pulses in the diode
- radiation in optical range
- X-ray and gamma-ray radiation

In the offline mode, for example, track [1,13-14] and mass spectroscopic measurements were conducted [1].

During the experiments at these units, the first results on self-organizing nuclear fusion in targets (anodes) made of various materials were obtained, and fusion products of both light and heavy elements were experimentally studied [1,11,16]. The mass of the target involved in the fusion processes in these experiments didn't exceed a few milligrams.

The next two units of Proton-21 laboratory, SING and ShAD with 30 kJ up to 55 kJ in primary energy storage, were designed to sequentially increase target mass and energy release in fusion reactions initiated by the impact of a high current pulsed electron beam on the target surface.

An increase in the mass of the target involved in the synthesis was possible to achieve both by increasing the power of the units, and accordingly, the energy of the pulsed electron beam from values of about kJ in the SING to values of about 10 kJ in the ShAD, and by increasing the radius of the target while maintaining the critical current density on the target. At the same time, in the ShAD, the mass of the part of the target involved in the synthesis approached values of the order of a gram.

In each experiment at the last generation units in the result of the impact of an electron beam with energies up to 10 kJ towards the surface of a target with a radius of millimeters, the energy release processes were initiated in blow-up mode (on blow-up mode, see, for example, [1,7,12]) and an explosion occurred in the central region of the target.

The anode-target explosion products and energy fluxes were dispersed from the central region and were observed by optical methods including: Doppler's spectral line broadening, time-of-flight method and high shutter speed recording of the explosion process and product dispersal.

The measurements trace the velocities of the product dispersal speed with values of the order of 10^7 cm/s. The products of target explosion performed the work on its deformation reaching the cathode system. This mechanical work was estimated as a result of mathematical modeling of the explosion products' pressure pulses impact on the cathode system.

Both simulation results and optical measurements lead to explosion product flux energy estimations in values of the order of hundreds of kJ.

The paper is devoted to presenting the results of these studies showing high energy efficiency of Proton-21's Q units (ratio of energy released in the process of target detonation to the primary storage energy), which is higher than 10.

2. The SING unit and mathematical modeling of deformation of its cathode system

The SING unit has become the result of the development of RVD type units, shown in Fig.1 A cathode system (electron beam source) and a target anode are located in the vacuum chamber (see Fig. 2). The cathode system consists of a copper rod on which a piece of plastic tube (PT) is put. The anode is made as a metal cylinder. 3 mm in diameter with a rounded end.

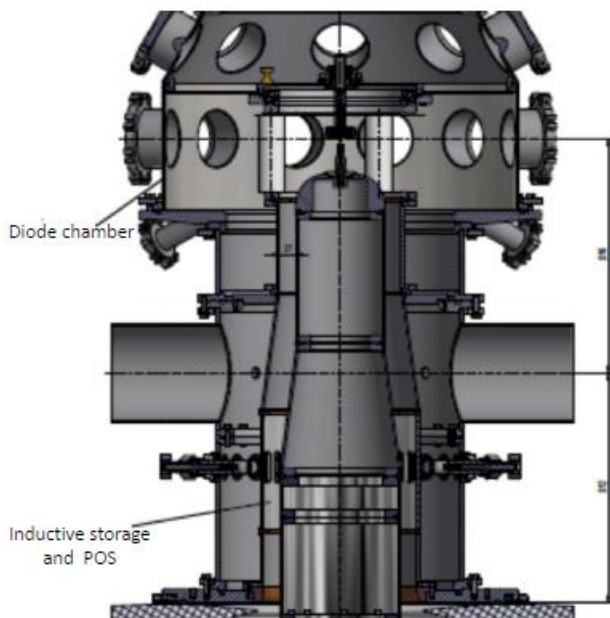


Fig.1. Sketch of SING unit with plasma disconnectors and diode

The SING unit's capacitive storage has a capacity of 1.875 μF and is usually charged to a potential difference of no more than 70 kV, i.e., the initial stored energy is about 50 kJ. The

energy of explosion products, flying out from the center of the target is clearly manifested by mechanical effect produced by their short impact on the structural elements and, in particular, on PT, which is being turned inside out on the cathode rod by this impact.

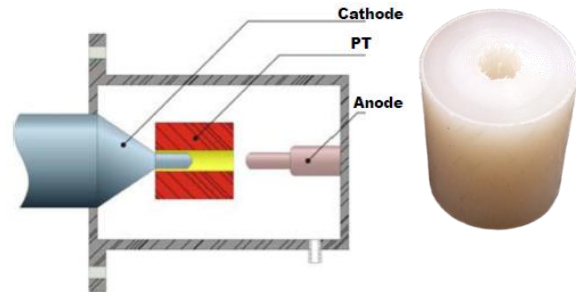


Fig. 2 Diagram of PT arrangement in diode and a picture of initial PT

The energy required for this is evaluated in the result of mathematical modeling of these processes by the finite element method [17].

The main evaluations were obtained for the PT model in the elasticity approximation of its shape change processes within the framework of mechanics of a deformable solid body.

For polymers at high loading rates and at amplitudes of force impact that do not let to viscous or brittle destruction elastic types of deformations are typical [18]. The plasticity mechanisms of polymers develop at sufficiently long exposure times (of the order of seconds and longer), and at force loading during the time of the order of microseconds and sufficiently large amplitudes, the stiffness of the material increases and, consequently, the energy required for deformation increases as well. It is claimed [19-20] that a polymer even in liquid state can exhibit elastic solid body properties with high strength when is subjected to a short-term load.

From the duration of electromagnetic processes in the diode and the determination of the time of the substance flows impact on the PT, it follows that the duration of the force impact on the tube is not more than 2 microseconds, i.e. the load is short-term. This testifies in favor of elasticity of the model, in which elastic processes would not have time to be realized, and consideration of elastic processes would lead to the need for even higher values of energy impacting on the PT within its same final states.

The flows of the substance acting on the tube were simulated by applying unsteady pressures to the finite element tube model surfaces, which were subjected to such influences according to the location of the PT in the diode (Fig. 2).

The magnitudes of pressure amplitudes during modeling ranged from tens of MPa to 10 GPa, the time of the force effect was investigated in the range from tens of nanoseconds

to tens of microseconds.

The whole set of experimentally observed final states of PT has been studied using simulation method. The solution to the inverse problem of determining the characteristics of the impact on the PT, which we obtained in the result of series of simulations of direct problems, showed this solution to be notably sensitive to the parameters of the impact, contained within a narrow range of the parameters' values, and the typical impulse load obtained in this way is shown in Fig. 3.

In the calculations we used data on composition and velocities of particle flows obtained from optical spectra.

The front of pressure pulse on PT is formed by a flux of light elements and elements with middle atomic masses. Following these elements, next to approach the surface of a tube are heavy elements which then form the maximum pressure.

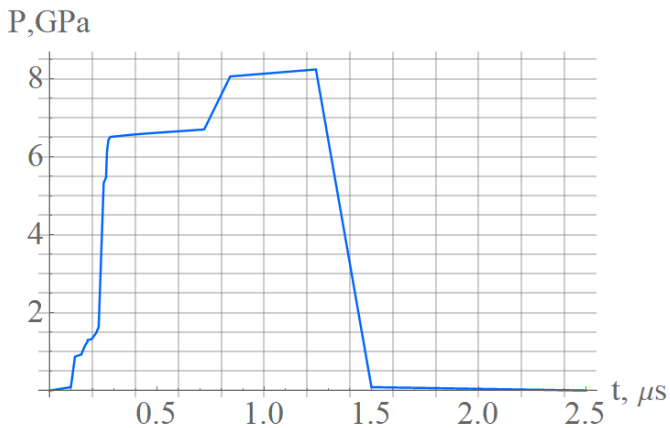


Fig. 3 Typical shape of pressure impulse on PT

The flows of heavy elements are propagating near the PT surface in the medium formed from earlier approached flows, wherein the pressure is damped and the curve of the pressure on the tube surface drops at the final stage. The duration of this process is less than 2 microseconds and front about 100 ns.

In conditions of diode chamber and electromagnetic fields formed in it the fluxes of particles with different masses form two impacts - to the end face of the tube and to the inner surface of the tube.

The lighter elements reach the surface of the tube along curved trajectories, while the heavy ones along almost rectilinear paths. During the time of about 1.5 microseconds the hydrodynamic pressure pulse of 9 GPa consisting from components of heavy elements is formed at the end of the tube. At the same time, depending on the experimental conditions, almost all studied components find themselves in the region of the tube's cavity.

Upon reaching the change of PT shape in the model which is well consistent with the deformations observed

during the experiments, the process of minimizing the received PT energy took place. For this purpose, the initial configuration of the loads was subjected to variations in which a decrease in the acquired PT energy preserved the type of deformation under consideration.

In the elastic approximation, there is no energy dissipation and during the exposure the energy of the tube consists of two components - deformation and kinetic. The kinetic energy of the tube is the energy of motion of its constituent parts irrespective of whether the center of mass moves or rests.


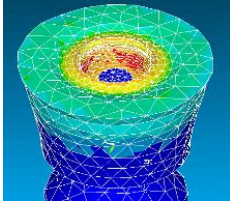

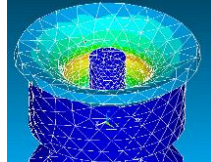

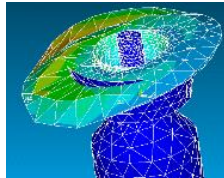
Comparison of PT shapes after exposure in the experiment and results obtained in the simulation are shown in Table 1.

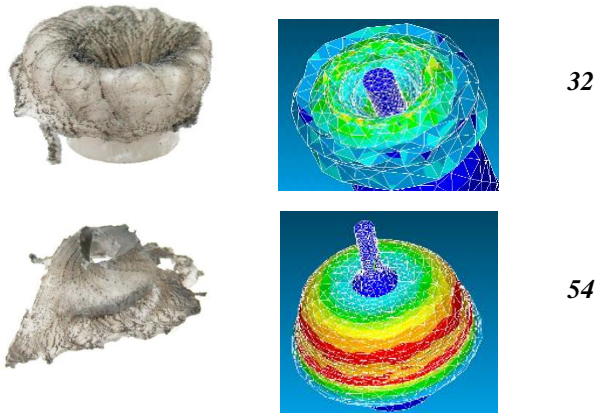
The right column shows the minimum flow energy values required to achieve the appropriate PT shape.

In the course of dispersal, the fluxes of heavy elements have almost isotropic nature of dispersal and, consequently, a fraction of this flux corresponding to solid angle of the tube from the initial product dispersal sphere enters the tube cavity.

According to the measurement data, heavy elements account for $\sim 2/3$ of the optically measured fraction of the energy of the explosion products flux, so we can simply estimate that the energy delivered to the tube, taking into account the solid angle of the tube end, is 2.4 times less than the flux energy. Thus, in order for 40-50 kJ to be delivered to the tube region, as previously estimated, it is necessary for about 90-120 kJ to be released in the explosion region.

Table.1. Comparison of experimental and simulational final states of PT

<i>PT states in the experiment</i>	<i>PT states by simulation</i>	<i>kJ</i>
		10.7
		16.4
		18



The use of plasma opening switch in the SING unit allowed to obtain the conversion of only a few percents of the energy of the capacitive storage into the energy of the electron beam, and the energy efficiency according to the evaluation of the cathode system deformation results in values in the range from 2 to 3, at the same time the released energy in relation to the driver (electron beam) energy turns out to be quite high and can reach values of the order of 10^2

3. ShAD unit and target explosion energy

In order to increase unit's and explosion energy's stability, the ShAD unit was designed with high voltage pulse amplitude greater than MV and currents of the order of 200 to 300 kA based on a DFL. A sketch of the ShAD unit is shown in Fig. 4.

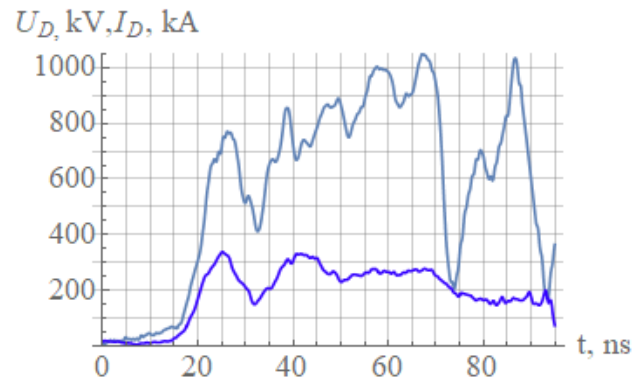
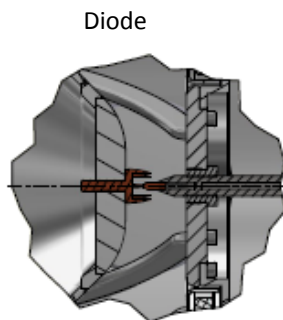
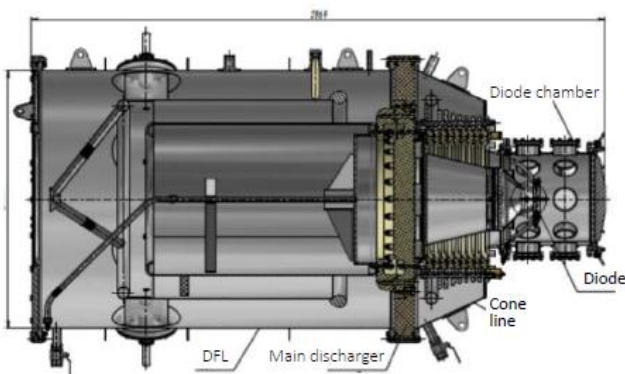


Fig.4. Sketch of the DFL and diode of the ShAD unit. Typical oscillograms of current (lower curve) in the electron beam and voltage (upper curve) on the diode (experiment number 41317) on the bottom.

High currents in the unit allow to obtain critical values of current [21] on the surface of the target with radius in a few millimeters and, therefore, capture a sufficiently large mass of matter in a non-linear wave to the center [1]. The explosion is initiated in the central region of the target, and products of its explosion are flown in all directions with velocities of about 10^7 cm/s.

The velocities of explosion products were measured using optical methods:

- Using Doppler's spectral line broadening
- By recording the time of reaching the optical radiation of three points located at different distances from the explosion center

In addition, optical imaging of the explosion process was carried out.

In processing the measured optical spectra standard spectral line contours were used [22,1]. An example of the optical spectrum from the explosion region is shown in the figure in Table 2.

At first, an operation to exclude the contributions made by instrumentation function of the device was performed, the data on which were obtained in the result of the mercury lamp spectrum measurements. Then the measured spectrum was decomposed into its components, i.e. into separate spectral lines. During the processing, the width and shape of the line were varied until an optimal concurrence between the total contour of spectral lines and experimental points was reached.

The results of measurements of the composition of the dispersed fluxes in the experiment with a hafnium target are presented in Table 2.

The average particle velocity of this flux during this experiment obtained using the Doppler's line broadening of the optical spectrum was about $6 \cdot 10^6$ cm/s. In the experiments, the flux velocities vary, but mainly lie in the

range from $2.0 \cdot 10^6$ cm/s to $1.9 \cdot 10^7$ cm/s.

The velocities of the dispersed flows were also estimated using the time-of-flight method, which showed values close to those obtained by Doppler's broadening.

The radiation from the given points was recorded using a monochromator (see Fig. 5), and knowing the distance between the measuring points and obtained time intervals of the optical signal appearance we get the velocities of the target explosion products flux propagation.

A small part of the explosion product fluxes at the flyout from the target center (proportional to the cathode element solid angle) interacted with the cathode elements and performed mechanical work to deform it.

Figure 6. shows typical states of the cathode - anode system before and after the explosion in the area of the target center

Table 2. Composition of dispersed flows from the center of the plumbum target and the optical spectrum used to reconstruct ion numbers and their velocities for experiment 41250

Element	10^7 cm/s	%
H		2.15
C	0.263	1.48
B	0.742	0.72
Na	0.524	1.38
Al	0.222	2.03
Ca	0.540	1.84
Ti	0.442	1.56
Cr	0.251	0.56
Mn	0.321	2.26
Fe	0.501	5.74
Cu	1.040	10.39
Zn	0.525	8.67
Hf	0.402	0.89
Pb	0.914	60.34

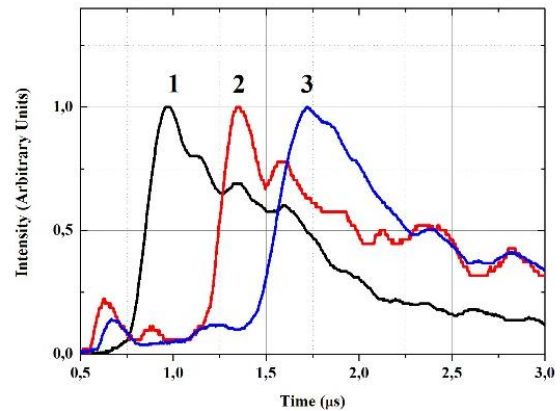
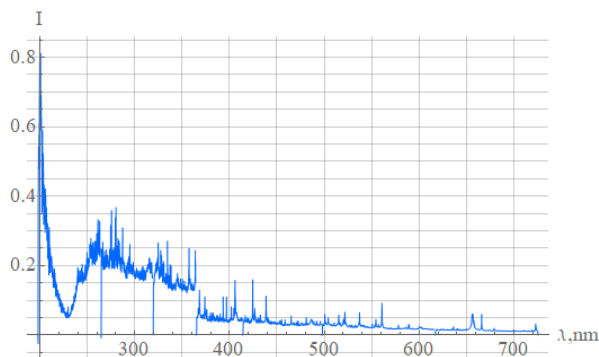


Fig. 5. Intensity of the light registered using a monochromator (NP250-2M) at different points and calculation of the target explosion products velocities.

$$u_{1-2} = 0,9\text{cm}/0,379\mu\text{s} = 2,38 \cdot 10^6 \text{cm/s};$$

$$u_{1-3} = 1,8\text{cm}/0,750\mu\text{s} = 2,40 \cdot 10^6 \text{cm/s};$$

$$u_{2-3} = 0,9\text{cm}/0,371\mu\text{s} = 2,42 \cdot 10^6 \text{cm/s}.$$



Fig. 6. Sketches of cathode - anode system before explosion (left) and after explosion (right). The cathode-anode system as part of the unit is shown in the sketch, see Figure 4.

The key role in the transparency of the medium for optical observations is played by Rosseland free path for the light quantum in the medium [23]:

$$l_p = \frac{10^{22} T^{7/2}}{z n^2} \begin{cases} 480 z^{-2} \\ 1.3(z^2 + z)^{-1} \\ 4.4(1 + z)^{-2} \end{cases}$$

where T is for plasma temperature in degrees, z is for degree of ionization of atom emitting a quantum of light, n is for density of ions in the medium of quantum propagation, one of three possibilities after the curly bracket represents features of realizations of light absorption in the medium (free-free transition of photons, single ionized, multiply ionized atoms).

If the medium's size exceeds the value of the Rosseland free path for the light quantum emitted by the atom, the quantum is absorbed by the medium and an optical device, of course, does not register it.

The ion density for the spherical expansion approximately decreases quadratically with the radius. Optical measurements in our experiment integrate the whole process from the beginning of the explosion to the moment of contact of the expansion sphere with the walls of the diode chamber.

In the course of this process the ion density decreases to the limits determined by the maximum possible radius of the expansion sphere. For the initial moment of the dispersal we obtain Rosseland free path, which is negligibly small in comparison with the radius at which the process is observed – such radiation cannot be recorded.

The ratio of the energy E_0 , contained in the transparent layer to the energy E_s of the exploded layer with energy approximately uniformly distributed on it will be equal to the ratio of the volumes of these layers. In the present case the energy of the explosion is greater than the one observed optically and E_s / E_0 is in the range from 300 to 3000

The explosion processes in the diode were also recorded using high-speed CCD-cameras. From the obtained images it was possible to estimate some representative times of the processes: it took about 50 nanoseconds for expanding cloud which was formed from the explosion of the target to pass through the gap of 1 cm, and the copper cathode elements bending took less than 500 nanoseconds.

Although the main efforts in the facilities have been made to recording the explosion energy and thorough analysis of fusion products (as in the case of low-power RVD-type facilities), fusion products in the form of rare elements had also being registered (see Fig. 7), which indicates the processes in the target at the nuclear level.

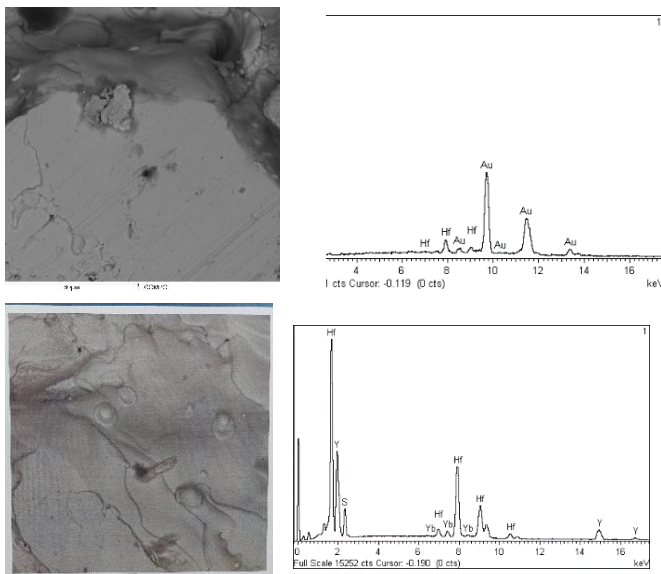


Fig. 7. Macroscopic accumulations of Au (top) and Yb and Y (bottom elements) on the target's remnants after the explosion of a hafnium target. A picture taken from the electron microscope on the left, the corresponding sections of the X-ray spectrum on the right.

Taking into account that the mass loss during explosion from different experiments ranges from 0.1 g to 0.9 g, and the velocity of this mass is in the range $(0.5-1.9) 10^7$ cm/s, the target explosion products energy can be estimated in the

average value from 300 kJ to 1 MJ

4. Conclusion

Experiments on nuclear fusion in high-current diode targets in Proton-21, which were started at small units with electron beam energy about 0.1 kJ and with target masses about 10 milligrams [16] were continued at units with beam energy about 10 kJ and with target masses about grams.

In experiments at such low-power units, fusion products in a wide range of nuclear masses were recorded [1,16].

At the high-power SING and ShAD units, it was possible to reach the release of energy during an explosion, that occurred in the center of the target after the processes initiated using electron beam on its surface.

The primary storage energy at the input of the SING and ShAD units ranged in 30 kJ-55 kJ, and the explosion energy released in the target center, estimated using optical measurements presented in this paper, ranged from 300 kJ to 1 MJ. Thus, the energy efficiency Q of the Proton-21's units was brought to an average values in the range of 10 to 30.

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