РОСАТОМ

ГОСУДАРСТВЕННАЯ КОРПОРАЦИЯ ПО АТОМНОЙ ЭНЕРГИИ «РОСАТОМ»

РФЯЦ ВНИИЭФ

STUDY OF PHYSICAL PROCESSES AT HIGH ENERGY DENSITIES WITH THE USE OF EXPLOSIVE MAGNETIC GENERATORS

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One of the methods to produce high energy density during modeling of physical processes and studies of material properties is to convert the kinetic energy of a high-velocity shell or a liner.

Traditionally, the liners are driven by:

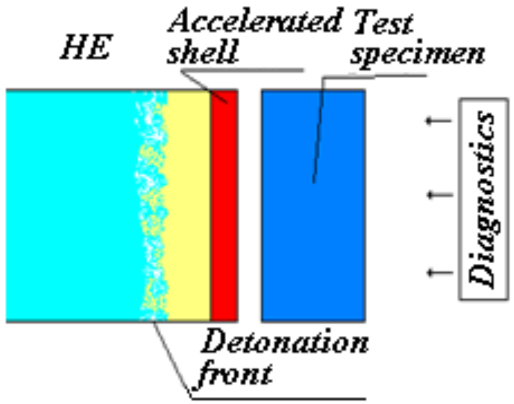
- an explosive charge (HE) on gas-dynamic complexes;
- a current pulse on electrophysical facilities;
- radiation on laser facilities.

In accordance with the solution proposed by E.I. Zababakhin, the maximum velocity of the incompressible liquid shell W_k is related to the detonation wave velocity D as

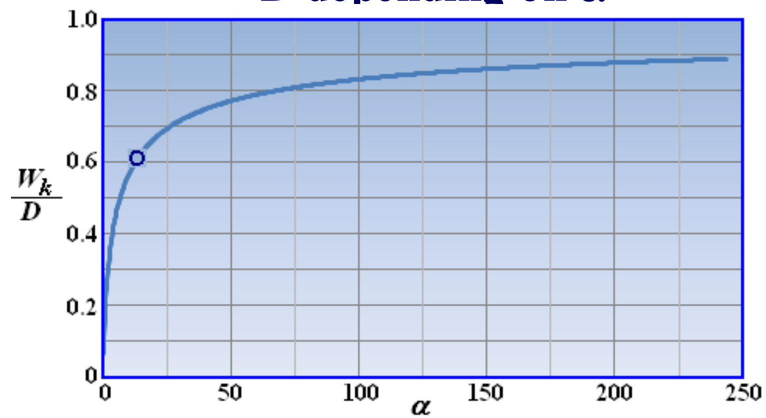
$$\frac{W_k}{D} = \left[1 + \frac{27}{16\alpha}\left(1 - \sqrt{1 + \frac{16}{27}\alpha}\right)\right]$$

where α is the ratio between the mass of HE unit area and shell unit area.

Scheme of experiments



Shell velocity W_k as a function of detonation rate D depending on α



At α=12.5 - W_k/D=0.6. At the detonation velosity equal to D=9 km/s, we get W_k≈5.4 km/s.

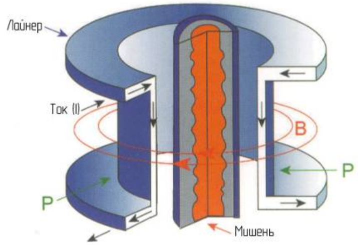
Intensive shock wave

(v_0=0, p_0=0, ε_0=0)

$$\begin{cases} p_1 = \frac{\delta}{\delta - 1} \cdot \rho_0 v_1^2, \\ \varepsilon_1 = \frac{v_1^2}{2}, \quad \delta = \frac{\rho_1}{\rho_0} \text{ -compression} \end{cases}$$

When the impactor and the target are from the same material, the shock wave velocity is $v_1 = W_k/2$=2.7 km/s, specific energy is ε_1 = 0.004 MJ/g. Pressure:
for aluminum shell p_1=0.2 Mbar;
for iron shell p_1=0.6 Mbar.

Scheme of loading



Liner motion equation

$$\begin{cases} m\dfrac{d\vartheta}{dt} = -\dfrac{\mu_0 I^2}{4\pi r} \\ \vartheta = \dfrac{dr}{dt} \end{cases}$$

Here t – time, r – coordinate, ϑ - velocity, I – current, $m = 2\pi\rho_0 r_0 h$ – linear mass (ρ_0, h and r_0 – matter density, thickness and initial position of the liner).

In dimensionless form

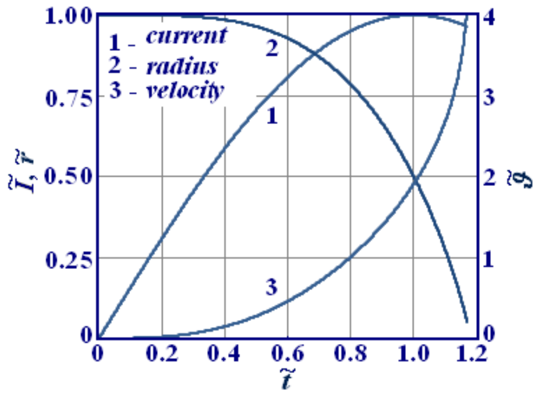
$$\tilde{r} = r/r_0,\ \tilde{t} = t/\tau,\ \tilde{\vartheta} = \vartheta/\vartheta_0 = \vartheta\cdot\tau/r_0$$

(τ - time of maximum current achievement I_{max})

$$\begin{cases} \dfrac{d\tilde{\vartheta}}{d\tilde{t}} = -\Pi\dfrac{\tilde{I}^2}{\tilde{r}} \\ \tilde{\vartheta} = \dfrac{d\tilde{r}}{d\tilde{t}} \end{cases}$$

Parameter $\Pi = \dfrac{\mu_0 I_{max}^2 \tau^2}{8\pi^2 \rho_0 h r_0^3}$ determines the scaling of liners.

At Π=3 the liner travels half of initial radius at the moment of current maximum and its velocity is $v \approx 2r_0/\tau$ (see the plot).



Current $I/I_{max} = \sin(\pi/2\cdot t/\tau)$, radius and velocity of the liner as a function of time at Π=3.

The liner is stable during acceleration on the base $N \le 5$ of initial thicknesses ($h = r_0/(2N)$). So,

$$v = \left(\frac{4\mu_0 N}{\pi^2\Pi}\right)^{1/4}\frac{1}{\rho_0^{1/4}}\cdot\sqrt{\frac{I_{max}}{\tau}} \Rightarrow v\,[\text{km/s}] = \frac{5.4}{\rho_0^{1/4}[\text{g/cm}^3]}\cdot\sqrt{\frac{I_{max}[\text{MA}]}{\tau[\text{mcs}]}}.$$

When the impactor and the target are made from the same material, the shock wave velocity is $v_1 = v/2$.

For the EMG with opening switches of microsecond range

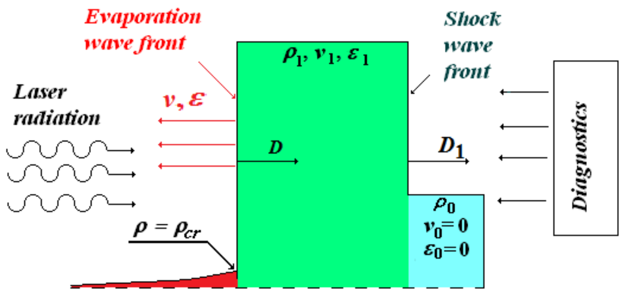
$I/t \le 50$ MA/μs and for AL (ρ_0=2.7 g/cm^3):

v_1=15 km/s; ε_1=0.1 MJ/g; p_1=6 Mbar.

When the pulse front is reduced to 100 ns:

v_1=45 km/s; ε_1=1 MJ/g; p_1=55 Mbar.

Loading scheme



Let's take that the LR energy is absorbed at density $\rho_{cr}=\pi \cdot A/Z \cdot m_p \cdot m_e \cdot (c/\lambda e)^2$.

Front conditions

$$\begin{cases} (v_* - D)\cdot\rho_* = (v - D)\cdot\rho \\ p_* + \rho_*(v_* - D)^2 = p + \rho(v - D)^2 \\ \varepsilon_* + \dfrac{p_*}{\rho_*} + \dfrac{(v_* - D)^2}{2} + \dfrac{S}{\rho_*(v_* - D)} = \varepsilon + \dfrac{p}{\rho} + \dfrac{(v - D)^2}{2} \end{cases}$$

Index «*» relates to the values behind the wave front. S is laser radiation flux power.

Intensive shock wave

($v_0=0$, $p_0=0$, $\varepsilon_0=0$)

$$\begin{cases} p_1 = \dfrac{\delta}{\delta - 1}\cdot\rho_0 v_1^2, \\ \varepsilon_1 = \dfrac{v_1^2}{2}, \quad \delta = \dfrac{\rho_1}{\rho_0} \text{ -compression} \end{cases}$$

Evaporation wave front

Velocity of plasma flow is $v\text{-}D_1=-c_0$.

At adiabatic process:

-sound speed $c_0=(\gamma p/\rho_{cr})^{1/2}$; pressure $p=1/\gamma \cdot \rho_{cr} c_0^2$.

For ideal gas $\varepsilon = \dfrac{p}{(\gamma - 1)\rho_{cr}} = \dfrac{c_0^2}{\gamma(\gamma - 1)}$

Taking this into account and the condition on the front of the intensive shock wave

$$\begin{cases} \dfrac{\delta}{\delta - 1} v_1^2 = \dfrac{\rho_{cr}}{\rho_0} c_0^2 \cdot \left(\dfrac{\gamma + 1}{\gamma} - \dfrac{1}{\delta}\cdot\dfrac{\rho_{cr}}{\rho_0}\right) \\ \left(\dfrac{\gamma + 1}{\gamma - 1} - \dfrac{1}{\delta^2}\cdot\dfrac{\rho_{cr}^2}{\rho_0^2}\right)\cdot\dfrac{c_0^2}{2} - \dfrac{\delta + 1}{\delta - 1}\cdot\dfrac{v_1^2}{2} = \dfrac{S}{\rho_{cr}\cdot c_0} \end{cases}$$

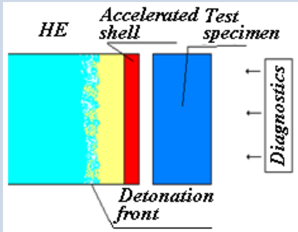
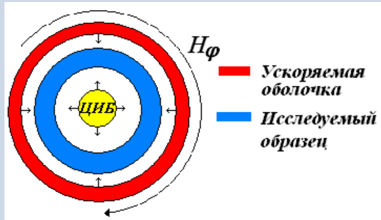
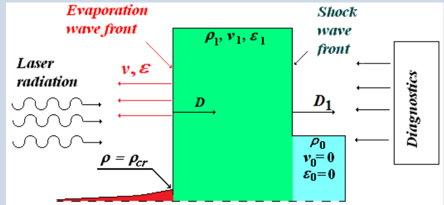
After the transformations we have ($\rho_{cr}/\rho_0 \to 0$, $\delta/(\delta\text{-}1) \to 1$)

$$\begin{cases} p_1 \approx 2\cdot\rho_{cr} c_0^2 \\ \varepsilon_1 = \dfrac{v_1^2}{2} = \dfrac{\delta - 1}{\delta}\dfrac{\rho_{cr}}{\rho_0} c_0^2 \cdot \left(\dfrac{\gamma + 1}{\gamma} - \dfrac{1}{\delta}\cdot\dfrac{\rho_{cr}}{\rho_0}\right) \approx \dfrac{\gamma + 1}{\gamma}\cdot\dfrac{\rho_{cr}}{\rho_0} c_0^2 \\ S = \dfrac{1}{2}\cdot\rho_{cr}\cdot c_0^3 \cdot \left(\dfrac{\gamma + 1}{\gamma - 1} - \dfrac{\delta + 1}{\delta}\cdot\dfrac{\rho_{cr}}{\rho_0}\cdot\dfrac{\gamma + 1}{\gamma} + \dfrac{1}{\delta}\cdot\dfrac{\rho_{cr}^2}{\rho_0^2}\right) \approx \dfrac{1}{2}\cdot\dfrac{\gamma + 1}{\gamma - 1}\cdot\rho_{cr}\cdot c_0^3 \end{cases}$$

The limiting value is $S_m \approx 10^{15}$ W/cm². At $\lambda=1$ μm -$\rho_{cr} \approx 4\cdot 10^{-3}$ g/cm³.

In the result for aluminum (ρ_0=2,7 g/cm³) we get:
$c_0=1{,}26\cdot 10^8$ cm/s; $v_1 \approx 62$ km/s; $\varepsilon_1 \approx 1.9$ MJ/g; $p_1 \approx 100$ Mbar.

Comparison of the research methods

	Gas-dynamic complexes	Electrophysical methods	Laser methods
Loading schemes			
Pressure	accuracy ~5%	$=H_\varphi^2/8\pi$ - accuracy ~ 1%	accuracy ~5%
Scales	1- 10 cm	1- 10 cm	0.1-1 mm
Symmetry	perturbation from the initiation system, instability on the detonation front	high	inhomogeneity of LR spot
Recovery of specimens	practically impossible	possible at shell velocities ≤ 1 km/s	practically impossible
Control of impact	possible on a limited scale	possible	possible by profiling the LR pulse

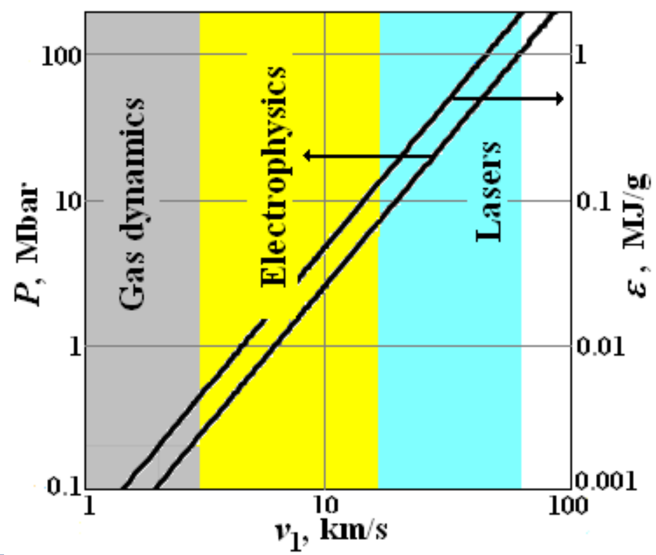
By this means:

Electrophysics

Control of impact, accuracy → **Gas-dynamics**

Scaling factor, accuracy → **Lasers**

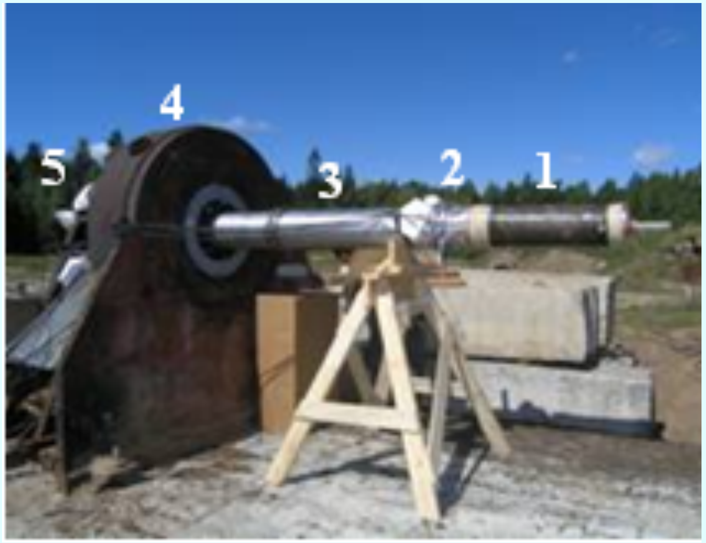
Specific energy and pressure as a function of time



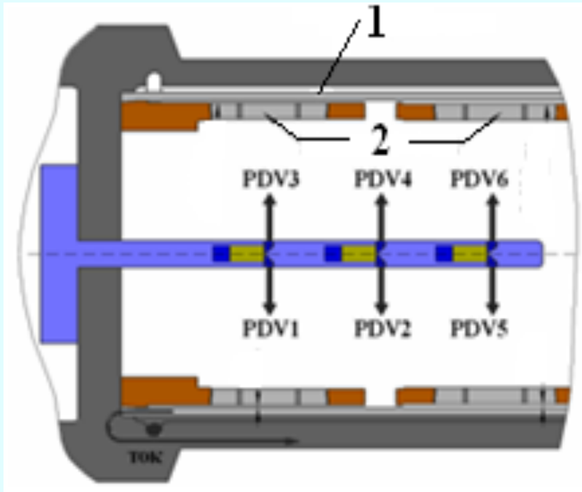
1. Low specific energies (≤ 10 kJ/g)

Of interest is the study of spall damage, dynamic strength, ejecta at shock wave release to surface.

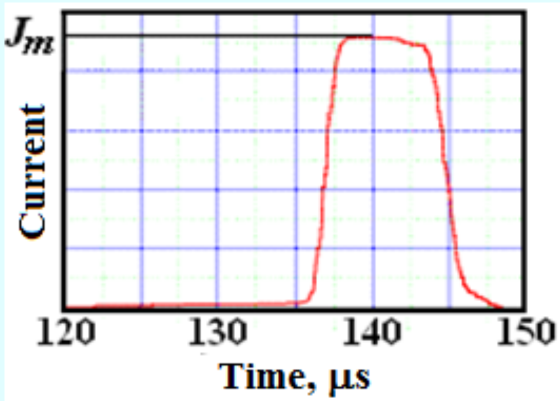
Experimental test bench



Outer view of experimental facility:
1- HEMG;
2 - units of current peaking and interruption;
3 - wave line;
4 - explored specimens protection;
5 - load



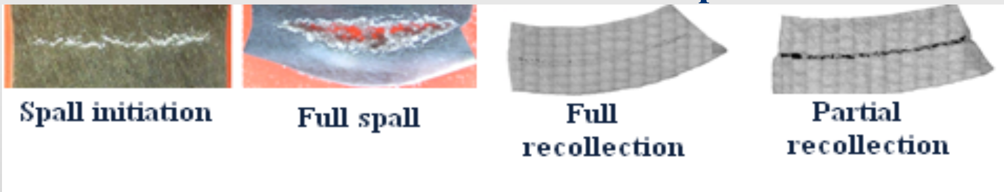
Loading scheme:
1 – driven liner;
2 – cylindrical targets from explored material.

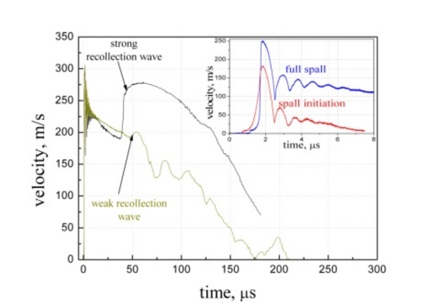


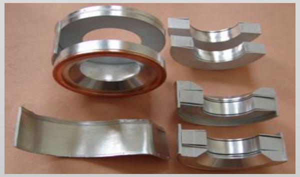
Current pulse:
amplitude to 10 MA;
controlled duration to ~30 μs;
rise and drop time ~2 μs.

Spall strength of matter. Series *R-damage* (10 experiments *AL*)

For the first time representative information was obtained on initiation, growth, full and partial recollection of spall in metal.







Recorded velocities of targets' inner surface.

ДОКЛАДЫ АКАДЕМИИ НАУК, 2013, том 448, № 3, с. 285–288

ФИЗИКА

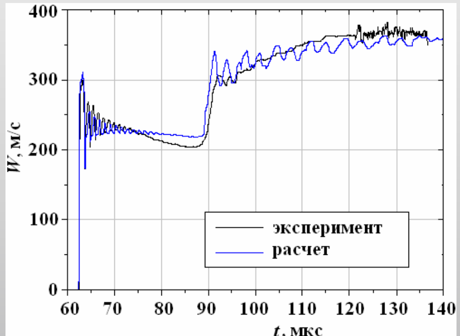
УДК 539.4

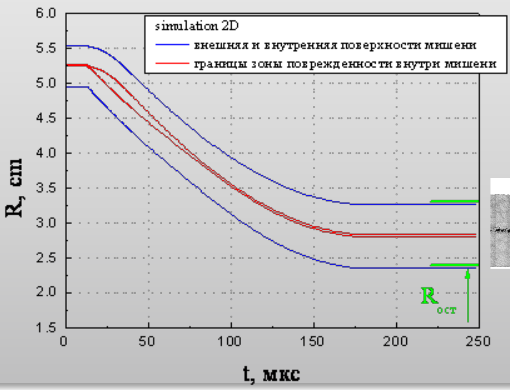
ИССЛЕДОВАНИЕ РЕОЛОГИЧЕСКИХ СВОЙСТВ АЛЮМИНИЯ С ПРИМЕНЕНИЕМ ВЗРЫВОМАГНИТНЫХ ГЕНЕРАТОРОВ

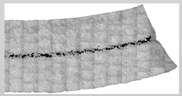
© 2013 г. В. А. Васюков, А. М. Глыбин, П. В. Дудай, В. И. Дудин, А. А. Зименков, В. А. Иванов, А. В. Ивановский, А. И. Краев, А. И. Кузяев, С. С. Надежин, А. А. Петрухин, А. Н. Скобелев, О. А. Тюпанова, W. L. Atchison, D. B. Holtkamp, A. M. Kaul, R. E. Reinovsky, G. Rodrigues, L. J. Tabaka, C. L. Rouscalp, J. B. Stone, D. M. Oro, M. Salazar, J. R.Griego, J. R. Payton, D. T. Westley

Представлено академиком Р.И. Илькаевым 30.03.2012 г.
Поступило 18.07.2012 г.

The results allowed verifying the numerical models of spall damage and recollection of damaged medium.







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Damage growth and recollection in aluminum under axisymmetric convergence using a helical flux compression generator

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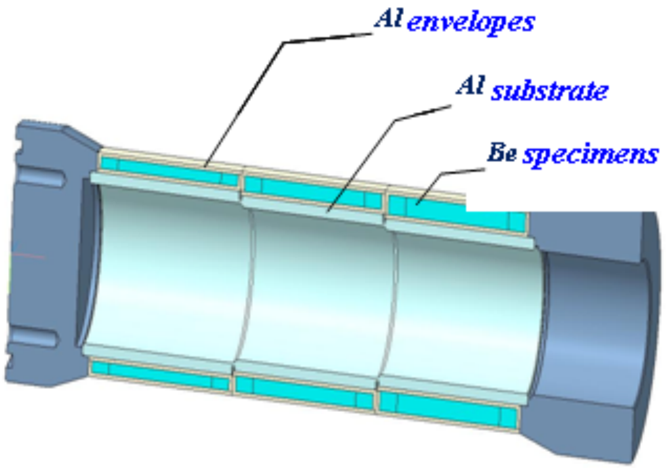
We have started the experiments to study the shear strength of beryllium

Target unit



The *Be* specimens 3, 4, 5 mm thick are enveloped into *Al* 1 mm thick to collect the debris in case of fragmentation.

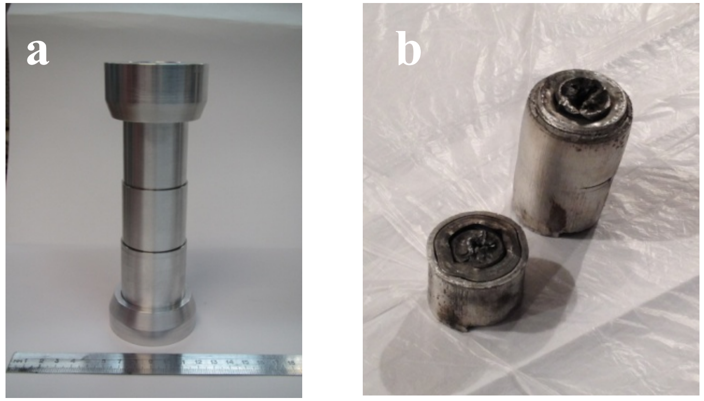
In order to avoid the spall damage in *Be*, the targets were placed on the aluminum “sacrificial” substrate 3 mm thick.

The current is flowing in 2 mm-thick *Al* liner.

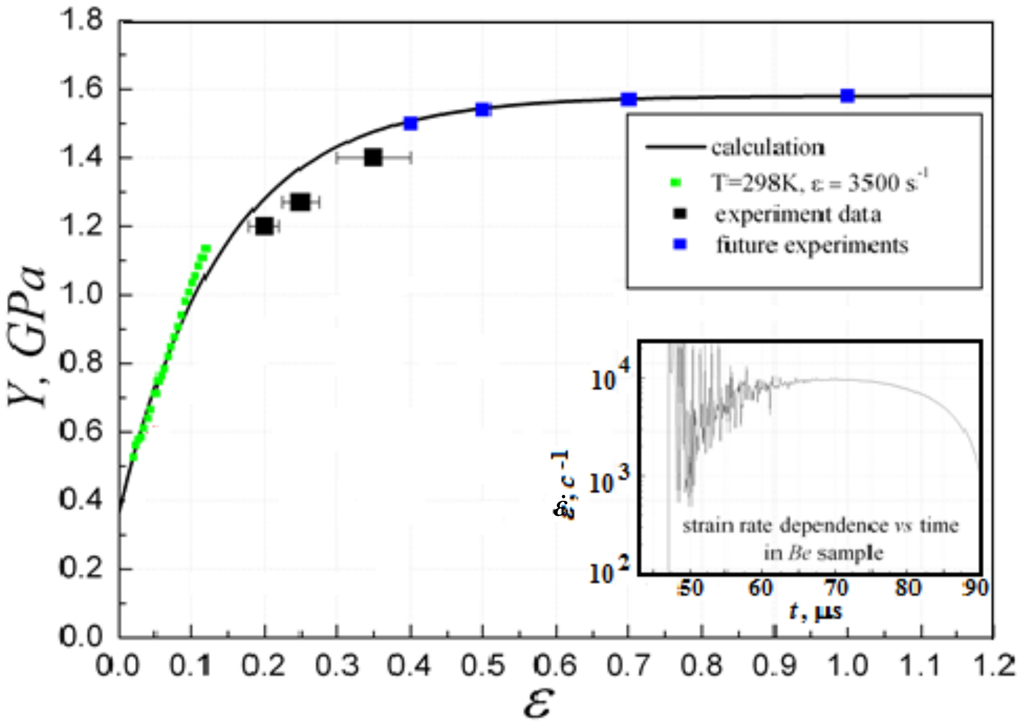
In the first experiment the liner was driven to ~ 1 km/s. that provided pressure of ~10 GPa during impact on the target.

The expected information on of the liner and targets velocities was obtained.

We managed to avoid the targets implosion to the axis. The test specimens were recovered for metallographic analysis.



Target unit with *Be*:
before experiment –a;
after experiment –b.

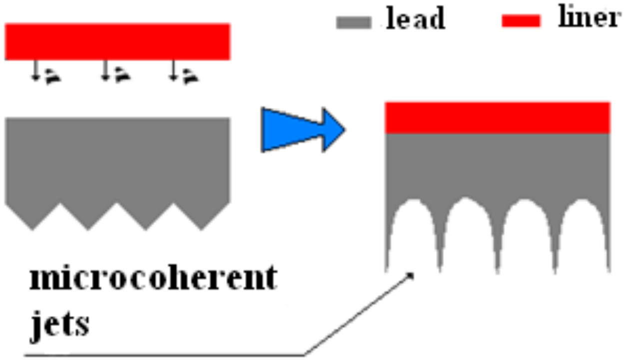


The shear strength data at the strain rate $\dot{\varepsilon}$ = 0.5÷1·10^4 s^{-1} have been obtained.

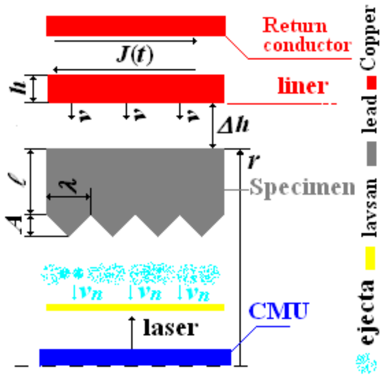
In the next experiment we plan to get higher levels of plastic deformation ε ~ 0.4÷1.0 while preserving the strain rates within the same range.

The ejecta of lead at shock wave release to the surface

Process scheme



Experimental scheme



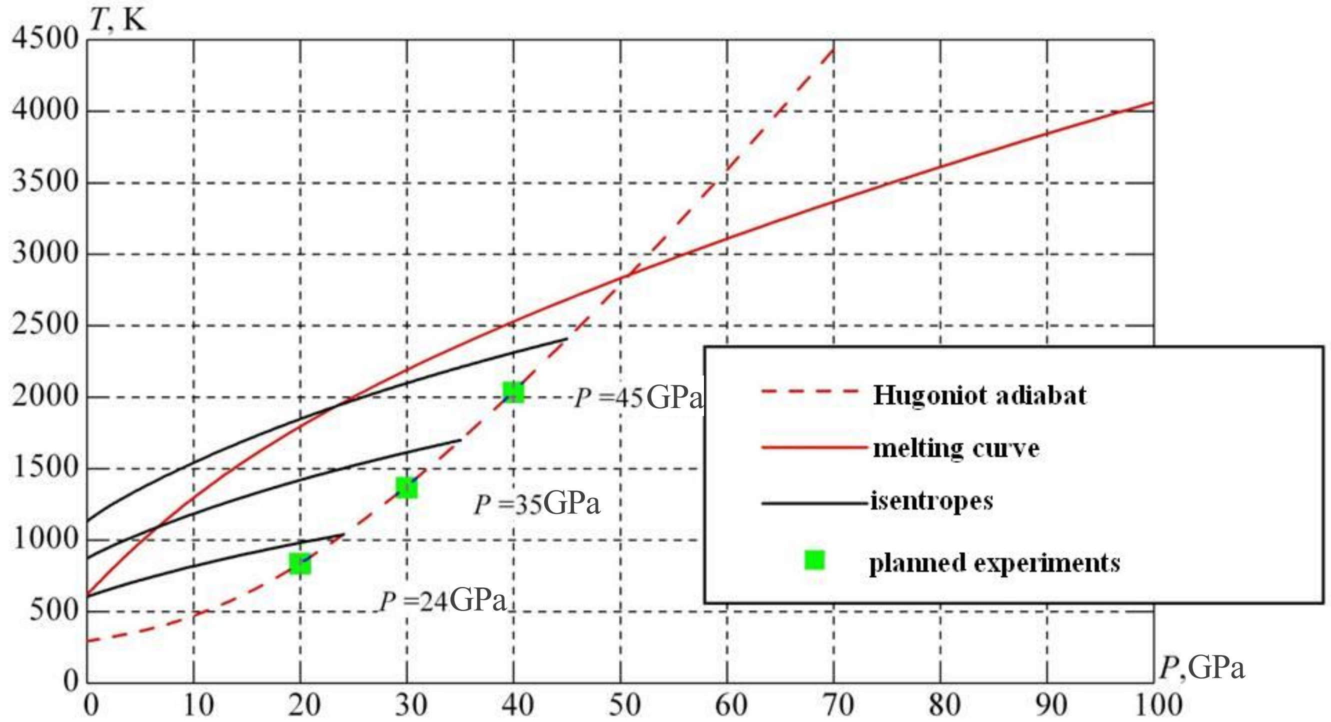
A series of experiments was realized. 5-6 specimens were loaded in every experiment.

- The specimens differ in surface finish - amplitude to 80 µm, wave length to 400 µm.
- *Cu*-liner thickness is h=1 mm. The current is the same in all experiments J_m = 10 MA, τ = 30 µs.
- The radius of the samples' surface changed the from experiment to experiment, that allowed varying pressure from 20 to 40 GPa.

In experiments we measured the current, the velocities of the liner, of ejecta–v_n and of lavsan tape - v_L with linear mass m_L (PDV). The linear mass of ejecta m was estimated by

$$m = m_L \cdot \frac{v_L}{v_n - v_L}$$

The ejecta processes were studied without dynamic diversity of effect caused by the system of HE initiation and by instabilities on the detonation front.



In the range of shock wave pressure of 20 - 40 GPa lead can both stay solid and turn to liquid at unloading wave.

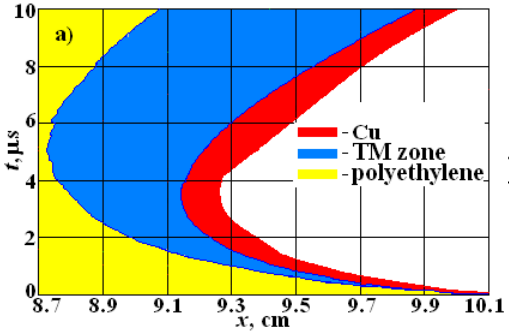
Analysis of results of the experimental series (green dots) will make it possible to evaluate the effect of the phase state of lead on the parameters of ejecta process.

2. Intermediate specific energies (10^{-2} MJ ≤ ε ≤ 10^{-1} MJ/g)

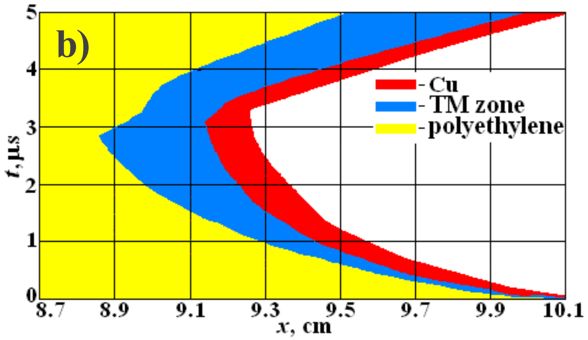
Of interest are the studies of turbulent mixing (TM) and equations-of-state (EOS) of matter.

Turbulent mixing (TM)

- **The study with solid bodies on gas-dynamic complexes at velocities of ~5 km/s is impossible because of the elastic-plastic effects impeding the development of TM.**
- **Velocity of ≥10 km/s can be achieved in the three-cascade systems or on light gas guns. The thicknesses of the shells (fractions of mm) are not enough for radiographic imaging.**
- **The models are verified using data obtained at acceleration to $10^5\,g_0$ in the experiments with gasses.**
- **DEMG allows driving cylindrical liners ~1.5 mm thick to velocities of 10-20 km/s. This will broaden the range of studies to $10^9 g_0$.**

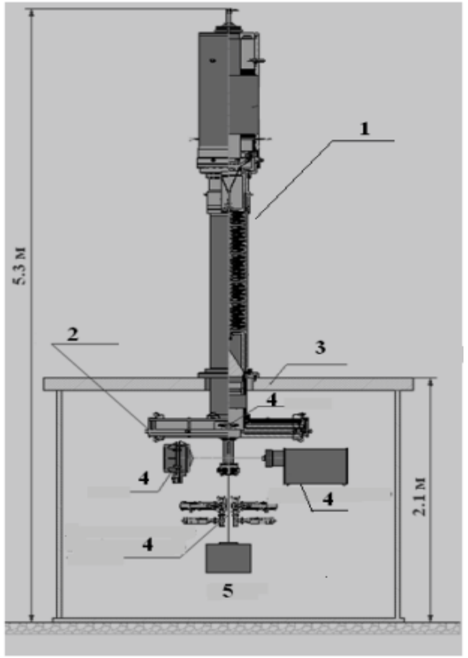


Calculated r - t diagrams of TM zone boundaries at deceleration of Cu plate 1,5 mm thick driven to 10 km/s against polyethylene with thickness: a) 10 cm; b) 3 cm.



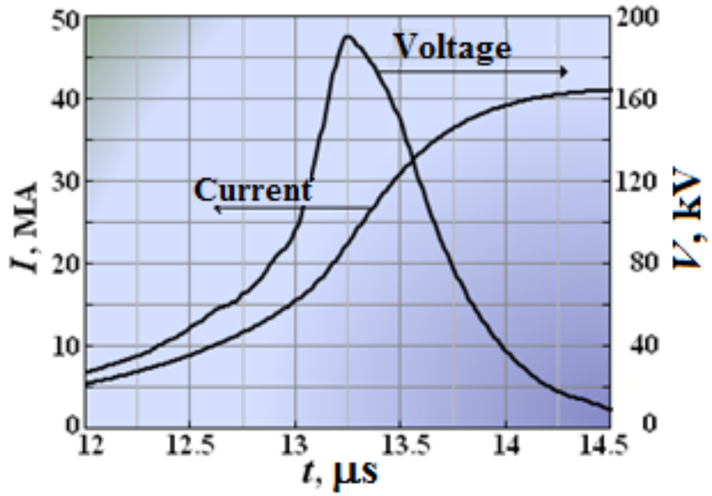
It is planned to conduct studies of TM zone development at deceleration of copper shells on a layer of light substance (polyethylene, water).

In addition, it is possible to study the EOS of substances during isentropic and shock loading by pressure of 3-4 Mbar.



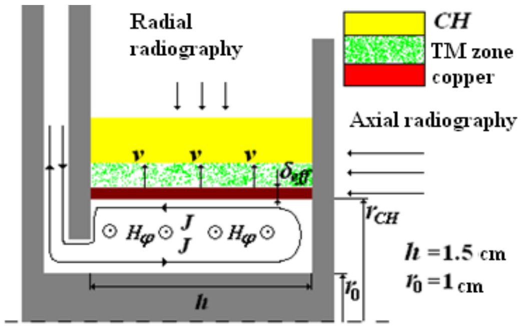
Experimental test bench layout:

- DEMG with diameter 0.25 m - 1;
- electrically exploded current opening switch - 2;
- system of protection from shock wave and debris - 3;
- radial and longitudinal x-ray imaging - 4;
- *PDV* technique - 5;
- optical and *B-dot* techniques to measure current pulses.

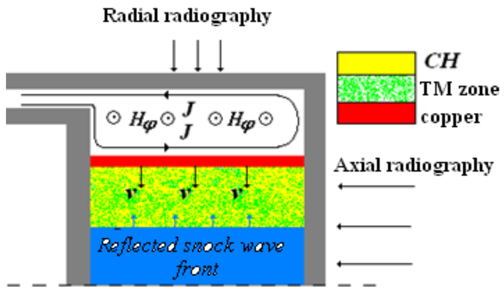


Time dependence of current and voltage on electrically exploded opening switch

Experimental diagrams



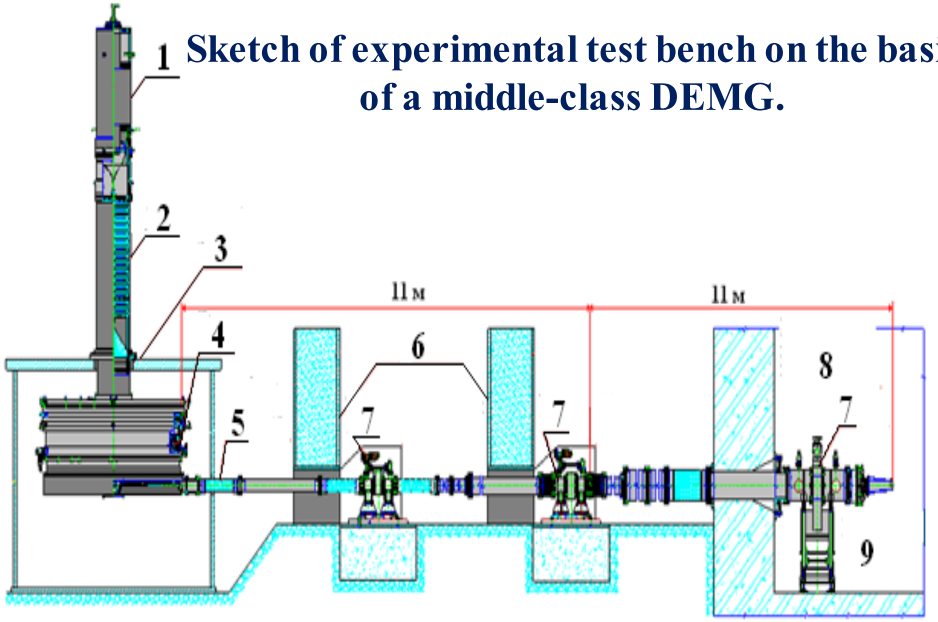
Study of TM zone formation



Study of TM zone interaction with reflected shock wave

3. High specific energies ($\varepsilon \geq 1$ MJ/g)

Sketch of experimental test bench on the basis of a middle-class DEMG.



Only the current source on the basis of EMG is destroyed during the operation.

Test bench comprises:

- current source on the basis of HEMG - 1 and DEMG- 2 of middle class (∅ 0.4 m);
- unit of current peaking to ~ 100 ns - 4 placed into a protective housing – 3.

Vacuum system of the current peaking unit and recording path comprises:

- flexible vacuum section – 5;
- gate valves– 7;
- protective constructions – 6;
- vacuum station – 9 located inside bunker - 8.

The test bench can be used to conduct experiments on Z-pinch implosion by the current ~ 25 MA for the time of ~120 ns. It will make it possible:

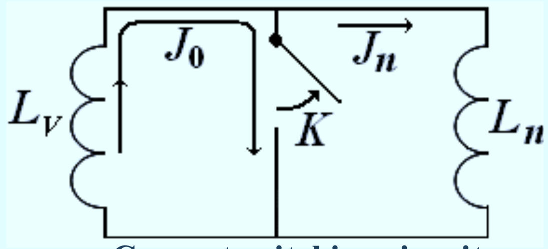
- to achieve pressures to 40 Mbar:
- to generate X-rays with the energy to ~3 MJ for the time ~10 ns.

Further increase of pressure and X-radiation energy is possible in single experiments with the use of super-power disk EMG 1 m in diameter.

The problematic point is realization of current peaking to ~ 100 ns.

Unit of current peaking to ~ 100 ns.

In the process of current J_0 switching from the inductive storage L_v to the load equal to inductance (L_n=L_v) the current is divided in half J_n=J_0/2, the energy decreases by a factor of 4.

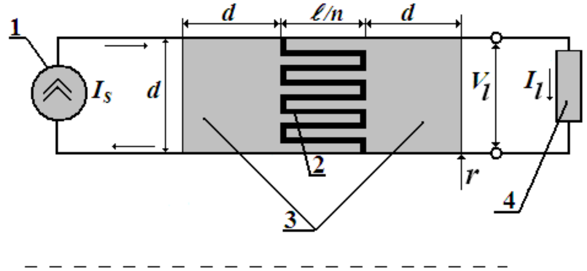


Current switching circuit

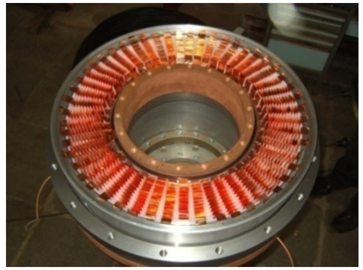
There are two ideas for realization of current switching for the time of ~ 100 ns:

- **electrically exploded corrugated current opening switch**

S.G. Garanin, A.V. Ivanovsky and L.S. Mkhitariyan An ICF system based on Z-pinch radiation produced by an explosive magnetic generator//Nuclear Fusion, 2011, V.51, N10 (15pp).

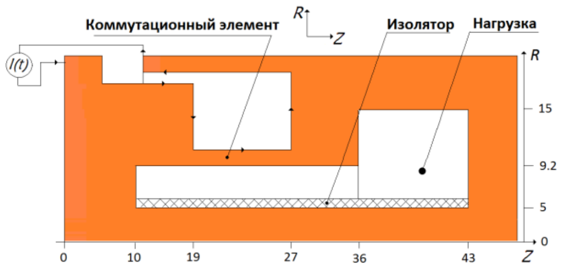


Schematic

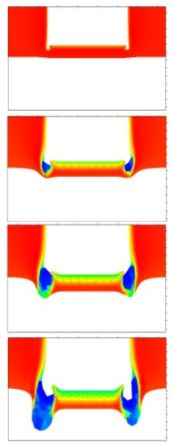

Outer view

- **magneto-dynamic current opening switch**

A.A.Bazanov, A.V.Ivanovsky, V.Sh.Shaidullin Magneto-dynamic current opening switch with submicrosecond time switching // ZhTF, 2010.



Schematic


Switching process

Time will show which idea is more acceptable.