Flyer acceleration by magnetic pressure on Angara-5-1 installation

E V Grabovskii, V V Alexandrov, A V Branitskii, I N Frolov, A N Gribov, A N Gritsuk, K N Mitrofanov, Ya N Laukhin, G M Oleinik, P V Sasorov, A O Shishlov and S I Tkachenko

1 State Research Center of the Russian Federation—Troitsk Institute for Innovation and Fusion Research, Pushkoykh Street 12, Troitsk, Moscow 108840, Russia
2 Keldysh Institute of Applied Mathematics of the Russian Academy of Sciences, Miusskaya Square 4, Moscow 125047, Russia
3 Moscow Institute of Physics and Technology, Institutsky Pereulok 9, Dolgoprudny, Moscow Region 141700, Russia
4 Joint Institute for High Temperatures of the Russian Academy of Sciences, Izhorskaya 13 Bldg 2, Moscow 125412, Russia

E-mail: oleinik@triniti.ru

Abstract. The high pressure created by magnetic field which was induced by the current flowing through the flyer allows one to reach the megabar pressures and to accelerate the flyers to high velocities. The effectiveness of the flyer acceleration was investigated on the Angara-5-1 installation at the linear current density up to 5 MA/cm.

1. Introduction
The aim of this work was to create megabar magnetic pressure in solids to accelerate the flyers up to 10 km/s and more. The loading of the sample by magnetic field pressure allows one to study the dynamic parameters of the substance at submicrosecond processes [1]; and such experiments intended to itemize the equation of matter state.

For an intense impact of the flyer with the test substance it is necessary that a significant portion of the flyer near the contact surface had a density close to the solid. Joule heating and the formation of the shock waves in the flyer cause heating, evaporation and expansion of its substance. The flyer heating depends significantly on the current waveform. On Z-facility for the current amplitude of 20 MA with a rise time of 100 ns the maximum achievable pressure in the aluminum flyer is 2.5 Mbar and the maximum velocity of its back surface is 20 km/s [2]. With increasing the current pulse duration up to 300 ns, the flyer velocity increases to 34 km/s, with no significant change in its density. In this mode the pressure in the flyer reached 5 Mbar. Similar acceleration of aluminum flyer was demonstrated on Julong-I installing (PTS); it was obtained that the velocity equals to 21 km/s at the current amplitude of 7.6 MA [3].

2. Experimental setup
The study was carried out at the Angara-5-1 facility [4]. Wire arrays were used as the generator load recent years [5–8], therefore it was necessary to modify the electrode system for new tasks.
Figure 1. Design of flyer mounting; here used following designation: A is the anode; C is the cathode; R is the rod. Dimensions are in mm.

We planned to obtain higher linear current density; therefore it was necessary to reduce the total inductance that requires a reduction in the gap between the electrodes. But reducing the gap can lead to increasing a current leakage, i.e. to decline the transporting properties and hence to reducing the current which transported to the load. So we need to solve some optimization tasks. The behavior of the electrodes in vacuum under high linear current density (more than 1 MA/cm) was studied in [9–12]. The current transportation outside the central area with a diameter of 20 cm was investigated in [13].

The gap between the anode and the cathode at the output unit at the radius less than 60 mm had been reduced to 3 mm.

2.1. Flyer attachment

Design of the flyer mounting is shown in figure 1. The anode has an internal anode chamber with a diameter of 44 mm. The anode and cathode are connected by the rod with the diameter of 6 mm. Due to asymmetric arrangement of the anode rod inside cylindrical chamber with the diameter of 44 mm the current in the anode cavity is concentrated near the rod. In figure 2 it is shown a conditional picture of the magnetic field lines inside the anode cavity. This picture was obtained under the following assumptions: (i) the height of the anode cavity is more than its diameter, and (ii) the penetration the current and hence magnetic field into the metal is negligible. Those are not true therefore the picture of the distribution of the magnetic lines is not precise but it is used only to demonstrate the qualitative picture of increasing of the magnetic field near the anode-rod gap. One can see that inside the gap of 1 mm between the rod and the anode a strong magnetic field with the scale of 6 MG is created. Under the influence of this field, this section is accelerated outward of the anode cavity (to the left in the figure 1). So the part of the anode shown in figure 1 with the size of 6 mm is the flyer.

The anode is an all-metal unit which machined entirely on a lathe from a single blank. This prevents the occurrence of plasma in space, where the flyer will fly. The presence of plasma may obstruct to get laser shadow picture which show flyer displacement.
2.2. Diagnostics
The voltage drop between the anode and cathode was measured at the radius of 6 cm using an inductive divider [14]. The total current was measured by magnetic probes system: 8 probes (one per module) were measured the current at the radius of 404 mm; 8 probes (one per module) measured the current at the radius of 102 mm; and 1 miniature magnetic probe was located close to a flyer at the radius of 22 mm from the load. The miniature magnetic probe was placed in the anode cavity probe. This probe was a similar those used in [15]. The probe was assembled on the basis of RK50-3-22 cable; at the end of the cable a loop with size of about 1 mm was located. The sensitivity of the probe was calibrated on the special generator [16]. The probe was lowered into the center of the anode cavity through the hole (figure 1).

Laser SL-233 ($\lambda = 532$ nm, pulse duration is 0.1 ns) was used to obtain 3 shadow pictures of the flyer position. The second beam was delayed relative to the first by 17.6 ns, and a third with respect to the second by 12.7 ns. Laser beams were directed into the plane of the upper part of the electrode unit shown in the figure 1. The spatial resolution by the object was $\pm 50 \mu m$ for the first and third frames and $\pm 25 \mu m$ for the second frame. These 3 beams pass close to the flyer at the different angles; it is necessary for separate registrations of the pictures. The angle difference is about $1.2^\circ$ in the horizontal plane.

3. Experimental results
3.1. Current measurement
The current waveforms recorded in the one of the experiments by the probes (see above) are presented in figure 3. It can be noted that on Angara-5-1 the moment of the current start is $t_{00} = 770$ ns with a standard deviation of 4.4 ns.

One can see that the current measured at the 22 mm is above 5 MA; and currents measured at the 102 and 402 mm are somewhat less. This can be explained by that these probes are shielded by the plasma.
Figure 3. The current waveforms recorded in the one of the experiments at the radii 404, 102 and 22 mm.

Figure 4. Two laser shadow images of the flyer: (a) presented picture before the shot and (b) at the 653 ns after current beginning.

3.2. Laser shadow pictures

Figure 4 shows two laser shadow images of the flyer. The shadow obtained before the shot is presented on the left side of the figure, and the shadow obtained at the time of 1423 ns (653 ns after current beginning) is presented on the right side of the figure. We see that at this point of time the outer boundary of flyer was shifted to 3.43 mm. In the both pictures the original position of the flyer marked by the white line on the right.

Figure 5 shows the shadow laser images of the flyer obtained in the same shot. On the left is presented the superposition of the image obtained before the shot, and the image obtained at the time 1098 ns (328 ns after the beginning of the current); on the right is presented the superposition of the image obtained before the shot, and the image obtained at the time 1128 ns (358 ns after the beginning of the current). In the both pictures the original position of the flyer marked by the white line on the right. At the probing time the outer boundary of the flyer on
the left image shifted by 1.32 mm, and on the right image this boundary shifted by 1.62 mm. As
we can seen in figure 5 the external border of the flyer is quite smooth, without features typical
for the development of large instabilities. Taking into account that considerable time (about
700 ns) has passed after the beginning of the current we can state that material at this surface
of the flyers is dense enough, close to the density of the solid.

An overview of few shots is presented below. Two or three shadow images were recorded at
different times in each shot. Figure 6 shows the displacement of the flyer at different times. Using
these data we can estimate the velocity of the external boundary of the flyer. The velocity can be
estimated as the differential dX/dt, where dX is the flyer displacement between the two probing
moment in the same shot, and dt is the time between probing. We can assume the movement
of the flyer begins at time \( t_0 = 970 \text{ ns} \); so we can estimate average velocity \( X(t)/(t − t_0) \), where
\( X \) is the flyer displacement relative to the original location, and \( t \) is the probing time. We can
state that as the differential so the average velocities reach 10 km/s.

Noteworthy is the fact that in a number of shots differential velocities are small, zero or even
negative, but in the same time the average velocity always is of about 10 km/s. This can be
explained by the fact that when displacements are greater than 1 mm, the external boundary of
the flyer starts to distort, to blur and ceases to be flat. Furthermore, since the probing beams
pass near the flyer at different angles, it can give misleading information about the position of
the flyer external boundary.

4. Numerical modeling
Numerical modeling of the evolution of the flyer parameters was conducted in the frame of
one dimensional MHD-model [11,17]. To determine thermophysical properties of aluminum in
the wide ranges of volumes and temperatures, we used equation of state from [18] taking into
account phase transitions (fusion and evaporation) and possibility of realizing metastable state,
which can be realized at the fast processes. To determine transporting properties of aluminum
we used the conductivity models from [19,20]. The time dependence of current was determined
as follows: \( I(t) = 0.5I_0[1 − \cos(\pi t/\tau_0)] \) when \( t < \tau_0 \) and \( I(t) = I_0[1 − t/t_1] \) when \( t \leq \tau_0 \), here \( I_0 \)

Figure 5. The shadow laser images of the flyer obtained in the same shot: (a) the superposition
of two images: the one obtained before the shot and the other obtained at 328 ns after the
beginning of the current; (b) the superposition of two images: the one obtained before the shot
and the other obtained at 358 ns after the beginning of the current.)
Figure 6. The time dependence of displacement of the external boundary of the flyer. The results obtained in the same shot, are connected by the lines; the sizes of the rectangles correspond to errors. Simulation results are presented by solid curve.

Figure 7. The time dependence of the velocity at the different layers of the flyer during passing the current pulse with the linear current density $I_l \approx 4.5$ MA/cm: 1 is the external surface of the flyer; 2 is the central layer ($x_0 = h_0/2$) and 3 is the inner surface of the flyer.

is the current amplitude; $\tau_0 = 180$ ns and $t_1 = 200$ ns. The thickness of the aluminum flyer was $h_0 = 0.9$ mm; and the linear current density was $I_l = I_0/s = 4.5$ MA/cm, here $s$ is the width of the flyer.

Figure 6 shows the comparison of the experimental and simulation results. Experimentally measured displacement of the flyer outer surface is represented by marks and result of calculation is represented by solid curve. One can see good agreement numerical results with experimental data.

Figure 7 shows the time dependence of the flyer velocity at the different layers. The figure scale has been chosen so as to present the velocity of the external surface of the flyer. One can
Figure 8. The temperature distribution on the thickness of the flyer at different moments: 80 (1), 160 (2), 200 (3), 240 (4), 340 (5) and 480 ns (6); the melting (7) and evaporating (8) temperatures for aluminum at the normal conditions are denoted by horizontal lines (the linear current density is \( I_l \approx 4.5 \) MA/cm).

see that up to 300 ns the velocities of the external surface and the central layer is equaled to each other; that is typical for the solid.

Figure 8 shows the temperature distribution on the thickness of the flyer at different moments. The figure scale has been chosen in similar way to present the parameters (temperature) of the external surface of the flyer. One can see that by the moment of 160 ns matter of the flyer located near its inner surface is in plasma state and its velocity is very high and directed to the opposite side (see figure 7). Starting from this time due to the recoil impulse of the vaporizing matter, the external surface of the flyer additionally accelerates.

It was obtained that for aluminum flyer with \( h_0 = 0.9 \) mm and \( I_l = I_0/s = 4.5 \) MA/cm by the moment of \( \approx 500 \) ns the velocity of the external flyer surface is \( \sim 10 \) km/s; its temperature is less than the fuse temperature. But at this time the velocity of the inner flyer surface is \( \sim 100 \) km/s; and its temperature is about few electron volts.

5. Conclusions
The output node of the Angara-5-1 installation was modified to reduce the inductance and hence to increase the current. It has allowed us to increase the current up to 5 MA. The preliminary experimental results show the possibility to reach on the flyer the linear current density of 4.5 MA/cm. In such conditions the flyer with thickness of 1 mm made of duralumin reaches the velocity of 10 km/s. It was obtained in numerical modeling that by the time of \( \approx 500 \) ns the flyer material is in the solid near its external surface; and the velocity of this surface is \( \sim 10 \) km/s. Experimentally measured displacement of the flyer outer surface and the numerical results are in a good agreement.

Acknowledgments
This work was supported by the Russian Science Foundation, project No. 16-12-10487.

References
[1] Kanel G I, Razorenov S V and Fortov V E 2004 Shock-Wave Phenomena and the Properties of Condensed Matter (New York: Springer)
[2] Lemke R W et al 2005 J. Appl. Phys. 98 073530
[3] Jianjun D, Weiping X and Xianbin H 2015 High energy density physics researches on the Julong-I (PTS) IEEE Int. Conf. Plasma Sciences (IEEE)
[4] Al’wikov Z A, Velikhov E P and Veretennikov A I 1990 At. Energy 35 34
[5] Grabovski E V, Aleksandrov V V, Volkov G S et al 2008 Plasma Phys. Rep. 34 815–29
[6] Aleksandrov V V, Grabovski E V, Gritsuk A N et al 2010 Plasma Phys. Rep. 36 482–506
[7] Aleksandrov V V, Grabovski E V, Gribov A N et al 2009 Plasma Phys. Rep. 35 136–48
[8] Grabovskii E V, Gritsuk A N, Smirnov V P et al 2009 JETP Lett. 89 315–8
[9] Anan’ev S S, Bakshaev Yu L, Bartov A V et al 2008 Plasma Phys. Rep. 34 574–86
[10] Bakshaev Yu L, Bartov A V, Blinov P I et al 2007 Plasma Phys. Rep. 33 259–70
[11] Grabovskii E V, Levashov P R, Oleinik G M et al 2006 Plasma Phys. Rep. 32 718–28
[12] Branitsky A V, Grabovski E V, Dzhangobegov V V et al 2016 Plasma Phys. Rep. 42 338–46
[13] Grabovskii E V, Gribov A N, Samokhin A A et al 2016 Plasma Phys. Rep. 42 773–8
[14] Oleinik G M 2000 Instrum. Exp. Tech. 43 328–30
[15] Zukakishvili G G, Mitrofanov K N, Aleksandrov V V et al 2005 Plasma Phys. Rep. 31 908–18
[16] Grabovskii E V, Gribov A N and Oleinik G M 2008 Instrum. Exp. Tech. 51 711–5
[17] Tkachenko S I, Khishchenko K V, Vorob’ev V S et al 2001 High Temp. 39 674–87
[18] Fortov V E, Khishchenko K V, Levashov P R and Lomonosov I V 1998 Nucl. Instrum. Methods Phys. Res., Sect. A 415 604–8
[19] Knoepfel H 1970 Pulsed High Magnetic Fields (North Holland, Amsterdam: Springer)
[20] Oreshkin V I, Baksht R B, Labetskii A Yu et al 2004 Tech. Phys. 49 843–8