Study of Microsecond Z-pinch Implosions with the Help of Magnetic Probes[1]

A.Yu. Labetsky, S.A. Chaikovsky, A.V. Fedunin, F.I. Fursov, V.A. Kokshenev,
N.E. Kurmaev, V.I. Oreshkin, A.G. Rousskikh, A.V. Shishlov, N.A. Zhidkova

Institute of High Current Electronics SB RAS, 2/3 Academichesky ave., Tomsk, 634055, Russia,
phone: +7 (3822)-492133, fax:+7 (3822)-491677, e-mail: aly@ovpe2.hcei.tsc.ru

Abstract – The experiments with multi-shell neon gas puffs were performed on the GIT-12 generator (4.7 MA, 1.7 μs) operated at microsecond implosion times. Dynamics of Z-pinch implosion was investigated by a set of B-dot probes placed at different radii inside a gas-puff. The results of experiments showed the following. The dynamics of plasma implosion is close to one-dimensional during most of the implosion time. Current penetration into the inner gas shells is not observed. At the final stage of implosion, the trajectory of current sheath differs from the calculated one. At the instant the radiation power peaks, the equivalent diameter of the current-carrying sheath is of the order of 2÷4 cm.

1. Introduction

The concept of magnetic compression of plasma implies the delivery of energy produced by a generator to the load region and its effective utilization in a volume as small as possible. With reference to Z-pinch geometry [1], this means that *all* of the matter taking part in the implosion process should be imploded by the *whole* current of a generator and should be gathered within the confines of the pinch at the stagnation phase. If it is supposed that the kinetic mechanisms of plasma heating prevail, the implosions from large diameters should be of interest. However, the transfer of a current from large radii to a pinch region is a serious problem.

The earlier experiments on the implosion of the large-diameter (14÷21 cm) cylindrical plasma shells driven by the megaampere-level, microsecond current pulses [2] showed that deep plasma compressions did not take place – the equivalent diameter of current sheath inferred from the current and voltage data was of the order of 2 cm. This was related with the formation of secondary current path due to the shunting of inter-electrode gap at the large (~8 cm) diameters by plasma ablated from electrodes. The increasing of the gap from 1 to 2 cm allowed reducing the level of current losses greatly, but not completely. Nevertheless, it was presumed that the leading edge of the current sheath continues to implode by the bulk of the current regardless of the current losses. The low efficiency of such radiative loads (at the load current of 9 MA, the total radiation yield did not exceed 100 kJ) have been associated with unstable implosion of the large-diameter plasma shells that predetermined the shift to the short implosion times.

It is evident that various mechanisms can be responsible for the current leakage in the periphery of a Z-pinch. 2D simulations of perturbed implosion [3] show that the equivalent inductance of the implosion can be reduced (i.e. the equivalent diameter becomes larger) due to the instabilities development. As the experiments show, this point of view does not contradict the experimental data. An analysis of leakage currents in collisionless peripheral plasma performed in [4] has shown that neutral current flows can also arise in tenuous plasma surrounding the pinch. At that, the plasma corona can contain an essential fraction of the implosion energy.

The use of multi-shell loads allows significant improvement of the implosion stability and achieving considerable increase in the radiation yield [5]. However, the efficiency of plasma radiation sources operating at microsecond implosion times is still less as compared to fast (100 ns) Z-pinch implosions [6]. To improve the efficiency of such sources, thorough investigations of implosion dynamics are required. A set of experiments with multi-shell gas puffs has been performed, which was aimed at investigation of plasma implosion dynamics with the help of magnetic probes.

2. Experimental setup

The experiments were carried out on the GIT-12 [7] pulsed current generator operated in microsecond implosion regime. At 50 kV charge voltage, the generator provides the current of 4.7 MA with the current rise time of 1.7 μs in the short-circuit load. When conducting Z-pinch experiments, the load parameters were chosen so that the implosion time was 1÷1.2 μs at the peak load current of 3.5÷3.7 MA.

A multi-shell gas puff was used as a load. Gas shells were produced by the electromagnet gas valve

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coupled to concentric annular nozzles [8]. The diameter of the outer shell was 24 or 27 cm; the diameter of the middle shells was 16, 10 or 8 cm. An inner shell was a solid fill gas jet with the diameter of 2 cm. The anode-cathode gap was 2÷2.5 cm. Neon was used as a working gas. The masses of the gas shells were determined as described in [9].

A conventional set of diagnostics was used in the experiments. The B-dot probes and voltage divider were used to monitor current and voltage of the generator. Single-loop magnetic probes were used to monitor the dynamics of a current sheath. The probes were located near the cathode and the return current conductor. Calibration of the probes has been conducted in the short-circuit shots. The radial and axial dynamics of implosion were also recorded by visible-light streak cameras. The K-shell radiation yield and power were measured by vacuum X-ray diodes. The time-integrated pinhole cameras produced the pinch image in the final stage of implosion in the spectral range of Ne *K*-lines and Ne recombination continuum ($h\nu > 2$ keV). The scheme of load unit and positions of B-dot probes are shown in Fig.1.

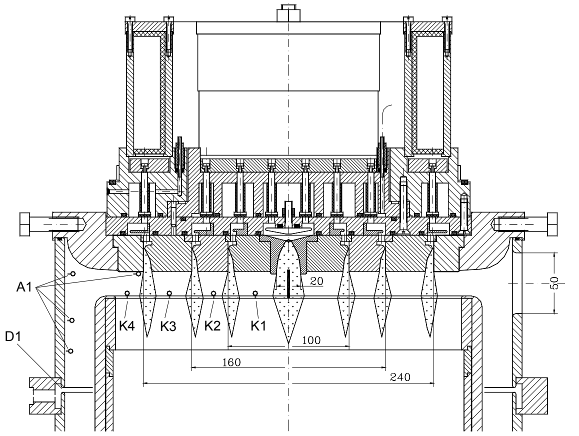

Fig. 1. The scheme of load unit and diagnostics

3. Experimental results

Though the implosion of large-diameter single-shell gas puffs is very unstable, the dynamics of current sheath motion is close to 0-dimensional during most of the implosion time (Fig.2). Plasma shell accelerated by the whole current of a generator implodes to the diameters of a few centimeters, and then the implosion stops. The equivalent diameter of the current sheath is inferred from the current and voltage traces:

$$L_{eq} = \frac{\int U(t)dt}{I(t)} = L_0 + \frac{\mu_0 \Delta z}{2\pi} \ln\left(\frac{d_0}{d_{eq}}\right), \qquad (1)$$

where: L_{eq}, $U(t)$, and $I(t)$ are the inductance, the voltage, and the current of the discharge; L_0 is the constant part of the discharge inductance; d_0, d_{eq}, and Δz are the diameter of return current conductor, the equivalent diameter and the length of the current sheath.

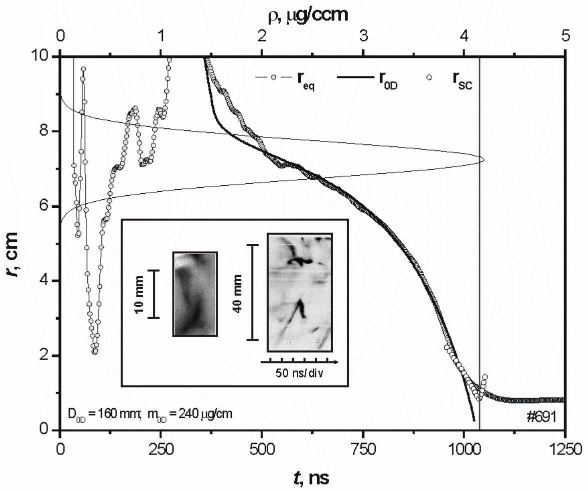

Fig. 2. Experimental r_{eq}, r_{SC} and calculated r_{0D} radii of the current sheath. Single gas shell, $d_0 = 16$ cm; the inset shows the pinhole and streak camera pictures

As can be seen from Fig.2, at the peak of x-ray radiation the current sheath has the diameter about 2 cm, so the radial compression ratio does not exceed 10. The data of visible-light streak camera (see inset in Fig.2) are consistent with these measurements, but the diameter of plasma column obtained from the pinhole camera picture in neon *K*-lines is about 4 mm. The final diameter of current sheath grows with an increase in the initial diameter of a gas shell, and for 24-cm-diameter shell, the equivalent diameter is 8 cm, so a distinct picture of the implosion is not observed. The comparison of the results with 0D snowplow simulations shows that the deviation of experimental trajectory from the calculated one takes place within the last 15% of the implosion time.

The experiments with multi-shell gas puffs show that the dependence $r_{eq}(t)$ coincides with the 0D trajectory of the implosion up to the moment the shells collide. The effect is especially distinct for the implosion of the gas puffs with equal masses of the gas shells. Typical dynamics of a triple-shell gas puff of 24/8/2 cm diameter with the shell masses of 150 μg/cm is shown in Fig.3. The corresponded B-dot signals and current traces are given in Fig.4. The dynamics of a four-shell gas puff of 27/16/8/2 cm diameter with shell masses of 250 μg/cm is shown in Fig.5.

The time dependencies of the trailing boundary of a current sheath shown in figures based on three independent measurements of *r*(*t*): circuit inductance data, streak camera data and B-dot probes data. It should be noted that the dependence $r_{eq}(t)$ is a lower estimate, because equation (1) implicitly includes a resistive component. The gas density profile shown in figures illustrates the placement of the shells in the interelectrode gap. The initial gas density distribution was calculated with the help of a ballistic gas-flow model [10] and was used for computation of $r_{0D}(t)$. The masses used in 0D simulations were close to those inferred from the pressure probe measurements [9].

It is obvious (Fig.3, Fig.5) that after the first impact of two shells the dynamics of current-carrying layer changes noticeably. The more diameter, where the collision takes place, the more essential trajectory deviation is observed (Fig.5). Subsequent interactions of colliding shells do not change the dynamics of current sheath so evidently. The instabilities do not have considerable effect on the pinch quality. A tight pinch is formed on the axis. The measured K-shell radiation yield was 8.1 kJ/cm for shot #752 and 5.6 kJ/cm for shot #753. At the peak of radiation power, the equivalent diameter of current sheath is 2.5 cm for shot #752 (Fig.3) and 4 cm for shot #753 (Fig.5); the plasma pinch diameter determined from the pinhole and streak camera pictures is 3÷4 mm. The average velocity of the implosion estimated from the streak camera pictures is 30 cm/μs; at that, the thickness of the plasma sheath is 3÷4 cm.

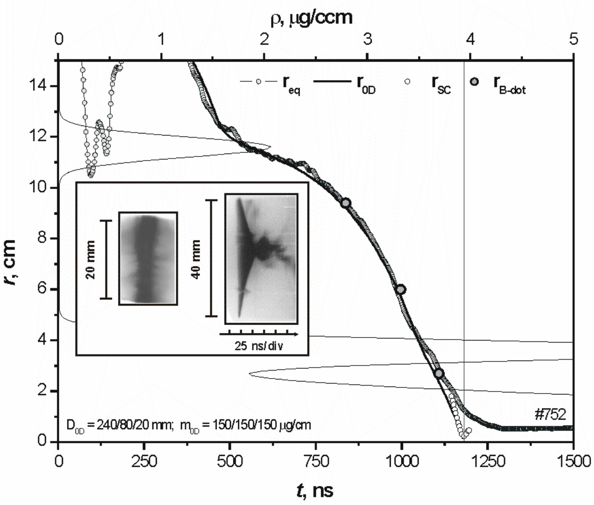

Fig. 3. Experimental r_{eq}, r_{SC}, $r_{B\text{-dot}}$ and calculated r_{0D} radii of the current sheath. Triple-shell gas puff, $d_0 = 24/8/2$ cm; the inset shows the pinhole and streak camera pictures

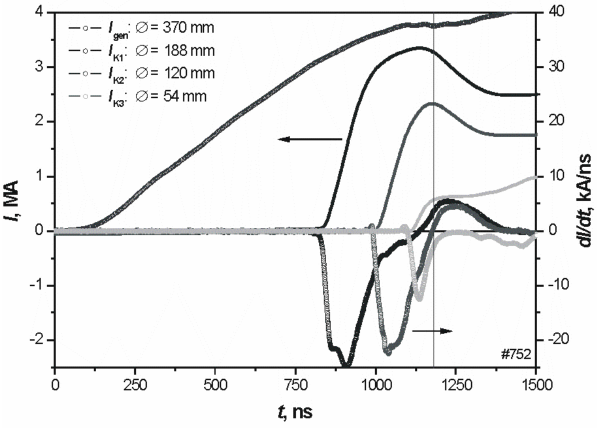

Fig. 4. B-dot signals and integrals for a triple-shell gas puff, $d_0 = 24/8/2$ cm

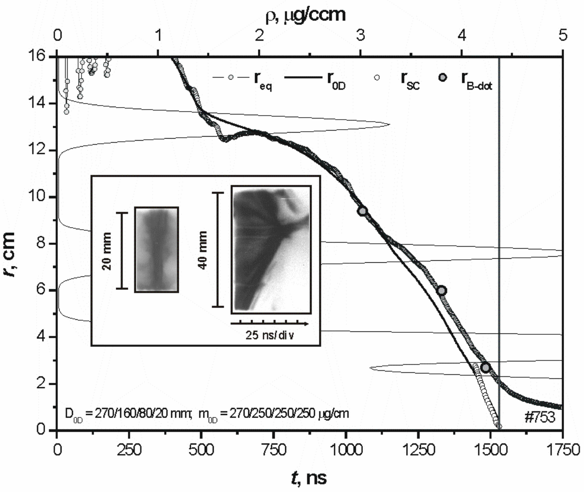

Fig. 5. Experimental r_{eq}, r_{SC}, $r_{B\text{-dot}}$ and calculated r_{0D} radii of the current sheath. Four-shell gas puff, $d_0 = 27/16/8/2$ cm; the inset shows the pinhole and streak camera pictures

1D RMHD simulations do not describe the change of current sheath trajectory after the first collision of the gas shells. The trajectory of current sheath movement in the 1D simulations does not differ from the zero-dimensional trajectory.

The onset of B-dot signals (taken at 20% level of the peak value) from the probes located at different radii follows well the current trace. The absence of the signals from the B-dot probes (see Fig.4) until arrival of the current to the location of the probe indicates that there is no penetration of the magnetic field into the imploding shell.

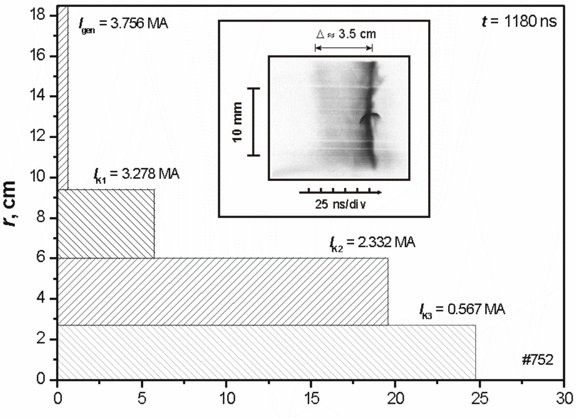

Fig. 6. The current distribution profile at the peak of K-shell radiation. The streak camera picture illustrates the thickness of current sheath

The integrals of B-dot signals show that the rise rates of the current measured at different probe locations are almost the same (see the slope of the pulse shape, Fig.4). The 5-fold sharpening of the generator current pulse was observed. The B-dot measurements give us an estimate of the current flowing in the pinch region, which is 0.5÷1.2 MA. These values of the current can be significantly understated because of shielding of the B-dot probes by surrounding plasma.

The current distribution profile inferred from the data of B-dot probes for shot #752 (Fig.4) is shown in Fig.6. As follows from this figure, approximately 12% of the total current distributed at the radii larger than 9.4 cm. This result is also confirmed by the data of B-dot probes placed at the anode-side.

The increase of the initial diameter of a gas puff leads to an increase of the gas density in the vacuum line. Though the gas density in this region is a few orders of magnitude less than the peak density of the outer shell, the current leakage outside the shell was registered by the B-dot probes in the experiments with large-diameter gas puffs. The B-dot probes D1 and A1 placed at the different distances from the anode plane (see Fig.1) measured the vacuum line current and the load current outside the gas puff. The difference in B-dot signals allows us to estimate the level of current losses in the region between the cathode and the return current conductor (Fig.7).

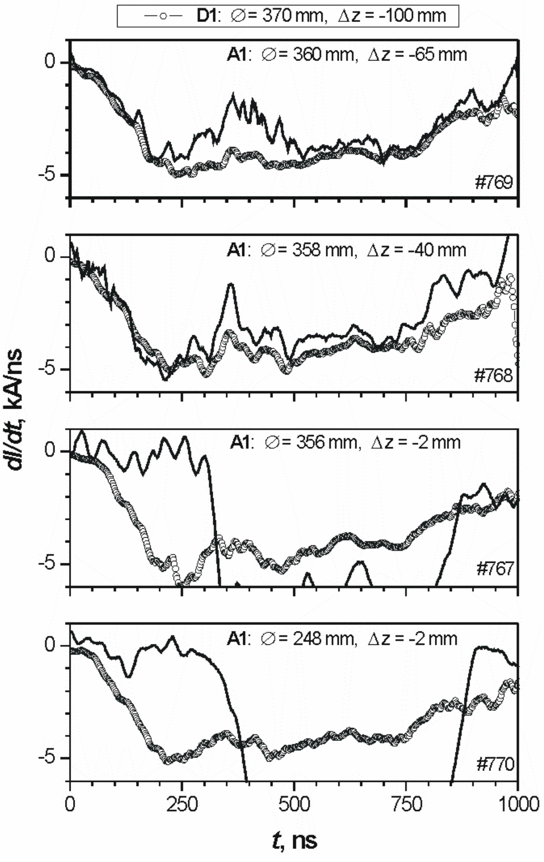

Fig. 7. The signals of B-dot probes: D1 (vacuum line current) and A1 (load current)

The measurements show that the formation of a radial current sheath takes place near the cathode plane (Fig.1). The sheath operates as a radial plasma flow switch. It reaches the anode plane with a delay of 300÷350 ns. The 3-fold current sharpening was registered at the instant when the current sheath and the outer shell merge. The 0D simulation showed that the current losses begin at the instant when the discharge geometry changes. The formation of secondary current path is associated with the presence of the residual gas in the vacuum line, which was not captured by the magnetic piston. At the instant of the peak radiation power, the current losses can be up to 15% of the load current.

4. Summary

The experiments with multi-shell gas puffs have been carried out to investigate the peculiarities of Z-pinch implosion dynamics at large initial diameters and microsecond implosion times. The experiments showed that the implosion dynamics is close to one-dimensional during most of the current carrying time. The deviation of experimental trajectory $r_{\mathrm{eq}}(t)$ from the calculated one occurs after the first impact of two shells. This effect is less pronounced for the implosion of multi-shell gas puffs from small initial diameters.

The instabilities do not have considerable effect on the pinch quality. A tight pinch is formed on the axis. The final diameter of the plasma pinch determined from the pinhole and streak camera pictures is 3÷4 mm. The respective equivalent diameter of current sheath inferred from the current and voltage data is an order of magnitude larger (2÷4 cm).

Current penetration into the inner gas shells was not observed. The current losses outside the pinch region were registered. According to the B-dot probe measurements, only a small portion of current flows at paraxial region (15÷35% of a load current) that is not consistent with the data of K-shell radiation measurements.

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