Wire Array Implosion Driven by a Radial Plasma Flow Switch on the GIT-12 Generator

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Abstract – The preliminary experiments were performed on wire array implosion driven by a radial plasma flow switch on the GIT-12 generator operating in a microsecond mode. Imploding gas puff z-pinch plasma was used to provide fast switching of the current to an aluminum wire array. The experimental results are presented in the paper.

1. Introduction

The use of inductive energy storage technique for pulse power has a number of advantages over conventional capacitive technique from the standpoint of cost and size (see, for example, [1, 2]). The key element of such inductive energy storage technique is an opening switch. In order to obtain a load current rise time of ≈ 100 ns, a plasma erosion opening switch (PEOS) or a plasma flow switch (PFS) can be used. The short current rise time is required for a high power plasma radiation source development to reach a high energy per atom and to provide stable implosion and a tight final pinch.

In the mid of 1980's, it was shown that a PFS could deliver to an imploding load 80÷100% of total current with a rise time of ≈ 200 ns at the total current level of 12 MA and its rise time of ≈ 3 μs [3]. Nevertheless, majority of experimental efforts were done in order to develop inductive energy storage technology with a PEOS (see [2, 3] and other papers in these issues). One of the possible reasons seems to be a higher operation voltage suitable for a bremsstrahlung radiation source. The experimental results being summarized have shown that some limitations on the PEOS performance at high power levels exist. For example, the product of the upstream current amplitude, duration of conductivity stage and switch resistance occurs to be approximately constant [4]. Hence, an increase in a current level can result in reduction of a switch resistance at the current rise time being unchanged.

A plasma flow switch probably should not meet this limitation. Moreover, recent experiments have shown that a nanosecond plasma flow switch operation is possible [5], and high dose rate bremsstrahlung γ-ray radiation could be produced using a plasma flow switch with a vacuum diode as a load [6].

The experimental results mentioned above make it very attractive to use an inductive storage with a plasma flow switch as a power conditioning system to drive, for example, z-pinch implosion. This paper presents experimental results on wire array implosion driven by a radial plasma flow switch (RPFS). In a conventional PFS (Fig. 1,a) magnetic energy is accumulated in the coaxial region behind the plasma bridge. When the plasma sheath passes by the end of the inner electrode, a low density plasma can expand radially inward carrying the magnetic energy to the load. In a radial plasma flow switch (Fig. 1,b) the plasma bridge, like a z-pinch, implodes radially. Again the magnetic energy is stored in the region behind the plasma sheath. Some fraction of supplied energy is definitely spent on the plasma kinetic energy. The magnetic energy can be delivered to the load by a low density plasma, when the sheath passes the edge of the electrode (right electrode in Fig. 1,b).

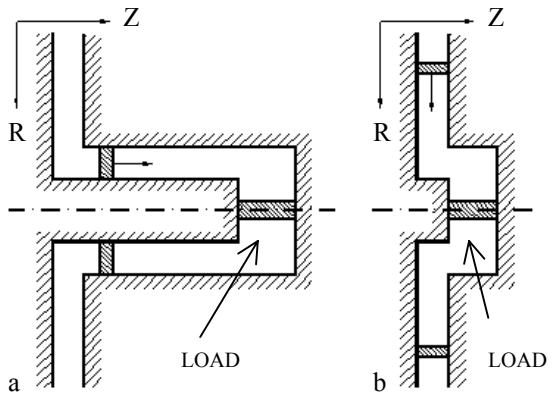

Fig. 1. Schematic of conventional plasma flow switch operation (a) and radial plasma flow switch operation (b)

This scheme was experimentally tested on a 10 kJ microsecond bank [7]. Efficient current switching to the load was not registered, possibly because of current reclosure in the region of initial plasma sheath position. Nevertheless, the scheme has a remarkable feature – both the switch plasma and the load plasma were formed by gas injection using a single gas valve. Thus, a very compact and not expensive power compression system combined with an imploding plasma load can be realized.

2. Load Description

The experiments were carried on the GIT-12 installation operated in a microsecond mode. In this mode the generator delivers 4.7 MA current with a rise time of

1.6 μs on a short-circuit load. The load scheme is shown in Fig. 2. Neon was used to form either single or double gas puffs with the help of a fast gas valve.

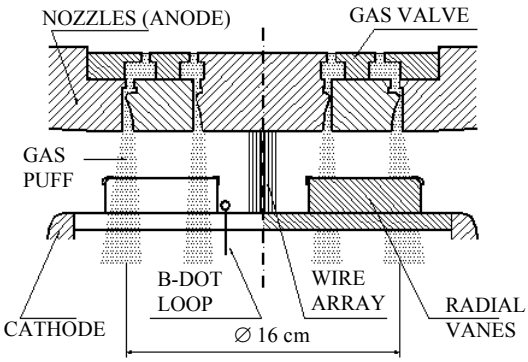

Fig. 2. Scheme of the load unit

The annular gas jets had diameters of 16 cm (outer shell) and 8 cm (middle shell). Gas puff masses were adjusted to provide the implosion time of 1 μs. An aluminum wire array with a diameter of 1.5 cm was used as a load. The wire array consisted of 16 fine wires with a diameter of 20 μm and had a linear mass of 136 μg/cm.

Stainless steel vanes were mounted on the cathode to provide good transparency for a gas flow. They were covered by a wire mesh in order to smooth azimuthal nonuniformities of plasma shell in the course of implosion (Fig. 3). The mesh was fixed by the inner and outer thin rings. The upstream current I and voltage U were measured by B-dot probes and an inductive divider (not shown in Fig. 2), respectively. Time variation of the total switch and load inductance L was estimated from relation: $L \approx \int U\,dt / I$, neglecting an active resistance. The load current was monitored by a single-turn B-dot loop located at the bottom of the pinch region (Fig. 2).

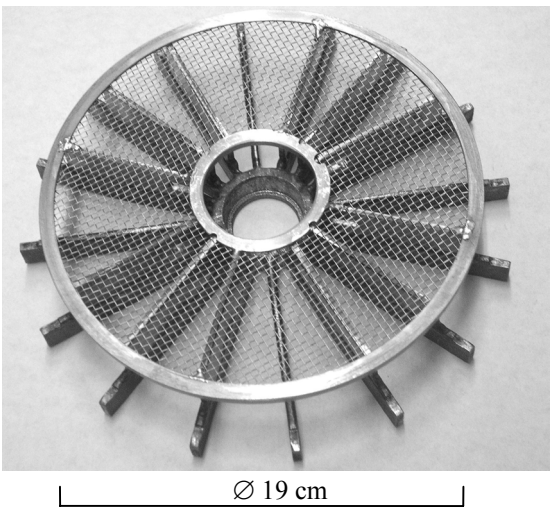

Fig. 3. The cathode vanes. The cathode wire mesh was mounted over the vanes

The radial vanes allowed diagnostic access to the pinch region (the region below wire mesh). The switch region and the pinch region were viewed by two visible light streak cameras. The streak camera slits were aligned perpendicular to the load axis. The pinch image in the final stage of implosion was registered by two time-integrated pinhole cameras aligned to view only the load region. One camera was filtered by 25 μm beryllium + 30 μm polypropilene to register aluminum K-shell x-ray image, $h\nu > 1.6$ keV, and the second one had a filter 20 μm teflon + 2μm kimfol + + 0.2 μm (harder x-rays $h\nu > 2.8$ keV).

The aluminum K-shell yield and power were measured by two XRDs with copper cathodes filtered by 2 μm kimfol + 0.2 μm aluminum + 30 μm polypropilene (XRD1), 10 μm aluminum + 6 μm mylar (XRD2). The XRD1 has the maximum sensitivity in aluminum K-shell spectral region. The XRD2 has high sensitivity in the region of the neon K-shell ($h\nu \approx 0.9 \div 1.4$ keV) and low sensitivity in the aluminum K-shell region. That allows elimination of neon K-shell radiation contribution to the XRD1 response. The aluminum K-shell radiation was also monitored by a PCD with 2 μm kimfol + 0.2 μm aluminum + + 30 μm polypropilene filters. The PCD has 5÷10 times lower sensitivity to the neon K-shell x-rays as compared to the XRDs.

The PCD and XRD were shielded to register only x-rays from the pinch region with a length of 1.5 cm. In a few shots, a wire array in the switch region (over the upper edge of the vanes (Fig. 2)) was replaced by a heavy aluminum cylinder with the same diameter of 1.5 cm. In these cases the PCD's and XRD's apertures were removed, and the detectors viewed both the switch and the pinch region. Also, a *pin*-diode filtered to view hard x-rays ($h\nu > 100$ keV) was used.

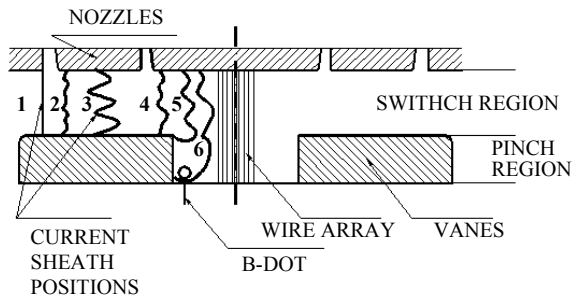

Fig. 4. Load view with presumable consequent current sheath position in the course of gas puff implosion. The region between the nozzles and the upper edge of the vanes is marked as "a switch region". The region below the vanes upper edge is marked as "a pinch region"

The main idea of the experiment is illustrated in by (3) in Fig. 4. Of course, this illustration is evidently far from reality, but it can explain in general the processes expected. The inner shell serves to stabilize the outer shell in order to reduce plasma sheath thickness d. The smaller is the plasma thickness, the shorter load

current rise time is expected, because the current rise time seems to be roughly $\tau \approx d/v$, where v is the plasma sheath radial velocity. The inner shell reduces also the plasma velocity, but it is difficult to conclude *a priori* which factor will dominate.

When the plasma shell reaches the edge of the vanes (positions 4 and 5 in Fig. 4) the main plasma continues its radial motion due to inertia, and a low density plasma sheath possibly forms between the main plasma sheath and the electrode edge. This light sheath (position 6 in Fig. 4) expands into the pinch region with a high velocity and can, in principle, provide current switching to the wire array.

3. Experimental Results

Only six shots were done. Shot #657 was performed with the outer and inner shell masses of 250 μg/cm. The B-dot loop was mounted in a 6 mm diameter protection tube that resulted in a very low and late loop signal. The K-shell pinhole image demonstrates a final pinch with a diameter of 4 mm (Fig. 5). The streak image of the switch region is not axially symmetric. The camera slit was aligned non-centered to the gas puff axis in order to view higher radius region. As a result, due to some streak camera adjustment features, lower (related to Fig. 5) part of the slit was slightly shielded by diagnostic window. Another reason could be azimuth nonuniformity of imploding gas puff. The nonuniformity could appear, for example, as nonsimultaneous gas puff arrival to the wire array. The streak image of the pinch region shows uniform and axially symmetric implosion. The wires "flashes" almost simultaneously. Aluminum K-shell yield was measured to be 600 ± 100 J/cm.

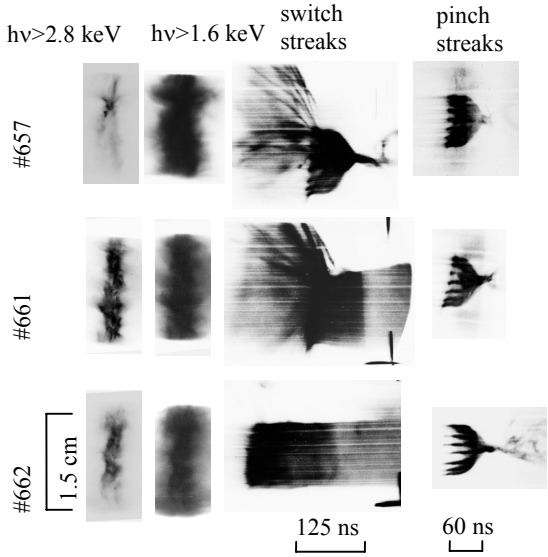

Fig. 5. X-ray pinhole images in the spectral range hν > 2.8 keV and the aluminum K-shell x-ray images, the streak photos of implosion in the switch region and in the pinch region. The space scale bar relates to pinhole images

In the next shots a wire array in the switch region was replaced by a heavy aluminum cylinder with the same diameter of 1.5 cm. It was done in attempt to reduce the amount of generator energy spent on the kinetic energy of the gas puff. The pinhole images clearly demonstrate a tight K-shell radiating pinch with the diameter of 3 mm (Fig. 5). The bright pinch with the diameter of 2 mm was observed in the spectral range $h\nu$ >2.8 keV. The oscillograms of shot #661 are shown in Fig. 6. The B-dot made of insulated wire had a diameter of 1.7 mm and had no protection tube.

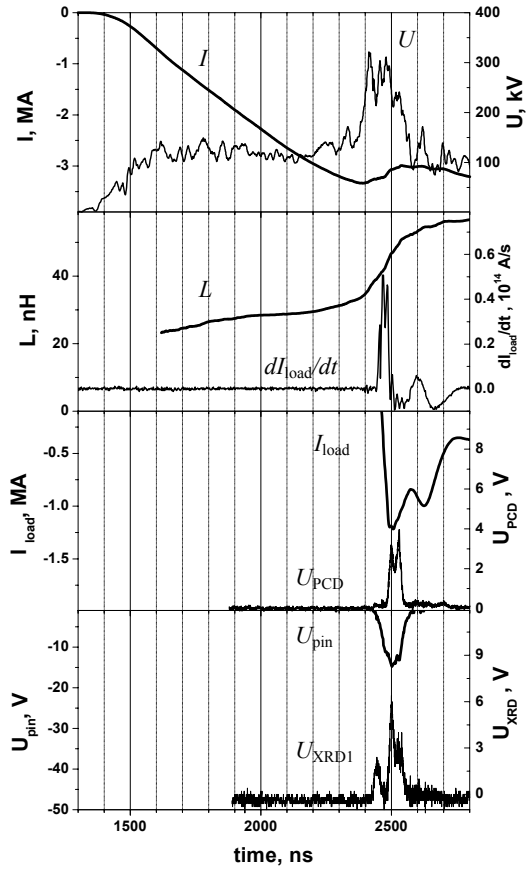

Fig. 6. The oscillograms in #661shot. I_{load} – the current obtained by integrating of the B-dot loop situated at the bottom of the pinch region

The load current rise time of 50 ns and the current rate of $5 \cdot 10^{13}$ A/s were measured by the B-dot. The load current was measured to be very low and did not exceed 1.25 MA. The XRD1 and PCD signals peak approximately 50 ns later than the load current begins, that is rather close to the implosion time measured by the pinch streak camera image (Fig. 5, shot #661). The XRD1 trace has prepulse just in the instant when the B-dot signal appears. The prepulse is possibly caused by neon radiation from the gas puff interacting with an aluminum cylinder in the switch region. The aluminum K-shell yield reaches 800 ± 250 J/cm.

Shot #662 was done without the inner shell. The outer shell mass was 250 μg/cm. A very axially symmetric and high velocity implosion (up to $3.6 \cdot 10^7$ cm/s)

was registered by the streak camera (Fig. 5. #662). The aluminum K-shell yield was measured to be 1100 ± 150 J/cm. The B-dot measurements failed in the shot. In shot #663, the outer shell was absent, and the inner shell mass was 1300 μg/cm in order to keep the gas puff implosion time constant. The B-dot did not show any current switching into the wire array; implosion of the wire array were not observed in the streak image, and no K-shell radiation yield was registered.

4. Discussion

The measured load current I_{load} reaches only 1.25 MA at the upstream maximum current I of 3.3 MA (Fig. 6). The rough 0-dimensional estimations show that this load current is too low to implode 136 μg/cm wire array during 50÷85 ns. Moreover, the calculated by the two-level model [8] K-shell yield for a pinch with the radius of 1.5 mm and the current of 1.25 MA does not exceed 400 J/cm, that does not correlate with the experimental yield.

The implosion of the wire array was calculated with the help of a 0-dimensional model in order to perform a comparison with the experiment. The current waveform was assumed to be linear ramp during 50 ns. Then, the current was suggested to be constant I_{max}. The 7-fold radial compression ratio was assumed in calculations, which is not far from the experimental ratio of the initial array diameter to the final pinch diameter. The value of the maximum current I_{max} was varied in calculations resulting in implosion time variation. The best agreement between the calculated and the experimental implosion times and final velocities for shot #662 was obtained at I_{max} = 2.0÷2.2 MA. The implosion time and the final velocity were calculated to be ≈ 80 ns and $(3.3\div3.6)\cdot10^7$ cm/s, respectively. These values of the final velocity correspond to the kinetic energy of 7.5÷9.2 kJ/cm. The aluminum K-shell yield calculated using the two-level model [8] at these values of kinetic energy and the final pinch radius of 1.2 mm (see pinhole images in Fig. 6 for shot #662) was 0.96÷1.5 kJ/cm, that is very close to the experimental data. Thus, the performed estimations show that the current switched to the wire array could reach 2 MA.

5. Concluding Remarks

The experiments on wire array implosion driven by a radial plasma flow switch were performed on the GIT-12 generator operating in a microsecond mode. Imploding gas puff z-pinch plasma was used to provide fast switching of the current to an aluminum wire array. The switched current rise time of 50 ns and the current rate of $5\cdot10^{13}$ A/s were measured by the B-dot probe. The analysis of experimental data suggests that 40÷65% of generator current was switched to the wire array load. In spite of low efficiency of the current switching registered in the preliminary experiments, the radial plasma flow switch seems to be a promising way to shorten a generator current rise time.

References

[1] P.J. Turchi, M.L. Alme, G. Bird et al., IEEE Trans. Plasma Sci. **PS-15**, 747 (1987).

[2] K. D. Ware, P.G. Filios, R.L. Gullickinson et al. IEEE Trans. Plasma Sci. **25**, 160 (1997).

[3] J.H. Degnan, W.L. Baker, K.E.Hacket et al., IEEE Trans. Plasma Sci. **PS-15**, 760 (1987).

[4] V.A. Kokshenev, N.E. Kurmaev, and F.I. Fursov, *in: Proc 12th Symp. on High Current Electronics,* 2000, pp. 268–273.

[5] A. Kingsep, Yu. Bakshaev, A. Bartov et al., *in: Proc. 5th Intern. Conf. on Dense Z-pinches*, 2002, pp. 33–36.

[6] B. Kablambaev, N. Ratakhin and S. Shlyakhtun, *in: Proc. 13th Intern. Conf. on High-Power Particle Beams,* 2000, pp. 1063–1066.

[7] S.A. Sorokin and S.A. Chaikovsky, *in: Proc. 5th Intern. Conf. on Dense Z-pinches*, 2002, pp. 59–62.

[8] D. Mosher, N. Qi, and M. Krishnan, IEEE Trans. Plasma Sci. **26**, 1052 (1998).