Tight Pinches Produced by a 16 cm Outer Diameter Multiple Shell Gas Puff Implosions

S.A. Chaikovsky, R.B. Baksht, A.V. Fedunin, A.Yu. Labetsky, V.I. Oreshkin, A.G. Rousskikh, A.V. Shishlov

Institute of High Current Electronics, 4 Akademichesky Ave., Tomsk, 634055, Russia, 3822-492-133, 3822-491-677, stas@ovpe.hcei.tsc.ru

Abstract – The experiments with a multiple shell gas puff z-pinch at microsecond implosion times were performed on the GIT-12 generator. Two concentric annular gas jets had diameters of 16 m (outer shell) and 8 cm (middle shell). The inner on-axis solid fill had the diameter of 2.2 m. It was shown that in order to produce a millimeter radius pinch either the middle shell mass or the inner shell mass should be equal to or higher than the outer shell mass.

1. Introduction

The wide range of a z-pinch plasma applications – from x-ray microlithography to inertial confinement fusion – requires a tight pinch to be produced in the final stage of implosion at a high implosion velocity, i.e. energy per atom, in order to reach a high plasma temperature. The final velocity is strongly determined by an initial z-pinch radius and an implosion time, which should be approximately equal to a generator current rise time.

In early 70's it was understood that a high initial radius implosion is severely affected by instabilities, mainly by Rayleigh-Taylor (RT) instability [1, 2]. Two dimensional calculations have shown that in order to avoid a damage of imploding shell by instabilities an initial radius not over 1÷2 m is required [3]. Hence, a final plasma velocity of $(2÷6)\cdot10^7$ cm/s could be attained if a generator current rise time is ≈ 100 ns. This fact has shifted a problem of stability to a region of pulse power progress. Fast generators (τ ≈ 100 ns) are now widely used for high-power soft ($h\nu \leq 1$ keV) and K-shell ($h\nu \approx 1÷4$ keV) x-ray pulses generation.

Nevertheless, the problem of stable implosion from a high initial radius ($r_0 > 4$ cm) is quite attractive. For example, the stable implosion from such initial radius on a fast generator could provide implosion velocity up to ≈ 10^8 cm/s and could provide, in principle, radiation with quantum energy up to 10 keV. Another possible application is exploiting of slower (τ ≈ 1 μs), hence, less expensive generators for efficient soft and K-shell x-ray production.

One of the way to mitigate the instability effects is the use of additional shell or shells inside a z-pinch. Probably the first experimental test of this approach to plasma implosion was performed in [4]. The efficiency of soft x-ray generation on a microsecond capacitor bank was increased using a double shell gas puff up to that observed with a fast waterline machine.

The numerous experiments with double and triple gas puffs were performed in High Current Electronic Institute, Tomsk, Russia on the generators with a current rise time of 300÷1000 ns. Some experiments tested a "snow plow" stabilization [5] approach. The approach implies that instability of an outer shell could be suppressed at collision of the outer shell with a heavier inner shell. Another approach is to allow an outer shell to be disrupted by instabilities (either RT or seeded by initial nonuniformity of the shell), then efficient current switching to an inner shell could probably occur due to high active impedance of the unstable outer shell or in a "plasma flow" fashion. Significant improvement of the final pinch quality, soft and K-shell x-ray yield were registered (see, for example, [6, 7, 8]). Nevertheless, the experiments have not born out whether "snow plow" stabilization itself or current switching itself work efficiently.

This paper discusses the stability of a multiple shell gas puff z-pinch imploded on the GIT-12 generator in a microsecond regime. The experiments were aimed at efficient K-shell x-ray production. The experimental results on K-shell yield are not a subject of this presentation and could be found in a companion presentation [9]. This paper puts accents on implosion stability and a possibility to obtain a tight pinch at high initial radius implosion.

2. Experimental Setup

The GIT-12 installation was redesigned for direct drive implosion experiments. In this mode the generator delivers 4.7 MA current with a rise time of 1.6 μs on a short-circuit load.

Experiments were performed with neon and argon multi-shell gas puffs (shell-on-shell-on-solid-fill) with the length of 1.8 cm (Fig. 1). Two concentric annular gas jets had diameters of 16 cm (outer shell) and 8 cm (middle shell). The inner on-axis solid fill had the diameter of 2.2 cm. The nozzles design according to snowplow calculation allows reaching an energy per ion of 40 keV required to ionize argon ions up to K-shell and efficiently excite K-shell electrons [9], at approximately 0.9 μs implosion time and ten-fold inner shell compression. The shell masses were varied in the experiments in order to find out the better stability and K-shell radiation yield performance. The masses were controlled by the gas pressure and were estimated using a pressure sensor in the manner [10].

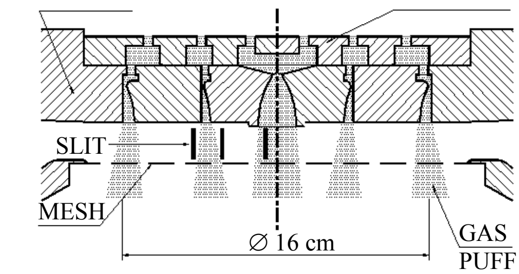

Fig. 1. Multiple shell gas puff scheme and positions of a axial viewing streak camera slit

Implosion dynamics was recorded by two visible light streak cameras. The inlet slit of the first camera (radial streak) was aligned conventionally normal to the z-pinch axis in the middle of the interelectrode gap. The gas puff image was projected on a inlet slit of the second streak camera so that the slit was arranged parallel to the gas puff axis (axial streak). The slit radial position was varied in the experiments from shot to shot. These slit positions relatively to the gas puff are shown in Fig. 1. The axial streak camera views the plasma along a chordal crossection of a gas puff, as illustrated in Fig. 2. Three radial slit position were used in the experiments: R_{slit} = 4.5 (position a, Fig. 2), 3.0 (position b), and 0.6 cm (position c).

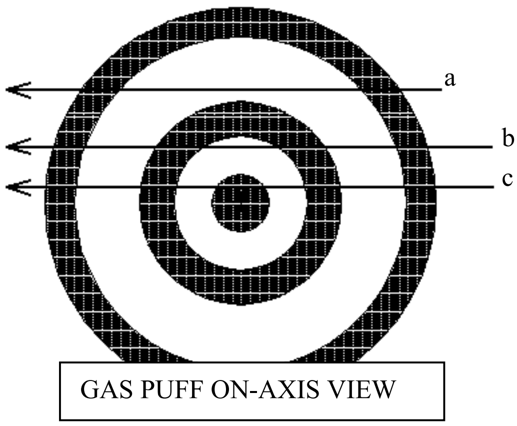

Fig. 2. Axial streak camera sights of view: a – the only outer shell is viewed, b – the outer and middle shells are viewed, c – all shells are viewed

The pinch image in the final stage of implosion was registered by two time-integrated pinhole cameras. In argon shots, the cameras had filters 20 μm teflon + 2μm kimfol + 0.2 μm aluminum to register argon K-shell x-ray image *h*ν > 3 keV, and 10 μm beryllium (softer x-ray range – *h*ν > 0.8 keV). In neon shots the cameras had filters 25 μm beryllium + 10 μm polypropilene to view a neon K-shell x-ray image *h*ν > 0.9 keV and 15 μm teflon + 2μm kimfol + 0.2 μm aluminum (harder x-ray range – *h*ν > 2 keV). The K-shell power and yield were measured by XRDs and PCDs filtered correspondingly to these spectral bands (for details see [8]).

3. Argon Experimental Results and Discussion

Depending on the total argon puff mass the implosion time was varied from 550 to 950 ns resulting in peak current variation in the range 2.2÷3.4 MA. K-shell x-ray pinhole images (Fig. 3) clearly demonstrate a dependence of the final pinch quality on a ratio of shell masses. In order to produce a millimeter radius pinch, either the middle shell mass or the inner shell mass should be equal to or higher the outer shell mass. The final pinches with a diameter of 2 mm were formed at outer/middle/inner masses M_o:M_m:M_i of 70:150:70 and 150:70:150 (μg/cm). In the latter case the bulk plasma seems to be too cold, because “hot spots” are evidently observed, and as a result, K-shell yield was not over 100 J/cm. The shot with a mass distribution of 70:150:70 resulted in higher K-shell yield of 380 J/cm. It was assumed that an electron temperature is still too low to reach optimum K-shell radiation power and yield. In order to increase the temperature shell masses were reduced proportionally. The highest K-shell yield of 500 J/cm (15 ns FWHM radiation pulse) and the best pinch quality were registered at the mass distribution of 50:110:50. Further reduction of the shell masses has led to K-shell yield falling due to lower implosion time and, hence, lower peak current.

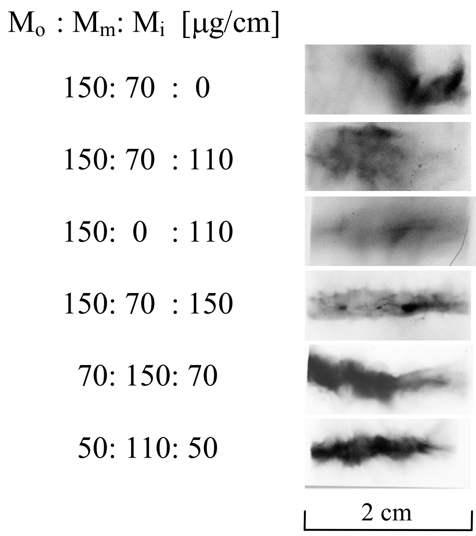

Fig. 3. Argon K-shell x-ray pinhole images at various mass distribution. M_o, M_m and M_i are the outer, middle and inner shell masses (in μg/cm), respectively. The distribution M_o:M_m:M_i is shown near corresponding image in the picture

4. Neon Experimental Results and Discussion

The experiments with neon were performed at a fixed outer mass of 250 μg/cm to keep the implosion time ≈ 1 μs. The middle shell mass was either 100÷150 or 250 μg/cm. The inner shell mass was varied. The peak current was in the range of 3.3÷3.8 MA; the implosion time was in the range 0.9÷1.0 μs in the shots.

Figure 4 shows neon pinhole x-ray images and radial streak photographs for mass distributions 250:250: 0 (a), 250:250: 100 (b) and 250:250:350 (c). It is clearly seen from Fig. 4,a that without an inner shell a tight pinch is not observed. The streak images demonstrate that without an inner shell the plasma does not assemble on the axis in contrast with shots with an inner shell.

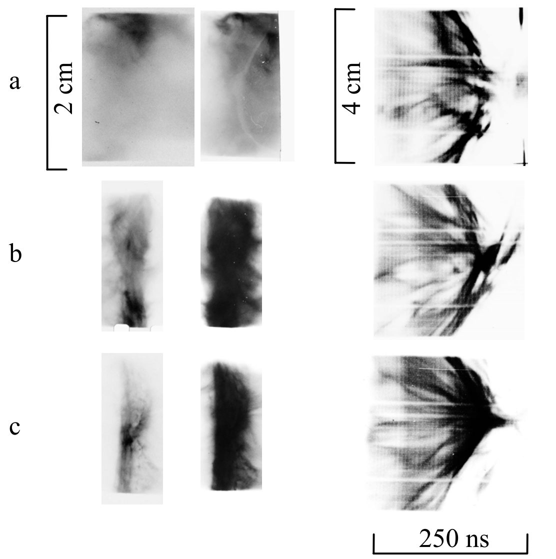

Fig. 4. Neon pinhole x-ray images and radial streak photograph for mass distributions 250:250:0 (a), 250:250:100 (b), and 250:250:350 μg/cm (c). The left pinhole pictures correspond to the spectral range > 2 keV, the right ones correspond to the neon K-shell x-rays

The highest neon K-shell yield of 11 kJ/cm was registered in shots with mass distribution 250:250:100. The final plasma velocity estimation from the streak image gives the value of ≈ $4\cdot10^7$ cm/s. An increase in the inner shell mass results in even better pinch quality, as one can see in Fig. 4,c, but the final implosion velocity drops significantly and does not exceed $2.8\cdot10^7$ cm/s. The K-shell yield reduces nearly twice.

Axial streak images in shots with different slit radial positions and the equal outer and middle shell masses of approximately 250 μg/cm are shown in Fig. 5. The images with three radial slit positions are presented: R_{slit} = 4.5 (a), R_{slit} = 3.0 (b), and R_{slit} = 0.6 cm (c). These three slit positions are illustrated relatively to a z-pinch in Fig. 2 and Fig. 6, where they are marked by (a), (b) and (c) letters, respectively. Unfortunately, these streak images (Fig. 5) were not synchronized with the generator current or a radiation pulse. When the slit is adjusted in position (a), only the outer shell is viewed by the streak camera.

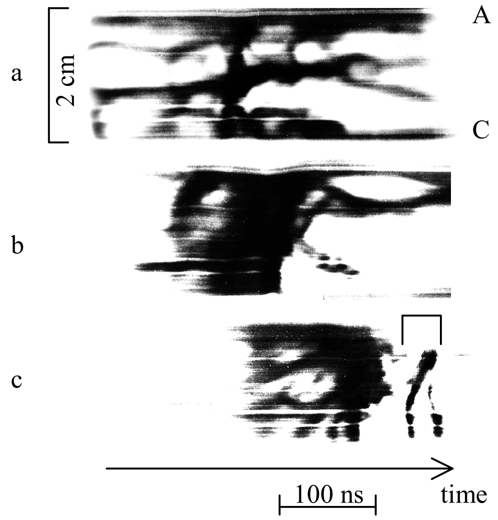

Fig. 5. Axial streak photos of neon implosions at the different slit radial positions: R_{slit} = 4.5 cm and M_o:M_m:M_i = = 250:250:350 (a); R_{slit} = 3.0 cm and M_o:M_m:M_i = 200:200:100 (b); R_{slit} = 0.6 cm and M_o:M_m:M_i = 250:250:100 (c)

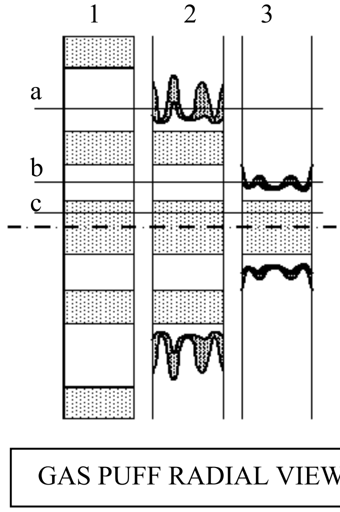

Fig. 6. The scheme explaining how an axial streak camera views the imploding pinch. a, b and c – positions of streak camera slit. 1 – an initial z-pinch position, 2 – an outer shell passes by slit (a) radial position, 3 – the outer and inner shells passes by slit (b) radial position. The slit were adjusted either at the position (a) or (b), or (c) in different shots

One can see that a visible plasma emission continues no less than 400 ns; an distinct plasma sheath is not observed. Having in mind that plasma velocity calculated by a "snow plow" model attains $1.5\cdot10^7$ cm/s at the radius of 4.5 cm, the plasma shell thickness could be estimated to be a few centimeters. This is not surprising, because estimated e-folding number of the most dangerous RT modes (a wavelength approximately equals to initial shell thickness of 5 mm) reaches 13, that means that a nonlinear break up of the shell is expected [11]. Fig. 5,b shows a streak image at the radius just below a middle shell initial radius. A distinct plasma sheath is observed. Plasma "tails" follow the plasma sheath. The estimated sheath thickness is ≈ 1 cm, i.e. some stabilizing effect of the middle shell is evident. At the radius of 0.6 cm (Fig. 5,c) shell thickness again becomes larger due to instabilities and reaches 3 cm; "snow plow" calculated velocity is $3\cdot10^7$ cm/s. The emission in the region marked by a bracket in Fig. 5,c is attributed probably to expanded plasma pinch.

Of course, such way of the thickness estimations is too rough and gives too high values. One should keep in mind that the slit "views" not only the sheath passing by, but some visible emission could be registered earlier, because of chordal line of sight of the streak camera (Fig. 2). The picture (c) in Fig. 5 was registered in the same shot where comparatively stable final plasma column was observed in the pinhole and the radial streak images shown in Fig. 4,b.

A few neon shots were done with a middle shell mass of 100 μg/cm. The pinhole images shown in Fig. 7 were obtained in a shot with the mass distribution of 250:100:250. The K-shell yield was 11 kJ/cm in this shot. The pinch stability is slightly worse as compared to the shot with the mass distribution of 250:250:100.

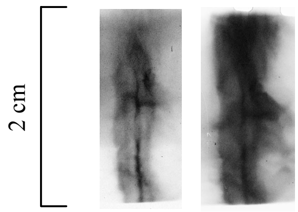

Fig. 7. Pinhole pictures of a neon implosion at mass distribution of 250:100:250. In the left – spectral range $h\nu > 2$ keV, in the right – neon K-shell x-rays

A distinctive feature of the harder x-ray image is a tight core with a diameter of 0.5 mm inside the bulk plasma pinch. More bright image as compared to Fig. 4,b could be a consequence of higher plasma electron temperature.

4. Conclusion

The experiments were performed with neon and argon multi-shell gas puffs (shell-on-shell-on-solid-fill) on the GIT-12 generator at microsecond implosion times. Two concentric annular gas jets had diameters of 16 cm (outer shell) and 8 cm (middle shell). The inner on-axis solid fill had the diameter of 2.2 cm. It was shown that a multiple shell z-pinch implosion with such high initial outer diameter allow producing a tight final pinch with a diameter of 1.8 mm (argon) and 5 mm (neon). In order to obtain the tight pinch, the inner shell mass or the middle shell mass should be equal to or higher the outer shell mass.

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