Microsecond Implosion Time K-Shell X-Ray Production on the GIT-12 Generator

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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 cm (outer shell) and 8 cm (middle shell). The inner on-axis solid fill had the diameter of 2.2 cm. The maximum Ne K-shell radiation yield reached 11 kJ/cm in a 40 ns FWHM pulse at the maximum current of 3.3 ÷ 3.6 MA and implosion time of 0.9 ÷ 1.0 μs. The maximum Ar K-shell yield achieved was measured to be 500 J/cm in a 15 ns FWHM radiation pulse at the current level of 2.2 ÷ 2.6 MA and implosion time of 0.6 ÷ 0.7 μs.

1. Introduction

Efficient K-shell x-ray plasma radiation sources (hν ≈ 1÷4 keV) are currently based on z-pinch implosion driven by fast pulse power generators. The generators conventionally consist of a comparatively slow (τ ≈ 1 μs) primary capacitive storage and power conditioning system (water transmission lines or inductive storage with an opening switch), which provides a load current rise time ≈ 100 ns. A z-pinch implosion driven directly by the primary storage seems to be an appropriate way to reduce cost, technical risk level and complexity of a plasma radiation source. A slow current rise time requires a high initial radius (> 4 cm) implosion to provide sufficient energy per ion for ionization and excitation of K-shell electrons. Instabilities are the main problem to be solved when a high initial radius z-pinch is exploited [see, for example,1, 2, 3]. They restrict plasma compression ratio, do not allow formation a well-defined tight final pinch. As a consequence, K-shell yield occurs to be low [1].

A multiple shell z-pinch implosion could produce a more stable final plasma pinch as compared with a conventional single shell z-pinch. Experiments with a multiple shell gas puff z-pinch have been performed on the GIT-12 pulse generator operating in a microsecond mode. The experiments were aimed at study of argon and neon K-shell x-ray generation efficiency at a microsecond rise time of a generator current.

2. Experimental Setup and Diagnostics

The GIT-12 installation is composed of 12 modules and a central collector with a load. Each module consists of nine parallel Marx generators, a vacuum insulator, a vacuum coaxial line connecting the module to the central collector. A plasma opening switch (POS) was used in our previous experiments. A current of 2.6 MA with a rise time of 300 ns was delivered to an imploding load. The generator was redesigned for direct drive implosion experiments. The POS was removed and the total inductance was slightly reduced. 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. According to snowplow calculation, the nozzles design allows reaching energy per ion of 40 keV required to ionize argon ions up to K-shell and efficiently excite K-shell electrons [4] at approximately 0.9 μs implosion time and ten-fold radial 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 a gas pressure in corresponding gas valve volume and were estimated using a pressure sensor.

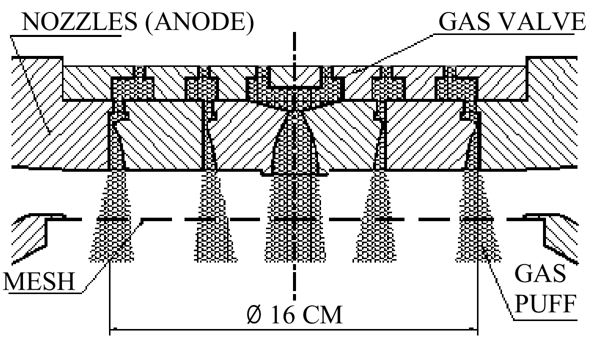

Fig. 1. Multiple shell gas puff scheme

The load current I and the load voltage U were measured by B-dot probes and an inductive divider, respectively. The time varying load inductance $L(t)$ was estimated from relation: $L(t) \approx \int U(t)\,dt / I(t)$, neglecting an active resistance.

The pinch image in the final stage of implosion was registered by a time-integrated pinhole camera with filters transmitted efficiently argon K-shell (> 3 keV) or neon K-shell (> 0.9 keV) x-rays. The argon K-shell yield and power were measured by two PCDs. The first one was filtered by 6.35 μm Ti + 10 μm polypropylene, the second one – 3 μm Pd + 10 μm polypropylene. Due to a sharp Pd L-edge cutoff at 3.17 keV, the second PCD registered net argon He-α line radiation, while the first PCD was sensitive to all K-shell lines and continuum.

The neon K-shell yield and power were measured by two XRDs with aluminum cathodes filtered by 6 μm kimfol + 0.6 μm aluminum (XRD1), 10 μm aluminum + 3 μm mylar (XRD2). The detectors sensitivities are shown in Fig. 2. The XRD's response ratio is sensitive to neon plasma electron temperature. This was used to estimate ion density, electron temperature and K-shell radiating mass in a fashion proposed
in [5]. The approach requires a plasma pinch radius r_k, a resonance K-shell lines ratio and a K-shell power to be measured. Then, collisional radiative equilibrium (CRE) model calculations are performed to fit experimental values with calculated ones. The calculated ion density and electron temperature of a uniform plasma column with the radius r_k, which provide this fit, are supposed to be some averaged parameters of the real plasma. The same approach was used in our experiments, but absolute voltages of two XRDs and their ratio were calculated to fit with the experimental ones, resulting in a simple and fast way to estimate plasma electron temperature T_{XRD} and K-shell radiating mass M_k.

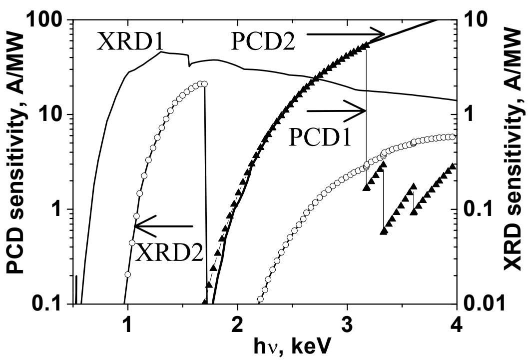

Fig. 2. X-ray detector sensitivities in experiments with a neon z-pinch

One of the PCDs was filtered by 3 μm Pd + 20 μm polypropylene (PCD1), another was filtered by 30 μm teflon + 20 μm polypropylene (PCD2) in shots with neon. Both detectors are sensitive to continuum radiation of the neon K-shell, but the first one has low sensitivity in the spectral region > 3.17 keV (Fig. 2). The ratio of PCD responses depends strongly on a slope of the continuum radiation, that allows measurements of the electron temperature (T_{slope}).

Total soft x-ray yield was measured by unfiltered bolometer with approximately 1 μs time resolution.

3. Argon Experimental Results

Figure 3 shows the typical load current and PCD traces for an Ar multishell z-pinch. Depending on the total puff mass the implosion time varied from 550 to 950 ns, resulting in peak current variation in the range 2.2÷3.4 MA. Analysis of pinhole pictures showed 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 (see presentation [6]). The highest K-shell yield of 500 J/cm (15 ns FWHM radiation pulse) and the best pinch quality (Fig. 4) were registered at outer/middle/inner masses M_o:M_m:M_i of 50:110:50 (μg/cm). The final pinch with a radius of 0.9 mm was formed. The K-shell yield is twice lower then that predicted by two-level model [7] for a maximum current of 2.4 MA and a pinch radius of 1 mm.

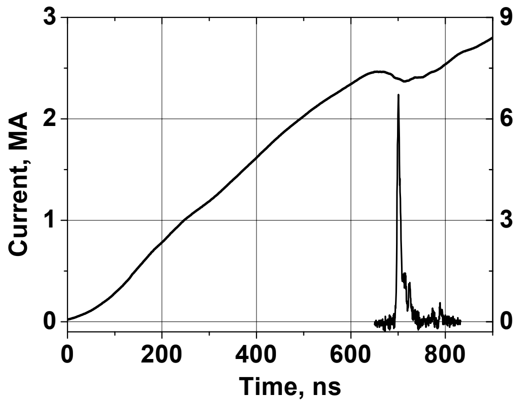

Fig. 3. Typical load current and PCD traces for an Ar multishell z-pinch

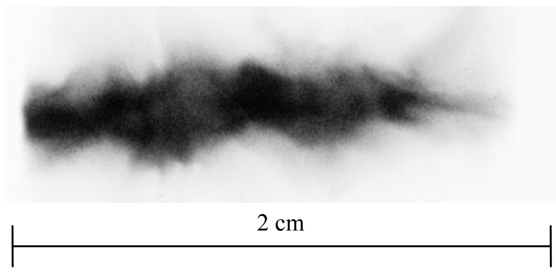

Fig. 4. K-shell x-ray pinhole image of argon implosion at M_o:M_m:M_i of 50:110:50 (μg/cm). Cathode is on the left

In this shot, PCD's peak voltages ratio were equal to their sensitivity ratio for argon He-α line, indicating that radiation of this line is an overwhelming portion of K-shell x-rays. According to CRE calculation, this is the case, when argon plasma electron temperature does not exceed 0.9 keV, while the temperature well above 1 keV is required to reach optimum K-shell radiation power.

4. Neon Experimental Results

Neon K-shell x-rays are much softer in comparison with argon. Hence, lower temperature are required to excite K-shell electrons. The experiments with neon were performed at a fixed outer shell mass of 250 μg/cm. The middle shell mass was either 100÷150 or 250 μg/cm. The inner shell mass was varied. The dependencies of K-shell yield Y_k and power P_k on the inner shell mass are shown in Fig. 5. The peak current was in the range 3.3÷3.6 MA, the implosion time was in the range 0.9÷1.0 μs for the shots presented in Fig. 5.

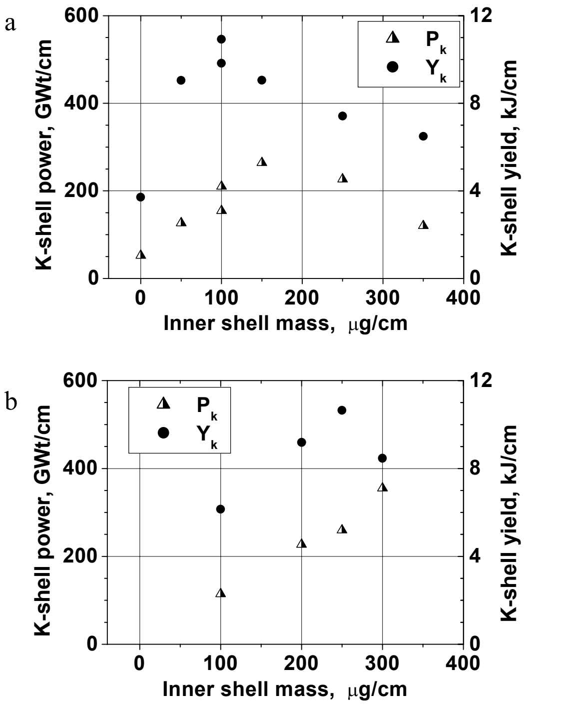

Fig. 5. Dependencies of neon K-shell yield Y_k and power P_k on the inner shell mass at the middle shell mass of 250 μg/cm (a) and middle shell mass of 100÷150 μg/cm (b)

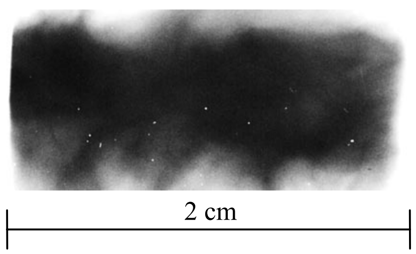

Fig. 6. Neon K-shell x-ray pinhole image in shot with a middle shell mass of 250 mkg/cm and inner shell mass of 100 mkg/cm

The K-shell yield reached 11 kJ/cm in a 40 ns FWHM pulse. The diameter of the plasma column radiating in K-shell was less than 5 mm (Fig. 5). In the two-level model [7], a K-shell yield depends strongly on a typical plasma kinetic energy K [J/cm] $\approx 2000\, I_{max}^2$ [MA] (a typical compression ratio of 10÷15 is assumed). In "strong" radiation regime, the K-shell yield should approach 0.5K, that is the case of our experiments with neon. Indeed, the typical kinetic energy is approximately 22÷26 kJ/cm, and K-shell yield is up to 11 kJ/cm.

Figure 5 shows that the K-shell yield peaks at the inner mass of 100 μg/cm, when the middle shell mass is 250 μg/cm, and at the inner shell mass of 250 μg/cm, when the middle shell mass is 100÷150 μg/cm.

Dependencies of the electron temperature T_{slope} and T_{XRD}, the K-shell pinch diameter D_k, the K-shell mass M_k and the total soft x-ray yield Y on the inner shell mass at the middle shell mass of 250 μg/cm are shown in Fig. 7.

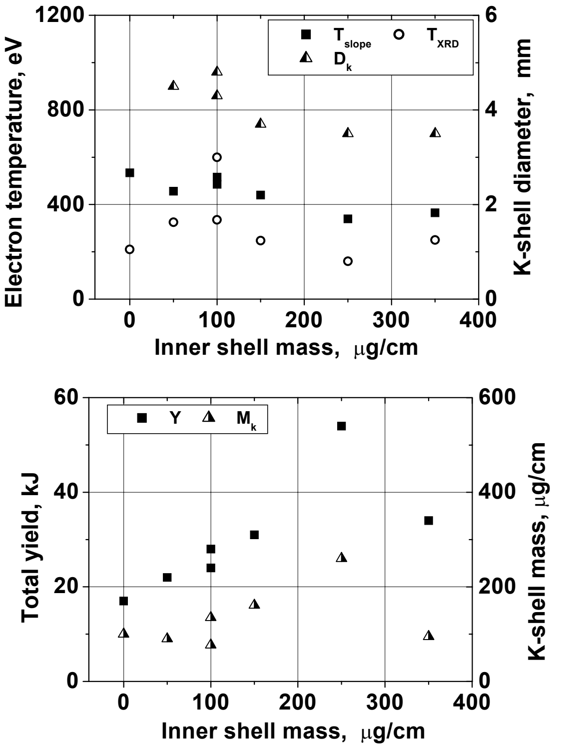

Fig. 7. Dependencies of electron temperature T_{slope} and T_{XRD}, K-shell pinch diameter D_k, K-shell mass M_k and total soft x-ray yield Y on inner shell mass at the middle shell mass of 250 μg/cm. Neon

We do not show error bars in the plots for a vivid presentation. The temperature and total yield measurement uncertainty was roughly determined to be not over ± 20%. In general, the electron temperature T_{slope} exceeds the electron temperature T_{XRD} (Fig. 7). A possible reason is that T_{slope} is measured by PCD's signal ratio caused by x-rays harder than 3.17 keV. The x-ray yield was estimated to be less than 50 J/cm in this spectral range, that is a quite small fraction of K-shell yield. Nevertheless, the temperature dependencies behave very similar (except for one point at the zero inner shell mass). The electron temperature is in the range 350÷600 eV in shots with the highest K-shell yield at M_i = 100 μg/cm. This is the temperature range, where the maximum Ne K-shell power is predicted by CRE model taking into account an opacity effect. Higher inner shell masses implosions result in reduction of electron temperature below the optimum value. As a consequence, K-shell yield reduces in spite of higher plasma density.

The K-shell radiating mass is slightly over the inner shell mass (Fig. 7), except for the shot with the inner shell mass of 350 μg/cm. In this shot, the K-shell radiating mass is significantly less than the inner shell mass. Only a small fraction of injected mass participates in K-shell radiation. The temperature diagnostics probably "feel" only this small plasma fraction, that could explain a faint rise in electron temperature in this shot.

The total soft x-ray yield dependence follows the K-shell mass dependence and reaches its maximum of 55 kJ at the inner shell mass of 250 μg/cm. In shots with the inner shell mass of 100 μg/cm the total radiation yield is only 20÷60% higher than the K-shell radiation yield.

5. Discussion

The neon K-shell yield peaks at the inner shell mass of 100 μg/cm, when the middle shell mass is 250 μg/cm, and at the inner shell mass of 250 μg/cm, when the middle shell mass is 100÷150 μg/cm. It was assumed that a significant fraction or the whole middle shell mass participates in pinch formation and K-shell x-ray production.

An additional argument to this viewpoint is that the estimated K-shell radiating mass exceeds the inner shell mass. For example, for the shot with the inner shell mass of 50 μg/cm, the K-shell radiating mass reaches 90 μg/cm. Moreover, the best K-shell yield shots were repeated, but with nitrogen in the middle shell. The K-shell yield with nitrogen middle shell was ≈ 40% lower at M_m = 250 μg/cm, M_i = 100 μg/cm; and ≈ 25% lower at M_m = 100 μg/cm, M_i = 250 μg/cm as compared with the shots where neon was in the middle shell. A simple estimation based on the assumption that $Y_k \propto (M_i + M_?)$ (where $M_? = 0$ for nitrogen middle shell, and $M_?$ is unknown for neon middle shell) shows that additional mass $M_?$ is approximately equal to 70÷80 μg/cm. It means that approximately 30÷80% of the middle shell mass participates in K-shell emission.

Let us discuss the reasons of the low argon K-shell yield obtained. From the neon shots we can estimate the energy K delivered to the plasma. Neon radiates in strong emission regime at the current level of 3.3÷3.6 MA, because the neon breakpoint current is well less than 1 MA [4,7]. In this regime the K-shell yield should approach approximately 0.5 of an energy delivered to the plasma [7]. In order to provide the neon K-shell of 11 kJ/cm the implosion energy K should be of 22 kJ/cm, that is close to estimated implosion energy K [J/cm] ≈ 2000 I_{max}^2 [MA]. Such estimation being performed for the best shot with argon (2.4 MA implosion current) gives K ≈ 11÷12 kJ/cm. To produce the highest argon K-shell yield, the pinch mass should be 70 μg/cm at this implosion energy K [7]. However, as the neon shots showed, the pinch mass approaches to the total mass of the middle and the inner shells. The total mass is 160 μg/cm for the best shot with argon, that is twice higher than the optimum mass. Indeed, the final plasma velocity being estimated from K = 11÷12 kJ/cm at the pinch mass of 160 μg/cm does not exceed $3.9 \cdot 10^7$ cm/s. Approximately the same value of the final plasma velocity $3.5 \cdot 10^7$ cm/s (see [8]) was estimated from time varying inductance $L \approx \int U\, dt/I$. This velocity value corresponds to the energy per ion of ≈ 25 keV/ion, that is insufficient to ionize argon ions up to K-shell and efficiently excite K-shell electrons.

6. Conclusion

The first experiments with a multiple shell gas puff z-pinch at microsecond implosion times were performed on the GIT-12 generator. The maximum Ar K-shell yield was measured to be 500 J/cm in a 15 ns FWHM radiation pulse at the current level of 2.4 MA and the implosion time of 0.7 μs. The maximum Ne K-shell radiation yield reached 11 kJ/cm in a 40 ns FWHM pulse at the maximum current of 3.3÷3.6 MA and the implosion time of 0.9÷1.0 μs. The neon K-shell yield reaches the value that can be obtained on the fast generator with the same current level.

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