Submillimeter high brightness pulsed x-ray source

J. H. W. Lau, M. M. Kekez, G. D. Lougheed, and R. P. Gupta
National Research Council of Canada, Ottawa K1A 0R6, Canada

(Received 23 December 1987; accepted for publication 21 April 1988)

By inducing an electrical discharge in an annular gas plenum connected to a vacuum diode by a narrow annular slit, we demonstrate that microgram preionized plasma liners can be formed and imploded by a dc charged Blumlein pulser to efficiently convert electrical energy into soft x rays. The submillimeter x-ray source can in principle be scaled to the high repetition rate needed for x-ray lithography. In a proof of principle experiment, we have observed using krypton up to 0.5, 20, and 100 J of x-ray output above 1.5 keV, 500 eV, and 150 eV photon energies, respectively.

The existing high brightness x-ray sources are not entirely suitable for production submicron lithography. While the compact synchrotron,[1] under development for this purpose in the U. S., Germany, and Japan, fits the technical requirements, it becomes cost effective only when ten or more stepper stations can be simultaneously employed. The gas puff (GP) based pulsed plasma x-ray source has been recognized as a viable alternative.[2] However, the repetition rate of the GP source is well below that required for a commercial lithography environment.

In a GP source the gas is puffed into a vacuum diode thorugh a supersonic annular nozzle attached to one of the diode electrodes. The nozzle is connected to a plenum which is instantaneously gas filled by opening and closing a fast valve. The gas enters the diode region with Mach 8-10 speed to form an annular gas jet liner which is preionized by UV radiation from an electric spark or other preionization system before a fast capacitor bank is discharged through the liner.[3,4] The resulting high current drives the hollow liner to its axis at high speed. Thermalization of the liner kinetic energy upon its collapse and subsequent Joule heating of the resulting plasma column gives rise to the x-ray emission.

While the GP approach is efficient in converting electrical energy to soft x rays on a single shot, high pulse energy level, scaling it to low energy per pulse, high repetition rate has been a major problem. The time needed to pump out the puffed and the plenum gas to achieve the desired vacuum in the diode region limits the repetition rate at best to a few Hz.[5] Since puffed gas is a small fraction of the gas in the plenum at several hundred Torr pressure, most of the time is taken in pumping out the unused gas.

To alleviate the above GP limitation, a novel approach has been developed to repeatedly form microgram liners.[6] One arrangement of the approach is shown schematically in Fig. 1. The gas continuously flows from an annular slit into the diode region evacuated using a turbomolecular pump. The slit opening is such that a pressure differential of 10 000 or so is maintained between the plenum and the diode. A one or two turn coil is placed in close proximity to the ceramic plenum which is maintained at approximately 0.5 Torr gas pressure. A capacitor bank discharge through the coil induces a current in the gas. The gas is heated and ionized, and driven towards the slit by the magnetic pressure due to the induced current. This results in an increased gas flow from the plenum to the diode for the 20–50 μs duration of the discharge, and forms a well defined, uniformly preionized, microgram gas liner in the diode region. In an earlier larger version,[7] the current induced in the plenum gas increases its pressure only by heating the gas but did not make use of the electromagnetic pressure to puff the gas. The maximum puff mass was therefore limited to approximately 0.5 μg as compared to more than 5 μg in the new version. Neon, argon, krypton, and xenon gases have been used with varying degrees of success. All the results reported in this letter are for krypton. The only gas to be pumped out in the new approach

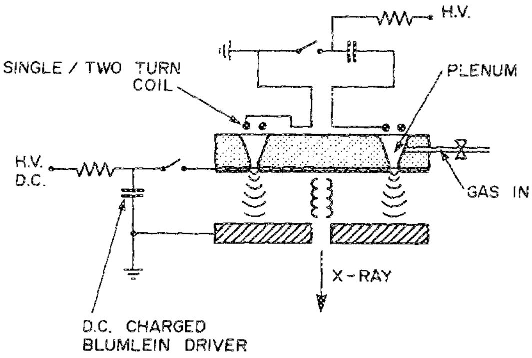

FIG. 1. Schematic of the electric discharge puff.

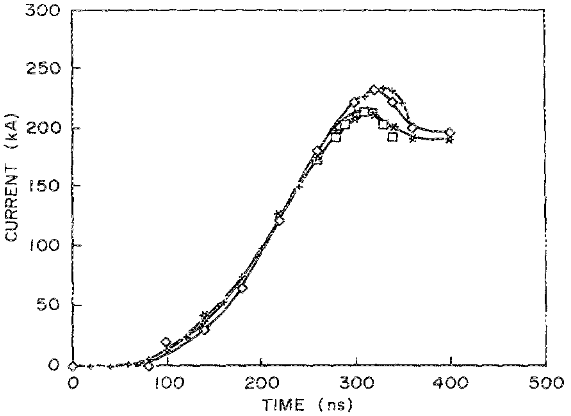

FIG. 2. Double Blumlein current through the imploding liner. Simulations with 0.2 μg (□) and 0.3 μg (+); experiment with short (*) and long (◇) delay.

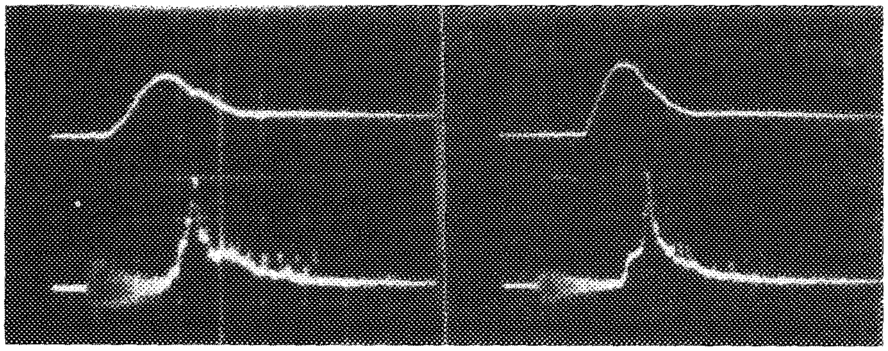

FIG. 3. Current (top) and saran filtered XRD (bottom) waveforms of two typical shots. 200 ns/div; current 250 kA/div; XRD 20 mV/div (left) and 50 mV/div (right).

is that which is puffed and used in the diode; there is no dead plenum gas to pump out between the shots. The repetition rate of a properly designed machine would thus be limited by vacuum insulation recovery time of the diode and by the diode vacuum conductance. Repetition rates of 100 pulses per second or higher should be possible with this approach.

To efficiently implode the ultralow mass plasma liner, dc charged Blumlein drivers made with aluminum foil conductors and kraft paper impregnated with castor oil have been developed.[8] Each 128 mΩ Blumlein stores 272 J energy at 25 kV. Two such Blumleins connected to a fixed inductive load (a metal slug placed at the initial position of the liner) give a peak current of 190 kA and a 10–90% rise time of 150 ns when switched by two separate simultaneously triggered, multichannel railgap switches. In a "double" Blumlein configuration, one switch is connected to two Blumleins in parallel, and the combination of two of these units is connected to the load. This gives a peak current of 290 kA and a rise time of 190 ns. In the "triple" Blumlein configuration, the above two arrangements are connected in parallel to drive up to 600 kA discharge current through a real load under certain conditions.

The peak current is reduced by up to 30% when the metal slug is replaced by the plasma liner—the implosion of the liner increases its inductance with time and the resulting dL/dt decreases the current. The lighter the liner, the faster it implodes and the current decrease is more pronounced, especially near the end of the implosion phase when the liner inductance is increasing most rapidly. The simulation of this fact by coupling the Blumlein discharge with the dynamics of the plasma liner under magnetic pressure, resulting from the current flow through the liner,[9] yields the liner mass (Fig. 2). Finally, the liner collapses and the kinetic energy is rapidly thermalized. The hot and dense plasma region thus formed radiated copiously with the spectrum depending on the plasma temperature.

Figure 3 shows typical records of the current through the liner and the x rays filtered through 12.5 μm saran (1.5–2.8 keV) observed by an aluminum cathode x-ray diode (XRD). The anode of the main diode was made of tungsten-copper alloy and the cathode was made of aluminum with four symmetrical 8 mm pins in the 25 mm central region to allow exposure to the XRDs and *p-i-n* diodes. The separation between the electrodes is 9 mm and the liner is puffed through a 30-mm-diam annular slit in the cathode. The current rise time, peak current, and the rate of current rise for the two shots are significantly different although driven by the same triple Blumlein configuration charged to 25 kV. The current initiation depends on the formation of the annular liner and on the discharge activation across the liner. Figure 3 (left) shows the case where the liner is well formed and preionized, allowing the current to flow with minimum delay when the voltage pulse arrives at the diode. Figure 3 (right) shows a delay of about 60 ns between the arrival of the voltage pulse and the current initiation. In the latter case, the load had the effect of a pulse shaping switch which appreciably increases the peak current and the rate of current rise and decreases the current rise time.

Figure 4 shows a six shot exposure taken with a pinhole camera having three holes of 750 μm diameter each. The camera sees the source at 45° to the pinch axis and has a

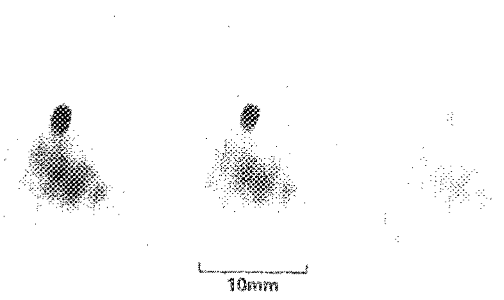

FIG. 4. Pinhole camera picture of the x-ray source with six shots superimposed. Left, 12.5 μm Be filter; middle, 25 μm Be filter; and right, 12.5 μm Be plus 12.5 μm saran filter.

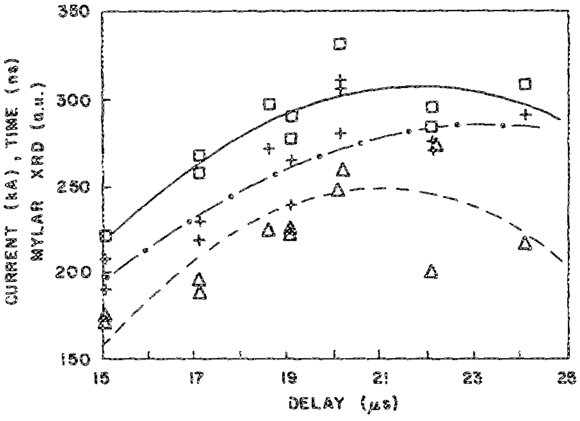

FIG. 5. Effect of delay in discharging the Blumlein relative to the plenum discharge. Solid curve—current; chained curve—implosion time; broken curve—Mylar XRD.

source to image distance ratio of 1. The first pinhole has a 12.5 μm Be filter, the second one has a 25 μm Be filter, and the third one has a 12.5 μm saran and a 12.5 μm Be filter. The diode for this exposure had a 9 mm electrode separation and a 76-mm-diam annular slit in the cathode. The central region of the anode was made of a coarse screen whereas that of the cathode was made of a fine screen. The coarse screen shows up in the pinhole pictures, possibly due to some accelerated electrons hitting the anode. The diameter of the bright spots normal to the pinch axis is 1.5 mm. The finite source size produces penumbral blurring. The observed blurring is so small that the upper limit on the source size has been taken as 300 μm.

The effect of changing the delay between the plenum discharge and triggering the Blumlein pulser on the Mylar filtered XRD signal, on peak current and implosion time is shown in Fig. 5. The diode configuration is the same as for the pinhole pictures. The delay essentially determines the mass accumulation in the liner before it is imploded. The heavier liners produced with longer delays have lower velocities and thus low motional impedance, and therefore permit higher peak currents. The current and implosion time saturation at delays greater than 20 μs indicate that there is no further mass accumulation with delays longer than the ring down time of the plenum discharge. The rapid decrease in the Mylar filtered XRD output for delays longer than 22 μs is most likely due to the diffusion of the initial plasma liner resulting in a decreased pinch density.

In these proof of principle single shot experiments, the electromagnetic plasma puff concept has been shown to work very effectively. Soft x-ray emission up to 0.5 J above 1.5 keV, 20 J above 500 eV, and 100 J above 150 eV has been observed with filtered XRD's corresponding to 0.03%, 1.3%, and 6.6% conversion efficiency from electrical energy to x rays. The electrode erosion problems are greatly reduced mainly because of the low discharge energy per pulse. Considering that only a few percent of the energy stored in the Blumlein is coupled to the liner kinetic energy in the present setup, an optimum system design of the diode and the Blumlein may be expected to reduce the pulser energy by a factor of 4 or more for a given x-ray output. Improvement in nozzle design should further improve the efficiency.

The authors gratefully acknowledge the continued support and encouragement of E. H. Dudgeon, J. Ploeg, and Dr. R. G. Williamson, as well as the untiring technical assistance of J. Diduch, D. Gareau, V. Gomez, P. Hunt, J. Lancaster, M. McMullin, and A. Shewchuk.

[1] J. S. Pearlman and J. C. Riordan, Electron-Beam, X-ray and Ion-Beam Techniques for Submicrometer Lithographies IV, SPIE **537**, 102 (1985).

[2] J. Pearlman and J. C. Riordan, J. Vac. Sci. Technol. **19**, 1190 (1981); J. Bailey, A. Ettinger, A. Fisher, and R. Feder, Appl. Phys. Lett. **40**, 33 (1982).

[3] J. Shiloh, A. Fisher, and N. Rostoker, Phys. Rev. Lett. **40**, 515 (1978).

[4] C. Stallings, K. Childers, I. Roth, and R. Schneider, Appl. Phys. Lett. **35**, 524 (1979)

[5] I. Okada, Y. Saitoh, S. Itabash, and H. Yoshihara, J. Vac. Sci. Technol. B **4**, 243 (1986).

[6] R. P. Gupta, M. M. Kekez, J. H. W. Lau, and G. D. Lougheed, "Gas Discharge Derived Annular Plasma Pinch X-ray Source" (patents pending since October 3, 1985).

[7] M. M. Kekez, R. P. Gupta, J. H. W. Lau, and G. D. Lougheed, "DC charged Blumlein development for imploding liner soft x-ray microlithography source," Sixth IEEE Pulsed Power Conference, 1987.

[8] J. H. W. Lau, R. P. Gupta, M. M. Kekez, and G. D. Lougheed, Bull. Am. Phys. Soc. **31**, 1581 (1986).

[9] I. N. Weinberg, Ph.D. thesis, University of California, Irvine, 1985.