A Compact High Current Generator for X-Ray Radiography

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Abstract – AX-1 generator was designed for small scale experiments with imploding liners, especially X-pinches. Main parts of the generator are capacitor bank and multichannel multi-gap spark switch. The capacitor bank consists of 12 Sorrento type capacitors (20 nF, 25 nH, 0.2 Ohm, 100 kV). It stores ~0.9 kJ at 85 kV charging voltage. The 24-channel, 7-gap spark switch, operating in air at atmospheric pressure, connects capacitor bank with the central load block. The generator provides ~200 kA with 140 ns risetime at 70 kV charging voltage with the 5 nH inductive load. Results of proof of principle experiments with the X-pinch load are presented. With X-pinch consisted of two 30 μm-diameter Ni wires image of the 6 μm tungsten wire was clearly resolved on film, indicating resolution close to diffraction limit. X-ray pulse duration (FWHM above 1 keV) was about 7 ns. The generator dimensions are 1m in diameter and 15 cm height, total weight is about 100 kg, so it could be easily employed for variety of applications.

1. Introduction

A dense hot X-pinch plasma, produced by exploding two or more fine metal wires that cross and touch at a single point (forming an "X"), is both object of fundamental investigations and useful diagnostic tool as point-like nanosecond (or sub-nanosecond) X-ray source within 1–10 keV range. For example, this radiation can be used for backlighting in Z-pinch experiments, providing high spatial and temporal resolution of the imploding plasma. These sources could be used also for a number of technological applications. Though X-pinch investigations count for about 20 years, starting from pioneering works [1, 2] at the P.N. Lebedev Physical institute, the vast majority of investigations has been carried out at conventional nanosecond accelerators with pulse forming lines [see, for example, 3–6]. Impressive results have been achieved, mainly by collaboration of two research groups (from the P.N. Lebedev Physical institute and Cornell University) [5, 6]. But it is quite hard for such accelerators to get output impedance lower than 1 Ohm, so coupling with X-pinch is low efficient. Another drawback is that these accelerators have large dimensions and so cannot be employed as diagnostic or technological tool. Very small number of experiments has been carried out with X-pinches at current risetime more than 100 ns [7, 8] and obtained there results were poor. The goal of the work was the development of portable generator with current 150–200 kA and risetime less than 150 ns, specially fitted for X-pinch experiments.

2. AX-1 Generator

Design of the AX-1 generator is given in Fig. 1. Its main parts are: 12 Sorrento 35404 – Type PDE capacitors (20 nF, 100 kV, double ended) connected in parallel (pos. 1); 24-channel, 7-gap plane circular switch with ball electrodes (pos. 2); polyethylene insulator 3; vacuum output line 5 and load chamber (7) with diagnostics windows. Operation of multi-gap sparks switches is described in detail in [4]. The generator has the shape of a disk, with 105 cm diameter and 15 cm height. The capacitors, 1, are placed evenly around the axis of the disk and connected to the output terminals by the mentioned above switch 2. The output voltage is applied to the electrode 4, which is connected to the center electrode of the output line, 5, with 4 mm spacing between the electrodes. An X-pinch load is located at the end of the output line.

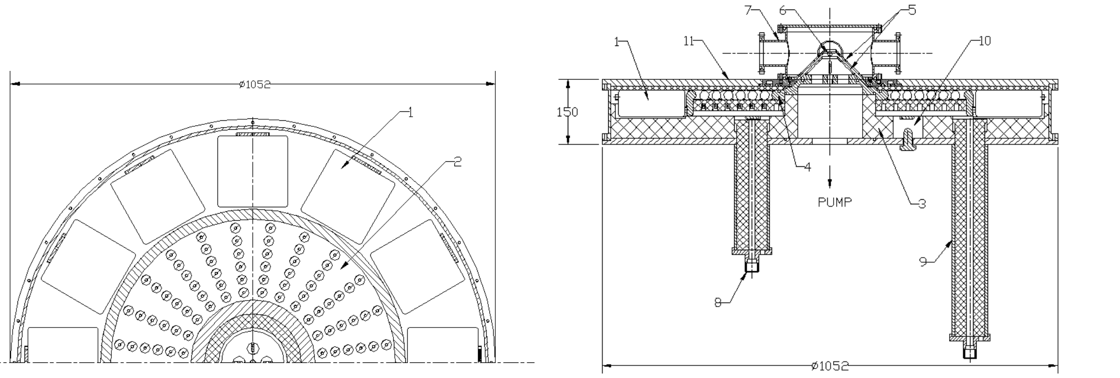

Fig. 1. Design of the AX-1 generator. Here are: 1– capacitors, 2 – multi-gap spark switch, 3 – polyethylene insulator, 4 – high voltage electrode, 5 – output vacuum line, 6 – load, 7 – load chamber, 8 – trigger input, 9 – charging input, 10 – crowbar switch, 11 – top flange

It is closed with a cylindrical chamber 7 with windows for diagnostics and control of the X-pinch placement. Typical operation pressure in vacuum chamber was at the 10^{-4} Torr level.

Triggering pulse comes through input 8 to the disk triggering plate, which is located across the second ball circumference and insulated from it by the 3 mm polyethylene sheet. Triggering is provided through capacitive coupling between triggering plate and ball electrodes. A self-breakdown crowbar switch, 10, protects the trigger cable from multiple reflections of the high voltage trigger pulse.

The generator is designed to operate at up to 80 kV charge voltage with air at atmospheric pressure, which quite simplifies its design and handling. Discharge current was measured by self-integrated Rogovsky coil located in air part of the generator and by measuring of the voltage drop on annular inductive grooves ($\approx$70 pH) upstream and downstream of the load. Temporal behavior of the X-ray emission was measured by filtered p-i-n diodes. Radiographic images of test objects were recorded on the Micrat-200 film, then scanned with 4800 dpi resolution.

3. Short Circuit Tests

Short-circuit waveforms are given in Fig. 2. Integrals from the upstream and downstream B-dots practically coincide, so only Id (Bdot_d integrated) is shown. Currents, derived from the B-dot signals, have jitter less than 5% from shot to shot, while Rogovsky coils signal deviates about 10%. It appears, most probably, due to some asymmetry in multi-gap switch operation, because Rogovsky coil signal is picked up in one point. Amplitude of current reaches 180 kA with ~140 ns risetime. It agrees reasonably with results of P-Spice modeling.

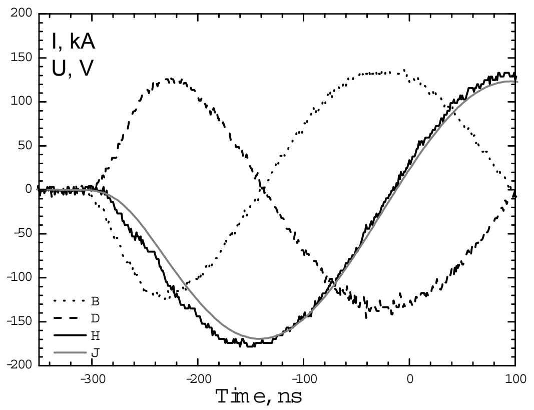

Fig. 2. Typical waveforms (U_{ch} = 70 kV) with short-circuit at the X-pinch place (~ 6 nH)

4. X-pinch Experiment

Most of experiments has been done with X-pinch made of two 30 μm Ni wires and only these experiments are discussed here. Wires were placed between electrodes with 15 mm gap. X-ray probes were made on the base of commercial Si photodiodes FD-256, placed inside of RF cable connectors. Bias voltage +90 V was applied to the probes through the 50 nF insertion unit, giving a time constant of 2.5 μs when fielded on a 50 Ω system. Glass window was thoroughly removed from the photodiodes and diode was covered by 15 μm Mylar to keep it clean. Probes were collimated on the central area of the X-pinch. Additional X-ray filters were applied as required. Fig. 3 shows typical experimental signals obtained by the X-ray probes.

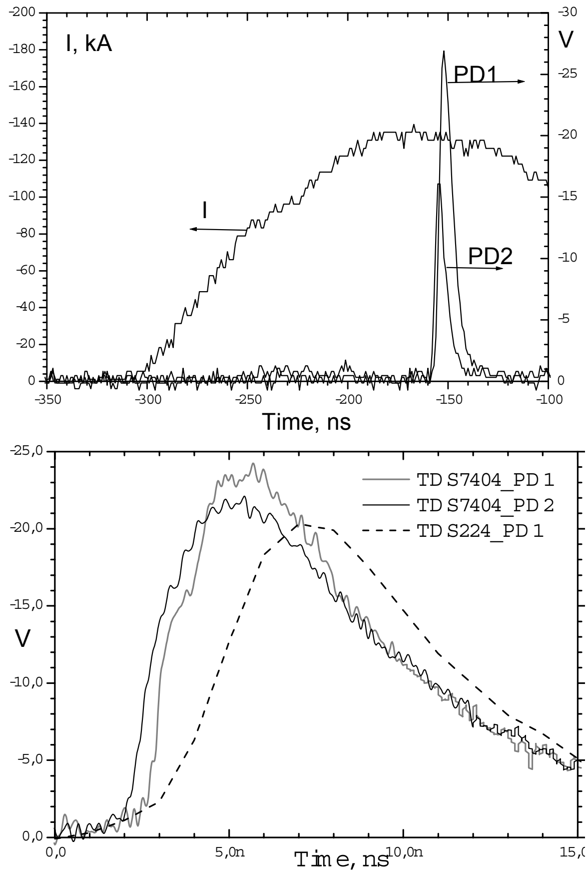

Fig. 3. Current and p-i-n diodes signals. Top picture: PD1 filtered by 15 μm Mylar + 30 μm Al, PD2 by 15 μm Mylar + 18 μm Ti. Signals acquired by TDS 224 digitizer. Bottom picture gives comparison of the photodiodes signals (all with 15 μm Mylar + 30 μm Al filters) acquired by fast scope TDS 7404 (4 GHz) and routinely used TDS 224 (100 MHz)

X-ray signals, acquired by fast digitizer, reveal risetime about 1 ns up to 15 V than slower rise and long tail. Effective bias voltage is lowering with signal rise and actual current passing through the photodiode is lowering also. This pulse distortion could be corrected mathematically, in principle, [10] but for it one need to provide absolute calibration of the probes at different bias voltages with good statistics. This work was definitely behind scope of this paper. Both this effect and diode saturation play role in a signal waveform distortion, so investigation of temporal behavior of the X-pinch burst is still underway. Transparency curves for filters, used in the experiments are shown in Fig. 4. Lower limit of the X-ray radiation yield can be estimated assuming 100% conversion efficiency of the X-ray energy to electron-hole pair production in i-layer of the photodiode. It results in following:

$$W_r \geq \frac{Q}{e} E_{\text{pair}} \frac{4\pi L^2}{Sp} K,$$

where $Q = \int I dt$ is charge, transferred through the p-i-n diode, e is electron charge, $E_{\text{pair}} = 3.64$ eV is well-known value of average energy for a electron-hole pair production in Si, $L = 12$ cm is distance between the X-pinch and photodiode, $\text{Sp} = 1.5 \cdot 10^{-2}\,\text{cm}^2$ is active area of the *p-i-n* diode, *K* stands for filter attenuation coefficient. For example, PD1 signal (15 μm Mylar + 30 μm Al filter), presented in the Fig. 3, provides $Q = 4 \cdot 10^{-9}$ C. With this filter main part of a transmitted radiation is in 1.2–1.5 KeV range and its average $K \approx 200$ value could be derived from Fig. 4. After substitution we get $\text{Wr} \geq 300$ mJ for this range. Analogous calculation provides value of $\text{Wr} \geq 10$ mJ for PD2 diode (filtered by 15 μm Mylar + 18 μm Ti), which transmits mainly in 3–5 KeV energy range.

The simplest way to obtain information about size of hot spots, emitting X-rays, is to make radiographs of small objects. Fig. 5 shows radiographs of thin *W* wires (6, 12, 20 μm diameter) superimposed on fine stainless steel mesh (25 μm wire, 45 μm cell).

Both radiographs provide well resolved image of the wires. Bottom picture, corresponding to harder X-rays and lower diffraction distortion of images shows more clearly difference between wires diameters. Lack of doubled images on radiographs indicate existence only one bright spot for this pinch. From radiography experiments one can make conclusion that spot size is quite less than 5 μm. Time moment of the X-ray pulse emission was close to maximum of current with jitter on ± 5 ns level.

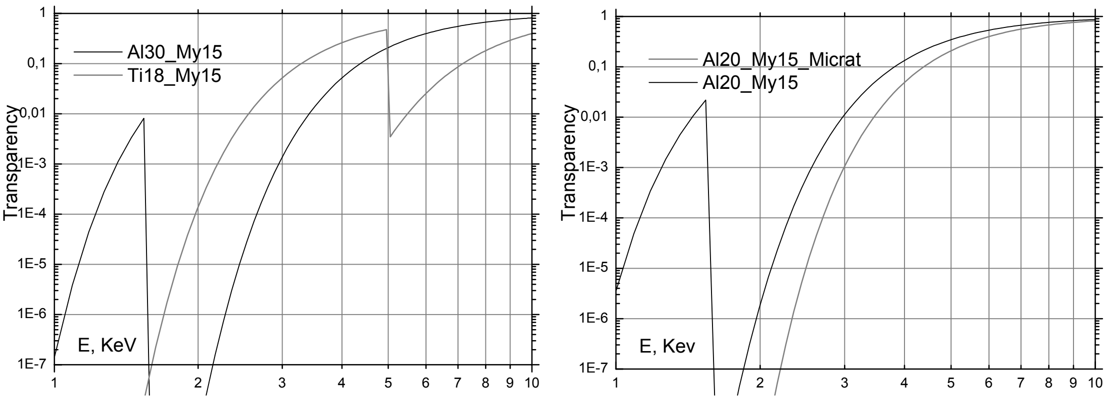

Fig. 4. Transparency curves for filters, used for the X-ray probes and radiography experiments. Al20_My15_Micrat means 20 μm Al + 15 μm Mylar + one layer of a Micrat 200 film and so on

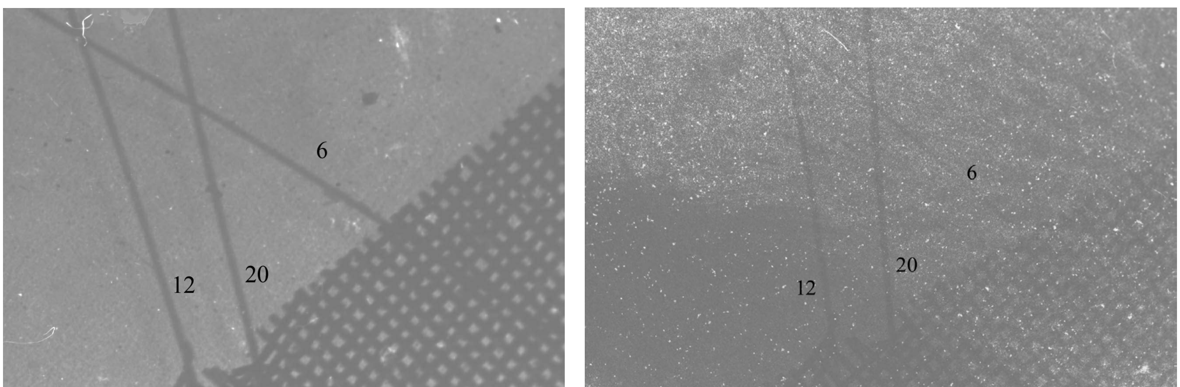

Fig. 5. Radiographs of W wires (6, 12, 20 μm diameter) superimposed on fine stainless steel mesh. Top picture is for first piece of film (15 μm Mylar + 20 μm Al filter), bottom one is for the second piece (i.e. additionally filtered by a 130 μm film)

5. Conclusion

We report here design of the portable high current generator, which can be used for a row of experiments and applications, including, but not limited to, X-pinch, plasma focus, vacuum spark, etc. It stores up to 1 kJ energy at more than 200 kA current amplitude and 140 ns risetime. Generator requires laboratory area about 0.5 m^2 with pumping system. The generator has been successfully employed for experiments on the X-pinch load. Radiation yield $Wr \geq 300$ mJ was observed in 1.2–1.5 KeV range and $Wr \geq 10$ mJ in 3–5 KeV energy range, which is comparable with results obtained on the nanosecond accelerators. Clearly resolved images of 6 μm wire indicate micron level size of hot spot. These results prove possibility of this generator applications for X-ray backlighting.

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