Design of a Compact Portable Plasma Radiation Source Generator at Idaho Accelerator Center

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Abstract. Ever since the x-pinch was first proposed it has created great interest as a small size short pulse (<1 ns) intense x-ray radiation source that could be used in different applications in physics, biology and radiography technology. In this paper we present the design of a compact portable x-pinch plasma radiation source generator capable to supply 200 kA peak current with 80 ns rise time (10%-90%). Our design utilizes only four fast high current capacitors discharged simultaneously in parallel to a low inductance "matched" x-pinch load. This device will be used in different applications including, but not limited to, fast time resolved X-ray radiography of various small objects at the Idaho Accelerator Center.

Keywords: pulsed power generator, plasma source, x-ray source, z-pinch
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INTRODUCTION

The x-pinch x-ray pulsed radiation source (in which the crossing and touching of two or more thin wires forms an "x", hence x-pinch) was first introduced by Russian physicists at Lebedev Physical Institute [1]. It has since generated great interest for use in a variety of different applications including high resolution point-projection radiography in plasma physics [2-4], phase-contrast imaging of soft biological objects [5], and for characterization of inertial confinement fusion capsule shells [6]. To produce a bright, small and fast radiation burst which is critical for x-ray radiography a pulse generator able to supply a high fast rising current (≥100 kA, ≥1 kA/ns) [7] to a low inductance x-pinch load is needed. The conventional design of such a device is a high voltage Marx generator coupled with one or more transmission lines to compress an initially long (few µs) pulse from Marx's output into a short (a few hundred ns) load pulse. However, such installations [8-10] are bulky and expensive. Smaller devices based on conventional Marx generator designs are available; however, the output current is usually not in excess of 100 kA [6, 11].

Recent progress in development of low inductance high current capacitors [12] and switches [13-14] opens up big opportunities in the design of compact high current pulse generators [15-16] for driving low inductance x-pinch [17] or even z-pinch loads [18]. Such newer technologies offer several advantages as compared to conventional Marx based generators, such as: lower capacitors bank voltage, lack of transmission lines, and intrinsic low inductance which allows effective coupling to low inductance loads. In addition, the compact and portable high current pulse generators are relatively inexpensive to build and thus can boost research opportunities at small universities.

In this paper we introduce the design of a compact portable plasma radiation source generator able to supply 200 kA peak current with 80 ns rise time (10-90%). Our design utilizes only four small (102cm × 152cm × 241cm) fast pulse capacitors [12] discharged simultaneously in parallel to a low inductance "matched" x-pinch load. LTspice [19] simulations were performed for this device and results are in good agreement with predicted values from LRC circuit analysis. The proposed approach is flexible and can be easily modified to a lower or higher load current device, if needed. After construction and testing, such a device will be used in different applications including, but not limited to, high resolution phase–contrast imaging of rapidly evolving moving objects.

DESIGN APPROACH

In our design approach we are following the description introduced by M.G. Mazarakis and R.B. Spielman [15]. For a small generator without long transmission lines, the lumped component approximation can be used. The whole generator can be approximated by the simple LRC circuit represented in Fig.1.

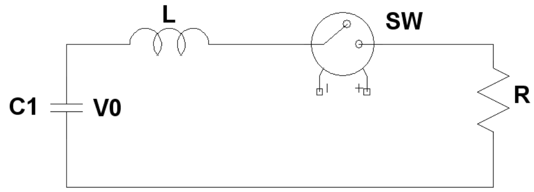


FIGURE 1. The simple LRC equivalent circuit of compact portable high current generator.

A pulse generator with a "matched" load $R = \sqrt{L/C}$ is, in general, able to produce higher pulse currents with faster rise times compared to the "critically matched" $R = 2\sqrt{L/C}$ case, and is more suitable for the design of a radiographic x-pinch machine, as was discussed in [16]. In the "matched" case the peak current, voltage and rise time (0-100 %) are given by the following expressions [16]:

$$i_{peak} = 0.546293\frac{V_0}{R}, \quad (1)$$

$$V_{peak} = Ri_{peak} = 0.546293\,V_0, \quad (2)$$

$$t_{peak} = 1.21\sqrt{LC}, \quad (3)$$

where V_0 is the initial voltage of capacitor C.

DESCRIPTION OF COMPACT PORTABLE PLASMA RADIATION SOURCE GENERATOR WITH 200 kA PEAK CURRENT

We chose the General Atomics Electronic System fast pulse capacitor 35477 [12] with the following characteristics: inductance L_c = 10 nH, capacitance C_c = 100 nF, voltage rating V_0 = 100 kV, peak current I_c = 50 kA and maximum voltage reversal of 45% from V_0. Such a capacitor has a lifetime of 3 x 10^3 cycles, a size of 102 x 152 x 241 (H x W x L) millimeters, an approximate weight of 5.9 kgs, and is double ended, so it can be naturally connected to a switch in one single line. Four such capacitors would be enough to supply the total peak current of 200 kA.

The schematic of the proposed generator is presented in Fig. 2. The capacitor bank is composed from four capacitors (C1-C4) initially charged to the maximum allowable voltage of 100 kV. Each capacitor is connected in series with a fast high current switch (S1-S4) which has the inductance value, L_{sw}, of 40 nH [14]. The total inductance of capacitor and switch, which is equal to 50 nH, is represented by elements L1-L4. After all capacitors are fully charged, they are simultaneously triggered through switches into the low inductance x-pinch load. The load is shown schematically by the resistor R_{load} and inductor L_{load} elements connected in series.

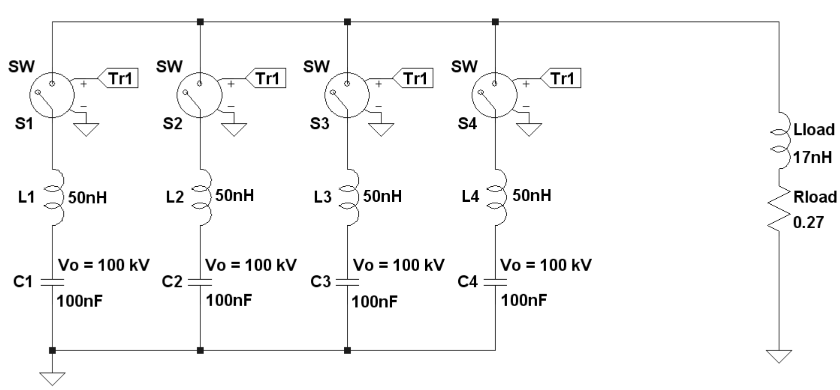


FIGURE 2. Schematic of compact portable high current low inductance generator composed of four General Atomics Electronic System capacitors 35477 (C1-C4) and four low inductance switches (S1-S4).

The total capacitance of such a generator is equal to:

$$C = 4C_c = 4 \times 100 \text{ nF} = 400 \text{ nF}. \tag{4}$$

To calculate the total inductance of our generator we chose the value L_{load} = 17 nH, which is a conservative estimate for the total inductance of the x-pinch and all connection lines between the elements of the generator. So, the total inductance of the generator presented in Fig.2 is equal to:

$$L = (L_c + L_{sw})/4 + L_{load} = (10 \text{ nH} + 40 \text{ nH})/4 + 17 \text{ nH} = 29.5 \text{ nH}. \tag{5}$$

Using (4) and (5) we can calculate the "matched" load's value as:

$$R = \sqrt{L/C} = \sqrt{(29.5 \text{ nH}/400 \text{ nF})} = 0.27\ \Omega. \tag{6}$$

By formulas (1-3) above, the load peak current, voltage and rise time (0-100%) are:

$$i_{peak} = 0.546293 \frac{V_0}{R} = 0.546293 \frac{100 \text{ kV}}{0.27\ \Omega} = 201.2 \text{ kA}, \tag{7}$$

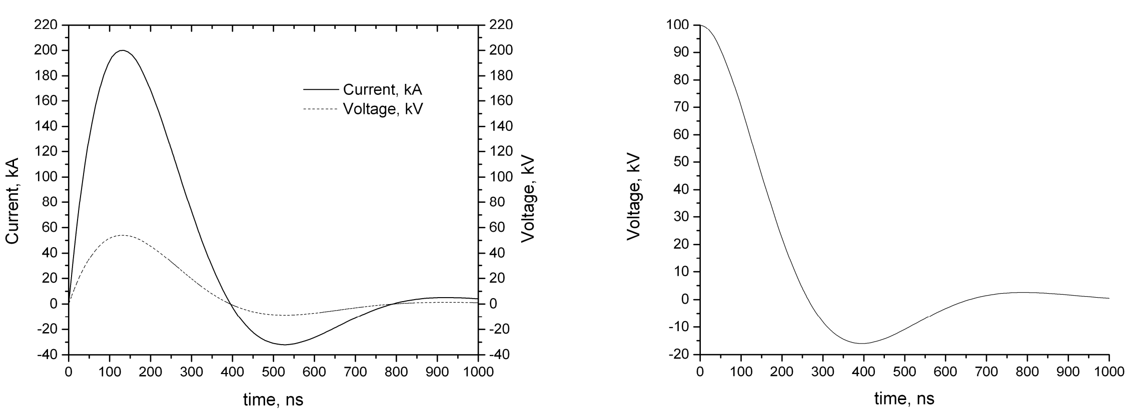
$$V_{peak} = Ri_{peak} = 0.27\ \Omega \times 201.2 \text{ kA} = 54.6 \text{ kV}, \tag{8}$$

$$t_{peak} = 1.21\sqrt{LC} = 1.21\sqrt{(400 \text{ nF} \times 29.5 \text{ nH})} = 131.4 \text{ ns}. \tag{9}$$

LTSPICE SIMULATION

We used LTspice [19] Linear Technology circuit simulation program to predict the behavior of the high current low inductance generator presented schematically in Fig. 2. There were several benefits in doing simulations. First, we verified the peak current, voltage and rise time, calculated above by formulas 7-9; second, we looked at the current and voltage behavior of various separate circuit elements to predict how they are developed in time.

Four capacitors C1-C4 are initially charged to the maximum allowable value 100 kV. After fully charged, at time t = 0 ns they are simultaneously discharged through switches S1-S4 into the "matched" x-pinch load. The results of simulation are presented in Fig. 3 (a, b) below.



(a) **(b)**

FIGURE 3. LTspice simulations of high current low inductance plasma radiation source generator for the "matched" $R = \sqrt{L/C}$ load case: (a) current and voltage measured on the output load (b) voltage measured on the capacitor C1.

The behavior of the current and voltage pulses as measured on the output load are shown in Fig 3(a). The load peak current, voltage and rise time are equal to I_{peak} = 200 kA, V_{peak} = 54 kV, t_{peak} = 130 ns, correspondingly, which are in good agreement with the values calculated earlier by formulas (7-9). Fig. 3 (b) shows the voltage measured on the capacitor C1 during the discharge time. The maximum reversal voltage equals -16 kV that is well below the maximum allowable value of 45% from V_0. The voltage behavior on the other capacitors is identical. The speed of the current rise (10-90%) of the proposed generator can be found from the output current in Fig. 3(a) and equals 2 kA/ns.

CONCLUSION

In this paper we presented the design of a compact portable x-pinch plasma radiation source generator capable of supplying 200 kA peak current with 80 ns rise time (10-90%). A total of four low inductance high current capacitors were discharged simultaneously in parallel into a low inductance "matched" x-pinch load. LTspice simulations showed the good agreement with predicted peak current, voltage and rise time values and give to us the ability to look at behavior of each element inside the generator.

The proposed approach is flexible and can be easily modified for higher or lower peak current, if desired. Plus, by introducing, for example, the small modifications in values of different elements of the electrical circuit, we can study various scenarios such as: the misfire of one of the switches, the "jitter" effect and how it changes the shape of the output current, or we can make our generator "under" matched or "over" matched and look at consequences.

After construction and testing, such a device can be used in a variety of applications including, but not limited to, high resolution phase–contrast imaging of rapidly evolving small objects.

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