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Development of compact nanosecond pulsed X-ray source

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Abstract

A compact nanosecond pulsed X-ray source is described. The X-ray source consists of two important subassemblies: a high-voltage pulse generator and an X-ray diode. The high-voltage pulse generator is designed based on the principle of triple resonance circuit producing a high-voltage pulse across the X-ray diode with amplitude of up to 500 kV. The X-ray diode is a sealed transmission target X-ray tube. Its cathode is comb structure formed from thin tungsten sheets with thickness 50 μm, while its target is made of 100 μm titanium film. The X-ray dose at a distance of 20 cm from the diode is 20 mR per pulse, while the diode voltage is 512 kV. In the case, the full-width at half-maximum of the X-ray pulse is ~5 ns.

Keywords: Pulsed X-ray source; Pulse generator; Triple resonance circuit; X-ray diode

1. INTRODUCTION

Scintillators are widely used in high-energy physics, tomography, radiography, and other areas for studying high-speed processes (Fehlau & Brunson, 1983; Kardjilov *et al.*, 2011; Tous *et al.*, 2013). The main scintillator characteristics such as decay time, light outputs, and emission spectrum are usually measured at excitation by gamma quanta or particles (electrons, protons, and neutrons). Rather recently, nanosecond X-ray pulses have been used for study of scintillators (Voloshinovskii *et al.*, 1994; Weber *et al.*, 2000; Zhang *et al.*, 2008).

The most modern of the developed devices generally generate of X rays based upon one of three methodologies: synchrotrons, laser plasmas, or electron beam discharges (Korobkin *et al.*, 2005; Dorchies *et al.*, 2008; Kostyrya & Tarasenko, 2009; Daniele *et al.*, 2011). Synchrotron X-ray pulses are typically in the 50–200 ps, and laser-based techniques such as the pulsed laser plasma and inverse Compton scattering have now demonstrated the ability to produce X-ray pulses in the 100 fs range (Uhlig *et al.*, 2011; Faenov *et al.*, 2016). These systems have met most of the application needs but for physical size and cost. While more conventional, X-ray diode driven by high-voltage pulsed power generator offers a very attractive alternative for the realization of X-ray source (Korenev & Korenev, 2004; Lavrinovich *et al.*, 2013; Hong *et al.*, 2016). As a rule, the standard structure of these pulsed X-ray sources includes pulsed high-voltage generator, electron source, and X-rays target. The pulsed high-voltage generator produces a high-voltage pulse across the cold cathode of an X-ray diode. These pulsed X-ray sources utilize the field emission at the cold cathode surface as the electron beam source, and the intense electron beams incident on solid targets of high-Z material to produce X ray with characteristic bremsstrahlung spectra.

In this paper, a compact nanosecond pulsed X-ray source based on pulsed power generator was developed. The high-voltage pulse generator is designed based on the principle of triple resonance circuit by adding a tuning capacitor and a tuning inductor between the iron transformer and the pulse-forming line (PFL). The X ray is a sealed transmission target X-ray tube. The design of the X-ray source is described and the results of its testing are given.

2. DESCRIPTION OF THE COMPACT X-RAY SOURCE

Figure 1 shows the configuration of the compact nanosecond-pulsed X-ray source, the whole equipment is filled with 25# transformer oil. The system employs a number of components, including high-voltage pulse generator, the control system, the charging power supply system, and the load.

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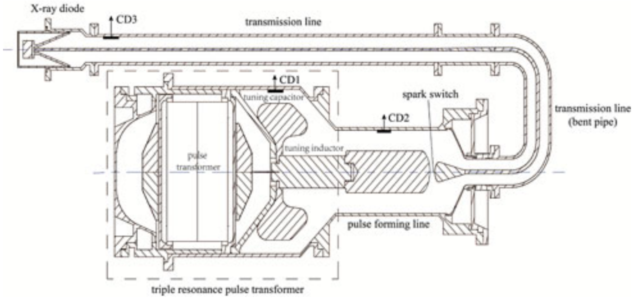

Fig. 1. Structure of compact nanosecond pulsed X-ray source.

The control system dominates the charging power supply system to charge the primary capacitors of high-voltage pulse generator. The charging power supply system is used to charge two groups of primary capacitors up to about 20 kV through two high-voltage coaxial cables.

The high-voltage pulse generator is designed based on the principle of triple resonance circuit (Bieniosek, 1990). Different from the triple resonance pulse transformer, which is reported at home and abroad, the triple resonance pulse transformer developed in this paper is based on closed iron core transformer (see details in Section III) instead of air core transformer (Nam *et al*., 2007; Li *et al*., 2015). Such design achieves the following purposes. First of all, the output voltage across the PFL is much higher than the voltage across the iron core transformer's high-voltage winding, which greatly reduces the insulation requirement of the high-voltage winding and enhances the stability of the transformer. Secondary, the coupling coefficient of iron core transformer (>0.95) is larger than air core transformer, leading to a fast rise time (~500 ns) in the secondary voltage waveform. Besides, the first peak of the output voltage of the triple resonance pulse transformer can be used to charge PFL.

A self-break oil switch with an adjustable gap is applied to discharge the PFL to generate nanosecond pulses. One end of the PFL with a spherical structure is acted as one electrode of the self-break oil switch. The gap of the switch can be adjusted in the range of 0–15 mm, according to the PFL voltage. When the switch is on, a high-voltage pulse is obtained on the load through transmission lines. For space saving, the transmission lines are turned up and then backward, which are located right above the transformer. The load is an X-ray diode with transmission target (see details in Section III). By using transmission lines with impedance overmatched to that of the PFL, the generator delivered a ~500 kV pulse across the X-ray diode.

The working principle of the X-ray source is described as follows. At command from the control system, the charging power supply system charges the primary capacitors of high-voltage pulse generator up to 20 kV. After the thyratron is triggered, the output of the capacitor is fed into triple resonance pulse transformer. A voltage with a peak value of ~500 kV is generated and charges the PFL, while primary capacitors are charged to 15 kV. When the self-break oil switch is on, a high-voltage pulse is obtained on the X-ray diode and X ray is generated.

3. DESIGN OF KEY COMPONENTS

3.1. Iron core transformer

The high-voltage pulsed transformer is made of two primary windings, two secondary windings in parallel, and a magnetic core. These specific characteristics make possible a limited mechanical size and a limitation of the leakage inductance.

The magnetic core used in the pulsed transformer is of silicon iron, due to the high-flux density and the low cost. To avoid core magnetic saturation without using a pre-magnetization control system, the core section may be oversized. The structure of the magnetic core is designed to be θ type configuration. The magnetic core is composed of four semilunar rings [shown in Fig. 2(b)], which are wound with 0.08 mm-thick silicon strip. Four magnetic rings have a total volt–second product of larger than 7.5 mV-s and a core section area of 62 cm^2.

Each primary winding has a turn number of 2 and is wound around the two ends of the middle leg of the core.

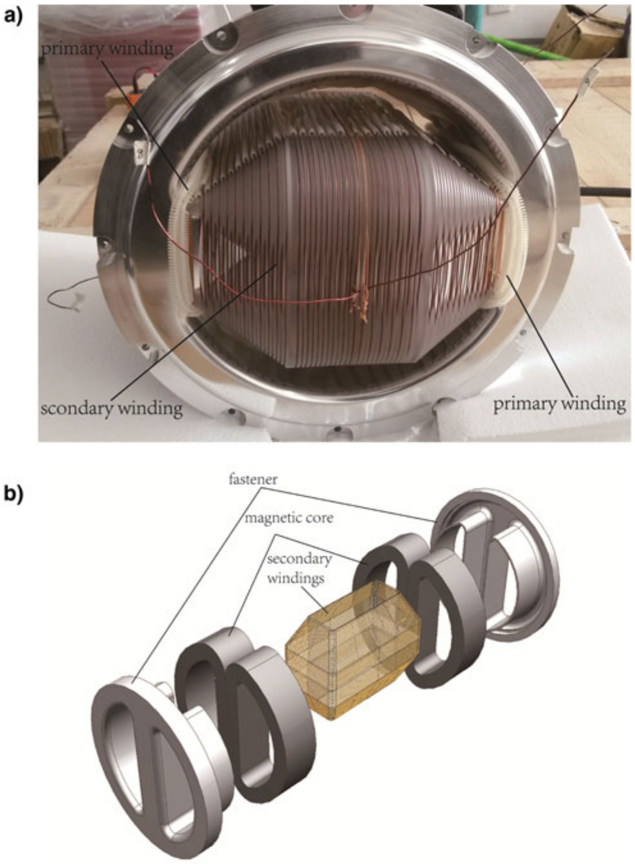

Fig. 2. Structure of iron core transformer with biconic windings: (a) completed assembly, (b) exploded view showing its various components.

It is made by insulated wire with section 5 mm^2 and withstand voltage 30 kV DC. Because of the high-voltage insulation requirements, a design for the secondary windings based on a conical form was chosen (Habibinia & Feyzi, 2014). Each secondary winding has a turn number of 33.5 and is wound on a cone-shaped plexiglass bobbin placed around the middle leg of the core. It is made by enameled wire with a diameter of 0.9 mm. The two high-voltage ends of the secondary windings, located on the axis, are connected to the tuning capacitor. The whole transformer is fastened by aluminous fastener. A photograph of the transformer is shown in Fig. 2(a). The dimension of the transformer is Φ320 mm × 265 mm.

3.2. LC tuning circuit

The triple resonance pulse transformer can be built by adding a tuning capacitor and a tuning inductor between the iron core transformer and the PFL.

The tuning capacitor is designed to be a coaxial capacitor (shown in Fig. 1) with capacitance of 70 pF. The end of the tuning capacitor's inner conductor connected with the tuning inductor is designed to be sunken configuration. With such design, it is provide a compact structure. Meanwhile, the inner conductor is used as a shielding ring, which may improve the field distribution of the tuning inductor.

The tuning inductor is made as a single-layer air core cylindrical inductor with dimensions of Φ60 mm × 140 mm. The photograph of tuning inductor is shown in Figure 3. Organic glass is used as the skeleton of the tuning inductor. The skeleton is carved with axial grooves as oil ducts, and the radial grooves are used for winding. The tuning inductor is wound un-uniform ~225 turns by enameled wire with a diameter of 0.25 mm. The measured value of the tuning inductor is 1.15 mH.

3.3. X-ray diode

The X-ray diode is a type of a transmission target X-ray tube consisted of a stainless steel chamber with thin-walled iron (DT8A) window, a ceramic insulator, a cathode, and a titanium target (shown in Fig. 4). It employs electron-beam and high-*Z* target interaction to produce bremsstrahlung radiation, with a spectrum determined by the voltage applied across the diode.

The cathode is comb structure formed from thin tungsten sheets with thickness 50 μm, bonded to a circular iron base with a diameter of 34 mm. This structure could improve electron emission because of sharp edge. The titanium target with thickness 100 μm on the iron substrate is used, assembled at 12.2 mm away from the cathode. Windows are opened on the iron substrate. The diode chamber is maintained at a pressure of $<5 \times 10^{-5}$ Pa. In order to achieve the vacuum, the ceramic insulator and ceramic brazing vacuum sealing technique is adopted.

4. EXPERIMENTAL RESULTS

After the assembly is completed, the global view of the X-ray source is shown in Figure 5. The whole device is 140 kg weight when filled with oil, possessing a dimension of 1.2 m long and 40 cm wide. It is fixed on a rise-and-fall cart.

Three capacitive voltage dividers, denoted by CD1–3 (shown in Fig. 1), plus secondary resistance attenuators were applied to measure the voltage waveform of the tuning capacitor, the PFL and the X-ray diode. The shape of X-ray pulses and their relative amplitudes were measured using a scintillation detector. The exposure dose was measured by a dose meter.

Previously, experiment was carried out to test the characteristics of the triple resonance pulse transformer. The maximum charging voltage on primary capacitors can be as high as 15 kV without any insulation failures. The typical voltage waveforms of the tuning capacitor (U_{c2}) and the PFL (U_{c3}) without the self-break oil switch breakdown are shown in Figure 6. When primary capacitors are charged with 13.5 kV, the peak voltage of U_{c2} is ~300 kV, and the peak voltage of U_{c3} is ~480 kV. Therefore, the peak voltage across PFL is 1.6 times than the peak voltage across the iron

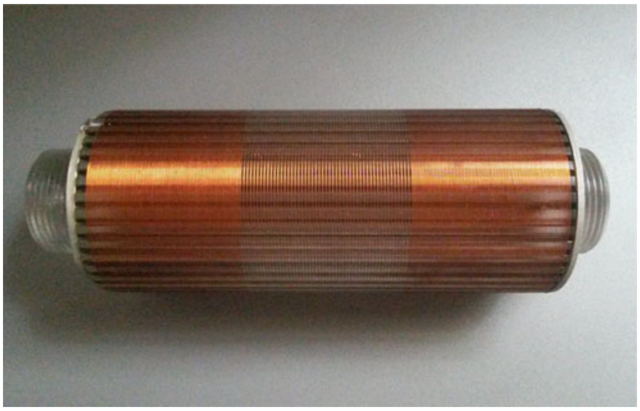

Fig. 3. Photograph of the tuning inductor.

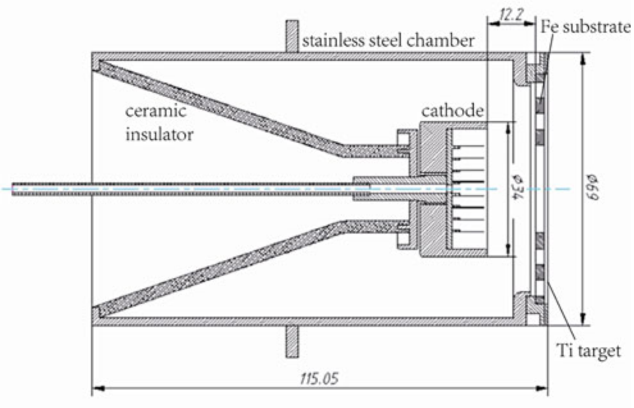

Fig. 4. Structure of X-ray diode.

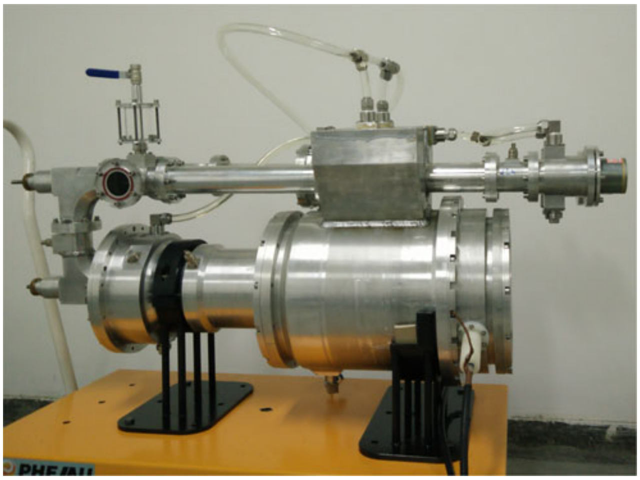

Fig. 5. Photograph of the compact nanosecond pulsed X-ray source.

core transformer. It is demonstrated that the performance of triple resonance circuit is achieved.

When the self-break oil switch is on, a high-voltage pulse is obtained on the X-ray diode and X ray is generated. The X-ray output was measured by a scintillation detector arranged at a distance of 20 cm ahead of the seal window of the X-ray diode. A set of oscillograms presenting the electrical pulse shape of the X-ray diode together with the associated X-ray emission are shown in Figure 7. With the charging voltage increased, the maximum voltage of the X-ray diode was increased. With a charging voltage of 14.5 kV, the maximum voltage of the X-ray diode is 512 kV, while the pulse width on full-width at half-maximum (FWHM) is 4.8 ns. In the case, the FWHM of the X-ray pulse was 4.5 ns.

The exposure dose was measured by a dose meter at 20 cm ahead of the seal window of the diode. It is primarily dependent upon the pulsed voltage applied to a diode load. In fact, the exposure dose varies from 0 to 20 mR per pulse, while the diode voltage varies from 350 to 510 kV.

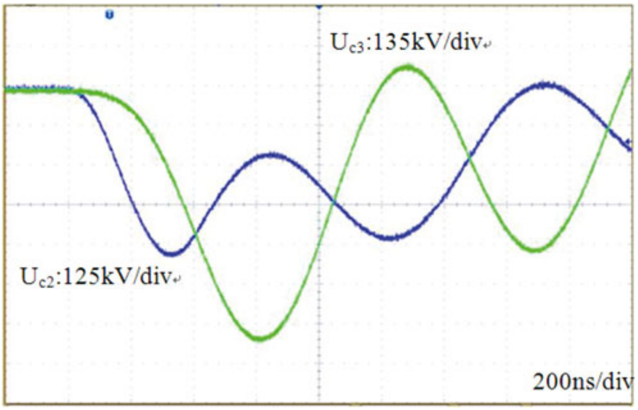

Fig. 6. Typical waveform of triple resonance pulse transformer with the gas switch off.

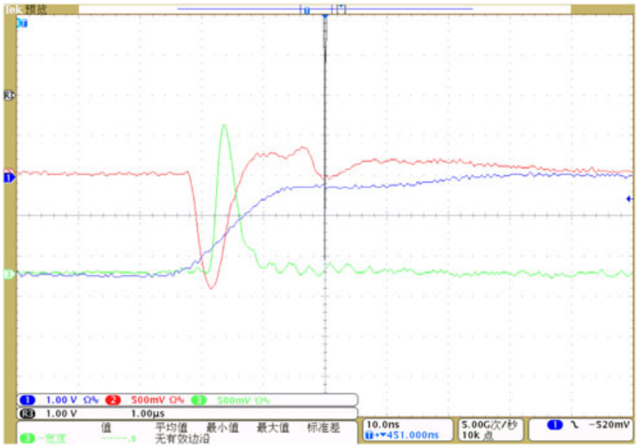

Fig. 7. Typical waveform of the X-ray source (10 ns/div): 1 – voltage of PFL, 2 – voltage of X-ray diode, and 3 – X-ray pulse.

5. CONCLUSION

In this paper, a nanosecond pulsed X-ray source is developed. The source has the characteristics of small size, light weight, compact structure, and flexibility. The X-ray dose at a distance of 20 cm from the diode is 20 mR per pulse when the voltage applied to the X-ray diode is 512 kV at a charging voltage of 14.5 kV, while the FWHM of the X-ray pulse is 4.5 ns. The X-ray source is applicable for investigations on characteristics of scintillation detectors (such as luminous efficiency and decay time), which are widely used in intense pulsed radiation detection.

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