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Measurement of the effective energy of pulsed X-rays emitted from a Mather-type plasma focus device

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ABSTRACT

The current study examined the effective energy of pulsed x-rays emitted from a Mather-type plasma focus device with copper anodes at an energy range of 2–3 kJ using x-ray transmission radiography. Aluminum filters of different thicknesses and dental x-ray film were used. When air gas was used at a constant voltage of 21 kV at 0.3, 0.6, 0.9 and 1.2 mbar, the effective energy of pulsed the x-ray was 10.9, 10.7, 17.3 and 15.8 keV, respectively. At 0.6 mbar of air, as the operating voltage increased to 19, 21 and 23 kV, the effective energy of the x-ray radiation was 10.6, 10.7 and 12.4 keV, respectively. Comprehensive investigation of the characteristics of x-ray emission from plasma focus devices makes it feasible to use this device as an intensive x-ray generator for medical and industrial purposes. The present study is a part of a program which is planned to realize these applications.

1. Introduction

In a plasma focus device, a plasma layer accelerates in response to the Lorentz force. At the end of the electrodes, the plasma column converts to a dense (10^{19} cm^{-3}), unstable (with a lifetime of 50–200 ns), thin filament of plasma under magnetic pressure. The dynamic behavior of the plasma focus includes the electrical breakdown and axial and radial acceleration phases. This device stores energy in the capacitor bank and it is then quickly transferred to the coaxial electrodes over a spark gap. The discharge current moves from above the insulator along the insulator surface. The Lorentz force moves the current-carrying plasma layer in the axial direction towards the tip of the anode.

By optimizing the device in terms of length and size of electrodes and operating gas pressure, it is possible to maximize the discharge current when the current layer reaches the axis. At this moment, a hot, dense plasma column (pinch) forms in front of the anode. After a few hundred nanoseconds, the plasma column becomes unstable and collapses. The device can be used as a powerful source of x-rays, electrons, neutrons (if deuterium gas is used) and charged particles. One of the main outputs of a plasma focus device over a short span of time is an x-ray pulse.

Three mechanisms are proposed to produce x-rays from the discharge of plasma focus devices. The first mechanism is Bremsstrahlung radiation from acceleration of electrons through the ion field inside the plasma. In this mechanism, the emission energy spectrum extends to tens of keV. The second mechanism is the production of x-rays having higher energies by the acceleration and collision of beams of electrons at the tip of the anode. In this case, the spectrum reaches energies above 100 KeV. The third mechanism of x-ray production is the emission of characteristic x-rays from elements with high atomic numbers. This mechanism is also observed in the plasma column (for example, in the discharge of neon and argon gases) and in the anode region, where the electron beams are stopped (Kα emission from the anode material).

In addition to these three mechanisms, another possible mechanism is creation of hot spots with dimensions of a few tens of micrometers inside the plasma column. These spots capture and accelerate electrons in a rotating form. The electrons reach very high energies and emit synchrotron radiation from the highest-field region at the core of the plasmoid (Bostick et al., 1975; Lerner et al., 2012; Cox and Larry, 1992). The hot spots are sources of intense x-ray emissions as well as sources of pulsed ion and electron beams emitted in the opposite direction (Decker et al., 1996; Jakubowski et al., 2001, 2004). In all cases, the width of the x-ray pulse equals tens to a few hundred nanoseconds.

The notion that these mechanisms result in hard x-ray emissions from the plasma focus are controversial and much experimental research is needed to optimize x-ray production for industrial applications. Very short x-ray pulses emitted from this device are challenging to measure and measurement tools for this are limited. X-ray radiation emitted from plasma focus devices have a wide energy range that can

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be controlled by gas injection, gas pressure and operating voltage. The maximum efficiency of the x-rays from these devices can be determined only by experimental and laboratory study.

Research has shown that x-rays emitted from a plasma focus device filled with neon can be used for lithography (Kato and Be, 1986; Kao et al., 1988). Argon gas in plasma focus devices provides higher energy x-rays that can be used in microlithography (Gribkov et al., 2002). It has also been shown that x-rays emitted from a plasma focus device can be used for tomography (Venere et al., 2001). A relevant topic in industry, medicine and research is radiography with x-rays obtained by plasma focus devices. Research has been conducted on the feasibility of using x-rays emitted by a plasma focus for radiography of objects, particularly objects having a high rotation speed (Hussain et al., 2005; Kanani et al., 2014; Raspa et al., 2004).

Harries et al. examined the site of production of soft and hard x-rays in plasma focus devices. They measured the spatial and temporal resolution of the x-rays and found that soft x-rays are emitted by plasma and hard x-rays are emitted by the tip of the central electrode from the collision of fast electrons on the anode (Harries et al., 1978). Beg et al. measured the efficiency of x-rays in a 2 kJ plasma focus device using gases with atomic numbers greater than 18. They used a Ross filter to study the maximum efficiency of the x-rays for neon operating gas in the energy region of 0.7–1.5 keV and reported a 16.6 J with pulse width of 10–15 ns. Time-integrated images from a pinhole camera with a soft x-ray filter shows a plasma column. Some hot spot structures were observed with the hard x-ray filter. This behavior indicates plasma transition from a columnar-shaped structure to a series of hot spots (Beg et al., 2000).

Hussain et al. put a lead disk in a copper anode (with an arched tip) to increase x-ray efficiency in a miniature-type plasma focus device. Measurement was done at energy windows of 5–9, 7.7–9 and 13–25 keV. The efficiency of energy conversion from electrical to radiation power was measured in 4π geometry at 0.5 mbar for hydrogen operating gas to be 1.52 ± 0.06% (Hussain et al., 2003). Verma et al. increased the x-ray efficiency in measurement windows of 3.2–7.7 and 0.9–1.6 keV 10-fold and 17-fold, respectively, by changing the gas and using a mixture of krypton and deuterium at less than 0.4 mbar. The device under investigation was improved for use in micro-lithography and micromachining (Verma et al., 2008).

Tan et al. described the selection of silicon photodiodes to measure medium energy (5–30 keV) x-rays from NX2 plasma focus device for H, N, Ar and Ne filling gases (Tan et al., 2003). They used aluminum filters to define a large x-ray energy range. They concluded that there are optimum pressures for x-ray yields and the plasma focus using hydrogen produced the highest x-ray energy and yield.

Raspa et al. (2004) analyzed the attenuation of pulsed x-ray at different metals in a 4.7 kJ plasma focus device filled with a mixture of deuterium-argon gas and found that the effective energy of the x-ray radiation was about 100 keV. They also used radiographic methods to understand the continuum spectrum of hard x-rays. They used samples of copper, nickel, titanium and silver with thicknesses of 0.1–10 mm as differential absorption filters. X-ray radiation was detected using standard radiography film. The results indicated a dominant peak at about 75 keV and important spectral elements at 40–200 keV (Raspa and Moreno, 2009).

Zambra et al. used a 400 J plasma focus device with an anode made of copper with silver inserts filled with hydrogen gas at pressure of 7.5 mbar and operated at a charge voltage of 28 kV to examine x-ray radiation using radiographic film and a step filter array. They estimated the average effective energy to be about 68.4 keV (Zambra et al., 2009).

Because the use of pulsed x-ray radiation emitted from plasma focus devices require more accurate measurement, the current study estimated the effective energy of pulsed x-rays emitted under different operating pressures and voltages. For an x-ray radiation pulse with a continuous spectrum, if energy E_{eff} is estimated such that has an effect equal to the effect of a continuous spectrum on a radiography film, E_{eff} can be defined as effective energy for an x-ray continuous spectrum. Effective energy is the most important factor affecting the resolution of the image in radiology systems and is an important parameter in the effective dose.

Fig. 1. Layout and position of Al filters on E speed Kodak dental film.

Effective dose values in standard radiographic tests vary from 0.01 to 1 mSv (Fred et al., 2008). The effective energy in two sets of x-ray tubes manufactured by Philips and General Electric were 30–46 keV and 27–41 keV, respectively (Chen et al., 2012). For mammography, a lower effective energy in the range of 14–25 keV is required (Correa et al., 2014). In tomography, a narrower effective dose is required in the range of 2–20 mSv (Fred et al., 2008). The effective energy in the tomography survey was 40–190 keV (Okayama et al., 2012). The effective energies of commercial radiography systems give us a suitable measure to gain a more practical understanding of plasma focus device's feasible applications.

2. Method

In radiography-based method, the effective energy of a pulsed x-ray source is measured after passing through filters of different thicknesses and affecting the film. The amount of darkness recorded depends on the film material, thickness of the filters, developing process of the film and the energy and intensity of the x-ray. The darkness level is converted to an x-ray dose using the appropriate calibration factors. The use of fresh developer solution and fixing the temperature and length of developing to the same values used for calibration allows dependence of darkness on the development process to be ignored.

Assuming that the continuous spectrum of pulsed x-ray in a plasma focus device is $S(E)$, the amount of photons per unit area affecting the radiography film after passing through an attenuation filter of thickness d is:

$$I(d) = \int_0^\infty AS(E)e^{-K(E)d}dE \quad (1)$$

where A is the total number of pulsed x-ray photons to reach the filter per unit area. The linear attenuation coefficient of the filter, $K(E)$, depends on the material and the energy of the photons hitting the filter. The absorbed X-ray dose in the radiography film, behind a filter with thickness d is:

$$D(d) = \int_0^\infty AS(E)e^{-K(E)d} \times E \times \mu \times dE \quad (2)$$

where μ is the mass energy absorption coefficient of the film material.

All values of d provide different optical densities on the radiography film. The optical density curve for dose can be obtained for any type of dental x-ray film through standard radiation of the radiographic film at