International Journal of Engineering and Technology
ISSN: 2180-3633 Electronic Version
Issue 1, Volume 1, December 2010
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Generation of Soft X-Ray (SXR) from Plasma Focus

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Abstract

The use of soft-x-rays (SXR) for applications such as nano-lithography, microelectronic device fabrication, and spectroscopy has been demonstrated to be feasible. Among the leading problems still being actively researched is the optimization of the SXR source. This paper looks at some of the results of research into SXR yield from several plasma focus machines.

Introduction

Electromagnetic radiation is classified based on frequency and wavelength spectrum such as radio waves, microwaves, terahertz radiation, infrared radiation, visible light, ultraviolet radiation (UV), x-rays and gamma rays. The types of electromagnetic radiation are illustrated in the electromagnetic spectrum in fig.1 (Wikipedia, 2009). In the spectrum, x-rays are between gamma rays and ultraviolet (UV). X-rays have a radiation wavelength of 10 to 0.01 nm and frequency range of 3 x 10^{16} hz to 3 x 10^{19} hz. X-rays are invisible and are able to penetrate substantial thickness of matter. X-rays can be classified into two types: namely soft x ray (SXR) and hard x ray (HXR). SXR has lower penetrating power while HXR has a higher penetrating power. SXR are useful in technological applications such as nano-lithography and microelectronic device fabrication (Se-Jung Oh). A recent example of an application uses SXR in lithography to develop 3D photonic devices (S.Lee et al, 2005).

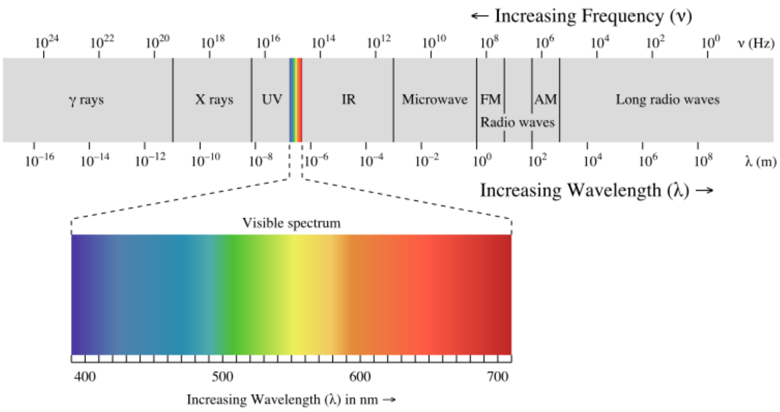

Figure 1. Electromagnetic spectrum (wikipedia)

Due to SXR's diverse technological applications, the generation and optimization of SXR has been the focus of research in several laboratories and institutions.

One way of generating SXR is to use the plasma focus. Small plasma focus devices can be built to compact, cost effective and easy to maintain (Mahe Liu et. al., 1998). Examples of such machines include the NX1, NX2, and UNU/ICTP PFF. The features of these three machines are detailed in the following sections.

The UNU/ICTP PFF

The UNU/ICTP PFF (United Nations University/ International Centre for Theoretical Physics Plasma Focus Facility) is a 3-kJ plasma focus machine (S.Lee, 2005; S.Lee, 1988). It is a simple system consisting of one capacitor (see fig.2) coupled to the focus with one spark gap. The UNU/ICTP PFF like all other plasma focus machine operates in two phases, namely the axial and radial phases.

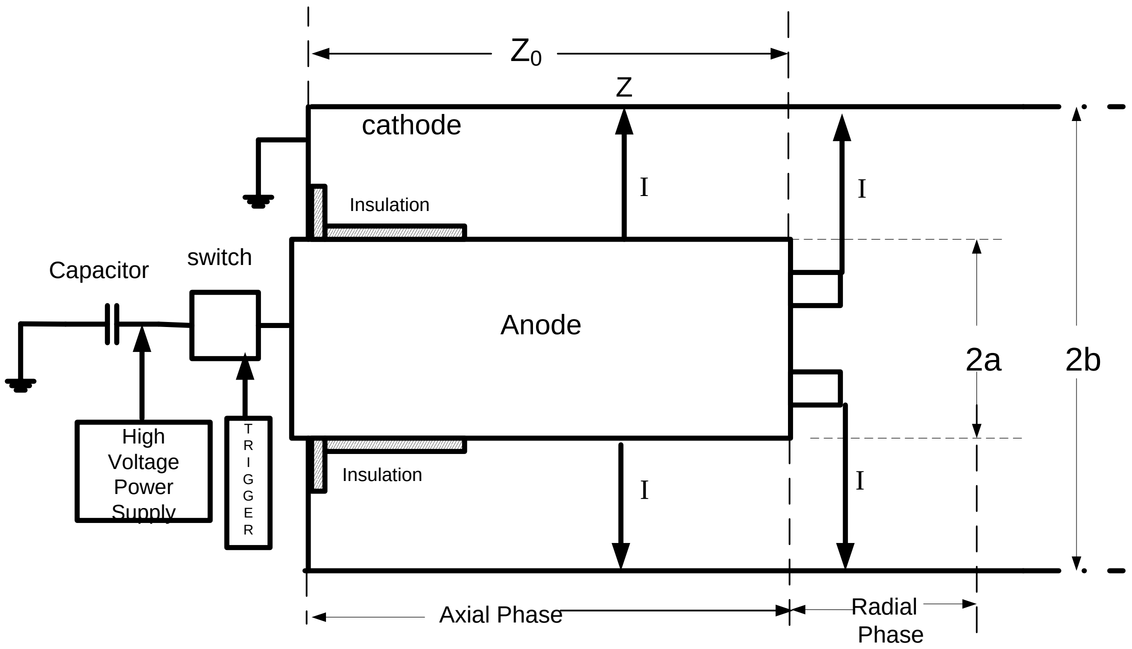

Figure 2. The axial and radial phases of a plasma focus; also illustrating a single capacitor discharge system

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In the axial phase, the current sheet accelerates down the coaxial channel of length z_0 (see fig 2). At the end of the axial phase, the current sheet expands into the radial phase. The axial phase may be further broken down into two phases, namely the breakdown phase and acceleration phase. The breakdown phase starts when the voltage from the charged capacitor C_0 is applied across the anode and cathode in the focus tube (see fig.2) that contains appropriate working gas. In particular, neon gas is used for SXR generation. On breakdown, a current moves along the z direction in the form of a thin axis symmetric sheath connecting the surface of the anode and the cathode. Gas encountered by the current sheet may be considered to be swept up in a thin layer ahead of the current sheet. This is the axial acceleration phase. The axial phase ends when the current sheath reaches the open end of the anode. The radial phase then begins.

The evolution of the radial phase is divided into four sub-phases (see fig.3), namely, the radial inward shock phase (curves 1-2 and 1-3), radial reflected shock phase (curves 2-3 and 3-4), slow compression (curve 4-5) and the expanded column axial phase (curve 5-6). In the radial inward shock phase, the plasma slug is formed (point 1), then the magnetic piston radius r_p and the shock front radius r_s decreases continually until r_s=0 (point 3). Then follows the reflected shock phase. The final phase, the pinch phase (curve 4-5) plays an important role in the plasma focus evolution because of its extremely high energy density. When neon is used, the neon pinch is a source of SXR. Finally, the plasma focus decays in an expanded column phase.

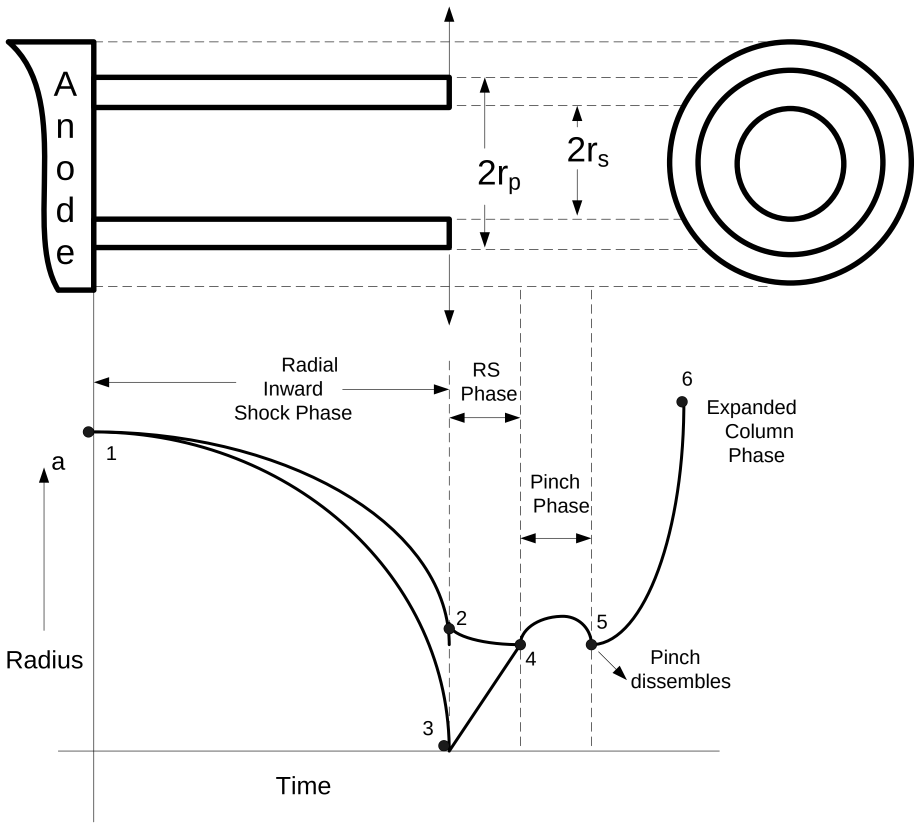

Figure 3. Exploded view of the radial phase

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For some applications such as microelectronics lithography for the wafer industry (S.Lee, 1998) 1 kW of SXR from a point source is required. High SXR yield is achieved through repetitive firing of the plasma focus machine. Two repetitive plasma focus machines NX1 and NX2 were developed by the Plasma Radiation Group at NTU/NIE, Singapore to investigate this requirement.

Development of repetitive plasma focus machines (NX1 and NX2)

The NX1 and NX2 (see Fig.4) is compact plasma focus (CPF) machine operating in neon for SXR generation. Fundamentally, they operate in a similar fashion to the UNU/ICTP PFF both in the axial and radial phases. Technically, the main difference is in the capacitor bank. The UNU/ICTP PFF has a single capacitor (see Fig.2) whereas the NX1 and NX2 have multiple capacitors connected as shown in Fig.4. This parallel arrangement in both the NX1 and NX2 is to decrease the stray (static) inductance L_0 in the external circuit down to as low as 15nH. NX1 is a four module system that uses a capacitor bank (7.8 µF x 4) arranged as in Fig.4. The capacitor bank produces a peak current of 320kA at a repetitive frequency of 3 Hz and SXR average yield of 300W into 4π. The NX2 is also a four module system. In the original configuration each module utilized a rail gap; switching 12 capacitors each with a capacity of 0.6 µF. NX2 operates at up to 16 Hz repetition rate and produces a peak current of 400kA at 11.5kV. Due to the higher frequency of the firing of NX2, the stainless steel electrode needs to be cooled by circulating water to avoid excessive heating. The SXR yield of NX2 is an average of 300W in burst durations for several minutes (S. Lee, 1998). Comparing the SXR yield of NX1 and NX2, it can be concluded that a high repetitive CPF machines (3 hz for NX1 and 16 Hz for NX2) is an important contributory factor for an improved SXR yield. Other factors have also been suggested.

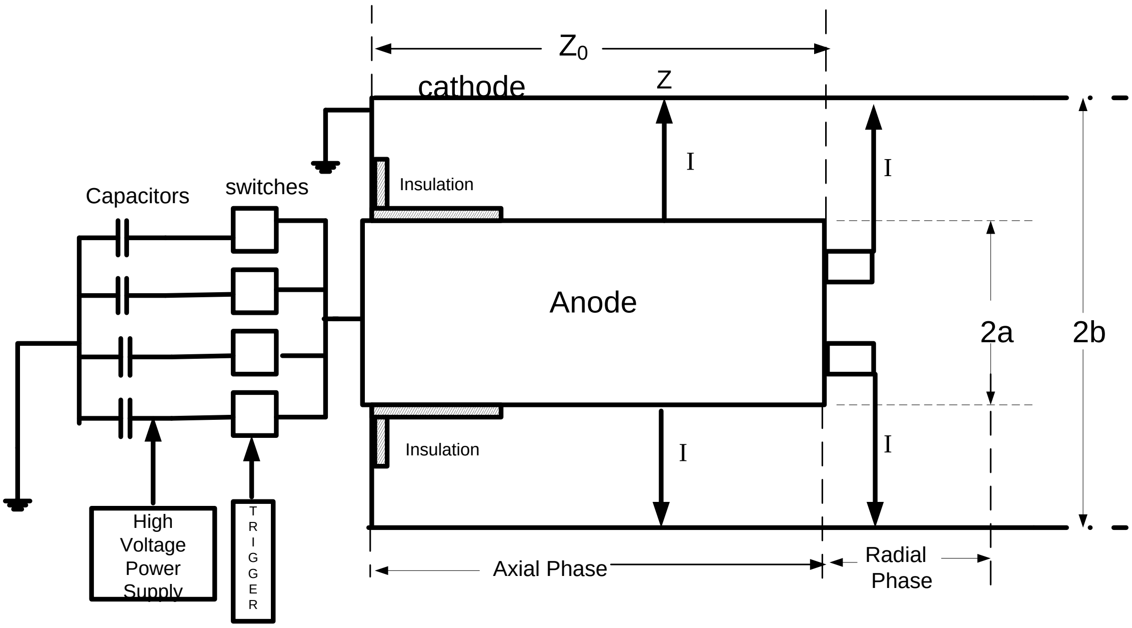

Fig.4: Schematic diagram of the NX1 and NX2

It has been shown in (Sor Heoh Saw et al, 2009) that the anode length and radius affects the SXR yield of both the NX1 and NX2. For example it was shown that an optimum anode length (4.5 cm) and axial speed (4.6 cmµs^{-1}) produces the highest SXR yield (105 Joules) for NX1. It was further speculated that the superiority of NX1 over NX2 in single shot performance was attributed to the difference in anode materials, chamber configurations and different backwall insulation materials.

Comparison of the UNU/ICTP PFF, NX1 and NX2

The UNU/ICTP PFF uses a single capacitor of 30 μF switched by a single spark gap. The external inductance is 110 nH. This high inductance results in lower discharge performance, the maximum current are only 180 kA at 15 kV. The SXR yield scales as the peak current as well as the pinch current (S.Lee et al, 2009). It also scales as storage energy E_0; but it was stressed in the paper (S.Lee et al, 2009) that scaling as E_0 is only valid for capacitors of similar performance; and that the scaling with currents, especially pinch currents is more robust that the scaling with E_0. This example of comparing UNU/ICTP PFF (E_0=3.4kJ) with NX1 and NX2 (both with operational stored energy less than 3 kJ) may be used to emphasize this point. The UNU/ICTP PFF in its standard configuration produces only 5 J of SXR per shot, whereas the NX1 with its much higher current for a lower E_0 and its special fabrication has had maximum SXR yields of up to 100 J attributed to it. The NX2 also with a much higher current has a very consistent record of producing 20 J per shot.

In (Sor Heoh Saw et al, 2009), the authors proposed a simple way to increase the yield. The idea is to optimize the anode length and radius of the UNU/ICTP PFF for operation in neon. The numerical experiments (Sor Heoh Saw et al, 2009) using the Lee model (S.Lee, 2009) show that SXR yield may be substantially improved. These optimized dimensions will be tested in due course in the laboratory.

Summary

The generation of SXR using UNU/ICTP PFF, NX1 and NX2 has been described. NX1 and NX2 provide substantially higher SXR yield per shot compared to UNU/ICTP PFF despite the latter having higher storage energy E_0. The main factor is higher discharge performance due to reduced external (static) inductance for the NX1 and NX2 capacitor bank. NX1 has other not so easily quantified performance enhancement factors in its use of special materials and fabrication.

The SXR power averaged over a period of operation is further enhanced in the case of particularly the NX2, by its ability to fire at a repetitive frequency up to 16 Hz.

Nevertheless, numerical experiments have suggested the possibility to substantially improve the SXR yield of the UNU/ICTP PFF by optimizing the anode length and radius of the plasma focus tube. The optimized configuration will be tested in the INTI plasma focus.

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