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Influence of Kr doping on neon soft X-rays emission in fast miniature plasma focus device

S.M.P. Kalaiselvi, T.L. Tan, A. Talebitaher, P. Lee, R.S. Rawat *

Natural Sciences and Science Education, National Institute of Education, Nanyang Technological University, Singapore-637616, Singapore

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ABSTRACT

An investigation on the possibility of enhancement of soft X-ray (SXR) (900–1600 eV) emission from a fast miniature plasma focus (FMPF) device of 235 J (at 14 kV) storage energy through doping of operating gas was performed. Neon (Ne), the operating gaseous medium, was doped with krypton (Kr) in different volumetric ratios at various operating pressures ranging from 2 to 14 mbar. The 1% Kr doping increased the average optimum SXR emission efficiency from 0.47% to 0.6% without enhancing the hard X-ray (HXR) (>1600 eV) emission. The Kr doping influenced the major pinching characteristics such as focusing efficiency and time to pinch with consequential effect on X-ray emissions. Synchronous operation of the 4 pseudo-spark gap (PSG) switches was mandatory for efficient discharge current delivery to the electrodes. A drastic improvement in the pinching efficiency was obtained with replacement of old and worn out PSG switches with the new ones. Optical imaging of current sheath dynamics was performed using gated ICCD camera to verify the normal operation of the device after the PSGs replacement. A numerical simulation analysis on the 2 cm long stainless steel tapered anode, used in this study, was done to predict the maximum SXR emission efficiency and the peak operating gas pressure. An analysis on the amount of SXR fluence generated at the source position and the proportion of it reaching the target position is also reported.

1. Introduction

Dense plasma focus devices have been established as efficient pulsed X-ray sources [1–6]. Various investigations have been performed to enhance the X-ray emission from this device through the optimization of various parameters such as anode shape and material [1,2], insulator sleeve length [7], anode length [4], gas composition, gas pressure [5], etc. An alternative way to enhance the X-ray emission is the doping of high Z impurity to the ambient gas, a feature which has been extensively investigated in the past [5,6,8–10]. The enhancement in SXR emission and the modification of the pinch characteristics are determined by the type and the volumetric ratio of the high Z gas added as impurity. A significant enhancement in SXR emission was observed in addition of rare gases such as Ne, Ar and Kr to the hydrogen plasma in a 2.8 kJ plasma focus device [5]. The doping of D_2 gas by Ar gas resulted in the formation of multiple micro pinches having lifetime typically in order of sub-nanosecond regime (∼250 ps) [6,8]. Successive compression peaks were observed when operated with H_2 and Ar doping in the volumetric ratio of 40:60 [5]. Anomalous hard X-ray emission mode was observed in plasma focus discharge with hydrogen–argon mixtures [9]. An enhancement in the spatial reproducibility of hot spot formations in the axial direction was observed by operating the low energy H_2 plasma focus with Ar (20%) doping with the radiation mainly in the range of 3.2–3.88 keV corresponding to k_α emission from highly ionized argon [10].

It may be noted that most of the experimental X-rays emission related studies from plasma focus devices have been performed on medium (kJ range) or high (hundreds of kJ to MJ range) energy devices. The investigations on X-ray emissions from low energy (in the range of tens to hundreds of joule) plasma focus devices are rather limited [11–13]. The low energy miniature plasma focus devices are an attractive option for SXR lithography because of the possibility of developing a very high repetition rate system with smaller sized X-ray emission zone [13]. An order of magnitude enhancement in X-ray yield at low pressure deuterium–Kr doping operation was observed in miniature plasma focus device of 200 J energy capacities [11]. For applications such as lithography [3], fast radiography [14] and micromachining [15], another important consideration is the amount of energy reaching the target, as the photoresist/target to be irradiated by X-rays for generation of micro patterns will be placed at certain distance from the pinch. For different anode geometry and different operating gas used, there is a specific gas pressure, at which the X-ray emission is dominant [1,2,4,7]. However, the best gas pressure with maximum X-ray emission at the source may not necessarily be the best gas pressure which delivers maximum X-rays at the target, as the X-rays

* Corresponding author.
E-mail address: rajdeep.rawat@nie.edu.sg (R.S. Rawat).

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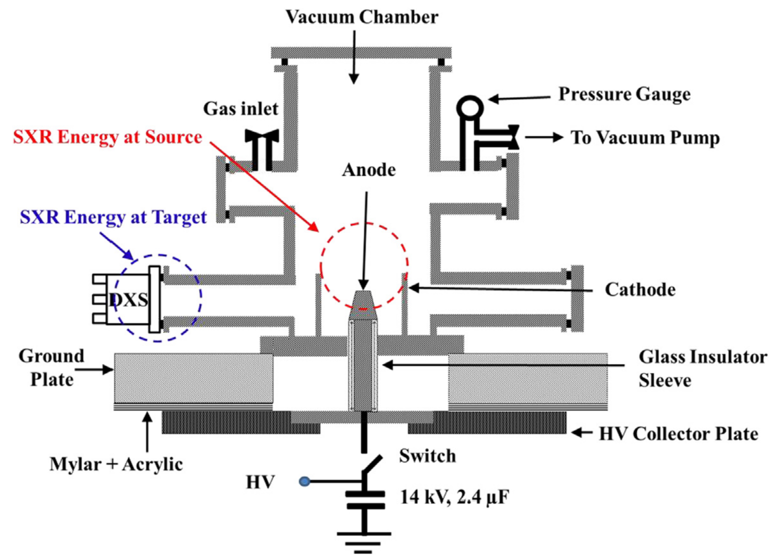

Fig. 1. Experimental setup.

generated at the source/pinch position are absorbed by operating gas medium between the source and the target. Hence, in present investigation, the amount of X-ray energy produced at the source and the percentage of it reaching the target is also estimated. Experiments were conducted to study the influence of Kr doping to the Ne operating gas on the SXR emission efficiency from a 235 J plasma focus device. Kr gas was mixed with Ne gas in different volumetric ratios of 1, 2, 3, 5 and 10%. For each specific volumetric ratio of doping gas added, the operating gas pressure was scanned from 2 to 14 mbar, in steps of 2 mbar. The influence of doping gas Kr, mixed with Ne gas in different volumetric ratios, on the emission of SXR (900–1600) eV, HXR (>1600 eV) and on the plasma pinch characteristics such as focusing amplitude and time to pinch were also analyzed in detail.

2. Experimental setup

The co-axial electrode assembly of FMPF-3 device consists of anode, cathode and an insulator sleeve. The anode used for this investigation is 2 cm long tapered stainless steel anode. The diameter of the bottom cylindrical part of the anode is 1.2 cm and it gradually tapers down to 0.8 cm at the top. The anode was made hollow at the centre for debris mitigation. The cathode is 3 cm in diameter and is composed of 6 cylindrical stainless steel rods dispersed in hexagonal symmetry around anode in 360 degrees. The geometry of the focus tube is closer to that of classical Mather type [16]. The insulator sleeve, made up of Pyrex glass with a breakdown length of 0.6 cm, is placed in between cathode and anode. The length of the insulator sleeve plays a dramatic role in determining the maximum average SXR yield achievable [7], hence, based on our previous experience, an insulator sleeve length of 0.6 cm delivering highest average SXR yield was used. A 4-channel Diode X-ray Spectrometer (DXS), comprising of windowless BPX 65 silicon PIN photodiodes, was placed at 90 degrees with respect to axial direction (as shown in Fig. 1) to detect the X-rays.

The active surface area of the BPX 65 photodiode for the detection of emitted SXRs is about 1 mm^2. A pair of filters was used to measure X-rays of specific range of energy. A 20 μm Al filter allows transmission of X-rays above 900 eV, and an Al-Mylar combination filter (10 μm Al + 125 μm Mylar) allows X-rays above 1600 eV. Therefore, when the transmission of (10 μm Al + 125 μm Mylar) filter is deducted from the transmission of 20 μm Al filter, we can have the exclusive measurement of desired characteristic spectral range, i.e., SXR emission in 900–1600 eV. Both SXR (900–1600 eV)

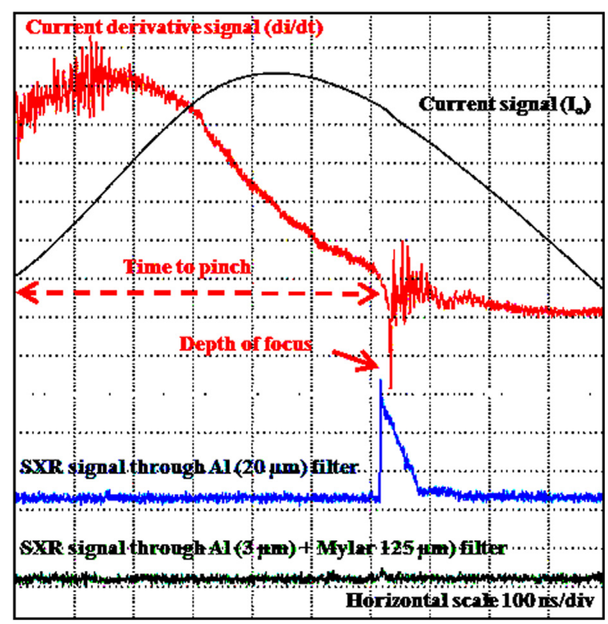

Fig. 2. Typical waveform of current derivative probe and Silicon PIN photodiodes through X-ray absorption filters.

and HXR (>1600 eV) components were investigated. The investigated SXR energy range (900–1600 eV) comprises the major dominant spectral lines of Ne gas emission spectrum [17]. The magnitude of dip in the current derivative signal, as shown in Fig. 2, corresponding to the focus phase is used as a measure of focusing efficiency of FMPF-3 device.

For SXRs, the absolute emission yield and efficiency were calculated, whereas, the HXR component was estimated, only on relative basis, by estimating the area under the signal received through absorption filters, which transmits only X-ray energies above 1600 eV. This is because Ne dominantly emits in 900–1600 eV range and the relative spectral emission in this range are known [18], whereas, the nature of spectrum in >1600 eV range is not known. Hence, the relative HXR emission yield is given in arbitrary units. To measure the SXR emission efficiency at source, the absorption by operating gas, transmission efficiencies of the pair of filters and absorption characteristics of dead and active layer of silicon detector (BPX65) were taken into account. The amount of