Chapter 5 Conclusion and Recommendation

5.1 Conclusions

A 600 joules small plasma focus has been investigated as a pulsed radiation source. The electrical characteristics are measured by the resistive voltage divider and Rogowski coil. The ultra-soft X-ray, EUV emission and ion beam from the pinched plasmas are successfully characterized by employing the X-Ray Diode (XRD), fast EUV diode with integrated thin film filters of 100 nm Si/ 200 nm Zr and biased ion collectors. The signals from the various diagnostic tools are registered by a high bandwidth digital oscilloscope interfaced to a computer.

In a narrow pressure regime of 9.0×10^{-3} mbar to 2.2×10^{-2} mbar, this plasma focus device is capable of producing pinched plasma with good reproducibility, where the ultra-soft X-ray, EUV and ion beam emission are also observed. The plasma focus is observed consistently, with good reproducibility of above 80 % in this pressure range. The best condition of focusing discharge is identified to be in the range of 1.0×10^{-2} mbar to 1.8×10^{-2} mbar. The average velocity of the current sheath varies from 8.5 ± 0.4 cm/μs to 12.2 ± 0.8 cm/μs.

The ultra-soft X-ray and EUV emission observed are due to the plasma focus where the signals registered are observed to coincide with the voltage spike. Average total EUV energy emitted per discharge is found to vary from 7.77 ± 1.69 mJ to 275.42 ± 23.56 mJ. The corresponding energy conversion efficiency is in the range of 0.0013 % to 0.046%. At the optimum pressure for EUV emission, the average current sheath velocity is about 9.5 cm/μs. Interpretation of the radiation output based on the coronal model and atomic database shows that the EUV emission should be dominated by *Ar-VII* and *Ar-VIII*. Plasma electron temperature estimated is approximately 20 eV to 30 eV. In this case, a mild plasma focus discharge is preferred.

The ion beams produced from the plasma pinch are found to have a broad range of energy. The average energy of the ion beam depends also on the operating pressure. The lowest and the highest energies are about 38 keV and 560 keV, respectively. The optimum argon pressure for high energetic ion beam production is found to be 9.0×10^{-3} mbar.

The design of the plasma focus tube employed here allows the operation of the discharge at very low pressure. Thus the drive parameter *S* of this system has registered a large value beyond the limit of the suggested drive parameter [Lee et al. (1996)]. Here, the drive parameter is about two orders of magnitude higher than the normal value of 89 ± 8 (kA/cm)/torr$^{1/2}$. On the other hand, the parameter of *D* which represents the ratio of the discharge current and the anode dimension is as usual. Nevertheless, the results have confirmed the successful operation of this system as a reproducible radiation source. Various improvement and optimization of the source are still needed.

5.2 Suggestions for Future Work

A necessary discharge current of about 20 kA is required to produce the focused plasma of the suitable temperature for EUV emissions [Stamm (2004)]. This required a pretty low input energy for the plasma focus discharge. Our plasma focus system can thus be further scaled down in term of the input energy if the ultimate objective is only the EUV emission. A lower input energy or faster discharge enables the design of the repetitive operation mode. A compact design, for example by employing doorknob capacitors is also advantageous for a portable radiation source. Repetitive mode operation allows accumulation of the radiation yield as required by some industrial applications such as Next Generation Lithography (NGL).

Enhancement of the EUV output at the wavelength of 13.5 nm can also be achieved by using Xenon as the working gas. Xenon plasma with Xe^{8+}, Xe^{9+}, Xe^{10+} and Xe^{11+} species would predominantly produce emission at 13.5 nm from the unresolved $4d$ - $5p$ transition arrays. The electron temperature of the plasma should be around 30 eV [Bowering et al. (2004)].

The diagnostic techniques can also be further improved. The EUV detector SXUV5A employed in this project mainly register the radiation with wavelength in the range of 11 nm -18 nm. To detect the in-band EUV radiation at the wavelength of 13.5 nm ± 2 % from the plasma focus, Mo/Si multilayer reflective mirror can be used. This reflective mirror has been widely used in EUV lithography system and it is capable of selectively reflect near to 65 % of incident 13.5 nm EUV photons when the angle of incident is 5° off normal. Thus the mirror can be incorporated in our detector system by placing it after a collimator, and the EUV detector to be relocated to detect the reflected photons from the mirror.

In the present system, the EUV detector is placed at the side on diagnostic port. We could also investigate the EUV emission from the end-on diagnostic port. This will allow us to check the isotropy of the radiation. However, the end-on direction could be bombarded by the axially moving ion beams and plasma streams. Therefore, a thin Si_3N_4 membrane window can be used as a filter in front of the EUV detector to avoid direct exposure to the pinch and possibly the particle beams. This will help to protect and increase the lifetime of the detector.

Pinhole image technique or Schlieren interferometer can be employed to study the radioactive plasma. Time resolved technique can be incorporated to understand the plasma formation and its evolution. Since the Schlieren interferometer is sensitive to the density gradient, it is useful to study the current sheath structure or even the pinch evolution. A deeper understanding of the plasma and its evolution shall lead to the development of a better controlled plasma radiation source.