CHAPTER 6

DISCUSSION AND CONCLUSION

6.1 : Discussion

i) The spatial distribution and structure of the x-ray emitting plasma are determined by pinhole photography. It is found that the x-ray emitting plasmas have various shapes and sizes. Some pinhole images show strongly emitting plasma clouds, some with distinct hot spot extending from the anode or embedded in the plasma cloud near to the anode and some images also show filament-like plasmas. It has been reported in the literature that the hot spots can be formed close to the cathode and off-axis *[Negus & Peacock, 1979]*; and also near the anode and on-axis *[Lee & Elton, 1971] [Welch & Clothiaux, 1974]*. In the present work, it is found that the hot spots can be formed on-axis, off-axis, close to the cathode or anode as long as the conditions are favourable. However, these conditions are not known precisely.

ii) The electron temperature which is the average kinetic energy of the electrons depend on the input energy and is not geometry dependent. This can be seen from the results of various electrode configuration used in this work. The electron temperature of the hot spots, which is estimated using the two-foil ratio technique, ranges from 2.0 - 2.8 keV. The estimated values are based on the assumption that the predominant emission is due to bremsstrahlung. This assumption is valid if the line emission is weak and the contribution due to recombination radiation is much less than bremsstrahlung radiation.

iii) The hot spot size is estimated using the slit-wire camera. It works on the same principles as the penumbra imaging of pinhole cameras. However, in the slit-wire camera a combination of slits, thin wires and filters allows enhanced detection of very weak and small hot spots of different energies for determination of their sizes. For the present work, an aluminized mylar of 36 μm in thickness is used as the filter. Therefore, the size of the hot spots estimated are for the bulk of the x-ray emitting source with energy greater than 1 keV. The errors in estimating the hot spot size can be reduced by using a wider range of wire diameters. Also, the limitation of resolution due to finite grain sizes on x-ray film does not arise because the size is determined by comparing the ratio of densities on the film from different regions of hot spot (See Sec. 3.4.2).

iv) The electron density estimated using the total dose of the PIN diode is between 4.7×10^{20} - 1.1×10^{21} cm^{-3}. The order of magnitude for the electron density agrees reasonably well with published results, even though the estimate is based on shorter wavelength radiation. In the literature, most of the electron density estimates were based on longer wavelength radiation. Therefore, the electron density estimation from the absolute measurement of PIN diode is quite reliable and can be used as an approximate value of the true electron density.

v) The hard x-ray energy computed from the PIN diode measurement, which is for x-ray energies of 1-25 keV, is about 10^{-3} J. The measured energy is actually an underestimate since some emission is absorbed by the filters and the dead layer in the PIN diode. This is also evident from the pinhole images where the x-ray emission traversing a few cm of air still produces a good image. Only high energy x-rays can transmit through a few cm of air without much attenuation. The efficiency of conversion of electrical energy to x-ray energy is 0.0008 - 0.002 %. However, this estimate is based only on bremsstrahlung emission of 100 eV to 100 keV. Inclusion of line radiation, recombination and longer wavelength bremsstrahlung emission would give higher values.

Using the radiative collapse model and the generation of high energy electron beams, a possible explanation for the nature of the x-ray emission observed in the discharges is given. During the breakdown, a plasma column is formed in the inter-electrode space. This plasma column acts as a conducting channel. The current flowing in the plasma generates an azimuthal magnetic field. Due to Joule heating of the plasma current, the plasma temperature increases. Since the Joule heating is less than the magnetic pressure, the plasma is compressed and pinching occurs. The flow of particles from the ends and radiative emission cause the pinch to collapse to a few μm in diameter. Simultaneously, the electron temperature increases greatly and the electron density decreases rapidly. The Joule heating becomes greater than the magnetic pressure causing the pinch to expand. Due to the turbulence or sudden change of inductance during the expansion, very high transient voltages are induced. The induced voltage which can be as much as 20 times the initial charging voltage accelerates the charges. The resultant electron beam interacts with the dense plasma causing the emission of hard x-rays.

Therefore, the soft x-rays is emitted during the collapse of the plasma column and the hard x-rays is emitted due to turbulence or instabilities occurring in the plasma. Emission of hard x-rays does not necessarily follow the formation of hot spots. Any form of instabilities or turbulence occurring in the plasma formed during the discharge can emit hard x-rays. This can be seen in the pinhole images and the time-resolved x-ray measurements described earlier.

6.2 : Conclusion

The x-ray emission from a low energy vacuum spark triggered by a transient hollow cathode device is studied. To find the best setup that produces good sparks (high intensity x-ray output) consistently, the electrode configuration is optimised. It is found that the yield of good sparks is 60-65 % for cathode aperture of 4 mm and anode-cathode separation of 2 mm.

Using this setup, the plasma parameters are estimated. The diameter of the hot spot is estimated to be 100-200 μm with electron temperatures of 2.0-2.8 keV. The other parameters that are estimated based on the electron temperature and hot spot size diagnostics are shown in Table 6.1.

The total emission energy of x-ray is estimated to be about 10^{-3} J, which would be sufficient for single shot exposure in some applications. The size of the x-ray source makes it possible for applications where point sources are needed to avoid blurring of the replication image. Due to spatial variation of the x-ray source, collimation of the x-ray beam is needed which could also be used to

Input energy (J)	370
Electron temperature, T_e (keV)	2.0 - 2.8
Hot spot diameter (μm)	100 - 200
Electron density, n_e (cm^{-3})	10^{20} - 10^{21}
Total radiation loss rate (W cm^{-3})	10^{11}
Total emission power (W)	10^5
Total emission energy (J)	10^{-3}
Efficiency (%)	0.0008 - 0.002

Table 6.1

produce sharp replication image.

This system can also be used as a pulsed x-ray source for time-resolved x-ray studies in x-ray diffraction studies, flash radiography, microlithography and microscopy.

6.3 : Suggestions for future work

The vacuum spark can be made into an inexpensive and mobile, high intensity pulse x-ray source. In order to do this, a better understanding of the hot spot formation and the required physical conditions have to be known. The following are some suggestions on how this can be studied.

To find out how the hot spot is formed, a time-resolved study can be carried out by using a multi-frame microchannel plate (MCP) camera. By varying the exposure time between each frame, the time development of the hot spot can be obtained. One of the problem for this type of study arises from the nature of the spark itself. Due to the jitter in the formation of the hot spot, it is difficult to set the exposure time of the MCP camera to be coincidental with the hot spot formation.

If the dependence of hot spot formation on the physical conditions can be found, it would improve the probability of imaging the hot spot formation. One way of doing this is to further study the contribution of electrode configuration on hot spot formation. Anodes and cathodes with various shapes and sizes can be used to do this. Other physical parameters which might contribute to the hot spot formation such as ambient pressure, charging voltage and triggering system can also be varied to find the best operating conditions.

In this thesis, a simple convex crystal spectrometer is used to study the emission spectrum. This spectrometer does not have a good resolution, therefore, it is only used for a preliminary scan. A higher resolution spectrometer would yield more information on the emission spectrum. To study the time development of the emission spectrum for each shot, a single shot focussing spectrometer coupled to a multi-frame camera can also be used.

The slit-wire camera which is used to estimate the hot spot size can also be used to study smaller structure and / or different energy regions of the hot spot. In the present work, only a single slit (~500 μm) and foil (36 μm aluminized mylar) are used. By using multiple slits filtered with foils of different materials and thicknesses, various energy regions can be studied for every shot. Therefore, a combination of multiple slits, various foils and wires can be used to estimate the size and energy of x-ray emitting regions in a hot spot.

Once the system is optimised, various anode materials can be used to study plasma x-ray emission from each material. This would allow the system to be tuned to various wavelengths, which would make it a valuable tool for a wide range of applications.