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Dynamics of X-ray emission from a small plasma focus

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ABSTRACT The dynamics of X-ray emission from a 3 kJ argon plasma focus has been studied using a five channel PIN diode X-ray spectrometer (DXS) and a time-resolved X-ray pinhole imaging system. The five channel DXS is used to investigate the spectral evolution of the X-ray emission from the focussed plasma whereas the time-resolved X-ray pinhole imaging system provides information on the temporal evolution of the structure of the X-ray emission regions during the focus discharge. Two periods of X-ray emission are observed during a focus discharge, one during the radial compression phase of the discharge and the second period occurs at a time of about 200 ns after the maximum compression. The first period X-rays are emitted from a hot argon plasma with an electron temperature of about 1.5 keV whereas the second period X-rays consist of predominantly the copper K_α line radiations. Time-resolved X-ray pinhole imaging of the focus discharge visualises the formation of the focussed plasma column during the radial compression phase corresponding to the first period of X-ray emission. The formation of a second compression at a time of about 65 ns after the first maximum compression has also been observed. The second period X-ray emission is observed at a time of about 200 ns from the maximum compression and it is believed to be emitted from the anode itself or from the copper vapour ejected from the anode due to electron beam bombardment.

ABSTRAK Dinamik pancaran sinar-X dari sebuah alat fokus plasma argon bertenaga 3 kJ telah dikaji dengan menggunakan sebuah spektrometer sinar-X yang dibentukkan dari lima saluran diod PIN (DXS) dan satu sistem kamera lubang jarum sinar-X terurai-masa. Spektrometer sinar-X lima saluran diod PIN itu diguna untuk mengkaji perubahan spektrum pancaran sinar-X dari plasma terfokus itu; manakala kamera lubang jarum terurai masa itu diguna untuk mendapatkan maklumat tentang perubahan masa struktur kawasan pancaran sinar-X dalam tempoh nyahcas fokus. Dua tempoh pancaran sinar-X telah diperhatikan semasa suatu nyahcas fokus, ia itu satu tempoh semasa fasa pemampatan jejari nyahcas fokus dan tempoh kedua berlaku pada masa sekurang-kurangnya 200 ns selepas masa pemampatan maksimum. Sinar-X tempoh pertama itu adalah dipancarkan dari plasma argon panas yang mempunyai suhu elektron sekurang-kurangnya 1.5 keV manakala sinar-X tempoh kedua itu didapati mengandungi sinaran garisan K_α kuprum yang kuat. Imej sinar-X lubang jarum terurai-masa nyahcas fokus yang didapati menunjukkan bahawa pembentukan turus plasma pada fasa pemampatan jejari itu adalah sepadan dengan tempoh pancaran sinar-X pertama. Pembentukkan satu pemampatan kedua pada masa sekurang-kurangnya 65 ns selepas pemampatan maksimum pertama juga telah diperhatikan. Tempoh pancaran sinar-X kedua itu diperhatikan pada masa sekurang-kurangnya 200 ns selepas pemampatan maksimum dan ianya disangka adalah dipancarkan dari anod atau dari wap kuprum yang dipancutkan dari anod kerana hentaman oleh bim elektron.

(Plasma focus, X-ray)

INTRODUCTION

In view of the possibility of various applications such as microlithography and microscopy [1,2], the plasma focus has recently been investigated intensively with respect to its X-ray emission characteristics. For effective utilization of the plasma focus as a X-ray source, it is important to determine the temporal and spatial characteristics [3,4] as well as the spectral distribution [5,6,7] of its X-ray emission. In general, two regimes of X-ray are observed during a plasma focus discharge. The first regime is associated with the maximum compression of the radial pinch phase during which a plasma of the operating gas is formed, while the second regime is observed at a late phase believed to be produced by the bombardment of the anode by energetic electron beam [8]. It has also been shown [9] that the X-ray emission in the late phase of a deuterium plasma focus comes from a deuterium plasma contaminated by copper impurity. In the past, there have been several efforts [3,10] to study experimentally the spatial and temporal evolution of the X-ray emission regions of the plasma focus. In this paper, we report on a series of experiments performed on a small 3.3 kJ plasma focus to study the temporal, spatial as well as spectral evolution of its X-ray emission. The diagnostics employed include a four frame time-resolved microchannel plate based X-ray pinhole camera and a five channel X-ray diode spectrometer.

The experiments have been carried out using the UNU/ICTP plasma focus [11] which is a Mather type plasma focus with 16 cm long electrodes of inner and outer diameter 1.9 cm and 6.4 cm respectively. The inner electrode is a hollow copper cylinder and the outer electrode consists of six copper rods arranged concentrically around the anode. The discharge is powered by a single 30 μF capacitor. When discharged at 15 kV, a peak current of 150 kA will be delivered from the capacitor through the plasma focus load with a rise-time of 3 μs. The gas used in the experiments reported here is argon. The filling pressures have been varied in the range of 1 to 3 mbar.

EVOLUTION OF THE ARGON PLASMA FOCUS X-RAY EMISSION SPECTRUM

A series of experiments have been carried out to investigate the time evolution of the X-ray emission spectrum of the plasma focus using a five channel diode X-ray spectrometer. The detectors used are five BPX65 PIN diodes with their glass windows removed to extend their spectral response to the X-ray region. When used with 24 μm of aluminized mylar (mylar coated with 0.16 μm thick aluminium to cut off visible light), the diode is sensitive to X-rays in the range of 1 to 10 keV. The five channel diodes are mounted to view the focussed plasma side-on with identical geometrical arrangement. Four of the five channel diodes are covered with additional aluminium foils of 30 μm, 60 μm, 90 μm and 120 μm thicknesses respectively. When the output of the five channel diodes are recorded simultaneously, it is possible to determine the time evolution of the electron temperature of the plasma by the X-ray foil absorption technique [12].

The output of the five channel diode X-ray spectrometer are recorded simultaneously together with the voltage signal. A typical discharge of the UNU/ICTP plasma focus at 15 kV with 1 mbar argon as shown in Fig. 1. In this discharge, multiple X-ray pulses are observed. The first two X-ray pulses are sharp pulses corresponding in time to the rising edge of the voltage spike. These X-ray pulses are believed to be associated with the focussed plasma during the first maximum compression of the focus discharge. The absorption curves of the five channel diode X-ray spectrometer corresponding to these X-ray pulses as depicted in Fig. 2 imply an argon plasma with electron temperature of about 1.5 keV. The shape of the measured absorption

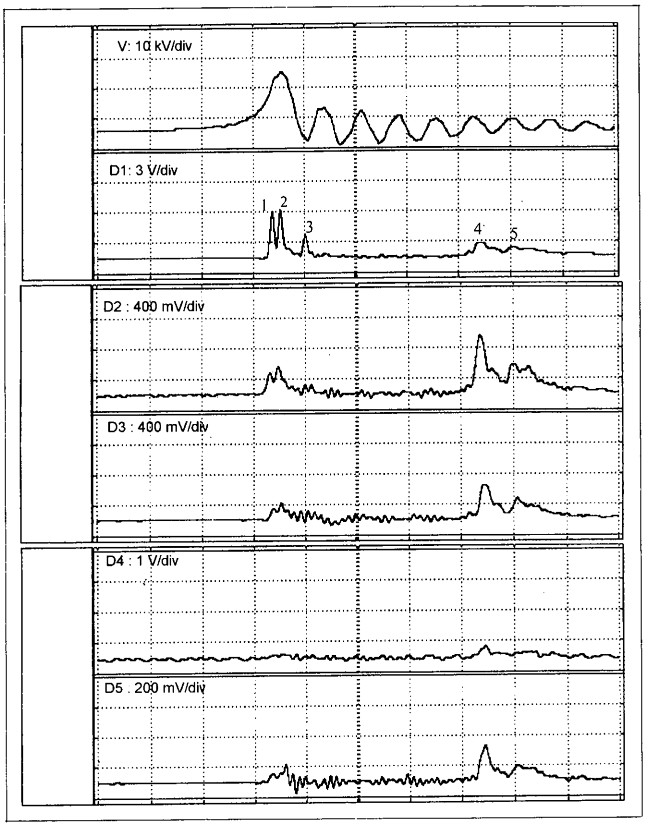

Figure 1. Simultaneous signals of the high voltage probe together with the 5 Channel diode X-ray spectrometer (Time scale : 50 ns/div).

curves follow closely those obtained from calculation assuming a pure argon plasma, suggesting that there is little copper contamination during this phase of the focussed plasma formation. Closer investigation of the voltage signal indicates that corresponding to the two X-ray pulses there are two voltage spikes which are not properly resolved by the voltage probe. The discharge shown in Fig. 1 is an example of a focus discharge with a double compression as indicated by the double voltage spike.

A third X-ray pulse is observed at a time of about 25 ns from the second X-ray pulse. This X-ray pulse is attenuated to below the detection threshold of the BPX65 by the addition of just 30 μm of aluminium foil to the 24 μm of aluminized mylar. Hence information concerning the spectral distribution of the plasma associated with this pulse cannot be derived from the signals.

The first three X-ray pulses in Fig. 1 are formed within less than 50 ns during the maximum compression of the plasma focus discharge and they can be considered to be the first period of X-ray emission of the plasma focus. From Fig. 1, a second period of X-ray emission is clearly seen at a time of about 200 ns from the first X-ray pulse. During this second period, two major X-ray pulses are observed. The electron temperature corresponding to these two pulses deduced from the ratio technique using Fig. 2 are above 10 keV. Their points are seen to be close to the Cu K_α line. This indicates that these two pulses consist of predominantly the Cu K_α line radiations. They may be produced by either electron beam bombardment of the anode, or from a dense but relatively cold copper vapour ejected from the anode due to the electron beam bombardment. The ejection of copper vapour from the anode has been observed previously in this laboratory by the laser shadowgraphy technique [13]. The presence of the dense copper plasma has also been visualised by using the time-resolved X-ray pinhole imaging system which will be described in the next section.

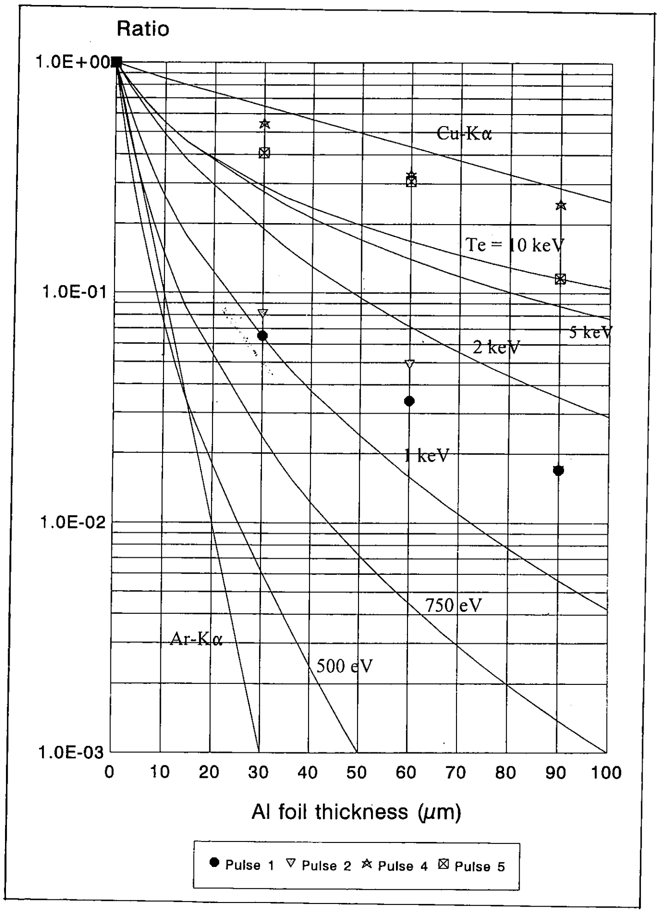

Figure 2. Measured and calculated X-ray transmission curves of aluminium foils for argon plasmas at various electron temperatures. In this graph, the vertical axis is the normalised ratio of five channel diode signals. The solid curves represent the calculated values of the ratios at various temperatures whereas the points are experimental values.

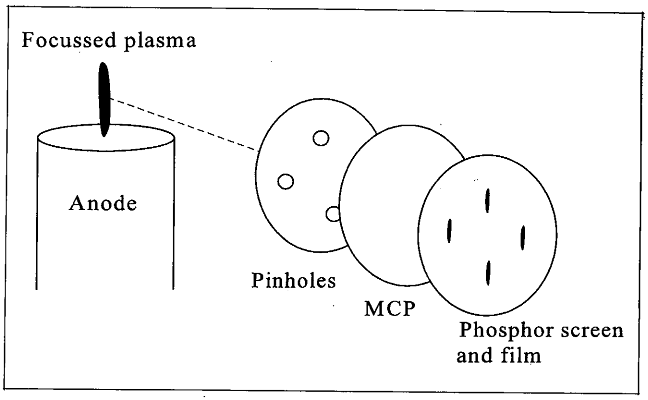

Figure 3. Schematic setup of the time-resolved X-ray pinhole imaging system employing a four frame MCP.

TEMPORALLY AND SPATIALLY RESOLVED X-RAY PINHOLE IMAGING USING FOUR FRAMES MCP

An independent series of experiments have been carried out on the UNU/ICTP plasma focus to investigate the temporal and spatial evolution of its X-ray emission. In these experiments, a multiple pinhole X-ray imaging system was used to image the X-ray emission regions of the plasma focus discharge and provide spatial and temporal (qualitative) resolution. In order to observe the temporal evolution of the X-ray emitting regions of the plasma, a circular microchannel plate that has been divided into four quadrants is employed to capture the X-ray images of four identical pinholes (each with a diameter of 500 μm) arranged in such a manner that the X-ray images of the four pinholes fall onto the four quadrants of the MCP simultaneously. These four quadrants are switched individually and their switching is controlled by a sequence of four pulses with adjustable durations between pulses. Each of these pulses provides an effective opening time of about 2 ns for each quadrant of the MCP. The output of the MCP is a phosphor screen producing visible light output that can be captured on a fast film by contact print. The setup is shown schematically in Fig. 3. The four pinholes are all covered by 2.5 μm of aluminised mylar. During each discharge, the discharge voltage signal, together with the signals from the five channel diode X-ray spectrometer are recorded simultaneously. In this case the set of absorption foils used is as follows:

Channel 1: 22 μm aluminized mylar + 20 μm Al;
Channel 2: 22 μm aluminized mylar + 10.5 μm Ti;
Channel 3: 22 μm aluminized mylar;
Channel 4: 22 μm aluminized mylar + 10 μm Cu;
Channel 5: 22 μm aluminized mylar + 7 μm Co + 7 μm Al.

Channels 1 and 2 are set to look at the argon plasma emission; while Channels 4 and 5 are used to isolate the copper Kα emission at 1.5 Å, since they in fact form a pair of Ross filters for this wavelength (Fig. 4). In order to synchronize the switching time of the MCP with reference to the discharge, the synchronized pulse of the first quadrant switching is superimposed on the signal of Channel 3 of the diode X-ray spectrometer. The timing of the MCP switching is controlled by using a Standford Research delay generator. The triggering pulse used to trigger the main discharge spark gap is taken to be the master pulse. Due to the jittering in the time of occurrence of the focus, the triggering of the MCP is set to be at the most probable time in order to capture the events during the focussing action. Fig. 5 shows the results of a focus discharge where the focussing action has been captured by the four frame MCP

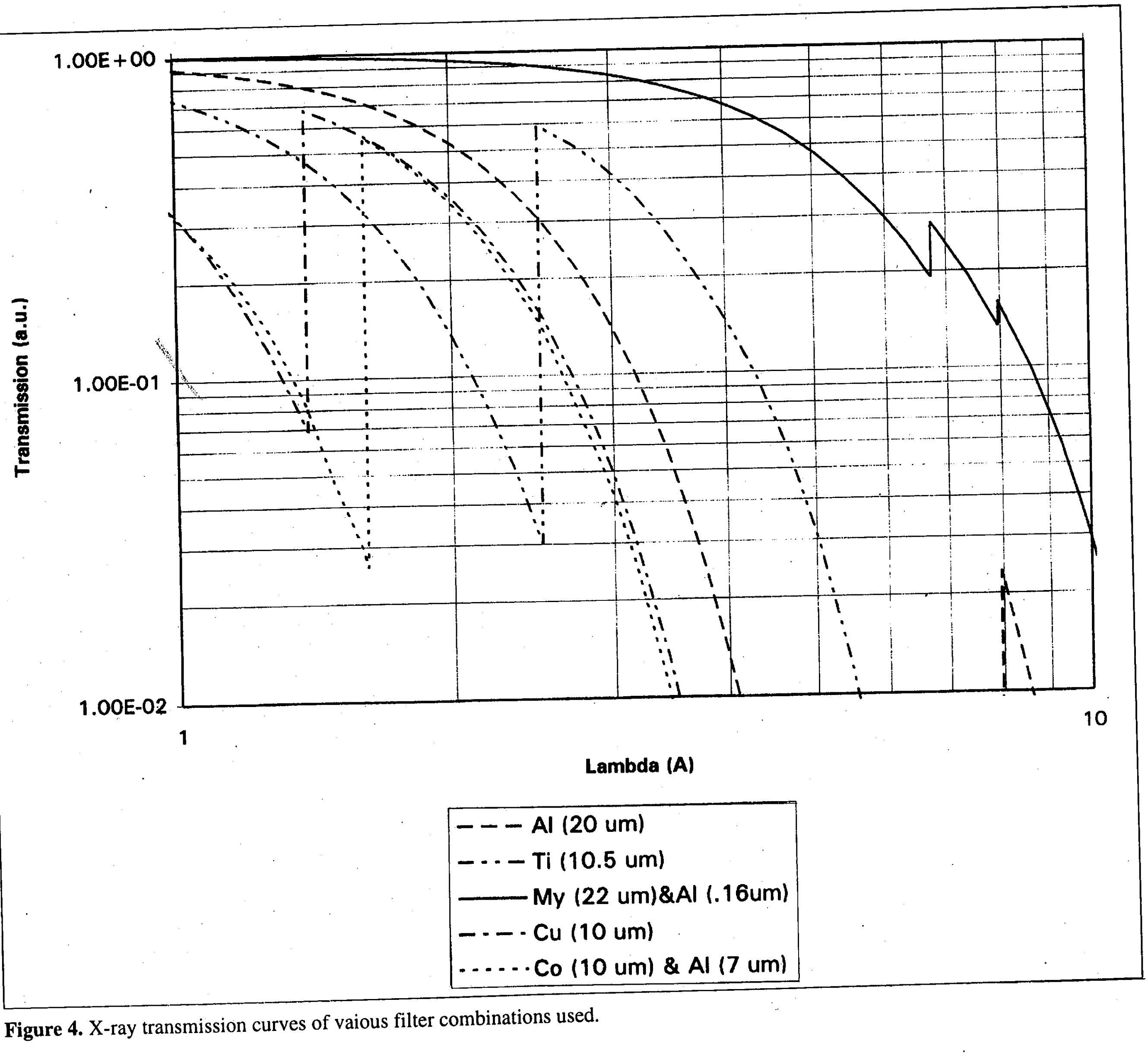

Figure 4. X-ray transmission curves of vaious filter combinations used.

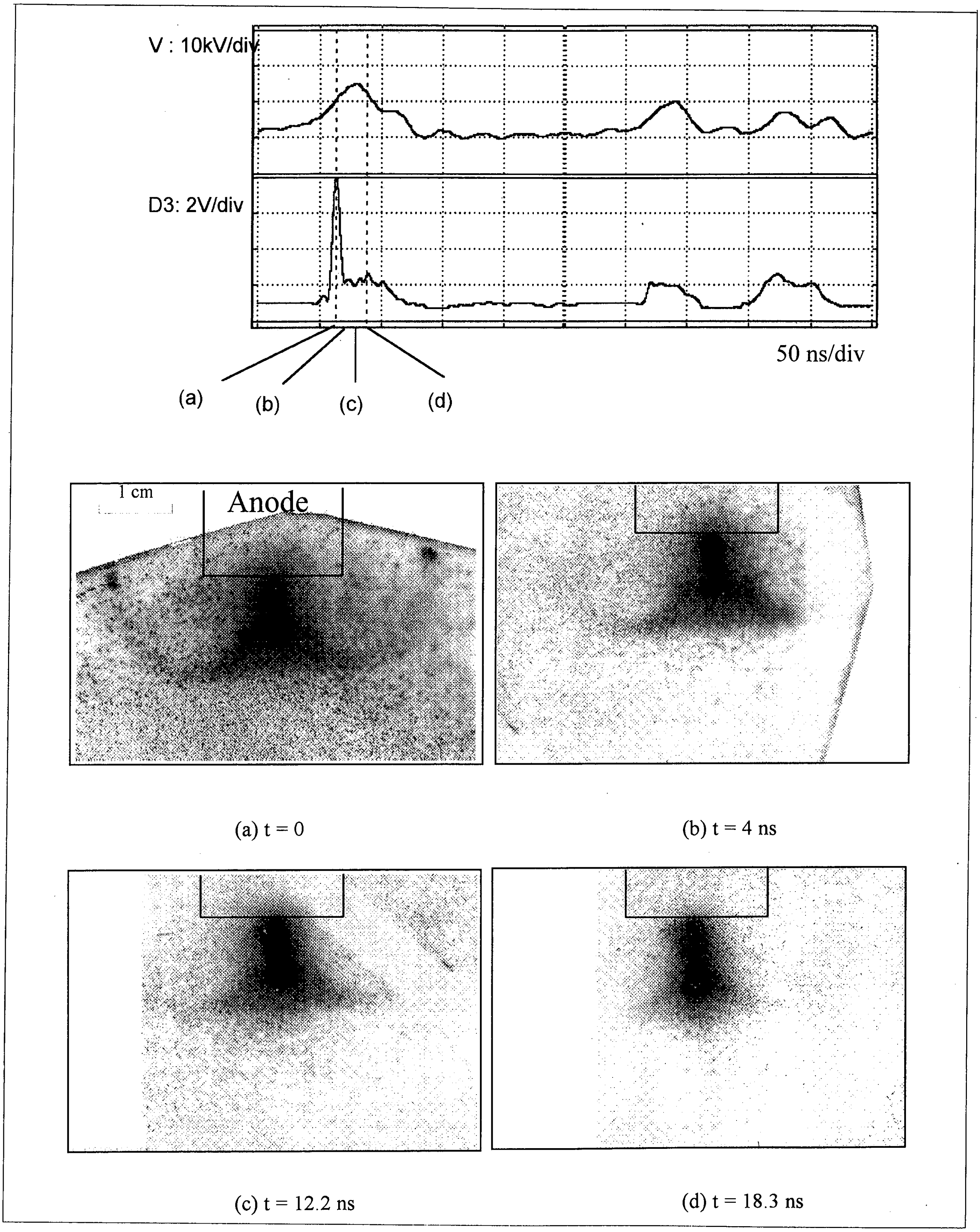

Figure 5. X-ray pinhole images at four consecutive times captured during the radial compression of the focus discharge.

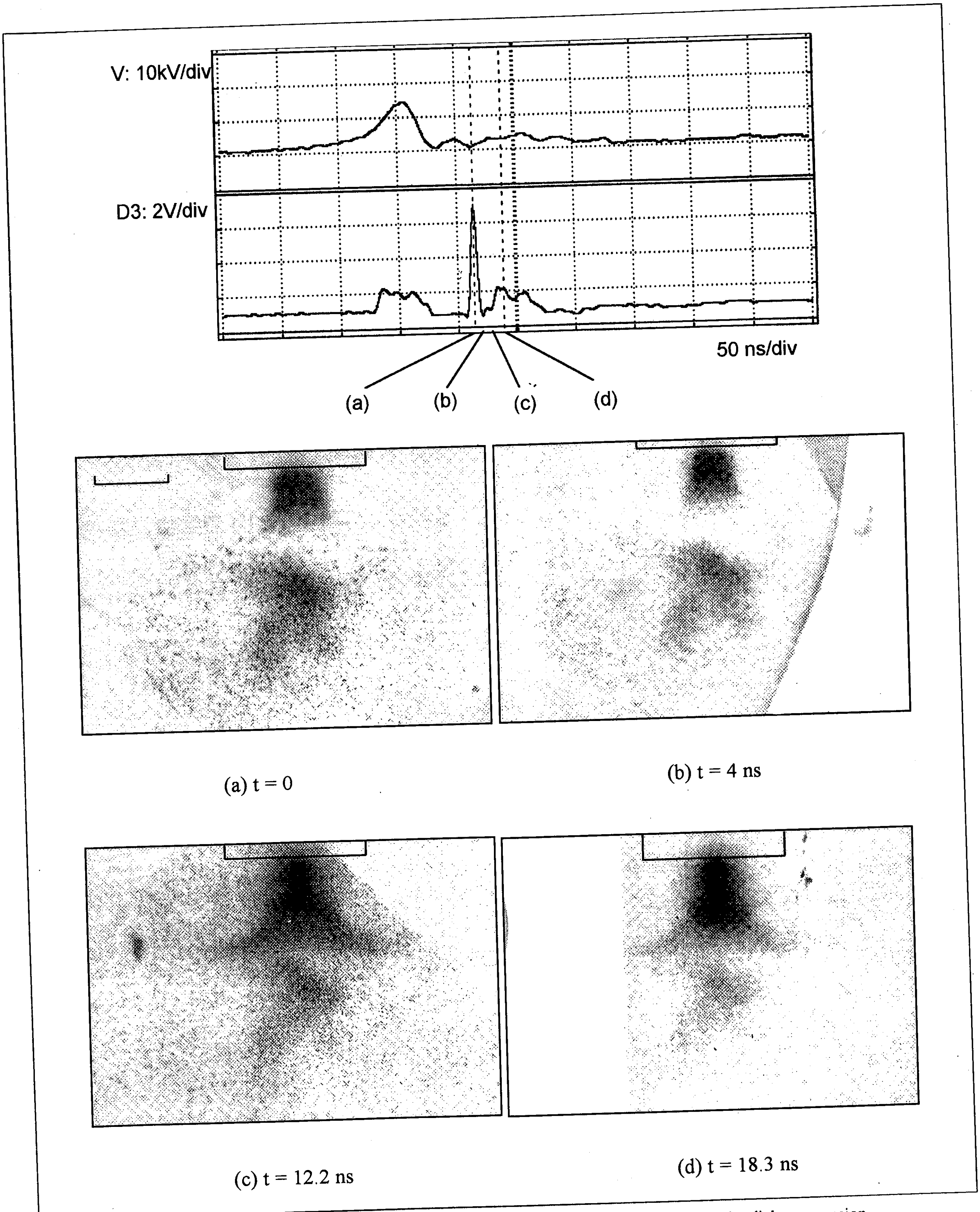

Figure 6. X-ray pinhole images at four consecutive times which capture the occurrence of the second radial compression.

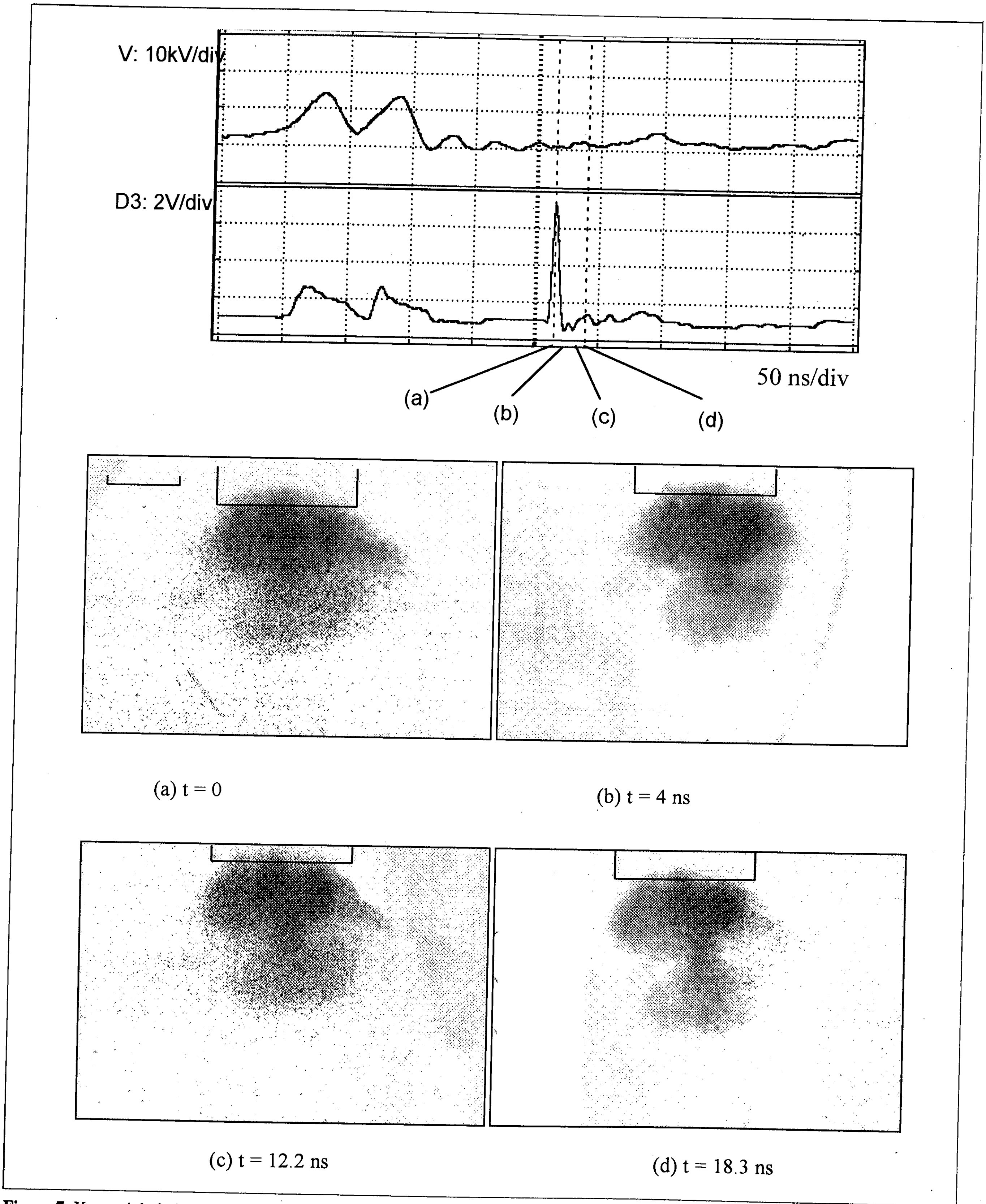

Figure 7. X-ray pinhole images at four consecutive times captured at about 200 ns after the maximum compression showing the development of the copper vapour ejected from the anode of the plasma focus due to electron beam bombardment.

X-ray pinhole imaging system. The time interval between the first and the fourth frames is 25 ns. The final stage of the current sheet collapse can be seen clearly from the four frame pinhole images in Fig. 5. The plasma slug attached to the current sheet at this stage is hot enough to emit in the soft X-ray region. The current sheet disappears when the plasma column reaches maximum compression as shown in frame (d). This seems to occur at about 5 ns after the peak of the voltage spike.

The occurrence of a second compression in the plasma focus has also been visualized through the four frame MCP X-ray pinhole imaging system. Fig. 6 shows the results for a focus discharge in which the first frame of the MCP is switched at about 65 ns after the first maximum compression. The first two frames in this series of time-resolved images show the plasma column being compressed radially towards the axis. Due to the remnant plasma from the first compression, the plasma column is seen to be emitting X-rays at an early stage of the compression. The current sheet starts to emit X-rays at about 10 ns later (as shown in frame (c)) and subsequently a tightly pinched plasma column is formed. Correspondingly, a second X-ray pulse is detected by the PIN diodes. However, this second compression seems to be less severe since the voltage spike corresponding to this second compression is observed to be low. This is in contrast with previous results which show that multiple voltage spikes can also be observed corresponding to multiple compression. It has been shown in the previous section (Fig. 1) that a second compression that occurs at a time of about 10 ns after the first compression is capable of producing a hot and dense argon plasma with little copper contamination similar to that of the first compression. In the discharge shown in Fig. 6, the X-ray pulse produced during the second compression is seen to be heavily contaminated by copper impurity, as can be deduced from the large signal registered by the copper filtered PIN diode.

The X-ray emitting region at the late phase of 200 ns from the maximum compression of the plasma focus discharge can be seen from the series of time-resolved X-ray pinhole images shown in Fig. 7. In this discharge, the first frame of X-ray pinhole image is taken at a time of about 200 ns from the first X-ray pulse. This image shows a plasma cloud above the anode. However, there is no corresponding signals on all the X-ray diode channel except channel 3, indicating that the X-ray is relatively soft. This plasma cloud is believed to consist of the copper vapour ejected from the anode due to electron beam bombardment similar to those observed earlier by laser shadowgraphy [13]. The electron beam may be produced during the break-up phase of the plasma column formed at the maximum compression. The plasma cloud is seen to break up into two regions, with one region moving slowly away from the anode, while the other region into the hollow anode. Meanwhile a plasma column seems to be maintained along the axis. In the particular discharge shown in Fig. 7, a third compression may have occured as indicated by the third voltage spike. During this compression, the pinch occurs in the environment of a weakly ionized copper vapour and it is expected to have a diffused structure. The corresponding X-ray produced consists of predominantly the copper K_α line radiations and constitutes to part of the second period X-ray emission from the focus.

CONCLUSIONS

From the results presented above, the sequence of X-ray emission from the focussed plasma may be visualized as follows. Within the last 25 ns or earlier during the radial compression phase of the plasma focus discharge, a hot plasma column emitting intensely in the soft X-ray region is formed. At this stage, the plasma formed consists of predominantly the working gas of the focus discharge. This plasma column is compressed to a high density under the focus action, while extending in the axial direction. It is seem that the whole plasma sheath, rather than just the central pinch column, is emitting soft X-ray. The electron temperature of the plasma formed is of the order of 1 to 2 keV. A second focussing may occur within a time of 40 to 100 ns resulting in the formation of the second plasma column with about the same condition as the first column, but it is usually slightly more contaminated with copper impurities. The second compression may sometimes be more diffussed and hence less severe when the copper contamination is higher. Subsequent to these compressions, one or two more bursts of X-ray may be observed at a much later time. These X-ray bursts are heavily dominated by copper K_α line radiations. A possible mechanism for the production of these X-ray burst is the compression of the copper vapour ejected from the anode due to electron beam bombardment.

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