2. Electro-explosion phenomena in needle-plate geometry

In this chapter, we discuss the basic requirements to perform electro-explosion of wire experiments in the novel needle-plate geometry. Highly polished metal plate electrodes and micron sized needle electrodes are necessities for a good experiment in this geometry. Plate polishing and electrochemical etching of wires to prepare plate and needle electrodes are discussed with all possible details. Specific information relating to the experimental setup is given here as well. We show optical micrographs of light emission during the explosion and time evolution of the current flow through the needle-plate geometry. Current plots during explosion and the characteristic light emission lead us to the conclusion that these are characteristics of the electro-explosion process which is thus established in the needle-plate geometry.
2.1 Basic requirements for explosion

On the basis of discussion presented in chapter 1, the phenomena of electric explosion of wires (EEW) can be described as follows. When a high-density \(10^4 \text{ to } 10^6 \text{ A/mm}^2\) current pulse, which is usually produced by discharge of a capacitor bank, passes through a wire, the density of the energy in the wire may considerably exceed the binding energy of the wire constituents because of the high rate of the energy injection and an expansion lag of the heated material. As a result, the material boils up in a burst, a bright light flashes and a mixture of superheated vapour and boiling droplets of the exploding wire material results and a shockwave scatter these to the ambient atmosphere [1,2]. Extremely high current density is required for the explosion process. So the key factor which controls the electro-explosion phenomena is the required large current density value i.e. 1.

2.2 The needle-plate concept

In the Z-pinch system, a plasma is produced by applying a high voltage pulse across an anode-cathode gap of cylindrical geometry bridged by a single wire [3]. Instead of using this geometry, we have designed a new two electrode system in the form of a metallic plate and a metallic needle. To achieve high current density at the contact point, micron sized needles are used. After building a contact between these two electrodes, a potential is applied suddenly by connecting them to a bank of batteries. Due to the suddenly applied voltage and high current density at the contact point, energy density in the wire is expected to considerably exceed the binding energy because of a high rate of the energy injection and an expansion lag of the heated material should result. Thus a possibility exists for electro-explosion which is the basic concept that is used for the needle-plate geometry.

2.3 Details of experimental requirements

2.3.1 Plate electrode

Metal plates of dimension 10 mm × 10 mm × 0.5 mm are used for the experiment. Micron sized tips are used to achieve high current density. For explosion experiment, two electrodes are brought in contact with each other. Thus in a good experiment, contact between two electrodes must be precise to the extent possible. Therefore sample plate
roughness is of prime importance. It should be of the order of or less than needle electrode tip size. To achieve this, metal plates are polished to get a roughness of the order of 50 nm - 500 nm, i.e., less than 1 μm. Here we provide the required steps for the plate electrode preparation.

**Purity:** Metal plate purity is checked by X-ray diffraction and EDX measurements.

**Etching:** Before polishing, the metal surface is chemically cleaned to remove the oxide layer and dust etc. Etching process requires chemicals depending on the metal to be etched. These requirements are discussed below:

**Iron plate:** The surface is cleaned by a chemical treatment using 5:10:1 solution of nitric acid (HNO₃), distilled water and hydrogen fluoride (HF). HF helps in removing the oxide layer formed by the etching procedure. When the plate surface appears clean, it is taken out from the solution and rinsed with distilled water. Then the plate is kept in a beaker containing distilled water and cleaned using an ultrasonic bath. After 20 minutes, the plate is taken out from the beaker, dried and kept inside a clean box.

**Copper plate:** The surface is cleaned by a chemical treatment which involves using 1:1 solution of nitric acid (HNO₃) and distilled water. Rest of the procedure is same as for the iron plate.

**Aluminium plate:** The surface is cleaned by a chemical treatment using sodium hydroxide (NaOH) solution (10% by weight). Rest of the procedure is similar as for the iron plate.

**Silver plate:** These plates are annealed and locally sourced. Their surfaces are clean on visual inspection and hence they are used for polishing directly.
**Nickel plate:** These plates are purchased from Sigma-Aldrich. Their surfaces are also clean as received and hence not subjected to any chemical treatment. Hence they are also used for polishing directly.

After surface cleaning, there is a long procedure to achieve smooth surface of required roughness. It is discussed in detail here.

### 2.3.1.1 Plate mounting:

The primary purpose of the plate mounting is convenience in handling the plate during the polishing steps. Thickness of the mount should be sufficient to enable the operator to hold the mount firmly during grinding and polishing and thereby prevent a rocking motion and also to maintain a flat surface [4]. We have used circular mounts of 1\(\frac{1}{4}\) inch diameter, as they are the easiest to handle.

**Mounting Method:** The method of mounting should in no way be injurious to the microstructure on the plate surface. Mechanical deformation and heat are the most likely sources of injuries. The mounting medium and the metal plate (specimen) should be compatible with respect to the hardness and abrasion resistance. We have used compression mounting, the most common mounting method which involves moulding around the specimen by heat and pressure using bakelite or acrylic resin as moulding material. Bakelite resins are thermosetting and acrylic resins are thermoplastic. Both thermosetting and thermoplastic materials require heat and pressure during the moulding cycle, but after curing, mounts made of thermosetting materials may be ejected from the mould at maximum temperature. Thermoplastic materials remain molten at the maximum moulding temperature and must be cooled under pressure before ejection. We have used conductive phenolic compound for specimen mounting. It also remains molten at the maximum moulding temperature and must be cooled under pressure before ejection.

A mounting press equipped with moulding tools and a heater is used for compression mounting. We have used a Buehler hydraulic specimen mounting press. It consists of a 1\(\frac{1}{4}\) inch diameter hollow cylinder of hardened steel, a base plug and a plunger. The metal plate (specimen) to be mounted is placed on the base plug, which is inserted at one
end of the cylinder. The cylinder is nearly filled with moulding material in powder form and the plunger is inserted into the open end of the cylinder. A cylindrical heater is placed around the mould assembly, which is positioned between the platens of the mounting press. Then the prescribed pressure is exerted and maintained on the plunger to compress the moulding material, until the mould assembly is heated to the proper temperature. Following this, it is cooled under pressure. Finally, the finished mount is ejected from the mould by forcing the plunger entirely through the mould cylinder.

2.3.1.2 Grinding: It is the most important operation in the specimen preparation. During grinding, the user has the opportunity to minimize mechanical surface damage that must be removed by subsequent polishing operations. Even if a large metal sheet is cut into pieces with severe surface damage, the damage can be eliminated by prolonged grinding [5]. However, prolonged polishing can do little towards the elimination of severe surface damage introduced by grinding.

Grinding is accomplished by abrading the specimen surface through a sequence of operations using progressively finer abrasive grit. Grit sizes from 40 mesh to 150 mesh are usually regarded as coarse abrasives and grit sizes from 180 mesh to 600 mesh as fine abrasives. Grinding is commenced with coarse grit size that will establish an initial flat surface and remove the effects of cutting within a few minutes. We have used grinding sequence involving abrasive grit of 180, 240, 400 and 600 mesh sizes.

The purpose of grinding is to lessen the depth of deformed metal to the point where the last vestiges of damage can be removed by series of polishing steps. The scratch depth decreases with decreasing particle size of the abrasive. It is imperative that each grinding step completely removes the deformed metal produced by the previous step. To ensure the complete elimination of the previous grinding scratches found by visual inspection, the direction of grinding is changed 90 degrees between successive grit sizes. In addition, microscopic examination of the various ground surfaces during the grinding sequence is worthwhile in evaluating the effect of grinding. Each ground surface should have
scratches that are clean-cut and uniform in size, with no evidence of previous grinding scratches.

Grinding is done under wet conditions, provided water has no adverse effects on any constituent of the microstructure. Wet grinding minimizes loading of the abrasive with metal removed from the specimen being prepared. Water takes away most of the surface removal products before they become embedded between adjacent abrasive particles. Thus the sharp edges of the abrasive particle remain exposed to the surface of the specimen throughout the operation. If the sharp edges are unexposed the result is a smearing of the abraded surface rather than removal of surface metal. Therefore throughout the sequence of grinding steps, the specimen is examined to check that the abrasive is actually cutting and not merely smearing or burnishing. Burnishing results primarily from using an abrasive beyond its effective limit. Use of worn-out abrasives and dulled cutting edges is detrimental to good preparation.

Another advantage of wet grinding is the cooling effect of water. Considerable frictional heat can develop at the surface of a specimen during grinding and can cause alterations of the true microstructure. Wet grinding provides effective control of overheating. The abraded surface of a specimen may become embedded with loose abrasive particles during grinding. These particles may persist at the surface and appear to be nonmetallic inclusions in the polished specimen. The flushing action of water removes many of the loose particles that could otherwise become embedded.

**Effect of applied pressure:** The success of grinding depends in part on the pressure applied to the specimen. A very light pressure removes insufficient metal. Somewhat heavier pressure produce polishing, while still heavier pressure brings about the desired grinding action. Very heavy pressure results in nonuniform scratch size, deep gouges and embedded abrasive particles. Generally, firmly applied, medium to moderately heavy pressure gives the best results.
Grinding of a metallographic specimen is performed by manually holding the specimen with its surface against a grinding material. To establish and maintain a flat surface over the entire area, equal pressure is applied on both sides of the specimen. If grinding operation is interrupted, one has to re-establish contact with the grinding material carefully in order to resume the grinding in the plane already established.

**Hand Grinding**

A simple setup for hand grinding is provided by a flat hard surface, on which an abrasive sheet rests. The specimen is held by hand against the abrasive sheet as the operator moves the specimen in rhythmic style away from and towards him/her in a straight line. Heavier pressure is applied on the forward stroke than on the return stroke. Grinding is done wet by sloping the plate surface towards the operator and providing a copious flow of water over the abrasive sheet. After each grinding step, the specimen is cleaned with water to avoid any carryover of abrasive particles to the next step. Instead one can also use ultrasonic cleaning, which is an effective technique. Cleanliness of the operator's hands is as important as cleanliness of the specimen during whole process. Contamination of the grinding equipment by flying abrasive particles must be avoided.

**Grinding Mediums**

The grinding abrasives commonly used in the preparation of specimens are silicon carbide (SiC), aluminium oxide (Al₂O₃), emery (Al₂O₃ - Fe₃O₄), diamond particles etc. These are generally bonded to paper or cloth backing material of various weights in the form of sheets, disks and belts of various sizes. We have used silicon carbide paper sheets. Silicon carbide has a hardness of 9.5 on the Mohs scale, which is near the hardness of diamond. Silicon carbide abrasive particles are angular and jagged in shape and have very sharp edges and corners. Because of these characteristics, silicon carbide is a very effective grinding abrasive and is preferred to other abrasives for metallographic grinding of almost all types of metals.

2.3.1.3. **Polishing:** Polishing is the final step in the production of a surface that is flat, scratch free and mirror like in appearance. Before the final polishing is started, the surface condition should be at least as good as that obtained by grinding with a 400-grit
(25 microns) abrasive. The term mechanical polishing is frequently used to describe the various final polishing procedures involving the use of cloth-covered laps and suitable polishing abrasives. Polishing is done in a relatively dust-free area, preferably removed from the area for sectioning, mounting and rough grinding. Any contamination of a polishing lap by abrasive particles carried over from a preceding operation or by dust, dirt or other foreign matter in air cannot be tolerated. Carryover as a result of improper cleaning between final polishing steps is another prime source of contamination. It is just as important for the operator to wash hand meticulously as is to remove all traces of polishing abrasive from the specimen before proceeding to the next polishing operation. The specimen is cleaned carefully by washing under running water and swabbing with cotton.

**Disk Polishing**

The most common type of motor-driven polishing equipment is the disk polisher. The metallographic specimen is held by hand against a moving, fixed-abrasive polishing material supported by a platen. We have used a Buehler polisher provided with a disk in horizontal position. It has a lap with a rotating motion and the specimen is held on to it by hand, i.e., mechanically. The specimen is continually moved back and forth between the centre and the edge of the wheel, thereby ensuring even distribution of the abrasive and uniform wear of the polishing cloth. The correct amount of applied pressure is determined by experience; in general, firm hand pressure is applied to the specimen in the initial polishing step and is proportionally decreased with successively finer polishing steps. For very soft materials, pressure other than that from the weight of the specimen itself may be eliminated entirely in the last polishing operation. The specimen is preferably washed and swabbed in running water, rinsed with methanol that does not leave a residue and dried in a stream of warm air. Alcohol can usually be employed for washing when the abrasive carrier is not soluble in water.

**Polishing Cloth**

The requirements of any good polishing cloth include the ability to hold an abrasive, long life, absence of any foreign material that may cause scratches and absence of any
processing chemicals that may react with the specimen. We have used a nylon cloth with nap for polishing. These cloths are available with a contact adhesive on the back, which greatly simplifies installation on the wheel. After installation, the cloth is charged with the polishing abrasive [6].

Polishing Abrasives
Polishing usually involves the use of one or more of five types of abrasives: aluminium oxide (Al₂O₃), magnesium oxide (MgO), chromic oxide (Cr₂O₃), iron oxide (Fe₂O₃) and diamond compound. With the exception of diamond compounds, these abrasives are normally used in a distilled water suspension. But if the metal to be polished is not compatible with water, other suspensions such as ethylene glycol, alcohol, kerosene or glycerine may be used. Aluminium oxide (alumina) is the polishing abrasive most widely used for general metallographic polishing; we have used this as well. The alpha grade aluminium oxide is used in a range of particle sizes from 15 microns to 0.3 micron. For some hard materials, the 0.3 micron size is sufficient for a final polish. We have used 3 to 0.3 micron alumina solution. Rough polishing is usually done with the laps rotating at 300 rpm with 3 micron alumina solution. Then with time, lap speed is reduced as we reach up to the final polishing. In final polishing, 0.3 micron alumina solution is used.

2.3.1.4 Cleaning and Storage: After polishing, the specimen is cleaned. Rinsing is most frequently used and consists of holding the specimen under a stream of running water and wiping the surface with a soft brush or cotton swab. After cleaning, the specimen is dried rapidly by rinsing in alcohol, benzene or other low-boiling-point liquids and then placed under a hot-air drier for sufficient time to vaporize liquids remaining in cracks and pores. When polished and etched specimens are to be stored for long periods of time, they must be protected from atmospheric corrosion. Desiccators are the most common means of specimen storage, although plastic coatings and cellophane tape are also used sometimes.

2.3.1.5 Atomic force microscope (AFM) analysis: The polished plate surface roughness is confirmed by atomic force microscope (AFM) measurements carried out employing the CP-Research model from ThermoMicroscope, USA (working is discussed in the
Figures 2.1a and 2.2a show AFM images of polished iron and copper plate. Line analysis of these AFM images provides the surface roughness. Other information which can be obtained from AFM Line analysis are the following:

**Height profile plot:** It displays the vertical amplitude along a cross-section of an image.

**Average roughness ($R_a$):** The average roughness is given by the average deviation of the data from the average of the data. For a line containing $N$ data points

$$R_a = \frac{1}{N} \sum_{n=1}^{N} \left| z_n - \bar{z} \right|,$$

where $\bar{z}$ = mean $Z$ height.

**Root mean square roughness ($R_q$):** It is given by standard deviation of the data using

$$R_q = \sqrt{\frac{1}{N-1} \sum_{n=1}^{N} (z_n - \bar{z})^2}.$$

$R_q$ and $R_a$ are drawn from elementary statistics, but also have a basis in common experience. A surface considered rough has higher $R_q$ and $R_a$ values than a smooth surface. If the selected line in an image crosses a large peak or a pit, these values increase. Since $R_q$ contains squared terms, large deviations from the average $Z$ height are weighted more heavily than they are in the calculation of $R_a$, similarly small deviations are given less weight.

Surface roughness values obtained using an SPM are usually higher than as obtained using stylus or optical profilers. The reason for such higher values is that an SPM measurement includes high frequency surface roughness due to fine scale features. As stylus and optical profilers average over an area on the order of a micron, measurements made using these instruments lose high frequency contributions to surface roughness.

**Mean height:** This is given by the average height within the selected height profile.

$$\bar{z} = \frac{1}{N} \sum_{n=1}^{N} Z_n,$$

where $\bar{z}$ is mean height. It is used as a reference for $R_q$ and $R_a$ calculations.
**Median height:** This is the height value which divides the height histogram into equal areas. At the median value, 50% of the data points have higher value and 50% have lower values.

**R_{P.V.}:** It gives the maximum peak to valley distance within the selected height profile. It is given by the highest point (Peak) on the height profile minus the lowest point (Valley).

![Diagram (a)](image1)

![Diagram (b)](image2)
<table>
<thead>
<tr>
<th>Rp-v</th>
<th>Rms Rough (Rq)</th>
<th>Ave Rough (Ra)</th>
<th>Mean Ht</th>
<th>Median Ht</th>
<th>Peak (Rp)</th>
<th>Valley (Rv)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.751 nm</td>
<td>1.336 nm</td>
<td>1.118 nm</td>
<td>4.118 nm</td>
<td>4.654 nm</td>
<td>1.699 nm</td>
<td>-3.052 nm</td>
</tr>
</tbody>
</table>

Figure 2.1: (a) AFM image of the polished iron plate, 0.5μm × 0.5μm scan size (p. 43) (b) Height profile along white line marked in 2.1a (p. 43) and (c) Calculated parameters from height profile data.
Figure 2.2: (a) AFM image of the polished copper plate, 20µm × 20µm scan size (p. 44), (b) Height profile along white line marked in (a) as line 1, (c) Height profile along white line marked in (a) as line 2 and (d) Calculated parameters from height profile data of line 1 and line 2.

From figures 2.1c and 2.2d, we can see that the surface roughness is even less than 50 nm. So by polishing, we get very smooth surfaces, necessary for the experiment.
2.3.1.6 Plate mount

We need an arrangement to mount the metal plate and to connect it to the rest of the circuit for the electro-explosion experiment. For this purpose we have made a plate mount (Figure 2.3). It is a solid cylindrical copper block having four screws on its top surface to mount the plate and a side screw to connect it to the electronic circuit.

![Figure 2.3: Front and top view of the plate mount.](image)

2.3.2 Needle electrode

This is another electrode in the needle-plate geometry. As we have discussed earlier, the current density is a key factor for the explosion, hence the tip diameter is a very important parameter in the explosion experiment. Smaller the tip diameter, larger will be the current density. Therefore micron sized tips (needle) are used in the experiments. These tips are prepared by electrochemical etching. We have designed an arrangement called "Cap" to prepare several needles simultaneously.

**Cap construction:** This is constructed from the material brass. A circular piece measuring 3.6 cm in diameter and 8 mm thickness is cut from a brass rod. Holes with 1 mm diameter are then fabricated in circular geometry of diameter 2.4 cm to hold the wires to be etched (one of the electrode for electrochemical etching). Tapered screws are required from the sides to hold these wires. For this purpose, holes are made in the cap.
from the side corresponding to each hole in the circular geometry. A large hole measuring 9 mm in diameter is contrasted in the middle to hold another electrode for electrochemical etching. The central electrode is also made up of brass. A Teflon washer separates the second electrode from the cap. Top and front view of the “Cap” is shown in figure 2.4.

![Front view](image1)

![Top view](image2)

Figure 2.4: Front and top view of the designed etching Cap.

This cap is placed on the top of a beaker containing the etching solution. A potential difference is applied by connecting the electrodes to a voltage source keeping the wires to be etched at positive polarity. Regulated DC power supply is used for etching. After electrochemical etching, the wires are cleaned in an ultrasonic bath and stored in a clean container. The tip diameters are measured using a scanning electron microscope (SEM) and an optical microscope. The crystallinity of the wires used for etching is checked by X-ray diffraction while their chemical purity is determined by EDX measurements. Electrochemical etching solution depends on the wire to be etched. These are discussed below:
2.3.2.1 Tungsten wire etching: Micron sized tungsten tips are prepared by electrochemical etching of 0.14 mm diameter tungsten wire in a KOH solution. Before electrochemical etching, the wire insulation layer is removed by placing them in sodium hydroxide (NaOH) solution (10% by weight) for one hour. Then wires are electrochemically etched using 20 ml KOH solution (0.28% by weight) and a potential difference of 2 volt is applied between the electrodes. An etch time of 7 hours is sufficient to get tips of size of the order of a few μm. The tip diameter is decided by etching time, applied voltage and solution concentration. With the help of the cap designed for this purpose, many tips can be prepared simultaneously. After etching, the wires are cleaned in an ultrasonic bath to remove dust from the tips and then cut with a fine cutter. These tips are pasted on a clean glass slide with the help of double sided tape for protection and kept in a clean container. Figure 2.5 shows scanning electron micrograph (SEM) of an 1- micron sized tungsten tip.

![Figure 2.5: Scanning electron micrograph (SEM) of one micron size tungsten tip.](image)

2.3.2.2 Iron wire etching: Micron sized iron tips are prepared by electrochemical etching of 0.37 mm diameter iron wires in FeSO₄ solution using a small amount of hydrochloric acid for pH control. For this, the FeSO₄ solution is prepared by dissolving 1 gm FeSO₄ in 100 ml distilled water and adding 300 μl of 1: 3 solution of HCl and distilled water. The wires are electrochemically etched using this solution at a potential difference of 5 volts between the electrodes. A 20- minutes etching is sufficient to get tips of size of the order of a few μm. The rest of the procedure is same as that for the tungsten tips.
2.3.2.3 Copper wire etching: Micron sized copper tips are prepared by electrochemical etching of 0.37 mm diameter copper wire in a KOH solution. For this purpose, 5% by weight of KOH solution is prepared. The wires are then electrochemically etched using this solution at a potential difference of 5 volt applied between the electrodes. Here too, a 20- minutes etch time is sufficient to get tips of the order of a few μm. The rest of the procedure is same as for the tungsten tips.

2.3.2.4 Other wires: Thick copper, iron and tungsten wires and other thin metal wires have been purchased from Goodfellow, UK, and used directly for the experiments.

2.3.3 Medium: In general an inert atmosphere is suitable as a medium, one which does not interact with the plasma formed during the explosion, e.g. butanol, heavy oils, etc. Experiments have been reported in the literature, which suggest that the initial stage of discharge is same in water and air [7]. So we have used water as a medium to carry out the explosion. Water helps to collect debris left on the metal plate following explosion. This debris consists of nanoparticles of the material exploded. It also helps in better observation of the modified surfaces. We have also used air as a medium in some specific experiments.

2.3.4 Reactor vessel: 250 ml borosil glass beaker is used as a reactor vessel for these experiments.

2.3.5 Tip approach system: The entire study of electro-explosion hinges on what can be termed as the single wire single explosion (SWSE) experiment. For a good experiment, fine contact between two electrodes is required. To achieve this, we need a special arrangement to bring the tip close to the stationary plate in a controlled fashion. For this purpose, we have designed a micrometer controlled tip-approach system. With the help of this system, a tip is brought in contact with the plate. A tip approach sensor is attached with this arrangement. The tip approach sensor measures the resistance at the tip-surface interface and an electronic sound generator is activated as soon as the resistance is below 0.2 ohms. Then the tip approach is stopped.
2.3.6 **Power supply:** Following the electrodes and the approach system, the energy source is of prime importance. Our energy source is different from the traditional capacitor banks used to discharge at high voltages. For the energy requirement of the explosion experiment, we have used a combination of 12 volt batteries (Panasonic, Valve regulated lead-acid battery (12V, 42 Ahr/20 hr)). All the experiments are carried out in the voltage range 12-48 V DC. We thus work at low voltages, which is the novelty of the needle-plate system.

2.3.7 **Connecting wires:** Since the technique used is electro - explosion of wires, we must choose suitable wires for the circuit, which can deliver electrical energy to the system for explosion. Thick wires can pass more current. So, thick high conducting silver and copper metal wires are used. When a large current passes through the thick wires to the thin sample wires, the current density through the thin wires becomes very high. So thick copper or silver coated copper wires measuring 241 cm in overall length and 1.5 mm in diameter are employed to carry the current to the needle-plate arrangement.

2.3.8 **Toggle switch:** After making a fine contact between the two electrodes, we need some means to connect these two electrode systems to an applied voltage in the shortest possible time. For this purpose, a toggle switch is used in the circuit. It is activated to connect the needle-plate arrangement to a battery bank. On sudden application of the voltage, the wire explodes at the contact point. As the initial spark breaks the circuit with considerable tip destruction on a microscopic scale, contact between electrodes breakdown after one spark. So the multiple sparks are eliminated and yields data corresponding to a single spark (the SWSE experiment).

2.3.9 **Digital oscilloscope:** A 0.5 Ω, 200 W resistor in series is used in the circuit to measure the current through the wires. The voltage generated across the resistor is recorded employing a digital oscilloscope (model Tektronix TDS 350) with a base time resolution of 2.5 ns. It is interfaced with a computer to get the current data whose time
evolution is employed for detailed analysis. Figure 2.6 shows the experimental arrangement.

1- Micrometer controlled tip approach system
2- Fe needle
3- Fe plate
4- Reactor vessel

Figure 2.6: The setup for SWSE experiments.

2.4 Experimental Observations
We have performed experiments in the needle-plate geometry using polished iron and copper plates and micron sized iron and copper needles. The plate is mounted on the plate mount and tip is approached towards the plate with the help of the controlled tip approach system. As the tip approach sensor records first contact, the approach is stopped. The toggle switch is activated next to connect this system to the battery bank and explosion takes place at the contact point between the two electrodes. During the experiment, current flowing through the needle-plate geometry is recorded by the digital oscilloscope connected in the circuit and its data is taken via an interfaced computer.

2.4.1 Optical Micrograph
During the explosion, light is emitted at the explosion point. This is recorded using a Mercury Pocket Camera having a memory of 64 Mbits with (640 × 480) VGA resolution. Figures 2.7a and 2.7b show optical micrographs of light emission during explosion of an iron needle (tip diameter = 30 μm) on an iron plate (Fe/Fe_{30p.48w} system, where w stands
for water medium, p for plate at positive polarity, 48 denotes applied voltage) and copper needle (tip diameter = 125 μm) on a copper plate (Cu/Cu$_{125p_{48w}}$ system) keeping plate at 48 V positive compared to the needle in water medium. From the micrographs, we can see that a characteristic colour is emitted which is determined by the material used, i.e., red-orange part of the visible spectrum in Fe/Fe$_{30p_{48w}}$ while blue-green part in the Cu/Cu$_{125p_{48w}}$ system. These are evidence of plasma formation as the electro-explosion process is accompanied by emission of visible light.

![Optical micrographs](a) (b)

Figure 2.7: Optical micrographs of light emission during explosion in (a) Fe/Fe$_{30p_{48w}}$ system and (b) Cu/Cu$_{125p_{48w}}$ system.

2.4.2 Oscilloscope data

To understand how well the needle-plate exploding system mimics the traditional wire explosion phenomena [8-15], we have studied the time evolution of the process. In figure 2.8, we show a plot of the current flowing through the needle-plate configuration during the explosion event for exploding iron wire on an iron plate (Fe/Fe$_{30p_{48w}}$ system) recorded using a digital oscilloscope. This plot is a real-time map of the SWSE event.
Following closure of the toggle switch, the current increases to show a maximum after which it drops to a low value (first current peak), increasing again, peaking and reducing to a stable value after some time (second current peak). The stable current value is maintained for a long time after which the current goes to zero. It shows similar behaviour as is observed in traditional geometry (already explained in chapter 1, section 1.1.2).

The first current peak represents heating, melting and then explosion, i.e., evaporation of the wire following toggle switch activation \((t = 0)\), similar to reports by other workers employing the traditional geometry \([8-15]\). The resulting gas is momentarily at very high density and hence electrons do not acquire sufficient energy to produce ionization by impact. Hence current continues to flow at a constant, low rate restricted by a limited supply of charge carriers, representing a dwell time (or dead time) between the two current peaks \([9,13,14,15]\). The high gas density is short lived as pressure drops, increasing the mean free path for the electrons, resulting in ionization by impact with attendant avalanching. This gives the second stable current peak, which can be called restrike or reignition \([8,9]\).
According to published literature, at this point, the formation of a high density vaporized gas core surrounded by low-density ionized corona starts. Compression of coronal plasma by self-induced magnetic field produces shock waves, which propagate through the plasma [16]. The current flows in the circuit as long as the two electrodes are in contact and drops to zero as contact breaks. In figure 2.9, we show the current plot for Cu/Cu_{125p.48w} system having similar behaviour as is observed in the case of the iron system.

![Current plot](image)

**Figure 2.9:** Time evolution of current flowing through the needle-plate geometry in the Cu/Cu_{125p.48w} system.

### 2.5 Discussion and Conclusion

From figures 2.8 and 2.9, we can see that the current behaviour during SWSE experiment in the needle-plate geometry is similar as has been observed by other workers who have employed a traditional geometry [8]. Also the characteristic light emission during explosion confirms the plasma formation (Figures 2.7a and 2.7b). As an outcome of this experiment, we have indeed collected nanoparticles of Fe in the water medium of sizes less than 15 nm as indicated by disappearance of the ferromagnetic Mössbauer signal [17] These observations confirm that we have established the electro-explosion phenomena in the needle-plate geometry.
References

[6] http://www2.arnes.si/~sgszmera1/others/help/m-polish.html#7#7