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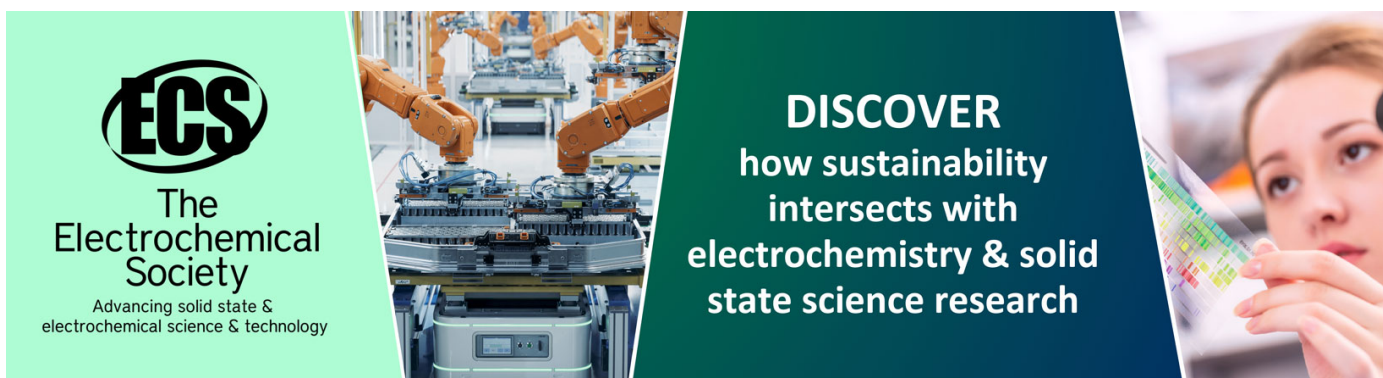
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To cite this article: Luna Basil Hazime and Zoory Muayyed Jabar 2021 *J. Phys.: Conf. Ser.* **1963** 012147

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Analysis of the Focusing Ion Beam Microscope Ion Mirror Method for Studying Influence of the Measuring Chamber

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Abstract. Using the ion mirror image (IMIM) technique, a focused ion beam (FIB) microscope is used to investigate the charging phenomenon of Polymethyl methacrylate (PMMA). The effect of the experimental chamber's finite size is studied using classical scattering theory. We test the widely held belief that the method tests the radius of curvature of the equipotential by performing a thorough calculation of the Ion orbits in the presence of extended sources. We show that, near to the chamber walls, the field lines bend until they are normal to the walls, the field is small, and the ion orbit is unaffected, as well as how to get rid of the "mirror effect".

1. Introduction

The ion mirror effect technique can be used to classify insulating materials using a Focused Ion Beam (FIB) microscope [1-5]. It uses a mono-energetic ion beam of 20 to 30 keV to inject a 'point' charge under the surface of the sample when scanning in the secondary emission mode. Then, a lower-energy probing ion (5keV) produces an ion mirror image of the microscope chamber on the FIB screen, since the probing ions are repelled by the injected charge and do not penetrate the sample surface. The mirror image system (IMIM) was proposed many years ago[6]. It has also been used to assess how much charge is trapped in dielectric samples as well as the potential distribution[7, 8]. The aim of this research is to understand the physical processes involved in ion dispersion in IMIM by investigating the direction of an ion moving in an electrostatic field.

2. Principal procedures

The effect of the measuring chamber is not discussed by most scholars, and it is expressly ignored by others [9]. The scattering model for calculating an ion's path in space has been tweaked to explain such an effect. The chamber's impact can be estimated as follows. Figure 1 shows a fictional spherical chamber with a radius (WD) in place of the real chamber.



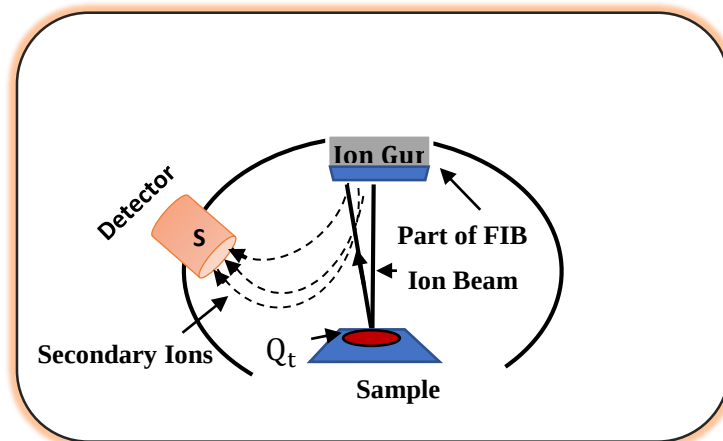


Figure 1: A Sketch in a (FIB) chamber showing the Ion Mirror Effect (IME).

The scattering method involves injecting a large volume of positive trapped charge into a dielectric sample at a very high voltage, followed by scanning the sample with a beam of positive ions at a low imaging voltage. The ion can deviate from its direction as a result of the trapped charge's existence. Ions with a greater angle of deviation than the others will collide with the FIB's inner surface, resulting in secondary ions. The detector will absorb these ions, resulting in a mirror image, as seen in Figure 1. As a result, we assume that the charge in the insulating sample is a point charge Q_t , and that the electric potential $V_{(r)}$ ((r)) is given by the following equation;

$$V_{(r)} = \frac{Q_t}{k r} \quad (1)$$

Where $\kappa = 1/[2\pi\epsilon_0(\epsilon_r + 1)]$, (r) is distance from a source point charge .

Rutherford scattering produces hyperbolic orbits as a result of this Coulomb potential [10, 11]. We also take advantage of the fact that the ion orbit in the exit plane of the FIB optics basically coincides with its asymptotes at the start and end of the actual flight path.

The distance of closest approach D in a head-on collision between the Ion beam and the fixed charge is given by

$$V_{acc} = \frac{k}{D} \quad (2)$$

And the radius of closest approach, r_{min} , is defined in terms of this quantity[12]

$$r_{min} = \frac{2V_{sc}C.P^2}{\kappa Q_t[e-1]} \quad (3)$$

The eccentricity e of the orbit is given by the following relationship[12];

$$e = \left(1 + \left(\frac{2V_{sc}C.P}{kQ_t}\right)^2\right)^{1/2} \quad (4)$$

Where $c.p$ is the collision parameter, which can be calculated using IMIM experiments, which will be addressed in more detail later. The scattering angle (γ) denotes the distance between two points (angle between the asymptotes of probing ion path before and after it is scattered). In addition, from Figure 2, we can deduce:

$$\tan\left(\frac{\pi}{2} - \frac{\gamma}{2}\right) = \frac{b}{a} = \cot\left(\frac{\gamma}{2}\right)$$

$$\gamma = 2\cot^{-1}\sqrt{(e^2 - 1)} \quad (5)$$

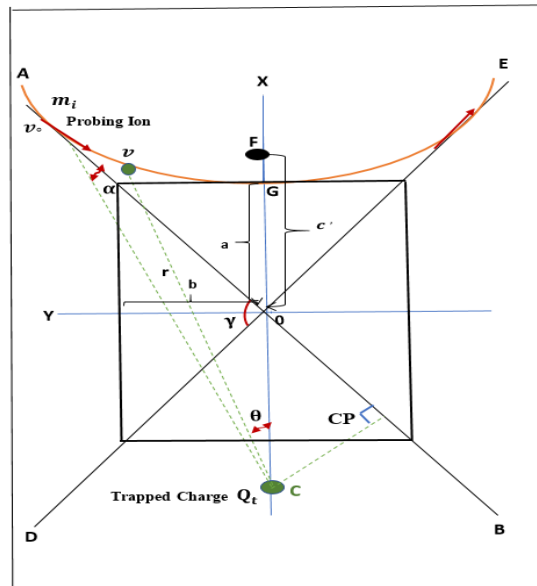


Figure 2: Geometrical illustration for the incident ion in an FIB chamber.

Figure 3 shows the geometrical configuration of the IMIM. Ions released in the direction AF are deflected by the potential of the charge Q trapped at point O in the sample before hitting point C on the objective lens pole's exit plane. The distance between point C and the FIB's optical axis is $AC=d$, where d is calculated using a distinguishing feature from the objective lens pole's exit plane. In Figure 3, OE represents the image of the chosen distinctive function, which is equal to r_o , and can be determined directly from the mirror image. We can find the distance between the reflected-back probing ion and the optical axis of the (FIB) column, known as the transverse distance, as well as the equation of working distance, using simple trigonometry.

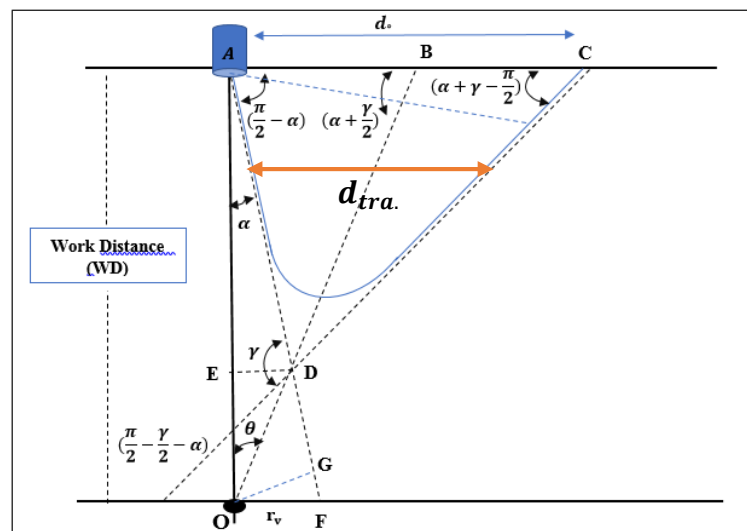


Figure 3: A diagram of the values of the probing ion angles in trigonometry.

From ΔAOD one can get;

$$\frac{\overline{OD}}{\sin(\alpha)} = \frac{\overline{WD}}{\sin(\frac{\pi}{2} + \frac{\gamma}{2})} \quad (6)$$

so;

$$\overline{OD} = WD \frac{\sin(\alpha)}{\cos(\frac{\gamma}{2})} \quad (7)$$

In similar way, one can get the following relation from ΔODE ;

$$\frac{\overline{ED}}{\sin(\frac{\pi}{2} - \frac{\gamma}{2} - \alpha)} = \frac{\overline{OD}}{\sin(\frac{\pi}{2})} \quad (8)$$

By substitute the value of equation (7) into an equation (8), and opening the sine angle, we get the following equation;

$$\overline{ED} = WD \frac{\sin(\alpha)}{\cos(\frac{\gamma}{2})} \cos\left(\frac{\gamma}{2} + \alpha\right) \quad (9)$$

From ΔAOB the following formula may obtain;

$$\frac{\overline{AB}}{\sin(\frac{\pi}{2} - \frac{\gamma}{2} - \alpha)} = \frac{\overline{AO}}{\sin(\frac{\gamma}{2} + \alpha)} \quad (10)$$

$$\overline{AB} = WD \cot\left(\frac{\gamma}{2} + \alpha\right) \quad (11)$$

Now for the triangle BCD and ABD the following expression can be formulated respectively;

$$\frac{\overline{BC}}{\sin(\frac{\pi}{2} - \frac{\gamma}{2})} = \frac{\overline{BD}}{\sin(\alpha + \gamma - \frac{\pi}{2})} \quad (12)$$

$$\frac{\overline{AB}}{\sin(\frac{\pi}{2} - \frac{\gamma}{2})} = \frac{\overline{BD}}{\sin(\frac{\pi}{2} - \alpha)} \quad (13)$$

By substitute the equation (11) and the value of $\overline{BD}$ from equation (12) in to equation (13), so we get this formula;

$$WD \frac{\cot(\frac{\gamma}{2} + \alpha)}{\sin(\frac{\pi}{2} - \frac{\gamma}{2})} = \overline{BC} \frac{\sin(\alpha + \gamma - \frac{\pi}{2})}{\sin(\frac{\pi}{2} - \frac{\gamma}{2})} \quad (14)$$

$$\overline{BC} = WD \cot(\frac{\gamma}{2} + \alpha) \left[\frac{-\cos(\alpha)}{\cos(\alpha + \gamma)} \right] \quad (15)$$

Because we have the following formula $\overline{AC} = \overline{AB} + \overline{BC}$ and $(\overline{AC} = d_{tra.})$ Therefore, we can conclude from that;

$$d_{tra.} = WD \cot\left(\frac{\gamma}{2} + \alpha\right) \left[1 - \frac{\cos(\alpha)}{\cos(\alpha + \gamma)} \right] \quad (16)$$

From equation (16) we can find the angle (γ) described by;

$$d_{tra.} - WD \cot\left(\frac{\gamma}{2} + \alpha\right) \left[1 - \frac{\cos(\alpha)}{\cos(\alpha + \gamma)} \right] = 0 \quad (17)$$

Finally, the image of distinctive feature $\overline{OF} = r_v$, from Δ AOF can be formulated to be as in the following form;

$$r_v = WD \tan(\alpha) \quad (18)$$

The collision parameter C.P is given by

$$C.P = r_v \cos(\alpha) \quad (19)$$

And, finally, the typical expression that defines the electric potential at any point located at a distance (r) from a source point charge is given by Eq. (1) We can be expressed (r) as the following $r = \sqrt{x_i^2 + y_i^2}$ then the above equation become;

$$V(x_i, y_i) = \frac{Q_t}{k \sqrt{x_i^2 + y_i^2}} \quad (20)$$

When ($x_i = 0$), equation (20) turns into the following form;

$$V_{(y_0)} = \frac{Q_t}{k y_0} \quad (21)$$

All points (x_i, y_i) having the same potential $V_{(y_0)}$ can be found from the following;

$$x_i = \pm \sqrt{\left(\frac{Q_t}{k V_{(y_0)}}\right)^2 - y_i^2} \quad (22)$$

In fact, it is an equation of circle whose center at the origin and its radius is y_0 . Thus, we can deduct from this equation the equipotential surface see Figure 4.

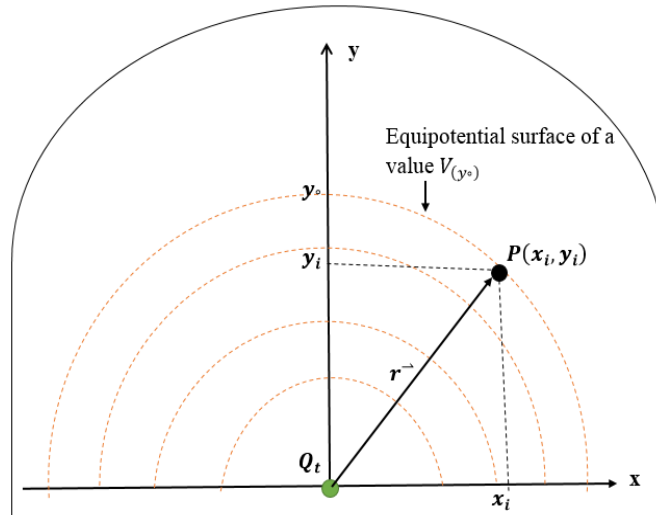


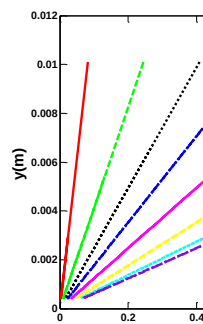
Figure 4: Representation for equipotential surfaces deduced from trapped charge located at the origin.

3. Results and discussion

In this section we will study the influence of the working distance. Figure (5a) shows a lot of ion mirror images that we obtained from reference[13]. According to this reference, a sample (PMMA) is

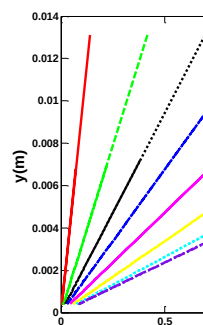
irradiated with an ion beam of a potential $V_i=30\text{kV}$ for 5 minutes over an area of radius $\approx 0.457\text{mm}$ the measured dielectric constant for this polymer material is (2.6), hence the sample acquired trapped charges of amount (508 pC). Wherefore, at different working distance (10, 13, 17, 22, 27 and 30mm) at ($V_{sc}= 6\text{ kV}$) these images are taken. Figure (5b) shows the stimulation for incident ion pathways that correspond to each selected image at various incident angles (α).

Many important conclusions can be drawn from the simulation graphs; however, as the incident angle ($C.P= v_r \cdot \cos\alpha$) increases, the scattering angle (γ) for paths belonging to the same image decreases. Since the Coulomb force between the incident ion and the trapped charges on the surface is inversely proportional to the squared distance, this is a natural occurrence. As (α) increased for a direction with ($WD=10\text{mm}$), the distance between the trapped charge and the incident ion increased. As a result, we can assume that the external ions in the scanning beam scan distant regions from the room's ceiling, allowing us to see a wide area of the chamber clearly, while the internal ions reach adjacent areas, resulting in a narrower field of vision than the previous one.



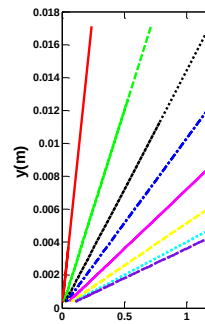
(a)

(b)



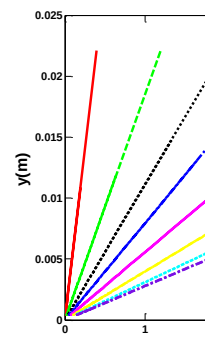
(a)

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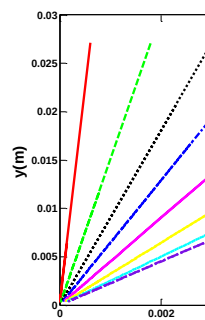
(a)

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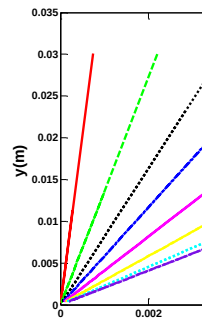
(a)

(b)



(a)

(b)



(a)

(b)

Figure 5 : (a)IMI recorded at different working distances with $V_i = 6KV$, [13]
 (b) The simulated ion pathways that lead to them.

Another inference drawn from Figure 5 is that the scattering angle (γ) for paths with the same deviation angle (α) decreases as the working distance increases, as shown in table 1. Indeed, this explains why these images tend to deteriorate as the working distance increases. As a result, as the working distance increases, so does the duration of the raster on the sample. As a result, the magnification of these images appeared to be increasing in accordance with the equation ($M = L_{Screen}/L_{Sample}$).

Table 1. Variation of scattering angle (γ) and polar angle (θ) of the probing ion paths have a same incident angle ($\alpha=0.01$) with different working distance (WD).

Work Distance(WD) (mm)	Scattering Angle (γ)	Polar Angle (θ)
10	$\gamma = 178.399^\circ$	$0.8201 \leq \theta \leq -0.8201$
13	$\gamma = 177.842^\circ$	$1.0690 \leq \theta \leq -1.0690$
17	$\gamma = 177.1782^\circ$	$1.4009 \leq \theta \leq -1.4009$
22	$\gamma = 176.3487^\circ$	$1.8156 \leq \theta \leq -1.8156$
30	$\gamma = 175.0225^\circ$	$2.4788 \leq \theta \leq -2.4788$

As a result, we can deduce from Figure 6 that as the working distance increases, a greater region of the chamber will be scanned, and vice versa. As mentioned in the reference [14].

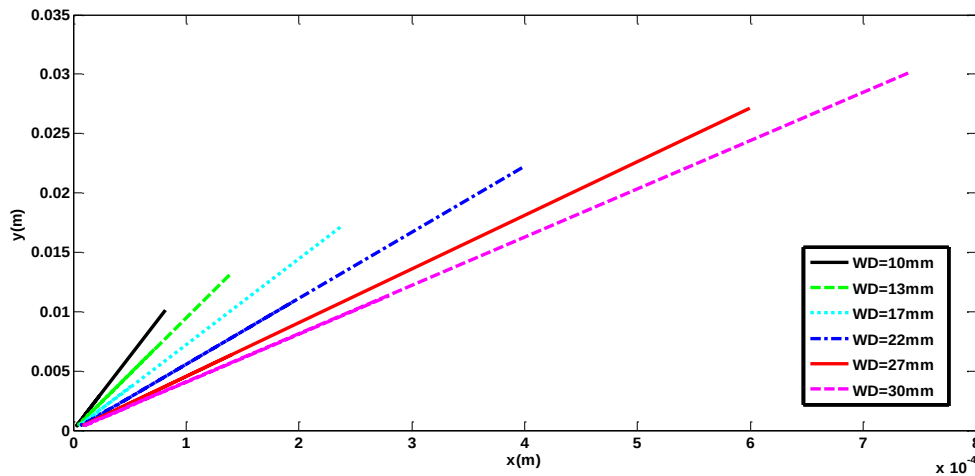


Figure 6: The incident ions paths have a same incident angle ($\alpha=0.01^\circ$) and different working distance.

Figure 7 depicts the variance of incident angle for various working distances as a function of transverse distance, as discussed in the previous debate. The three paths would clearly cross the column at $(0.167^\circ, 0.186^\circ, 0.199^\circ)$ respectively. For working distances of 30mm, 27mm, and 22mm, respectively. As a result, an ion mirror image loses a lot of details due to the short working distance.

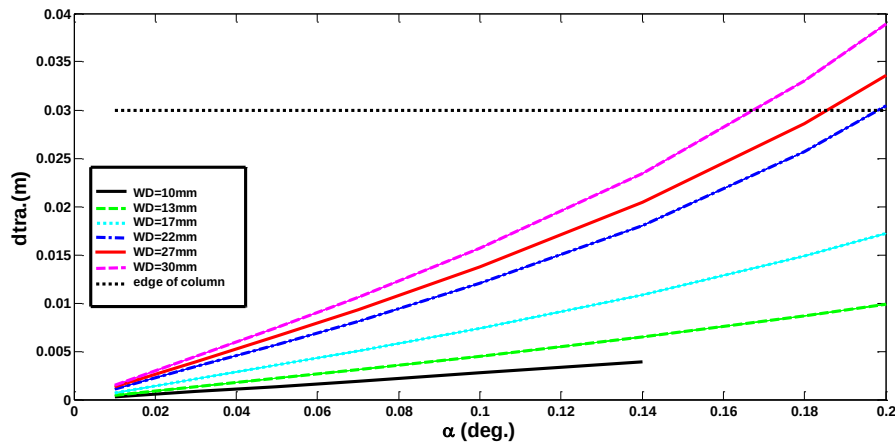


Figure 7: Transverse distance variation with incident angle at various working distances.

Figure 8 shows the variances of the incident angle as a function of the scattering angle at various working distances. The difference in the scattering angle corresponding to the incident angle leads one to believe that increasing the work distance causes tracks of the same slope to deflect. This finding is consistent with the two previous ones.

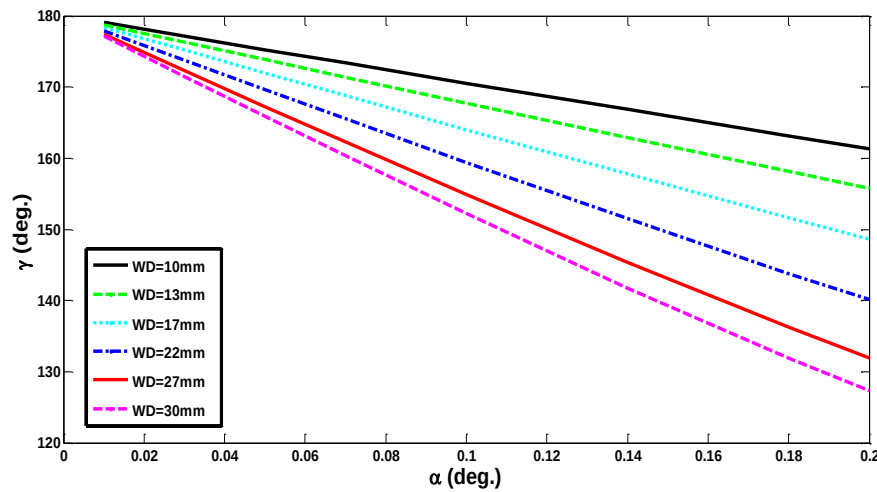


Figure 8: Scattering angle variation with incident angle at various working distances.

Figure 9 depicts the (x,y) location of path reflection points for various incident angles. The following alpha values are used to describe these paths: 0.01° , 0.03° , 0.05° , 0.07° , 0.1° , 0.14° , 0.18° , and 0.20° . To build the curves in Figure 9, two different working distance values, 10 and 30 mm, were chosen. As long as (α) rises, it can be shown that the horizontal change of this stage is more important than the vertical shift.

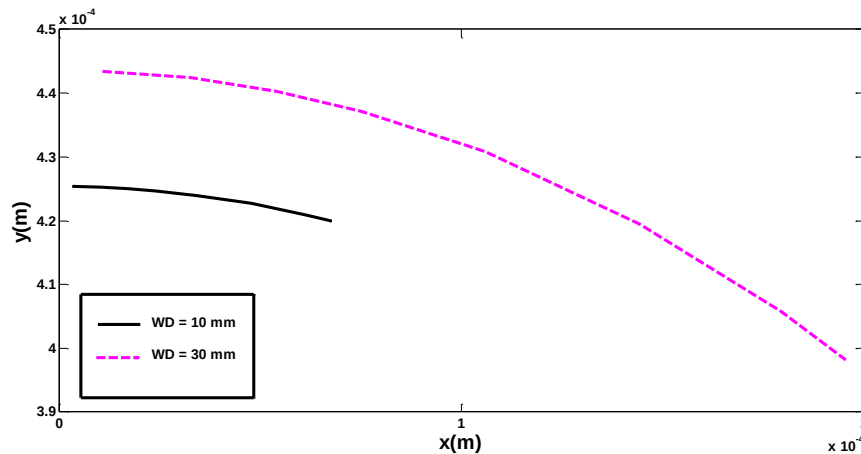


Figure 9: Inflection point vertical coordinates as a function of horizontal coordinates for paths of varying inclination angles.

4. Conclusions

It is clear; there are many benefits to use an ion beam focusing device instead of an optical microscope. According to the presented simulation mode can be deduced the equipotential surfaces of these dielectric materials with good accuracy. It is frequently possible to locate the reflected-back probing ions using the mathematical presented in this paper. As a result, additional evidence for the white and dark areas, which are typical in any ion mirror image, can be obtained. Furthermore, it is simple to determine which direction probing ions will take to penetrate the column diaphragm or hit the detectors. In conclusion, the working distance in FIB should be larger distance to avoid the damage of the sample.

5. References

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Acknowledgments

The authors would like to thank Mustansiriyah University (www.uomustansiriyah.edu.iq) Baghdad - Iraq for its support in the present work.