Measurements of the electron beam size at the absorber prototype test bench

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1. Introduction

Project X is a proposed accelerator system that will provide intense beams of protons. One of the main peculiarities of Project X is that it is supposed to deliver beams of protons with different structure almost simultaneously to multiple users (Figure 1).

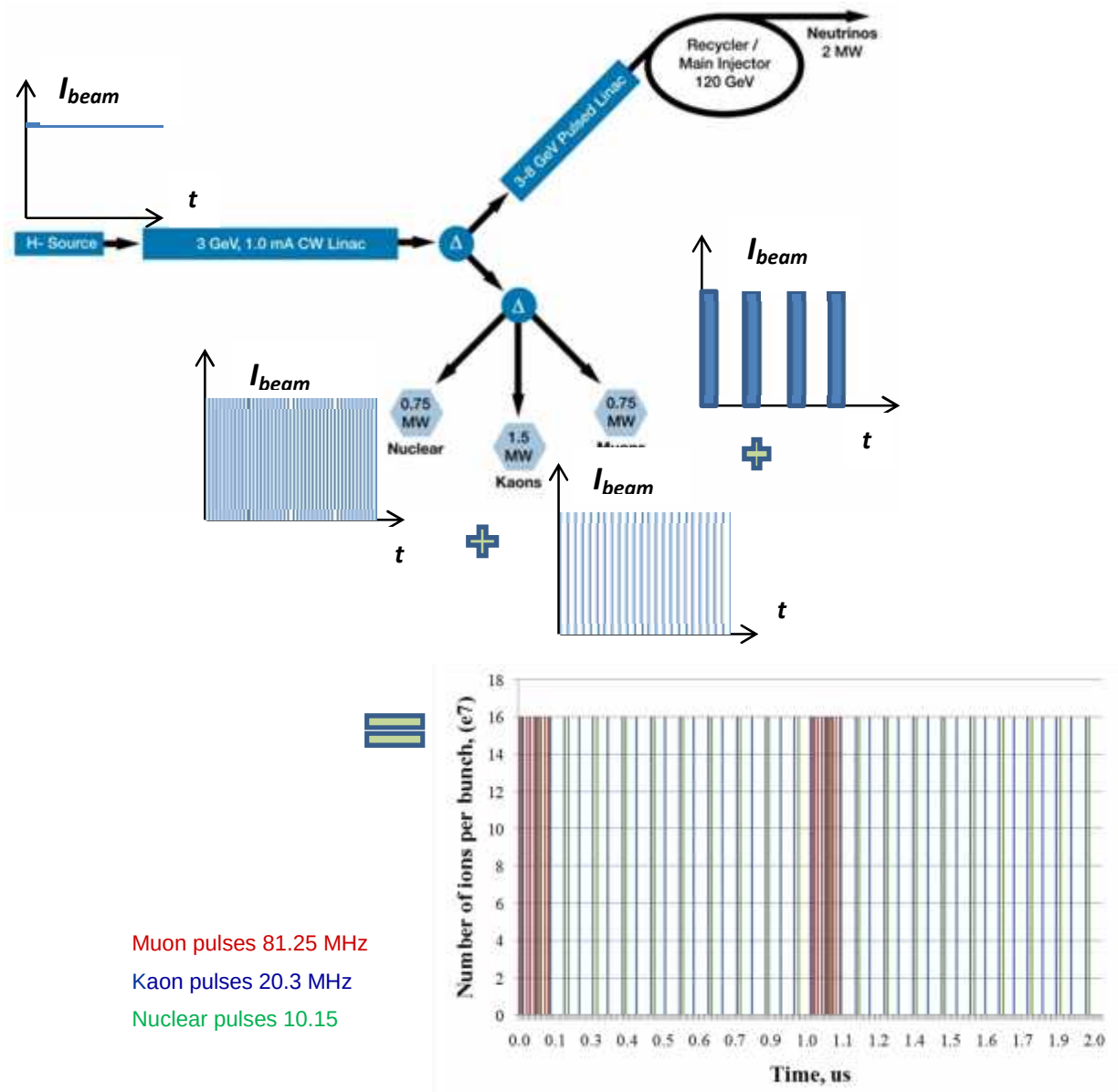

Figure 1. Scheme of Project X. Delivery of different beams to multiple users. Proton beams of different structure will be used to produce intense beams of muons, kaons, neutrinos and rare nuclei for various experiments.

To obtain such proton beams at the same time, it needs an initial beam with an arbitrary structure. PXIE (Project X Injector Experiment) [1] is created to verify the operation of such a system and

to test Project X front end main components (Figure 2). The MEBT (Medium energy beam transport) is a part of PXIE. The so-called chopping system (Figure 3) was designed to remove particular bunches from the beam. It will be placed in the MEBT.

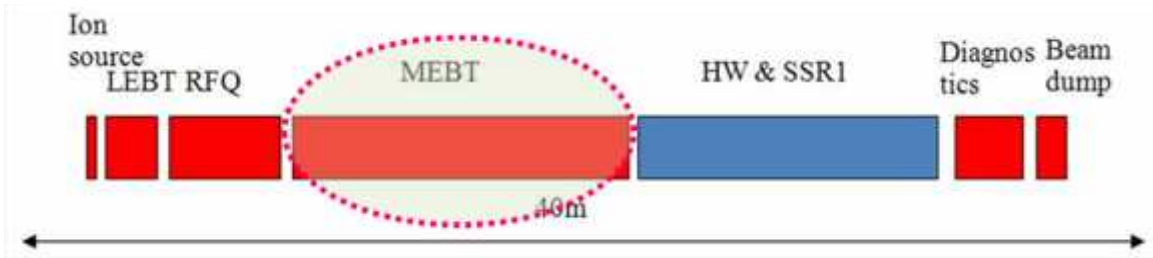

Figure 2. PXIE schematic layout.

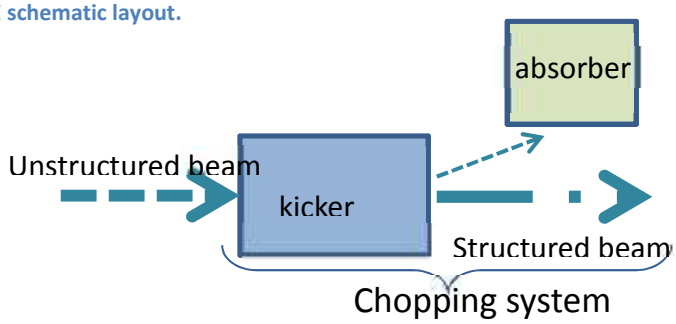

Figure 3. Chopping system.

The chopping system at MEBT (Figure 3) will operate with the 2.1 MeV H^- beam. It consists from the kicker, which will remove particles from the 162.5MHz CW beam, and the absorber, where almost 80% of the beam will be deposited. Thus, the absorber should withstand high power focused into a spot of the order 2mm rms radius. Partially, this problem may be eliminated by placing the absorber at a shallow angle with respect to the beam (Figure 4). With a 30mrad angle of incidence the power density at the absorber is 25W/mm2.

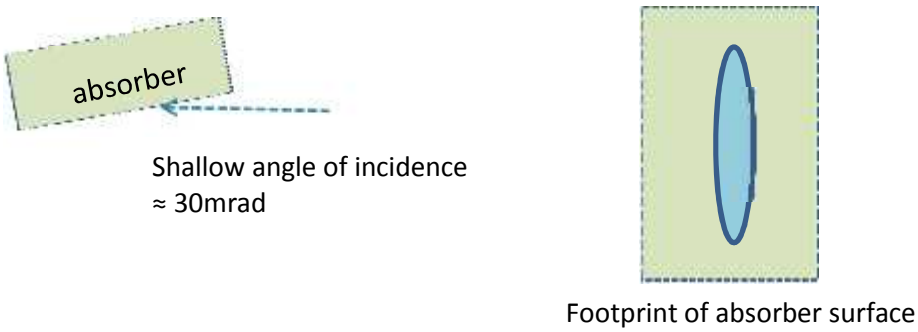

Figure 4. Absorber will operate at a shallow angle with respect to the incident beam.

In such conditions different difficulties may occur: thermal load, outgassing, blistering and sputtering [2].

The material of the absorber was chosen to diminish all of these effects. It is made from Mo TZM (a dispersion-strengthened alloy of Molybdenum, containing small additions of Ti and Zr), which is a blistering resistant material, has high melting and crystallization points, high conductivity and good tension resistance properties.

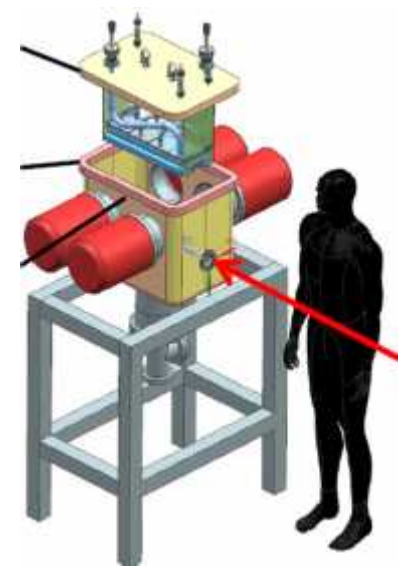

Figure 5. Conceptual design of the absorber by C. Baffes.

The absorber will operate at very high temperature (~1000°C) and will have a water cooling system (Figure 5). The thermal load of the absorber could be tested with an electron beam. To test the absorber prototype a test bench was assembled.

2. Description of the measurements

2.1. Scheme of the absorber prototype test bench and description

The test bench consists from the electron gun, the focusing solenoids, the correctors, the chamber with the window, where the absorber prototype will be installed and the collector. The correctors, that are called X and Y correctors, can move the beam inside the test bench in two different directions, and the angle between these directions should be defined.

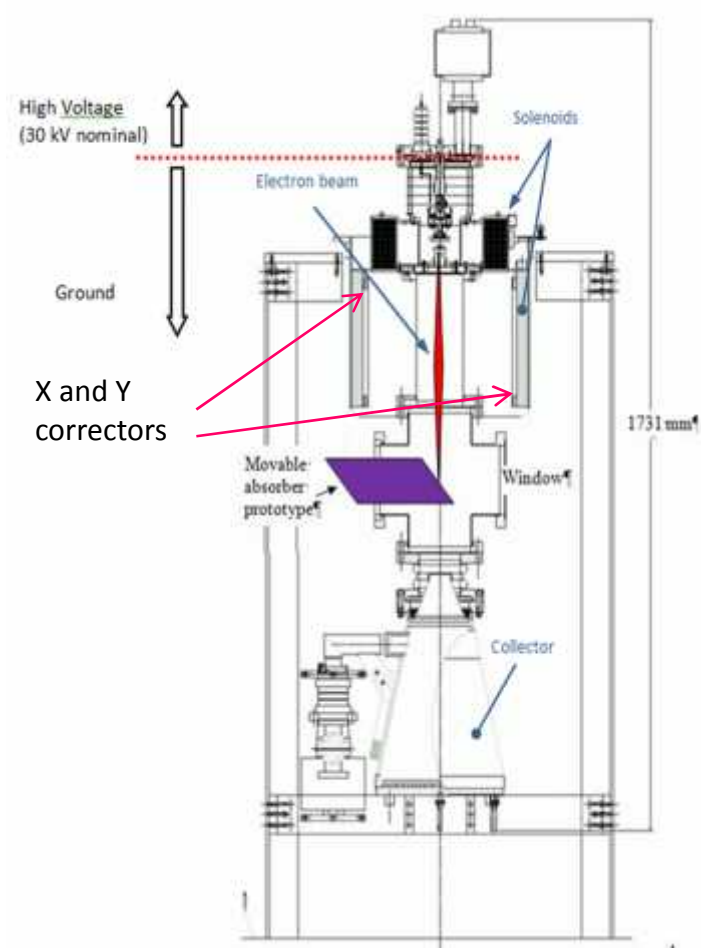

Figure 6. Drawing of the test bench. Main components: the electron gun, the focusing solenoids, the X and Y correctors, the chamber where the prototype will be placed and the collector.

2.2. Nominal parameters of the beam at the test bench

To simulate the thermal load of the absorber prototype, the following parameters of the electron beam were chosen:

- Operational voltage 29 kV
- Beam current 180 mA
- Rms radius: 2 mm

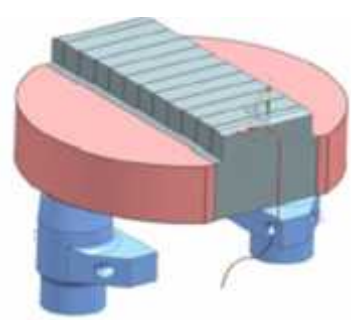

Figure 7. Absorber prototype design by C. Baffes

In order to obtain the same power density at the absorber prototype (25W/mm^2), it will be placed at a 0.12 rad angle with respect to the beam.

The absorber prototype is shown in Figure 7. It is one quarter of the actual absorber and it will be water cooled similarly to the full size absorber.

2.3. Examples of beam simulations with SAM

The propagation of the electron beam in the test bench was simulated by a program called SAM [3]. Preliminary calculations showed that the electron beam can be obtained with the given parameters of the test bench. Using focusing solenoids, we can prepare a 2 rms radius electron beam at the absorber prototype surface.

An example of such simulations is shown on Figure 8 [4]. Parameters of the beam and the currents in the focusing solenoids for this particular simulation:

- Voltage 30 kV
- Current in the focusing solenoid that is closest to the gun is 1.9 A
- Current in the second long solenoid is 5.3 A

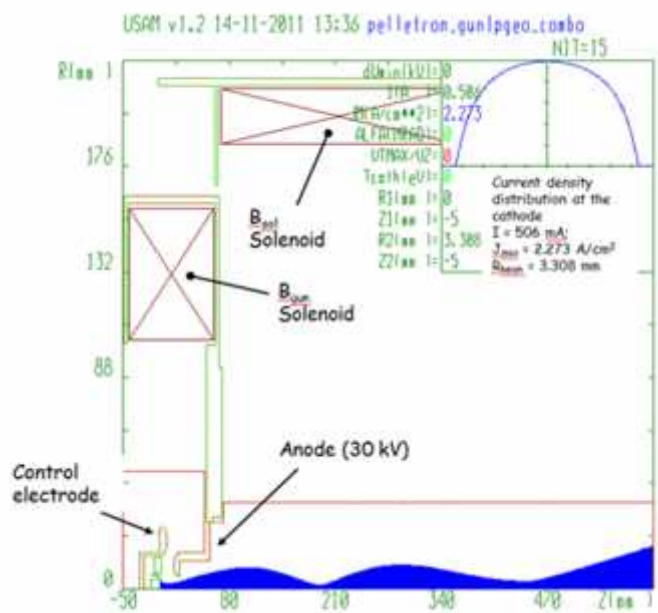

Figure 8. Beam simulation by L. Prost. Configuration with "2 humps". The absorber prototype would be placed at the second crossover.

2.4. Goals

To test the thermal load of the absorber, a 25W/mm^2 power density with 5-10 % accuracy should be obtained at the absorber prototype surface. Thus a procedure that allows measuring the size of the beam with 10 % accuracy is needed.

The goals were to put in operation of the absorber prototype test bench and to develop a procedure of the electron beam size measurement.

3. Methods of the beam size measurements

3.1. Scan of the plate with the correctors

To measure the low current beam size, a 93mm×100mm copper plate (Figure 9) with two holes was inserted into the same chamber of the test bench as where the absorber prototype would be placed. The beam can be moved by the correctors. The sensitivity of the correctors should be determined in the separate independent measurements. The result of these measurements presents the calibration values of the X and Y correctors – the ratio between the displacement of the beam on the plate and the corrector current that produces this displacement. When the beam passes the hole, the currents at the collector and at the plate are changing (Figure 10). Assuming that the beam is much smaller than the hole, the center of the beam passes the edge of the hole when the plate current is reduced by a factor of 2. Thus, given the calibration of the correctors and the hole diameter, the beam size can be determined.

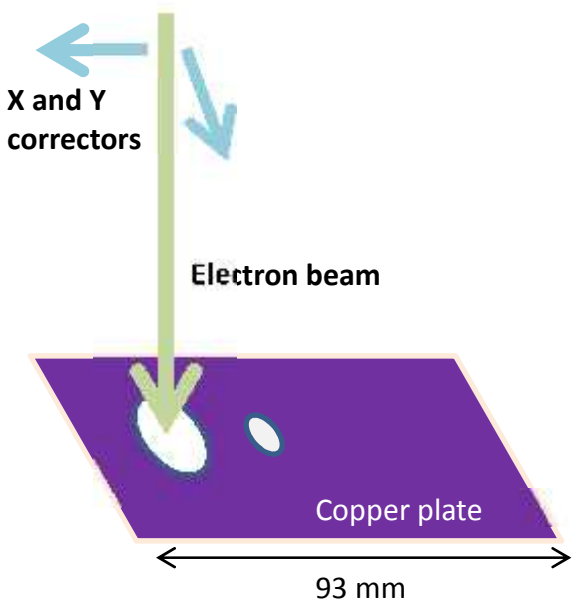

Figure 9. The 93×100 mm copper plate with two holes (4.98 mm and 11.9 mm in diameter).

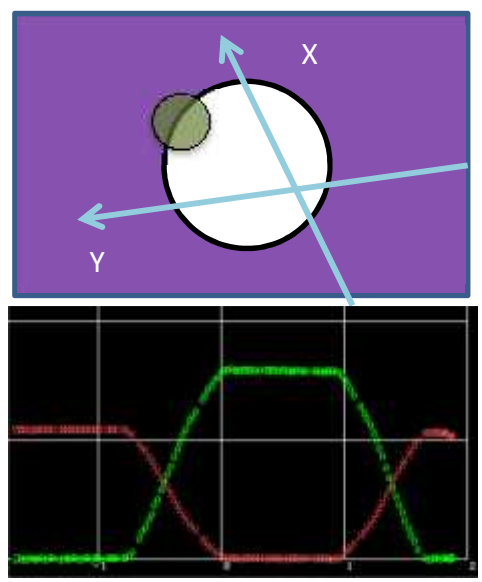

Figure 10. Example of a scan of the hole with one corrector. The green curve at the lower picture is the collector current, the red one – the plate current. When the beam passes through the hole completely, the collector current is maximum and the plate current is zero.

3.2. Mechanical scan of the plate

One of the possible ways to measure the low current beam size is to move the plate, using the actuator, along the central line (Figure 11). Given the dimensions of the hole, one can determine the size of the beam. The diameter of the beam could be calculated as the distance that passes the plate between the moments, when the beam is completely off and on the plate.

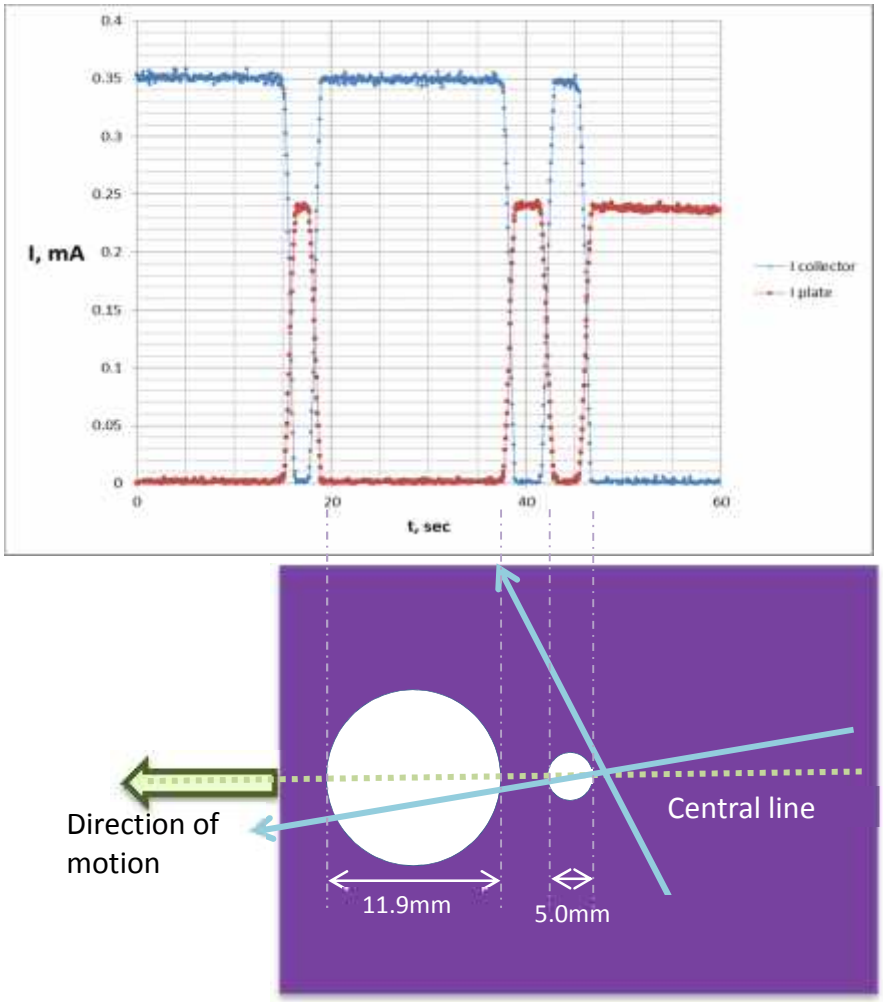

Figure 11. Mechanical scan of the plate. The upper picture is the plot of the collector (blue) and the plate (red) current vs time.

Due to the secondary emission of electrons from the plate, the maximum current in the plate is smaller than the maximum current in the collector (Figure 11). Since the plate is rather thick (3mm), the significant fraction of secondary electrons maybe kicked out from the edge of the plate and from the edges of the holes. These secondary electrons can go to the collector and be deposited inside of it. This fact can affect the result of the beam size measurement.

To prove that no secondary electrons from the edges get to the collector, the total current from the collector and the plate current, multiplied by the coefficient of the secondary emission (0.314), was calculated (Figure 12).

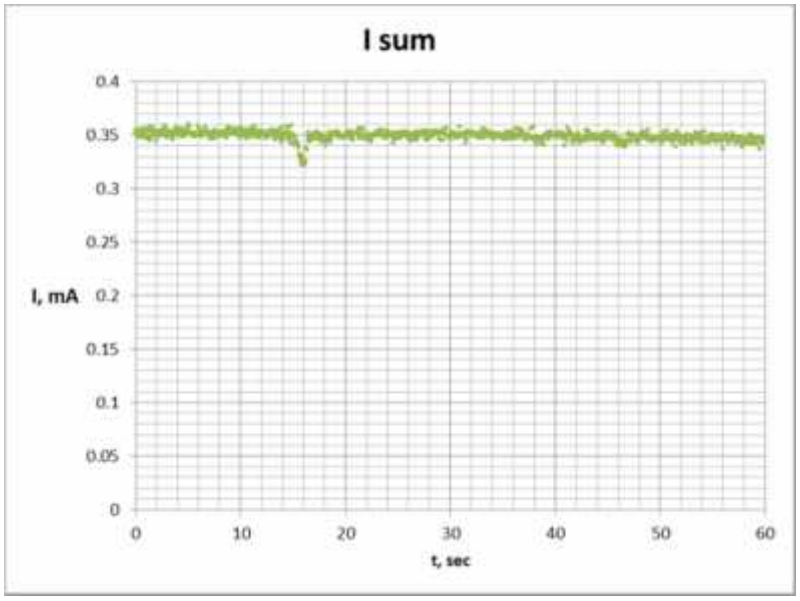

Figure 12. The plot of the total current from the collector and from the plate. The coefficient of the secondary emission 0.314 is taken into account.

At Figure 12 there is only one small bump that corresponds to the moment of time, when the beam passes the edge of the plate. The nature of the bump is unclear to as. At least, from Figure 12 we can tell that secondary emission from the edges of the hole doesn't affect the plate current measurement, when the beam hits that area.

3.3. Scan of the edges of the hole

When the power density of the beam is high (i.e. high beam current), it is possible to deposit only part of the beam on the plate. In this case, the edges of the hole will be scanned with the beam. It is considered that the beam touches the plate, when the current at the plate reaches the critical value (Figure 13).

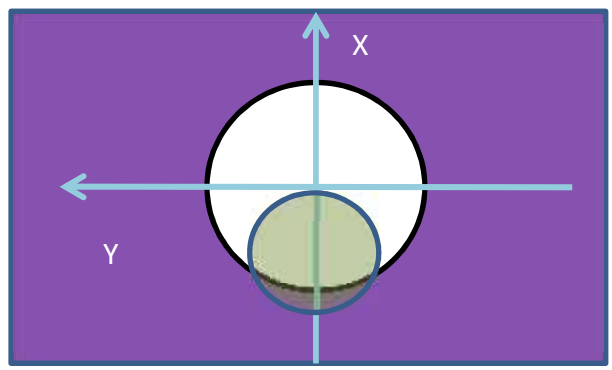

Figure 13. Scan of the edges of the hole. The beam is partially deposited at the plate.

4. Calibration of the correctors in three independent measurements

First of all, directions and calibration coefficients of the correctors should be defined. All calibration measurements were performed with low DC current in order not to damage the plate. The procedure that allows determining calibration of the correctors with three independent measurements was developed.

4.1. Calibration coefficients

In this measurement it is given that the diameter of the small hole is 4.98 mm, and the scans of the hole need to be performed through its center. To find the center of the hole, the following procedure was used. The hole was scanned with one corrector (X) in a fixed position of the second corrector (Y). The plot of such a scan is shown on Figure 10. Then the coordinates of the corrector (X), that correspond to having half of the beam on the plate, are determined. Using these data, preliminary center for this (X) corrector coordinate is calculated (Figure 14), and the scan along the other corrector direction is performed with the central X corrector position. Similarly, the preliminary central position for the other corrector (Y) is defined. Then the procedure was repeated until the needed accuracy in the definition of the center of the hole was achieved.

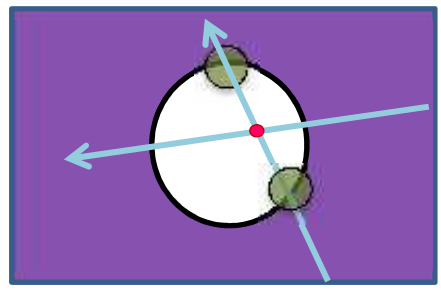

Figure 14. Scan of the hole along the X corrector direction. Two positions of the beam when the plate current is half of the maximum are recorded. The red point is the preliminary center for the X coordinate.

The second step is to determine the diameter of the hole in the units of the correctors current. Using scans of the hole through its center, the left and right coordinates of the hole can be determined. By definition, the left and right corrector coordinates correspond to the beam position, when the plate's current is equal to the half of the maximum plate's current (Figure 15). The diameter of the hole is the difference between the right and the left coordinates of the hole. Given the value of the hole diameter in mm and the corresponding values of the X and Y corrector currents, the calibration coefficients can be found as the ratio between the diameter of the hole in mm and in Amps. The measurements were performed for different plate's positions, and calibration coefficients were obtained for three various focusing solenoid currents (Figure 16).

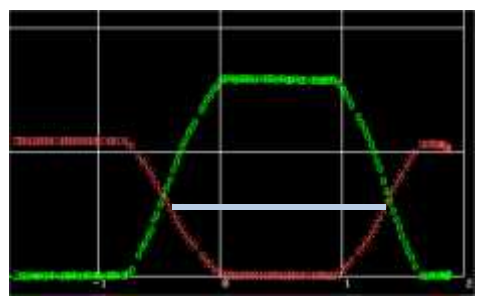

Figure 15. Definition of the diameter of the hole in the X corrector direction. The line represents the diameter of the hole.

Solenoid current, A	X calibration, mm/A	Error, %	Y calibration, mm/A	Error, %
2.0	4.87	0.3	4.73	0.3
2.1	4.69	0.2	4.57	0.2
2.2	4.62	0.3	4.49	0.1

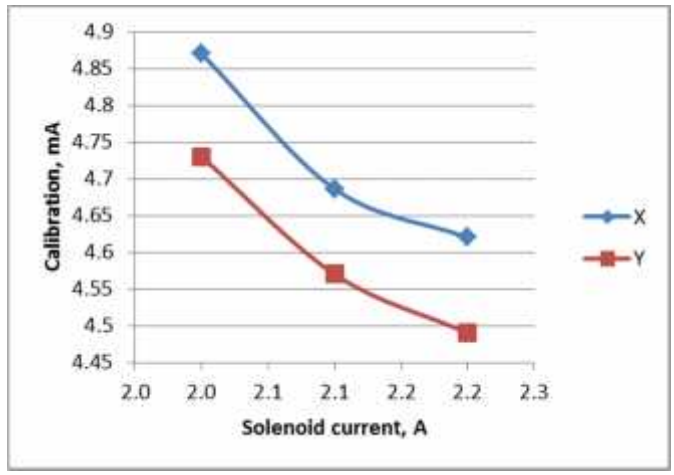

Figure 16. Calibration coefficients and their statistical errors for three different currents in the focusing solenoid. On the right there are plots for X and Y calibration coefficients vs solenoid current.

4.2. Directions of the X and Y correctors

To determine the direction in which the X and Y correctors move the beam, the calibration coefficients obtained in the previously described measurement were used. In this measurement the corrector currents that place the beam in the center of the hole were determined for a definite position of the plate. Then the plate was moved by the actuator, and the new coordinates of the center of the whole were measured (Figure 17).

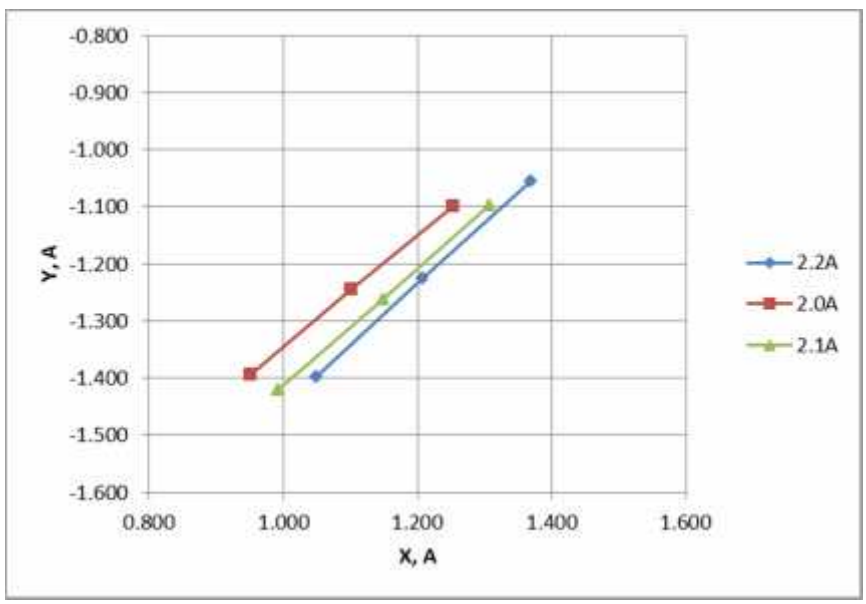

Figure 17. Pass of the center of the hole in X and Y corrector coordinates.

From these plots (Figure 17) slope coefficients are obtained. Given the calibration coefficients for the X and Y correctors, the angle between correctors and the angle between the X corrector direction and the central line of the plate (Figure 18) are calculated (Figure 19).

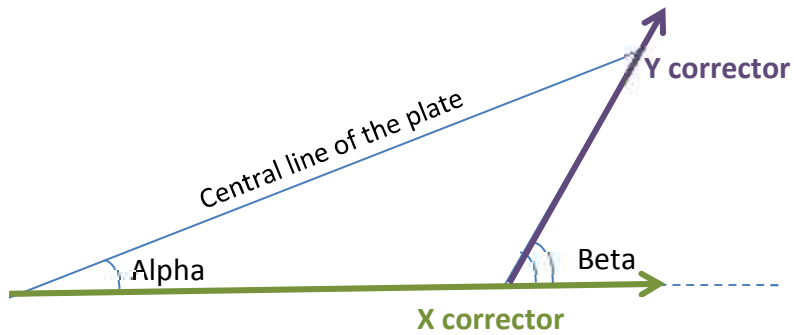

Figure 18. Picture showing the direction of the X and Y correctors with respect to the central line of the plate.

Solenoid current, A	Angle between X and Y, deg	Statistical error, deg	Rotation angle, deg	Statistical error, deg
2.0	91.31	0.01	44.2	0.2
2.1	93.90	0.02	46.9	0.2
2.2	96.87	0.02	49.7	0.2

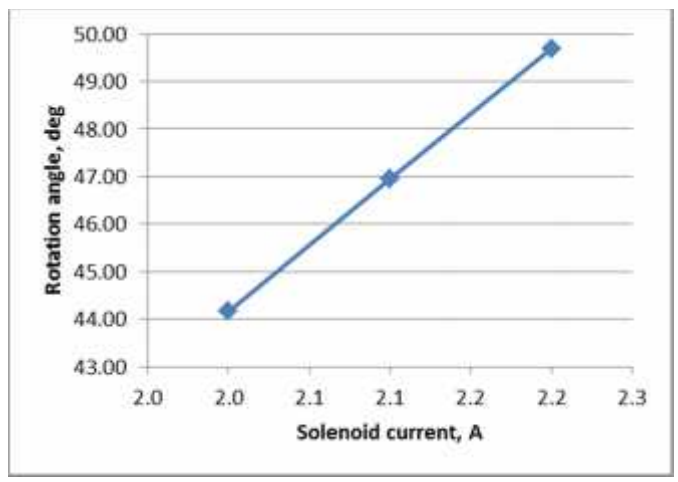

Figure 19. Results of the calculations of the angles that define the directions in which the beam is moved by the correctors. The 'rotation' angle is the angle between the X corrector direction and the central line of the plate. The plot on the right shows the rotation angle vs solenoid current.

The results above show that the rotation angle of the X corrector changes linearly with the solenoid current, which was predicted. Also, the angle between the correctors changes with the solenoid current by a value that is a lot larger than the indirect error of the measurements. That can be explained by the displacement of the correctors, but as far as we know the correctors are properly installed and the reason for such inconsistency is unclear.

4.3. Additional measurement for self-consistency

An additional independent measurement was performed to check the results of the calibration measurements. Given previously obtained data for the correctors calibration, the ratio between the X and Y corrector currents that allows moving the beam along the edge, was calculated. The plate was scanned along its edge with half of the beam; the other half was going to the collector. If during this measurement the plate's and the collector's currents remained the same, the beam was moving parallel to the edge of the plate. Then the ratio between X and Y correctors currents was manually clarified with 0.2% accuracy and compared to the calculated one (Figure 20). The difference between these two values was less than the indirect error of the calculated ratio (1%).

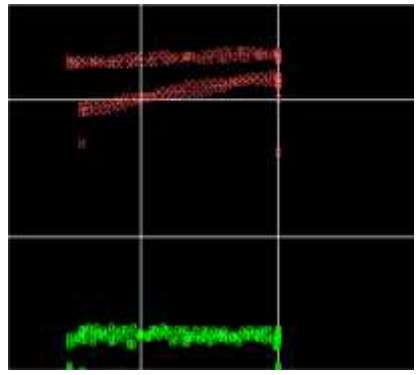

Figure 20. The scan along the edge of the plate. The red curves are plate current, green – collector current. The curves have 0.2% difference in the ratio between X and Y corrector currents.

4.4. Measurements of the diameter of the small hole with the bias voltage at the plate

Measurements with the bias voltage at the plate were carried out to examine the contribution of the secondary emission to the measurement of the small hole diameter. The small hole was scanned in the directions of the X and Y correctors with different bias voltage at the plate. Similarly as in paragraph 4.1., the diameter of the hole in the directions of each corrector was determined (Figure 21). Also, using the values of the maximum plate and collector currents during the scans, the coefficient of the secondary emission was calculated for different bias voltages at the plate (Figure 22).

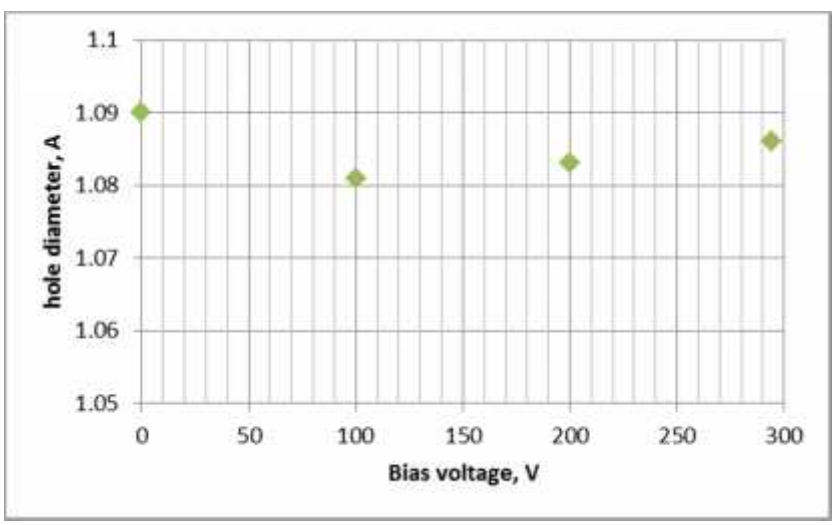

Figure 21. The plot of the hole diameter in the units of the corrector current vs bias voltage at the plate.

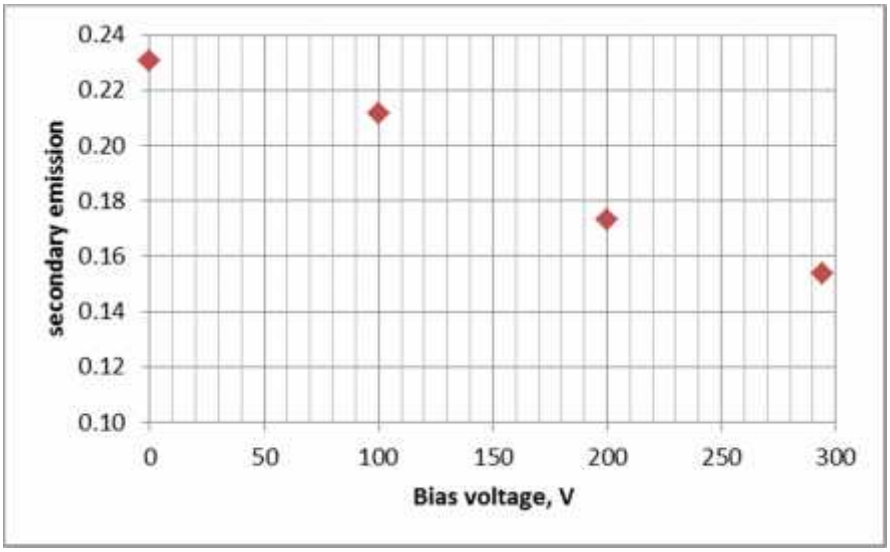

Figure 22. The plot of the coefficient of the secondary emission from the plate vs bias voltage. The plot shows that a 294 V bias voltage couldn't overcame secondary emission and the spectrum of the secondary electrons is very wide.

Accordingly with the results of the measurement of the hole's diameter with the different bias voltage, the statistical error, made by secondary electrons, was calculated. With calibration of the Y corrector 4.57mm/A this error is 0.02 mm, and corresponding relative error for the hole diameter (4.98mm) measurement is 0.4%. This fact allows using non-biased plate in the beam size measurements.

5. Parameters for operation of the test bench in a safe regime

5.1. Limitations in removed power and safe temperature

A fill beam current, high power (5kW) is deposited onto the plate, and the plate is not water cooled. The power of radiation cooling of the plate at 200°C (this temperature is considered as a safe temperature for operation with the plate) is 25 W, and the heat removal due to thermal conductivity at the same temperature is negligible (2W). The beam is perpendicular to the plane of the plate, so the power density is also very large (0.25kW/mm^2).Thus, the electron gun should operate in pulsed mode with short pulse duration, and only small part of the electron beam could be deposited on the plate. Since, we wanted to do everything in the least expensive way, the limitation of the pulses duration by the power supply was 0.3 seconds.

5.2. Model showing that short pulses are needed and pulse duration limitation

For rough estimation of the maximum temperature of the copper plate after one electron beam pulse the following model was considered. The plate was regarded as a half of an infinite copper plate with thickness equal to the actual plate (3 mm). In the simplest model the beam hits the edge of the plate, and the temperature distribution throughout the surface of the plate was calculated at the moment, when the beam pulse was terminated. With a 30 keV energy of the electrons, all the heat is deposited on the surface of the plate, but considering that the plate is thin, the heat reaches the opposite side of the plate by the time much smaller than the minimum pulse duration (0.3s). That allows using the model, in which the plate is heated by the half of the cylindrical homogeneous source. The radius of the source is equal to the beam radius (~2mm), the thickness is 0.3mm, the axis of the cylinder is perpendicular to the plate surface and goes through the edge of the plate (the problem has axial symmetry), the power of the source is 5kW.

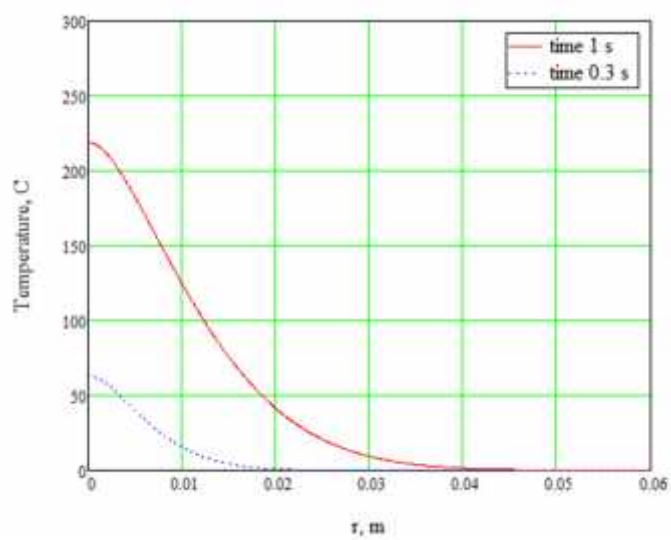

Figure 23. The plot shows the temperature distribution in the plate after 1 sec and 0.3 sec pulses. The beam current is 200mA and the power density of the beam is 0.25kW/mm^2.

The temperature distribution throughout the plate after one 200 mA electron beam pulse is calculated for 1s and 0.3 s pulses. From Figure 23 one can tell that short pulses (0.3 sec) of 200mA beam are needed in order not to damage the plate. After 1 sec pulse temperature in the center of the plate surpasses 200°C.

5.3. Temperature distribution and time intervals between pulses

In order to assess the process of the heat distribution after heating the following model was considered. Instead of the half of the infinite copper plate, a 5 cm circular plate with the same thickness (3mm) was examined. The initial temperature distribution at the plate is axially symmetrical, and the dependence of the temperature on the radius of the plate is taken from the previous calculations of the maximum temperature after 0.3s pulse. The temperature distribution at the plate was calculated at the different moments of time (0.01s, 0.5, and 1s after the heating was terminated).

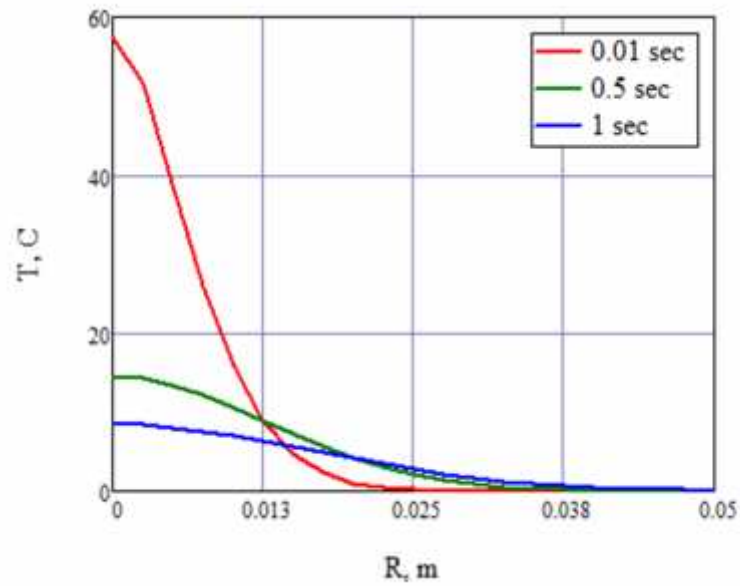

Figure 24. The temperature distribution in the plate after heating with 0.3 sec 200 mA electron beam pulse. The model of the infinite plate. Radiation cooling is neglected.

Figure 24 shows that 1 sec should be taken for the time of temperature relaxation throughout the plate. It means that in 1sec a new 0.3 sec pulse can hit the plate.

5.4. Conclusion about the pulse duration and the time interval between pulses

Taking into account the rough estimations of the processes of the temperature distribution and the heating of the plate, the parameters of the time mode for safe operation of the test bench with a 200mA electron beam were chosen. The test bench operates with 0.3 sec electron beam pulses and 1 sec intervals between them. To keep the plate at constant temperature (200°C) only a 3 mA part of the beam can be deposited at the plate. So, for the measurements with the high power beam, the method of scanning the edges of the hole should be used.

6. Measurements with high current beam

6.1. Procedure of performing pulse regime of the test bench and read back analysis

In the pulse mod the gun is opened for 0.3 sec, then it is closed for 1 sec, the correctors move the beam, and the gun opens again. This regime is produced with a dedicated Java application ("Wave Generator" by Z.Yuan).

Figure 25 provides read back from data logger. The data is analyzed with a program written in MathCad. The program was written especially for analysis of the read backs from the beam size measurements. It takes maximum plate's and collector's currents during 1 pulse, coordinates frequencies of read back and prepares the plots of the scans – currents at the plate and at the collector vs corrector's currents (Figure 26).

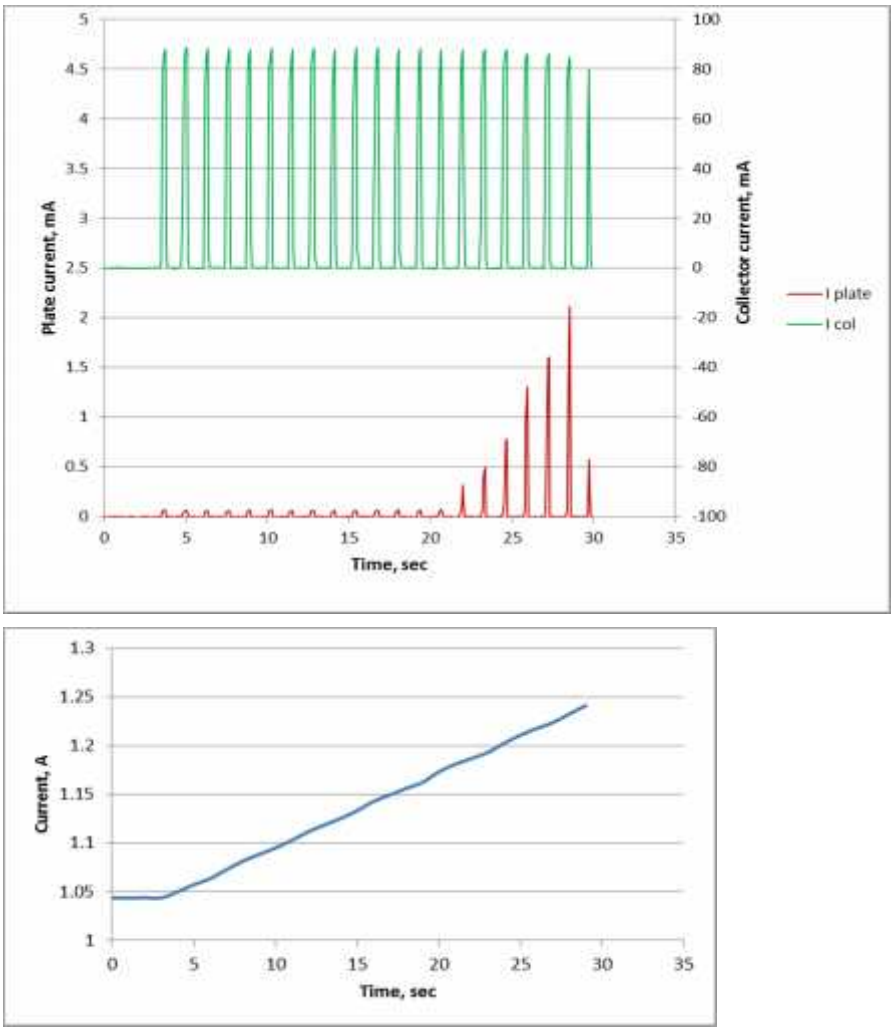

Figure 25. Scans of the edge of the small hole(4.98 mm diameter) with the X corrector. At the top is the plot of the plate and the collector currents vs time. Below – the X corrector current vs time.

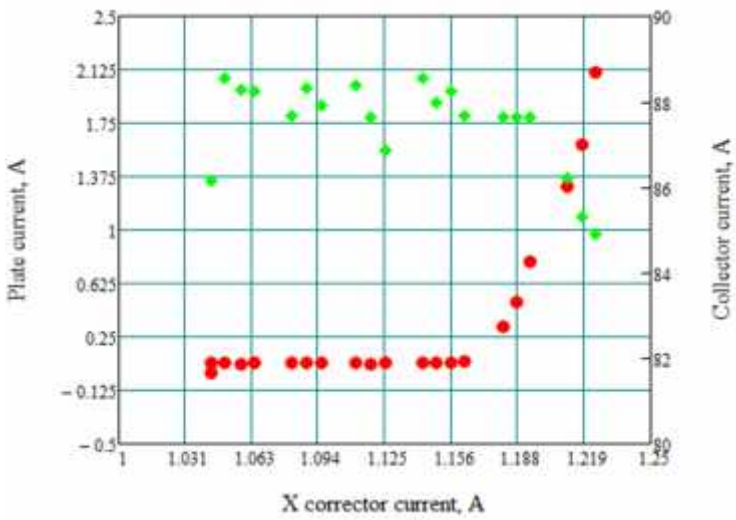

Figure 26. Mathcad program output of the X corrector scan of the hole edge. The plot shows of the plate and collector currents vs X corrector current.

6.2. Beam size measurement in pulsed mode

To measure the beam size of an 88 mA beam, the small hole was scanned along 4 different directions with 45° between them and passing through the center of the hole. The coordinates of the center of the hole were taken from the calibration measurements with the same solenoid current. The beam was moved by the correctors toward the edge of the hole, and the gun was closed when the beam touched the plate. By definition, the beam touches the plate when the plate current reaches 2 mA (3%). At this moment the program that produces pulses and moves the correctors was stopped, and the correctors currents, hence beam position was extracted (Figure 27). These positions form a circle in the X and Y correctors' currents coordinates (Figure 29). The difference between the diameter of the hole and the diameter of this circle is the beam diameter (Figure 28).

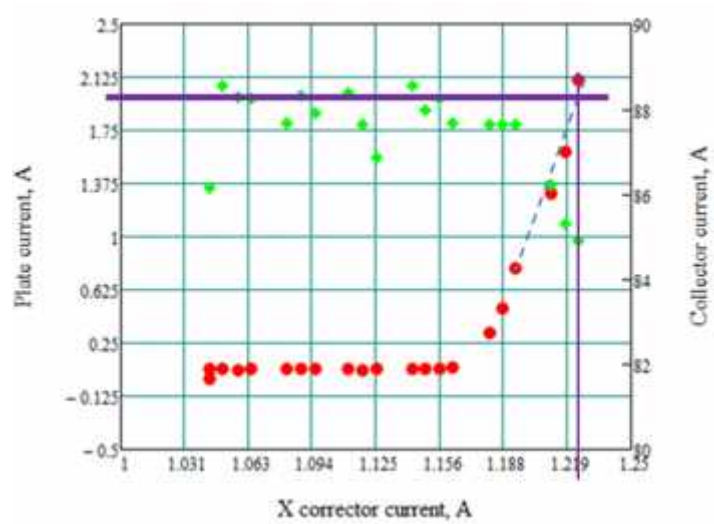

Figure 27. Assessment of the correctors' currents when the beam touched the plate.

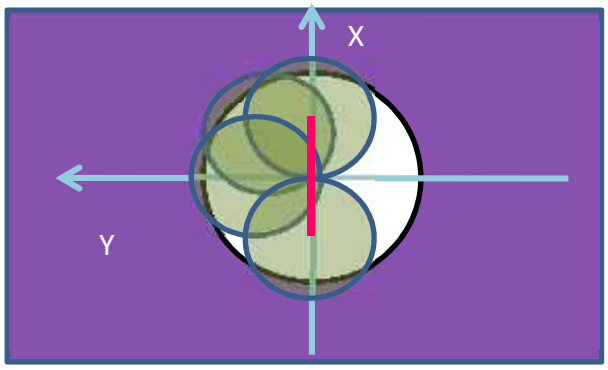

Figure 29. The beam is defined as "touching" the plate when 2 mA (3%) of the beam is on the plate. Using this method only 90% (by diameter) can be determined.

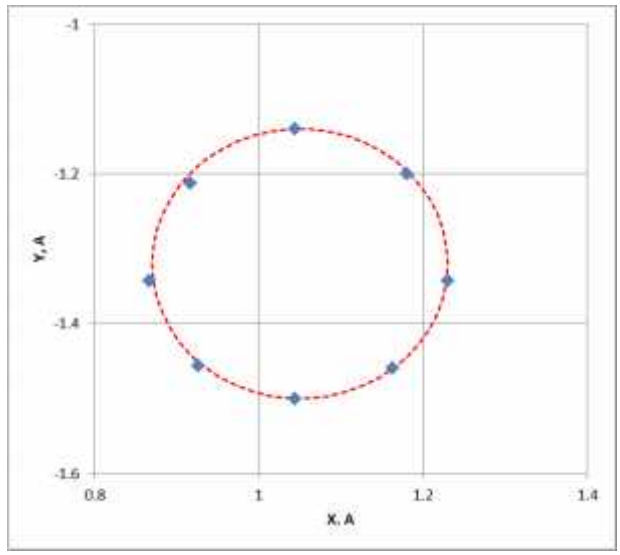

Figure 28. Coordinates of the center of the beam when it touches the hole. The data is fit with the circle (dashed red line).

Given calibration coefficients, the diameter of the 88 mA electron beam was calculated. It was found to be 3.3 mm with the focusing solenoid current equal to 2.1A. Actually, in this measurement only 80% of the beam transverse area can be detected, because the position of the beam center is defined when 3% of the beam is already being intercepted by the plate. This corresponds to the 90% of the diameter value.

7. Summary

The cathode was activated, and the 200 mA current was reached. The procedure of correctors calibration in three independent measurements was developed. Correctors calibration for 2.0 A, 2.1 A and 2.2 A solenoid current with DC low current beam was performed. Characteristic times of thermal processes in the plate were estimated, and the parameters of the time mod for safe operation were chosen. The procedure of the beam size measurement was developed, and the size of the 88 mA beam was measured.

8. Acknowledgements

Acknowledgments to the people who designed the test bench, assembled it or took part in the measurements: Jim Walton, Kermit Carlson, Bruce Hanna, Lionel Prost, Sasha Shemyakin.

9. References

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