# The Effects of Geometrical Modification on the performance of Faraday cup A Thermal Analysis approach

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***Abstract :*** ***In any experiment involving a charged particle beam, the intensity of the beam is off fundamental importance. Beam intensity dictates the type of activities that can be performed, as well as the basic limitations on the types and accuracy of the measurements that can be acquired. For this reason, the charged particle beam current, being directly related to the beam intensity, is an important parameter to monitor and control. To this end, a Faraday cup is commonly used to obtain an absolute beam current measurement in a variety of experimental settings, including particle accelerators .The primary objective of this paper is to describe the simulation and design of a Faraday cup system to be used as a current monitor and emergency beam dump in the extraction line of the Table Top Accelerator. The text of this paper and its references represent a fairly comprehensive introduction to Faraday cups with details that are relevant to accelerator systems with abroad range of designs and power ratings. The paper has been organized as follows I) Introduction II) Principles of Faraday Cup and Design III) Application of the Faraday cup IV) Problems related with the FC V) selection of material for FC design VI) Simulation and results VII) Mechanical drawings of the FC VIII) Conclusion.***

***IndexTerms - Faraday cup, Beam current, Beam Intensity, Design, simulation, thermal analysis material for FC, application of FC.***

## I. INTRODUCTION

The text of this paper and its references represent a fairly comprehensive introduction to Faraday cups with details that are relevant to accelerator systems with abroad range of designs and power ratings. The paper has been organized as follows I) Introduction II) Principles of Faraday Cup and Design III) Application of the Faraday cup IV) Problems related with the FC V) selection of material for FC design VI) Simulation and results VII) Mechanical drawings of the FCVIII) Conclusion

## II. PRINCIPLES OF FARADAY CUP (FC) AND DESIGN

The Basic schematic design of a very simple Faraday cup system is shown in Fig 1. The most basic design consists solely of an electrically conductive material in the shape of a cup, typically with cylindrical symmetry, which is placed in the path of the charged particle beam whose current is to be measured. Ideally, all the particles in the beam are absorbed by the Faraday cup, there by inducing a charge on the cup that can be read out as a current with the appropriate electronics. In this theoretically ideal case, the current passing through the Faraday cup is a direct continuation of the charged particle beam, (i.e. the Faraday cup by itself acts as a resistor) so the current readout from the Faraday cup is exactly equal to, and is therefore a direct measurement of, the beam current. Hiding the underlying complexities of the interactions involved with the transfer of charge from the beam line to the conducting material, visually the Faraday cup looks simple. The information related to Faraday cups in this section has been culled primarily from references [5]. Some general aspects of Faraday cup design and operation are discussed in multiple references and, as such, it is difficult to determine the originator for some topics. For this reason, this section only explicitly cites statements that are unique or seminal with the rest of the information being considered common knowledge among the accelerator physics community. Some of the terminology in this paper is perhaps unique and is used to help organize some of the concepts relevant to Faraday cup design and phenomena.

(Fig.1 The metallic FC in the real picture .It looks like a simple sup as discussed above in the text.)

## III. APPLICATION OF THE FARADAY CUP

Faraday cup has wide application some of them has explained as below: Beam current measure: As discussed in the Introduction, beam current monitoring is an essential component of the diagnostics system of any charged particle beam experiment. A number of techniques have been developed to accomplish this task [6]. Prominent non-destructive examples include the beam current transformer and the wall current monitor. Beam current transformers typically consist of two ideal pickup coils through which the charged particle beam passes, inducing a signal that is Proportional to the beam current which can be measured and filtered by some associated activator passive electronics. A wall current monitor consists of a resistor connected across a physical gap in the beam pipe wall. Both of these methods have distinct strengths and weaknesses in terms of mechanical complexity, compatible frequency range, and measurement sensitivity. Additionally, along with all nondestructive current monitoring schemes, they share the advantage of not disrupting beam operation. However, all non-destructive schemes share the disadvantage of yielding only a relative measure of the beam current and, consequently, requiring an absolute current measurement for calibration. This absolute calibration measurement is often accomplished with the use of a

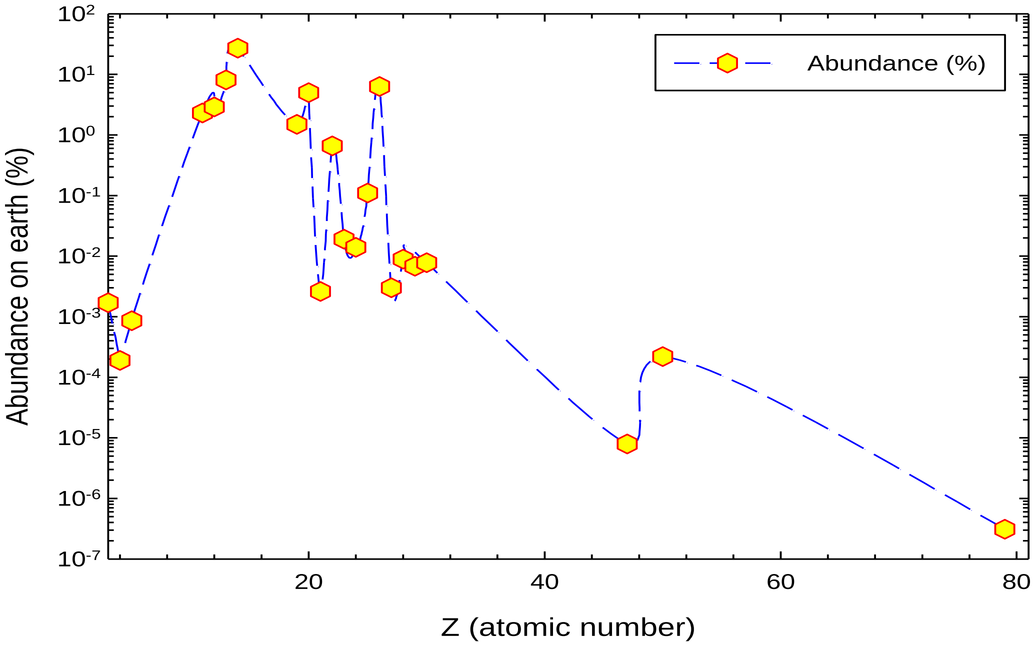
Faraday cup. The interaction of ions with matter is a rich and complex subject and many books and papers have been written on the issue [7-2] and the references within. The treatment here follows the development in several of these references, but it is necessarily brief and cursory, presenting primarily those results which directly relate to the physics involved with Faraday cups. Ionization can be an important process in Faraday cup. Due to the secondary electron production that can occur through collisions with valence shell ions within the Faraday cup target metal. However, as discussed below, this is not the primary mechanism involved with the electromagnetic particle cascade. For ion interaction with matters, Coulomb scattering becomes the extremely dominant energy loss mechanism. Coulomb scattering is an elastic process whose scattering events deflect the angle of the incident ions' trajectory through an interaction with the Coulomb potential of the constituent atoms within the Faraday cup's metal target. Coulomb scattering is the process responsible for the large angular deflections that can lead to backscattered ions. This process is elastic only in the sense that the interaction between the incoming ion and the target. Transmission efficiency of the accelerator: It is important to measure the transmission efficiency of an accelerator using many devices one of them is FC. In a simplest way first one can place the FC in one position and note down the beam current (extract the incident in flux) and then changed the position of the FC to another location of the transport section and take the beam current measurement again. Compared both the result and one can inform about the transmission efficiency, say for example if the measurement of both the places is same that indicates the transmission efficiency is 100% between those points. Similarly one can place these FC at different locations and extract the transmission efficiency of the accelerator. From the FC current measurement one can able to extract the ion information as follows. Let us consider the case where the FC shows a current of 100nA current of proton beam. The proton has charge one and I mole contains the Avogadro number so if we do a small math we will see that 100nA ~62.5*1010particles per second.

## IV. PROBLEMS RELATED WITH THE FC

Even if the FC looks simple and the operations principle is based on simple mechanism there are many important problems related with it. Some of the important issue has been discussed below .Faraday Cup Current Loss Sources, The goal of a Faraday cup is to completely absorb all of the charged particles in the incident beam and to fully encapsulate the electromagnetic cascade so that the charged absorbed by the Faraday cup will accurately and directly correspond to the charge in the incident beam. However, in practice, this is not trivial and there are a number of sources of current loss that can lead to erroneous measurements and need to be considered during the design process. This include: Penetration Losses, Back scatter Losses, and Current Leakage Sources. These potential sources of error and some possible solutions are discussed in greater detail below. We will find that avoiding penetration losses sets the size scale of the Faraday cup, avoiding backscatter losses requires some clever design ideas, and avoiding current leakage sources is simply matter of proper design of the physical apparatus. Back scatter Losses: ion back scattering occurs when an ion is scattered or produced such that its trajectory forms an angle with the incident ion beam axis that is greater than 900. Ions emitted from the Faraday cup in the back scatter direction come from Coulomb backscattering. In case of back scatter Coulomb backscattering occurs when an incident ion comes very close to scattering off the center of the Coulomb potential produced by the constituent molecules of the Faraday cup target material. This is directly analogous to the observation of alpha particles backscattering off a gold foil in Ernest Rutherford's famous experiment. Nevertheless, since Faraday cups have the potential to provide extremely accurate direct current measurements, it is in the Faraday cup designer's best interest to consider methods to mitigate the current measurement error due to backscatter losses. A number of clever backscatter loss reduction techniques have been developed. They generally fall into the following categories: The goal of geometry-based backscatter reduction techniques is to choose a Faraday cup shape in such a way that back scattered ions that escape the beam stop region are less likely to escape the neck region. This idea suggests the genesis of the Faraday "cup" concept itself. Including a neck on top of a solid beam stop introduces the possibility that ions backscattered off of the beam stop will scatter off the side of the neck before reaching its opening. While the backscatter direction includes all angles greater than 900, those angles closest to900 are the most probable which suggests that scattering off the side of the neck is likely to occur. The probability can be improved by increasing the length of the Faraday cup neck, thereby decreasing the solid angle available for other more extreme geometry techniques, such as introducing a bend into the neck region, are also possible. However, the simple inclusion of a neck region in the Faraday cup is typically the only geometry-based backscatter reduction technique that is commonly utilized. Another very common backscatter reduction technique involves the use of a low-Z material that possesses a smaller backscattering cross section than the high-Z Faraday cup target material to "cushion" the incoming charged particle beam. In addition to having a low atomic number, the cushion material should also be conductive to allow any charged particles that are absorbed by the cushion to flow out to the Faraday cup target material so they can be included in the incident beam current measurement. To satisfy these criteria, graphite is very often selected as the cushion material. Copper, having a relatively low atomic number compared to the other common elemental Faraday cup materials lead and molybdenum, is also occasionally used. In our case we have used the longer dimension of the cup and also provided a conical shape including we have used also the suppressor for this purpose .Current Leakage Sources: Leakage current sources take the form of any electrically conductive route from the Faraday cup to a different electric potential. This is most commonly formed by the support structures to hold up the Faraday cup within its enclosure, if such an enclosure is used. To avoid this, only insulating material should be used where appropriate, such as plastic screws or ceramic legs. Additionally, since the ion beam hitting the Faraday cup may lead to sputtering, the insulating supports should be periodically cleaned to avoid a conductive path being formed by a thin deposited layer of the conductive Faraday cup material on the insulating materials. Another potential current loss source similar to a leakage current is the presence of a cycling water cooling system. Some type of cooling system can be necessary in higher energy beam facilities, especially if the Faraday cup is kept under a vacuum, where the lack of heat conduction through makes ambient cooling more difficult while the temperature of the Faraday cup should be minimized to avoid excessive out gassing. However, the use of a water cooling system does introduce an error in the beam current measurement as some of the scattering ions will be absorbed and swept away by the water flow. So when one can design the cooling channel a more precaution has to be taken for the above thing.

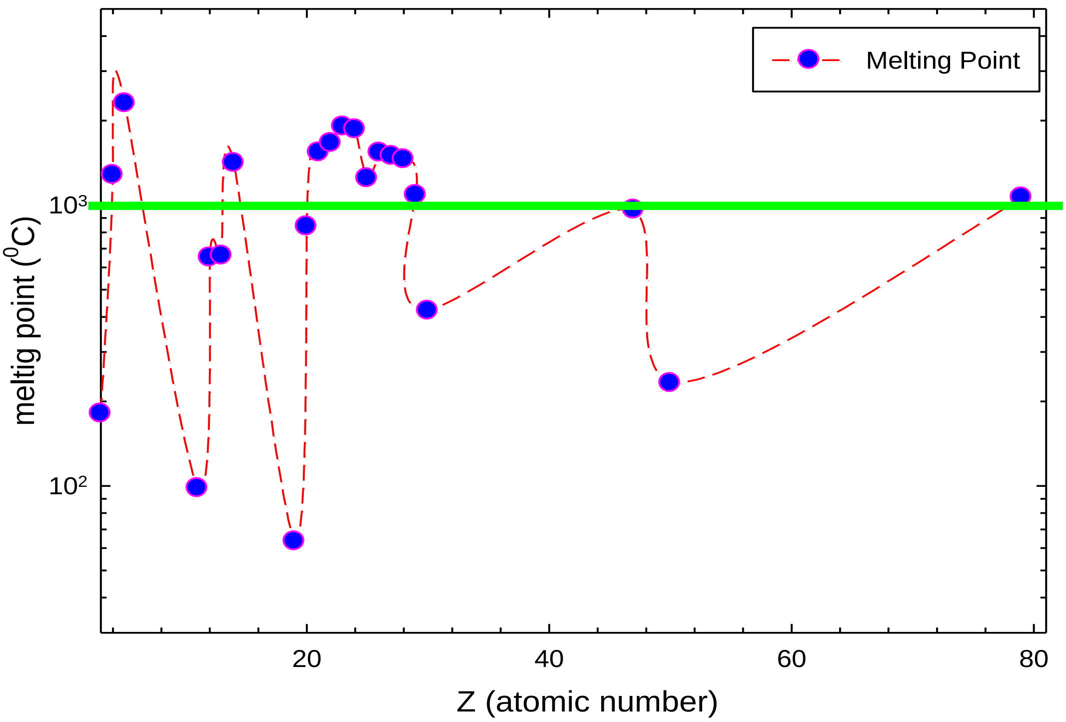
## V. SELECTION OF MATERIAL FOR FC DESIGN

As we discussed above the faraday cup is based on the simple mechanism but the mechanical design is complex as many points has to be taken care. Bellow three important aspects has be end is cussed which serves as three important properties to choose the material for FC design.1) Natural abundance of the material: As Faraday cup is a metallic cup as discussed above the material which will be used to make the FC should must have cost-effective. The natural abundance of the material is very important for the cost-effective point of view. In the below Fig 2 we have shown the natural abundance of many materials. One can see from Fig.2 that many material satisfy the properties of more abundance but only few material are the most promising candidate.




(Fig.2 The natural abundance of many different material over the earth crust.)

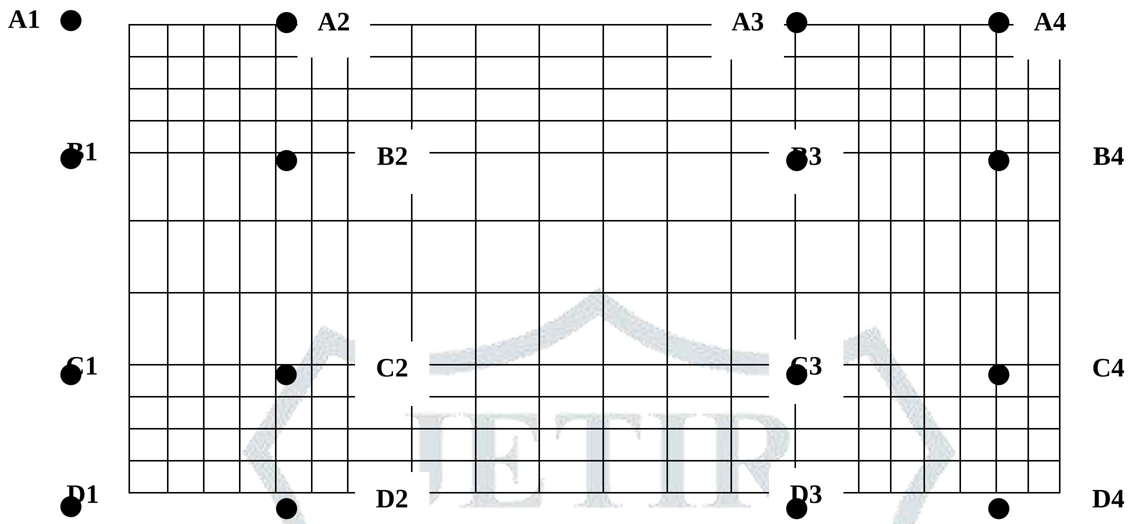
Many material shows the promising candidates including Al and Cu. Only the natural abundance is not sufficient to choose a material there are other properties which is important one of them is 2) electrical conductivity: As the FC will made up of metallic body and the important job of the FC is to provide the ion information which lead to a very small current reading using sophisticated electronic device, so the electrical conductive of the material is very important and it should be very high. Fig 3 shows the electrical conductivity of the many material. One can see from the Fig.3 that out of many material Au and Ag has very high electrical conductivity. Which seems to be the good candidate from second point of view but when we compared the w.r.t the Fig.2 (natural abundance) it is very expensive to use them for FC. In addition with the electrical conductive 3)thermal conductivity is also another important aspect of the material. When the ions will strike the metallic cup which will provide the number of ions information via beam current measurement in a destructive way as explained above, it will produce substantial amount of the thermal heat at the point of Interaction which has to be dissipates quickly to avoid the secondary effect like Melting, degassing from the material and the secondary electron emission. Therefore the thermal conductivity of the material is important which shows in Fig3. One can observe that the Au and Ag has good electrical conductivity but from Fig.4 it has cleared that they low melting point compared to Al & cu which makes them not to use for FC design.




(Fig.3The melting point of many different material. The Cu and Al high melting point compared to the AU and Ag)

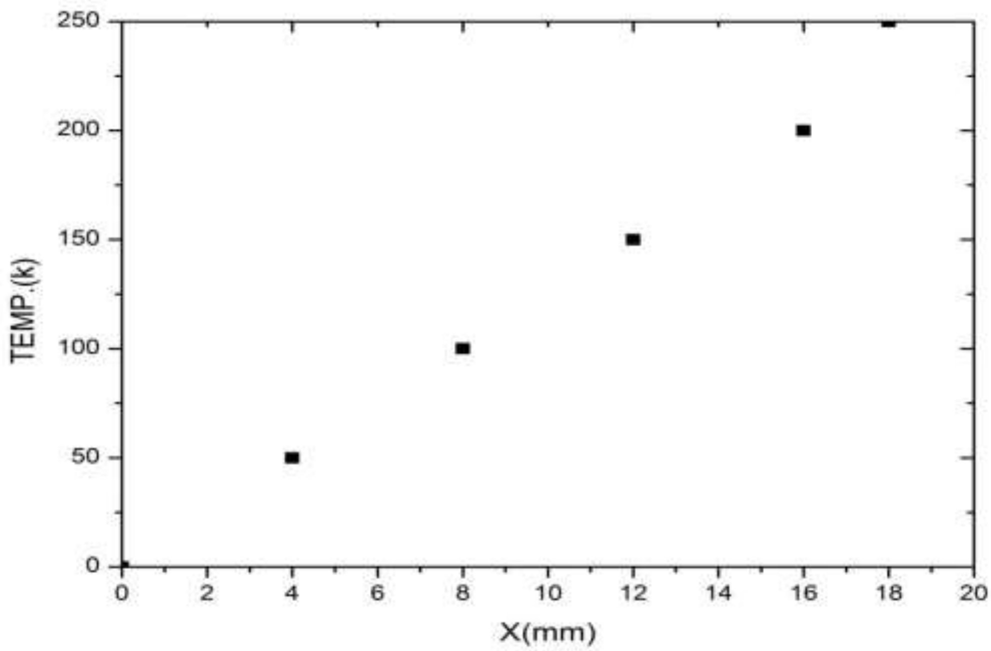
## VI. SIMULATION AND RESULTS

The numerical simulation as explained below. For a clear picture of the thermal analysis we have considered a practical example. Let us consider400µA of "p" beam having energy200KeV will strike a 20mm *20mmmetal (Al & Cu) sheet which will produce ~ 80W of power. Here we have considered the incident beam dia is 6mm i.e. a large beam. One the beam will strike the metal surface it will produce the thermal heat as calculated above. The thermal heat need to be dissipate very fast. For the heat distribution (a static picture) has been generated using the Laplace2D heat equation ( ∂2U/∂x2 +∂2U/∂y2 = 0) .This equation has been solved for 2D case using the Finite difference approximation . For Temperature distribution in a rectangular plate The Fig 5 represents a thin rectangular solid body whose temperature distributions to be determined by the solution of Laplace's equation. The rectangular body is Covered with a computational grid as shown in the Fig.4 The gridding of the metal sheet for the numerical solution as discussed bellow.

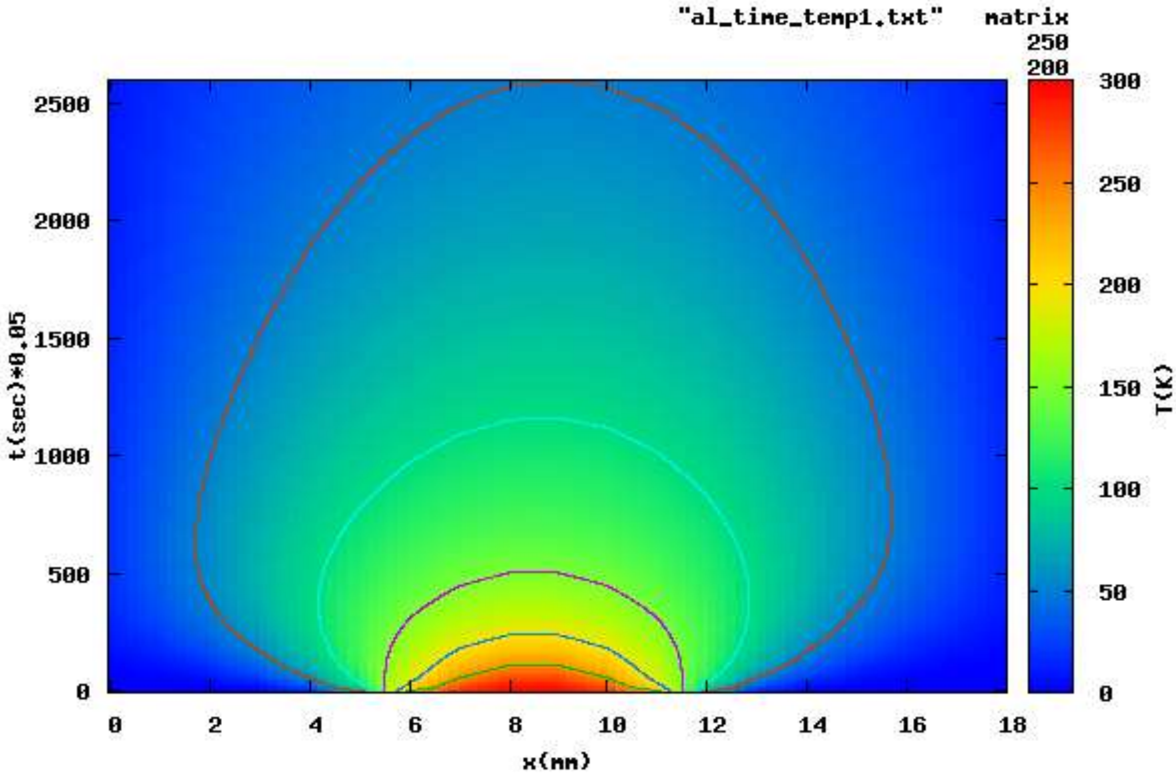



(Fig4The gridding of the sheet for the numerical solution as discussed below)

Notice that we have arbitrarily divided the domain into 9 sub-domains (e.g.,A1,A2,B1,B2,etc.) in such a way that each sub-domain contains points on a grid with constant increments $\Delta xi$ and $\Delta yi$. Here, the sub index i describes a given sub-domain
e.g., sub domain A1,A2,B1,B2 could be identified as i=1, while sub-domainA2.A3.B2.B3 would be i =2, etc. Dirichlet boundary conditions for this case requires us to specify the temperature along the boundaries A1A4,A1D1, D1D4, and A4D4. For the solution we have used the Finite difference approximation as mentioned above. We have considered in one boundary the temperature is due to the striking of the ions where as in the other boundary it is zero.
The solution has been carried out and shown in Fig.5 for both Cu and Al. One can observed from the Fig.5 that the temperature at the initial surface high whereas on the lateral stages it decreases which one can expect from thermal point of view from the graph.Fig.5 The Graph for the temperature distribution inside the metal surface when one side has been strike but he proton beam. For this case we have consideredthe20mm*20 mm metal sheet.

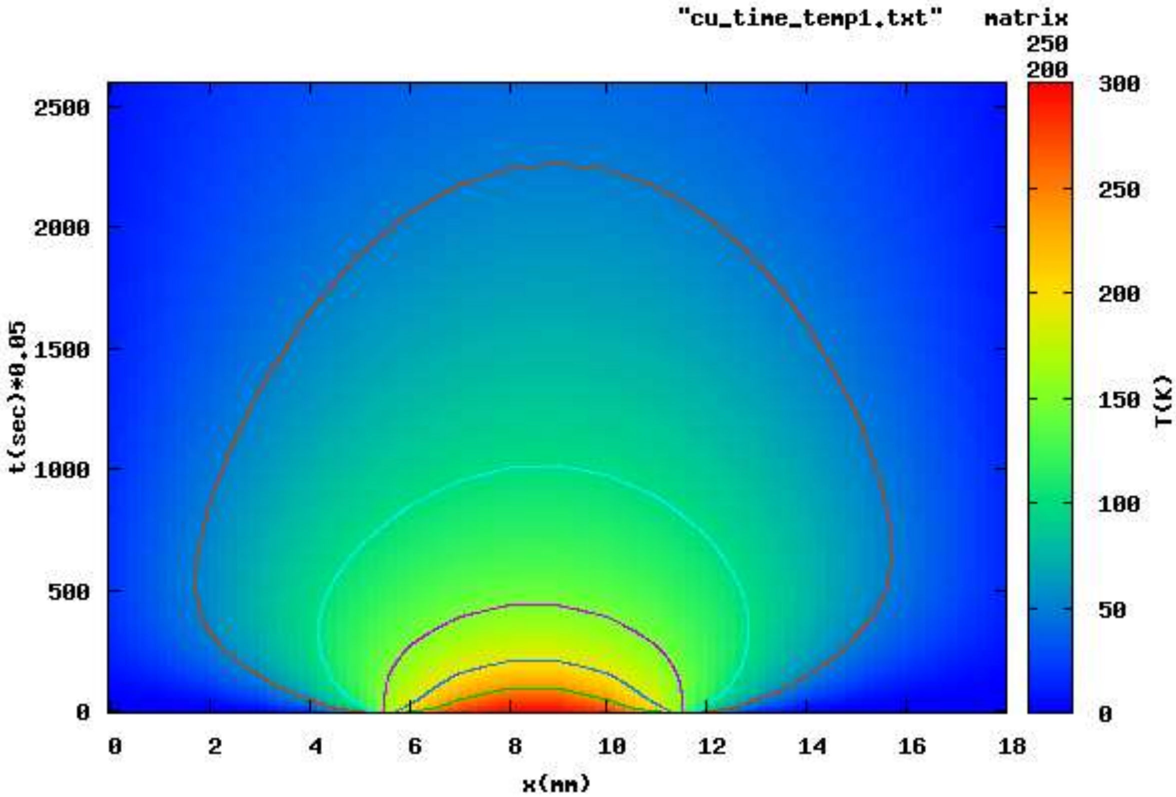



(Fig.5Temperature Distribution inside the metal surface 20mm metal sheet)

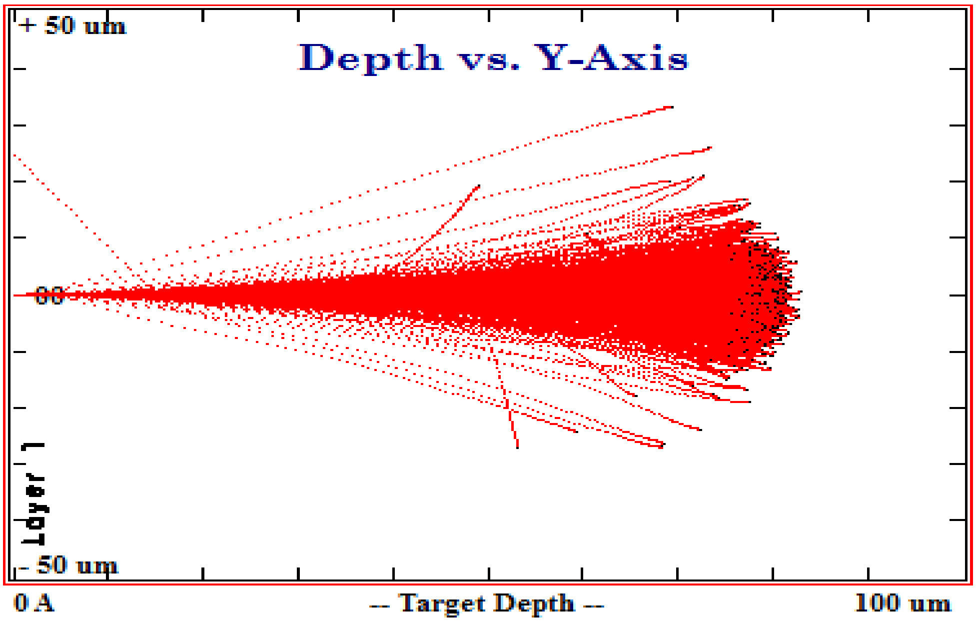



(Fig.6The time dependent solution for heat transfer inside the material. one can seen it will take ~3min to reach the last contour. This is for the material Al )

To know which material is more efficient we have solve the time dependent solution which has been solved in the similar way & presented in fig 6 and Fig.7 . From both the Fig 6 and7 one can see that to cool the Al it takes~3 min where as for Cu to dissipate the same heat it needs < 1.5 min i.e. it will cool faster rate. Finally combining all the above explained properties we fixed the material as Cu . Fig.7 The time dependent solution for the heat transfer inside the material .one can see that it will take ~3min to reach to the last contour. This is for the material Al.




(Fig.7 The time dependent solution for heat transfer inside the material. one can seen it will take <1.5min to reach the last contour. This is for the material Cu )

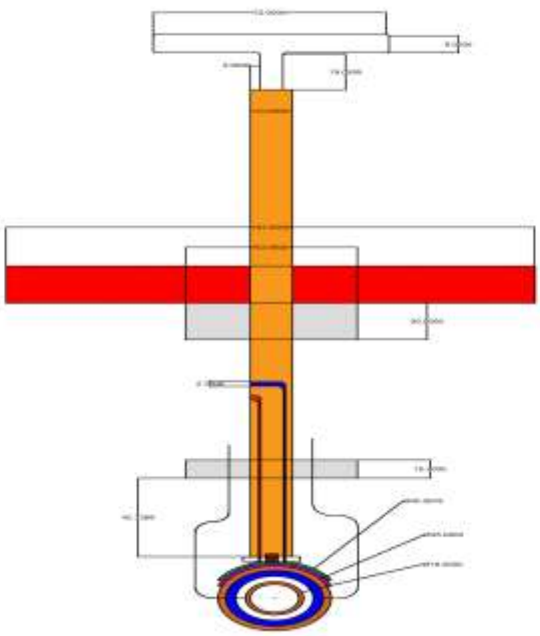



(Fig.8 Monte Carlo simulation for the thickness of the Cu when 5Mev (p) has strikes the material has done by SRIM /TRIM software. Above is the longitudinal view.)

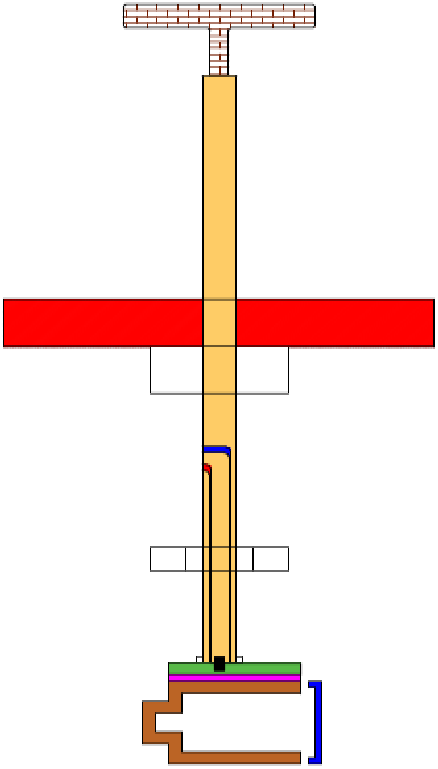
Fig.8 The time dependent solution for the heat transfer inside the material .one can see that it will take <1.5 min to reach to the last contour. This is for the material Cu. After the heat simulation we choose the material as the Cu. But to choose the thickness of the material such that the beam will completely stop within the material we have performed some calculation. To get the thickness we performed the SRIM/TRIM calculation which provide the stopping range of a material we have taken a 5Mev of proton beam & strikes the Cu material which has shown in Fig. 8. From the Fig.8 one can see that the thickness of the materials < 2mm but for the safer side we have taken 5mm of thickness as we have to incorporate the cooling channels also.

**VII. MECHANICAL DRAWINGS OF THE FC**

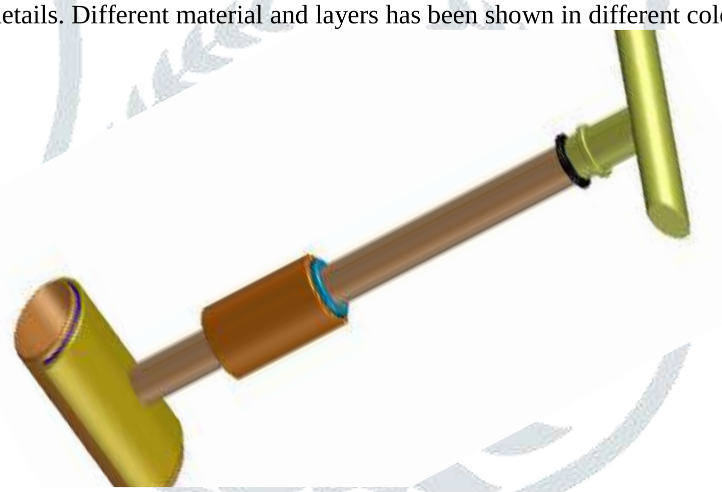
After fixing the material as Cu thickness of the material has been fixed by the prediction of the e SRIM / TRIM software we started to make the design using Autocad-16. The 2D drawing with dimension has shown in fig 9 andFig.10. from the fig one can see many components as explained bellow .There are three main components. The vacuum flange, The detection system and The cooling channel. The vacuum flange is very important as it has to separate the atmosphere air & the vacuum pipe. The pipe ( beam pipe) having vacuum 10-7mb has to be well insulated . So the O rings & all the parts shown in fig 9&10. The detection system is consists of the Cu metallic cup as shown in the Fig the beam will strike the internal conical shaped Cu the special conical shape will reduce the back scattered possibilities &dissipate the thermal heat very fast. A complete 3D drawing has been performed for future development. the automated system can be developed in future. The cooling pipe has designed but a cooling mechanism needs to bethink. One possible solution is to use a fully closed chilled water cooling system, which need further investigation. the whole metallic cup is well insulated electrically where as conned by thermally using Be O layer. This material poses very good thermal conductivity but electrically insulated. all the conducting wire has to be insulated &connected to detection system independently as shows in fig . The electron suppressor has shown very clearly shown which placed at –ve potential & connected independently to reduce the secondary effect. All the component has been shown in both2D&3D. Different view has been shown in the subsequent Figs.



(Fig.9 Faraday cup 2D drawing front view using Autocad-16. All the dimension is in mm. see the text for the details. Different material and layers has been shown in different color.)



(Fig.10 Faraday cup 2D drawing side view using Autocad-16. see the text for the details. Different material and layers has been shown in different color. )



(Fig11 Faraday cup 3D drawing)

## VIII. CONCLUSION

A complete analysis has been done to choose the material. different aspects has been discussed. Monte Carlo simulation has been performed to fix the thickness of the material. a heat analysis has been performed using the Laplace equation and the results has been shown by different Fig. A complete 2Ddrawing of the faraday cup has been presents from different view point with dimension. A complete 3D drawing has been performed for future development the automated system. A complete 3Ddesign has been presented. For future development the whole system can be made automated and a special type of cooling material can be designed.

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