Multi-wire Emittance Measurements

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Abstract

An emittance measurement was carried out on June 13, 2009 on the Fermilab linac. In this study, the emittance of the beam was measured before Tank 1, in the horizontal direction x and vertical direction y using Probes 3 and 4 respectively. The result of this measurement, which is presented in this paper, is intended to be used as a basis for future emittance measurements of the linac. A step by step procedure in which measurement of this kind can be performed at Fermilab linac has been documented and can be viewed in Appendix A. To make the data analysis faster and repeatable for future emittance measurements, a VB/Excel program has been developed, which will be referred to as the Multi-wire Emittance Measurements Program (MEMP) in this paper. A detailed manual of how to use MEMP and how calculations are done in it is available in Appendix B. Because the discussion of the results of this particular measurements conducted on June 13, 2009 has been intended to be independent of the materials presented in Appendix B, a much shorter explanation of how the raw data was reduced, which has been done entirely in MEMP, is given in the Results section (Section 4) as well.

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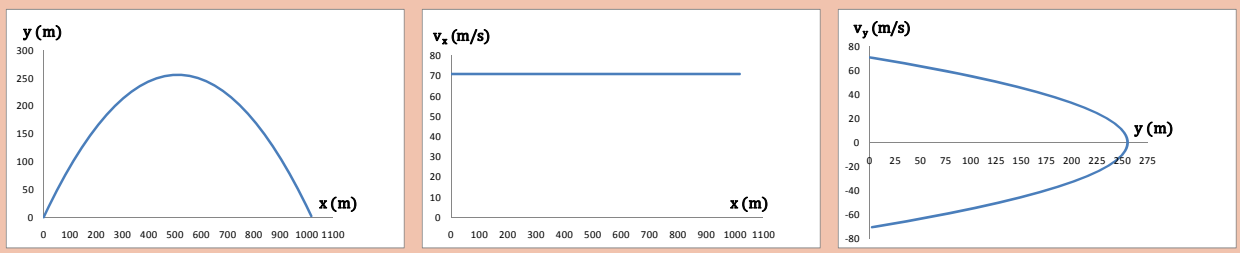
1 Introduction

The purpose of this measurement is to find the emittance of the H^- ion beam generated for the Fermilab's linear accelerator (linac), and to give a general overview of what beam emittance means and how it is measured. Emittance measurements are highly important in determining the behavior of particle beams. Knowing the emittance of a beam along its nominal trajectory can be used to apply corrections to the beam. There are several methods used to measure the emittance; one of the more common ways, which is the subject of this paper, is called Multi-wire Emittance Measurements. This method provides a relatively simple way to measure the emittance of a particle beam.

2 Transverse Emittance

To understand beam emittance, it is essential to have a comprehension of *phase space*, which is a space consisting of all possible values of position and momentum of a system. This mathematical tool is often confused with *physical space*, which contains only position information. It is important to note that for every dimension in the physical space of a system, there is a separate phase space associated with it that has two dimensions. As a very simple example, these two different spaces are illustrated in Figure 1 for a classic physics problem of a general ballistic trajectory, in which a ball is launched with an initial velocity of 100m/s at an angle of 45 degrees.



(a) (b) (c)

Figure 1: Comparison between Physical Space and Phase Space for the Trajectory of a ball. (a) Physical Space of the Ball, (b) Phase Space of the Ball in the Horizontal Direction, and (c) Phase Space of the Ball in the Vertical Direction.

In this example, the physical space of the ball has two spatial dimensions of xy that leads to a 4D phase space with dimensions of xv_x and yv_y, where v_x and v_y are the rate of change of x and y with respect to time and represent the velocity of the ball in their respective directions

Of course, the dimensions and shape of the physical and phase spaces of a particle beam are very different than those of a ball shown in Figure 1, but mathematically, they contain the same information

about their respective systems. In the case of a particle beam, phase space is used to define the trajectory information about the ensemble of particle. The physical space has three spatial dimensions of xyz, where x and y are the transverse dimensions and z is the longitudinal dimension, relative to the nominal trajectory. This leads to a 6D phase space, where the transverse dimensions are represented by $xx'yy'$, where x' is defined as ${P_x}/{P_z}$, where P is the momentum of the beam in the direction denoted in its subscript, and similarly y' is ${P_y}/{P_z}$; that is, they represent the angles in the respective planes (1). In the case of the longitudinal dimension, phase space is generally represented by changes relative to nominal beam trajectory, most commonly as $\Delta t \Delta E$.

Now, with a firm understanding of what a phase space is, beam emittance can be described simply as a measure of the area of a particle beam in its phase space and is denoted by ε. In many practical cases, this area has an elliptical shape, as can be seen in Figure 2. The equation for the area of an ellipse can be used to confine the distribution of the beam in its phase space and calculate emittance. Recall that this area is πab, where a is the semi-major axis and b is the semi-minor axis of the ellipse. There are different conventions in defining the emittance of a beam; some include π in the numerical value of the emittance and some keep it as a unit—the latter convention is used in this paper. Using this convention, the units of emittance becomes $\pi\ mm.mrad$ (the reason for having the units of radians will be discussed later).

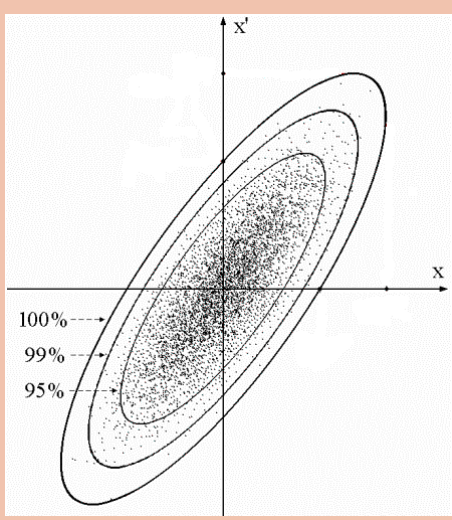


Figure 2: Area of a Beam in its xx' Dimension (1)

There are three ellipses shown in Figure 2, each of which contains a different percentage of the emittance. This is a convention that is used to indicate how much of the beam is actually confined by the calculated

emittance. This arises from the problem that due to nonlinear forces in an accelerator, particles cannot quite fit in an elliptical shape, and hence one needs to be specific about how his or her emittance is defined. (2)

In the case of transverse motion, the phase space area is decreased by a factor of $\gamma\beta$ of the beam, where γ is the Lorentz Factor and β is the velocity of the beam in units of c. Therefore, the physical emittance is commonly multiplied by this factor to give the "normalized emittance" ε_n, This factor must be divided out again when deriving physical quantities. When represented as $\Delta t \Delta E$, the longitudinal emittance remains constant with energy, although the shape will change.

In a particle beam, the emittance represents the distribution of particles about the nominal trajectory. The importance of measuring emittance for a beam is that, by measuring it in two or more different points along the beam, corrections can be applied to keep the shape of the emittance constant, and avoid irregularities and gaps in the shape, which would result in an effective increase.

3 Multi-wire Scanners/Emittance Probes

3.1 The Theory behind Multi-wire Scanners

There are different tools used to measure the emittance of a particle beam. One of the more commonly used devices is a multi-wire scanner, also known as emittance probe or just probe for short. In this method, as shown in Figure 3, only a very thin strip of the beam is allowed to pass through a slit and project onto a series of wires parallel to the slit on the opposite side.

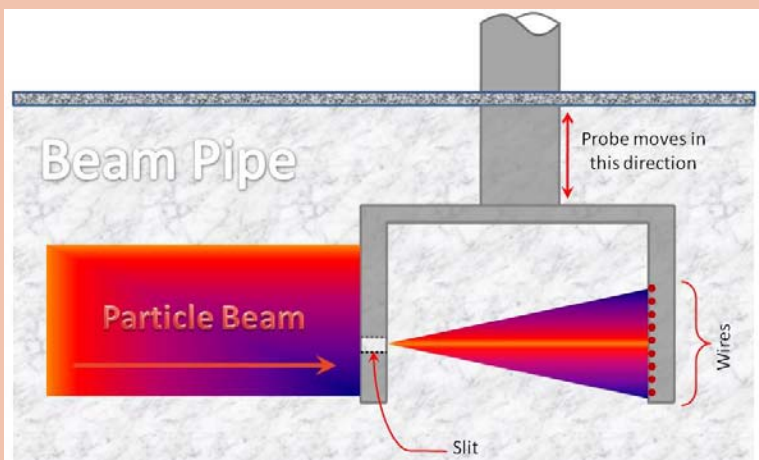


Figure 3: Schematics of a Multi-wire Probe and its Interaction with a Particle Beam

Note that Figure 3 only illustrates a very general schematic of the whole mechanism, and dimensions are not scaled and are crudely exaggerated; also note that a probe will not be confined by the beam pipe when it is not in use.

When wires get hit by particles, a voltage difference is generated across them. This voltage is proportional to the intensity of the beam, meaning that the wire that gets hit by the most number of particles registers the highest voltage. This allows for measuring the distribution of the strip of the particles that have passed through the slit and then calculate their very small angular deflection from the longitudinal direction—this is why units of radians are used for emittance. An example of this distribution can be seen in Figure 4—ideally this distribution should be a Gaussian.

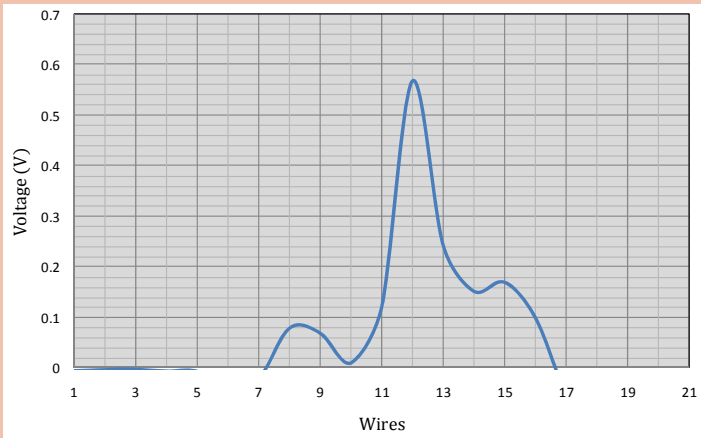


Figure 4: An Example of a Beam Distribution across the Wires of an Emittance Probe (This probe has 21 wires)

To make this picture clearer, note that in an ideal beam, every particle has a zero momentum in x and y direction, and therefore, is moving only in the longitudinal direction; such a beam has no angular deflection and its particles will be projected only onto the wire directly behind the slit.

Note that so far, only one thin strip of the beam has been scanned. To be able to calculate the emittance, the entire cross section of the beam needs to be scanned by moving the probe across the beam to construct a full distribution of the particles. Another important point to notice is that the deflection of the particles can only be measured along the direction perpendicular to the direction of the slit and wires. This means that if the probe is being moved in the horizontal direction x, the slit is in the vertical direction y, and the deflection can only be measured in the horizontal direction. Therefore, to construct the distribution of the particles in both phase spaces of xx' and yy' the beam needs to be scanned once in the horizontal direction and once in the vertical direction.

As an example to help visualizing how the motion of a probe and the location of its wires are related to the phase space of a beam, say the one illustrated in Figure 2 for a horizontal measurement, picture that the probe is moving along the x-axis in the plot and every time that it stops, wires measure voltages that are directly related to the particle density of the beam along the x'-axis for that specific x.

3.2 The Mechanical and Electronic Parts

An emittance probe, as seen in Figure 3 and Figure 5 consists of a rod attached to a cage that houses the slit on one side and the wires, parallel to the slit, on the opposite side. As can be seen in Figure 3, the probe is inserted radially into the beam pipe. For an accurate insertion rate into the pipe, a stepper motor is used to drive the rod connected to the cage. The motion of the probe is stepwise, meaning that the probe moves a certain distance into the pipe, it pauses for a certain time, and then it moves again. Every time that the probe stops, the slit scans a strip of the pipe's profile and projects it onto the wires behind it. Since the size of the particle beam is less than the size of the beam pipe, the slit does not see the beam at the beginning and the end of its motion as it moves across the pipe. However, as the slit comes into contact with the beam, the strip of the beam that passes through the slit is projected onto the wires behind the slit.

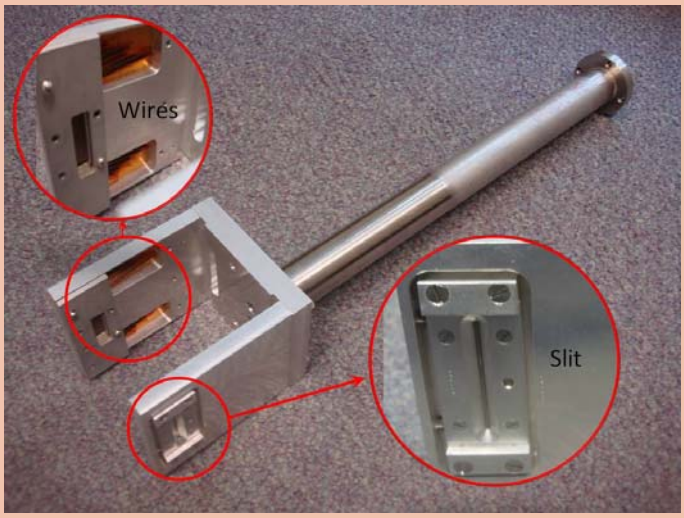


Figure 5: A Typical Multi-wire Scanner and its Main Features

The resolution of a measurement highly depends on the density of the wires embedded in a probe and the number of scans taken from the beam. The probe shown in Figure 5 has 21 wires separated by thin layers of plastic. A more sophisticated wire configuration, with higher wire density than the one in Figure 5, can be seen in Figure 6, where wires are compactly printed on a circuit board.

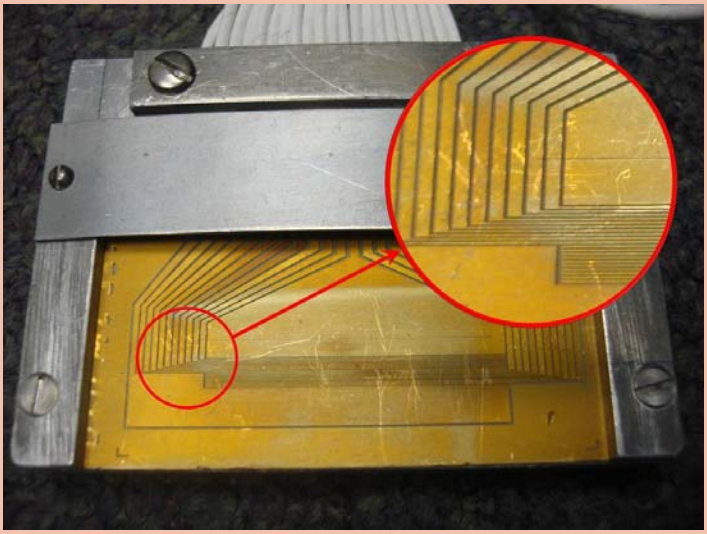


Figure 6: Wires on a Printed Circuit Board

Emittance measurements using multi-wire scanners are done in special circumstances and for a very short period of time to avoid beam interruption for too long (3). Another reason why emittance probes should not be exposed to a particle beam for too long is that radiation can damage them.

4 Results of the Emittance Measurements from the Fermilab Linac

For the emittance measurements of the Fermilab linac conducted on June 13, 2009, the step-size of $\Delta x = 0.051 cm$ is used for both the horizontal and the vertical probes, both of which have 21 wires with the angular resolution of $\Delta x' = 4.058\ mrad$.

The values of γ and β of the beam are 1 and 0.040 respectively—note that these values are unique for the location where the measurements are taken in the linac. At each stop that the probes make, as they scan the beam, the values of probe position, current, and voltage readings of each wire are collected three separate times to form a data set for each wire at each probe position.

As the first step in data reduction process, each data set is averaged to form a data point. Note that each of the voltage data points represents a unit area in the phase space of the beam, which is the product of Δx and $\Delta x'$ and is equal to $0.207\ mm.mrad$. To construct the area that represents the 100% emittance of this beam, a series of data filtering are applied.

As the first step in filtering the data, it is assumed that the slits on neither of the probes see the beam at the first five stops, meaning that the wires are not hit by particles and the voltage readings at these locations must be zero. Therefore, the data points (voltage readings) for each wire at its first five

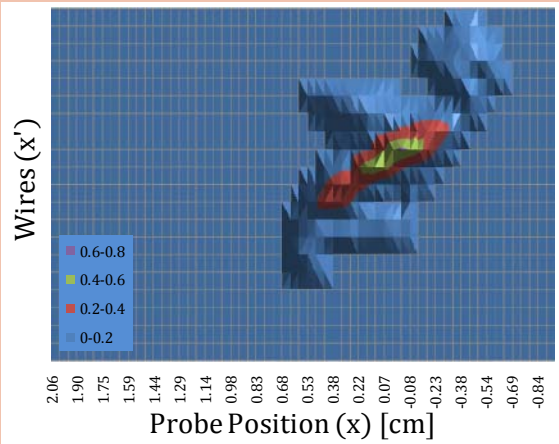
probe positions are considered background signal noise and are averaged and then subtracted from the rest of the data points of that wire. Since the values of these averaged data points are small compared to the rest of the data, this initial filtering introduces a small change in the data. To filter the data further and achieve a flat background for the particle distribution, two different methods are independently used as the next step. In the first method, all the data points that are within 99% of the maximum voltage are kept intact and the rest are set to be zero. In the second filtration method, all the data points that are above 0.01 are kept and the rest are changed to zero—Note that the cut-off value used in the second method highly depends on the gain used in the voltage readings.

As the next step, these two sets of filtered data, which represent the 100% emittance, are analyzed independently from each other using the same method to calculate the 95% emittance of the beam. For this stage, the remaining data points are added up to calculate the total voltage of the 100% emittance. After sorting these remaining data points from the largest to the smallest, the number of the top data points that account for 95% of the total voltage of the 100% emittance are counted; the 95% emittance is then calculated as the product of this number multiplied by the area of the unit cell of the probes. For a more detailed explanation of the above data reduction steps see Appendix B.

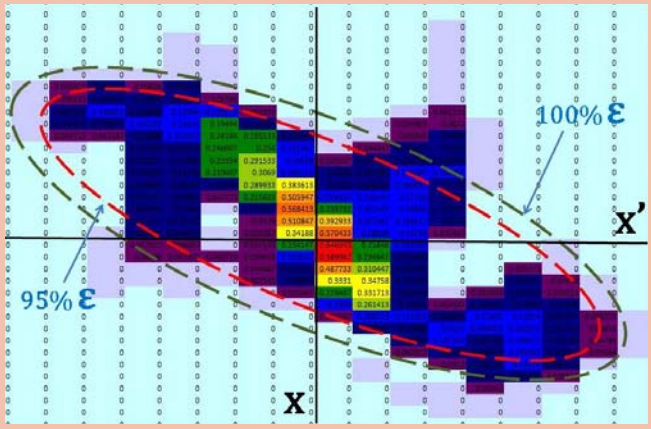
The results of the horizontal and vertical emittance calculations using the data filtered by *99%* of the maximum voltage are presented in Figure 7 and Figure 8 respectively. In these figures, the (a)-plots show the *95%* emittance and the (b)-plots show the comparison between the *95%* and *100%* emittance. In the (b)-plots, which have been rotated *90°* clockwise with respect to the (a)-plots, the very light blue background is the results of the data filtering by a percentage to achieve a flat background, the slightly darker blue shows the *100%* emittance and are the data points that survived this filtering, and all the other darker colors illustrate the final remaining data after counting how many data points account for *95%* of the slightly darker blue data—for color coding, please refer to Appendix B. And finally, the (c)-plots in Figure 7 and Figure 8 illustrate 3D graph of the *95%* emittance for the horizontal and vertical emittance respectively.

Because the difference between the results generated from the two different filtering methods are very subtle and cannot easily be seen, the plots of the data filtered by a cut-off value are not shown in this paper.

The final results of this measurement for the horizontal and vertical emittance are tabulated in Table 1 and Table 2 (These are the only two tables tabulated in this paper and should not be confused with Table 1 and Table 2 in MEMP which are discussed in detail in Appendix B).



(a)



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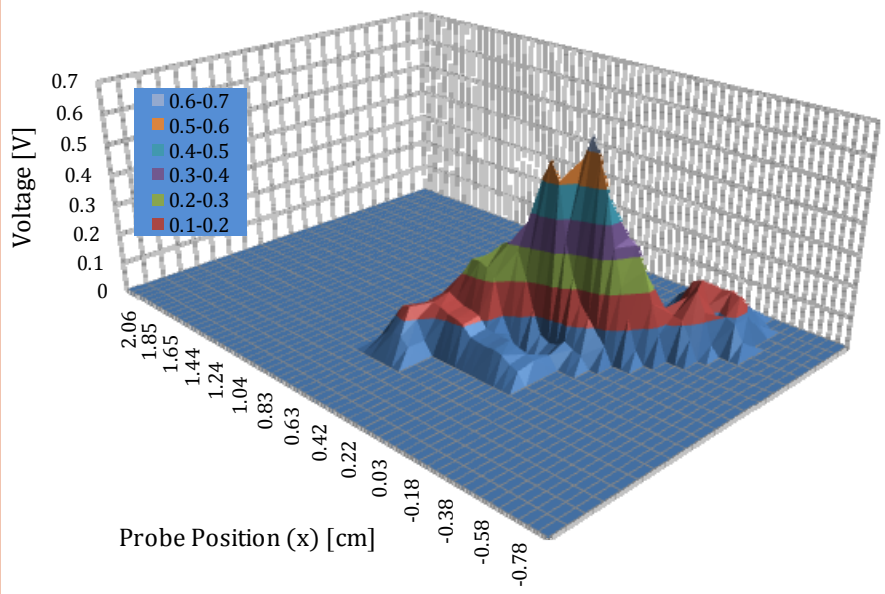
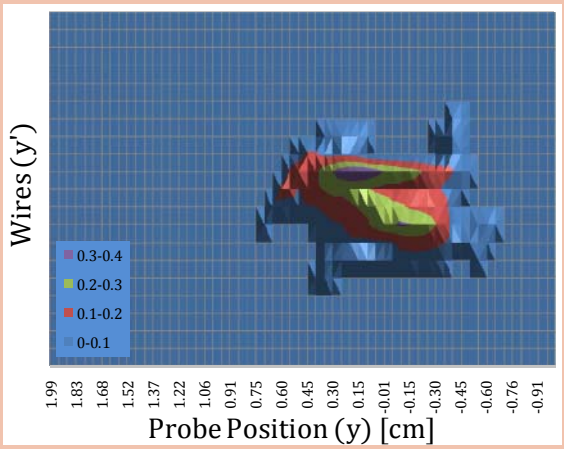


(c)

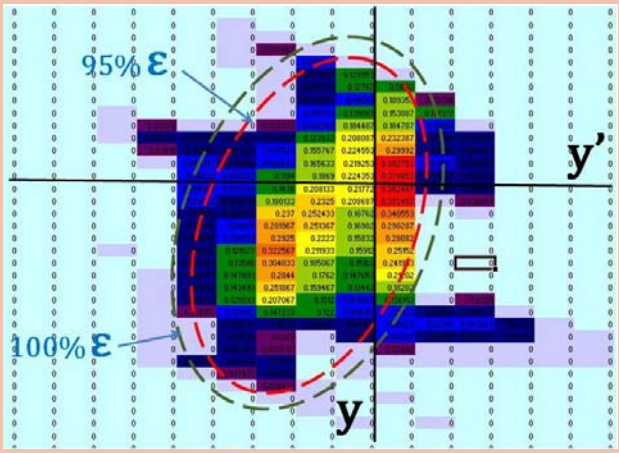
Figure 7: Emittance in the Horizontal Direction (□□'): (a) Plot of the 95% Emittance, (b) Comparison Between the 100% and 95% Emittance, and (c) 3D Plot of the 95% Emittance.

Table 1: Comparison of the Final Horizontal Emittance Measurements Using the Two Different Filtering Methods

Horizontal Emittance	100%ε π mm.mrad	100%ε_n π mm.mrad	95%ε π mm.mrad	95%ε_n π mm.mrad
Data Filtered by a Percentage	170.6	6.825	117.3	4.690
Data Filtered by a Cut-Off Value	158.1	6.324	114.6	4.585



(a)



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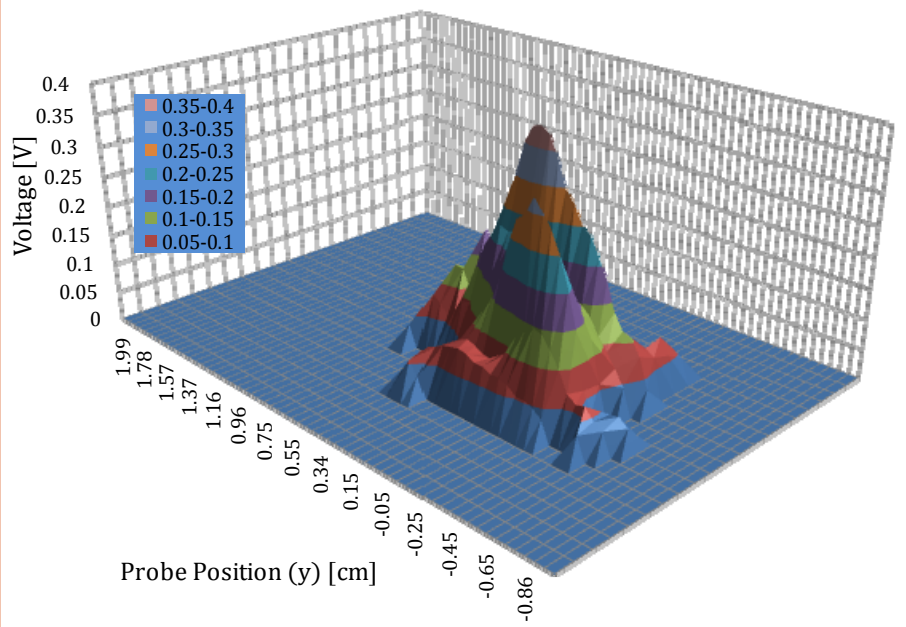

(c)

Figure 8: Emittance in the Vertical Direction (□□'): (a) Plot of the 95% Emittance, (b) Comparison Between the 100% and 95% Emittance, and (c) 3D Plot of the 95% Emittance.

Table 2: Comparison of the Final Vertical Emittance Measurements Using the Two Different Filtering Methods

Vertical Emittance	100%ε π mm.mrad	100%ε_n π mm.mrad	95%ε π mm.mrad	95%ε_n π mm.mrad
Data Filtered by a Percentage	142.3	5.692	99.47	3.979
Data Filtered by a Cut-Off Value	125.8	5.033	96.18	3.847

5 Conclusion

Detailed discussion of the results has been omitted in the previous section because the results of these measurements are entirely meant to be an example and basis for future emittance measurements in the linac. An effort was made throughout this paper to combine and gather all the necessary tools that one might need to know in order to measure the emittance of the linac using the Multi-wire Emittance Measurements method.

6 Acknowledgements

My stay at the Fermi National Accelerator Laboratory (Fermilab) as a summer undergraduate student, through the Lee Teng Internship, has undoubtedly been an unforgettable experience. Throughout the ten-week period of this program, I have met with many great scientists and engineers who have helped me a great deal in my research and guided me towards becoming a scientist myself.

First and foremost, I would like to thank the Department of Energy (DOE) for supporting the growth of science and knowledge and creating opportunities for young scientists, like me, to gain experience. I would also like to thank Fermilab for creating such amazing and interactive environment for the students and others to learn, teach, explore, and appreciate the beauties of science.

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Appendix A: How to Use Multi-wire Scanners at Fermilab Linac

Preparations before Measurements

There are several emittance probes located along the Fermilab linac. Probes 3 and 4, which were used for the emittance measurements conducted on June 13, 2009 and presented in this paper, are used as an example here to show what preparations need to be done before an emittance measurements. Probes 3 and 4 are used to scan the beam in the horizontal and vertical directions respectively. These two probes are located at the beginning of the line and before Tank 1 in the linac as seen in Figure 9 and Figure 10.

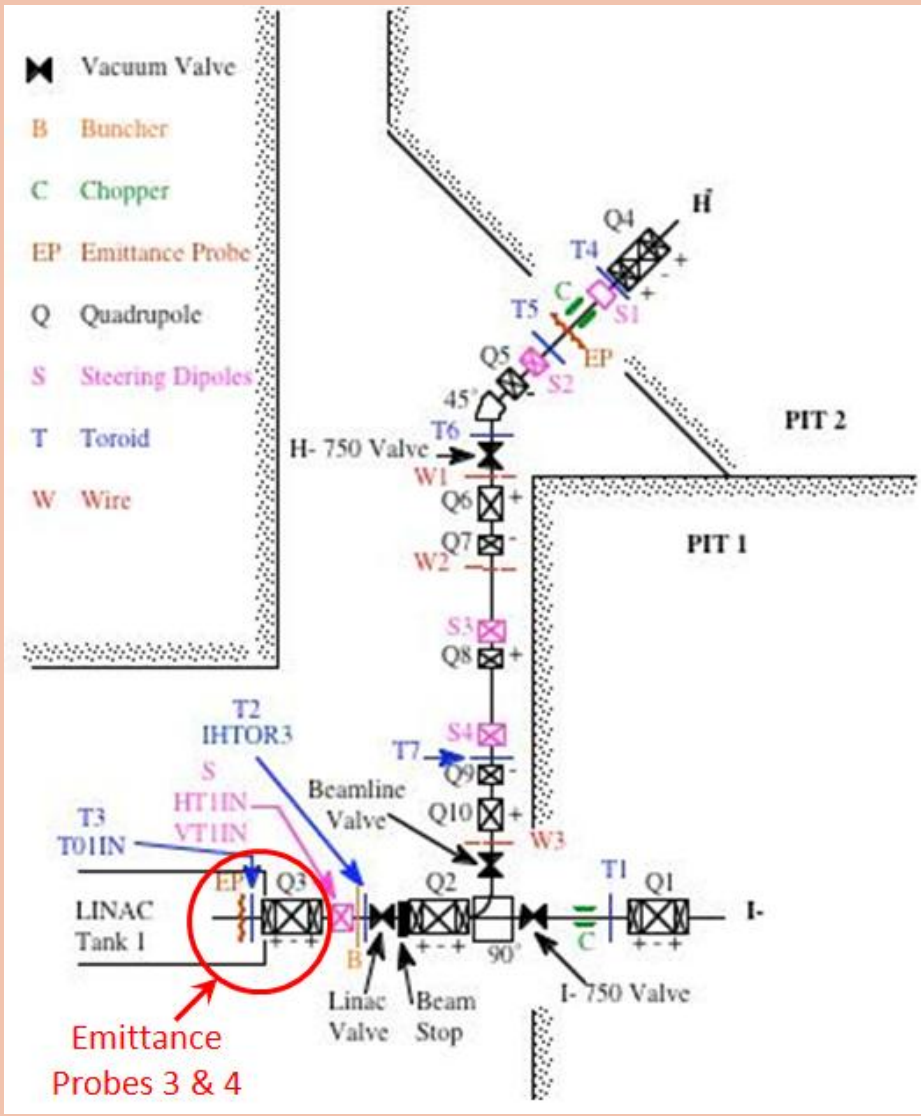


Figure 9: Layout of the Fermilab's 750 KeV Transport Line (3)

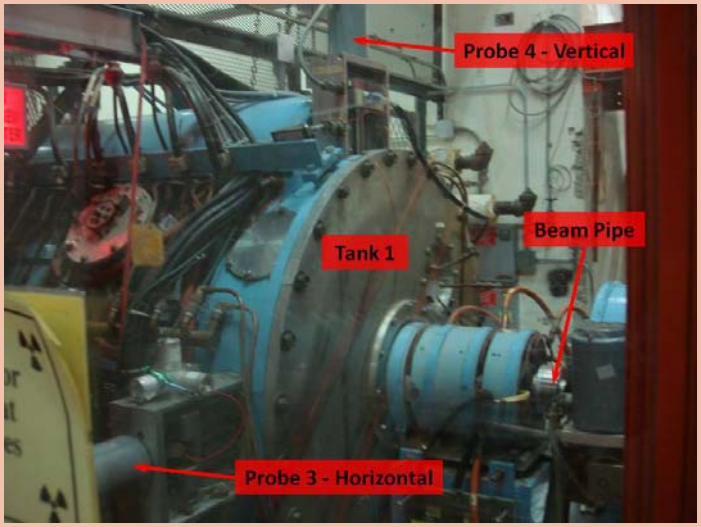


Figure 10: Location and Orientation of Probes 3 & 4

A close-up of Probe 3 attached to its stepper motor is shown in Figure 11.

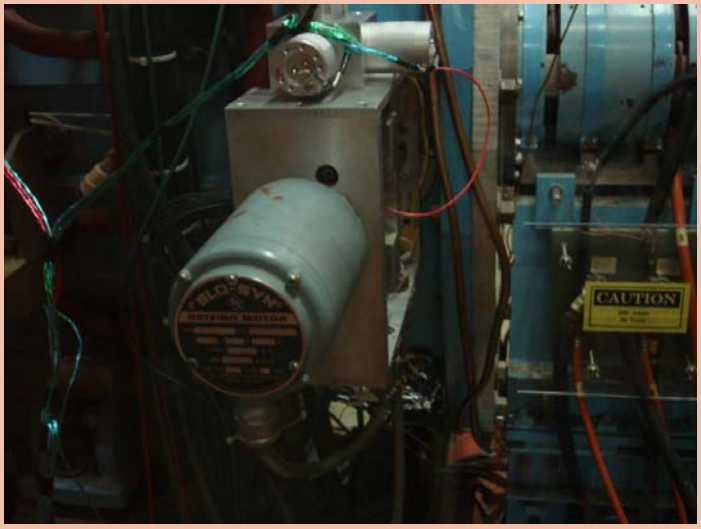


Figure 11: Close-up of Probe 3

An emittance measurement can be operated from the Main Control Room (MCR). However, prior to the start of the measurement, a few procedures must be taken manually to prepare the emittance probes. Since these measurements are not taken very often, the probe connection cables are kept unplugged. Figure 12 shows the location of these cables.

Figure 12: Connection Cables for Probes 3 & 4

Note that there are three cables in the picture; the two black cables belong to Probes 3 and 4, and the green cable is used to connect one probe at a time to MCR. In order to control the motion of a probe from MCR its cable must be plugged into the right connection manually.

It should also be noted that the "control" of a probe, when the probe is not in use, is always set to "Local". For emittance measurements, when the motion of the probe needs to be controlled from MCR, the control must be switched to "Remote." Note that the probes' control box, seen in Figure 13 and Figure 14, is located on the opposite side of the cables in Figure 12.

Figure 13: Probe Control Box

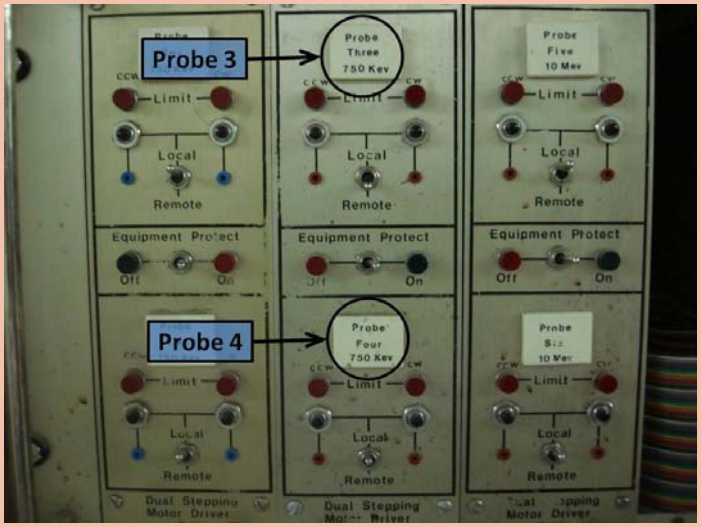


Figure 14: Close-up of the Control Box

Measurements and Recording Data at the Main Control Room

The program that controls the probe has the access code of L43 and can be accessed in MCR. Several options can be adjusted in this program such as the step-size of the probe and the timeout of the measurements. Changing the step-size allows users to change the resolution of the measurements by increasing the number of scans that probe takes from the beam. The starting position of the probe can also be indicated in the program.

After the initial preparations and once the probe is fully ready to start the measurements, beam can be switched on from MCR. The master switch is the top-left switch on the "Fermilab Beam Switch Box" seen in Figure 15—the beam is switched off in this figure.

Figure 15: Fermilab Beam Switch Box

Note that the exposure time of the probe to the beam must be minimized—radiation can greatly damage the probe. This means that the master switch should only be activated when all the preparations have been done.

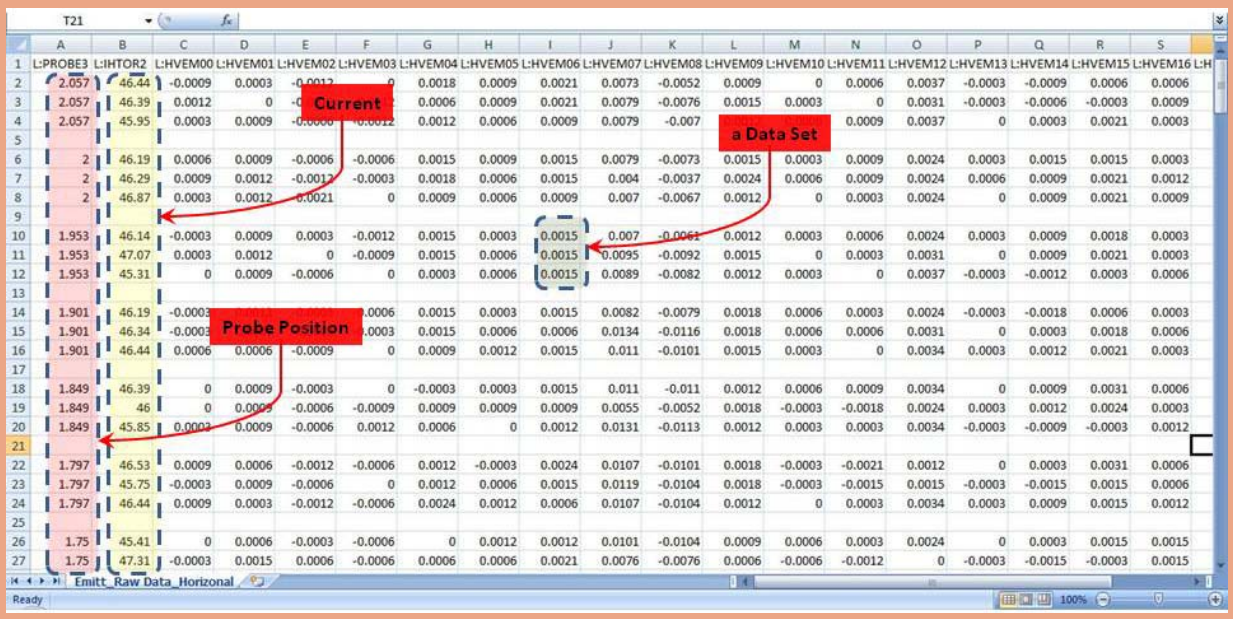
The motion of the probe can be controlled manually by either clicking a button in the program or turning the knob on the beam switch box. The difference is that clicking moves the probe slowly and accurately, but turning the knob moves the probe fast and less accurate. To reduce the probe's exposure time, it is recommended to take the following procedure. First, switch the beam on, then use the knob to scan the beam-pipe to find the beam as fast as possible and record the radial location of the probe at this point, turn the beam off and set the starting position of the probe to a slightly lower number in the program, and then switch the beam on again and use the program to move the probe to make measurements.

The L43 program window, some plots of the intensity of the beam, and the Fermilab Beam Switch Box can be seen in Figure 16—this is one of the control stations in MCR.

Figure 16: A Control Station at the Fermilab's Main Control Room

Appendix B: Data Reduction and Analysis

The L43 program generates an Excel sheet similar to the sheet seen in Figure 17.



	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S
1	L:PROBE3	L:IHTOR2	L:HVEM00	L:HVEM01	L:HVEM02	L:HVEM03	L:HVEM04	L:HVEM05	L:HVEM06	L:HVEM07	L:HVEM08	L:HVEM09	L:HVEM10	L:HVEM11	L:HVEM12	L:HVEM13	L:HVEM14	L:HVEM15	L:HVEM16
2	2.057	46.44	-0.0009	0.0003	-0.0012	0	0.0018	0.0009	0.0021	0.0073	-0.0052	0.0009	0	0.0006	0.0037	-0.0003	-0.0009	0.0006	0.0006
3	2.057	46.39	0.0012	0	[illegible]	[illegible]	0.0006	0.0009	0.0021	0.0079	-0.0076	0.0015	0.0003	0	0.0031	-0.0003	-0.0006	-0.0003	0.0009
4	2.057	45.95	0.0003	0.0009	[illegible]	[illegible]	0.0012	0.0006	0.0009	0.0079	-0.007	[illegible]	[illegible]	0.0009	0.0037	0	0.0003	0.0021	0.0003
5																			
6	2	46.19	0.0006	0.0009	-0.0006	-0.0006	0.0015	0.0009	0.0015	0.0079	-0.0073	0.0015	0.0003	0.0009	0.0024	0.0003	0.0015	0.0015	0.0003
7	2	46.29	0.0009	0.0012	-0.0012	-0.0003	0.0018	0.0006	0.0015	0.004	-0.0037	0.0024	0.0006	0.0009	0.0024	0.0006	0.0009	0.0021	0.0012
8	2	46.87	0.0003	0.0012	-0.0021	0	0.0009	0.0006	0.0009	0.007	-0.0067	0.0012	0	0.0003	0.0024	0	0.0009	0.0021	0.0009
9																			
10	1.953	46.14	-0.0003	0.0009	0.0003	-0.0012	0.0015	0.0003	0.0015	0.007	-0.0061	0.0012	0.0003	0.0006	0.0024	0.0003	0.0009	0.0018	0.0003
11	1.953	47.07	0.0003	0.0012	0	-0.0009	0.0015	0.0006	0.0015	0.0095	-0.0092	0.0015	0	0.0003	0.0031	0	0.0009	0.0021	0.0003
12	1.953	45.31	0	0.0009	-0.0006	0	0.0003	0.0006	0.0015	0.0089	-0.0082	0.0012	0.0003	0	0.0037	-0.0003	-0.0012	0.0003	0.0006
13																			
14	1.901	46.19	[illegible]	[illegible]	[illegible]	[illegible]	0.0015	0.0003	0.0015	0.0082	-0.0079	0.0018	0.0006	0.0003	0.0024	-0.0003	-0.0018	0.0006	0.0003
15	1.901	46.34	[illegible]	[illegible]	[illegible]	[illegible]	0.0015	0.0006	0.0006	0.0134	-0.0116	0.0018	0.0006	0.0006	0.0031	0	0.0003	0.0018	0.0006
16	1.901	46.44	0.0006	0.0006	-0.0009	0	0.0009	0.0012	0.0015	0.011	-0.0101	0.0015	0.0003	0	0.0034	0.0003	0.0012	0.0021	0.0003
17																			
18	1.849	46.39	0	0.0009	-0.0003	0	-0.0003	0.0003	0.0015	0.011	-0.011	0.0012	0.0006	0.0009	0.0034	0	0.0009	0.0031	0.0006
19	1.849	46	0	0.0009	-0.0006	-0.0009	0.0009	0.0009	0.0009	0.0055	-0.0052	0.0018	-0.0003	-0.0018	0.0024	0.0003	0.0012	0.0024	0.0003
20	1.849	45.85	0.0003	0.0009	-0.0006	0.0012	0.0006	0	0.0012	0.0131	-0.0113	0.0012	0.0003	0.0003	0.0034	-0.0003	-0.0009	-0.0003	0.0012
21																			
22	1.797	46.53	0.0009	0.0006	-0.0012	-0.0006	0.0012	-0.0003	0.0024	0.0107	-0.0101	0.0018	-0.0003	-0.0021	0.0012	0	0.0003	0.0031	0.0006
23	1.797	45.75	-0.0003	0.0009	-0.0006	0	0.0012	0.0006	0.0015	0.0119	-0.0104	0.0018	-0.0003	-0.0015	0.0015	-0.0003	-0.0015	0.0015	0.0006
24	1.797	46.44	0.0009	0.0003	-0.0012	-0.0006	0.0024	0.0012	0.0006	0.0107	-0.0104	0.0012	0	0.0003	0.0034	0.0003	0.0009	0.0015	0.0012
25																			
26	1.75	45.41	0	0.0006	-0.0003	-0.0006	0	0.0012	0.0012	0.0101	-0.0104	0.0009	0.0006	0.0003	0.0024	0	0.0003	0.0015	0.0015
27	1.75	47.31	-0.0003	0.0015	0.0006	-0.0006	0.0006	0.0006	0.0021	0.0076	-0.0076	0.0006	-0.0006	-0.0012	0	-0.0003	-0.0015	-0.0003	0.0015

Figure 17: An Example of the Raw Data Generated by L43 in Excel

The first column in this sheet shows the position of the probe in units of cm, the second column shows the recorded current in units of mA, and the rest of the columns each represent one of the wires in the probe and show the voltage readings in units of volts. Every time that probe stops to scan the beam, L43 makes three measurements of the position, the current, and the voltage—each three rows of data in the raw data sheet will be referred to as a data set from this point on. By taking the average of each data set, the accuracy of the measurements can be slightly improved.

The amount of raw data that needs to be reduced for a single reading depends on the number of wires, designated step-size of the probe, number of readings that L43 performs in each stop, and obviously the size of the beam. Probes usually have in the order of 20 to 50 wires (this can vary!), and depending on the desired accuracy, the step-size of the probe can vary for different measurements—the smaller the step-size, the more stops the probe needs to make before it scans the beam completely. As an example, the probe used for the measurements performed in this paper has 21 wires with a step-size of 0.051 cm; and to scan the Fermilab's linac beam, in the horizontal direction, 60 stops had to be made. This means that there are 60 times 23 (21 wires plus one position and one current readings) times 3 (cells per data set) cells that need to be analyzed. To make the data reduction process faster and repeatable for future measurements, a series of macros have been written and combined in an Excel file that allows one

to copy-paste his or her raw data into a table in the program and analyze the data to calculate the emittance—this program will be referred to as the Multi-wire Emittance Measurements Program (MEMP) in this paper.

How to Use the "Multi-wire Emittance Measurements Program" (MEMP)

The details of this program are explained in the next two sections. The first section is a quick manual and is aimed to familiarize users with the general layout of the program; this section also contains some recommendations that can make emittance calculations in MEMP a lot faster. The second section goes into more details and explains how the calculations are carried out in each table in the program.

Please note that MEMP is a combination of nine tables (Tables 1, 2, 3, 4, 4a, 4b, 5, 5a, and 5b), and referring to any of these tables means that it exists in the program and NOT in this paper.

A Quick Manual and Recommendations for MEMP

To use this program, follow this procedure:

1- MEMP is an Excel Macro-Enabled Workbook. Once this Excel file is opened, a security warning is shown above the "Formula Bar" that states that macros have been disabled. To proceed, click on "Options…," choose "Enable this content," and then click "Ok."

2- To start a new emittance measurements, all the data and colored cells must be refreshed/cleared in all tables (Tables 1, 2, 3, 4, 4a, 4b, 5, 5a, and 5b). This can be done by doing one of the followings:

(a) Automatic Clearing: First, click "Clear All Tables" button above Table 2 to clear Tables 2 through 5b (this can take several minutes!); and then click "Clear Table 1" button above Table 1 (this only takes a few seconds!),

or

(b) Manual Clearing: Highlight all the data inside each table separately, then press the "Delete" button on the keyboard and then change the "Fill Color" in Excel to "No Fill."

3- After clearing all data, copy the raw data (including the headings) from your Excel sheet and paste it onto cell A11 in MEMP.

4- To the left of each table (except Table 1) there is:

(a) a button that executes the specific task assign to that table.

(b) a message box that reads either “Processing!” with a red background during the execution of the code or “Done Processing!” with a green background after the calculations are done.

(c) a box with the table number in it.

(d) a box showing the table’s caption (A short phrase that describes what the table does)

(e) a box with instructions and detailed description of the table, and instruction of which table to use next.

(f) a box that allows users to choose a value (Only Tables 4, 4a, 5, and 5a have this box)

(g) a reference guide for the color-coding (Only Tables 4a, 4b, 5a, and 5b have this feature)

(h) a box called “Location Reference Values.” Note that this box is ONLY used to keep track of where each table is located and such.

The above features are shown in Figure 18 and Figure 19.

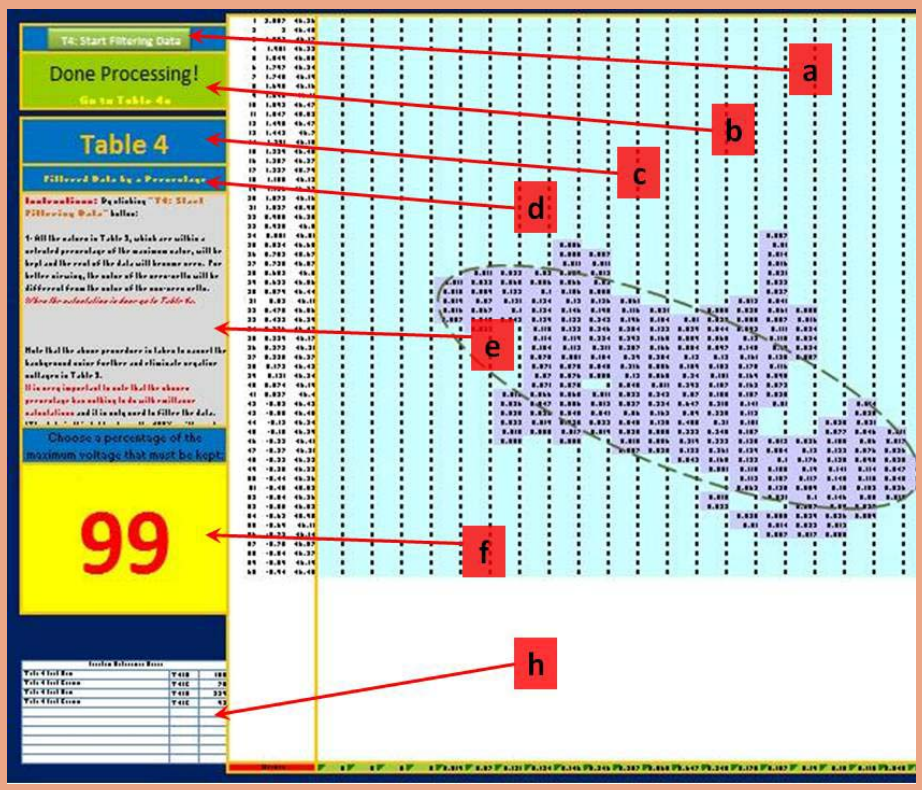


Figure 18: Illustration of the Features Explained in Step 4 of the Quick Manual for MEMP (Table 4 in MEMP)

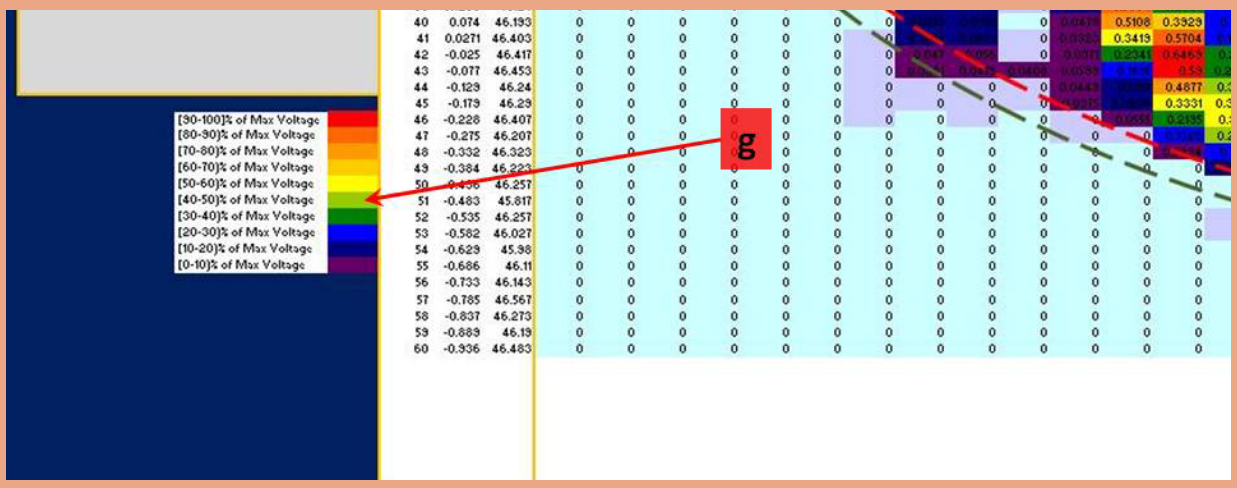


Figure 19: Illustration of the Features Explained in Step 4 of the Quick Manual for MEMP (Cont.) (Table 4b in MEMP)

5- To the right of each table (except Table 1) there is:

(a) a small table that shows the maximum voltage, the average current, and the total voltage calculated in the corresponding table. For Tables 4, 4b, 5, and 5b this box also shows the number of non-zero cells and the total sum of the non-zero cells (note that this sum must be equal to the total voltage).

(b) six windows reserved for any plots deemed appropriate by the user. (Each of these reserved windows has a small box below it for descriptions).

The above features are shown in Figure 20.

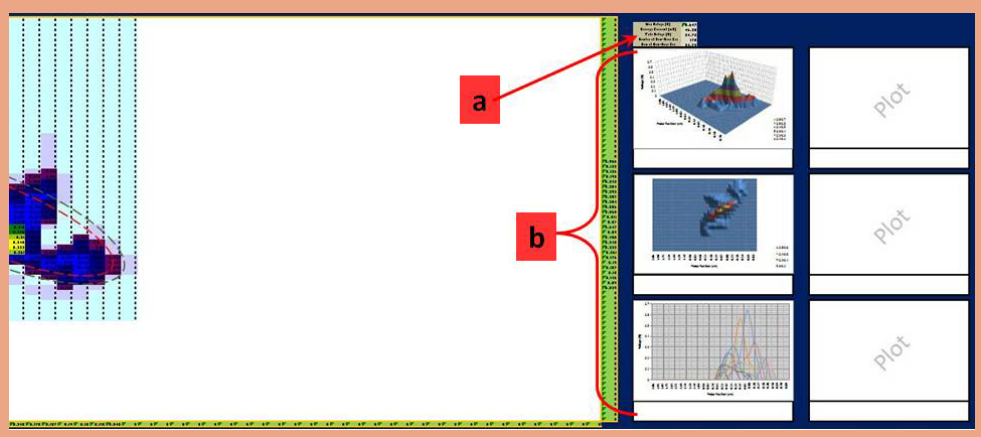


Figure 20: Illustration of the Features Explained in Step 5 of the Quick Manual for MEMP (Table 4b in MEMP)

6- After going through all tables, a summary of all calculations can be seen to the right of Table 4b. There are several boxes here; the one on the top that contains all the general parameters that can be adjusted and/or entered. The boxes below that contain the data from the tables and final calculations of emittance. These tables can be seen in Figure 21.

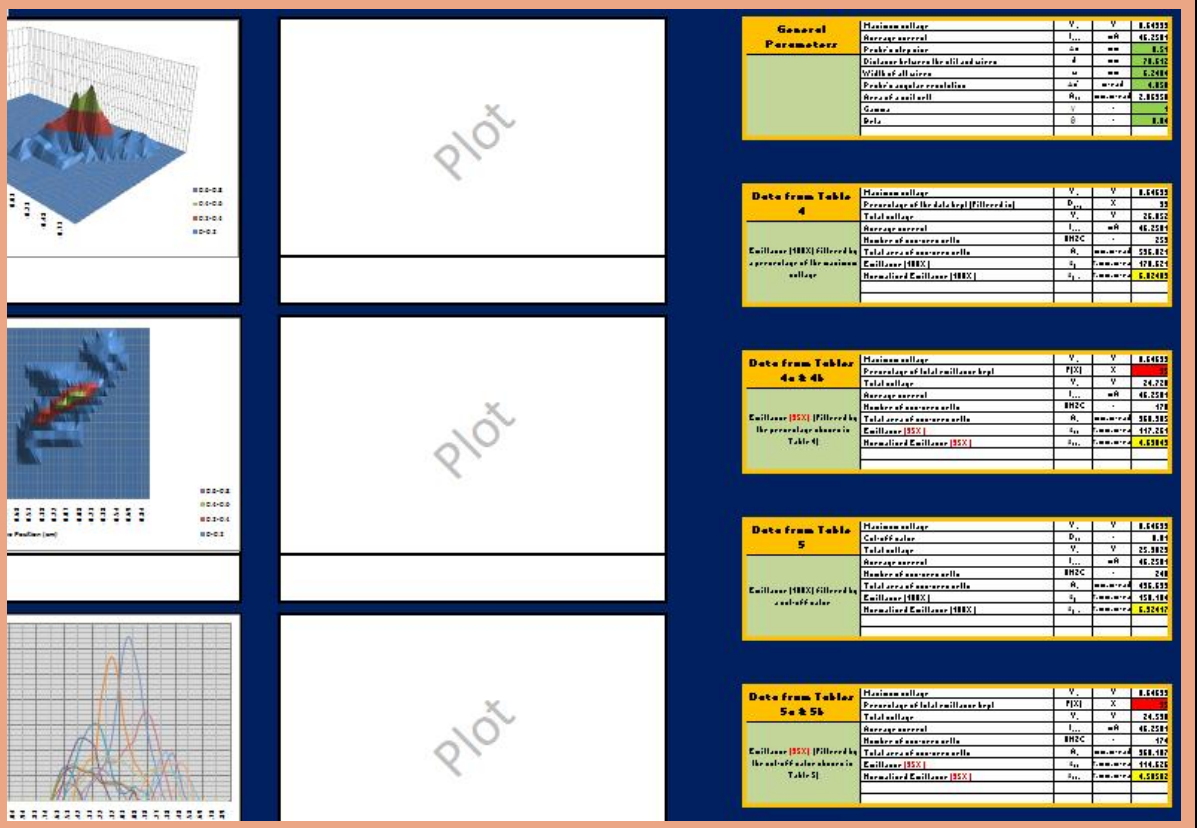


Figure 21: Data Summary Tables in MEMP

Calculations in Excel are relatively slow; therefore, to make the measurements faster it is highly recommended to:

(a) Use Manual Clearing (See 2b above).

(b) When clicking on a button to execute the code for a table (see 4a), try to zoom-in on the execution button to the point where not much of the respective table can be seen on the screen. When a bigger zoom is used, Excel shows the execution of the Visual Basic codes graphically and cell by cell—this slows down the code execution drastically! (This is very important to note)

(c) To make the navigation between different tables easier, a series of custom views are predefined in Excel. To use this feature, go to "View" on Excel's menu bar, click "Custom Views," and then choose any of the predefined views.

(d) The maximum number of wires and probe positions that this program can handle is 50 and 80 respectively. If a larger number is needed, the code can be modified. Note that this requires changing the location of the tables and some calculations.

(e) The maximum number of non-zero cells that this program can handle is 700. This limitation is caused by the size of Tables 4a and 5a. The code can be modified if a larger number is needed.

Detailed Description of the Calculations in MEMP

The calculations in this Excel program are divided into a series of tables. The reason for having a step by step calculation through different tables, rather than a single step calculation, is to allow users to have more control over some of the variables throughout the process. For instance, sometimes it might be needed to go back and change one or two options in a few tables, and therefore, the execution of the entire program from scratch is unnecessary. The flow of data reduction in MEMP is shown in Figure 22.

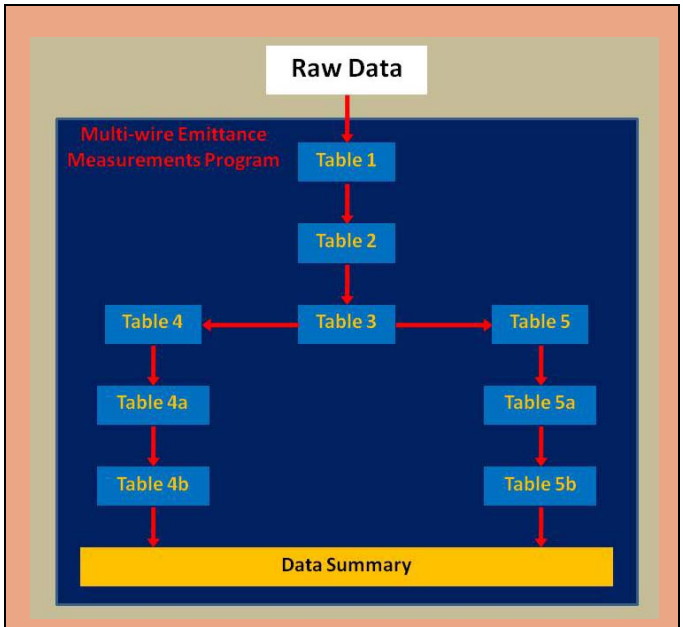
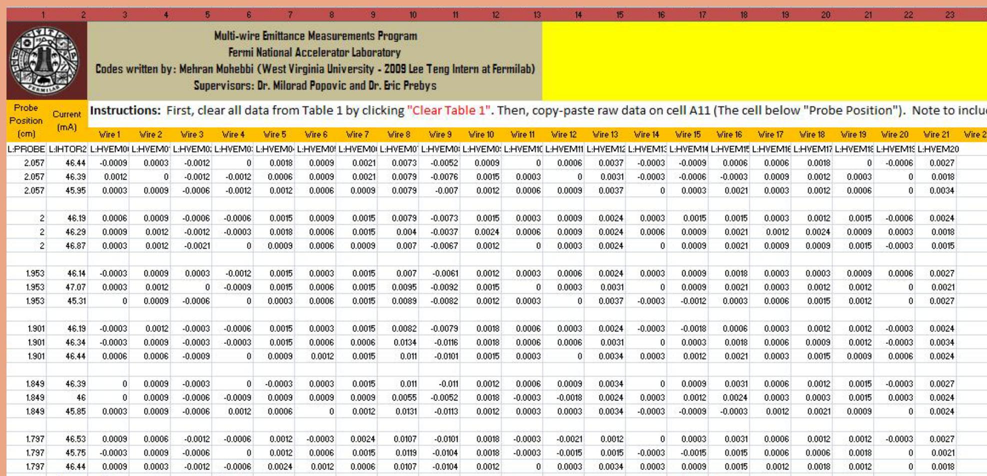


Figure 22: Flow of Data Reduction in MEMP

Table 1

After taking Step 2 of the procedure in the previous section and clearing all the old data from all tables, the new raw data can be pasted into Table 1 of the program. This table can be seen in Figure 23.

Note that all the tables in this program, except for Tables 1, 4a, and 5a, show the maximum voltage, the average current, and the total voltage in a small table to the right of them.

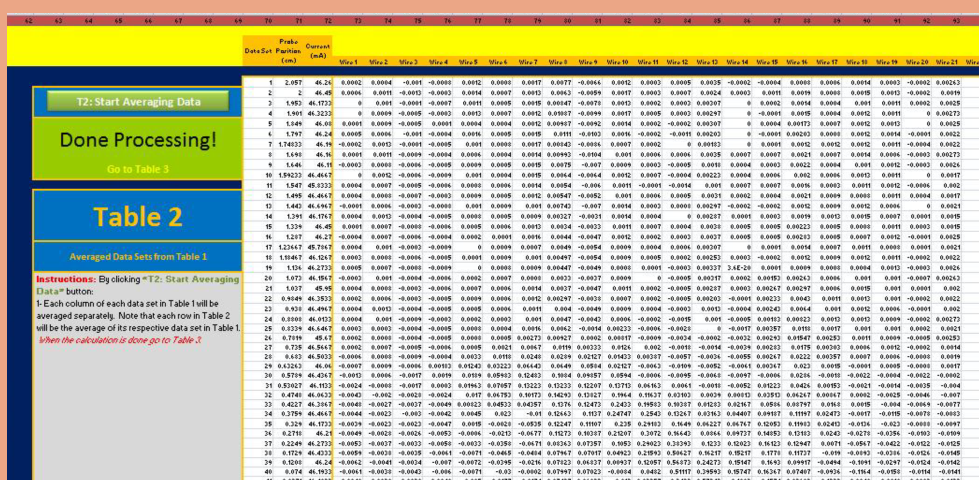


Probe Position (cm)	Current (mA)	Wire 1	Wire 2	Wire 3	Wire 4	Wire 5	Wire 6	Wire 7	Wire 8	Wire 9	Wire 10	Wire 11	Wire 12	Wire 13	Wire 14	Wire 15	Wire 16	Wire 17	Wire 18	Wire 19	Wire 20	Wire 21	Wire 22
L:PROBE	L:IHTOR2	L:HVEM0(	L:HVEM0'	L:HVEM0:	L:HVEM0:	L:HVEM0·	L:HVEM0!	L:HVEM0(	L:HVEM0'	L:HVEM0:	L:HVEM0:	L:HVEM1(	L:HVEM11	L:HVEM12	L:HVEM1:	L:HVEM14	L:HVEM1!	L:HVEM1(	L:HVEM1?	L:HVEM1(	L:HVEM1!	L:HVEM20	
2.057	46.44	-0.0009	0.0003	-0.0012	0	0.0018	0.0009	0.0021	0.0073	-0.0052	0.0009	0	0.0006	0.0037	-0.0003	-0.0009	0.0006	0.0006	0.0018	0	-0.0006	0.0027	
2.057	46.39	0.0012	0	-0.0012	-0.0012	0.0006	0.0009	0.0021	0.0079	-0.0076	0.0015	0.0003	0	0.0031	-0.0003	-0.0006	-0.0003	0.0009	0.0012	0.0003	0	0.0018	
2.057	45.95	0.0003	0.0009	-0.0006	-0.0012	0.0012	0.0006	0.0009	0.0079	-0.007	0.0012	0.0006	0.0009	0.0037	0	0.0003	0.0021	0.0003	0.0012	0.0006	0	0.0034	
2	46.19	0.0006	0.0009	-0.0006	-0.0006	0.0015	0.0009	0.0015	0.0079	-0.0073	0.0015	0.0003	0.0009	0.0024	0.0003	0.0015	0.0015	0.0003	0.0012	0.0015	-0.0006	0.0024	
2	46.29	0.0009	0.0012	-0.0012	-0.0003	0.0018	0.0006	0.0015	0.004	-0.0037	0.0024	0.0006	0.0009	0.0024	0.0006	0.0009	0.0021	0.0012	0.0024	0.0009	0.0003	0.0018	
2	46.87	0.0003	0.0012	-0.0021	0	0.0009	0.0006	0.0009	0.007	-0.0067	0.0012	0	0.0003	0.0024	0	0.0009	0.0021	0.0009	0.0009	0.0015	-0.0003	0.0015	
1.953	46.14	-0.0003	0.0009	0.0003	-0.0012	0.0015	0.0003	0.0015	0.007	-0.0061	0.0012	0.0003	0.0006	0.0024	0.0003	0.0009	0.0018	0.0003	0.0003	0.0009	0.0006	0.0027	
1.953	47.07	0.0003	0.0012	0	-0.0009	0.0015	0.0006	0.0015	0.0095	-0.0092	0.0015	0	0.0003	0.0031	0	0.0009	0.0021	0.0003	0.0012	0.0012	0	0.0021	
1.953	45.31	0	0.0009	-0.0006	0	0.0003	0.0006	0.0015	0.0089	-0.0082	0.0012	0.0003	0	0.0037	-0.0003	-0.0012	0.0003	0.0006	0.0015	0.0012	0	0.0027	
1.901	46.19	-0.0003	0.0012	-0.0003	-0.0006	0.0015	0.0003	0.0015	0.0082	-0.0079	0.0018	0.0006	0.0003	0.0024	-0.0003	-0.0018	0.0006	0.0003	0.0012	0.0012	-0.0003	0.0024	
1.901	46.34	-0.0003	0.0009	-0.0003	-0.0003	0.0015	0.0006	0.0006	0.0134	-0.0116	0.0018	0.0006	0.0006	0.0031	0	0.0003	0.0018	0.0006	0.0009	0.0012	-0.0003	0.0034	
1.901	46.44	0.0006	0.0006	-0.0009	0	0.0009	0.0012	0.0015	0.011	-0.0101	0.0015	0.0003	0	0.0034	0.0003	0.0012	0.0021	0.0003	0.0015	0.0009	0.0006	0.0024	
1.849	46.39	0	0.0009	-0.0003	0	-0.0003	0.0003	0.0015	0.011	-0.011	0.0012	0.0006	0.0009	0.0034	0	0.0009	0.0031	0.0006	0.0012	0.0015	-0.0003	0.0027	
1.849	46	0	0.0009	-0.0006	-0.0009	0.0009	0.0009	0.0009	0.0055	-0.0052	0.0018	-0.0003	-0.0018	0.0024	0.0003	0.0012	0.0024	0.0003	0.0003	0.0015	0.0003	0.0024	
1.849	45.85	0.0003	0.0009	-0.0006	0.0012	0.0006	0	0.0012	0.0131	-0.0113	0.0012	0.0003	0.0003	0.0034	-0.0003	-0.0009	-0.0003	0.0012	0.0021	0.0009	0	0.0024	
1.797	46.53	0.0009	0.0006	-0.0012	-0.0006	0.0012	-0.0003	0.0024	0.0107	-0.0101	0.0018	-0.0003	-0.0021	0.0012	0	0.0003	0.0031	0.0006	0.0012	0.0012	-0.0003	0.0027	
1.797	45.75	-0.0003	0.0009	-0.0006	0	0.0012	0.0006	0.0015	0.0119	-0.0104	0.0018	-0.0003	-0.0015	0.0015	-0.0003	-0.0015	0.0015	0.0006	0.0006	0.0018	0	0.0021	
1.797	46.44	0.0009	0.0003	-0.0012	-0.0006	0.0024	0.0012	0.0006	0.0107	-0.0104	0.0012	0	0.0003	0.0034	0.0003	0.0009	0.0015	0.0012	0.0018	0.0012	0	0.0018	

Figure 23: Table 1 in the Multi-wire Emittance Measurements Program

Table 2

To take the average of all the data sets seen in Figure 23, go to Table 2 in the program and click "T2: Start Averaging Data." In this table, as seen in Figure 24, each three rows of data from Table 1 (each data set), is reduced to one row—this means that the number of rows of data in Table 2 is equal to the number of stops made by the probe when scanning the beam.



Data Set	Probe Position (cm)	Current (mA)	Wire 1	Wire 2	Wire 3	Wire 4	Wire 5	Wire 6	Wire 7	Wire 8	Wire 9	Wire 10	Wire 11	Wire 12	Wire 13	Wire 14	Wire 15	Wire 16	Wire 17	Wire 18	Wire 19	Wire 20	Wire 21	Wire 22
1	2.057	46.26	0.0002	0.0004	-0.001	-0.0008	0.0012	0.0008	0.0017	0.0077	-0.0066	0.0012	0.0003	0.0005	0.0035	-0.0002	-0.0004	0.0008	0.0006	0.0014	0.0003	-0.0002	0.00263	
2	2	46.45	0.0006	0.0011	-0.0013	-0.0003	0.0014	0.0007	0.0013	0.0063	-0.0059	0.0017	0.0003	0.0007	0.0024	0.0003	0.0011	0.0019	0.0008	0.0015	0.0013	-0.0002	0.0019	
3	1.953	46.1733	0	0.001	-0.0001	-0.0007	0.0011	0.0005	0.0015	0.00847	-0.0078	0.0013	0.0002	0.0003	0.00307	0	0.0002	0.0014	0.0004	0.001	0.0011	0.0002	0.0025	
4	1.901	46.3233	0	0.0009	-0.0005	-0.0003	0.0013	0.0007	0.0012	0.01087	-0.0099	0.0017	0.0005	0.0003	0.00297	0	-0.0001	0.0015	0.0004	0.0012	0.0011	0	0.00273	
5	1.849	46.08	0.0001	0.0009	-0.0005	0.0001	0.0004	0.0004	0.0012	0.00987	-0.0092	0.0014	0.0002	-0.0002	0.00307	0	0.0004	0.00173	0.0007	0.0012	0.0013	0	0.0025	
6	1.797	46.24	0.0005	0.0006	-0.001	-0.0004	0.0016	0.0005	0.0015	0.0111	-0.0103	0.0016	-0.0002	-0.0011	0.00203	0	-0.0001	0.00203	0.0008	0.0012	0.0014	-0.0001	0.0022	
7	1.74833	46.19	-0.0002	0.0013	-0.0001	-0.0005	0.001	0.0008	0.0017	0.00843	-0.0086	0.0007	0.0002	0	0.00183	0	0.0001	0.0012	0.0012	0.0012	0.0011	-0.0004	0.0022	
8	1.698	46.16	0.0001	0.0011	-0.0009	-0.0004	0.0006	0.0004	0.0014	0.00993	-0.0104	0.001	0.0006	0.0006	0.0035	0.0007	0.0007	0.0021	0.0007	0.0014	0.0006	-0.0003	0.00273	
9	1.646	46.11	-0.0003	0.0008	-0.0006	-0.0005	0.0009	0.0005	0.0015	0.0075	-0.007	0.0009	0.0003	-0.0005	0.0018	0.0004	0.0003	0.0022	0.0004	0.001	0.0012	-0.0003	0.0026	
10	1.59233	46.4667	0	0.0012	-0.0006	-0.0009	0.001	0.0004	0.0015	0.0064	-0.0064	0.0012	0.0007	-0.0004	0.00223	0.0004	0.0006	0.002	0.0006	0.0013	0.0011	0	0.0017	
11	1.547	45.8333	0.0004	0.0007	-0.0005	-0.0006	0.0008	0.0006	0.0014	0.0054	-0.006	0.0011	-0.0001	-0.0014	0.001	0.0007	0.0007	0.0016	0.0003	0.0011	0.0012	-0.0006	0.002	
12	1.495	46.4667	0.0004	0.0008	-0.0007	-0.0003	0.0009	0.0005	0.0012	0.00547	-0.0052	0.001	0.0006	0.0005	0.0031	0.0002	0.0004	0.0021	0.0009	0.0008	0.0011	0.0004	0.0017	
13	1.443	46.6967	-0.0001	0.0006	-0.0003	-0.0008	0.001	0.0009	0.001	0.00743	-0.007	0.0014	0.0003	0.0008	0.00297	-0.0002	-0.0002	0.0012	0.0009	0.0012	0.0006	0	0.0021	
14	1.391	46.1767	0.0004	0.0013	-0.0004	-0.0005	0.0008	0.0005	0.0009	0.00327	-0.0031	0.0014	0.0004	0	0.00287	0.0001	0.0003	0.0019	0.0013	0.0015	0.0007	0.0001	0.0015	
15	1.339	46.45	0.0001	0.0007	-0.0008	-0.0006	0.0005	0.0006	0.0013	0.0034	-0.0033	0.0011	0.0007	0.0004	0.0038	0.0005	0.0005	0.00223	0.0005	0.0008	0.0011	0.0003	0.0015	
16	1.287	46.27	-0.0004	0.0007	-0.0006	-0.0004	0.0002	0.0001	0.0016	0.0044	-0.0047	0.0012	0.0002	0.0003	0.0037	0.0005	0.0005	0.00283	0.0005	0.0007	0.0012	-0.0001	0.0025	
17	1.23667	45.7867	0.0004	0.001	-0.0003	-0.0009	0	0.0009	0.0007	0.0049	-0.0054	0.0009	0.0004	0.0006	0.00307	0	0.0001	0.0014	0.0007	0.0011	0.0008	0.0001	0.0021	
18	1.18467	46.1267	0.0003	0.0008	-0.0006	-0.0005	0.0001	0.0009	0.001	0.00497	-0.0054	0.0009	0.0005	0.0002	0.00253	0.0003	-0.0002	0.0012	0.0009	0.0012	0.0011	-0.0002	0.0022	
19	1.136	46.2733	0.0005	0.0007	-0.0008	-0.0009	0	0.0008	0.0009	0.00447	-0.0049	0.0008	0.0001	-0.0003	0.00337	3.6E-20	0.0001	0.0009	0.0008	0.0004	0.0013	-0.0003	0.0026	
20	1.073	46.1567	-0.0003	0.001	-0.0004	-0.0006	0.0002	0.0007	0.0008	0.0033	-0.0037	0.0009	0	-0.0005	0.00317	0.0002	0.00153	0.00263	0.0006	0.001	0.001	-0.0007	0.00263	
21	1.037	45.95	0.0004	0.0008	-0.0003	-0.0006	0.0007	0.0006	0.0014	0.0037	-0.0047	0.0011	0.0002	-0.0005	0.00287	0.0003	0.00267	0.00297	0.0006	0.0015	0.001	0.0001	0.002	
22	0.9849	46.3533	0.0002	0.0006	-0.0003	-0.0005	0.0009	0.0006	0.0012	0.00297	-0.0038	0.0007	0.0002	-0.0005	0.00203	-0.0001	0.00233	0.0043	0.0011	0.0013	0.001	-0.0002	0.0022	
23	0.938	46.4967	0.0004	0.0013	-0.0004	-0.0005	0.0005	0.0006	0.0011	0.004	-0.0049	0.0009	0.0004	-0.0003	0.0013	-0.0004	0.00243	0.0064	0.001	0.0012	0.0006	-0.0001	0.002	
24	0.8808	46.0133	0.0004	0.001	-0.0009	-0.0003	0.0002	0.0003	0.001	0.0047	-0.0043	0.0006	-0.0002	-0.0015	0.001	-0.0005	0.00183	0.00823	0.0013	0.0013	0.0009	-0.0002	0.00273	
25	0.8339	46.6467	0.0003	0.0003	-0.0004	-0.0005	0.0008	0.0004	0.0016	0.0062	-0.0014	0.00233	-0.0006	-0.0028	0	-0.0017	0.00357	0.0118	0.0017	0.001	0.001	0.0002	0.0021	
26	0.7819	45.67	0.0002	0.0008	-0.0004	-0.0005	0.0008	0.0005	0.00273	0.00927	0.0002	0.00817	-0.0009	-0.0034	-0.0002	-0.0032	0.00293	0.01547	0.00253	0.0011	0.0009	-0.0005	0.00253	
27	0.735	46.5667	0.0002	0.0007	-0.0005	-0.0006	0.0005	0.0021	0.0067	0.0119	0.00333	0.0126	0.002	-0.0018	-0.0014	-0.0039	0.00283	0.0175	0.00303	0.0006	0.0012	-0.0002	0.0014	
28	0.683	46.5033	-0.0006	0.0008	-0.0009	-0.0004	0.0033	0.0118	0.0248	0.0289	0.02127	0.01433	0.00387	-0.0057	-0.0036	-0.0055	0.00267	0.0222	0.00357	0.0007	0.0006	-0.0008	0.0019	
29	0.63263	46.06	-0.0007	0.0009	-0.0006	0.00183	0.01243	0.03223	0.06643	0.0649	0.0584	0.02127	-0.0063	-0.0109	-0.0052	-0.0061	0.00367	0.023	0.0015	-0.0001	0.0005	-0.0008	0.0017	
30	0.5789	46.4367	-0.0013	0.0006	-0.0017	0.0019	0.0189	0.05983	0.12483	0.1084	0.09857	0.0594	-0.0006	-0.0095	-0.0068	-0.0097	-0.0006	0.0286	-0.0018	-0.0022	-0.0004	-0.0022	-0.0002	
31	0.53027	46.1133	-0.0024	-0.0008	-0.0017	0.0003	0.01963	0.07057	0.13223	0.13233	0.12207	0.13713	0.06163	0.0061	-0.0018	-0.0052	0.01223	0.0426	0.00153	-0.0021	-0.0014	-0.0035	-0.004	
32	0.4748	46.0633	-0.0043	-0.002	-0.0028	-0.0024	0.017	0.06753	0.10173	0.14293	0.13827	0.1964	0.11637	0.03103	0.0039	0.00813	0.03513	0.06267	0.00867	0.0002	-0.0025	-0.0046	-0.007	
33	0.4227	46.3867	-0.0048	-0.0027	-0.0037	-0.0049	0.00823	0.04533	0.04357	0.1376	0.12473	0.2433	0.19583	0.10387	0.01283	0.02167	0.0586	0.08797	0.0168	0.0015	-0.004	-0.0069	-0.0077	
34	0.3759	46.4667	-0.0044	-0.0023	-0.003	-0.0042	0.0045	0.023	-0.01	0.12663	0.1137	0.24747	0.2543	0.13267	0.03163	0.04407	0.09187	0.11197	0.02473	-0.0017	-0.0115	-0.0078	-0.0083	
35	0.329	46.1733	-0.0039	-0.0023	-0.0023	-0.0047	0.0015	-0.0028	-0.0535	0.12247	0.11107	0.235	0.29183	0.1649	0.06227	0.06767	0.12053	0.11983	0.02413	-0.0136	-0.023	-0.0088	-0.0097	
36	0.2718	46.21	-0.0049	-0.0028	-0.0026	-0.0053	-0.0006	-0.0213	-0.0677	0.11273	0.10387	0.21207	0.3072	0.16643	0.0866	0.09737	0.14853	0.13183	0.0243	-0.0278	-0.0356	-0.0103	-0.0109	
37	0.2249	46.2733	-0.0053	-0.0037	-0.0033	-0.0058	-0.0033	-0.0358	-0.0671	0.08363	0.07357	0.1053	0.29023	0.38393	0.1233	0.12023	0.16123	0.12947	0.0071	-0.0567	-0.0422	-0.0122	-0.0125	
38	0.1729	46.4333	-0.0059	-0.0038	-0.0035	-0.0061	-0.0071	-0.0465	-0.0484	0.07967	0.07017	0.04923	0.21593	0.50627	0.16217	0.15217	0.1778	0.11737	-0.019	-0.0893	-0.0386	-0.0126	-0.0145	
39	0.1208	46.24	-0.0062	-0.0041	-0.0034	-0.007	-0.0072	-0.0395	-0.0216	0.07823	0.06837	0.00937	0.12057	0.56873	0.24273	0.15147	0.1693	0.09917	-0.0494	-0.1091	-0.0297	-0.0124	-0.0142	
40	0.074	46.1933	-0.0061	-0.0038	-0.0043	-0.006	-0.0071	-0.03	-0.0002	0.07997	0.07023	-0.0084	0.0482	0.51117	0.39593	0.15747	0.16367	0.07407	-0.0936	-0.1164	-0.0158	-0.0114	-0.0141	
41	0.0271	46.4033	-0.0049	-0.0028	-0.0028	-0.0048	-0.005	-0.0177	0.0174	0.07437	0.06023	0.012	0.03257	0.3422	0.57343	0.1882	0.1574	0.03693	-0.1332	-0.0948	0.0019	-0.0083	-0.0122	

Figure 24: Table 2 in the Multi-wire Emittance Measurements Program

Table 3

It can be assumed that in the first five stops (first five rows of data in Table 2), none of the wires has still detected the beam. This means that the voltage readings in the corresponding cells should

theoretically be zero. This assumption leads to the calculations used in Table 3 of the program. In this table, which can be seen in Figure 25, the average of the first five voltage readings of each of the wires is calculated from Table 2 and recorded in a row above Table 3 with a yellow background. These average values can be interpreted as the background noise, and therefore, are to be subtracted from all the voltage readings of each of the wires in Table 2 of the program—this constitutes Table 3.

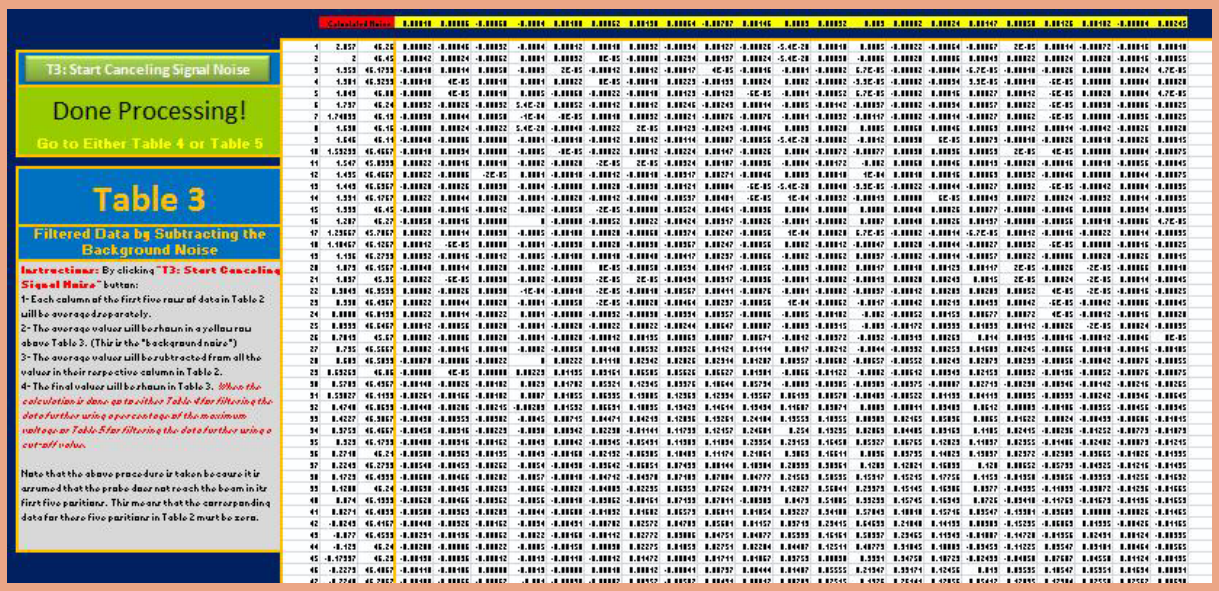


Figure 25: Table 3 in the Multi-wire Emittance Measurements Program

It should be noted that the average values recorded above Table 3 of the program are very small and subtracting them from the data in Table 2 introduces only a very subtle filtration—this makes the difference between Tables 2 and 3 of the program almost unnoticeable.

Table 4

At this point, the data needs more filtering. As can be seen in Figure 22, there are two different options available. One is to use Tables 4, 4a, and 4b and the other option is to use Tables 5, 5a, and 5b of the program—in fact, to check the difference in the final result, both paths can be used in parallel.

In Table 4, which can be seen in Figure 26, users can select a percentage of the maximum voltage. By clicking "T4: Start Filtering Data," the program keeps all the cells that are within that percentage of the maximum voltage intact and changes the rest to zero. (e.g. if the maximum voltage is 1 V and the percentage chosen is 99, then all the values less than 0.01 are changed to zero). To help with visualizing the data, the zero cells are then colored with light blue and the remaining data is colored with a darker blue.

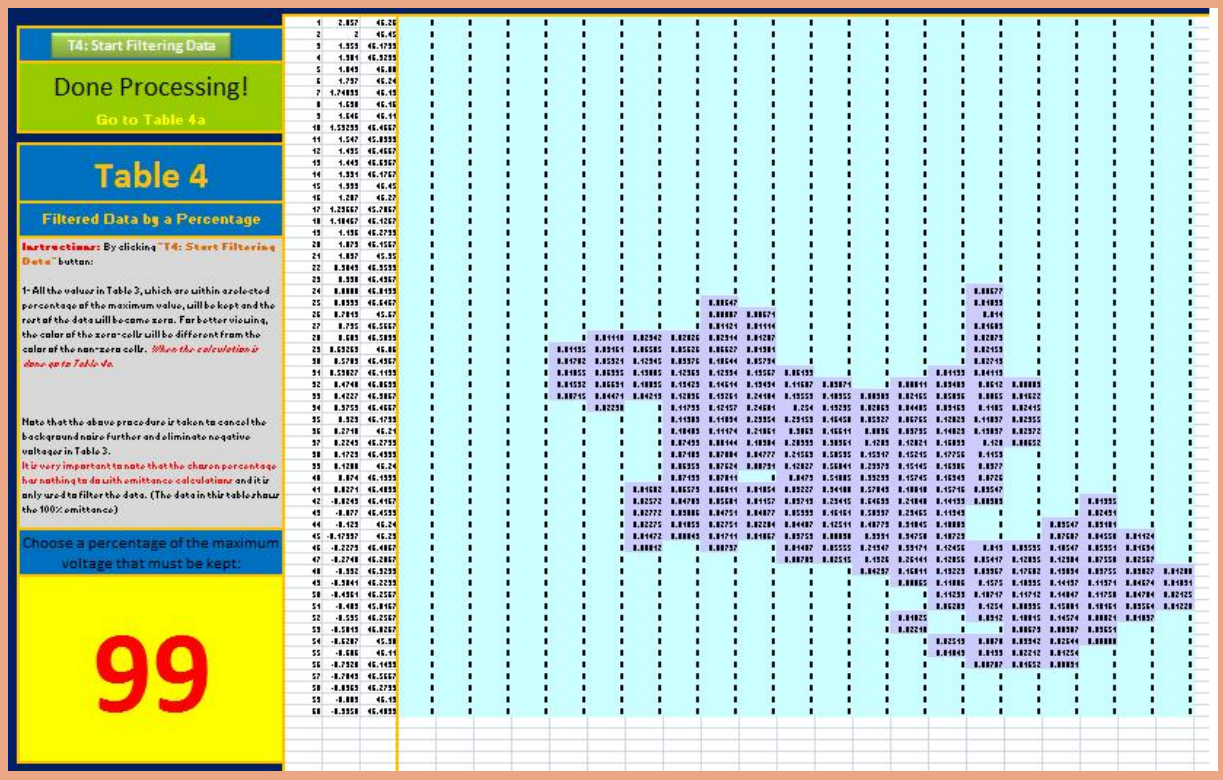


Figure 26: Table 4 in the Multi-wire Emittance Measurements Program

Furthermore, the number of non-zero cells are counted in Table 4 and recorded along with the maximum voltage, average current, and the total voltage in the smaller table to its right. The total sum of the non-zero cells, which must be equal to the value of the total voltage of this table, is also recorded in the small table.

Table 5

Choosing the other option and going to Table 5 of the program, users can select a cut-off value instead of a percentage; and then by clicking "T5: Start Filtering Data," filter out any cell that has a value less than the chosen cut-off value. Similar to Table 4, the data that is filtered out becomes zero and the remaining stay intact. Table 5 of the program can be seen in Figure 27. Again, similar to Table 4, a color coding has been applied to help with data visualization. The zero cells are colored light cream and the non-zero cells are colored with a darker cream color. The number of non-zero cells and the sum of non-zero cells are recorded in the small table to the right of Table 5.

The data shown in Figure 26 and Figure 27 are from the same readings and it can be seen that the results of these two different filtering methods are somewhat the same. In fact, one of the reasons for having two different methods is to figure out how bias the calculation can get.

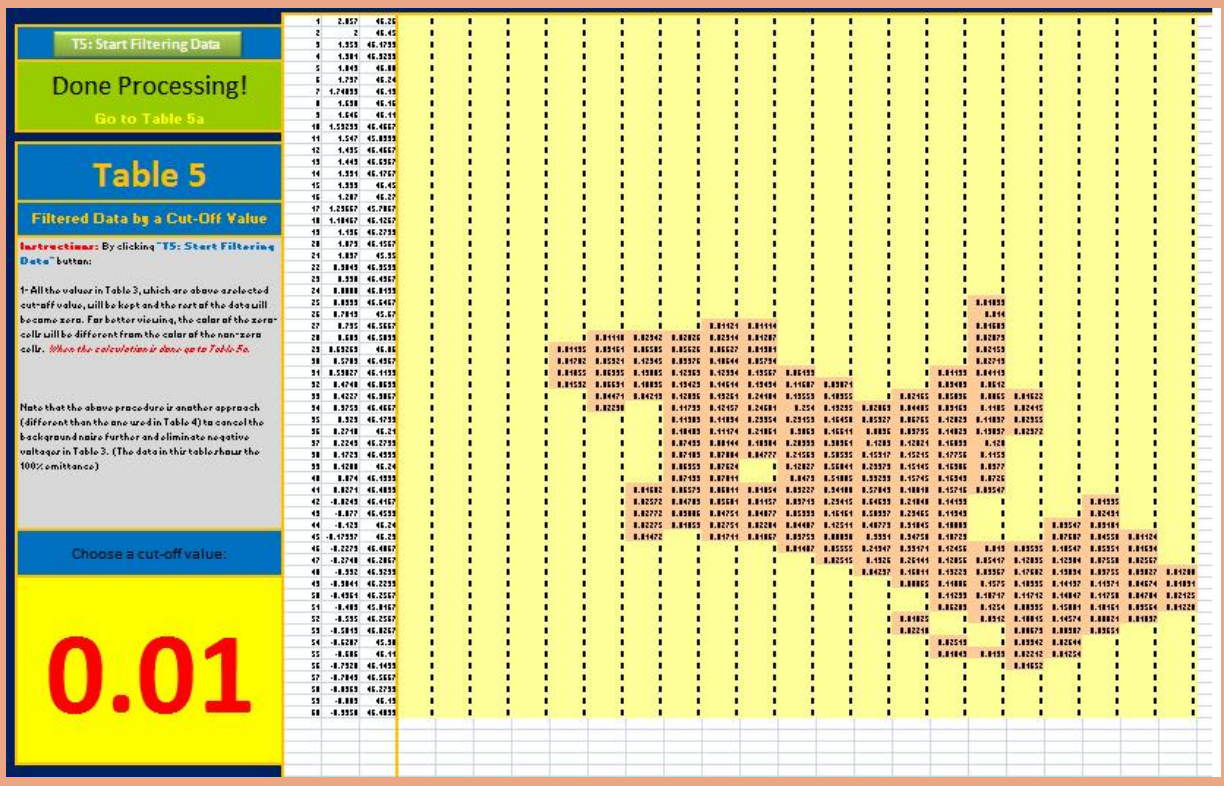


Figure 27: Table 5 in the Multi-wire Emittance Measurements Program

Tables 4a and 5a

The next step is to go to one of the "a" tables—depending on which filtration method has been chosen. Both Tables 4a and 5a of the program do exactly the same calculations; the difference is that they read their data from their respective sources—namely Tables 4 and 5 respectively. Therefore, the explanation of Table 4a suffices.

In Table 4a, as can be seen in Figure 28, users are asked to choose a percentage. Note that this percentage has nothing to do with the percentage chosen in Table 4. The percentage chosen in Table 4a is the emittance percentage. i.e. if a 95% emittance measurement is desired, users must type 95 in the designated box in Table 4a. After choosing a percentage, by clicking "T4a: Start Accumulating Data," all the non-zero cells from Table 4 are copied into the second column of Table 4a, and then sorted from the largest to smallest. After sorting the data, a diagonal table is generated in Table 4a; each column in this diagonal table lists the first n number of values from the second column of Table 4a—where n is the column number. (i.e. the fourth column in the diagonal table lists the first four sorted values from the second column in Table 4a). After this procedure is done, all the columns (the ones in the diagonal table and the second column in Table 4a) are summed up and the sum is recorded below each respective column. Note that the total sum of the second column is equal to the sum of all non-zero cells from Table

4 and is associated with the 100% emittance. Then, program calculates the percentage of the total sum of each diagonal column with respect to the total sum of the second column and records them below each respective sum. The next calculations that Table 4a does is that it finds out how many of the columns in the diagonal table are needed to reach the selected emittance percentage. All the cells beyond that are then colored light blue and will not be used anymore. The only data that will be used from Table 4a is the remaining cells in the second column (that are NOT light blue). As the last step in Table 4a, a color code is applied to these remaining cells; a reference for this color code can be seen to the left of Table 4a.

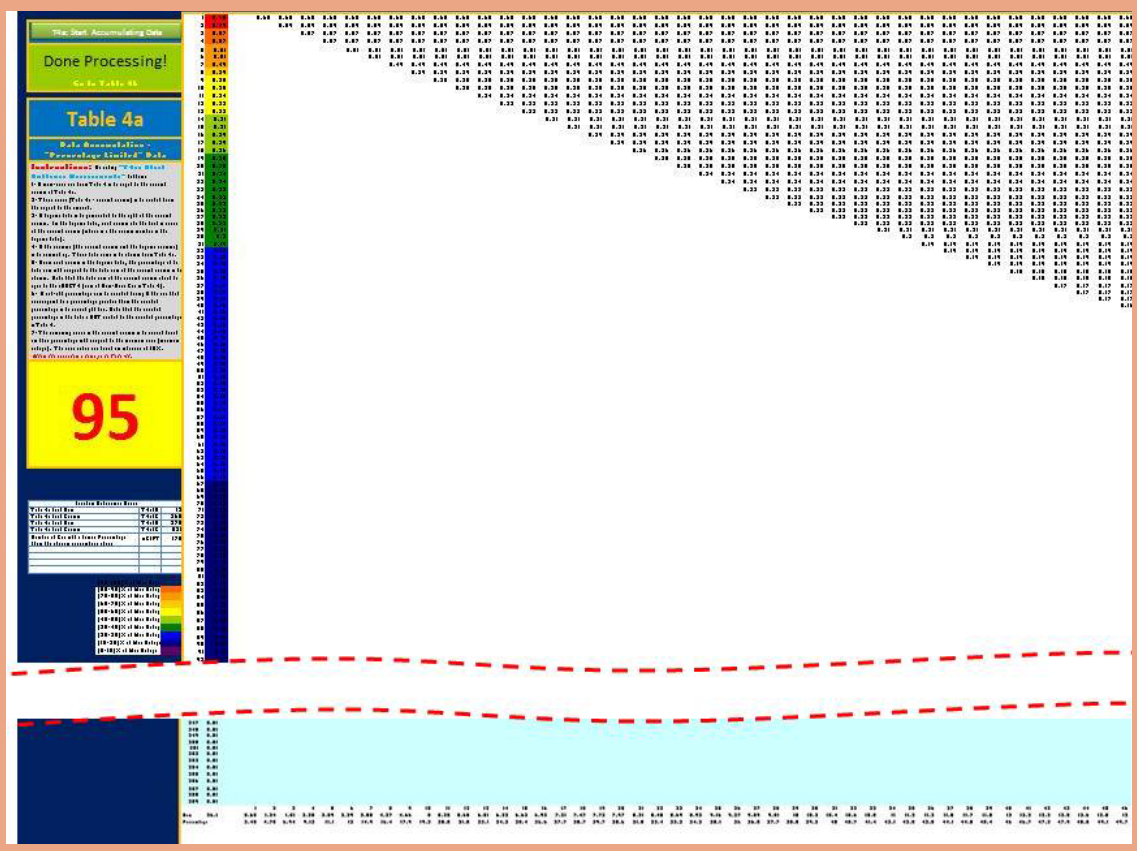


Figure 28: Table 4a in the Multi-wire Emittance Measurements Program

Because the number of rows of data in Table 4a is very large, the dashed red line in Figure 28 is used to show the top and bottom of this table in the same figure. Note that the three last rows in Table 4a, as seen at the bottom of Figure 28, show the column number of the diagonal columns, the total sums of each column in the table, and the percentage of the total sum of each diagonal column with respect to the total sum of the second column.

Tables 4b and 5b

Now that the number of cells needed to reach the emittance with the chosen percentage is calculated, the task of Table 4a is done. The last step is to go to Table 4b, where by clicking "T4b: Start Plotting Emittance," all the data (values and colors) from Table 4 are initially copied to Table 4b. Then, MEMP matches the color coding of the second column of Table 4a with Table 4b (i.e. for example if a cell in the second column of Table 4a is red, the cell that has the exact numerical value in Table 4b will become red). After matching the colors, the numerical value of all the cells that were initially copied from Table 4 but their color did not change will become zero—the dark blue color of the cell however, will stay unchanged. The reason for doing so is to visualize the difference between the 100% emittance, which comes from Table 4, and the emittance with a lower percentage chosen in Table 4a. The results of Table 4b can be seen in Figure 29.

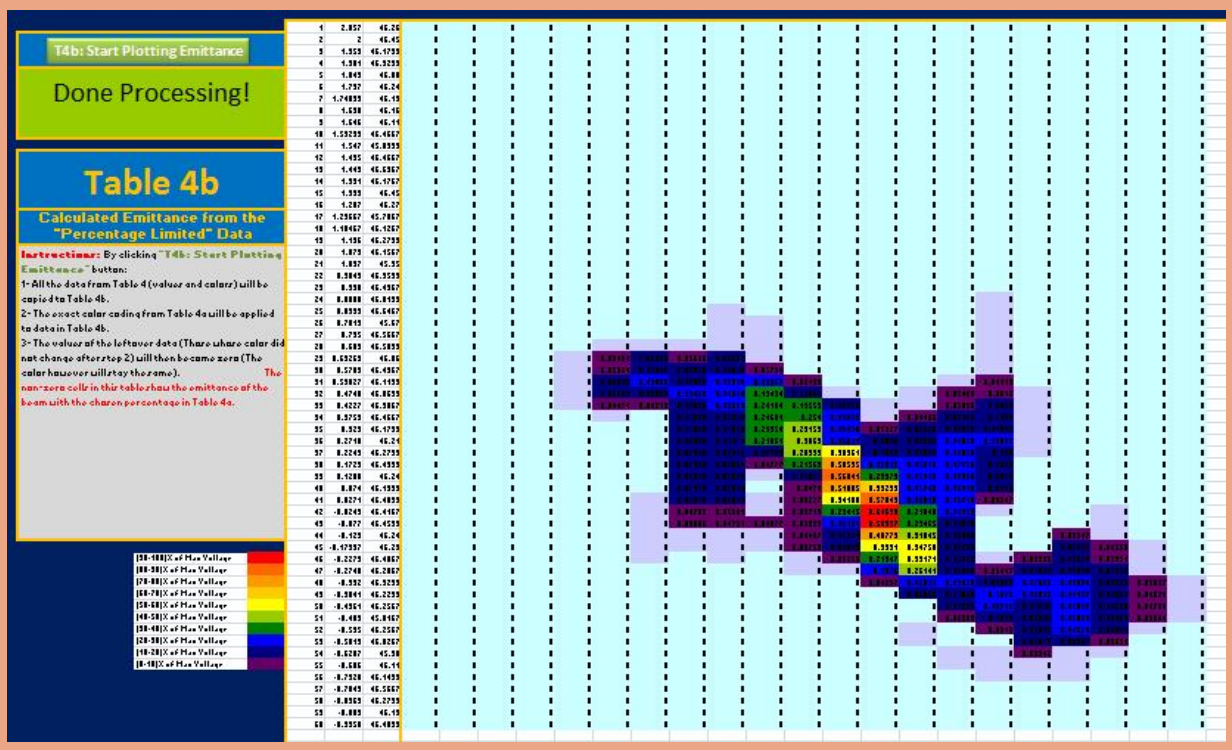


Figure 29: Table 4b in the Multi-wire Emittance Measurements Program

Note that, as seen in Figure 29, Table 4b is a combination of Table 4 (seen in Figure 26) and Table 4a (seen in Figure 28).

As a reminder, the calculations in Tables 5a and 5b are similar to Tables 4a and 4b but only have different sources.

Data Summary Tables

The very last step in emittance measurements in MEMP is to go to “Data Summary” tables seen in Figure 21. Cells that are colored green in these tables are input values, such as the probe’s step-size, angular resolution and etc. and may vary for different measurements. The red cells show the emittance percentage chosen in Tables 4a and 5a; and the yellow cells show the final value of the normalized 100% emittance and the lower chosen percentage emittance.

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