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Phase Space Tomography at Triumf

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Abstract: Currently, the main way to obtain the phase space diagram of the beam is to either use an emittance scanner, or to run a complicated program requiring the manual collection of many data points. Unfortunately, emittance scanners are few and far between, and manually collecting data requires expertise in the theory, and the controls system. This report outlines the efforts made to create a framework at Triumf to make general phase space tomography more accessible. Through comparisons to both manual data analysis, and emittance scan data, the validity of automatic tomography is explored. Curiously, this process has brought about high suspicion of inaccurate measurements or properties of the IOS emittance scanner.

Contents

1 Introduction

Phase space diagrams are a very useful tool in describing particles as it contains information on both the position and momentum of a particle. For the purposes of this report, the phase space diagram will be represented in the format of a 2-D plot of position along an axis vs. angle about that axis.

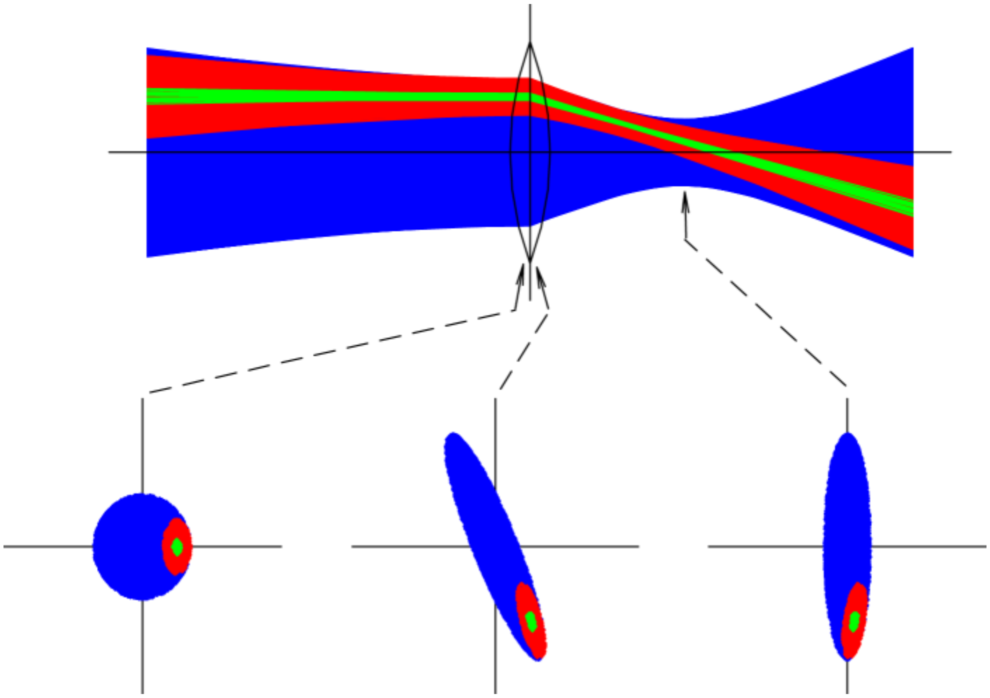
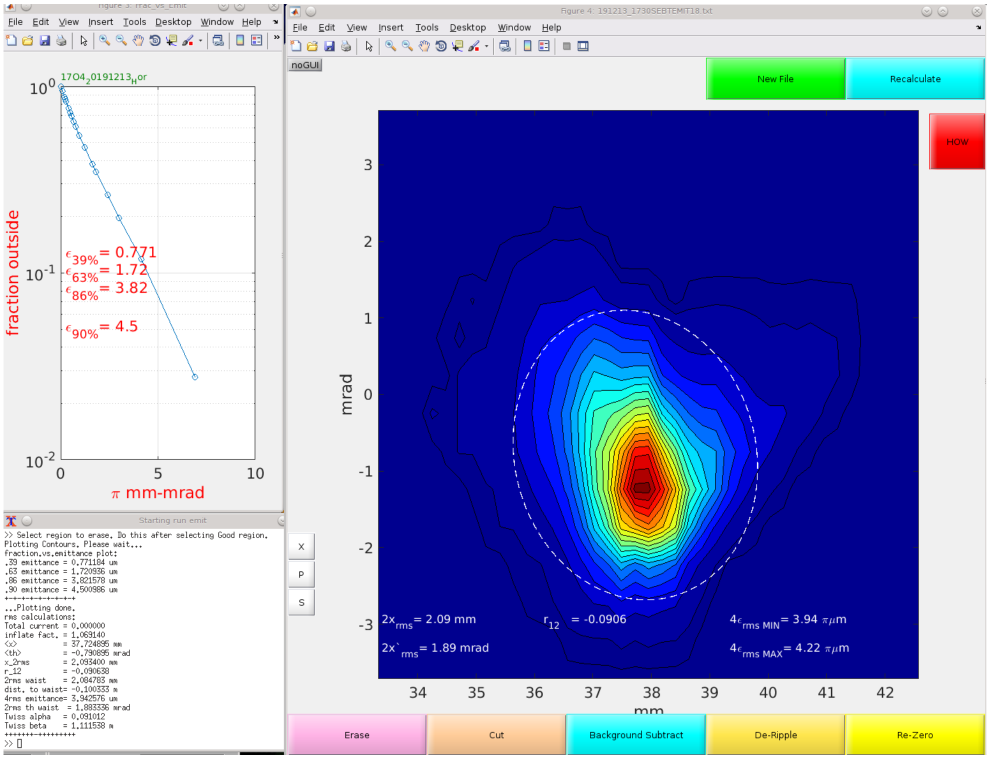


Figure 1: Particle Beams and Focusing - R. Baartman

This is relevant to particle accelerators because it provides an initial condition for models, as it can be used to predict how the beam will behave travelling through the beam-line. These plots can be directly produced using a device known as an emittance scanner. These operate by simply making a cut in the position, with the use of a slit, and a cut in angle, by analyzing the path of the particles through a known field.



```
>> Select region to erase. Do this after selecting Good region.
Plotting Contours. Please wait...
fraction.vs.emittance plot:
.39 emittance = 0.771184 um
.63 emittance = 1.720936 um
.86 emittance = 3.821578 um
.90 emittance = 4.500986 um
+-+-+-+-+-+-+-+-+
...Plotting done.
rms calculations:
Total current = 0.000000
inflate fact. = 1.069140
<x>           = 37.724895 mm
<th>          = -0.790895 mrad
x_2rms        = 2.093400 mm
r_12          = -0.090638
2rms waist    = 2.084783 mm
dist. to waist= -0.100333 m
4rms emittance= 3.942576 um
2rms th waist  = 1.883336 mrad
Twiss alpha   = 0.091012
Twiss beta    = 1.111538 m
+++++++-+++++++++
>> ▯
```

Figure 2: Sample Emittance plot obtained in ISAC facility

Although this is a great way to determine the phase space diagram, it is very limited. The scanner itself is expensive, and requires installation onto the beam-line. This means that in places with various devices, it is impossible to install. This is where tomography comes in. Tomography, meaning the reconstruction of the phase-space diagram using 1-D scans, has been shown to create accurate reconstruction's of the phase space of the beam [1] [2]. It is especially useful in that it can be done using almost any profile monitor, and the reconstruction point can be almost anywhere along the beam-line. This report outlines the work done to automate the tomography process so it can be used throughout Triumf, and to explain the process used to verify the reconstruction results.

It is assumed that the reader has a general understanding of what MENT [3] is, how to run it, and how phase space tomography is executed. This is meant to give an overview of the work done, to further the efforts to create the tomography application.

Also note that the value of the value of the emittance is not the focus of this report. It mostly focuses on agreement to the shape of the emittance plot. Although, this is a valid topic of investigate.

2 Collecting Data

Before any tomography is done, data needs to be collected from the control system. Meaning in order for the tomography process to be understood, the methods used to collect data should be understood as well. Whereas with manual data collection it can be easy to understand the exact process taken to obtain the data, automatic data collection makes it is easy to maintain a blind eye to the collection processes. Without knowing how the data is collected, it is hard to diagnose problems with the reconstruction. This section outlines the various processes that go into making the data files, to both educate the users, and allow for easy bug fixes.

2.1 Collecting Scan Data from Jaya

In order to successfully collect a scan, several checks are in place to ensure scan data is correctly saved. When the website attempts to collect a scan, it changes the SCAN-RPM PV to the 'scan' value. This is either 1 or 0, and is set in the monitors experiment file. However, there are a few checks to account for the different scan times, and if a scan is already in place.

When the user clicks the scan button, the first check is whether the live setpoint of the quad matches to desired one. This is done as an on click function bound to the id 'scan_rpm'. If the two values match the function rpm_set_check will be called. This function uses the jaya_get function to obtain the value of the parked_boolean PV of the monitor. Note that this PV is set in the monitors experiment file, as well as the the value corresponding to the monitor being idle. If the monitor is found to be idle the process with continue, if not the monitor must be currently in a scan, and the process will not continue.

This process leads to the set_rpm function, which starts a timer for the maximum time a scan can take to start. If the scan exceeds this time limit, it is assumed that something with the control system malfunctioned and the scan is not able to complete. This time limit can be changed to the digression of the developer. This function leads into the the first loop. Starting with rpm_complete the idle PV of the monitor is read. This value is fed into scan_check. This checks if the value of the idle PV corresponds to either its idle state, or its scanning state. If it is idle, it activates rpm_complete again, until the timer runs out. This is set to 2 seconds, but can be changed by the developer. If this value changes to its 'scanning' value, the process continues to the function scan_loop.

This loop is exactly the same as the last one, except it waits to see if the PV returns to its idle state, ensuring the scan is complete. The function scan_loop obtains the PV value, and the function update_rpm checks whether or not it has returned to its idle state. This timer lasts 15 seconds until it throws an error value. Once the value returns to its idle state within the time limit, it waits an additional 2 seconds before reading the scan data from the server - to ensure it is updated with the new scan data. With this information, given as a JSON file of lists of position and current values, as well as other properties of the scan, it is plotted for the user to see, and the collected data is stored as a object in the 'tomoDict' dictionary. This dictionary is rewritten if a new scan is completed, and is only saved to a file if the user clicks the 'save data' button.

If any of these processes fail, it will print the error into the console of the web browser. This can give insight on the nature of the problem, for bug fixes.

2.2 Pre-processing of Data

As explained previously, the data collected from the scan is not saved, but only passed in a dictionary. When the user clicks the save data button the data goes through a few processing techniques before it is written to the data file. This is done in the 'lib.py' file, under the function 'live_manual_tomography' and its many sub routines.

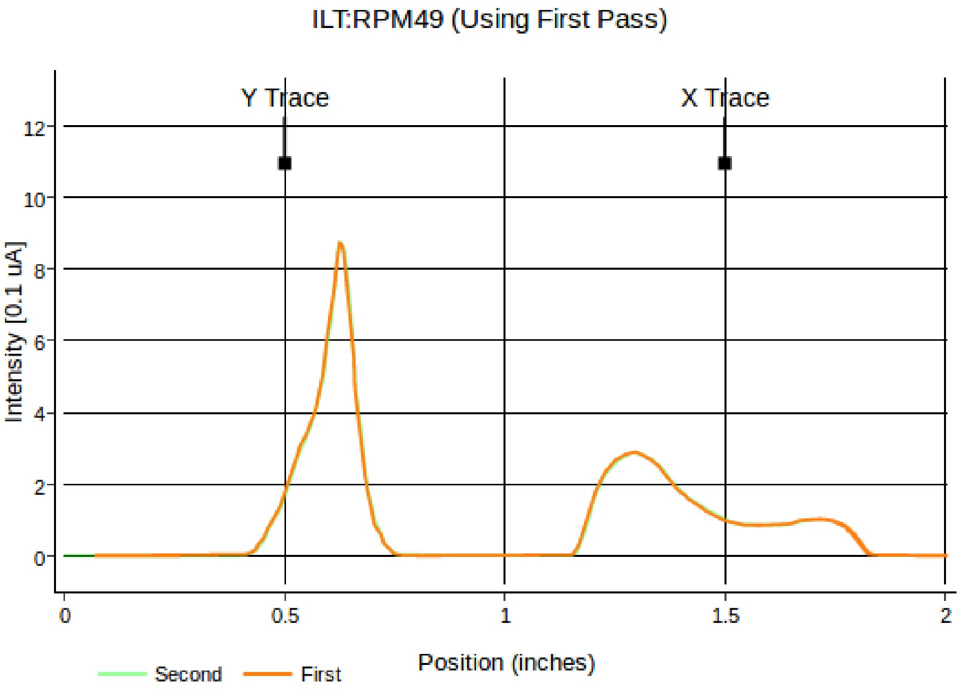


Figure 3: Sample RPM trace obtained in the ISAC facility

The first data processing technique is a series of cuts. Depending on the type of scanner, there may be various traces. The first cut chooses only the trace that is requested, either horizontal or vertical. In the case of multiple scans over the same axis (i.e. a RPM (rotating profile monitor) moves forward through the beam, then back out of the beam causing two traces of both x and y), only one is selected.

With the now cut data, a few processes verify the quality of the data, and change it for easy use in MENT, the reconstruction algorithm. The first centers all data points around the expected center. The value for the center is the half way point of the range for the scan (of either x or y). Once the values are centered around this point, there is a check to ensure the position in the list is always increasing - discarding decreasing data points. It also ensures there is a minimum width between saved position values. At this step, the data should be only a single trace of the desired axis, have increasing position values, and have a large enough gap between position values.

The last data processing done at this point is a simple noise reduction at tails of the trace. The 2RMS is determined for a section with only noise - assumed to be the first 20 points. Any data point with a current value below this noise value is set to zero.

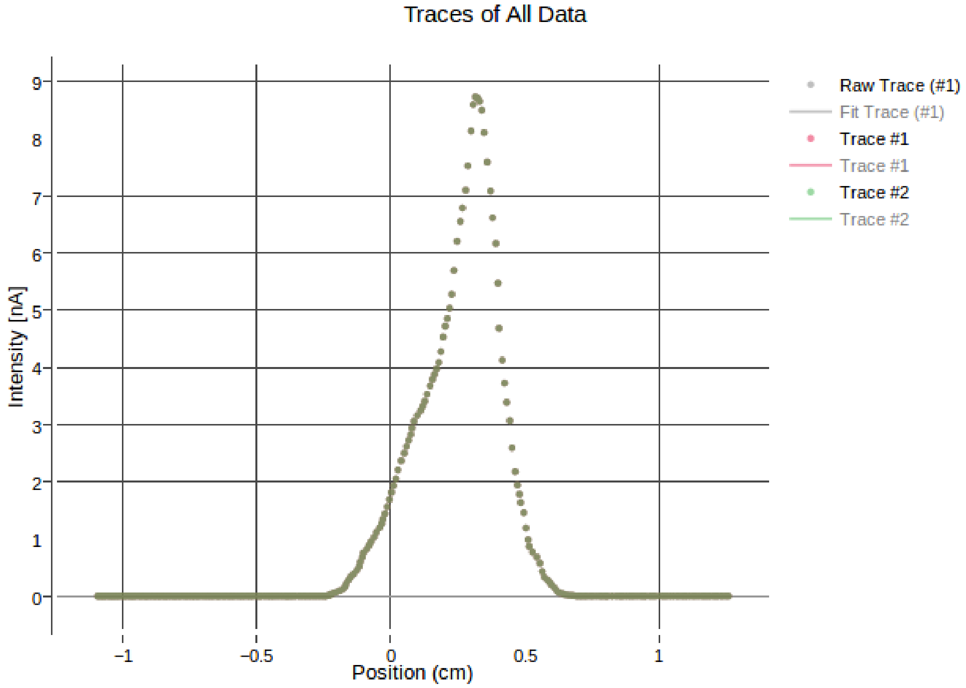
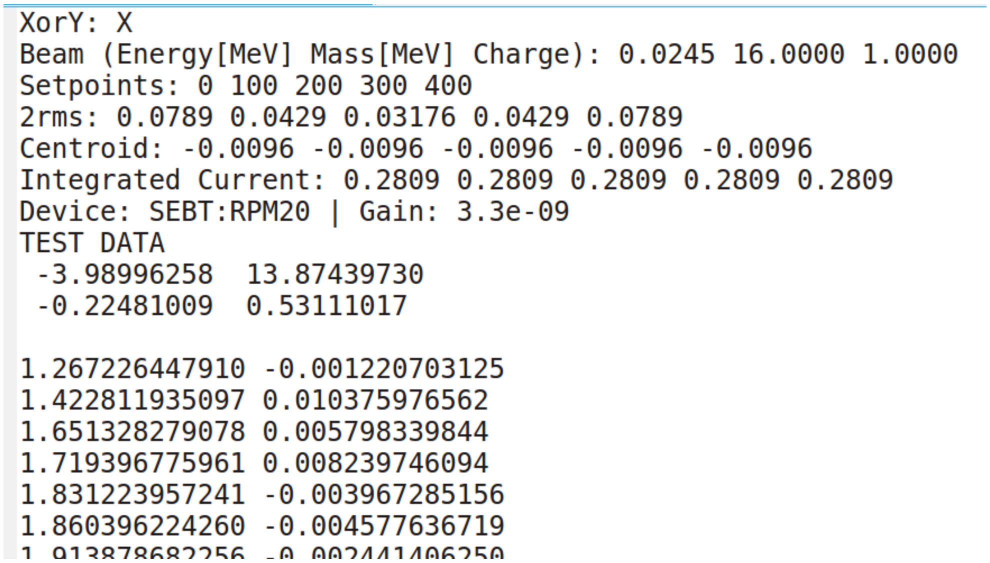


Figure 4: Processed x Trace from previous sample

3 Data Files

A MENT input data file contains the information from many scans. In order for it to run, the scan needs the transfer matrix from the reconstruction point to the point of the RPM. When data is collected, the website writes the data to a file with the current date string as the filename. It is stored in the folder of the chosen RPM. This data file contains two parts: the header, containing information on the settings used for the entire test, and the MENT input file. Data points can only be added when the file is originally collected, during its various scans. Comments can be changed at anytime during or after the data collection.



```
XorY: X
Beam (Energy[MeV] Mass[MeV] Charge): 0.0245 16.0000 1.0000
Setpoints: 0 100 200 300 400
2rms: 0.0789 0.0429 0.03176 0.0429 0.0789
Centroid: -0.0096 -0.0096 -0.0096 -0.0096 -0.0096
Integrated Current: 0.2809 0.2809 0.2809 0.2809 0.2809
Device: SEBT:RPM20 | Gain: 3.3e-09
TEST DATA
 -3.98996258  13.87439730
 -0.22481009  0.53111017

1.267226447910 -0.001220703125
1.422811935097 0.010375976562
1.651328279078 0.005798339844
1.719396775961 0.008239746094
1.831223957241 -0.003967285156
1.860396224260 -0.004577636719
1.913878682256 -0.002441406250
```

Figure 5: Sample test data file created by the website

3.1 Header

The data file headers are simply the first seven lines of the text file. The information contain are the following: Axis of reconstruction, set points applied to the quad in the order they were collected, the 2rms and centroid values of each scan, name of the scanning device, the gain setting of the scans, beam energy mass and charge, and a line for general comments. Whenever a new data set is added to the file, the old header is read, deleted, then rewritten with the new information added. It is meant to be understood by a person reading the file. This is the only place where information about the scan can be found.

The web-site reads this header file, and displays the information to the user. The main functionality involved with this information is the ability to disregard points when running MENT, without deleting the entire point. This is especially useful when manually analyzing the 2RMS^2 plot, and removing data points that stray too far away from the minimum.

3.2 Scan Information

The data collected from each scan is stored below the header. Each scan is separated by a slash, with the transfer matrix at the beginning. This matrix is separated from the scan information by an empty line. The matrix is obtained by using the program OPTR, which is automatically set by the website. Whenever a scan is saved to the file, the corresponding 'data.dat' file is parsed for the relevant devices between the reconstruction point to the scan location. The script will then read the settings for each of these devices, and determine the transfer matrix between the two points. This is then written to the file, above its corresponding scan data.

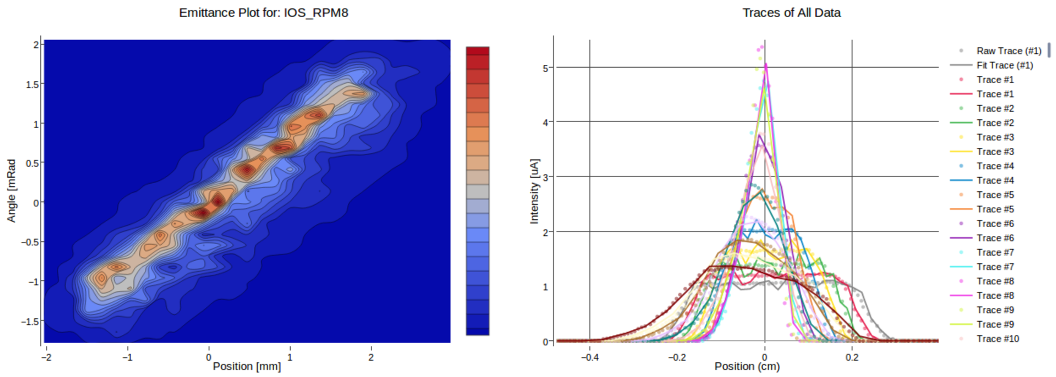
4 Reconstruction Results

With the data obtained through the processes outline above, reconstruction of the phase space of the beam can be done. However, the input parameters of MENT and other data processing techniques can be done to obtain slightly different reconstruction results. This section outlines these techniques, and discusses their merit. For simplicity's sake, the results shown in this section is from one set of scans. The results are representative of similar tests with other data sets.

Note that MENT input parameters are: max iterations, interpolate N and smooth factor. The notation used in this report is [max iterations, interpolate N, smooth factor], with negative smooth factor meaning no internal smoothing.

4.1 Without Smoothing

It is not preferred to use the internal smoothing of MENT, as it is not easily changed or understood. The most direct way to avoid this internal smoothing, is to do no smoothing whatsoever.



(a) MENT reconstruction with no smoothing (b) Comparison of input and output traces

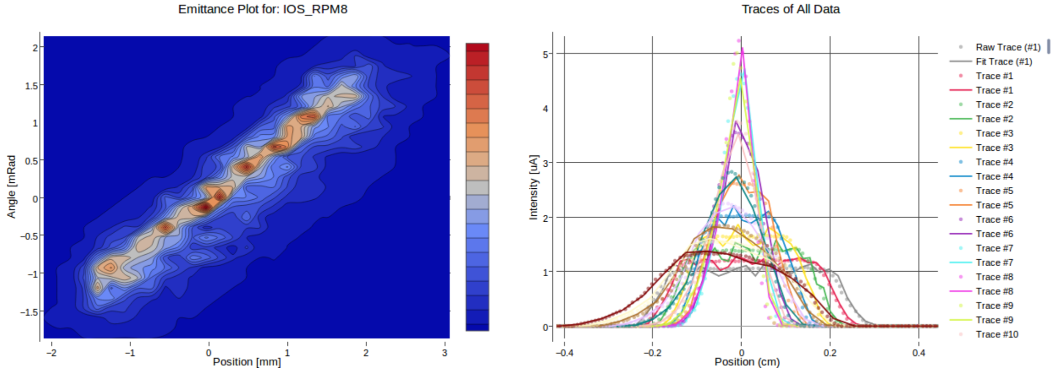
Figure 6: IOS:RPM8 reconstruction results. Parameters = [30, 200, -1]

A useful way to verify the reconstruction is to look at the traces. When MENT reconstructs the phase space, it takes the discrete input data, and fits a continuous curve to it. By comparing the input and output traces, one can gain insight on the validity of the curve.

The results show here without smoothing is clear; the data does not converge to a meaningful solution. The reconstruction results to have 'wavy' features, that should not be present. Also, close examination of the fit data, shows very little correlation; the curve fit seems to have noise, even if the input data has very little noise. Without any smoothing, tomography through MENT is not recommended.

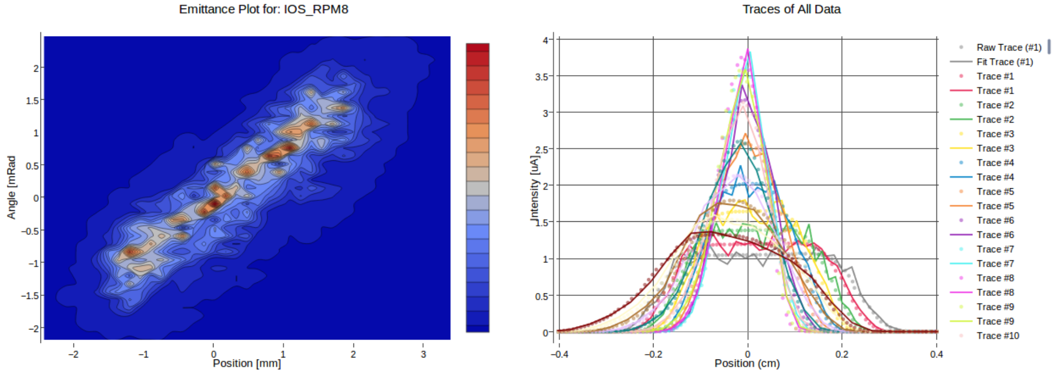
4.1.1 Window Smoothing

The next best simple smoothing technique is a moving box average. The specific script used simply changed the intensity value with the average of N surrounding values, with different values for N.



(a) MENT reconstruction at IOS:RPM8 (b) Comparison of input and output traces

Figure 7: Box smoothing of 3. Input parameters [30,200,-1]



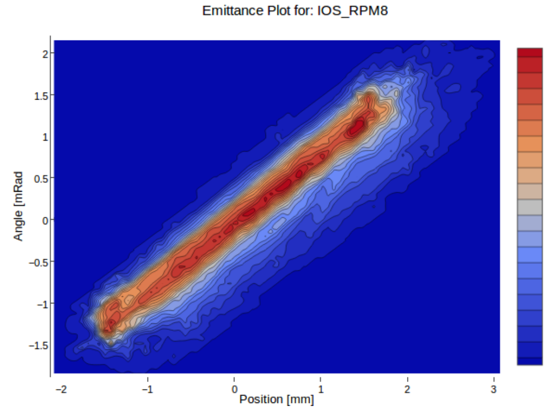
(a) MENT reconstruction at IOS:RPM8 (b) Comparison of input and output traces

Figure 8: Box smoothing of 11. Input parameters [30,200,-1]

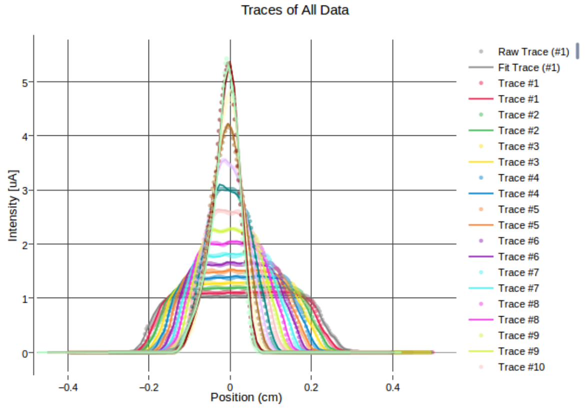
Window smoothing does not remove the key issues with no internal smoothing - noisy reconstruction and trace fitting. With the use of large N values, these problems go away, but the traces are changed drastically - possibly losing important information from the scan data.

4.1.2 Manual Smoothing

A more complicated method of smoothing the data was also applied to the data. Y.N. fit a Fourier series to the data, cutting out higher order terms. The specific cut off term was different for each data point, determined visually.



(a) Reconstruction result after manually smoothing done by Yi-Nong. Input parameters [30,200,-1]



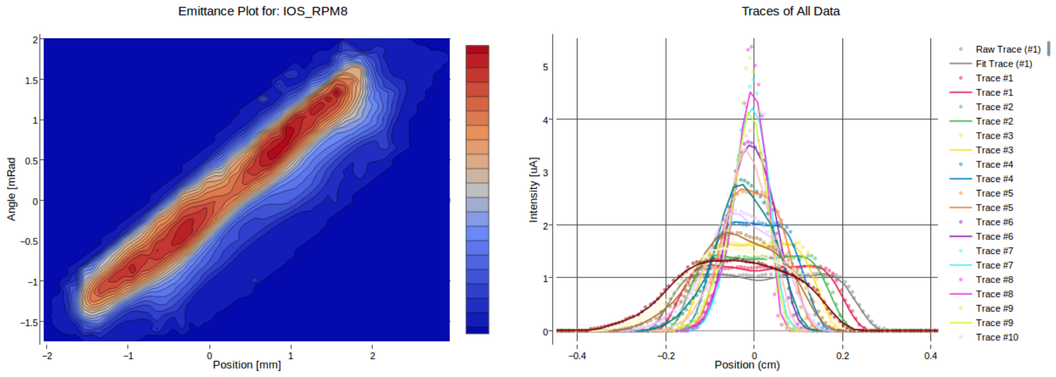
(b) Comparison of input and output traces

Figure 9: Results of manual smoothing

This method results in very good reconstruction - the emittance plot appears to be smooth, and the fit curves do not have the noise present in previous methods. However, this method is impractical to implement for the website; visually determining the cut off term requires the user to have to process each scan taken, which would make the entire process take far too long. This method can be used to verify results, but cannot be fully implemented into the website functionality.

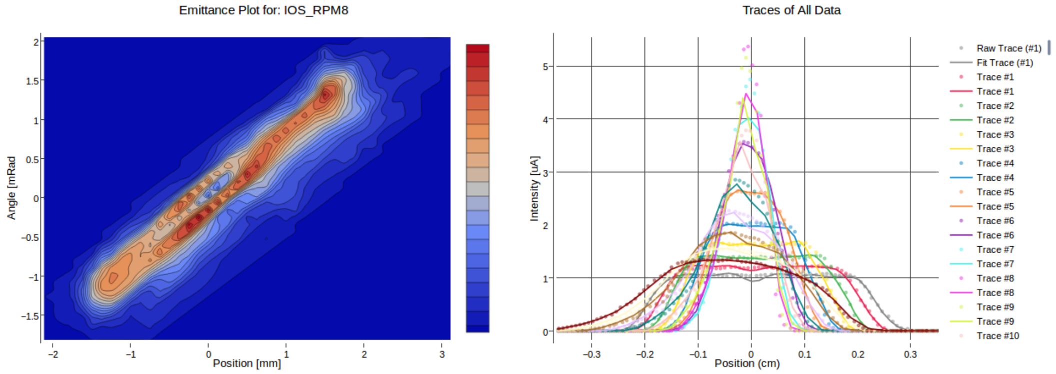
4.2 Internal Smoothing

The internal smoothing done by MENT has the user select a set of parameters. These parameters can vastly change the output, and there is no general output for every set of data. These plots are shown below.



(a) MENT reconstruction at IOS:RPM8 (b) Comparison of input and output traces

Figure 10: Input parameters [30,200,7]



(a) MENT reconstruction at IOS:RPM8 (b) Comparison of input and output traces

Figure 11: Input parameters [30,200,12]

These results show that, depending on the smooth factor, the reconstruction can be very accurate. Although it removes the apparent noise present in previous examples, it can introduce large scale features that are not physical. The specific settings that will result in the optimal reconstruction is not clear.

Internal smoothing is much faster than manually smoothing, and it results in sensible tomography reconstruction. Also, depending on the specific parameters, the reconstruction changes. Also, the settings that result in meaningful reconstruction for one location, do not seem to work for different locations. This means that, at the very least, each monitor should have its own settings determined. Further tests should verify if different beam settings merit more changes in these settings.

5 Emittance Scan Measurement

In order to verify the reconstructed phase space diagram produced by MENT, it should be compared to real measurements. This section outlines these efforts to compare emittance scanner results, to the reconstructed profile.

5.1 Obtaining Scan

Unfortunately, there is not an RPM/Quad close enough to an emittance scanner that can also provide a wide range of scans for tomography. For these tests, the emittance scanner chosen is (NAME OF EMITTANCE SCANNER), with the RPM being ILT:RPM8, and quad being ILT:Q6.

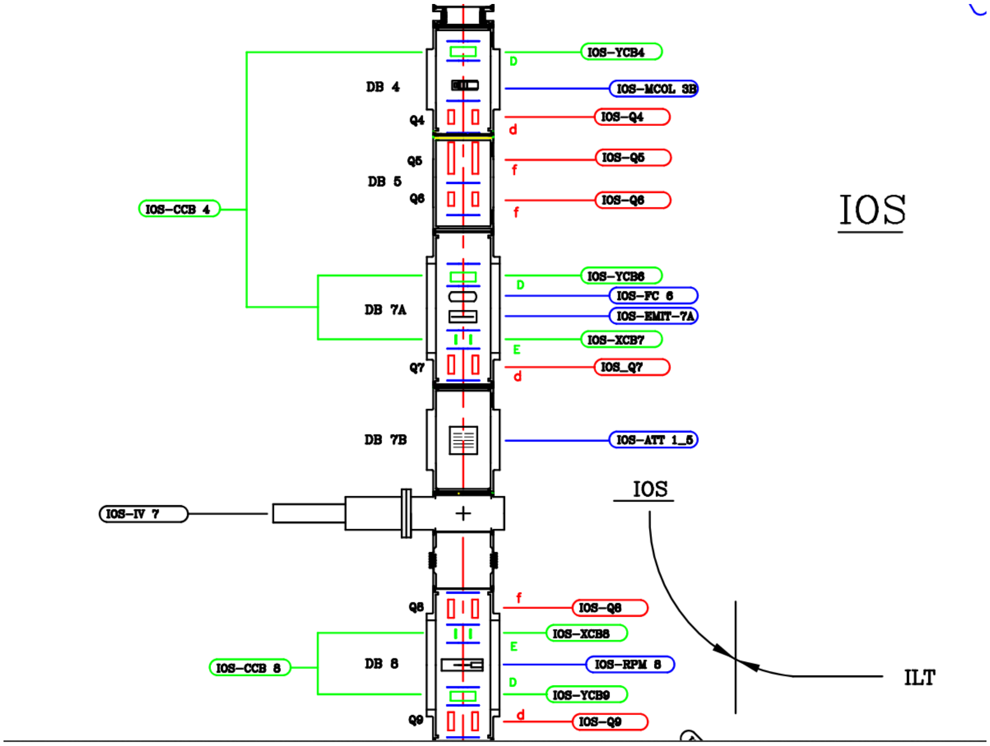
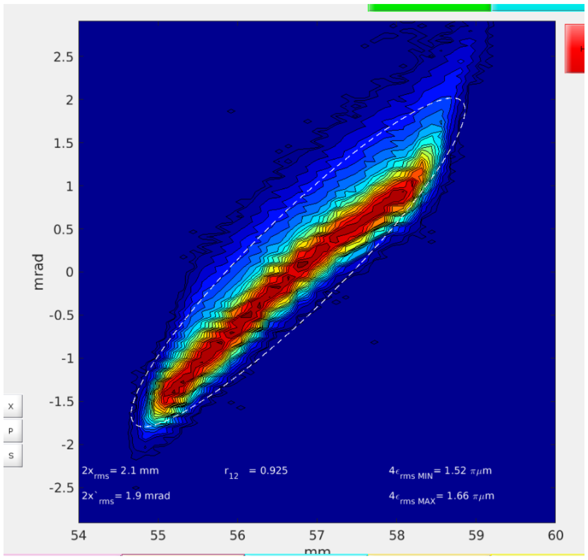
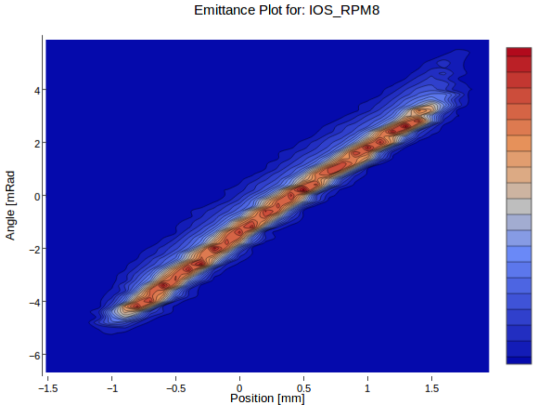


Figure 12: Layout of the beam-line relevant to reconstruction

Note that the emittance scanner, which reconstructs the phase space at its location, is between the RPM and quad. Tomography reconstruction can only be done anywhere before the varying quad meaning that for a direct comparison, a calculation for moving either the reconstructed diagram or the emittance scan is required. This is most easily done by transporting the emittance scanner results to the location of the reconstruction using EmitX, a matlab program written by R. Baartman. This program takes the phase space diagram, and a transfer matrix between initial and final location, and returns the transported phase space diagram.



(a) Emittance scanner measurement



(b) Transported Beam - Matrix [11 12; 21 22] = [0.954119 -0.284432;1.87621 0.489167] (in Radians and Meters

Figure 13: Note that in (a), the scales are different because it is in the co-ordinate system of the RPM, but when using MENT, the absolute value is changed in order to center the traces. The only relevant value is the size.

5.2 Reconstruction

On the same day, and with the same beam settings, IOS:RPM8 was scanned for various voltages of IOS:Q6. This is the reconstructed results.

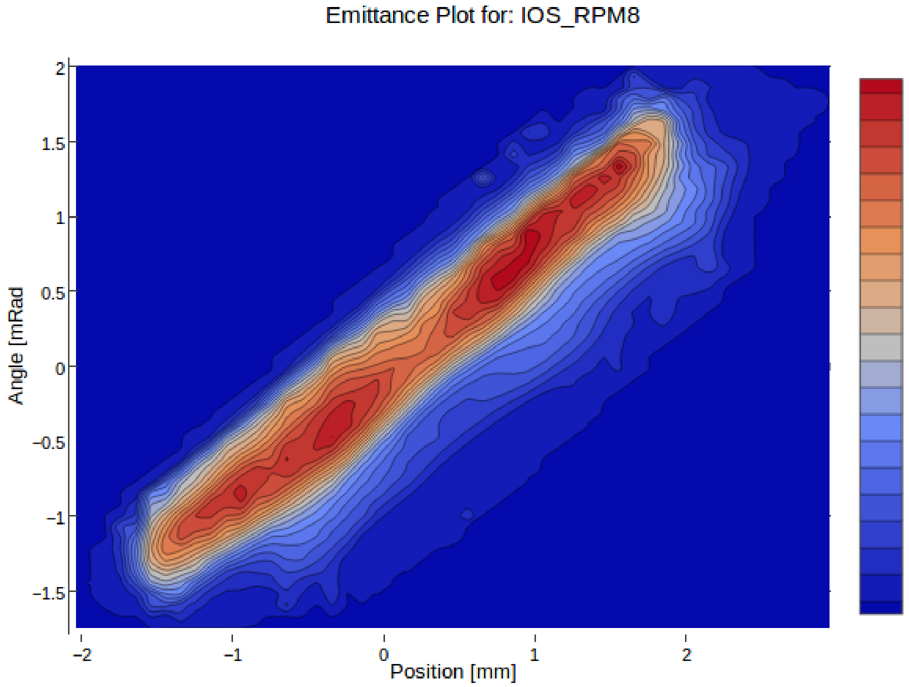
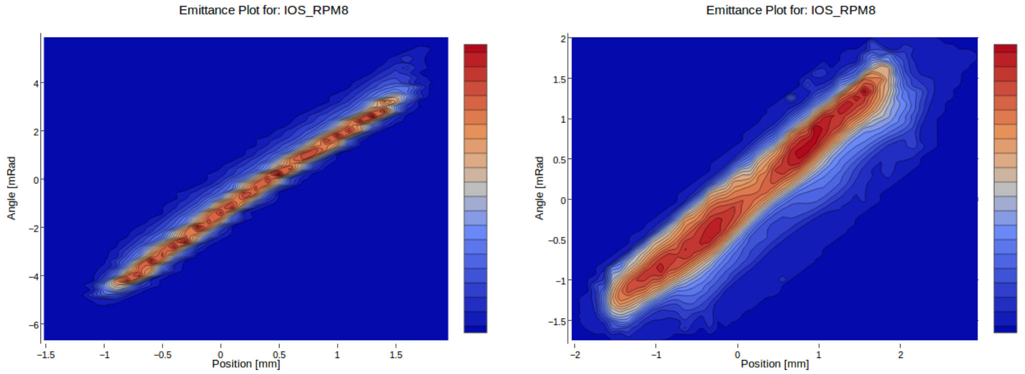


Figure 14: Input parameters [30,200,-1]

5.3 Comparing the two scans

Looking at the two plots, there are some similarities, and key differences. One thing to note, is that the absolute position of the plot is not important, since the scan data is centered around zero in the one of the data processing routines. This means only the scale in position should matter.



(a) Emittance Scan Measurement

(b) Reconstructed Beam

Figure 15: Comparison of emittance scan and reconstructed plot

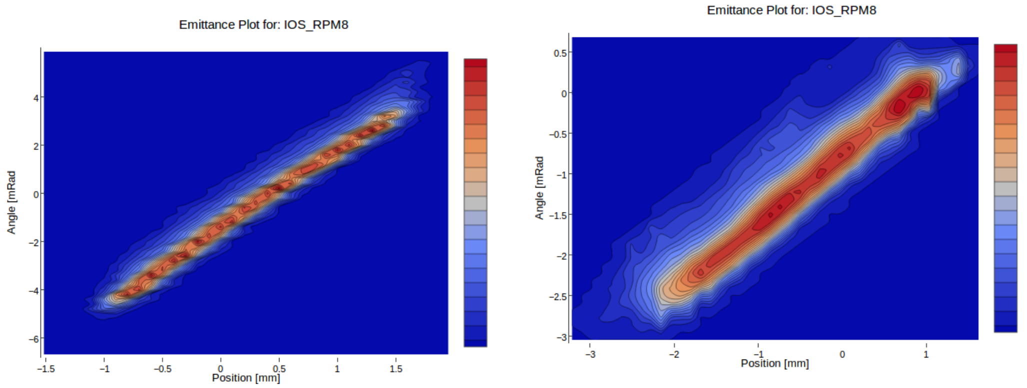
The similarities are the shape of the plot, a clear tail on one of the edges, and the size in terms of position. However, it is clear that the angular size and location are different: the scanned result has a range of -4 to 4, while the reconstructed is from -1 to 3. Also, the trailing edge for the measured diagram is vertically upward, while the reconstructed one is to the horizontally to the right.

5.4 Simple Checks for Diagnostic Tools

Since it has been shown that the the scans differ in only a few aspects, there are some simple changes to the data or data collection itself that could cause these differences.

5.4.1 Flip in Position

When obtaining the data from the scan, it is possible that the exact co-ordinate system of the plots are incorrect. If the values, which have a domain of zero to two inches, are supposed to be flipped - instead of increase from 0 to 2, decreasing from 2 to 0 - the trailing edge of the plot would be on the correct side.



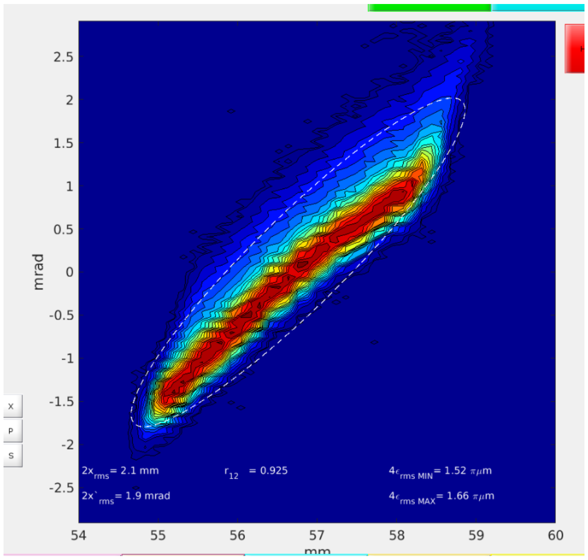
(a) Emittance Scan Measurement

(b) Reconstructed Beam from traces with flipped x axis

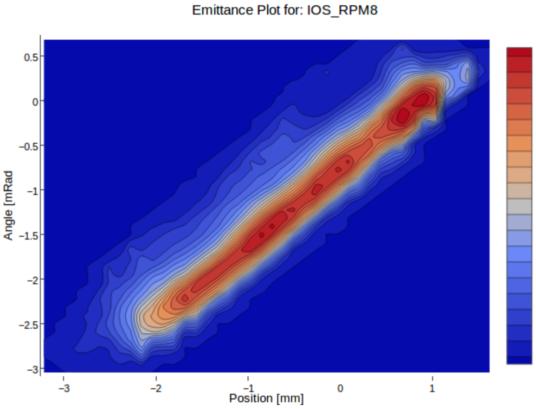
Figure 16: Transported Beam - Parameters = [30, 200, 7]

In order to verify this, a simply examination of the co-ordinate system of ILT:RPM8 would need to be done, as well as possible a check on other relevant rotating profile monis.

Curiously the reconstructed beam is almost the exact same as the unmoved emittance scanner. This should not be the case as reconstruction occurs at Q6, while the emittance scanner reconstructs at its entrance. This can be verified further to confirm correct transfer matrices are used.



(a) Emittance scanner measurement



(b) Reconstructed Beam from traces with flipped x axis

Figure 17: Figure showing the same shape for both of the plots - tail on the edge, and similar scales in both position and angle

5.4.2 Emittance Scanner

The data taken directly from the emittance scanner can also be the source of the problem. The particular scanner used for the testing was an Allison Scanner. This makes a cut in position using a slit, and a cut it angle by having a field present in its inside cavity. This means that if the distance of the inside cavity, or the exact properties of the field present are not completely understood, the result would be the discrepancy in the range of angles found.

6 Conclusions

The framework for phase space tomography is in place. The website can successfully collect data after changing properties of the beam-line, and can perform phase space tomography. The data files collected contain relevant information about the scans, and can successfully be input to MENT. It is found that MENT requires internal smoothing for accurate reconstruction, and that the level of smoothing may need to be determined for each profile monitor.

Moving forward, some key properties of the beam line need to be examined: the orientation of the data collected by the rotating profile monitor and the measurements of the emittance scanners length and cavity field. Once the tomography results in accurate reconstruction, the website can be extended to more locations throughout Triumf.

References

[1] O. Lailey, "Tomography Reconstruction for ARIEL CANREB Beam Commissioning," Tech. Rep. TRI-BN-19-07, TRIUMF, 2019.

[2] Y.-N. Rao, "Maximum Entropy Tomography Validation," Tech. Rep. TRI-BN-18-16, TRIUMF, 2018.

[3] G. Minerbo, "Ment: A maximum entropy algorithm for reconstructing a source from projection data," *Computer Graphics and Image Processing*, vol. 10, no. 1, pp. 48 – 68, 1979.