UNIVERSITY OF WATERLOO

Faculty of Science

TOMOGRAPHY RECONSTRUCTION FOR ARIEL CANREB BEAM COMMISSIONING

TRIUMF

Canada's Particle Accelerator Centre

Vancouver, B.C

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2A Mathematical Physics

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Abstract

This report focusses on describing how tomography was used during the commissioning of the ARIEL CANREB LEBT beamline. Tomography reconstruction was performed in real space and phase space at various sections of the beamline using MENT and python code written by the author. Emphasis is placed on explaining these scripts so they can be used and understood for continued ARIEL beam commissioning and to hopefully be made more robust and/or used to develop a web application or HLA. At the time of writing, beam has been sent from the AGTIS into the Periodic Section and just recently, through the RFQ. This report concludes that tomography reconstruction has been a success in both phase space and real space for this low energy beamline. It is recommended that the code continues to be refined and updated as it is used throughout the rest of the beam commissioning process.

Acknowledgments

I would like to thank the CANREB project and team for funding my work in starting to commission the CANREB LEBT beamline through the use of tomography. I have learned a lot from my supervisor Suresh Saminathan and would like to thank him for his encouragement and for answering my many questions. I would also like to thank the whole CANREB commissioning team for all the work they have done to produce great data for us to analyze. I am grateful for Rick Baartman's leadership and the whole beam physics group for their advice and direction throughout my whole four months here at TRIUMF. Finally, I want to thank the TRIUMF coop student program for providing me with this oppurtunity to work at such an amazing facility. I have learned so much about beam physics compared to what I knew before and I will not forget my time spent here. I truly owe any of the successes to everyone mentioned above for their efforts in educating me. I hope to come back and work at TRIUMF on a future coop term.

1 Introduction

The Advanced Rare IsotopE Laboratory (ARIEL) aims to triple the radioactive ion beam production at TRIUMF. Commissioning began with the CANadian Rare isotope facility with Electron Beam ion source (CANREB) Low Energy Beam Transport (LEBT) beamline at the ARIEL Ground Level on February 21st, 2019. The CANREB project at TRIUMF is needed in order to deliver pure highly charged radioactive ion beams for acceleration and nuclear reaction experiments [1]. The beamline is now in its commissioning stage.

2 ARIEL LEBT Commissioning Layout

Outlined below is a brief qualatative summary of the ARIEL LEBT beamline commissioning plan/layout for context (Fig:1) [2]. The ARIEL Ground level Test Ion Source (AGTIS) is used to create a test beam of alkali ions, Cs^{1+} at 20 keV-60 keV which is transported throughout the Radioactive Ion Beam (RIB) beamlines [3]. The beam travels downstream into the Periodic Section through various quadrupoles and diagnostic elements until the beam of particles reaches the Radio Frequency Quadrupole (RFQ) which focuses, bunches and accelerates an initially continuous beam of charged particles. The beam is deflected into the Pulsed Drift Tube (PDT) by two 45° benders. The PDT is used to adjust the energy of the bunched beam from its original 60 keV to about 10-14 keV for the injection into the Electron Beam Ion Source (EBIS). The EBIS is used as a charge state breeder to increase the charge state of the injected ions. The EBIS hits the injected ions with an electron beam in order to knock off more electrons and thus create highly charged ions. The Cs^{n+} ions are sent back into the EBIS Matching Section and get deflected through a 9°, 36°, and then 45° bender into the Nier Spectrometer (NIS). The NIS consists of a 90° magnetic bender and is used to separate the highly charged ions from the background of residual gas ions and for the required mass over charge, m/q, selection. This covers the first main section of the ARIEL beamline that will be commissioned. This report will focus on analysis from the AGTIS to the RFQ entrance which will then be applied to the rest of the beamline as commissioning continues.

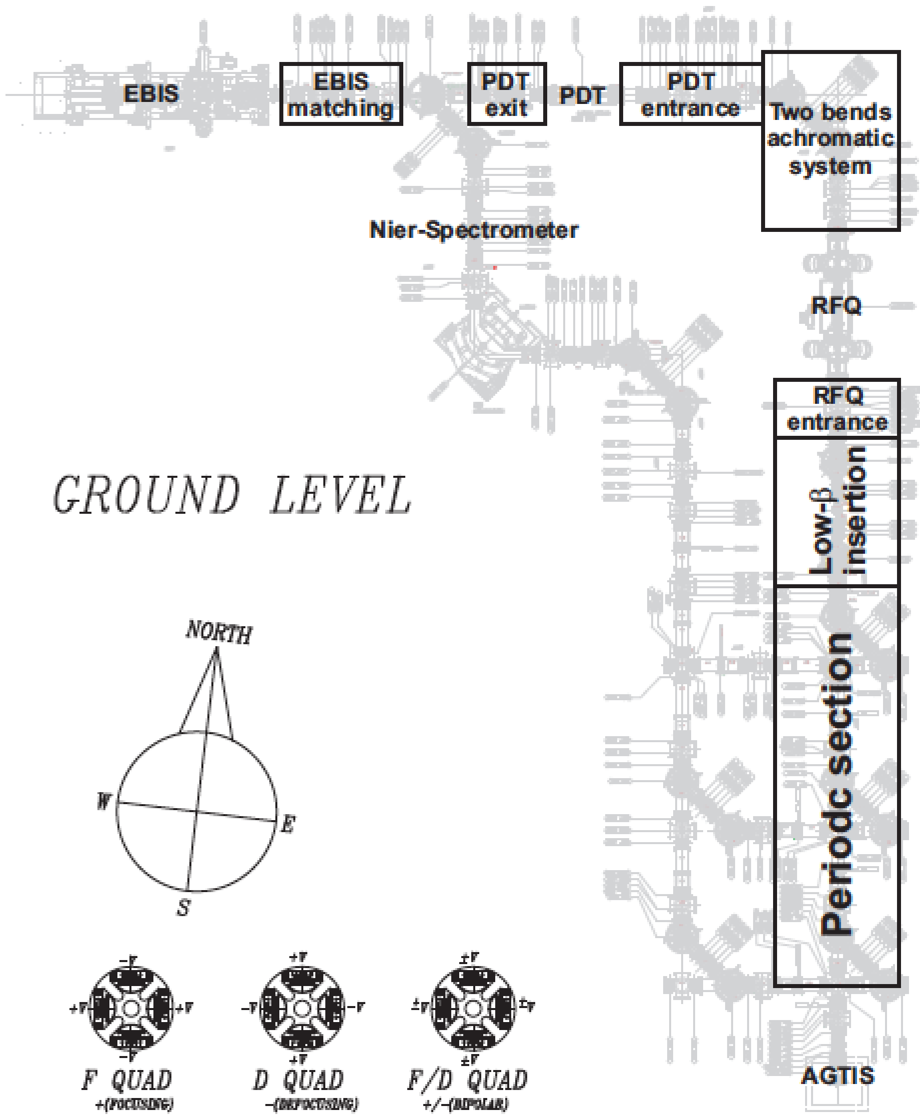

Figure 1: ARIEL CANREB LEBT Beamline

2.1 Diagnostics

The two areas with diagnostic equipment in place are near the test ion source and at the RFQ entrance. Beam is extracted from the source and is sent downstream through three quadrupoles (a triplet) and then reaches a Profile Monitor (PM3) and a Faraday Cup (FC3) (Fig:2). The first quadrupole is also coupled as a steerer in order to keep the beam on axis as needed. PM3 utilizes a wire scanner to scan the beam and thus produce the beam profiles. The wire scanner has three wires in it (Fig:3). A horizontal, vertical and 45° wire. The wires move through the beam's path at the three different angles and produce three different beam profiles which can be used for tomography reconstruction in both real space and phase space. PM3 is physically positioned at 45° with respect to the beamline as indicated in the drawing. The vertical wire measures the horizontal profile and vice versa. Since PM3 is rotated by 45° in the beamline the measured data needs to be divided by $\sqrt{2}$. Also, due to how the monitors move, some profiles need to be flipped horizontally depending on which side should be negative and which should be positive based on the coordinate system used. When scans are performed the data is plotted as Beam Current versus Potential as it is read with a potentiometer. This has to be converted to position for the calculations and tomography analysis.

At the RFQ entrance, beam is sent through a pair of quadrupoles before reaching the Linear Profile Monitor (LPM23) and FC23. There are two more quadrupoles before the beam is injected into the RFQ. LPM23 uses two slits that pass through the beam during a scan and FC23 to measure the beam current and thus the beam profiles (Fig:4). The slits are at 90° to each other. Since there is not a third slit at 45°, data from LPM23 is not used for tomography reconstruction in real space.

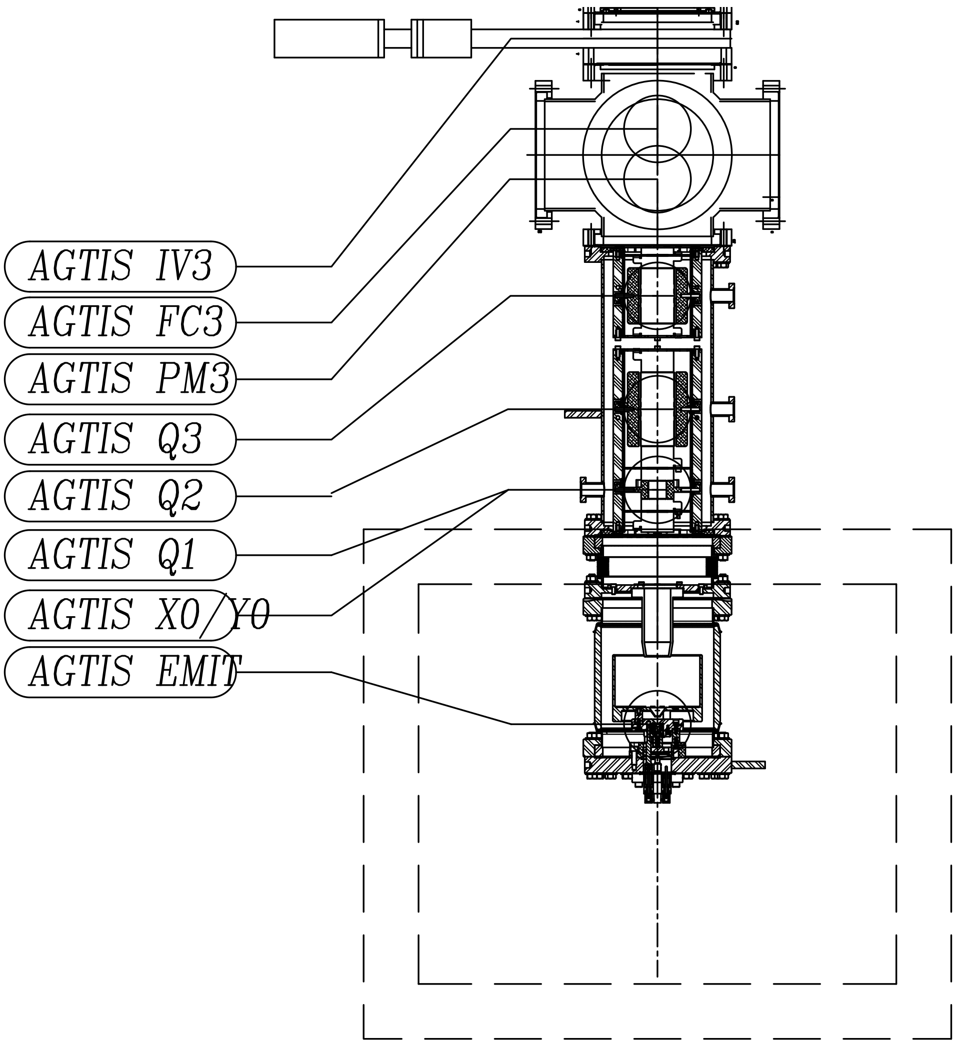

Figure 2: Layout of AGTIS and its beamline.

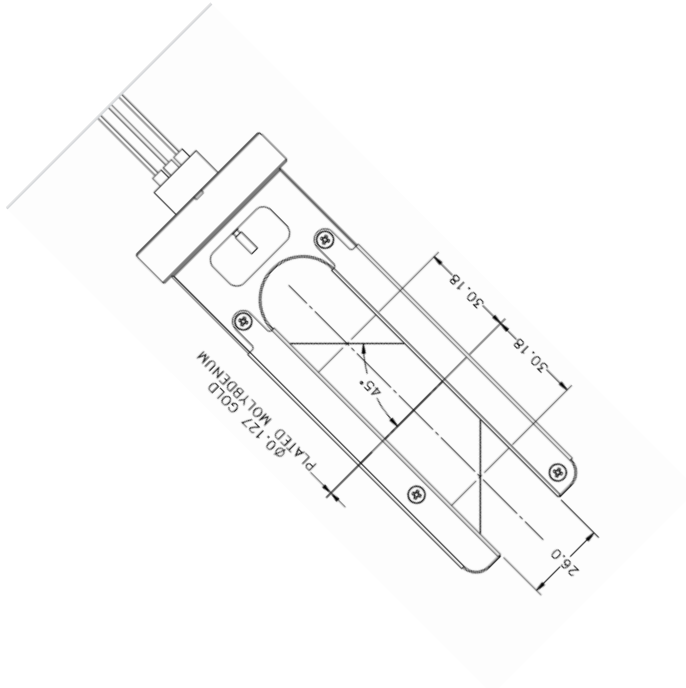

Figure 3: AGTIS:PM3 Wire Scanner. Rotated 45° to show physical orientation installed in beamline. Horizontal, rotated, and vertical wires.

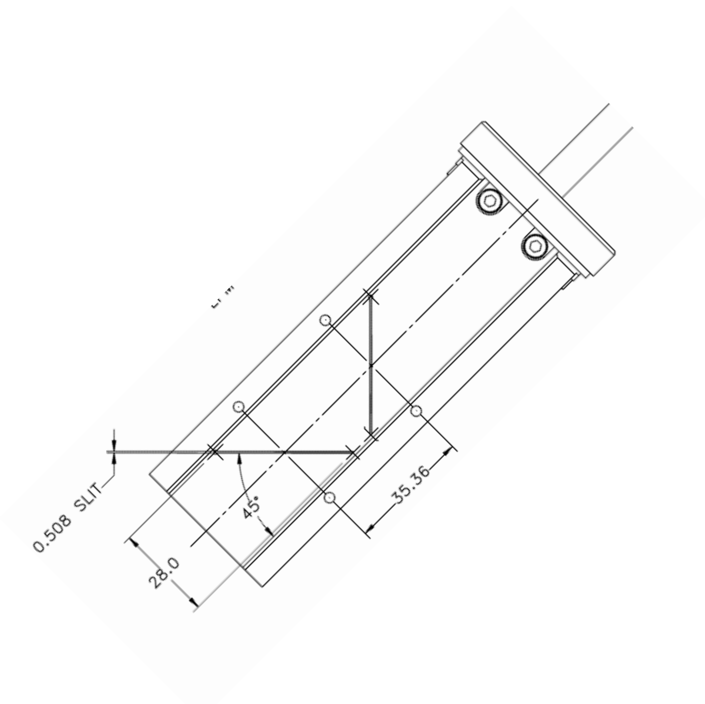

Figure 4: AGTE:LPM23 Slits. Rotated 45° to show physical orientation installed in beamline. Two slits measure vertical and horizontal profiles.

3 Simulations

Tomography in Beam Physics is the reconstruction of a 2D image from multiple 1D profiles/projections. Outside of beam physics, tomography is used frequently in medical imaging to produce 3D images from 2D data (i.e a CT scan) [4]. A very efficient tomography algorithm has been developed and refined over the last 50 years or so. This algorithm is called Maximum Entropy Tomography (MENT) and was used extensively for this beam commissioning data analysis [5]. Simulations were run and python scripts were written to look at beamline sections where real data would be collected when the AGTIS was operational. Running simulations at different locations provided a better understanding of how to use MENT and how accurate tomography reconstructions can be.

The first location to start the tomography simulation process is at the AGTIS. It is important to understand what kind of beam is being extracted from the source and if it agrees with theoretical predictions. A tool known as a beam envelope is analyzed to gain a better understanding of how the beam behaves in each section (Fig:5). It is extremely useful to be able to see all the elements, the x and y beamsize of the beam as it travels downstream, the energy of the beam, and the focal power of the quadrupoles. This is an important way to check that the particular tune is correct so that the beam of particles is being focused adequately and not going to collide with anything on the inside of the beamline. Observe how the beam gets focused in one plane and defocused in the other as it passes through the triplet.

Tomography can be performed in both real space and phase space. Real space would be the standard X vs. Y image and would resemble what the beam actually looks like in the beamline. Phase space is slightly more complicated and very useful for analyzing the particle beam dynamics as a whole.

3.1 Phase Space

In phase space, every particle has its coordinates represented by six components, x, y, s, p_x, p_y, p_0 [6]. The x, y, s variables represent the position and the p_x, p_y, and p_0 variables represent transverse momenta and the ideal particle momentum. The six dimensions are uncoupled into three 2D phase planes which are easy to work with and visualize. In this section, when tomography reconstruction is performed it is done in phase space and so the x-plane and y-plane are analyzed separately.

The main purpose of doing phase space tomography reconstruction is to calculate the emittance. Emittance is defined as the region the beam occupies in phase space [7]. Emittance is a very important parameter of a charged particle beam because it is conserved in uncoupled phase planes. This is well known as Liouville's Theorem. The most commonly quoted emittance value is the statistical definition known as RMS emittance

$$\varepsilon_{RMS} = \sqrt{< x^2 >< p_x^2 > - < xp_x >^2} \tag{1}$$

This report uses ε_{4RMS} which contains about 90% of the beam and is just four times the RMS emittance.

3.2 Tomography Simulations in Phase Space

The first problem in the initial simulation work was to find which quadrupole would be the best to use for the tomography reconstruction in phase space. The beam envelopes help determine this as it is possible to scan through the voltage range for different quadrupoles and tunes and observe where the envelope produces a minimum in beam size near the profile monitor for either the x or y-plane. In this case, Q1 and Q3 produced the most parabolic-like data when varying the quadrupole voltage and calculating the respective beam sizes (fig:6,7). A parabola is ideal since linear beam optics shows that beam size has quadratic dependence between two locations [8]

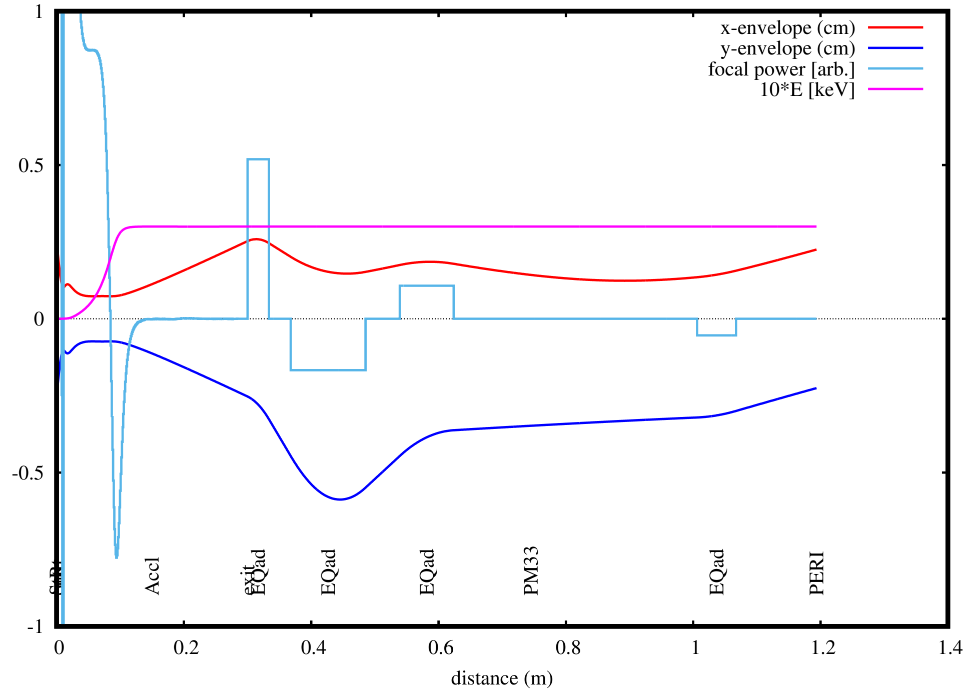

Figure 5: AGTIS Beam Envelope with quadrupoles at theoretical voltage values. Labels on bottom represent the elements along the AGTIS section. The pink line is the energy of the beam and the blue and red lines are the transverse beam sizes in the beamline. Cyan lines represent focal power of the quadrupoles. Profiles are taken at PM3 and then the images are reconstructed in front of Q1.

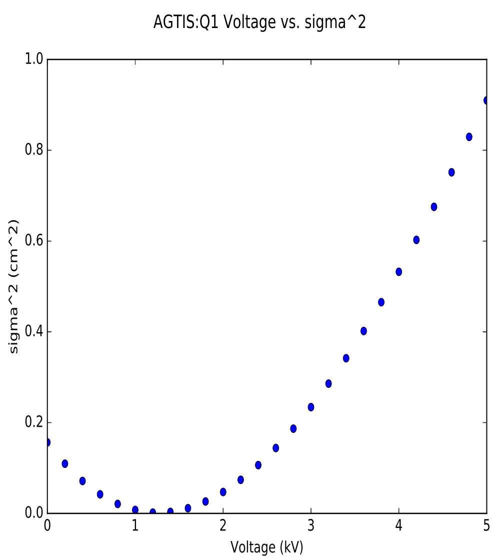

Figure 6: X-plane Beam Size squared vs. Voltage for AGTIS:Q1. Suited for tomography with this tune in x-plane.

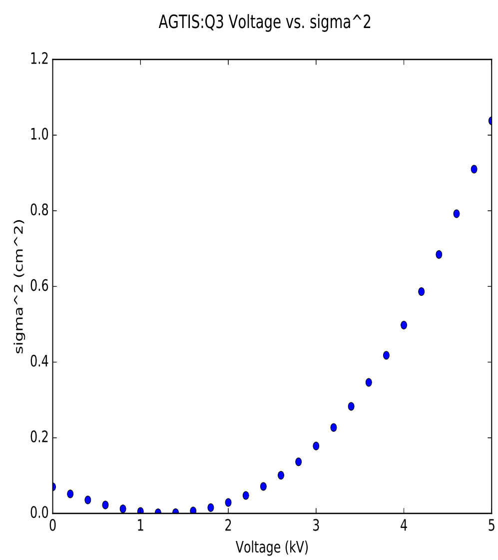

Figure 7: Y-plane Beam Size squared vs. Voltage for AGTIS:Q3. Suited for tomography with this tune in y-plane.

The next step is to generate the required input file for MENT. A set of Fortran code is used called TRANSOPTR to produce required transfer matrices and beam envelopes [9]. When a beam of particles passes through various optical elements it is focused and defocused in different planes. A transfer matrix is used to calculate how the beam has changed from one position to another. For AGTIS:Q1, the voltages are varied from zero to the max power supply rating of 5 kV and TRANSOPTR calculates a new transfer matrix every time. The various transfer matrices get multiplied with theoretical initial particle coordinates to produce the final image of the beam after the particles have traveled through optical elements. Upon producing the final position of the particle beam near a profile monitor on a beamline, the MENT algorithm is implemented. The one dimensional beam profiles are calculated from the final particle density distribution and MENT takes this data as if a real profile monitor had measured it and the corresponding transfer matrices as input.

Tomography reconstruction is performed by running MENT which outputs the data that the algorithm predicts the beam looked like originally back where the initial particle distribution was used. Observe how similar the input and reconstructed 1D beamprofiles are that MENT produces (fig:8,9). Initial noisy data and one or two slightly shorter output profiles are the only clear differences between the input and output profiles. This is one way to check how well the created tomography simulation is working and in this case is fairly successful for this data. Ideally, the tomography reconstruction will look very similar to the initial beam and have very similar properties (fig:10). On the corner of all contour plots are four calculated beam parameters. The 2RMS calculations are statistical values of the distribution along both axes and relate to the beam size. The r12 and r34 values are corresponding sigma matrix elements that have to do with the orientation in phase space. Finally, the 4RMS emittance is the region the beam occupies in phase space that contains approximately 90 % of the beam. Sometimes, it is visually difficult to tell how close two contour plots look. These four parameters provide valuable information about characterizing the beam and are also useful for comparing how accurate the tomography reconstruction is. Observe how similar the results are. This is a positive start to the simulations.

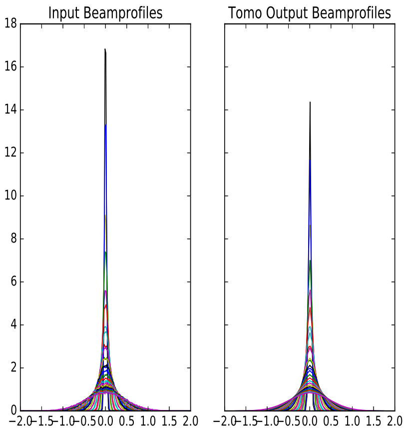

Figure 8: 1D beamprofiles in x plane. Input and output profiles.

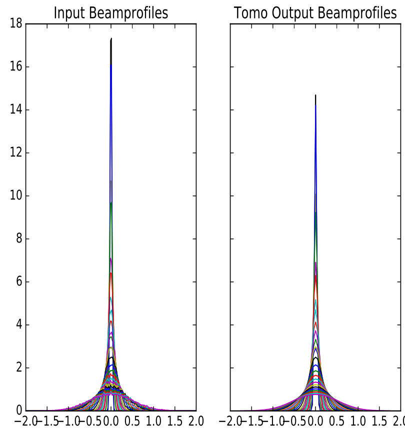

Figure 9: 1D beamprofiles in y plane. Input and output profiles.

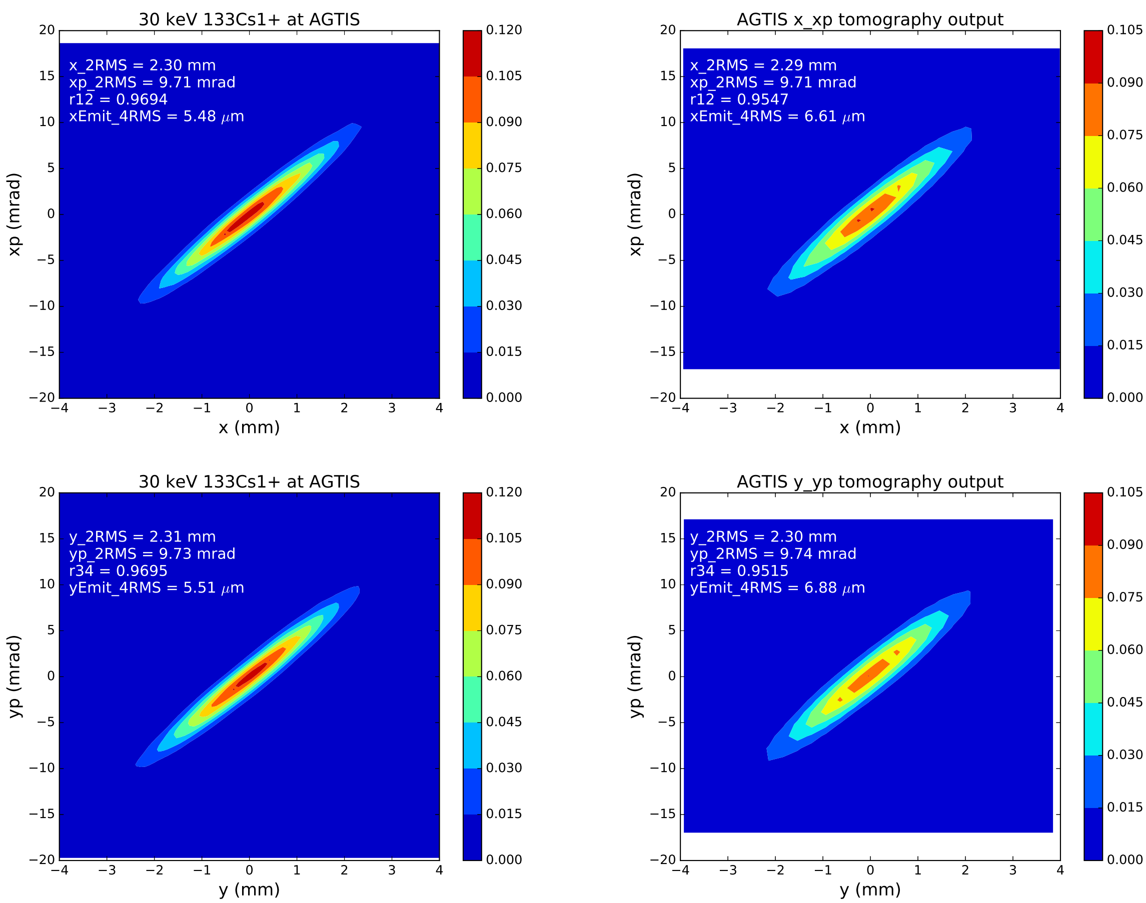

Figure 10: Top Row: x plane, Bottom Row: y plane. Initial particle distribution calculation on left, tomography reconstruction on right. Observe how similar the shape, orientation, position, and parameters are for each phase plane.

This is all done using theoretical data in both the x and y phase planes. This is a great way to verify that things are working correctly for when beam from the ion source is used and real data can be collected from the profile monitors. The analyzed data shown above can also be manually altered to observe how the beam and the algorithms react to unexpected shapes and parameters. For example, data can removed, squared or cubed to create holes, banana-shaped or s-shaped beams respectively (fig:11,12). The beam can also be moved off axis by adding a few millimetres or milli-radians to the data to see if MENT can process poorly steered beams. Several python scripts were developed in order to do all of this data processing and analysis above. All of this simulation analysis shows that the scripts and programs are working correctly and are ready to be updated and revised for working with real measured data.

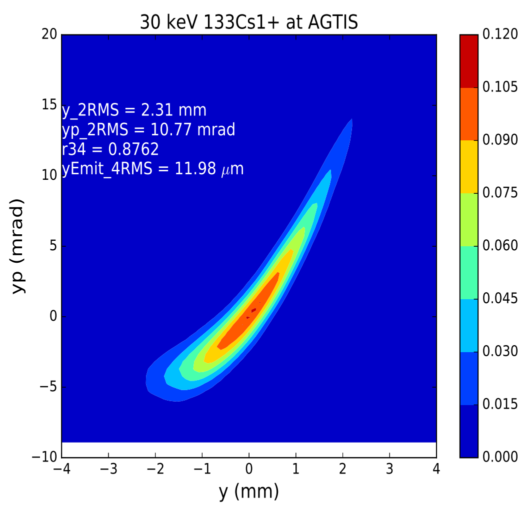

Figure 11: Altered particle distribution produces banana-shaped Beam in the y plane. Created in python by adding squared initial particle positions to initial partical angles. $ypi = c * (yi * 10)^2$ where ypi is initial angle (mrad), c is any constant, yi is initial position (cm).

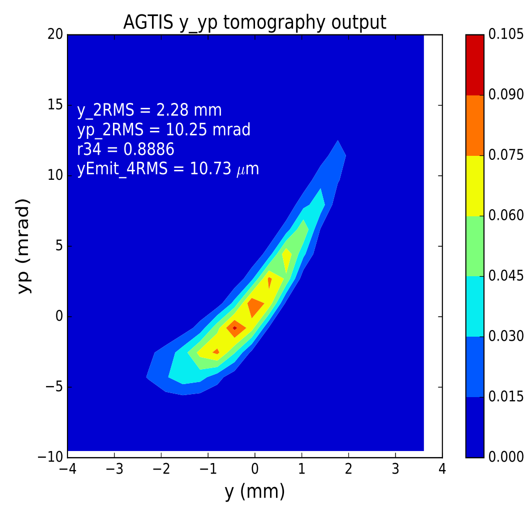

Figure 12: Tomography reconstruction of banana-beam in y plane. MENT can handle this test.

4 Tomography Analysis

Tomography reconstruction is used to visualize what the beam looks like both in phase space and real space. This is very useful in order to characterize the beam and confirm that elements along the beamline are performing as theoretically predicted. Tomography reconstruction can reveal the quality of the beam and is useful for calculating standard beam properties.

4.1 Processing Beam profiles

The most important step in this work with tomography is preparing and processing the raw beam profiles that the monitors measure. A python script was written, profiles.py, to do this for a wire scanner with three wires. There is a seperate script, LPM_profiles.py, for the monitors that use two slits. The code is very similar except that LPM_profiles.py records one less profile. The main goal of this beam profile script is to remove noise, clip profiles, calculate beam centroid and 2RMS beam size values, and plot the profiles (Fig:13,14). Most of the code is copied into a script called functions_for_tomo.py so that other scripts can import these functions and loop over many scans to get the clipped profiles rather than having to see all the plots and print statements that profiles.py is used for.

First, in order to read the desired data file, update the filename at the top of the code and update the path to the data file in the function fun(filename). The code first reads from a data file, diagnostic_position.dat, that contains information about position of the wires/slits. These values are used to convert the x-axis from potential (V) to position (mm) and to find the wire beam axis centers using this equation:

$$Position = A * ((B - C)/10) + C \tag{2}$$

where A is Potential Readback (V), B is EGUF and C is EGUL. PM3 scans the profiles using a potentiometer but the profiles need to be in distances to calculate centroid and 2RMS values.

Another important fix is that since the profile monitor is situated at 45° with respect to the beamline, the horizontal and vertical plane profiles have to be divided by $\sqrt{2}$ by basic geometry.

The stats function is very important as it calculates the centroid and 2RMS values for any profiles given input. It was previously written in Fortran in 2011 for ISIS at TRIUMF[1]. The stats function in Fortran was converted into python. The function takes in an individual profile as input (position vs. current) and the length of the data. It steps through the potential data (converted to position) and calculates the statistical beam centroid and 2RMS beamsize values.

The main function is mywst which gets called from fun(filename). The mywst function takes all the data that is read by fun(filename) and the length of the data. The raw data is plotted and is the exact same as what operators see from the controls. The next section of code is the most important as it finds the indices for where the three profiles start and end. If the code breaks, this is a good spot to look first as if the data is too noisy this code will think that a large noise peak is the start of a profile. The idea is simple though: the loop steps through the current values and it stops roughly where a profile begins by saying the previous value must be smaller, the next value must be larger, and the value a few points away must be very large. This roughly defines the start of a profile. The # in $current[i + 2] > \#$ is the value that should be increased if the data is very noisy. Finding the end of a profile is easier as the next value just has to be smaller than the one before it which will continue until the profile is over. The variables one to six represent the indices of where the profiles start and end for the three respective profiles. These indices don't have to be exact because the code finds the middle between the indices and uses those values to clip the profiles. So in the end, clipping only requires the start of the scan, the middle of the first and second profile, the middle of the second and third profile, and the end of the scan. A point is plotted at all the calculated indices to check accuracy. This code is assuming that there is only one trace for each profile. If PM3 reads two full traces consistently than additional code would be added to get the profiles for the other trace. This is shown in LPM_profiles.py in the large commented out sections.

[1] http://lin12.triumf.ca/text/ISIS/wirescanner/wst.f

Profiles.py converts potential to position using equation (1). A small section of code clips the raw profiles. Notice in the loops how the code is written $xwire - potdata[i]/fix$. This centers the data and the fix variable is our root two factor. This format also means that the data is flipped horizontally. This is due to how the wire scanner moves through the beam and figuring out which side of the profile is the negative side and which is the positive side based on the coordinate system used. The data is clipped as three raw profiles according to their lengths and plotted and outputted at the end of the function.

The next main section does noise filtering. In the code's early stages, all data below a maximum amount of noise was set to zero but a more systematic approach has been implemented. Note that the background noise should all be zero to get an accurate 2RMS value and also for MENT to process the profiles correctly. Sometimes there are scans where the data is vertically offset. To solve this, look at an arbitrary amount of points on each end of the clipped profiles and find the average current reading in these regions for each profile. This value is the offset. This offset is subtracted from each profile seperately to have an average zero offset. This works for positive or negative offset. To date, the offset tends to be quite small. To remove the noise, the code looks in the exact same regions but this time calculates the RMS. This can be RMS, 2RMS, 3RMS, etc, depending on how much noise needs to be removed. Everything below the RMS value in these regions is set to zero for all the profiles. Two small loops deal with isolated noise peaks that make it passed the RMS calculation. The smoothed profiles are found the same way as the raw profiles and the stats function is called to calculate the centroid and 2RMS values. In hindsight, some rearrangement is possible to just find the clipped raw profiles and then smooth those individually for more efficient/concise code but the clipping of the raw profiles was a last minute addition to the beginning of the code.

The main purpose of this code is to process and collect the profiles in order to create real space and phase space tomography reconstructions. It is also very useful to observe how large the beam is and how well centered the beam is in the beamline. This type of plot is convenient for beamline commissioning as it can help the operators determine by how much they should steer the beam based on the centroid calculations. Another beneficial aspect of this code is that it uses minimal filtering/smoothing. The code only deals with noise where the monitor should read zero beam current in an ideal situation. This makes sure that the peaks of the profiles are not altered at all. This is important as many profiles have features of multiple peaks or being very tall and narrow, etc. Low pass filters tend to decrease the height of the profiles or smooth together multiple peaks if the user is not careful.

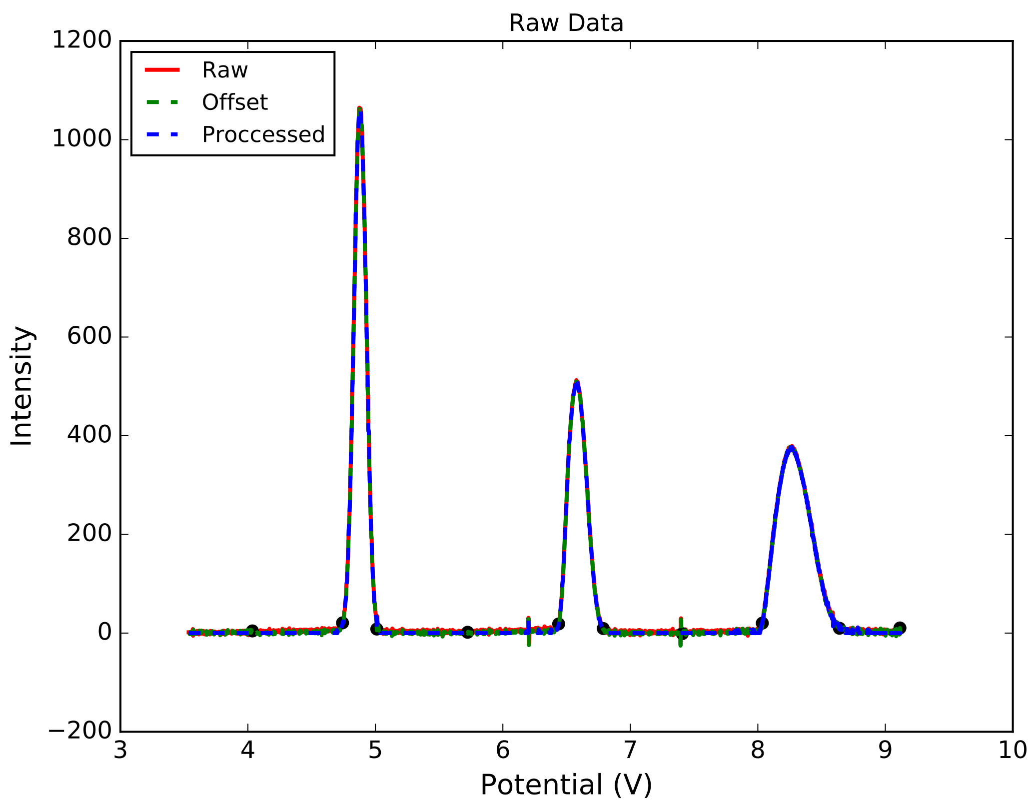

Figure 13: This figure is generated when profiles.py is run. It plots the raw data, offset data, and processed data. In this scan there is minimal noise and only a small offset. Black points are the calculated profile indices.

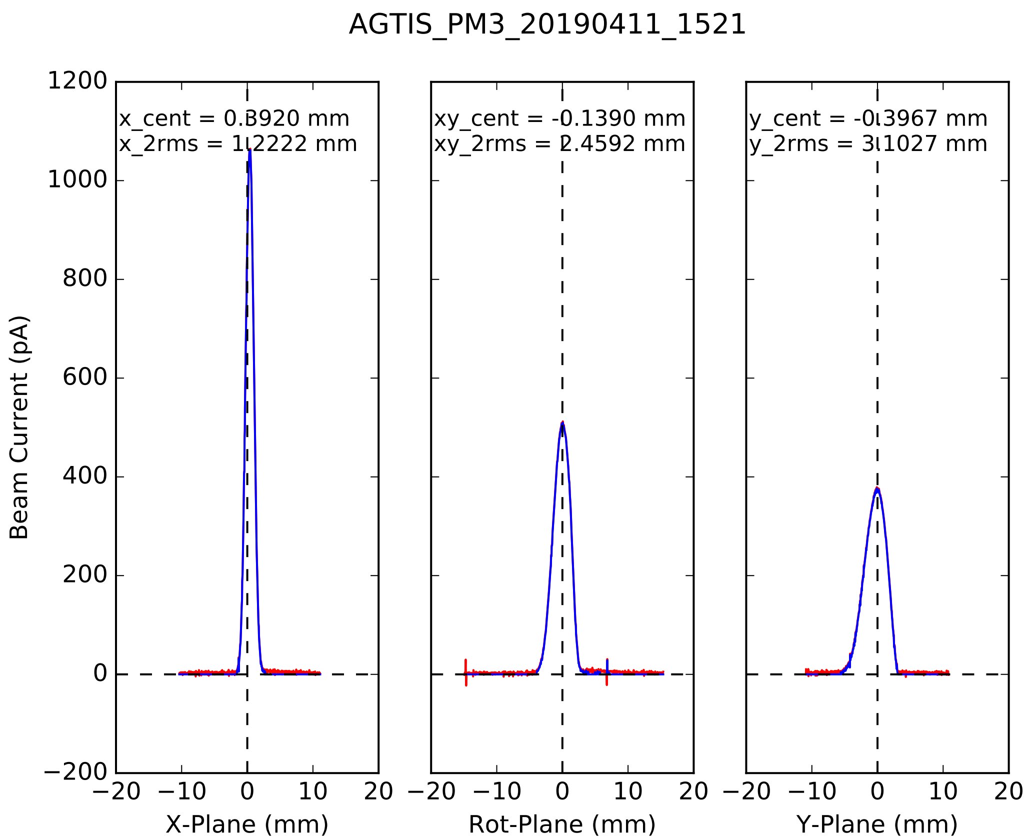

Figure 14: This figure is generated when profiles.py is run. It plots the raw and smoothed clipped profiles. Each centroid and 2RMS value is calculated and printed. Observe how well centered this particular scan is. The name of the data file is the title. This scan is with Q1,Q2,Q3 at 1671V, 2071V, 2438V ATIS:BIAS at 30 kV and Extraction Electrode (EE) at 50V.

4.2 Tomography Reconstruction in Real Space

Tomography reconstruction in real space was done using data taken from PM3 for this low energy beamline. From profiles.py the clipped, smoothed profiles are found. The next step is to generate the input file for MENT. A short script, create_tomo_in.py, does this for real space. The current working version of MENT is particular about the format of the input file. This script calls the mywst function to provide the profiles. Then the code loops over the three angles of the wires. The rotation matrix is calculated and written to the top of the input file. Then the profile data is written beneath its respective rotation matrix. So when MENT reads this file, it knows how each profile is orientated in order to generate the image. Notice there are specific spots to skip lines and add a '/' symbol. Then at the very end of the file, there should not be a '/' written. One final observation is that the input file, for_tomo.dat, overwrites itself when the script is rerun to update for the new data.

In the 'in' file that MENT needs, specify the filename and run MENT. Another short script, general_contour_plot.py is used to produce the reconstructed image based on the various files MENT creates. The x2RMS and y2RMS values are recalculated from the tomography data and printed on the plot to compare with the measured values. Using Fig:13,14 data, this contour plot was reconstructed (Fig:15). This contour plot shows what the beam is actually predicted to look like inside of the beamline. The beam is round with most of the particles being contained in the inner contours. The beam is very close to being centered at (0,0) since the centroid calculations were very close to zero. The input and output 2RMS calculations are essentially the same. This increases the confidence that MENT is producing accurate data. Another important check is to look at the tomography input and output profiles (Fig:16). The three profiles are plotted and appear to be very similar. This is a positive result as MENT is basically just taking the profiles the user provides to create the image. The reconstructed plot appears trustworthy based on these comparisons.

Using a different scan, another real space plot is created as an example (Fig:17,18). This scan has two peaks in the x-profile and the contour plot reflects this with two seperate regions of high intensity. Once again, the x2RMS and y2RMS values are quite similar. Finally, observe that in both the initial profiles and the contour plot that the beam is centered in the x-plane and off by about 1.0 mm in the y plane.

Real space tomography reconstruction has been an apparant success based on the scans taken and analyzed. The wire scanner provided three accurate profiles which were enough to create the real space tomography reconstruction in this Low Energy Beam Transport beamline.

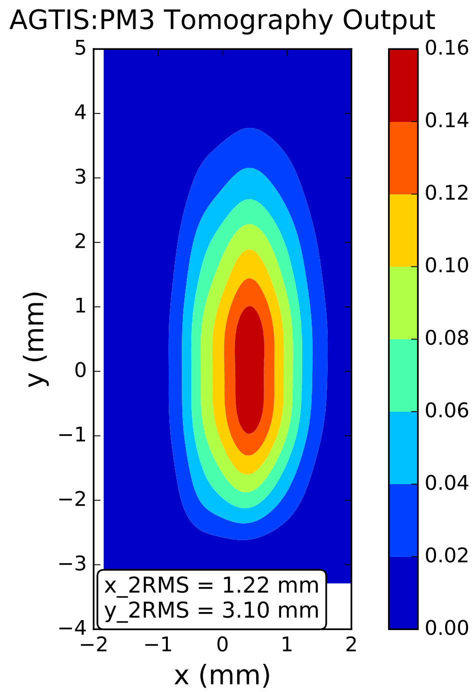

Figure 15: Tomography reconstructed image in real space using AGTIS_PM3_20190411_1521 data. First time tomography reconstruction in real space performed at TRIUMF for a low energy beamline.

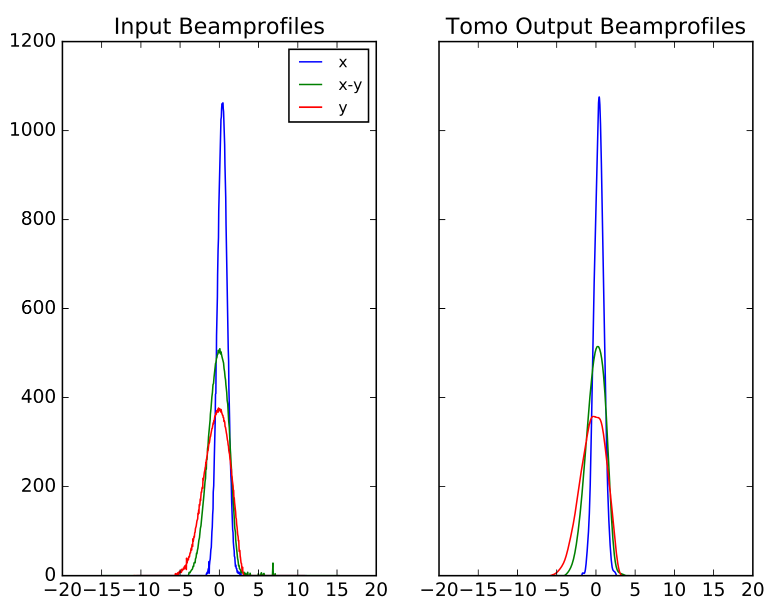

Figure 16: Comparing tomography input and output profiles. They are very similar in this case and show that the contour plot can be trusted. Position (mm) vs. Beam Current (pA).

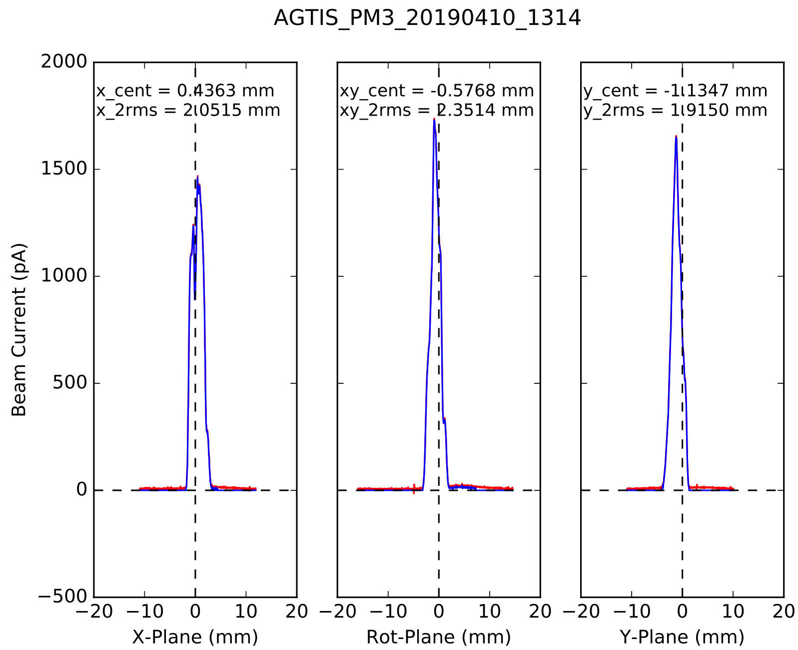

Figure 17: A different scan with Q1, Q2, Q3 at 1415V, 1982V, 1933V, EE at 420V and an AGTIS:BIAS of 30kV. Horizontal plane has a two-peaked x-profile.

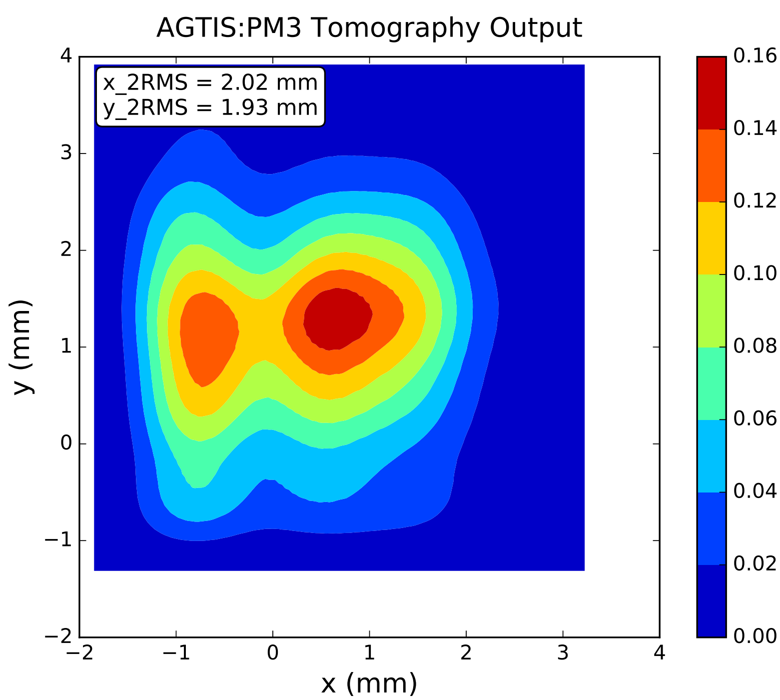

Figure 18: Tomography reconstructed image in real space using AGTIS_PM3_20190410_1314 data. Two peaks from x-profile.

4.3 Tomography Reconstruction in Phase Space

A number of different quadrupoles were scanned using different tunes for phase space reconstructions. One example was scanning AGTIS:Q1 (Fig:2). Using this tune: AGTIS:BIAS=30kV, EE=50V, Q1=1671V, Q2=2071V, Q3=2438V, and then varying the voltage of Q1 from 0kV to 3.0kV at 0.2kV intervals gave a decent scan for the x-plane. It was neccessary to use a lot of steering in order to keep the y-profile semi-centered. This meant that the data in the y-plane was not suitable for tomography reconstruction as the y-steering varied throughout the scan. Since the y-steering did not have an effect on the x-profiles, those are acceptable to use for tomography reconstruction. Q3 was scanned using the same tune in order to get a nice parabola in the y-plane. These scans were predicted to work based on TRANSOPTR simulations and looking at how the beam envelope changed as the quadrupoles were scanned. An acceptable scan must meet a few requirements in order to successfully use the data for tomography reconstruction. The profile integrals must be conserved to confirm that there is no beam loss (Fig:19,20). The plot of beamsize squared versus voltage must be parabolic and contain its minimum (Fig:22). A short script, integral_and_parab.py checks these conditions. These scans looked very promising as the desired parabola was produced in one plane each. Sometimes, during the commissioning process, scanning one quadrupole with normal polarity only produces the desired parabola in one plane. The solution is to either flip the polarity of the quadrupole or scan a different quadrupole to get a parabola in the other plane. The scan of Q1 and Q3 are acceptable to give to MENT for only the x and y plane respectively.

Next step was to gather all the corresponding transfer matrices from TRANSOPTR. Another python script, for_emit.py, is necessary to generate the input file for MENT. The data files and matrix files are read and then the user has the option to remove any bad data. For example, if the last two data points start losing beam then those get removed from the end of the list. The lists must be sorted correctly. The first data file has to correspond to the first matrix in the list and so on. Once the range is correctly chosen, the script loops through all the files (like create_tomo_in.py for real space) and saves the x-plane and y-plane data to seperate files. Update the filename in the 'in' file and run MENT. MENT does not care about units as long as they are consistent throughout all the data. The transfer matrices are generated in cm and mrad. general_contour_plot.py is used again to create the contour plots (Fig:23,24). The tomography input and output profiles are compared to verify that MENT is successfully generating an accurate image (Fig:25,26).

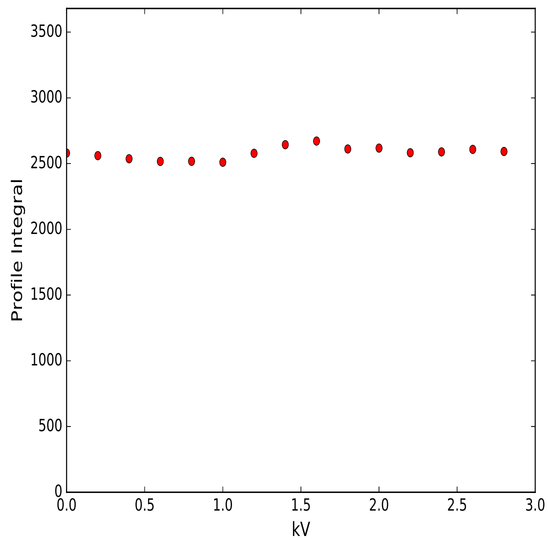

Figure 19: X-plane. Integral is conserved as required up until about 3.0kV. One or two points appear to have a slightly larger integral and can be removed if neccessary.

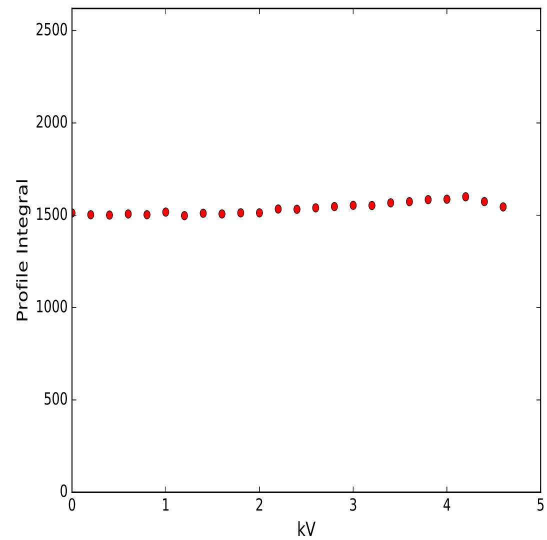

Figure 20: Y-plane. Integral is conserved as required for most of the range. Last few points begin to decrease and so those points are not used in tomography reconstruction.

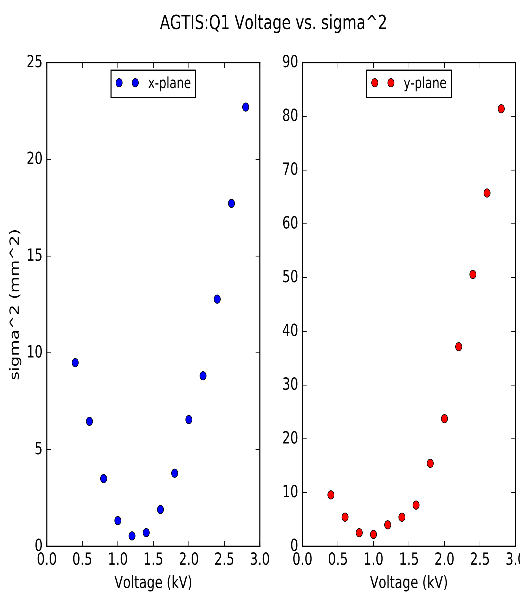

Figure 21: 2RMS^2 versus voltage for x-profiles is acceptable but not for the y-profiles even though there is a parabola as the steering was changed in the y-plane throughout the scan to keep the y-profiles more centered.

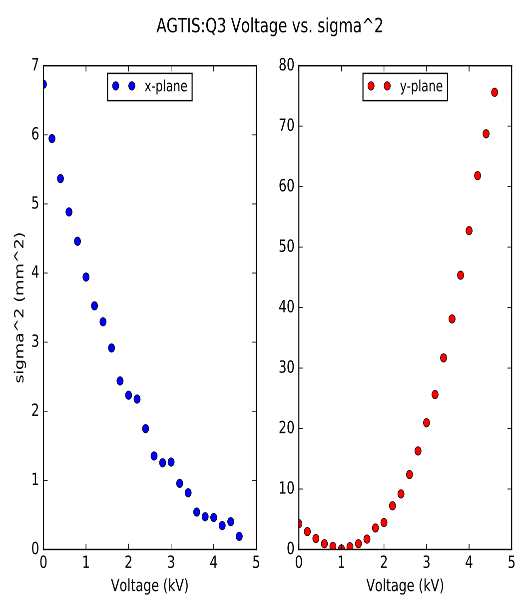

Figure 22: 2RMS^2 versus voltage for y-profiles is acceptable as it contains its minimum while the x-plane does not.

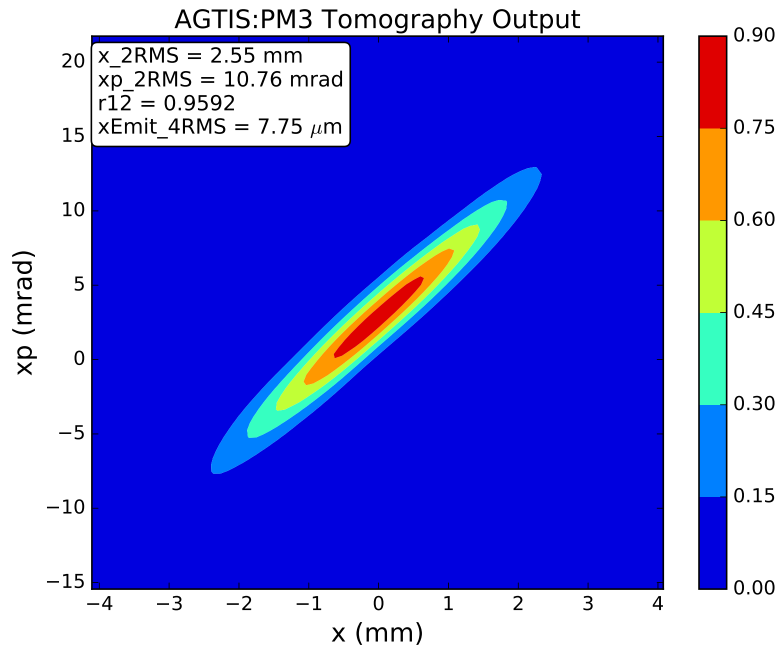

Figure 23: AGTIS:Q1 scan phase space tomography reconstruction in the x-plane. Profiles used from 400V to 2800V minus two profiles at the minimum of the parabola.

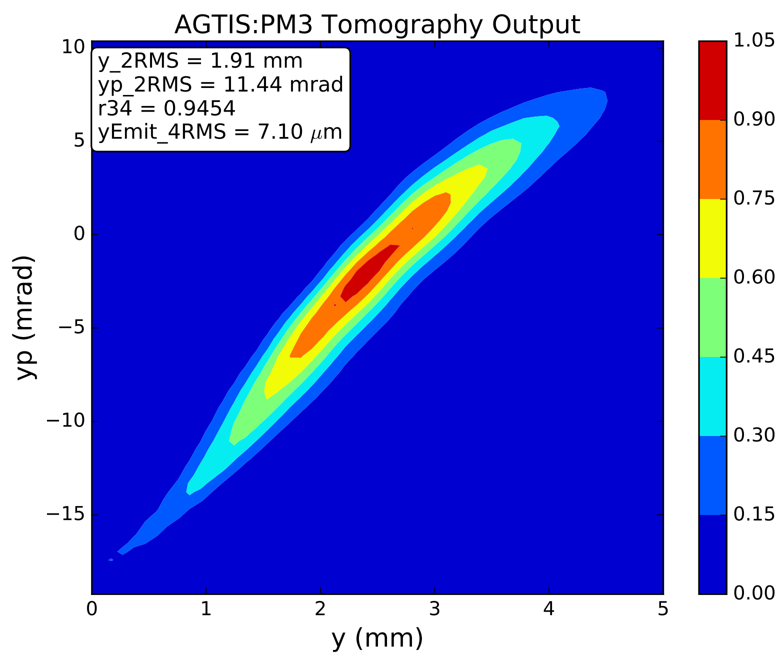

Figure 24: AGTIS:Q3 scan phase space tomography reconstruction in the y-plane. Profiles used from 0V to 4200V minus four profiles at the minimum of the parabola.

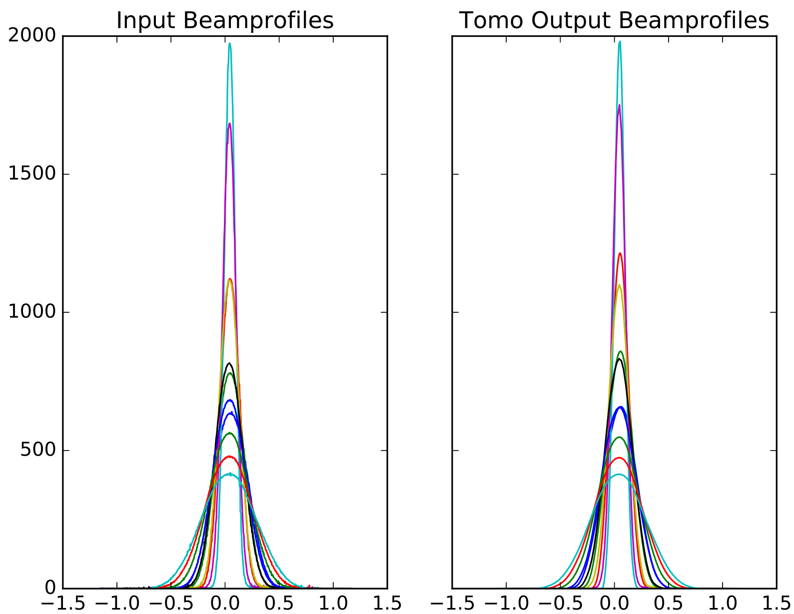

Figure 25: AGTIS:Q1 scan tomography input and output profiles in the x-plane. Position (cm) vs. Beam Current (pA).

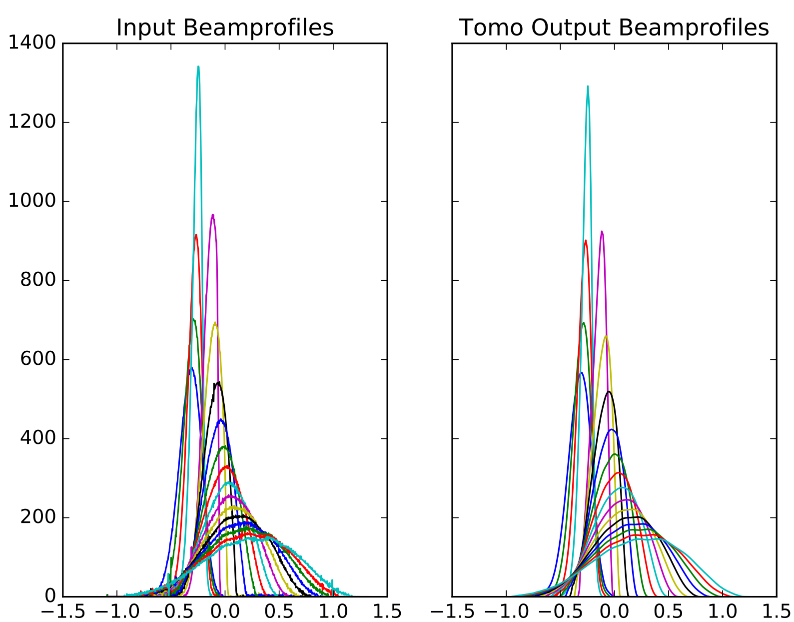

Figure 26: AGTIS:Q3 scan tomography input and output profiles in the y-plane. Position (cm) vs. Beam Current (pA).

The results shown above were very positive. In phase space, an elliptical shaped beam is produced which is very similar to what is desired from the theoretical simulations. For additional context, shown below are the results produced for a different tune (Fig:27,28,29,30,31,32). Clearly the beam in phase space has many aberrations and is very s-shaped. The main difference between the reconstructions is that these were done with an extraction electrode setting of 500V. When the extraction electrode is decreased to 50V the nice elliptical figures in the report are produced.

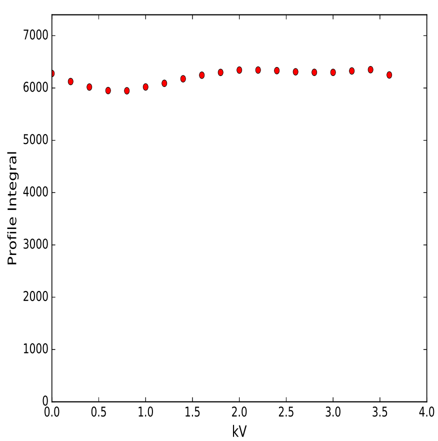

Figure 27: X-plane. Integral is mostly conserved as required.

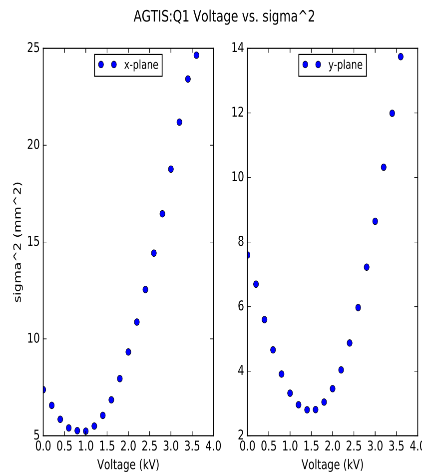

Figure 28: Good parabolas in both planes as both contain minimum. Suitable for tomography.

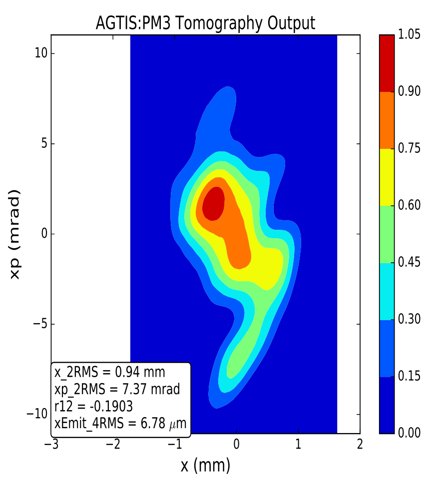

Figure 29: AGTIS:Q1 scan phase space tomography reconstruction in the x-plane.

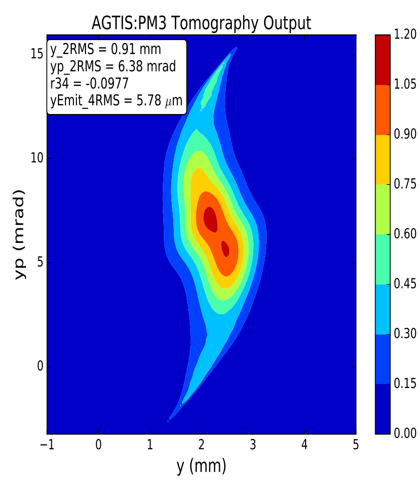

Figure 30: AGTIS:Q1 scan phase space tomography reconstruction in the y-plane.

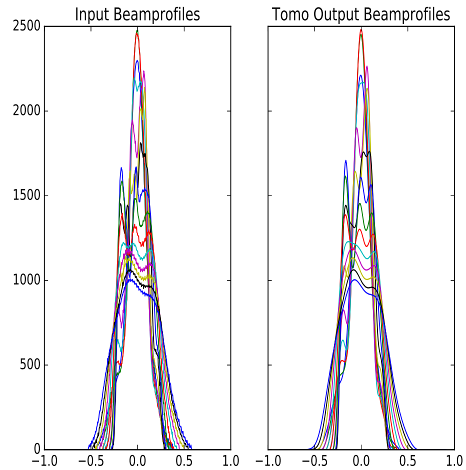

Figure 31: AGTIS:Q1 scan tomography input and output profiles in the x-plane. Position (cm) vs. Beam Current (pA).

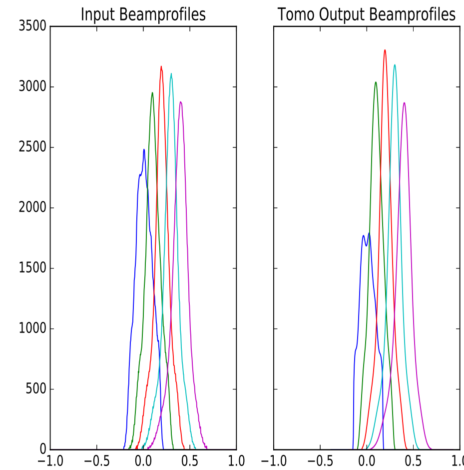

Figure 32: AGTIS:Q1 scan tomography input and output profiles in the y-plane. Position (cm) vs. Beam Current (pA).

5 Conclusion

Three main goals have been acheived. A python script is created to process the beam profiles measured from the beamline diagnostics. Calculations of 2RMS beamsize and beam centroid values are done for each profile to determine how large the beam is and how well centered it is. It has been shown that tomography reconstruction in real-space has been a success for this low energy beamline. This is a good achievement as tomography reconstruction in real space was only done before for high energy beams at TRIUMF. Finally, successful results were obtained with the tomography reconstruction in phase-space. The AGTIS is confirmed to be producing a very stable and almost ideal beam for commissioning. All of this work has led to a deeper understanding of tomography and how it works with MENT in beam physics. All of the python code and analysis that has been performed up to this point will continue to be used and improved upon as the RFQ, PDT, EBIS, NIS, and rest of the ARIEL beamlines are commissioned.

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