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Data Processing and Analysis on the HiRadMat Beamline

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Abstract. HiRadMat (High Radiation to Materials) is a CERN Facility that uses a beam from the Super Proton Synchrotron along the Large Hadron Collider injection pipe. This facility sends high intensity short-pulse proton beams to various materials. The HiRadMat group aids experimental groups by providing them with the data of this beam's behavior. I improved the logging process of the data to include additional devices and be accessible to all users of *acc-py*, allowing better real-time beam analysis. In addition, I preformed an analysis on the optics and beam position of the SMAUG HiRadMat experimental week runs. This allowed the STI experimental group to be better prepared for their run in the beam line.

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1 Introduction

HiRadMat (High Radiation to Materials) is a CERN Facility that uses a beam from the Super Proton Synchrotron (SPS) along the Large Hadron Collider (LHC) injection pipe. It provides high intensity (440 GeV) short-pulse proton beams to materials, allowing experimental teams to test how their equipment (such as detectors or accelerator assemblies) withstand this radiation damage. Other groups, like the Fireball group, run experiments in this facility which produce novel results. The HiRadMat facility is operated in a way, that all of the necessary data about the beam need to be carefully monitored in order to ensure that it the beam and equipent are working properly. In addition, the data need to be made available and provided to the experimental groups.

During my internship in HiRadMat, I worked to improve our Logbook which allows the beam data to be viewed in real-time as well as stores all of the necessary data and plots. This allows us to ensure that it is working as expected while we are actively operating the beam while also being able to go back after the experimental days and analyze our results with this beam data. In addition, I made the VISTAR screen accessible to any user with *acc-py* access by developing it into one of the CCC apps. I also used the data stored in the logbook to analyze the HRMT-65 optics in our beam line to gain an understanding of how the beam behaved with various optics and intensities and compared to the theoretically calculated beam sizes. These results allowed the SY/STI group which is responsible for the HRMT-65 experiment to properly prepare for their experimental run planned for August 5, 2024. Lastly, I characterized the movement of the beam in each shot by analyzing the beam position of each bunch. This helped us identify trends that need to be accounted for when using different screens and optics. Overall, these analyses allow us to find a cause of potentially odd experimental results and mitigate it before the HRMT-65 physics run.

2 Beam Instrumentation

HiRadMat uses a variety of beam instrumentation to ensure that the beam is properly monitored One of the principal devices HiRadMat uses is a beam television (BTV). A BTV uses a screen that is installed in the beamline, intercepting the beam trajectory. This screen interacts with the beam, producing OTR radiation with an intensity proportional to the beam intensity. The image is then picked up by a camera that is located outside the beam line. Our logbook or VISTAR script then projects these data from the camera in the normal axis to obtain the horizontal and vertical projections of the incident beam. A normal projection is used to correct all of the effects of the screen angle with respect to the beam in the camera optics. This ensures that the values obtained from these BTV devices would match the theoretical predictions of the beam.

Another type of device used by HiRadMat is a beam position monitor (BPM) or a beam pickup monitor (BPKG). These two devices work in slightly different ways but are used in the same manner in our beamline. They deliver the center of mass of each bunch without affecting the beam. This is done by measuring the charges induced by the protons in the beam on an insulated metal plate which creates an alternating current on the plate. From this current, we are able to obtain the position of each bunch [1]. Using multiple plates allows us to determine the bunch's horizontal and vertical center of mass. This data is then sent to the logbook as the position of that bunch.

I also worked analyzing data that would help to understand the signal of Beam Current Transformers (BCT) which are located along the the TT60 HiRadMat extraction beamline and the TT66 HiRadMat beamline. These BCT devices analyze the current of the beam [2] wherein the magnitude of the current gives us an idea of its intensity. This allows us to measure the intensity of the beam along the extraction line and in HiRadMat, telling us if there are any problems with the transfer.

The final piece of beam instrumentation that is relevant to this report are the beam loss monitors (BLM) which are located on both sides of the beam line at various points. They work to absorb the shower of particles that arise from interactions with the air or the walls of the beam line. In doing so, their signal should be proportional to the number of lost particles along that section of the beamline [3]. This helps give us an idea of the momentum and number of particles that are lost to improve our ability to determine potential causes of noise in the data.

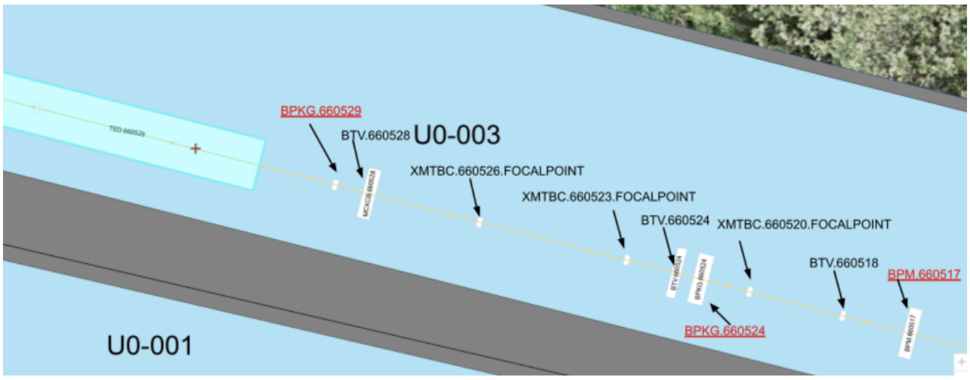


Figure 1: This image shows the elements on the HiRadMat beamline in the section I am studying. The three elements in red are the beam position monitors. There also are three focal points, two beam TVs, and no magnets along this beam line. Each of the focal points correspond with an experimental area where the furthest upstream one is solely for HiRadMat equipment while the other two are set up for the use of experimental groups.

2.1 Logbook Work

Recently, a new BTV (designated BTV 660528) downstream from the experimental setup (at position 660528) to their beamline. This, in combination with the upstream BTV 660524 allows us to identify the precise location of the beam at the experimental location (figure 2). This also can give us an idea of if the beam behavior changes while in the experimental apparatus because we can see a different shape on the BTV screens.

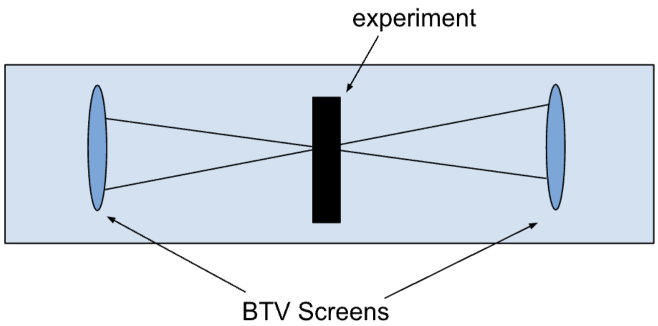


Figure 2: This image shows the location of the two BTVs in with respect to the experimental apparatus. From it, you can see that the second BTV prevents us from needing to extrapolate and provides us with confidence in the position of the beam at the experimental apparatus.

To make the analysis of this second BTV easier in real-time, I updated our logbook and vistar script to include the data from this second BTV. This entailed virtually connecting to the BTV to acquire its data then figuring out a reasonable way to display the data in a way that would let us come up with meaningful results. This meant that I rearranged the vistar screen that is attached to the logbook and printed important BTV data to the logbooks.

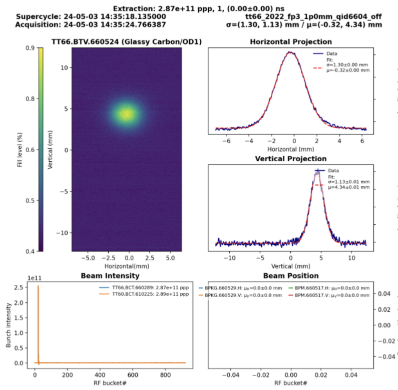
It was observed that the BPM was not properly connecting to the loogbook and the data was not being plotted. This left us with no idea of how the beam position was changing from bunch to bunch within the multi-bunched shots. Thus, I also changed the connection to these BPM and BPKG devices and fixed their plotting mechanisms.

It also was noted that the emittance is used in the theoretical beam size calculations and that having the beam spot size accounting for any rotations would be helpful on the BTV VISTAR screen and in the logbook. Panos Zisopoulos built us a tool using UCAP (the United Controls and Acquisition Processing framework [4]) that calculates these values which I connected to and added to the logbook and VISTAR screens. This will significantly improve the accuracy of the comparisson with the theoretically predicted beam size values.

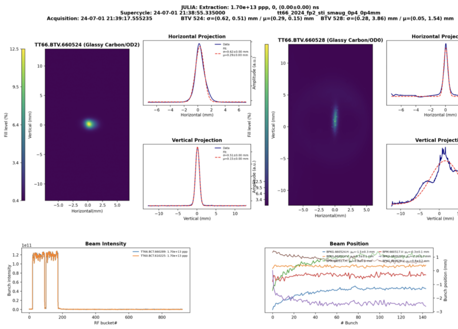
The last important step was making the Logbook accessible. I began this process by deploying it to *acc-py* which allows it to be run by any user with access to *acc-py*. To do so they can run

```
acc-py app run hrmt-vistar
```

on the command line or they can open it on the SPSOP concole of any machine in the CERN Control Center (CCC). The deployment details are included in the HiRadMat VISTAR Gitlab page.



(a) The VISTAR screen from a shot before mine had been implemented and tested. It shows the how the beam position plot isn't plotting any data and that the second BTV isn't included.



(b) This is the current version of my VISTAR screen. It shows the working beam position plot and the inclusion of the downstream BTV. This allowed us to use one screen to analyze the necessary data efficiently before moving on to the next shot.

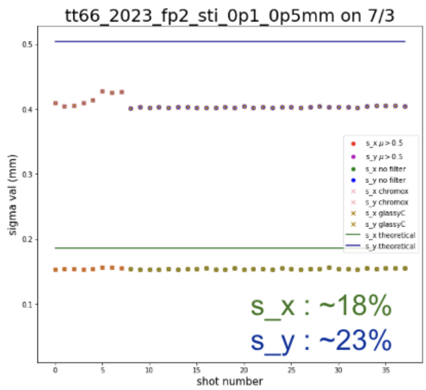
Figure 3: This is the BTV VISTAR screen from before my project began and after it's completion. These screens are from different trials so they show different beam shapes.

3 Optics Analysis

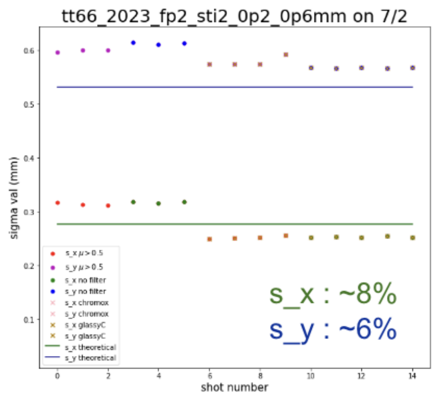
When the BTV produces an image of the beam spot, we project this beam spot in the horizontal and vertical directions. This provides us with a curve that shows the shape of the beam spot in each of these directions. A Gaussian fit is then applied to the curve and its σ_x and σ_y values are reported in the VISTAR 3. These values are also stored in a `.csv` file which is updated when the logbook is updated and in an NXCALS file which can be accessed on the CERN Timber page. This gives us a backup dataset in case one is erroneous.

While preforming the HIRadMat Experiments, it was noticed that the σ_x and σ_y recorded in the logbook didn't match their respective theoretical values. Thus, I sought to determine the cause of this problem by acquiring the σ_x and σ_y data from the NXCALS BTV 660524 dataset and plotting it for each optic that was used. I chose the NXCALS data set because there was a problem with the bunch number calculations in the Logbook. This arose because of an external device not functioning properly so it was ideal to use the data that had the proper number of bunches in case they became needed.

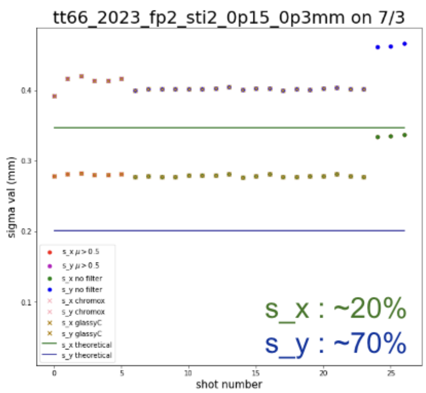
The problem with these σ_x and σ_y plots was that they were really noisy and it was hard to identify any major patterns. A quick scroll through the logbook showed me that there were some outliers being included in these calculations that were adding to the noise. The first and most obvious ones were the shots with a fitting coefficient of $R^2 < 0.95$. This meant that the fit was bad and it would give us an inaccurate σ value. In addition, if the beam wasn't properly centered, it could be experiencing some effects from the edge of the beam pipe and would likely have an inaccurate fit. We identified our centers with the parameter μ and if $|\mu| < 0.5$mm, it was deemed too far off center to be a shot that had statistical meaning. Lastly, it was determined that different BTV screens could give us different data so, to get a true analysis of the behavior, it is worth marking what screen was used.



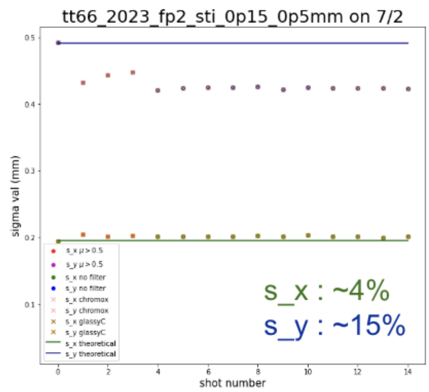
(a) The σ_x and σ_y values from the 0.1mm $\times$ 0.5mm STI optics. The measured σ values hover about 20% off from the theoretically calculated ones.



(b) The σ_x and σ_y values from the 0.2mm $\times$ 0.6mm STI optics. The measured σ values hover about $5-10\%$ off from the theoretically calculated ones.



(c) The σ_x and σ_y values from the 0.15mm $\times$ 0.3mm STI optics. The measured σ_x values hover about 20% off from the theoretically calculated ones while the measured σ_y values hover about 65% off from them.



(d) The σ_x and σ_y values from the 0.15mm $\times$ 0.5mm STI optics. The measured σ values hover about $10-20\%$ off from the theoretically calculated ones.

Figure 4: The points show the sigma values for each of the optics over each shot to the optics. The theoretically calculated values are the green line (x) and the blue line (y). The green and blue points lie within the constraints we set while the other colored points indicate values that were deemed erroneous. In addition, the x marks over the points indicate the presence of a screen. The pink x marks indicate the chromox (chromium-doped alumnia ceramic [5]) screen while the brown ones are for glassy carbon screen. Lastly, shots with $R^2 < 0.95$ or $|\mu| > 0.5$ are marked in red and purple.

In addition, we sought to compare the experimental σ values to the theoretical ones to see if the beam was behaving as expected. These values were calculated for each optic by using a MAD-X file and they were compared with the theoretical values obtained by the STI group. Initially, we had different theoretical values so I checked the inputs into our calculation. In the CERN Layout system, I found the location of the BTVs in our beamline and the input file to our MAD-X matched those but the STI group had incorrect locations. This allowed them to fix their theoretical values to match mine. Next, we were able to verify that they were seeing similar magnitudes of differences between the experiment and the expectation to my calculations.

The percent errors of the measurements with regards to the theoretical measurements were all on the order of about $10 - 20\%$ which was significantly larger than we'd initially expected. First, we met with Stephane Burger who informed us that we should not expect anything much greater than 5% error on the beam size from the BTVs. This led to the belief that all of our measured values were very far off from the expected ones and we needed a way to predict this offset for future experiments. For this reason, we met with Francesco Velotti who provided us with figure 5 which demonstrate that the noise in the optics will drastically increase our error percentage to the order of $5 - 10\%$. In this discussion, it was also noted that the emittance value isn't checked for every shot. This means that it could have shifted without our noticing. Because MAD-X also uses a defined emittance value to calculate the theoretically expected σ values, having inaccurate emittance values could double our percent error. This is most likely why we are seeing errors of $10 - 20\%$ instead of $5 - 10\%$ like those predicted by Velotti and it is why I updated our logbook to record the emittance values of most shots.

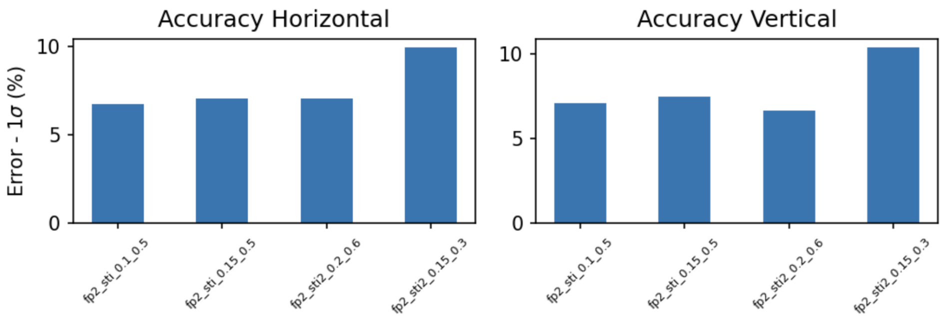


Figure 5: This image shows the predicted percent accuracy of the HED or STI optics with known emittance values. It was provided in [6]

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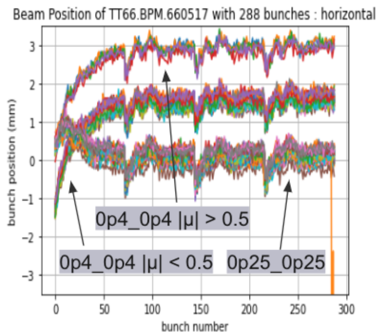
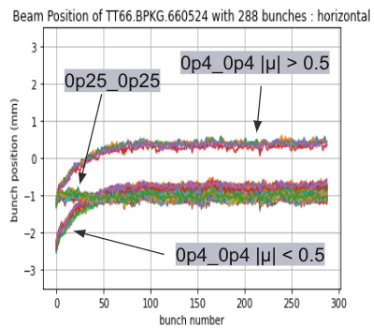
When looking at the 0.15mm × 0.3mm HRMT-65 optics, we notice that the error in σ_y is approximately 65% which is much greater than the rest of the optics. It was also noticed that the beam spot was slightly rotated with this optic. This meant that our horizontal and vertical projections which are done in the lab frame did not exactly line up with the horizontal and vertical parts of the ellipse in the beam frame. Yet, [7] proved that σ is independent of the correlation between the horizontal and vertical projections. So this rotation should not be affecting the calculation of the beam width manipulating the rotation or planes of measurement would yield incorrect results. This rotation, however, comes into play when the beam surface is being calculated. These calculations allow us to find the density of the beam but they require a calculation of the beam spot ellipse. The calculations of the beam spot ellipse come from these beam widths so a rotation of the beam would yield a different ellipse. Thus, the rotation only needs to be applied when calculating this beam surface to obtain an accurate estimate of the beam density.

4 Beam Position Monitors Analysis

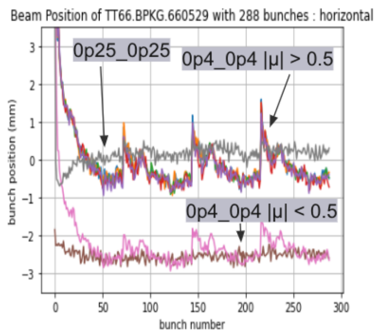
When running the Logbook and vistar screen with the Beam Position graphs that I'd fixed, it was noticed that there was a drift in the multi-bunched beams. So, the beam gradually moved from bunch 1 to bunch 288 over these shots. This could be very problematic because it means that the beam isn't always in the expected location. Thus, I sought to quantify this drift. I graphed the BPM results for the three BPMs in the HiRadMat experimental beam line: 660517, 660524, and 660529 as seen in figure 6. I also checked the CERN layout in figure 1 and learned that there are no magnets in this part of the beam line which means that the beam position shouldn't change significantly between BPM devices. There, however, are three focal points: one between 660517 and 660524 and two between 660524 and 660529 which could have an effect on the beam position. In addition, the focal points between 660524 and 660529 correspond with the experimental areas. This means that the apparatuses in the experimental area of the beamline could affect the results of BPM 660529. It also is important to note that the STI 0.4mm × 0.4mm optic was tested for all number of bunched shots while the STI 0.25mm × 0.25mm optic was only tested for 144 and 288 bunched shots. In addition, the chromox and glassy carbon screens were both used with both of these optics. The NXCALS data also recorded some of the shots as having "screen out" though this is thought to be a glitch and glassy carbon or chromox were most likely used in those shots.



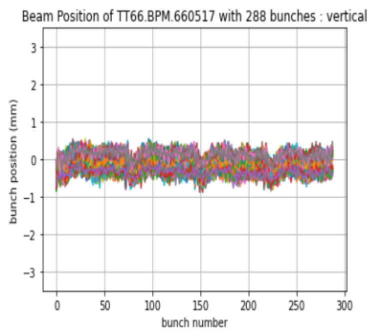
(a) The horizontal beam position at location 660517.



(b) The horizontal beam position at location 660524.

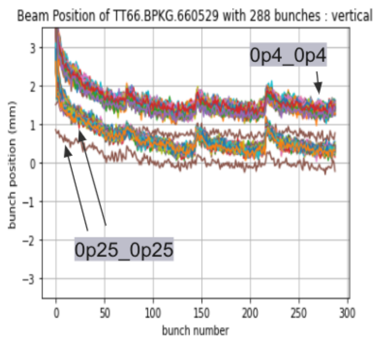


(c) The horizontal beam position at location 660529.



(d) The vertical beam position at location 660517.

(e) The vertical beam position at location 660524.

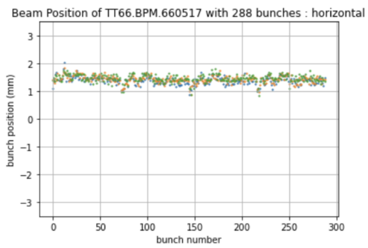


(f) The vertical beam position at location 660529.

Figure 6: This is the set of beam position analysis plots over the multi-bunched tests during the SMAUG tests. These were taken before the kicker timing was fixed and show significant drifting in the horizontal direction.

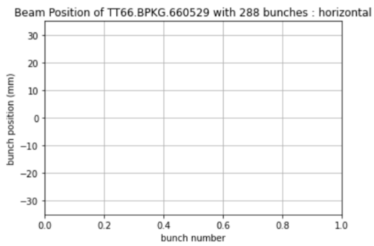
From the plots in figure 6, we can see that the vertical beam positions of monitors 660517 and 660524 were relatively linear and hovered around zero. The horizontal ones, however, drifted over the first 50 bunches. This drifting was also shown in shots of 24, 48, and 144 bunches but mainly only with the STI 0.4mm × 0.4mm optic and less so with the STI 0.25mm × 0.25mm optic. This means that this may be a behavior of the optic or it could be a technical problem along the beamline. In an attempt to resolve this issue, during the STI pre-commissioning tests, these plots were shown to Velotti. When analyzing the drift in the horizontal direction and the lack thereof in the vertical direction, he realized that the beam kicker was most likely off. This meant that it is not timed properly with the beam so if it acts a fraction of a second too late, the first bunches will show the movement of the kicker as the beam shifts into position in the later bunches of each shot. He then fixed this during the STI pre-commissioning tests on July 25 which are shown in figure 7. It, however, is difficult to use this as conclusive evidence that the kicker was the problem with these shots because the plots in figure 6 show that the nature of the drift is somewhat optic dependent and the sti 0p15-0p5mm optic was used.

In addition, it was noted that fewer bunches were recorded in by BPKG 660529 than by the other BPMs. This may have been a result of interactions with the air in the beamline or with the experimental apparatus. To ensure that the beam was not being deflected and leaving the beamline, I checked the horizontal BLMs at positions 518, 523, 526, 530, and 531. None of these devices recorded any lost beams which means that there must have been some other cause for the fewer shots being recorded by BPKG 660529.



(a) The horizontal beam position at location 660517.

(b) The horizontal beam position at location 660524.



(c) The horizontal beam position at location 660529.

(d) The vertical beam position at location 660517.

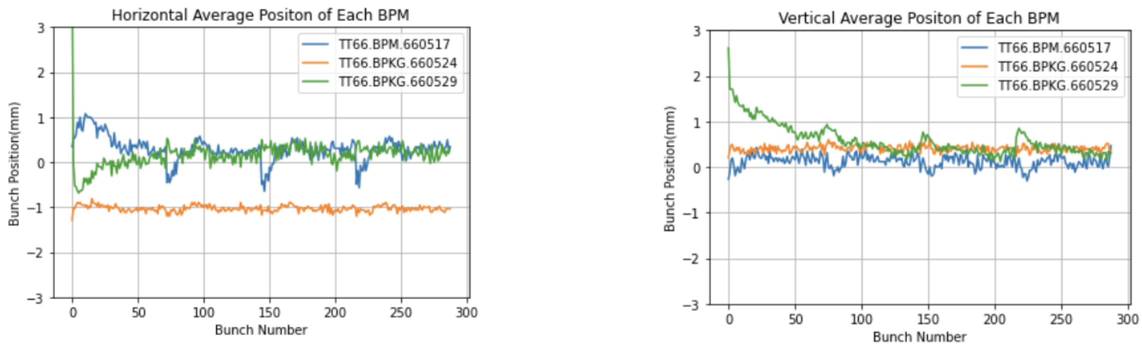
(e) The vertical beam position at location 660524.

(f) The vertical beam position at location 660529.

Figure 7: This is the set of beam position analysis plots over the multi-bunched tests during the STI pre-commissioning runs. These were taken after the kicker timing was fixed and show much less drifting in the horizontal direction than before this fix.

Figure 7 shows that no beam was recorded by BPKG 660529 in the horizontal projection and fewer beams were recorded in the same vertical projection than in the BPMs at 660517 and 660524 which come before the experimental apparatus instead. This experiment used a different experimental apparatus than the ones used in the experiments from July 1 - July 3. Thus, it is possible to conclude that this could be a result of a problem in this device though further testing without any experimental apparatus in the beam line would be necessary to be confident in this.

While the previous analysis gave us some idea of how the shots were behaving per bunch, it wasn't very easy to identify how they compared from optic to optic. This was especially prevalent in the 288-bunched beams because there were too many bunches to notice any major changes that were in all of the shots but blurred out by the massive number of shots. For this reason, I decided to take the average of all of the shots per bunch in making figure 8.



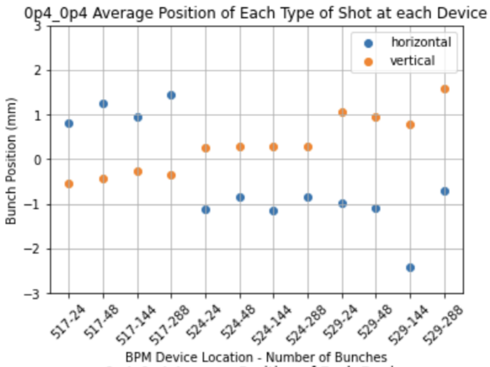
(a) The average position of each bunch at each of the BPMs in the horizontal plane.

(b) The average position of each bunch at each of the BPMs in the vertical plane.

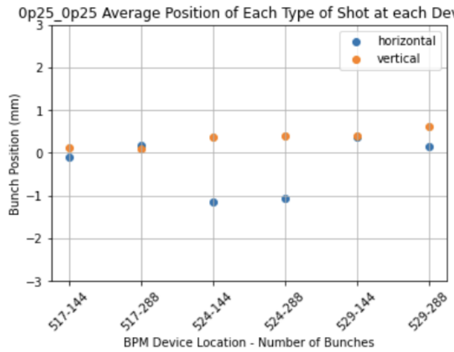
Figure 8: These show the average position of each bunch per BPM location from the SMAUG HiRadMat beam week tests. From it, we can see that the positions of the BPMs all hover around zero in the vertical plane but the odd drifting that is seen in figure 6 for BPKG 660529 does affect the average as well. The 660517 and 660529 BPM positions also hover around zero in the horizontal plane but BPKG 660524 is offset by about -1mm.

From these average plots, we can see that they are relatively consistent except for the horizontal plane of BPKG 660524. This one appeared to be ffset by about -1mm in the STI pre-commissioning tests (figure 7) as well. In addition, there is very little fluctuation in its average behavior which leads me to believe that this could be a characteristic of the beam at that location. We can also see that BPM 660517 shows the drop spikes at similar locations in both the horizontal and vertical directions and that these spikes line up with the jump spikes in the vertical projection of BPKG 660524. This is odd because 660517 is before the experimental apparatus and 660529 is after it so the experimental apparatus can't be causing these spikes. Interestingly, these peaks have a mean peak spacing of 72.3 ± 0.5 bunches and the CERN Proton Synchroton (PS) injects 72-bunched beams into the SPS for acceleration [8]. This is only a correlation and further testing of the intensity of all of these bunches in the beams at the entry and exit of the SPS would be necessary to determine causation. This credibility of the correlation is further inhibited by the fact that only the BPM 660517 horizontal and vertical and the BPKG 660529 vertical projections of these beam position plots displayed this behavior and had prominent enough peaks to be used in these calculations.

Lastly, I sought to find a simpler demonstration of the beam position at each optic and BPM. This was done in figure 9 by taking the average location of each shot then averaged all of the shots of the same number of bunches together for each optic. In the 0.4mm $\times$ 0.4mm optic, the vertical position seems to increase at each position on the beam line while the horizontal position is high then is flipped to negative and stays there at 660524 and 660529. In the 660529 shots, the vertical position is relatively constant while the horizontal position has a drop for only the 660524 BPM. This drops it to the position of the beam with the 0.4mm × 0.4mm optic at that same BPM but then it is changed for the 660529 BPM. The 660529 BPM is the one that acquired fewer shots in the horizontal direction so this could entirely be a result of the noise.



(a) The average position of each shot for each shot length and at each BPM in the 0.4mm × 0.4mm STI optic.



(b) The average position of each shot for each shot length and at each BPM in the 0.25mm × 0.25mm STI optic.

Figure 9: These show the average position of all of the shots for each BPM and optic. It allows us to obtain a simple, more direct comparison of the behaviors of the two optics that were used during the SMAUG week tests on July 1 - July 3.

5 Conclusions and Future Steps

This project resulted in a functioning VISTAR screen that incorporated emittance and predicted beam spot size data with that emittance. In addition, a downstream BTV device was connected to the screen and the beam position monitors plots were fixed to properly display their data as well. The VISTAR is able to be run by anyone with access to *acc-py*. Currently, work is being done to move the running of this screen from the command line to the SPSOP CCM center whose window can be accessed by any of the computers in the CCC. The logbook connection still needs to be run to the command line. Creating a pop up screen that allows the user of the SPSOP CCM page to select if they want to connect to the logbook and provide the necessary credentials to do so would further increase the accessibility of this program to users and HiRadMat staff.

This project also included an analysis of the HRMT-65 optics from the SMAUG HiRadMat beam week trials. It was determined that the error in the optics was similar to the expected error when the emittance wasn't calculated for every run. By measuring the emittance more consistently, we can obtain better theoretical predictions and better guide experimental users in determining their optic of choice. In addition, it was shown that our theoretical calculations rely on an unrotated beam and calculate the approximate beam spot area from that. If the user wants to know the exact beam spot area in order to calculate the beam density, then the rotation needs to be accounted for so the exact elliptical beam surface can be taken into account.

The final part of this project was an analysis of the beam position monitors. It was shown that the choice of optic affected the position of the bunches of a beam in each shot. The choice of screen, however, did not seem to have any significant affect on this behavior. One problem in the SMAUG HiRadMat beam week BPM plots may have been an incorrect kicker which was fixed during the STI pre-commissioning tests. The same optics, however, were not tested again so it is impossible to identify whether this had any affect on these results. In addition, there appeared to be some jumps in the bunch position plots when they were averaged. A peak finding algorithm showed that they were located 72.3 ± 0.5 bunches apart from each other. This is very similar to the number of bunches ejected by the CERN PS into the SPS though further analysis of the behavior of these shots and their energies and positions by bunch at their entrance into and exit from the SPS is necessary to determine causation. Lastly, it was determined that far fewer shots are reaching BPKG 660529 than the two upstream BPMs. The beam loss monitors are not picking up on any scattering so it is likely that the beam is being lost in the experimental apparatus or that BPKG 660529 is broken. Testing this without the experimental apparatus or running a diagnostic test on this BPKG would help to clarify this problem.

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