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Beam Analysis for the Large Hadron Collider

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Abstract

Wire scanners are used in the Large Hadron Collider (LHC) to obtain measurements of the beam profile during low intensity calibration runs. These measurements are used to calibrate Beam Syncrotron Radiation Telescopes (BSRTs) which can be used to obtain beam profiles during high intensity data runs. This paper examines emittance, brightness, and intensity measurements obtained through wire scanner aquisition for calibration fills 6699 and 6913. Wire scanners can also be used to collect beam profile information during the injection phase of normal runs. This paper demonstrates that the data collected by the wire scanner during the normal runs is faulty.

Contents

1 Introduction

The Large Hadron Collider (LHC) is the largest and most powerful particle accelerator in the world. It consists of a 27 kilometer long ring that intersects the countries of Switzerland and France. To accelerate protons to a speed of $0.999999990c$, the LHC uses superconducting magnets cooled to a temperature of $-271.3°C$- a temperature colder than outer space. Once the protons are travelling this fast, two opposing beams are aligned with eachother, allowing the protons to collide with each other at an energy of 13 TeV. These collisions produce a variety of subatomic particles which are picked up by the various detectors around the LHC.

By 2012, data acquisition in the LHC reached a rate of 25 petabytes/year (1 Petabyte = 1000 Terabytes = 1000000 Gigabytes). Not only is this a significant amount of hard-drive space, but it is a *colossal* amount of data to analyze. To store and manage large data sets, one needs to use an appropriate programming language and adequate datatypes within that language. Most research groups in particle detection at CERN use ROOT- a C++ extension particularly useful for creating histograms and storing them efficiently.

During my summer at CERN, I worked for the Accelerating Beam Physics (ABP) group. The ABP studies the properties of the LHC beam before, during, and after collisions. For data-analysis, the ABP recently replaced using C++ and ROOT with PYTHON and the corresponding extension pandas. pandas is an open source PYTHON extension used for working with heterogeneous (tabular) data. It was created by Wes Mckinney while he was working at AQR Capital Management.

Figure 1: Sample pandas datatype showing properties of LHC beam at different times

	BEAM	BEAM_WIDTH_IN	BEAM_WIDTH_OUT	EMIT_IN	EMIT_OUT
2018-05-18 18:44:18.685730+00:00	B1	959.089847	967.060820	1.289582	1.311107
2018-05-18 18:44:48.830614+00:00	B1	963.240678	979.978021	1.300769	1.346366
2018-05-18 18:45:18.967784+00:00	B1	1018.795530	978.634395	1.455139	1.342677
2018-05-18 18:45:49.109372+00:00	B1	970.702711	983.153806	1.321001	1.355107
2018-05-18 18:46:19.249585+00:00	B1	979.378347	975.394424	1.344719	1.333801

For a programming environment, I used CERN's System for Web Based Analysis (SWAN). SWAN is an online application that uses a Jupyter Notebook interface and allows one to analyze data without the need to install any software. Furthermore, it allows one to access the power of CERN's computing grids- this was particularly useful when performing operations on large datasets.

The data I analyzed this summer was collected by two independent instruments; a **wire scanner** and a **beam synchrotron radiation telescope**. These devices are particularly useful for determining the **emittance** of the beam.

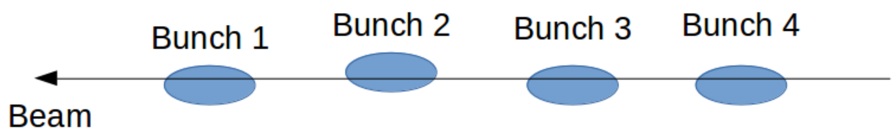
2 Preliminaries

Before discussing the results of this project, important terminology is explored.

2.1 Bunches

The LHC beam is not continuous; it consists of little packages of protons known as **bunches**.

Figure 2: Representation of the LHC Beam



There are approximately 3000 available 'bunch slots' to be injected into the LHC beam, but usually only 10 are filled for a given run.

The question, "What is the beam width σ of the beam at time t," can be better phrased as "What is the beam width σ of the beam at time t for the nth bunch?" This is how data is stored for analysis:

Figure 3: Data Separated by Bunch

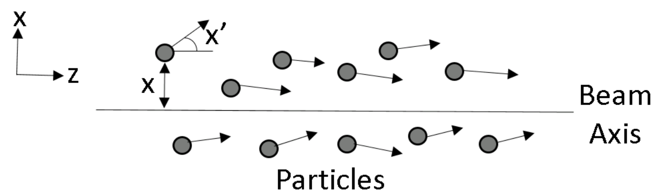
	BEAM	BUNCH	BEAM_WIDTH_IN	BEAM_WIDTH_OUT
2018-05-18 18:44:03.612791+00:00	B1	894	1183.172456	1157.747936
2018-05-18 18:44:03.612791+00:00	B1	1200	1199.573626	1175.620889
2018-05-18 18:44:03.612791+00:00	B1	3117	743.703265	712.810515
2018-05-18 18:44:03.612791+00:00	B1	2800	768.148799	741.960376
2018-05-18 18:44:03.612791+00:00	B1	2450	783.089240	751.858154

The suffixes "IN" and "OUT" will be discussed later. The expression "emittance evolution of the beam" is typically understood as "emittance evolution for a given bunch in the beam".

2.2 Emittance

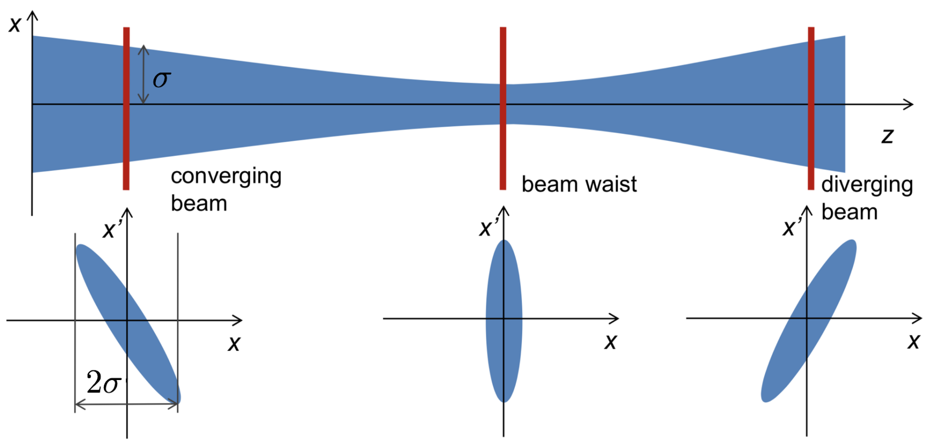
Consider the following two dimensional depiction of the LHC beam

Figure 4: 2D Depiction of the LHC Beam



In such a model there exist a distribution of x (distance from the beam axis) and x' (angle from the z direction) values. If we produce a scatter plot of the distribution of such values, then we get an image that tends to look like an ellipse.

Figure 5: Different Phases of the Beam



The shape of the ellipse depends on the beam width σ and whether or not the beam is converging or diverging. We can express the equation for the boundary of the ellipse as

$$\epsilon = \gamma x^2 + 2\alpha x x' + \beta x'^2 \tag{1}$$

ϵ is known as the emittance of the beam and has units of meters. Under non-relativistic conditions, this value should not change. The beam width is given by

$$\sigma = \sqrt{\beta\epsilon} \tag{2}$$

Our devices measure β (can be determined given the strength of magnets) and σ (using wire scanners or BSRTs). We can thus use (2) to determine the emittance of the beam. When a high energy physicist mentions emittance, however, they are probably referring to the invariant quantity

$$\epsilon_N = \frac{E}{m}\epsilon \tag{3}$$

where E is the energy of the protons in the beam (at max energy ≈ 6.5 TeV) and $m \approx 938$ MeV is the mass of a proton. This quantity is known as the *normalized emittance* and it theoretically should not change as the protons in the beam are accelerated.

2.3 Measurement Devices: The Wire Scanner

A wire scanner is a device that allows us to determine the width (σ) of the LHC beam. A wire is oriented perpendicular to the direction of the beam and is engineered to pass through the beam approximately every minute.

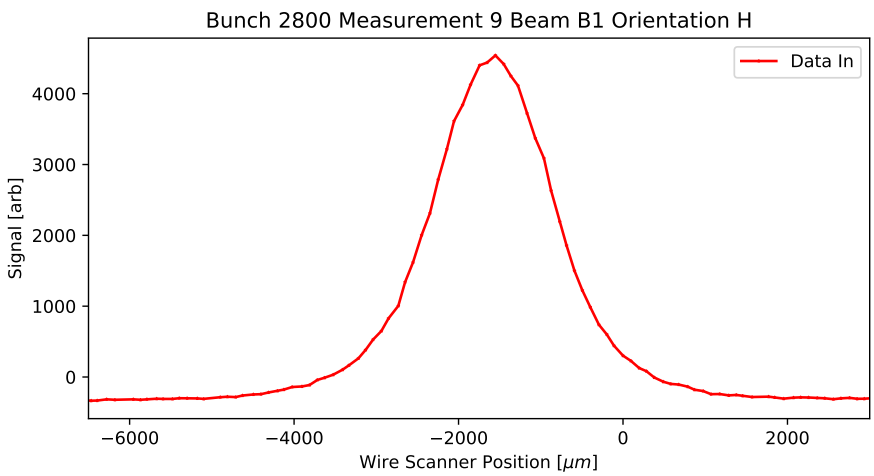
Figure 6: Wire Scanners

How a wire scanner is used | Simple wire scanner | Wire scanner being placed in LHC during next upgrade

The center picture in Figure 6 displays two arms that rotate with a wire attached between their tips. At some point, the wire will intersect the beam if it is oriented perpendicular to the beam axis.

When the wire intersects the beam, a particle spray is created and detected by scintillators located nearby. The strength of the signal from the scintillator is proportional to the intensity of the beam at the wire scanners position. As the wire gets closer to the center of the beam, the particle spray becomes strongest (which signifies a maximum in intensity).

Figure 7: Wire Scanner Data



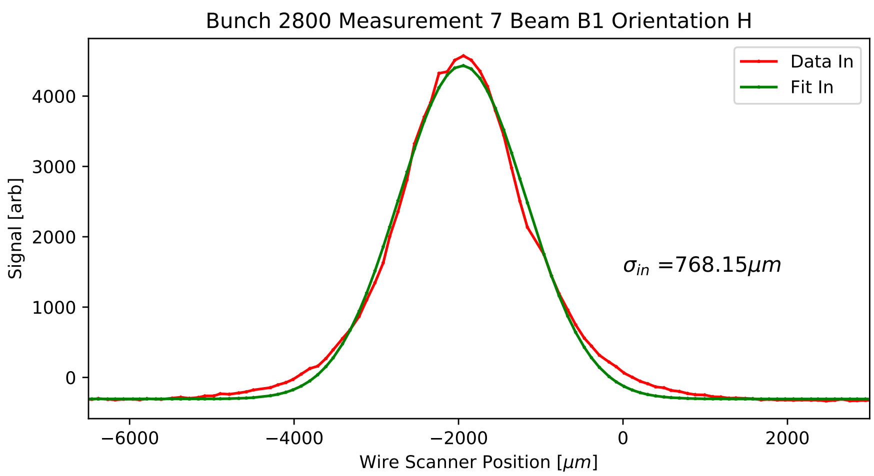
The data from Figure 7 is for bunch 2800; to separate the signal by bunch, precise timing techniques are used. This is the 9th measurement of this bunch (for LHC run 6699) in beam B1 (B1 and B2 collide with each other). Orientation 'H' is the geometric orientation of this particular wire scanner. Two perpendicular wire scanners are used to obtain the beam profile from two orthogonal axes - one is defined to be 'Horizontal' and the other 'Vertical.' In Cartesian coordinates, one could picture a wire parallel to $\hat{x}$, another wire parallel to $\hat{y}$, and the beam travelling along $\hat{z}$.

We can fit the data from Figure 7 to the normal curve

$$f(x) = ae^{-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2} \tag{4}$$

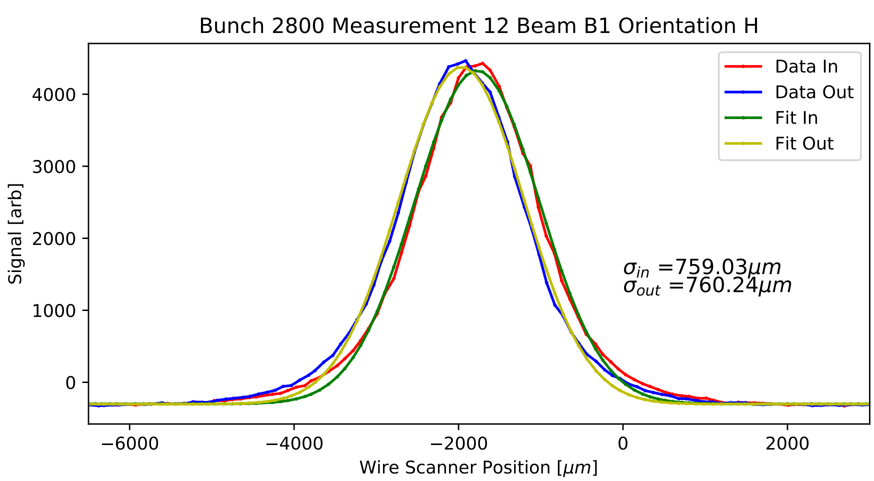
A particular parameter of interest is the standard deviation σ, which is defined to be the width of the beam:

Figure 8: Wire Scanner Data Fit With Normal Curve



The suffixes 'IN' and 'OUT' from DataFrame in Figure 3 can be explained as follows. Each time the wire scanner passes through the beam, it first moves down through the beam and then up through the beam. It then proceeds to rest for about 30 seconds. 'IN' is the data collected as the wire scanner moves down, and 'OUT' is the data collected as the wire scanner moves back up through the beam. The data should look fairly similar, as they do in the Figure 9.

Figure 9: Wire Scanner Data IN and OUT



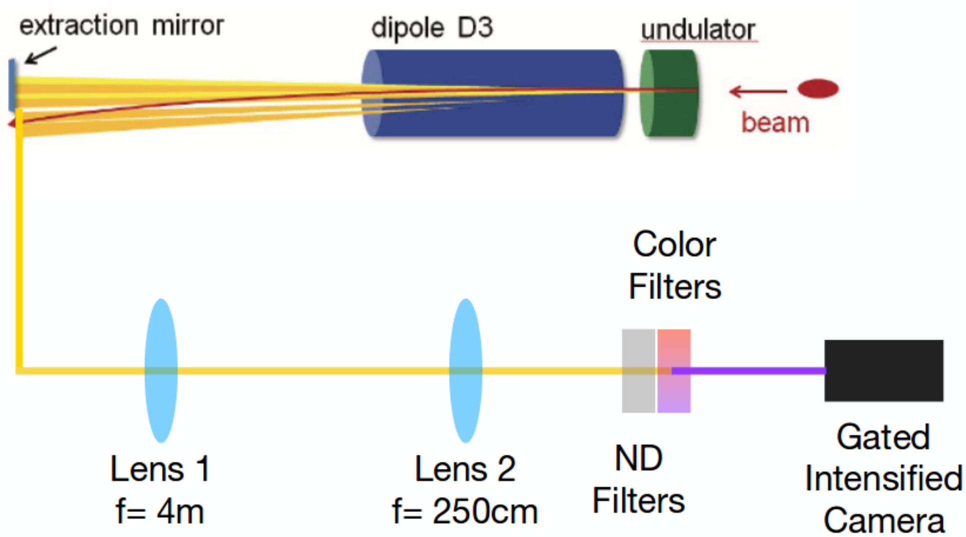
Using this information and equation (2), we can determine the emittance of the beam.

2.4 Measurement Devices: The BSRT

Synchrotron radiation is the electromagnetic radiation emitted when charged particles are accelerated radially, i.e., when they are subject to an acceleration perpendicular to their velocity.

The beam is shown in red here. The beam is bent as it travels through the dipole D3 and it emits synchrotron radiation. The radiation is picked up by an extraction mirror and sent through a complex focusing system. Through careful data analysis, the beam profile can be determined.

Figure 10: Diagram of the BSRT



3 Outline of Project Goals

The wire scanner cannot be used during full strength runs of the LHC - it is instead used in 'calibration' runs to calibrate the BSRTs. The BSRTs are used during full strength runs to obtain the beam profile.

3.1 Part 1: Data From Calibration Runs

Wire scanner data from the LHC calibration runs 6699 and 6913 was examined. Data selection was used to remove incorrect data. Various plots of emittance and brightness evolution of the beam (brightness=emittance/intensity) were created using matplotlib and seaborn. Intensity data was plotted against the area under the wire scanner profile; interesting relationships between these data sets was explored.

3.2 Part 2: Data From All Runs

Wire Scanner data during injection for all fills was used to plot emittance distributions. Inconsistencies between σ_{IN} and σ_{OUT} in fill 6642 were studied to determine possible measurement errors.

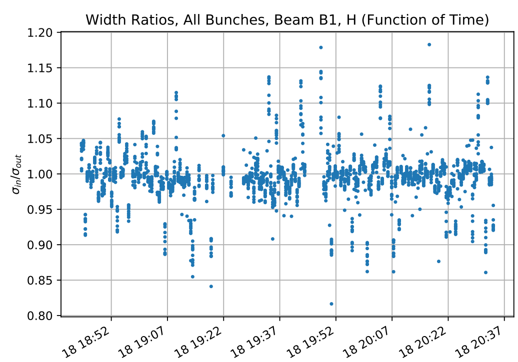
4 Beam Analysis During Calibration Fills

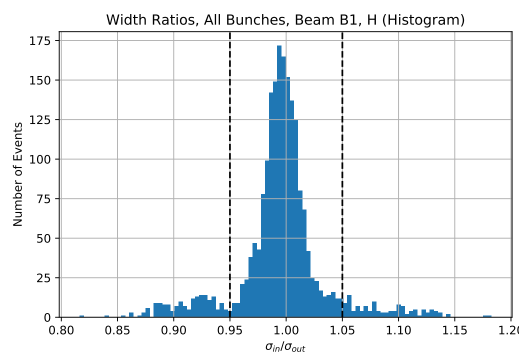
4.1 Data Selection Based on Beam Width

As shown in Figure 9, fitting a normal curve to wire scanner data allows one to determine the beam width σ_{IN} and σ_{OUT} corresponding to the "IN" and "OUT" motion of the wire scanner respectively. In order to plot the emittance from (3), one needs β, (a property of the accelerating magnets) and E, which can be determined by the speed of the protons.

σ_{in} and σ_{out} aren't always equal; Figure 11 shows the ratio σ_{in}/σ_{out} both as a function of time and as a histogram. This data was collected during the LHC calibration fill 6699 from the PRERAMP-ADJUST phases.

Figure 11: Beam Width Ratios

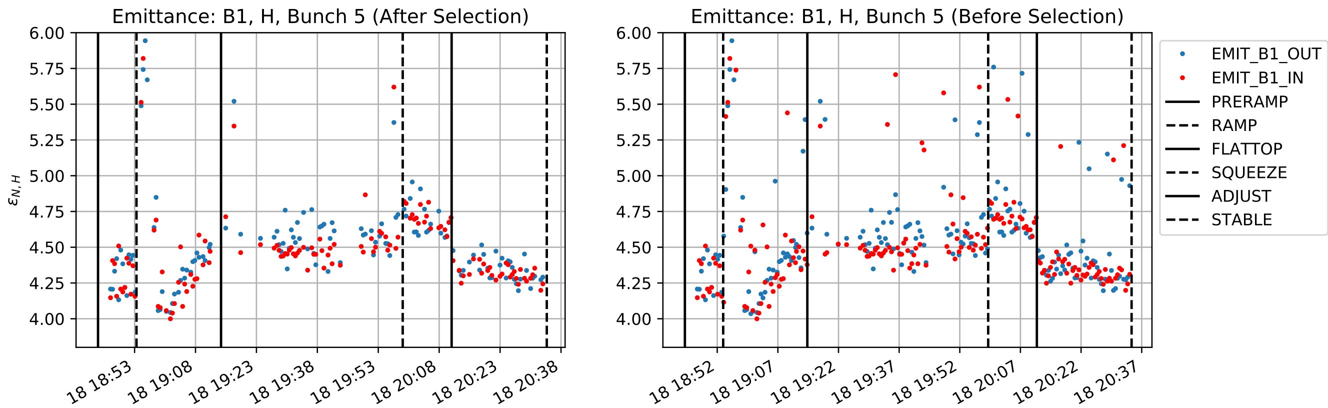




The histogram peaks at 0.9 and 1.1 hint at some sort of systematic error occurring in the wire scanner. Data points lying outside the dotted lines are thus removed.

4.2 Emittance and Brightness Plots

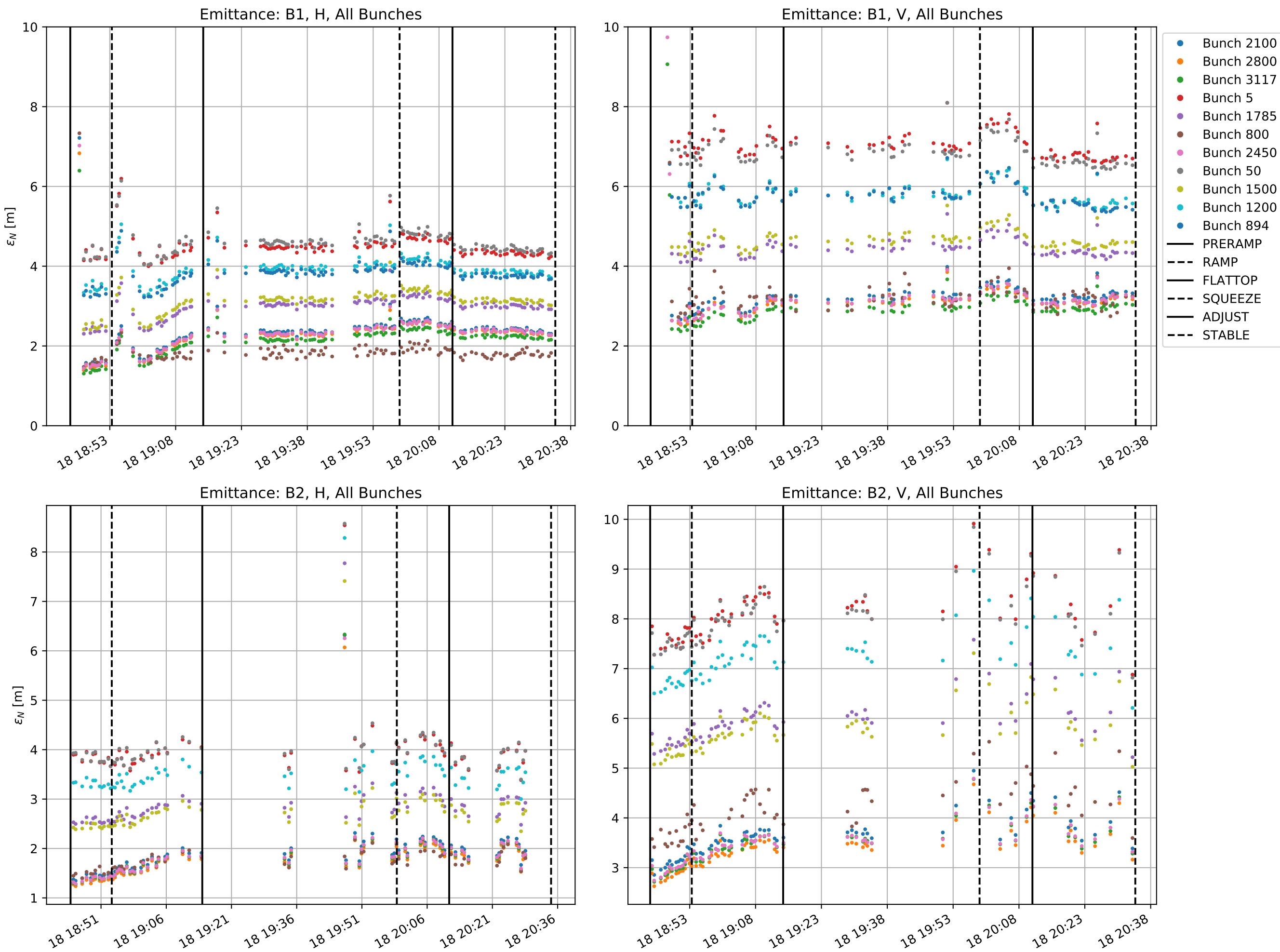
Figure 12: Emittance Before and After Data Selection



Although most of the outlier points have been removed, a few have not. These points correspond to instances where the systematic error in the wire scanner occured for both the 'IN' and the 'OUT' movement, and the ratio σ_{IN}/σ_{OUT} is close to 1.

In Figure 12, the emittance measurements obtained using both σ_{IN} and σ_{OUT} are shown. It is common practice in the ABP to only use 'IN' measurements and this convention will be used for the rest of this paper. Emittance evolution for all bunches during fill 6699 is shown in Figure 13. Horizontal and vertical measurements for both beam 1 (B1) and beam 2 (B2) are included.

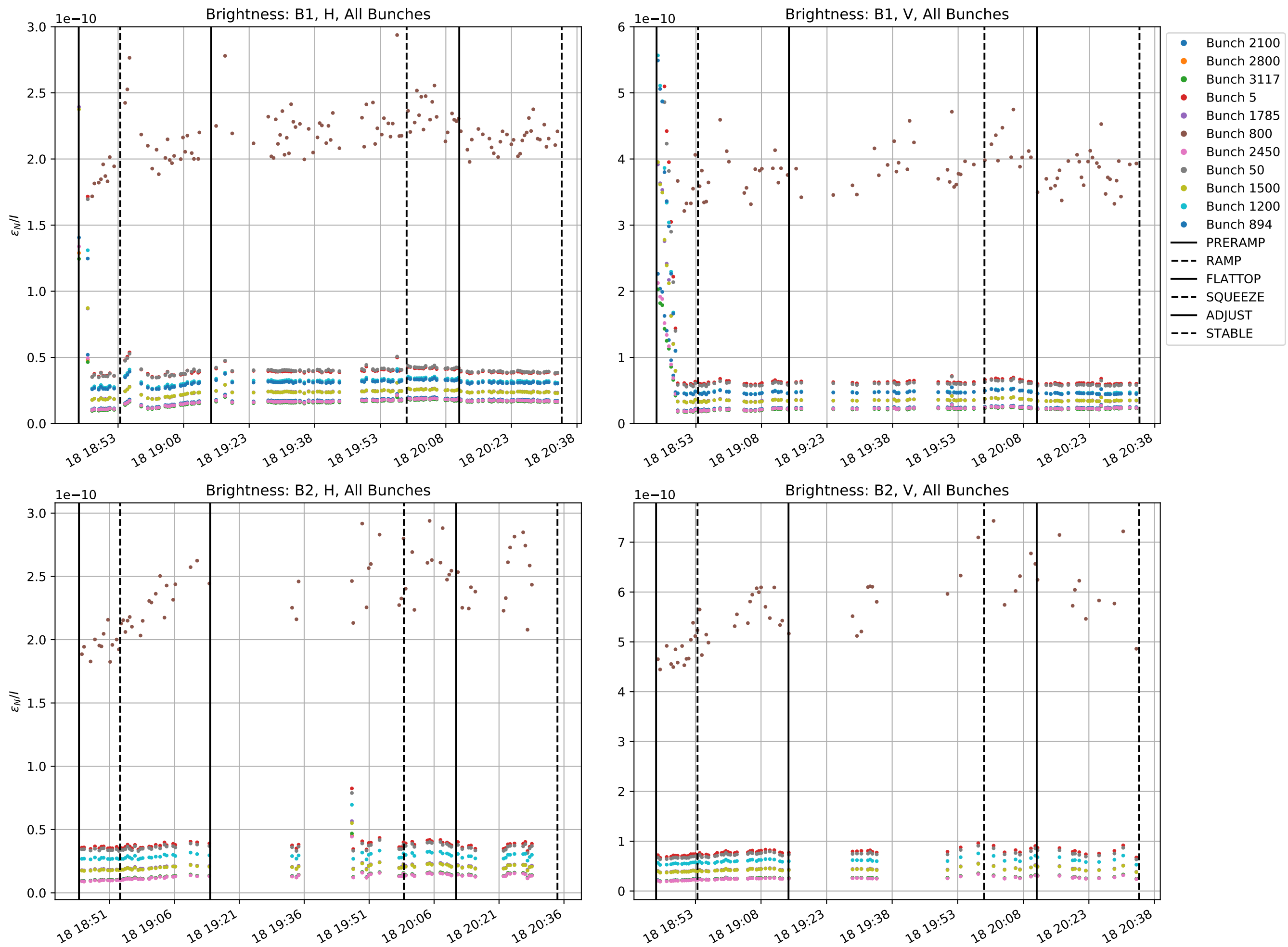
Figure 13: Emittance For All Bunches (Fill 6699)



There exist large gaps of empty data for beam 2; these are times when the wire scanner was not collecting data. Theoretically, the normalized emittance should be conserved for each bunch: Figure 13 demonstrates that this is not the case. In particular, during the RAMP phase, the emittance tends to grow linearly for all bunches.

Figure 14 shows the brightness measurements for the same fill. Recall that brightness = emittance / intensity.

Figure 14: Brightness For All Bunches (Fill 6699)



As opposed to time series plots, we can also plot histograms of emittance for all phases (per bunch). The python package *seaborn* has a class *violinplots* for this purpose.

Figure 15: Emittance Histograms For All Bunches (Fill 6699)

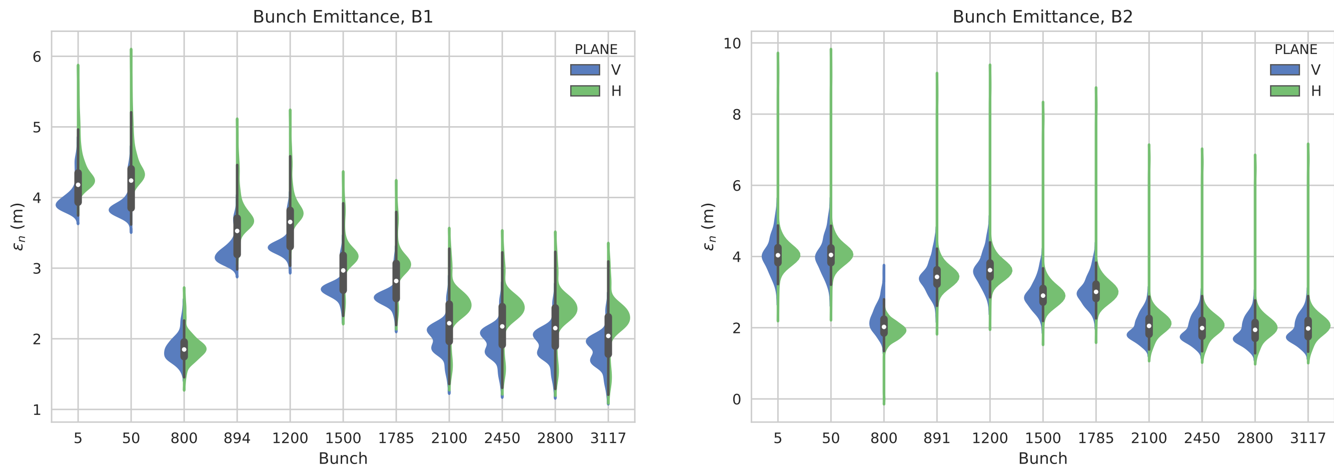
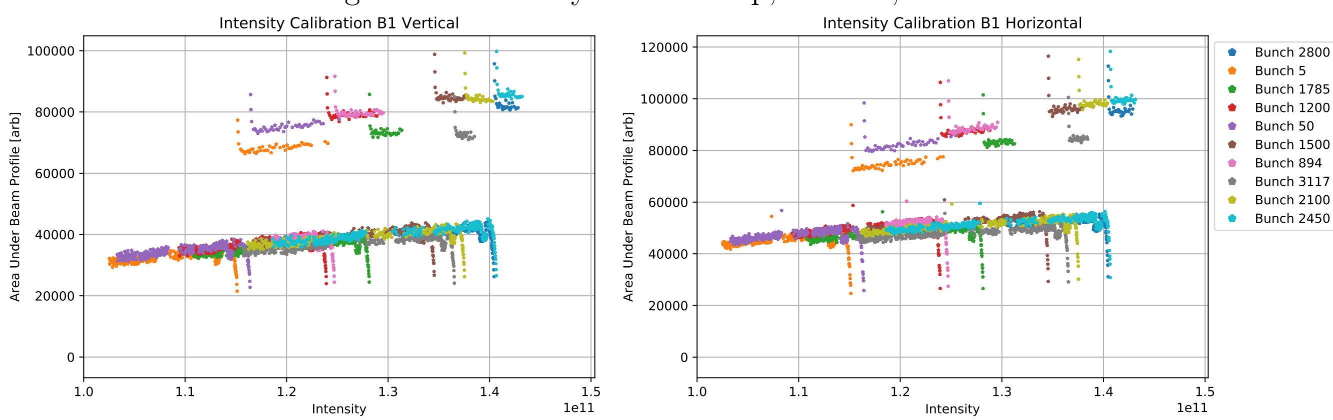


Figure 15 explores the emittance variation of each bunch for all phases. Theoretically, the conservation of ϵ_N should enforce that each histogram resemble a dirac delta function: these plots show that this is not the case.

4.3 Further Examination of Intensity

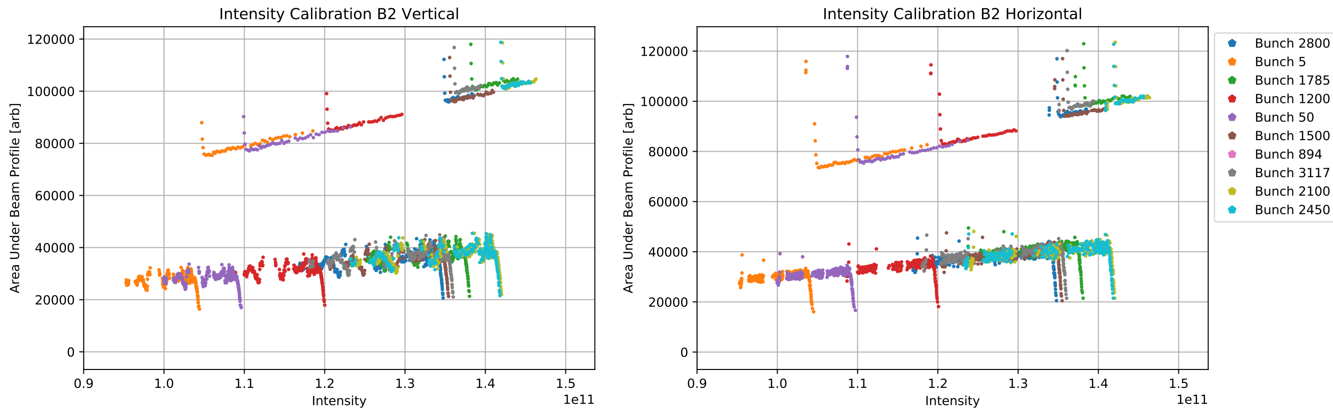
The intensity measurements of the beam should theoretically be proportional to the area under the wire scanner profile raw data.[1](Figure 7). Figures 16-19 examine this proportionality relationship in calibration fills 6699 and 6913 for each beam.

Figure 16: Intensity Relationship, Beam 1, Fill 6699



[1]This is assuming that the baseline is zero. When data analysis is performed, the baseline is calculated by averaging the first 50 points on the plot. It is then subtracted from the data.

Figure 17: Intensity Relationship, Beam 2, Fill 6699



Note that intensity is steadily decreasing throughout this fill. As such, the plots should be read from right to left for time evolution. A common effect occurs for each bunch in the following order:

- **SETUP-PRERAMP**: The relationship is approximately linear; the intensity and area under the beam profile are steadily decreasing. (The lines on the upper half of the plots).
- **RAMP**: The area under the beam profile quickly increases, 'jumps down' the plot, then quickly increases again. (The vertical 'hairs' on the plots).
- **FLATTOP-SQUEEZE**: Data points are still contained in the 'hairs' at the bottom of the plot where the area under the beam profile is increasing quickly.
- **ADJUST-RAMPDOWN**: The relationship is approximately linear; the intensity and area under the beam profile are steadily decreasing. (The lines on the lower half of the plots).

These observations suggest that the bunches may have become unstable during the RAMP phase. Figures 18-19 explore a similar effect for calibration fill 6913.

Figure 18: Intensity Relationship, Beam 1, Fill 6913

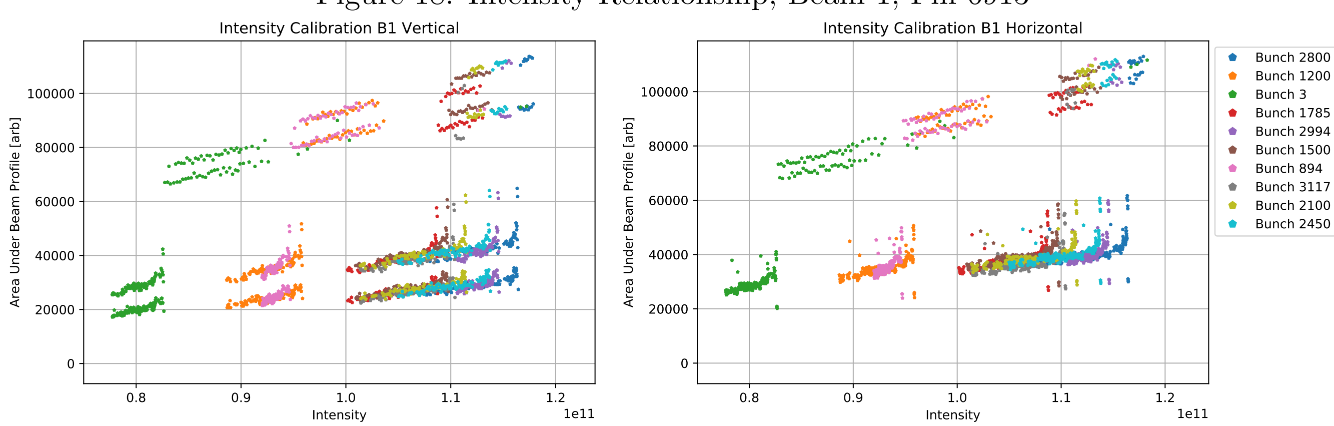
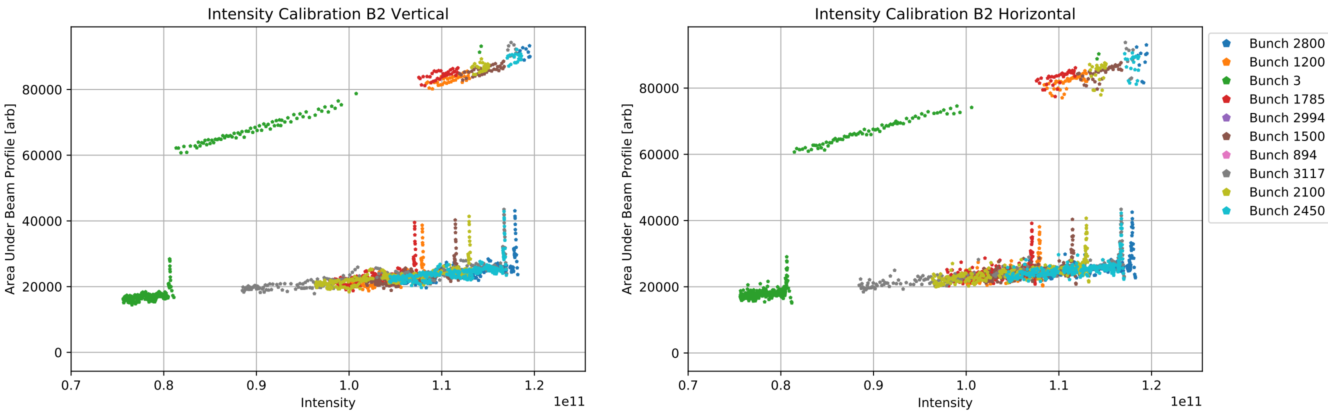


Figure 19: Intensity Relationship, Beam 2, Fill 6913



5 Emittance Distribution For all Fills

Figures 20-21 examine the emittance distribution for all fills during the injection phase. The emittances of all bunches are used for these distributions. The emittance was obtained using the same method as before; the beam width was determined by fitting wire scanner beam profiles to normal curves and equation (2) and (3) were used to calculate ϵ_N. Both the IN and OUT measurements are shown.

Figure 20: Emittance Of B1 During Injection

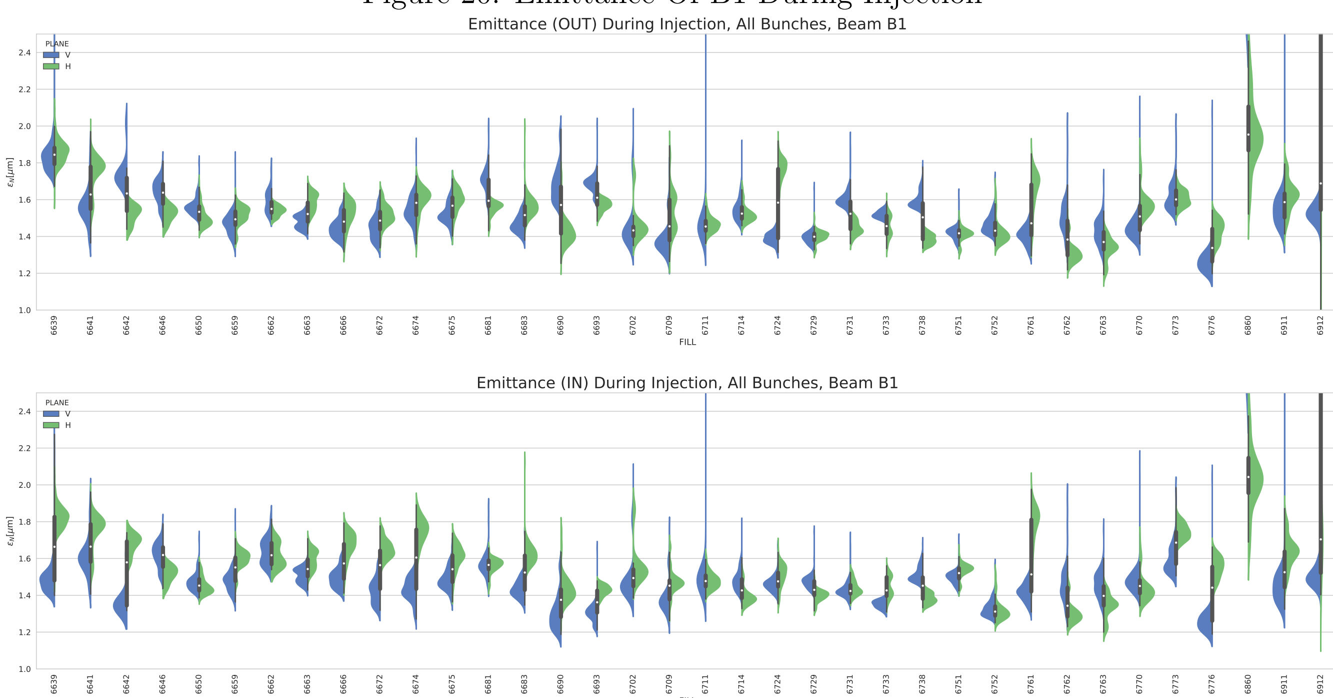
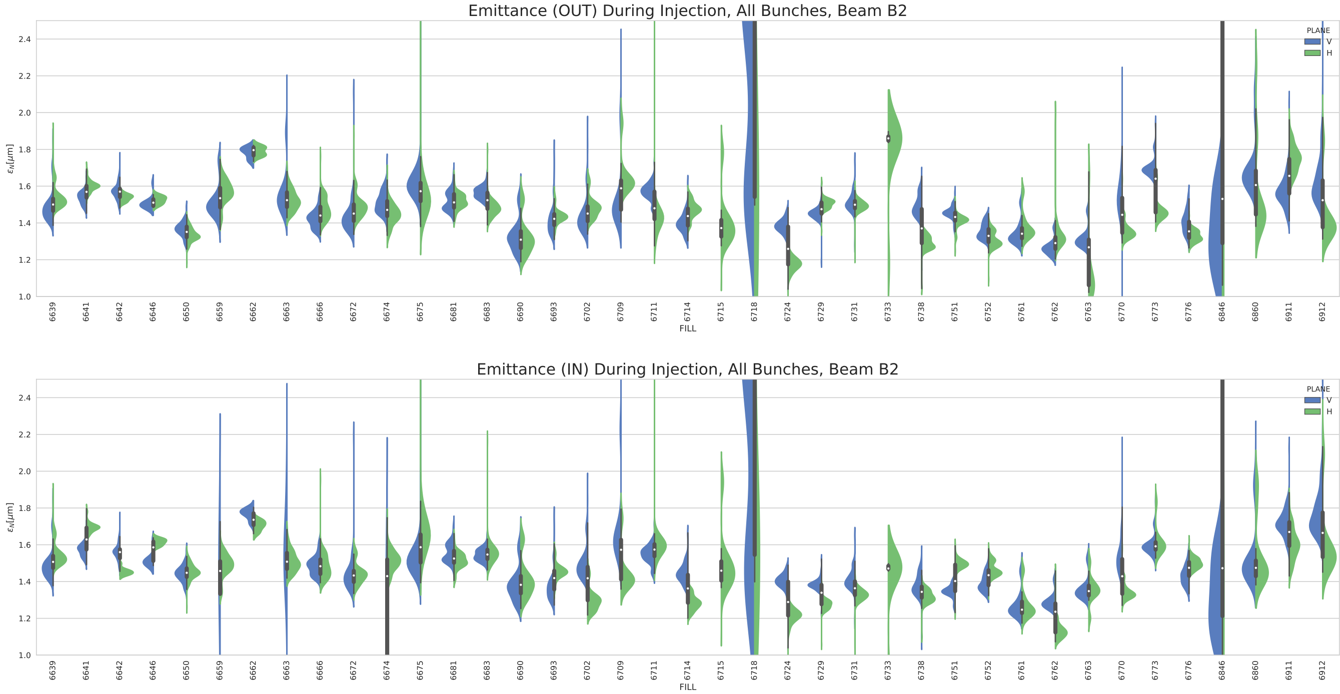
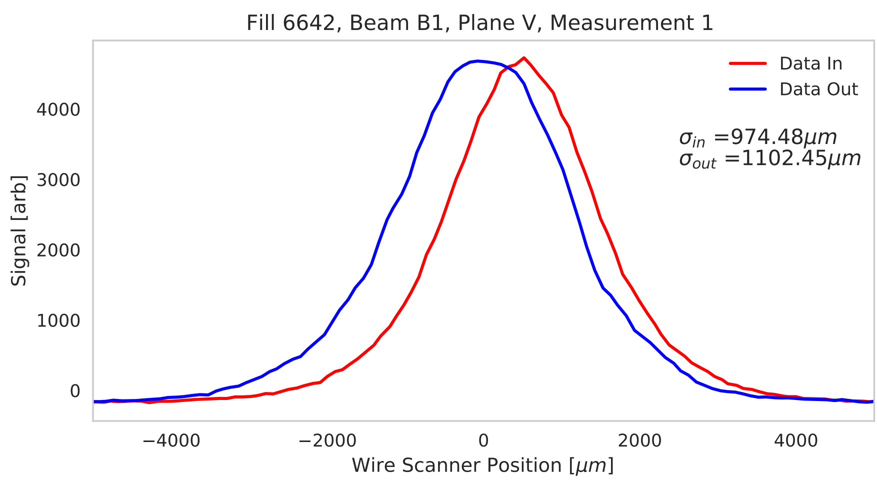


Figure 21: Emittance Of B2 During Injection



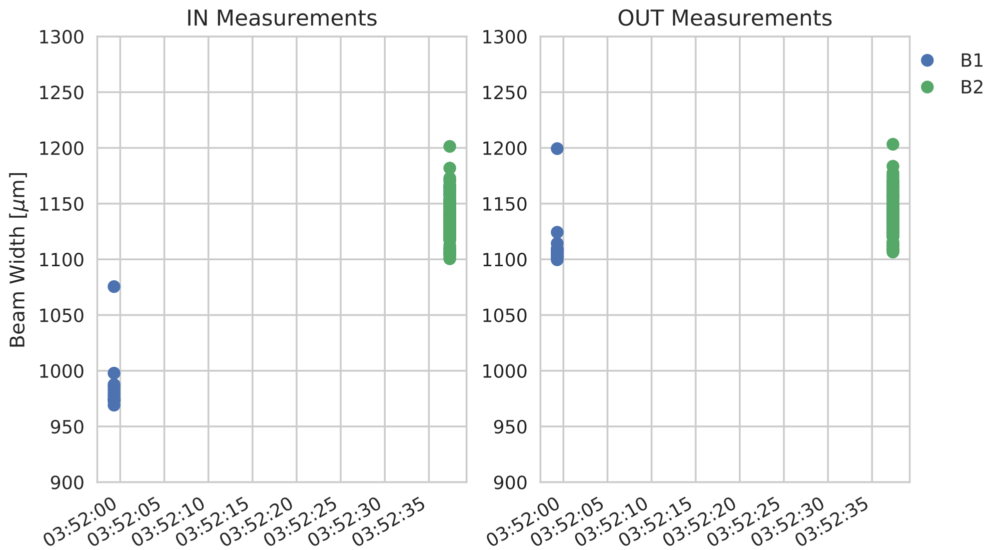
Occasionally the IN and OUT measurements significantly disagree with each other; this is most likely due to errors in the wire scanner measurement. For Fill 6642, Plane V, the IN-OUT measurements are consistent for B2 but significantly inconsistent for B1. Figure 22 examines a sample beam profile from B1. The data shown is raw data (not Gaussian fits).

Figure 22: Example of Bad Wire Scanner Profile



Similar inconsistencies occur for all B1 measurements in this plane/fill; this is examined in Figure 23 where σ_{IN} and σ_{OUT} measurements for both B1 and B2 are shown. From the plot, it is clear that one vertical wire scanner measurement was made for each beam during injection. The multitude of points at each time correspond to all the different bunches.

Figure 23: Width Measurements for each Beam



While the IN and OUT measurements for B2 are consistent (seen in Figure 21/23), the measurements for B1 have clearly changed between the IN-OUT measurements (seen in Figure 20/23). There are two possible explanations for this, and two possible solutions:

- If the beam width of B1 significantly changed between the IN and OUT measurements of the wire scanner, then the emittance was changing rapidly in time. The wire scanner must make more than one measurement to obtain accurate emittance histograms such as those in Figure 20.
- If a technical error occurred in the wire scanner at 3:51:59, then the cause of this error needs to be determined and fixed to ensure accurate measurements. More than one measurement may not be required, as it is possible the emittance remains constant during this period.

6 Special Thanks

I would like to give a special thanks to my supervisor Dr. Ilias Efthymiopoulos for his guidance and assistance this summer. The door to his office was always open and he encouraged me to stop by and ask questions whenever I had a problem. We would often get into hour long passionate discussions about physics. I will treasure his mentorship for the rest of my life.