Study of Electron Cloud Instability in the Main Injector at FNAL

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Electron Clouds are one of the primary concerns in design or upgrade an accelerator. The Main Injector at FNAL will soon be upgraded to operate at higher beam intensity. Most experiments and simulations show that the electron cloud appears abruptly and at threshold beam intensity. The goal is to find this threshold for the currently available data and determine the Beam Intensity region at which the electron cloud is most likely to exist. A program in C was written and data sets were taken at different times. Moreover, bunching configurations were studied and compared. This study will give a better understanding of the parameters that increase or decrease the threshold. Determining such parameters would help preparing the main injector for the future upgrade.

I. Introduction

The Electron Clouds (EC) are dense pockets of electrons in the accelerator. In most cases, EC is due to irradiation of vacuum chamber by photons or particles (protons in the main injector) and bombardment of electrons (which is the secondary emission). EC can affect the beam by changing trajectory of the beam with each turn, and increasing the emittance of the beam; with high enough intensity it can degenerate the beam completely. [1] At FNAL, the electron cloud is measured using a prototype of an electron cloud meter in the Main Injector. This meter is located at the beginning of the beam pipe. It measures the EC density at its maximum by recording the voltage caused by passing of electron (current) through the pipe during the regular operation of the Main Injector.

Currently, the Main Injector is working with beam intensity of 4×10^{13} which corresponds to a beam current of approximately 0.5 Amps. At this state, the EC do not disrupt the accelerator performance. However, the proposed upgrade requires the Injector Intensity to be increased by a factor of 3 or 4. In other words, the Main Injector will be operating at intensity levels that correspond to beam current of 1 Amps or higher. In other hadron machines, beam currents around 1 Amps have shown destructive level of Electron Cloud Instability.

In order to prepare the Main Injector for this upgrade, the parameters contributing to the formation of electron clouds must be identified. Most simulations as well as pervious measurements show that the electron clouds appear at a sudden threshold beam intensity. The goal of this project was to determine this threshold to one sigma uncertainty for different sets of data which were recorded in 2007. In the end, data obtained from week-long runs of multiple cycles during the regular operation of the machine was used. The primary focus was on a series of data which were taken for two months continuously and had similar bunch configuration of 11-batch. The aim was to see the effect of time that the Main Injector had been running on the threshold beam intensity.

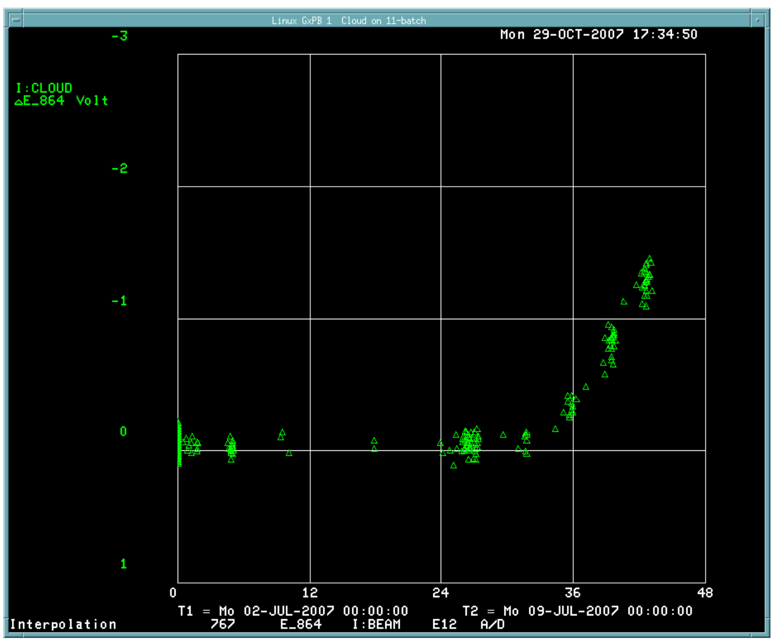

Figure 1: Picture of the raw data from the week of 07/02/07 (beam intensity shown on the x-axis)

II. Method

In order to determine the threshold to one sigma uncertainty for different sets of data, few important, primary steps were taken. The first step included pedestal subtraction. After this, the data was binned and the sigma and delta for each bin were calculated. Then, a method of minimum chi-square was used to find the best-fit threshold as well as the best-fit slope (the rate by which the intensity of electron clouds increased after its appearance). Next, Null chi-square was calculated. The difference between the Null and the best fit chi-square was used to determine if the data set contained an Electron

Cloud or not (to 99% accuracy). For the sets that enclosed a cloud, a contour map was generated. For the sets that did not contain cloud, a minimum slope was assumed (using the minimum slope of the data that showed a cloud) to determine the threshold region and see if the intensity had been raised high enough. All the above was done by a program named Threshold.c that was saved on a FNAL cluster named heimdall. [2]

II.a Pedestal Subtraction

As it is illustrated in Figure 1 (the raw data), there are many points around or very close to zero. The beam intensity varies in the main injector. However, it is a reasonable approximation and safe to say that the beam will never have an intensity of a value less than 0.4×10^{12} (beam intensity is the horizontal axis). Any point with a smaller value for beam intensity is not representative of the beam. Therefore, the average value of beam intensity and cloud intensity of all the points the absolute value of their beam intensity was less than 0.4×10^{12} was calculated. The calculated average values for beam and cloud intensity (pedestals) were subtracted from all the data points in the set. The typical size of pedestals for Beam Intensity and Cloud intensity were 0.00357×10^{12} protons and -0.0505×10^{12} volts respectively. Figure 2 represents the data after the pedestal subtraction. The x-axis contains beam intensity and the y-axis reflects the voltage measured by the Electron Cloud counter prototype in the Main Injector which corresponds to the Electron Cloud intensity.

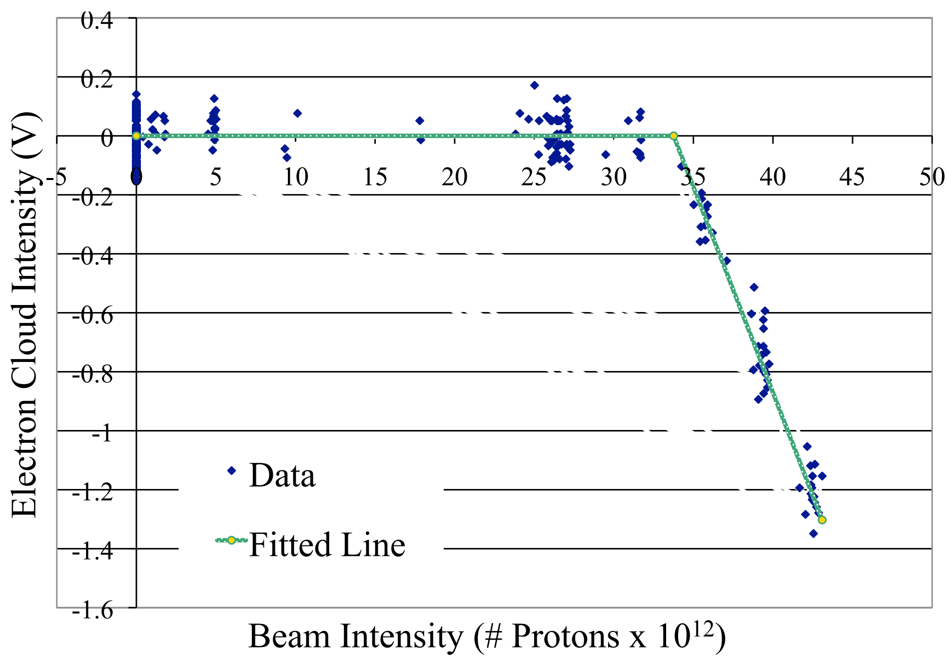

Figure 2: The same data set (from week of 07/02/07) after Pedestal subtraction

II.b. Binning the Data

As shown in Figure 2, the data is not homogeneous. Therefore, some beam intensity regions are more populated than others. These high populations can have an effect on the obtained best fit from minimum chi-square. Thus, the data was binned using bin size of 1×10^{12} protons for the start. Then, the average beam intensity and the average cloud intensity of all the points in each bin were calculated. Next, the uncertainty for each bin was measured to be used in calculating the chi-square. For bin zero, the uncertainty was calculated using the root mean square as σ_0 and $\delta_0 = \frac{\sigma_0}{\sqrt{N_0}}$. For rest of bins, the following formulas were used: $\sigma_i^2 = \frac{1}{N_i - 1} \times \sum_{1 \Rightarrow N_i} (I_{N_i} - I_{ave_i})^2$ and $\delta_i = \frac{\sigma_i}{\sqrt{N_i}}$.

where i is the number of bin, I is the cloud intensity and N_i is the number of data in bin i. For bins with only one data point (where $(I_{N_i} - I_{ave_i})$ was zero), σ_0 was used to calculate their δ_i. The low beam intensity bins (zero and one) in most data sets had very large N_i which could affect the χ^2 by causing the uncertainty δ_i to become too small. In order to avoid this, a lower bound was picked for the maximum number of data in one bin. Since the typical N_i for bins with higher beam intensity never passes 40, $N_{i_{max}} = 40$ was set and δ_0 was set as the minimum uncertainty for all bins. On the other hand, for bins that had no points, all the values were set to zero. Figure 3 shows the binned data as well as the uncertainty of each bin. [3]

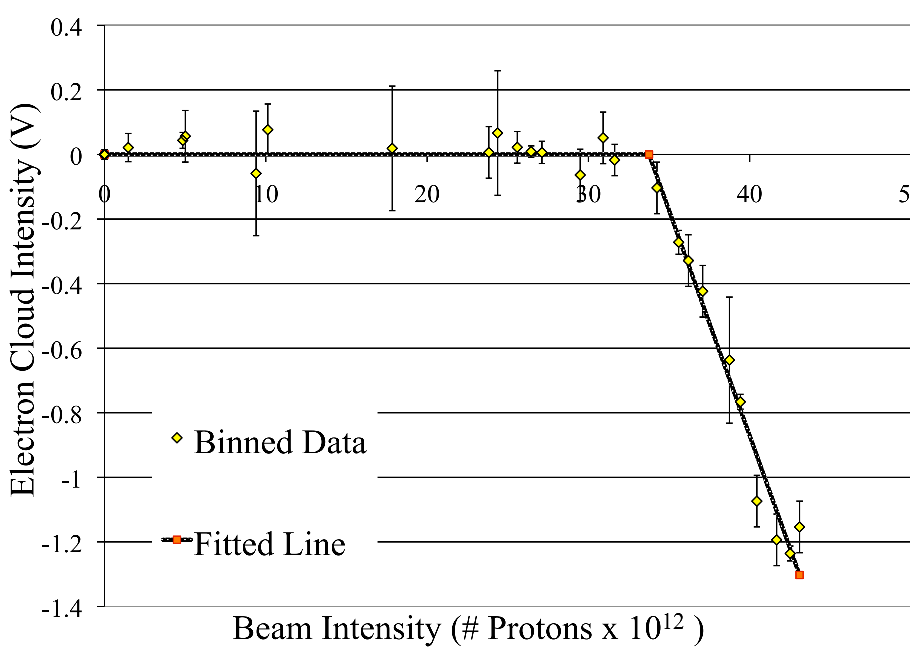

Figure 3: The data after it was binned and the average cloud intensity for each bin was calculated

II.c. Minimum Chi-Square and determining if there is a Electron Cloud

The Electron Cloud intensity seemed to rise quickly after the threshold. However, the data only includes the beginning of EC intensity rise. In order to find the threshold, the functional form for the EC intensity was expected to be zero until the threshold and to increase linearly thereafter. Using the expected functions and the binned data, chi square was evaluated.
$\chi^2 = \sum \frac{(I_{Expected_i} - I_{ave_i})^2}{\sigma_i{}^2}$.

In order to find the minimum χ^2, relatively large ranges of values for the threshold Beam Intensity and for the slope with which the EC intensity increases was chosen. The threshold range was from zero to hundred with step size of one, ensuring that the threshold value was included. The slope ranged from -1 to 0 and had step size of 0.1. The χ^2s for all these values were calculated. The minimum χ^2 between them was selected. The threshold and slope for this minimum value were called the initial best fit values. Then, using smaller step size, the χ^2 for the eight neighboring points of the initial best fits were calculated. The minimum between all nine calculated χ^2 was chosen and was called the new best fit. Again, the eight neighboring χ^2 were calculated and compared. If the new minimum χ^2 was the same as the old best one, a smaller step size was picked. The same process was repeated till $\Delta\chi^2$–the difference between the new and old χ^2–was less than 0.0001, which gave the final best fit for the Threshold Beam Intensity and slope.

In order to determine if there was a cloud in the set, the null χ^2 was calculated–χ^2 for when slope was zero for all beam intensity values in absence of a threshold. After this, the difference of these two chi-square and assuming that the distribution is close a 2D Gaussian the α value was calculated: $\alpha = e^{-\Delta\chi^2/2}$. Since $1 - \alpha$ is the percentage of the distribution that falls with in $\Delta\chi^2$ from the best fit, $1 - \alpha = 99\%$ was used to determine whether the cloud was not generated or not.

II.d. Contours and the Uncertainties

If it was found that there was no Electron Cloud to 99% in the machine when the data was taken, a minimum slope of 0.1 was used to determine the threshold and its uncertainty in presence of a cloud. The uncertainty from the positive side goes to infinity. For the negative side, the lowest threshold when slope is 0.1 and $\Delta\chi^2$=2.30 (one sigma in 2D) was used. If there was Electron Cloud in the machine when the data set was obtained, contour plots for when $\Delta\chi^2$ equal one sigma and when $1 - \alpha$ was 95% and 99% (instead of two or three sigma) were plotted. The boundary lines were calculated using a finer grid. The Max and Min Threshold on the one sigma boundaries were used as the uncertainty for the threshold.

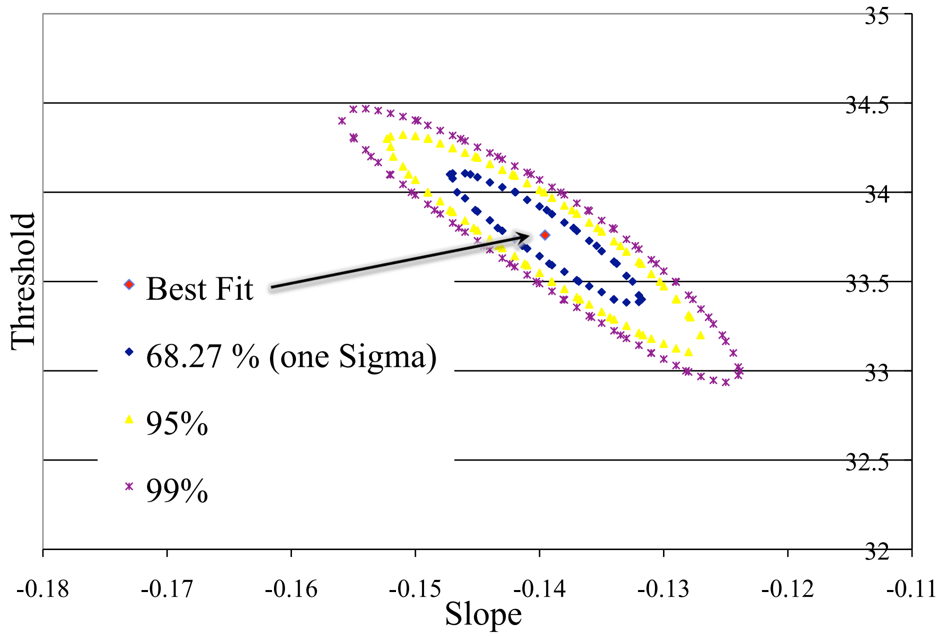

Figure 4: Contour Plot for the same data set which had Electron Cloud

III. Analysis

Once the program was completed, Threshold.c was used to analyze different data sets. All the data sets studied until today are 11 batch data sets that were taken between the months of April and July. Nine of these data sets contained EC and five of them did not. The slope and threshold obtained from this part was used to add the fit line in Figure 2 and 3 on the data after pedestal subtraction and after binned. In addition, all the best fit lines for different data set were plotted in one graph shown in Figure 5.

Figure 6 shows the thresholds of all the data sets studied and their uncertainties plotted. Table one lists the summary of the information obtained from compiling all the data sets in 11 batches. Figure 6 and table 1 both illustrate that the data sets threshold does not vary by much (taking the uncertainty to account) except for 3 data sets (highlighted with red in Figure 6), which need further studying.

The dashed line in Figure 6 is the best fit line for the data with electron cloud excluding the unusual sets which need further studying (the data highlighted with green). The slope of the dashed fit line was 0.01 and the y-intercept was 33.8. This can suggest that the intensity was not high enough for studying the effect of the running time of the machine on the surface chemistry of the machine.

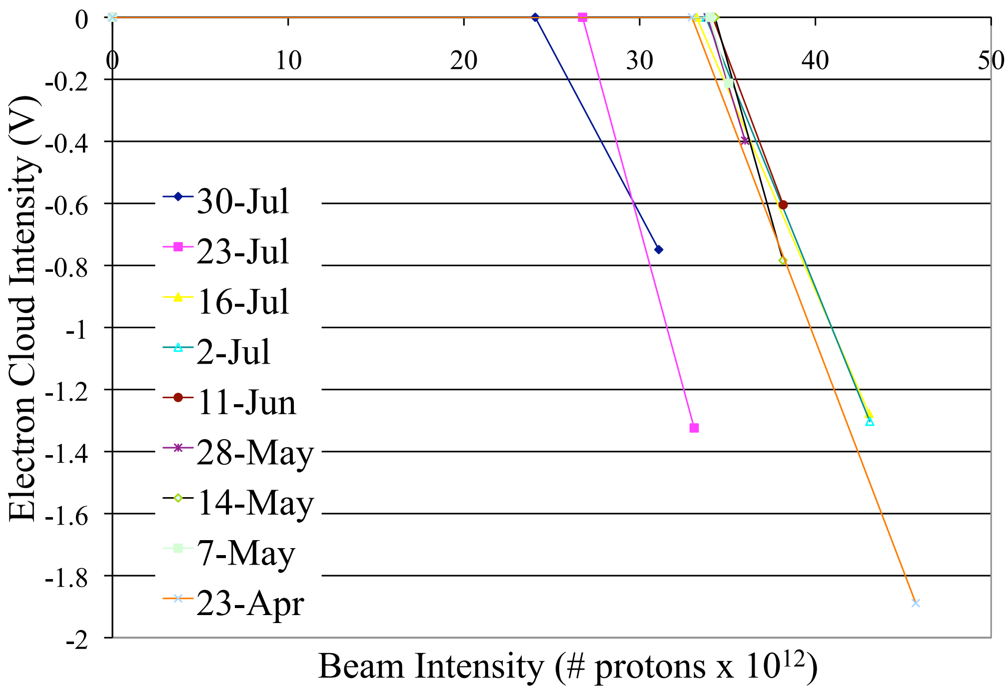

Figure 5: all the thresholds for the 11batch data sets

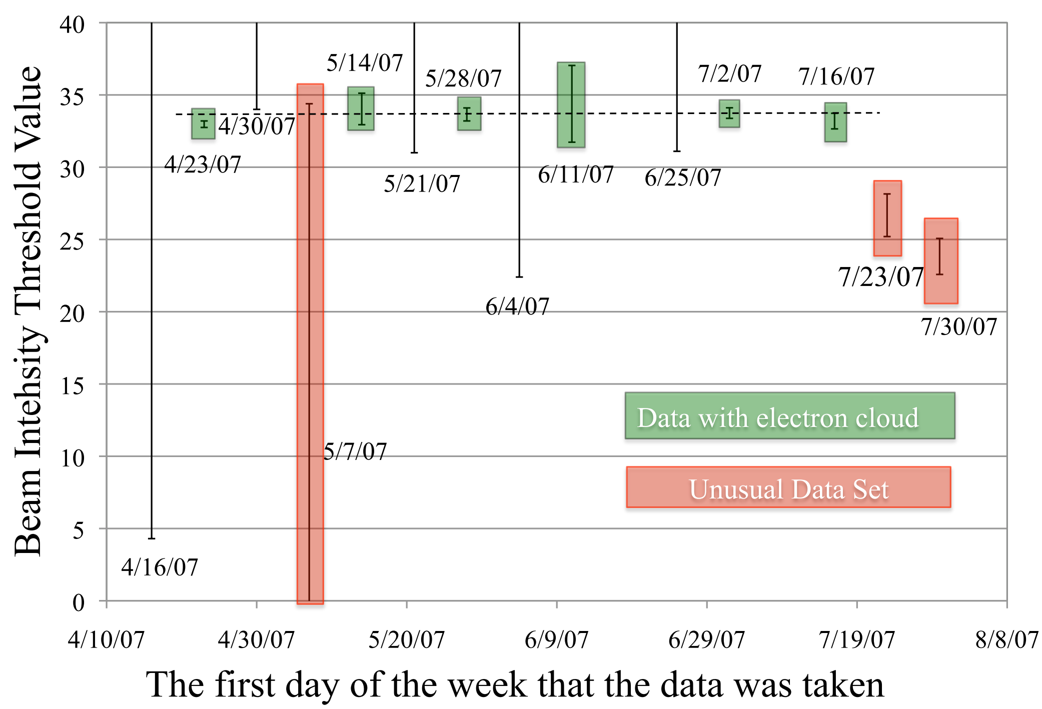

Figure 6: Plot of thresholds vs Time for the 11 batch data sets

Date	Slope	Threshold	Threshold Range	Comments
4/16/07	---	---	4.3--infinity	NO Cloud to 99% confidence
4/23/07	-0.14826	32.97	32.75-33.20	There is a Cloud to 99% confidence
4/30/07	---	---	34.0--infinity	NO Cloud to 99% confidence
5/7/07	-0.19960	34.00	Infinity--34.39*	There is a Cloud to 99% confidence
5/14/07	-0.20274	34.29	32.94-35.12	There is a Cloud to 99% confidence
5/21/07	---	---	31.0--infinity	NO Cloud to 99% confidence
5/28/07	-0.18640	33.87	33.2-34.1	There is a Cloud to 99% confidence
6/4/07	---	---	22.4--infinity	NO Cloud to 99% confidence
6/11/07	-0.15074	34.16	31.73-37.04	There is a Cloud to 99% confidence
6/25/07	---	---	31.1--infinity	NO Cloud to 99% confidence
7/2/07	-0.13956	33.76	33.38-34.11	There is a Cloud to 99% confidence
7/16/07	-0.13012	33.23	32.65-33.73	There is a Cloud to 99% confidence
7/23/07	-0.2085	26.75	25.20-28.15	There is a Cloud to 99% confidence (data with different bunching configuration)
7/30/07	-0.10652	24.06	22.58-25.07	There is a Cloud to 99% confidence (data with different bunching configuration)

Table 1: All the Thresholds calculated for the 11 batch sets with their uncertainty

The data sets for the weeks of July 30th and July 23rd showed a lower threshold. Looking at the data log-book, it was observed that these two data sets had different bunch configurations [4]. In order to compare these to the rest of the 11 batch data, it is important for the data to be divided to different sections for different configurations. Figure 7 and 8 exhibit the contour plot for these two weeks. Comparing these figures to figure 4, it is evident that for some range of slopes larger range of threshold corresponds to one sigma, which may suggest that the data set includes more than one threshold.

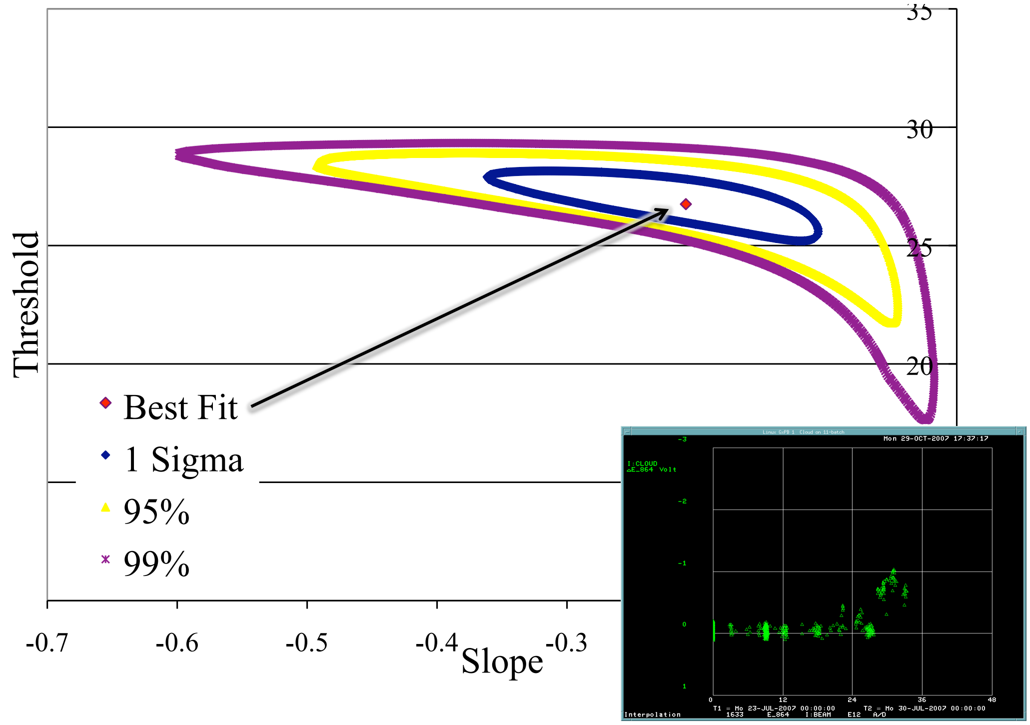

Figure 7: The contour plot for the data set from week 07/23/07

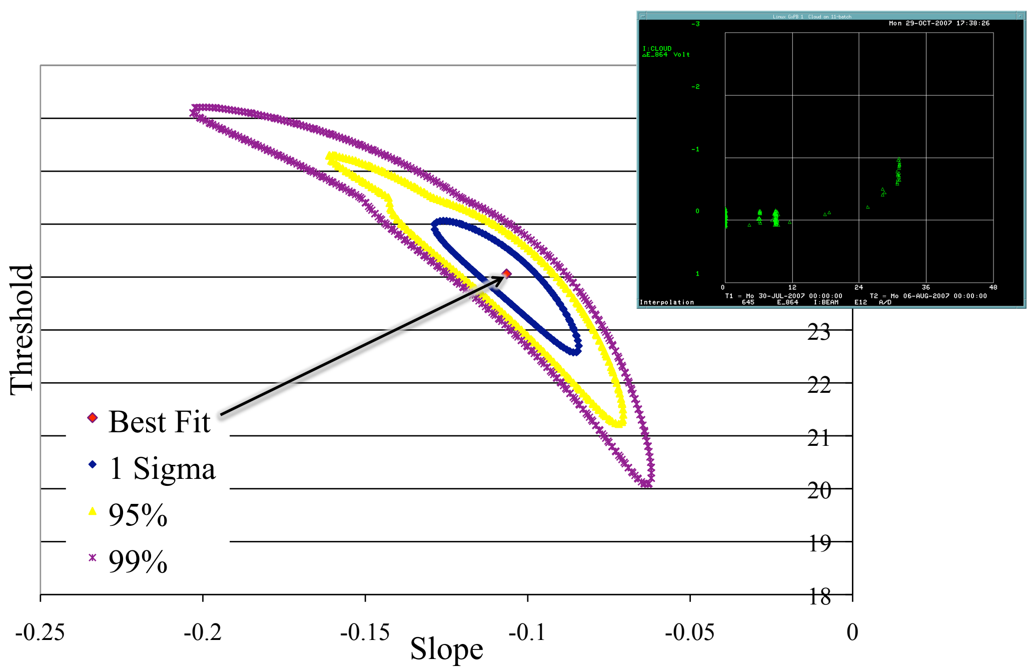

Figure 8: The contour plot for the data set from week 07/30/07

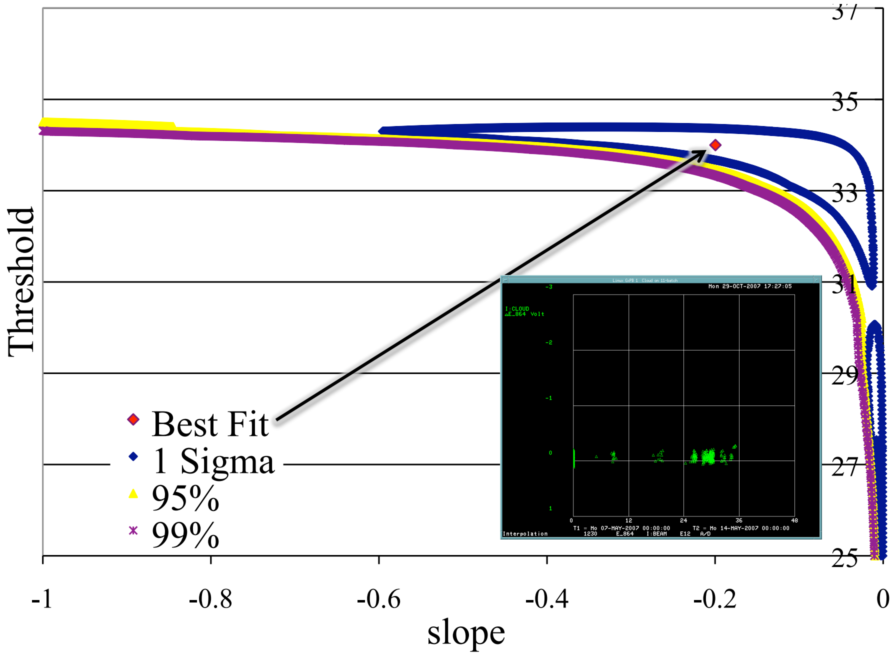

Figure 9: The contour plot for the data set from week 05/07/07

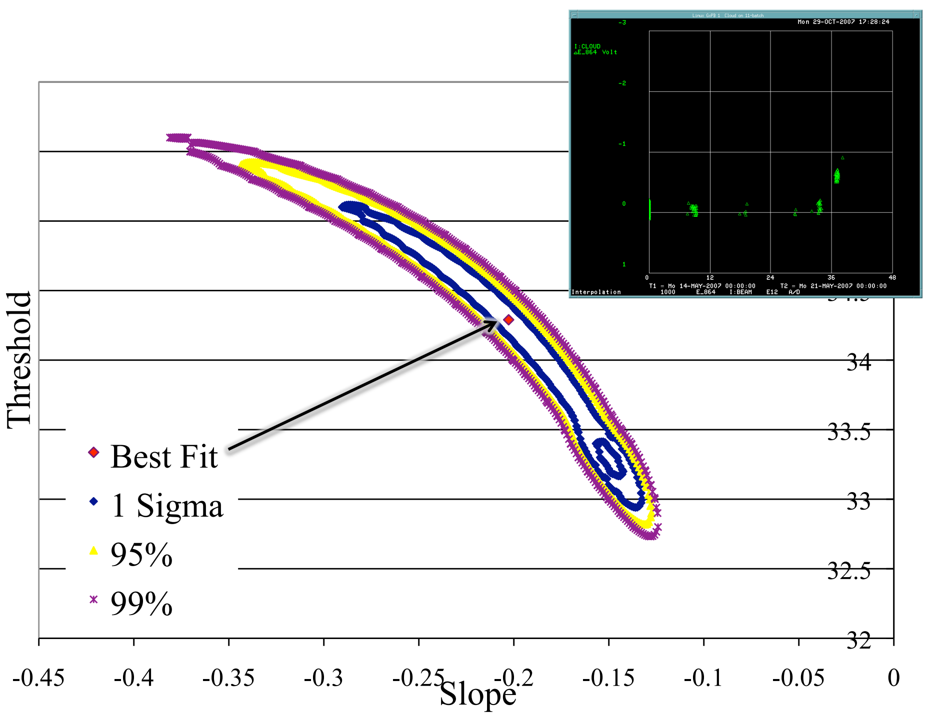

Figure 10: The contour plot for the data set from week 05/14/07

After studying the contour plots for all the data sets, some more sets needed further studying. For instance, the data set from May 7th only shows a hint of Electron Cloud formation (See Figure 9). Unlike Figure 4 which shows well defined and thin ellipses for the contour plots, Figure 6 shows that large range of thresholds will result in $\Delta\chi^2$ less than 2.3 or one sigma. It is possible that usage of smaller bins would help understand this data set. Also, the contour plot for May 14th shows an odd effect: inside the one sigma region, there is a small region that is excluded (Figure 10). Again, the next step for this data set is using smaller bin size to study it in finer details.

IV. Conclusion

In this study, first the data was prepared for analysis–pedestal subtraction and binning. Then, the method of minimum χ^2 was used to determine whether the data had an Electron Cloud or not. The threshold and the slope with which the Electron Cloud intensity increases was determined also from finding minimum χ^2 . Then the Threshold range was calculated from one sigma as $\Delta\chi^2$. Fourteen data sets with similar configurations –batch 11–were studied. Seven sets showed a sign of Electron Cloud and five did not. Three of the data sets with cloud needed further study: one only showed a hint of Electron Cloud and the last two included multiple bunching configuration. However, from the suitable data it was determined that threshold was constant over the run.

It was also determined that there were few more aspects of the data sets in hand need to be studied in order for the behavior of EC be fully understood in the beam intensity range of $(20.0 - 50.0) \times 10^{12}$. For instance, the data sets in July needed to be broken down to parts so that each part will only have one bunch configuration.

In order to make the Main Injector ready for the purposed upgrade, it is necessary that the reflect of the Machine to all range of Intensities be studied and well understood. Also, at higher intensities, it would be possible to understand if the running time of the machine or the number of proton passed through will effect the chemistry of the walls–conditioning–and will cause the threshold for the Electron Cloud to fall. Above stated are some of the future steps of this study.

Acknowledgment

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References

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