The Ecloud Measurement Setup in the Main Injector*

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Abstract

An ecloud measurement setup was installed in a straight section of the Main Injector in 2009. The goal of the setup was to compare the characteristics of different beam pipe coatings when subjected to proton beam. The setup consists of one coated and one uncoated beam pipe with the same physical dimensions installed at the same location. Four RFAs (retarding field analyzers) and three BPMs (beam position monitors) used for microwave measurements have been used to measure the ecloud densities. The RFAs have performed very well and have collected both the time evolution and energy distribution of the ecloud for bare and two types of beam pipe coatings.

INTRODUCTION

Ecloud has been observed in many high intensity accelerators which can limit the amount of current that can be stored in them. In particular, for ProjectX, the amount of beam current that will be stored in the MI (Main Injector) will be $\sim 160 \times 10^{12}$ protons while the present maximum intensity is $\sim 45 \times 10^{12}$ protons which is about $3.5\times$ less beam. Although ecloud has been observed in the MI, it has not caused instabilities at the present running conditions. However, there is no guarantee that instabilities caused by ecloud will not be a problem at ProjectX intensities. Therefore, a program has been started to study the ecloud effects with both computer simulations and experiments.

In this papers, we will be focusing our attention on how coatings can affect the production of secondary electrons. We have installed an ecloud measurement setup in a straight section of MI which consists of one coated and one uncoated beam pipe with the same physical dimensions and at the same location, together with four retarding field analyzers (RFAs) and three sets of beam position monitors (BPMs) which can be used for the microwave measurements.

In the following sections we will introduce the installed setup and discuss the design of the RFAs and briefly touch on the microwave measurements. The experimental results of both titanium nitride (TiN) and amorphous carbon (aC) coated beam pipes when conditioned by proton beams will also be discussed here.

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MAIN INJECTOR

The MI is a 2 mile ring which nominally ramps protons from 8 GeV to 120 GeV for the experiments and for anti-proton production or at 150 GeV for proton or anti-proton injection into the Tevatron. Figure 1 shows a bird's eye view of the Fermilab site and MI-52 where the ecloud measurement setup is located.

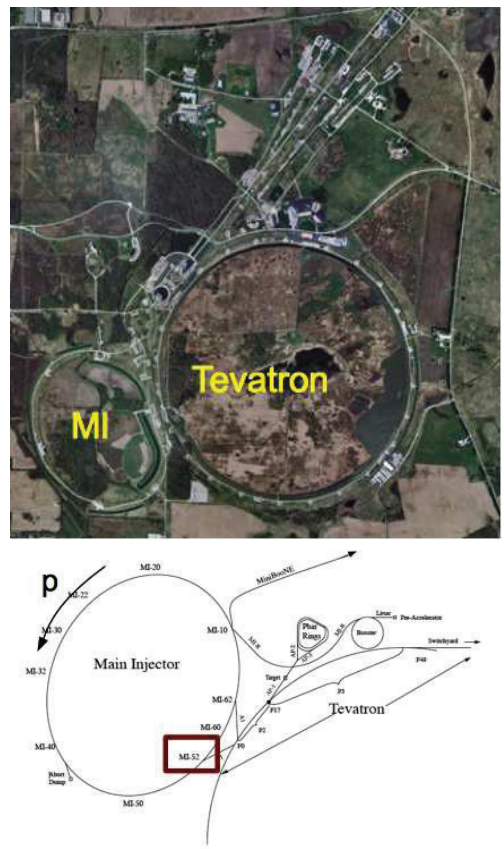

Figure 1: A bird's eye view of the Fermilab site and MI-52 where the the ecloud measurement setup is located.

The MI has many modes of operation. The highest proton intensity 40×10^{12} protons is achieved for the NuMI (Neutrinos from the Main Injector) experiment. In normal operations, NuMI is spilled from MI every 2.2s.

THE ECLOUD MEASUREMENT SETUP

The ecloud measurement setup is shown in Figure 2. The coated and uncoated beam pipes are 6" in diameter and are each 1 m long. The detectors on the setup are:

- RFAs. There are four RFAs installed. Three of the

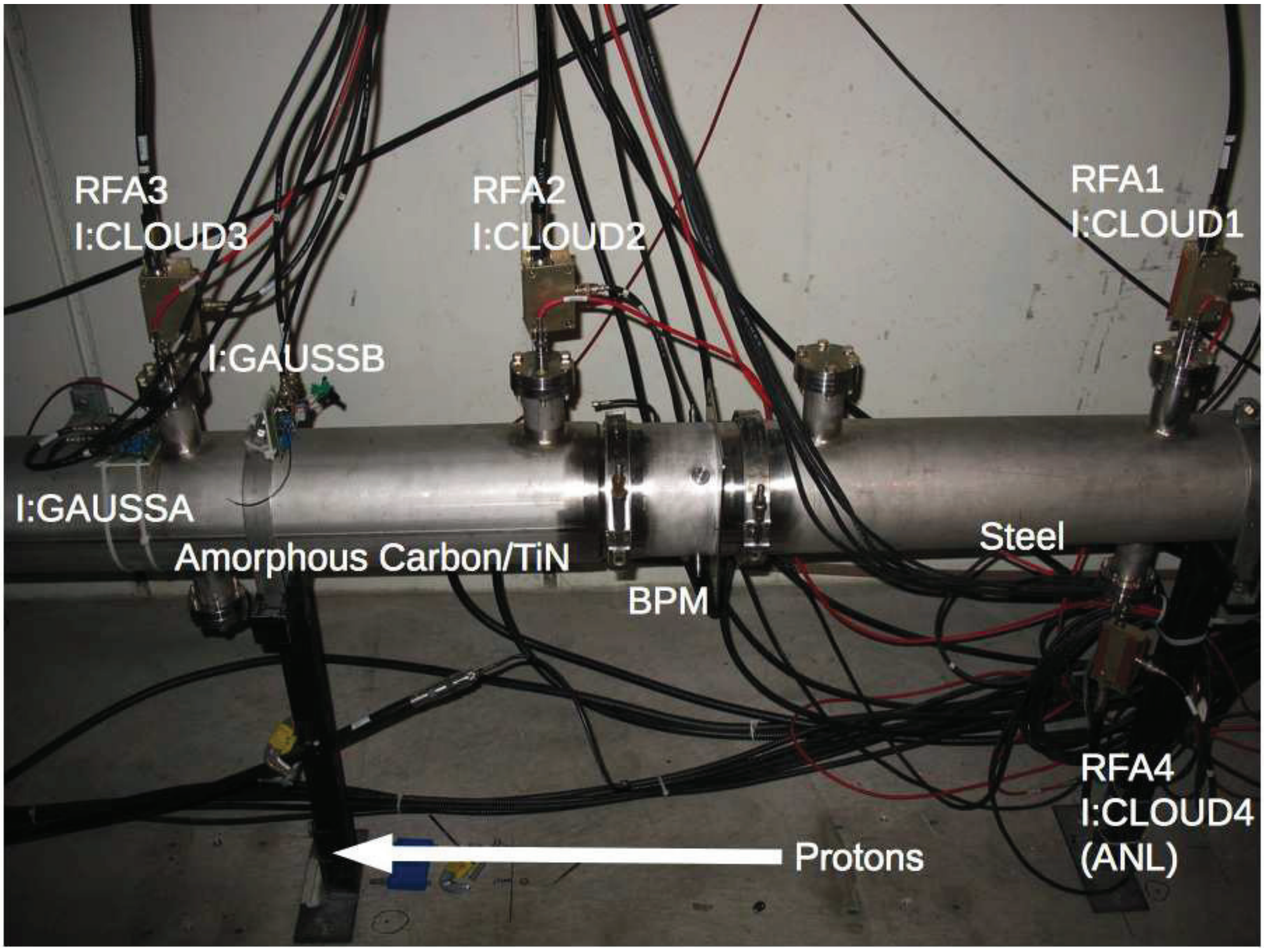

Figure 2: The ecloud measurement setup at MI-52. There are four RFAs and 3 BPMs (only one is shown here). The beam pipe is 6" in diameter and the coated and uncoated beam pipes are each 1 m long.

RFAs are FNAL (Fermi National Accelerator Laboratory) style which we will discuss below and one ANL (Argonne National Laboratory) style used for comparison.[1] The placement of the RFAs are shown in Figure 3.

- Magnetic Probes. Two magnetic probes which we have designed to be non-directional are called `I:GAUSSA` and `I:GAUSSB` in Figure 2.
- BPMs. Three BPMs are located at the positions shown in Figure 3. The BPMs are used in the microwave method for measuring ecloud densities.[2] Microwave absorbers were installed for the TiN coated beam pipe experiment. They were removed when we replaced the TiN coated beam pipe with aC.

RFAs

The design of the RFAs have been discussed in [3]. We will only highlight the reasons why certain choices were made in its design here. The RFA and its high gain amplifier are shown in Figure 4 and Figure 5 show how the amplifier is directly connected to the RFA.

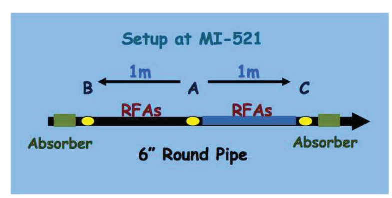

Figure 3: This is a cartoon of the measurement setup shown in Figure 2. Note that the absorbers were removed when the aC coated beam pipe was installed. (Courtesy of N. Eddy)

- Improved Sensitivity Using SIMION[4], we optimised our design so that it improved its sensitivity compared to the ANL RFA. The improvements are
  - a larger collecting surface area.
  - a cup rather than a flat surface for collecting the electrons.
  - a geometry which focuses the electrons onto the cup with the grid.
  - reduction in the number of grids to one because each grid reduces sensitivity by about 20%.

Our *in situ* ecloud measurements, show that our RFA is almost $2\times$ more sensitive than the ANL RFA.

- High Gain Amplifier A specially designed radhard, high gain amplifier with a 3 kHz low pass filter (LPF) is directly connected to the RFA. The 3 kHz LPF has been chosen because previous measurements show that there is strong 10 kHz in the MI tunnel. The LPF attenuates this noise to better than 40 dB. The electronics also has bypass relays so that the signal can be monitored if the amplifier becomes saturated.
- High quality cables All the signal cables are heliax cables which are isolated from the beam pipe and grounded in the relay racks upstairs in the service building. Only grounding upstairs prevents ground loops and reduces ramp noise which can contaminate the ecloud signals.

One limiting factor in the design is that we need to bias the grid at 20V because electrons will bounce off the RFA without this bias. From bench experiments, we find that 20V is sufficient for electron beam energies up to 600 eV. Unfortunately, for energy spectrum measurements, this will limit us to above 20 eV electrons.

Magnetic Probes

Computer simulations with POSINST and VORPAL and bench experiments have shown that a magnetic field can both affect the collection efficiency of the RFAs and the electron cloud distribution.[5]

We built two axis independent magnetic probes to measure the B-field in our setup. Figure 5 shows how the two probes are installed in the setup. The probes show that the B-field follows the MI ramps and gets to a value between 5 to 6 gauss at flattop. See Figure 6.

We also covered up the coated beam pipe with mumetal to shield it from the B-field. There are small differences between the shielded and unshielded results. Figure 8 shows the before and after effects on the RFA signal located in the TiN coated section. It is clear from here that a pedestal appears at the ramp flattop.

Microwave Setup

There are three BPMs in the setup which are used as microwave antennæ for the transmission or reception of RF (radio frequency). A typical microwave setup is shown in Figure 7. Unfortunately, no phase shift has been measured when there are microwave absorbers at the end of the setup. This is because the present setup is only 2 m long and without any reflections, the phase shift is so small that it cannot be measured. On the other hand, after the microwave absorbers were removed, multiple reflections are supported in the setup and our measurements do show a phase shift from ecloud. However, more work needs to be done to understand how to correlate the phase shift to ecloud density. [6].

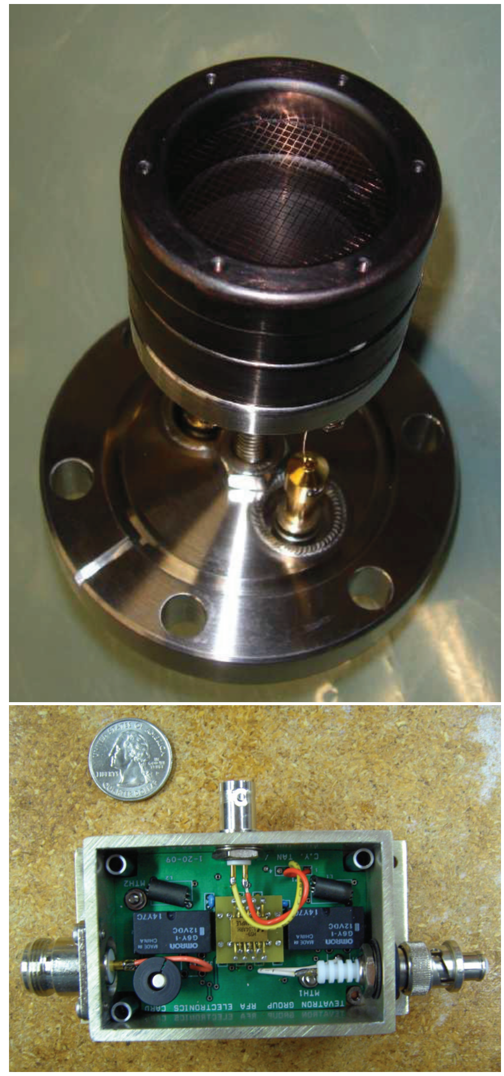

Figure 4: The FNAL RFA and the amplifier package. On the amplifier package, the gold colored integrated circuit (HS-5104ARH) is the radhard operational amplifier and the two black rectangular packages are the bypass relays. Figure 5 shows how the amplifier is directly connected to the RFA.

EXPERIMENTAL RESULTS

We will compare the RFA measurements for steel, TiN and aC in this section. We remind the reader that the locations and beam coating types are shown in Figure 2.

Figure 8 shows the typical signal that is seen on the RFAs for steel and TiN coated beam pipes. (Note: in this plot and Figures 10 and 11, the span of the plots cover part of the MI cycle which is 2.2s. The RFA data from each cycle are superimposed.) The maximum electron current that we see in the RFA signal occur soon after transition which is at 20.48 GeV. Note: for convenience we will call the "maximum electron current" measured on the RFA "dips".

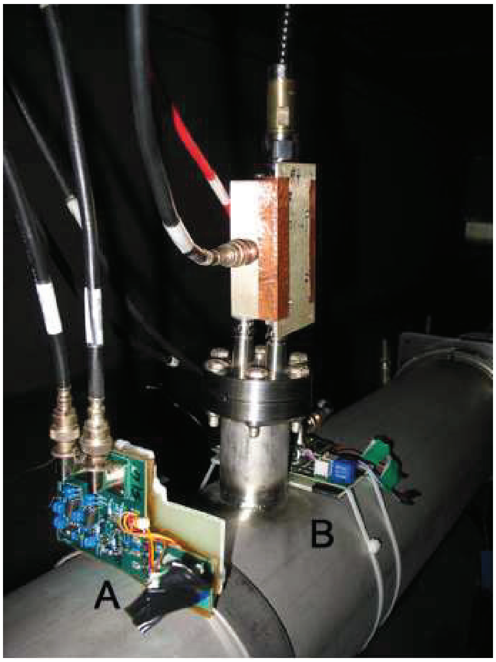

Figure 5: Two probes are installed in the setup labelled A and B here. The RFA amplifier is directly connected to the RFA in the tunnel.

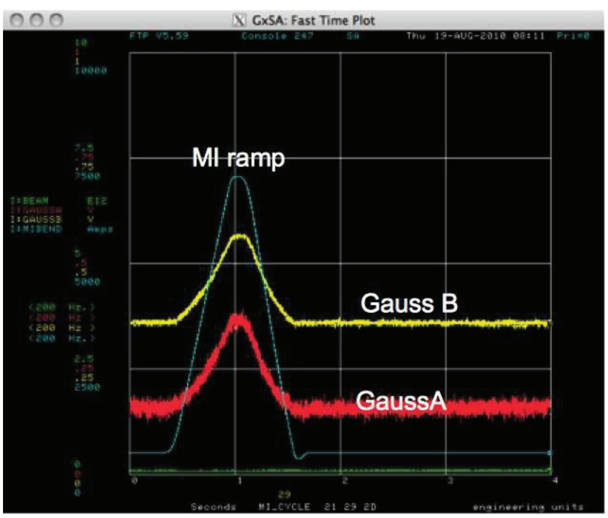

Figure 6: The B-field on the setup follows the MI ramp. The maximum field is between 5 to 6 gauss at flattop.

Comparing TiN, aC and Steel

Figure 10 is a signal comparision between TiN, aC and steel. There is a very strong double dip structure on CLOUD3 (aC) which is absent on CLOUD1 (steel). In this figure, the amplifier on CLOUD3 is turned on while it is off for CLOUD1. The same double dip structure is seen whether the amplifiers are on or off. Figure 11 shows a snapshot of the RFA signals after aC has somewhat conditioned and the double dip structure vanishes.

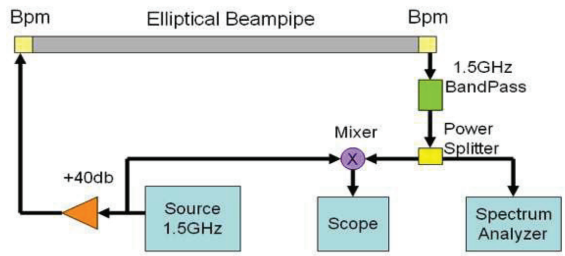

Figure 7: The microwave setup used for microwave measurements. Unfortunately, the length of the setup precluded this method. (Courtesy of N. Eddy)

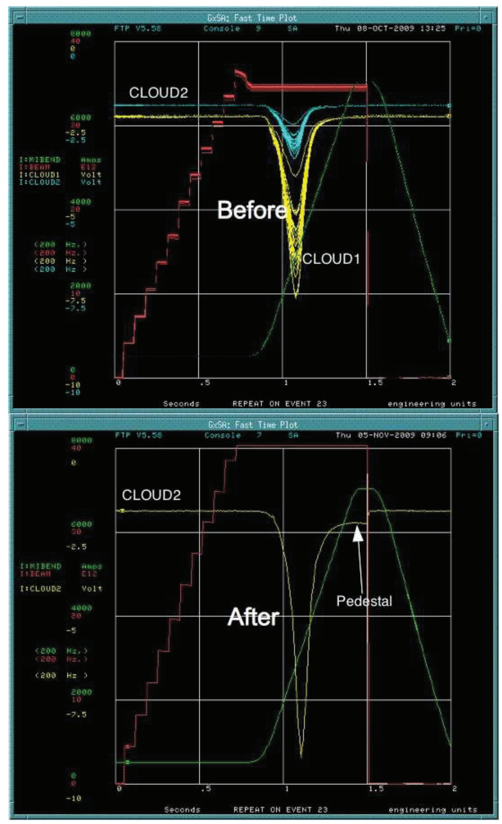

Figure 8: These are typical RFA signals on TiN and steel with the ampifiers on. The before picture compares CLOUD1 (yellow) on steel and CLOUD2 (cyan) on TiN. The after picture is when the TiN beam pipe is wrapped in mumetal. There is a clear pedestal in the RFA signal at flattop indicated by the arrow. (The red trace is the beam current and the green trace is the MI ramp.)

Tracking Conditioning

We refer to Figure 9 for how conditioning of the beam pipe is tracked. Using steel (green curve) as our example, we see a small amount of ecloud until the current in MI is about 30×10^{12} protons. When the MI current is increased from 30×10^{12}, we see that the ecloud signal takes off very quickly. The result is a curve that takes the shape of a

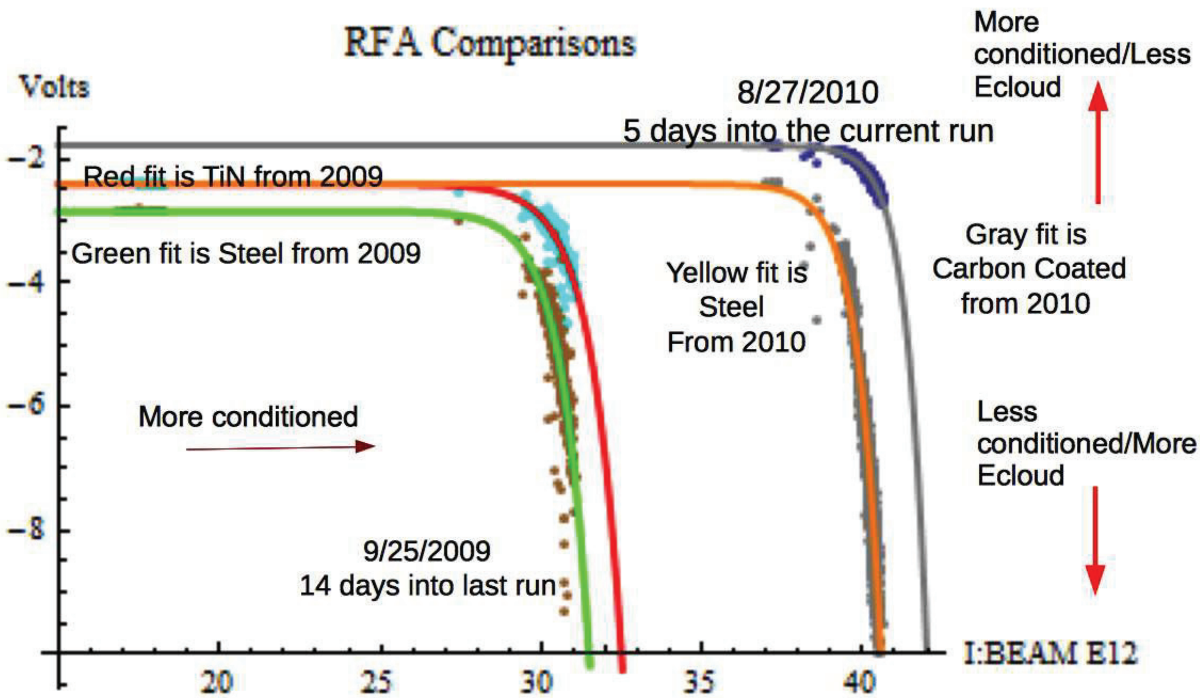

Figure 9: This is a comparision between TiN, steel for the first run and aC, steel for the current run. The beam pipe appears to condition faster after 5 days for aC, steel than TiN, steel after 14 days because of the higher initial intensity in MI.

"knee". The location of the "knee" is a very good way to track the threshold current for ecloud because as the beam pipe is conditioned, the curve flattens out at that conditioning intensity. When the intensity of MI is increased, a new curve (for example the yellow curve) with a knee coincident with the higher MI intensity is formed. And again, as the beam pipe is conditioned at this intensity, the curve flattens out. Therefore, as the beam pipe gets more conditioned, the knee moves towards the right and thus by tracking the knee we can see how the threshold current in MI evolves as a function of electron exposure.

All the necessary data for tracking conditioning is data logged and analyzed offline with the following procedure (also see Figure 12):

- conditioning is tracked by data logging the dips in the RFA (Figure 12(a)) signals and plotting them (Figure 12(b)).
- The knee from Figure 12(b) is tracked and forms the ordinate of Figure 12(d). Each dip is integrated to get a total charge. This forms the abscissa of Figure 12(d).
- Figure 12(d) is the conditioning plot.

The knee in Figure 12(b) for the first run where TiN and steel beam pipes were used and for the current run where aC and steel beam pipes are used are shown in Figure 9. It appears that aC and steel in this current run has conditioned better after 5 days compared to TiN and steel in the previous run after 14 days. However, this is accounted for by the higher initial MI intensity for the present run.

The conditioning curves for TiN and steel are shown in Figure 13. The signal gets very small for TiN after $\sim 3.5 \times 10^{17}$ are absorbed — this is the "hook" in the plot. However, there is still a strong ecloud signal in the steel beam pipe despite having absorbed more than twice the number of electrons (Note: the TiN conditioning curve shown in the talk is incorrect.)

The conditioning curve for aC, steel is much more interesting. There was a vacuum leak near RFA3 which affected the aC properties. After the leak, the aC at this location seems to follow the steel condition curve rather than the aC conditioning curve at the RFA2 location. We spoke to the vacuum group and found that the leak only got up to 10^{-6} torr (normal vacuum $\sim 10^{-8}$ torr) before gate valves closed. The repair was done in atmosphere and normal procedures were followed. Figure 14 shows the clear drop in the conditioning curve after the vacuum incident for aC at the RFA3 location. Note that as of this writing we only have 1 month worth of aC data compared to 1 year of TiN data.

Ecloud Energy Spectrum

The ecloud spectrum has been measured for TiN, aC and steel at RFA1, RFA2 and RFA3. The measurements are shown in Figure 15. We are unable to measure the energy below 20 eV because we need to bias the grid of the RFAs

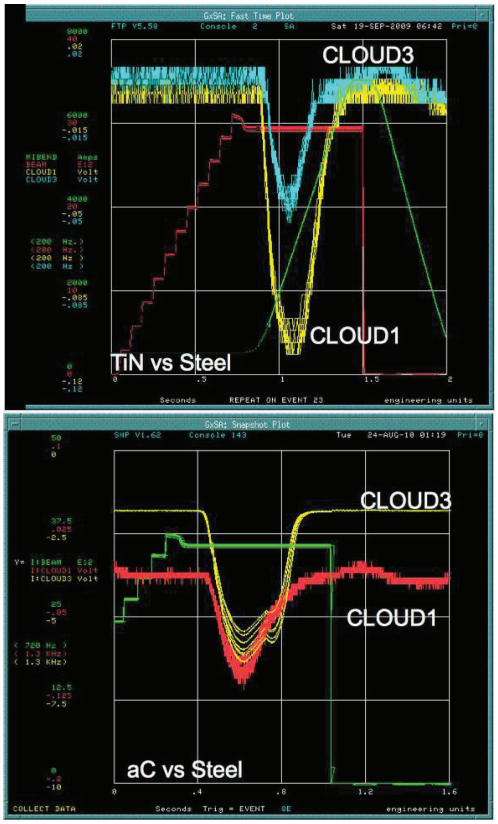

Figure 10: These two figures compare the TiN, aC and steel signals on CLOUD1 and CLOUD3. There is a strong double dip structure from CLOUD3 with aC installed. This double dip structure is not seen on CLOUD1. Note: On this figure only CLOUD3 on aC have the amplifiers on.

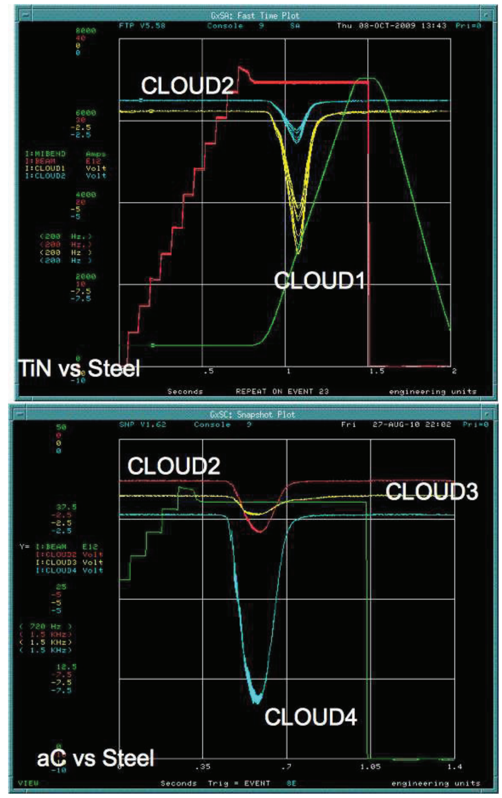

Figure 11: As time evolves, the double dip structure on CLOUD3 (aC) vanishes and the signals on all the RFAs get smaller.

by 20V. No errorbars are shown in these graphs at this time because they data is still being analyzed. The negative fraction for the RFA3 spectrum for the region midway between the TiN beam pipe and steel beam pipe has a negative fraction which is unphysical. These negative values should be consistent with zero with the errorbars included.

CONCLUSION

The ecloud setup in MI-52 has yielded many important results which will guide us in deciding which type of coatings will be necessary for ProjectX. At least from our experimental results so far, TiN and aC seem to have very similar performances in ecloud mitigation. A fortuitous vacuum leak at our test location also show that aC may not be very robust. Steel, on the other hand, even after $\sim$1 year of exposure to electrons is still conditioning and still shows ecloud buildup.

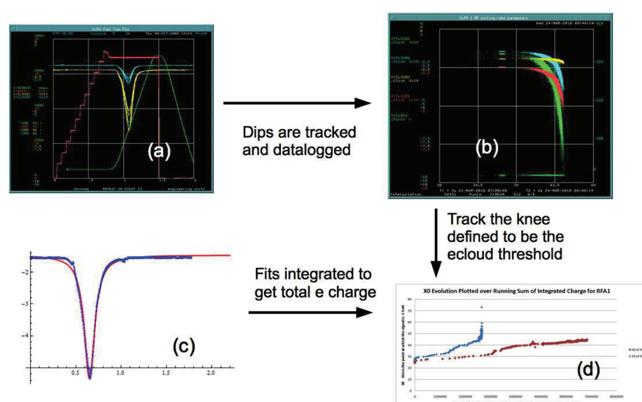

Figure 12: This figure shows how conditioning of the beam pipe is tracked. See text for details.

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[4] SIMION 8.0.4, `http://www.simion.com`.

[5] P.L.G. Lebrun, "Simulation of the electron cloud in the Fermilab Main Injector using VORPAL", these proceedings.

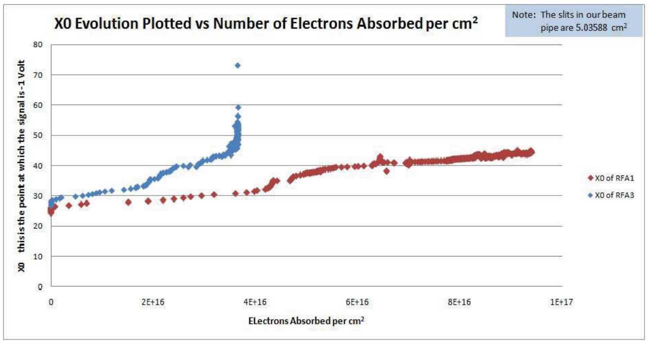

Figure 13: The conditioning curve for TiN and steel. The RFA signal on the TiN becomes very small after about 3.5×10^{17} are absorbed while the steel continues to condition.

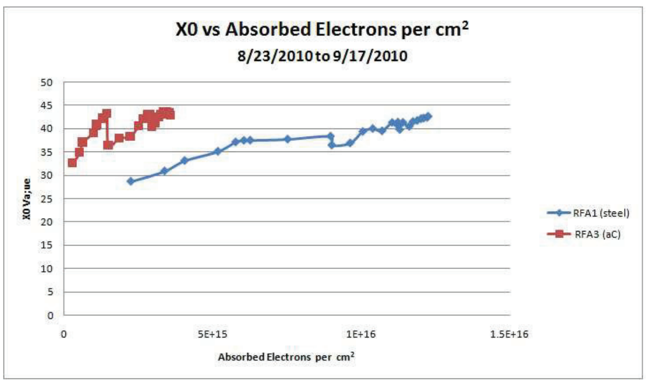

Figure 14: After the vacuum incident, there is a sharp drop in the conditioning curve of aC. Note that as of this writing we only have 1 month worth of aC data compared to 1 year of TiN data.

[6] C. Thangaraj, "Electron Cloud Studies in the Fermilab Main Injector using Microwave Transmission", these proceedings.

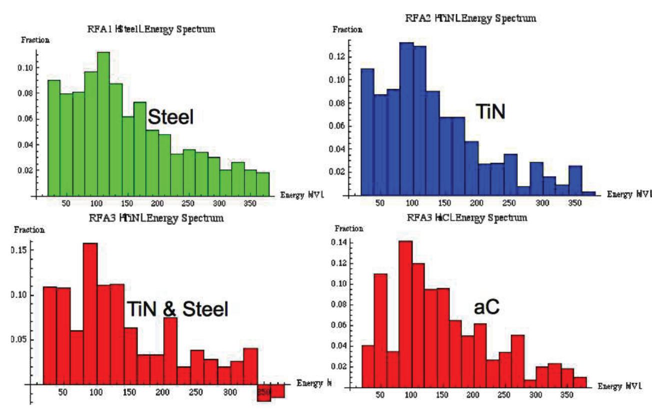

Figure 15: The energy spectrum of the ecloud collected for TiN, aC and steel at RFA1, RFA2 and RFA3. The negative fraction for the case of the RFA3 spectrum which is for the region between TiN coated beam pipe and steel beam pipe is probably consistent with zero after the error bars are included.