

# ELECTRON CLOUD STUDIES AT TEVATRON AND MAIN INJECTOR\*

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## Abstract

Estimates indicate that the electron cloud effect could be a limiting factor for Main Injector intensity upgrades, with or without the presence of a new 8 GeV superconducting 8GeV Linac injector. The effect may turn out to be an issue of operational relevance for other parts of the Fermilab accelerator complex as well. To improve our understanding of the situation, two sections of specially made vacuum test pipe outfitted for electron cloud detection with ANL provided Retarding Field Analyzers (RFAs) were installed in the Tevatron and the Main Injector. In this report we present some measurements and discuss future plans for studies.

## INTRODUCTION

The basic mechanism of the electron cloud effect is well known for proton storage rings. Electrons generated either by beam ionization of the residual gas or by beam particle loss or photons of the synchrotron radiation (high energy ring) on the beam pipe are accelerated across the vacuum chamber by the electrostatic field of a bunched beam. Through secondary emission resulting from electronic impact, more electrons are emitted and accelerated, eventually resulting in an avalanche effect. Saturation is reached when the beam is neutralized or when the electron space charge field near the wall surface suppresses secondary emission. Clearly, the secondary electron yield (SEY) is a determinant factor in setting the threshold intensity for cloud generation.

Electron cloud buildup around the beam in the vacuum chamber can reach quasi equilibrium on a relatively short time scale. The cloud can in turn interact with the beam and affect operation of the accelerator through beam loss, instability, emittance growth, vacuum pressure increase and degradation of the beam diagnostic system, etc. Deleterious effects of the electron cloud have already been either observed and/or studied at proton storage rings such as PSR (LANL), RICH (BNL), SNS, SPS and LHC (CERN). Substantial resources have been invested to mitigate these problems. In principle, both the Tevatron (Tev) and Main Injector (MI) could be affected by the electron cloud effect. So far, there has been little operational impact because both machines appear to be operating below the threshold: the Main Injector because of low bunch intensity and the Tevatron because of large bunch spacing. Nevertheless, in view of a plan to increase the intensity of the MI to meet the requirements of the High Intensity Neutrino Source (HINS) project, electron cloud effects (ECE) have become a major concern. Beam studies and simulations are being carried out to understand possible consequences of the ECE as

the proton intensity grows in the Fermilab accelerator chain.

Parameters relevant to the electron cloud experiments in the Tevatron and MI are summarized in Table 1. Results of the experimental studies will be presented and discussed the following sections.

Table 1: The main machine parameters during studies

	<b>Tevatron</b>	<b>Main Injector</b>
Energy	150~980GeV	8~120GeV
Circumference	6283.2 m	3319.4 m
RF frequency	53MHz	53MHz
Bunch Intensity	$\sim 4 \times 10^9$ p	$\sim 12 \times 10^9$ (slip-stack)
Bunch Spacing	19 ns	19 ns
Bunch Length (rms)	$\sim 1.7$ ns (150GeV)	$\sim 10$ ns (8GeV)
Beam Emittance(rms)	$\sim 15 \pi$ mm mrad	$\sim 40 \pi$ mm mrad

## THE ELECTRON DETECTORS

To provide a direct measurement of the total number of the electrons in selected vacuum pipe sections, Retarding Field Analyzers (RFA)[1] were installed. These RFAs were designed by Richard Rosenberg of ANL and used in APS to measure the Electron Cloud with very satisfactory results. They were installed in both the Tevatron and MI during the summer shutdown of 2006. Figure 1 shows the RAF assembly. The electrode in front is a fine meshed retarding grid coated with very low SEY graphite; the one in the back is the collector electrode. The signal and bias voltage are applied through the two vacuum feed-throughs.

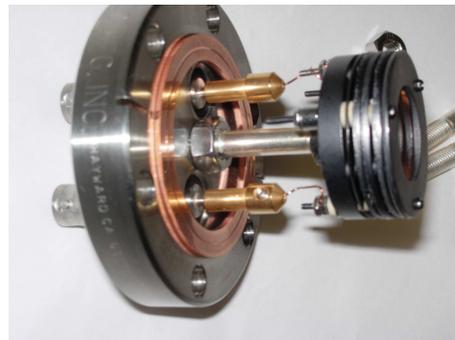


Figure 1. RFA assembly

Figure 2 shows a CAD drawing of the 3-foot Tevatron test beam pipe section with an ion pump port, a RFA port and an ion gauge port. The test beam pipe is a MI type

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with elliptical cross section of 12.3cm×5cm. Both ends are adapted to the 76mm round Tev beam pipe.

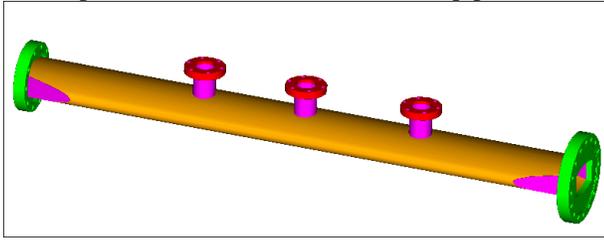


Figure 2. The designed test beam pipe in Tevatron

The test beam pipe for the MI is of a similar design but is based on a round 6" beam pipe. In order to minimize beam signal leakage, the openings for the RFA in the vacuum pipes are small narrow slots. The RFA is magnetically shielded with a few layers of mu-metal at Tevatron. The test beam pipe sections were designed to easily accommodate further experiments with solenoids, clearing electrodes, special coatings.

In addition to the RFAs, ion pumps were used to monitor changes in vacuum level, and flying wires were used to observe any emittance growth.

### OBSERVATIONS AT THE TEVATRON

The Tevatron is a 980GeV, 6 km long high energy proton antiproton collider operated in a 3 fold symmetric mode with 36 proton bunches on 36 antiproton bunches. For each beam type, the 36 bunches are divided into three 12-bunch trains with 396 ns bunch spacing and three equal length abort gaps of 2.52μs. For normal High Energy Physics (HEP) operation, the proton bunches are, prior to injection in the Tevatron, coalesced in the main injector at 150GeV. In this process, a few low intensity proton bunches (usually seven) are merged into one big intense bunch through RF manipulations. Since the bunch spacing in the Tevatron is quite large, we do not normally observe ECE.

To study the ECE, uncoalesced beam consisting of 30 consecutive bunches, with parameters summarized in Table 1, was intentionally injected into the Tevatron. The number of bunches is limited the flat top of the injection kicker, and the bunch intensity is limited by the Linac and the Booster in the accelerator chain.

#### Vacuum Pressure Rising

Vacuum pressure rise was first observed in Dec. 2002. In an attempt to observe ECE, following some machine tune-up, 30 uncoalesced bunches of approximately four times the usual intensity were injected into the Tevatron. When the beam intensity reached the expected threshold of about 4e10 protons per bunch, the vacuum pressure jumped two orders of magnitude with respect to the level observed in warm straight section ion pumps. Figure 3 shows a typical observation from May 19, 2005, when a total beam current of 116e10 protons was injected.

In this graph, T:BEAM represents the total beam current as measured by a DCCT; T:A0IP02, T:C0IP02 and T:E0IP02 are the vacuum readings of the ion pumps in

different warm sections. A0 is the abort kicker location where ceramic beam pipes are used, C0 is the section with MI magnets with elliptical vacuum chambers and E0 is the place where a vacuum leak occurred previously.

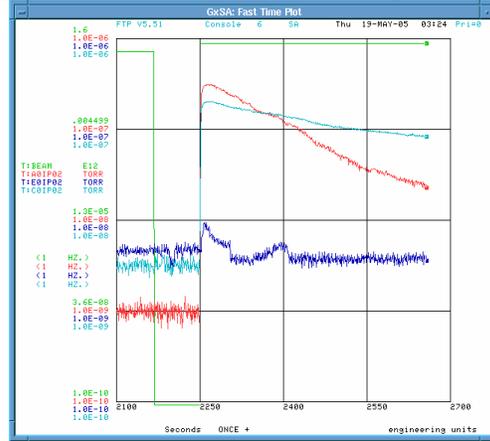


Figure 3. Vacuum pressure vs. total beam intensity for 30 consecutive bunches.

In the graph, the green curve of the beam intensity shows the end of a previous injection and the start of another injection with higher intensity. When the intensity is above the threshold, the vacuum pressure at A0 (red) and C0 (cyan) jumps over two orders of magnitude. This phenomenon was observed at other accelerators such as RICH and SPS in conjunction with ECE.

#### Emittance Growth

A flying wire was used to measure the emittance of the beam during a period of about 30 min, concurrent with the vacuum pressure rise. Figure 4 shows the change in vertical emittance during this period.



Figure 4. Beam vertical emittance (normalized, 96%, averaged over the 30 bunches) measured by flying wire at E=150 GeV

A linear fit of the average emittance growth rate yields about 34.8 π•mm•mrad/hr. This fast emittance growth was most likely caused by the ECE.

### OBSERVATIONS AT MI

For current MI operations, a total of seven booster batches of protons are injected with first two batches slip-

stacked together in the MI to form a double intensity batch. Each batch consists of 84 bunches[2]. The beams are injected at 8GeV and then are ramped to 120GeV. At 120GeV, they are extracted to produce antiproton or generate neutrinos. To monitor ECE, the RFA was used to parasitically collect electrons during each MI cycle.

### Electron Signal of the RFA

The signals from the RFA are fed through a 1 MOhm high impedance input of the Stanford Research SRS640 filter, which also has an internal amplifier, and then connected to a Tektronix TDS3034B scope. Since the electron signals expected are almost DC signals of approximately  $\mu\text{A}$  and are corrupted by the power line harmonics, beam signals, and other noise sources, frequencies higher than 50Hz are filtered out. A typical filtered signal is shown in Figure 5.

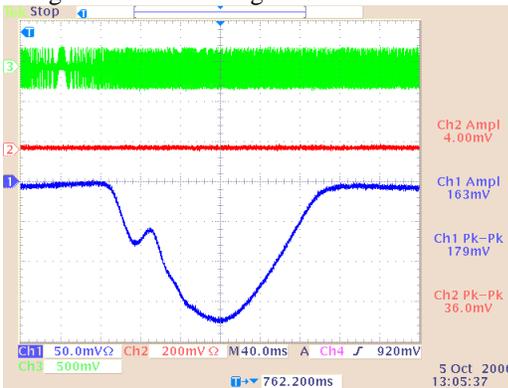


Figure 5. The electrons collected by the RFA collector

In the graph above, the scope was triggered by the MI cycle clock. The blue trace is the electron signal from the RFA collector. For this particular case, there was no bias voltage, and the maximum amplitude corresponds to  $0.03\mu\text{A}/\text{cm}^2$ . The proton beam during this measurement was about  $12 \times 10^{10}$  protons for each slip-stacked proton bunch. The actual collecting efficiency is unknown, but this result is roughly equivalent to a maximum SEY of 1.7 assuming the total collecting efficiency is 50%. The dip at the beginning part of the trace occurs at 25GeV and corresponds to transition crossing, where minimum bunch length is reached. The green trace is the beam intensity signal for the MI cycle, from injection to extraction.

In Figure 6, the electron signals for multi injection and extraction cycles are plotted. The horizontal axis shows the time elapsed in seconds since one of the MI cycle clock trigger. The magenta trace shows the beam intensity I:BEAM read from a DCCT during each batch injection, ramp, and extraction. The blue trace shows the energy of the MI ring, and the cyan traces are the overlays of electron signals for a few tens of cycles (the tail part is mostly noise). The thickness of the flat top of the I:BEAM shows that the total beam intensity variations were very small while the electron signals varied from zero to a maximum, which is consistent the threshold nature of the ECE. The narrow pulse shape shows that at current MI intensities, the ECE only takes place over a very short range during acceleration.

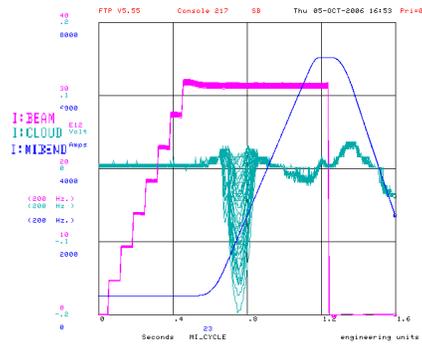


Figure 6. The RFA electron collector signal during multi MI beam cycles.

## DISCUSSIONS

The abrupt vacuum pressure jumps observed in Tevatron when the threshold beam intensity is reached are characteristic of the ECE. The observed subsequent fast emittance growth can also be attributed to the ECE. Unfortunately the electron signals from the RFA were too small to be distinguishable from noise. At this point, our attempts to directly measure the electron density have been unsuccessful. It has been proposed that the electron density at C0 could be established by measuring the RF phase shift in a signal fed into the vacuum chamber.

In the MI, a rise in the electron density was clearly observed during ramping when the beam intensity was over the threshold. Vacuum pressure rise and beam scrubbing effect were also observed. These observations remain preliminary. More detailed studies are needed in order to obtain information about electron energy distributions, effects on beam dynamics, etc.

With the MI beam intensity expected to increase by up to a factor of 5 in the future, we plan to use the test regions to investigate the effectiveness of various mitigation techniques including a solenoid field, clearing electrodes, and various coatings.

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