# AN IMPROVED RETARDING FIELD ANALYZER FOR ELECTRON CLOUD STUDIES *

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## *Abstract*

We have designed a retarding field analyzer (RFA) and a rad-hard amplifier which improves the sensitivity over the present RFA installed in the Main Injector of Electronc Cloud measurements. From computer simulations and bench measurements, our RFA will have a 20% improvement in sensitivity compared to the Argonne National Laboratory (ANL) design. And when we couple our RFA to the matched rad-hard amplifier, S/N will also be improved.

## INTRODUCTION

The electron cloud is a collective instability that may limit the performance of high-intensity particle accelerators [1]. The electron cloud consists of an accumulation of electrons in the vacuum vessel of an accelerator. The electrons are non-relativistc, but are accelerated transversely by the beam's electromagnetic field and are multiplied through secondary-electron emission on the vacuum vessel. The electron cloud can interact adversely with the beam through the direct driving of instabilities and through tune shifts onto other, pre-existing instabilities.

Retarding Field Analyzers (RFAs) have been routinely used for electron cloud detection [2, 3]. An RFA directly measures the flux of electrons at the interior surface of the vacuum vessel above a certain energy. Electrons are allowed to ballistically exit the vessel through slots cut on the surface. Beyond the surface, there is some grid, ring, or other potential surface that provides a retarding electric field that prevents the transit of electrons below a certain energy. After the retarding field, the electrons are collected on an electrode configured like a Faraday cup. The current from the cup is a direct measure of the number of electrons entering the device with energies above the cutoff established by the retarding field.

The flux of electrons at the surface of the vessel is directly related to the density of electrons within the vacuum. For protons bunches in the range of the Main Injector's spacing, electrons will typically bombard the surface once per bunch passage. Thus, the flux at the pipe surface can be related to the density as:

$$\mathcal{F} \approx \frac{\lambda}{C} \cdot f_{RF} \cdot \frac{b}{h} \quad (1)$$

Here, $\lambda$ is the linear electron density, $C$ is the tranverse circumference of the vacuum vessel, $f_{RF}$ is the RF frequency, $b$ is the number of bunches within the machine, and $h$ is the harmonic number. The relation is approximate becuase it is possible for an electron to not impact the surface on one bunch passing, and it is possible for there to be multiple impacts. In practice, a detailed simulation of the electron cloud dynamics must be performed to make a prediction of the flux; such simulations have confirmed the above relation for the Main Injector to within 10% [4]. For a 1% neutralization of the Main Injector beam at typical operational intensities ($\lambda_{beam} = 10^{11}$ protons per $5.7$ m, $C = 48$ cm, $f_{RF} = 53$ MHz, $b = 500$, $h = 588$), we would expect a flux of $0.26$ $\mu$A/cm$^2$.

An RFA borrowed from Argonne National Laboratory [5], herein known as the ANL RFA, was installed in the Main Injector in 2006 and has been operating since then [6]. This device was used for successful measurements of high-intensity electron cloud formation. However, it has suffered from significant noise, limiting the measurable signal and making energy spectrum measurements impractical. Currents as high as 4 $\mu$A were measured. In typical operation the noise floor limits us to measurements of more than $0.1$ $\mu$A, though careful noise cancellation allowed specific runs to be measured to $0.001$ $\mu$A. One of the discoveries was that the Main Injector pipe conditions over time such that the signal was below the measurable threshold.

The need for RFAs required new construction. This paper describes an evolution of the ANL design for the purposes of the Main Injector. The desired attributes are high signal efficiency, low noise, and sharp energy discrimination. A very-high signal efficiency will allow us to measure the weak electron cloud in a conditioned beam pipe, and perhaps allow measurement of the residual electron flux which would provide a baseline signal and possibly calibration. A primary source of the noise on the previously installed ANL RFA was the long cable run from the detector to the amplifier on the surface, and the poor quality of that cable. This noise will be addressed by amplification and filtering in the tunnel and a higher-quality cable.

## DESIGN

We have used SIMION[7] to simulate the various trial RFA designs. We have used it to calculate the electric fields and the capture efficiency for each trial design before coming up with our final design with dimensions shown in Figure 1. The improvements to the ANL design[5] are as follows:

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- Increased surface area. The collector area has been increased by $1.8\times$ compared to the ANL RFA. Clearly, more electrons will be captured and thus sensitivity improved because of this increase.

- Better focusing. The electric fields of our RFA have been designed so that electrons which have

  - energy greater than the voltage on the grid at the entrance of the RFA and
  - momentum vectors within an azimuth and elevation of $\pm 10^\circ$ w.r.t. the symmetry axis of the RFA

  will be focused onto the collector.

- Fewer grids. From the results of the simulations shown in Figure 2, we have found that each 25 lines per inch grid reduces the number incident electrons by $\sim 20\%$. The ANL design has two grids while our design only has one. (Note: The grid reduces the slope of the energy filter and allows electrons below the grid voltage to slip through because the centre of each hole is at a lower voltage than at the grid wire). We have also tested our RFA and the ANL RFA on a test stand and have found that the grid only shields the collector by about 8 dB in voltage while the slots in the beam pipe shield the collector by 17 dB (or 25 dB including the grid). Therefore, a single grid should be sufficient for shielding the collector from the beam.

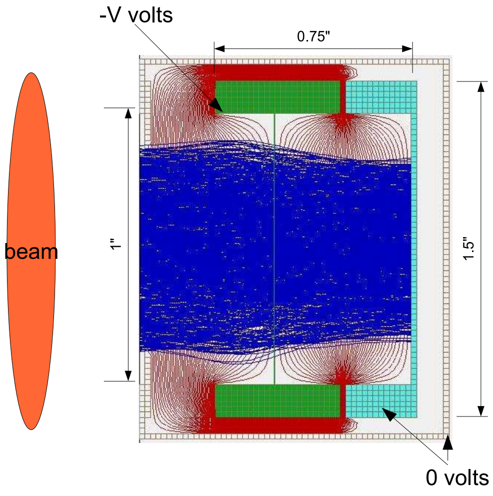

Figure 1: This is the cross section of the RFA model, including the pipe which encloses it, used in SIMION. The major parts of the RFA are the grid shaded in green and collector shaded in cyan. The equipotential lines are in red, and the trajectories of the electrons are in blue.

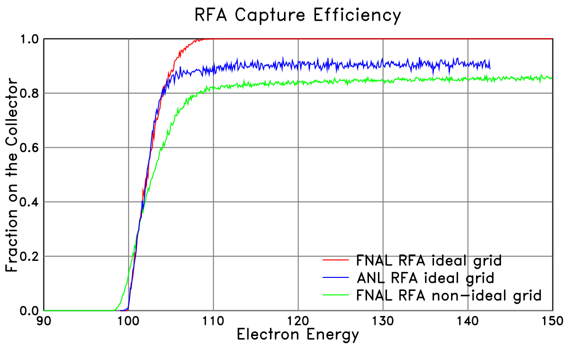

Figure 2: The capture efficiency of the our RFA (red) and the ANL RFA (blue) when the grid is ideal and set to $-100$V are compared here. The green trace shows the result when the grid is non-ideal. Notice that electrons with energy $< 100$ eV can slip through a non-ideal grid.

### *Realization*

A prototype of our RFA is shown in Figure 3. An electrical feedthrough with SHV coaxial connections is used to supply a voltage to the grid and return a signal from the collector cup. The grid is an electroformed copper mesh with 25 lines per inch which covers approximately 12% of the surface area. The clamps which hold the grid and the collector cup are machined from OFHC copper and will be coated with graphite. The support plate, collector cup, and grid are isolated from one another by the use of alumina tubing and washers. Figure 4 shows a cross section drawing view of our RFA.

### *Electronics*

From our measurements of the ANL RFA in the Main Injector (MI), we have found that the noise is $\sim 10$ mV going into 1 M$\Omega$ load. In fact, the noise spectrum is dominated by signals starting from 10 kHz. We have designed a high gain low pass filter (LPF) around a low noise, high slew rate, rad hard opamp (HS-5104ARH)[8]. This filter is an 8th order Butterworth filter with its 3 dB point at 3 kHz and a voltage gain of 40 dB. Figure 5 shows the measured response of this filter. We intend to install this filter in the tunnel so that the small electron cloud signal can be amplified and filtered before it is sent upstairs to the electronics room. This high gain LPF should improve the S/N ratio of the signal seen upstairs.

As a precaution, we have designed the circuit so that the electron cloud signal can bypass the LPF in case the electronics fail or the signal is much larger than 10 mV. The bypass is in effect when the LPF is not powered.

## CONCLUSION

A new installation is planned in 2009 for Main Injector electron cloud experimentation. This installation will

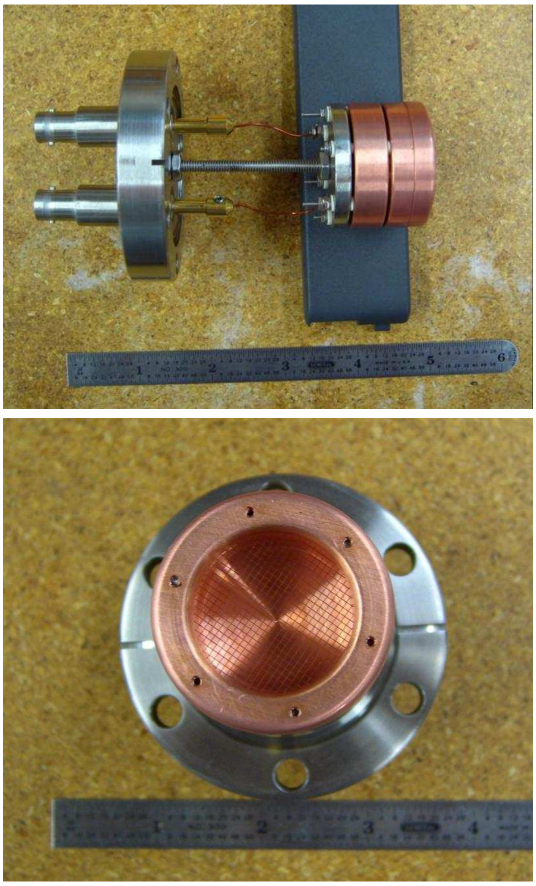

Figure 3: Side and top view of our RFA. The side view shows the wires connecting the grid and the collector to the feedthroughs which are clearly not $50\Omega$. The top view shows the aperture and the grid.

include a one-meter pipe coated with TiN, and an identical uncoated tube, to validate TiN's mitigation effect in the Main Injector. To measure the effect requires substantially more instrumentation. Four RFAs described in this paper will be installated as well as microwave antennæ [9] for electron cloud detection.

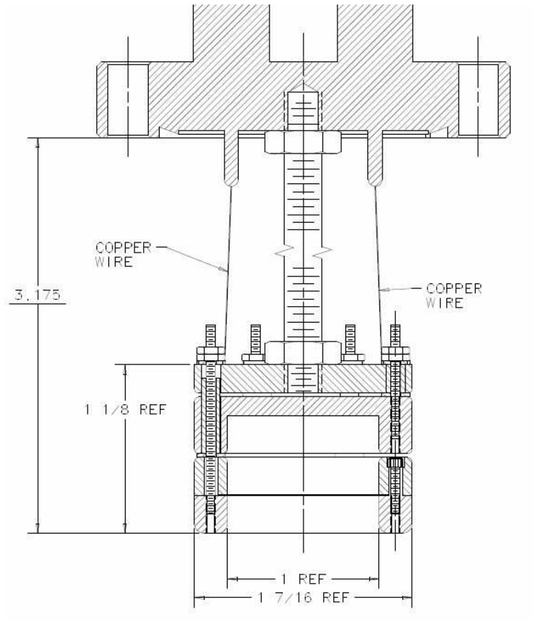

Figure 4: Cross section drawing view of our RFA.

Figure 5: The frequency response of the LPF. The measured gain is 39 dB and the 3 dB point of the filter is 2.6 kHz which is close to the SPICE model calculation.

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