Diagnostics for Electron Cloud Measurements in CESR

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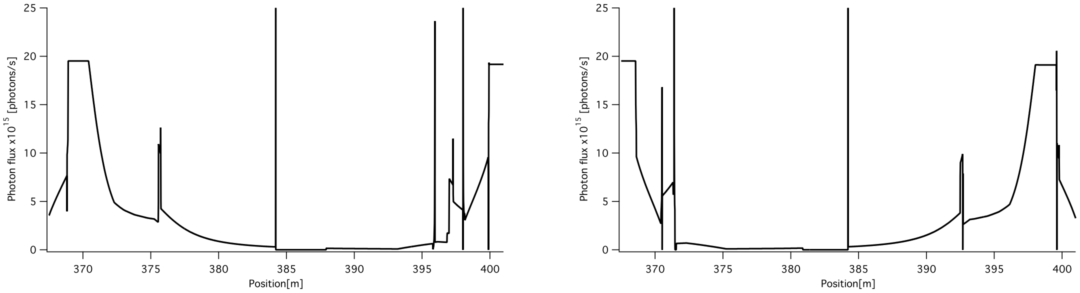
Introduction

Clouds of low energy electrons frequently build up within the beam chambers of particle accelerators. In many cases, electron cloud effects (ECEs) cause beam instabilities and degradation of performance. This is of particular concern for high intensity positron rings, in which ECEs can lead to emittance blow-up. Understanding and mitigating electron cloud build up is thus of particular importance in designing the positron damping ring of the International Linear Collider. To this end, electron cloud studies carried out in the Cornell Electron Storage Ring (CESR), beginning with a series of indirect measurements (tune shift, etc), and continuing with the installation of EC diagnostics are intended to allow direct measurement of the cloud density and energy spectrum. Such measurements can potentially provide much greater insight into the physics underlying the development of the electron cloud. As a first step in this stage of the project new diagnostic equipment has been added to the storage ring. This report documents the initial tests of these instruments and their readout electronics.

Bending magnets, wigglers, and other latice elements produce synchrotron radiation which upon striking the chamber walls generates photoelectrons. These electrons can in turn produce others by secondary emission. If the secondary electron yield (SEY) is sufficiently high, large numbers of electrons can build up during the passage of a train. Under certain combinations of bunch current and spacing 'resonant' amplification can occur, greatly increasing the density of the cloud, but even without these conditions the cloud can cause adverse effects on the beam. The details of photo-production significantly affect the initial magnitude and spatial distribution of the cloud and strongly depend on many features of the pipe and local illumination. Since these factors must be known to predict the behavior of the cloud in a given location, modeling becomes a non-trivial task. Direct measurements of the cloud are also useful to the extent that they can supply constraints on model parameters[1].

Retarding Field Analyzers

The energy spectrum of an electron cloud can provide insight into its dynamics and so is a key parameter to measure. A Retarding Field Analyzer (RFA) is a rudimentary electron energy analyzer that consists of a series of grids and a collector that can be biased independently to collect or reject electrons depending on their energies. The planar RFAs used in CESR, which were originally designed[2] at Argonne National Laboratory for use in the Advanced Photon Source, are comprised of a stack of elements including a perforated plate intended to exclude RF, a mesh retarding grid, a focusing grid of similar construction, and a collector plate. Each of these elements is graphite coated to reduce the SEY[3]. Each RFA accesses the beam chamber via a series of slots; while this arrangement obviously diminishes the effective aperture, it also reduces interference. Electrons with kinetic energy sufficient to cross the retarding grid are gathered on a collector and the current is then read out by one of a variety of methods. Thus, sweeping the potential of the retarding grid yields a reverse integrated spectrum. In the ideal case of a collimated and mono-energetic beam traveling perpendicular to the plane of the grids, response should be a step function at the potential of the retarding grid. In practice, however, response may be closer to $I = I_0(1 - e * U/U_0)$, where U is the electron energy, U_0 the retarding potential, I_0 the total incident current and e is Euler's number [2]. Spectrum analysis can



(a) Wall illumination from positron beam

(b) Wall illumination from electron beam

Figure 1: Position is given clockwise from the south, and the RFAs are located at ~ 385 meters. The peaks and shadows in the immediate proximity of the RFAs are due to the presence of the synchrotron light mirror.

in some cases be complicated.

Since the development and dynamics of the cloud are heavily dependent on the local synchrotron illumination and magnetic fields they vary greatly from location to location, so instrument placement is critical. Due to the complications involved in vacuum intervention, however, CESRs first RFAs were installed in the spring of 2007 in a straight at the north end of the ring (L3). The wall in this section of the ring is comparatively weakly illuminated by soft bend dipoles several meters away. The shallow incidence angle also introduces some uncertainty in the photo-electric yield (PEY) since this value is typically quoted for normal incidence and increases at shallower angles. Furthermore, light from positrons is partially blocked by a synchrotron light mirror.

The distribution of electrons around the circumference of the beam pipe is generally not uniform, so the placement of the RFAs around the circumference of the pipe is also significant. Predicting the spatial distribution of cloud electrons at this location is further complicated by the possibility of substantial reflection of synchrotron light onto the inner wall of the pipe, as well as the fact that in the absence of strong magnetic fields, cloud electrons drift freely. In the present installation, RFAs are mounted in a round section of stainless steel pipe in three positions: radial inward, downward, and 45°below radial outward. As a consequence of the position on the ring and the circumference of the pipe, therefore, we may expect each RFA to respond differently to photons from positron and electron beams.

An order of magnitude estimate of the current striking the RFA aperture is useful in the design and diagnosis of problems with the readout electronics. In order to make such an estimate, we begin with the tune shift measurements previously carried out in CESR by Codner, et al. Tune shift is caused by electron cloud build up and can therefore be construed as a measure of the average cloud density around the ring. The tune shift observed was consistent with electron cloud densities of order $10^{11}m^{-3}$ after the passage of a long train. Because the ring is dominated by dipoles and the RFAs are in a straight, we estimate that the photon flux, and hence cloud density, is some factor of 20 lower than in a dipole[1]. The density at L3 generated by long trains is then perhaps 5×10^9 electrons per cubic meter. For measurements taken under CLEO conditions short trains will result in still lower cloud densities.

Assuming the RFAs can collect electrons from the transverse slice of the pipe that they span, each is sensitive to a volume of $\sim 1.2in. \times 9.6in.^2 = 1.9 \times 10^{-4}m^3$, and $\sim 10^6$ electrons. Since each RFA covers about 10% of the circumference of the pipe and the slots are about 21% transparent, each RFA could collect about 10^4 electrons per train. With a train spacing of 400 ns, the average current would then be around 13 nA. This does not take into account, however, the transparency of the retarding and focusing grids, which is expected to be less than 10%.

[1] This is a conservative estimate of the cloud density in that it assumes the cloud is photoelectron dominated, and therefore scales with the number of photons striking the wall

Readout

There are a number of methods for reading out the RFAs, each of which allows measurement of different properties of the cloud. The simplest of these, which has been carried out at several accelerators [4][5][6][7], is to detect the current output of the RFAs over long period of time (i.e. "DC"). In this manner it is possible to measure the density and energy spectrum of the cloud averaged over many turns and the dependence of these quantities on beam current, fill pattern, as well as other operating parameters. A more complicated measurement, but one that yields much more insight, is to attempt to resolve the fast current pulses that occur when beam bunches pass the RFAs, measuring the density and energy spectrum of the cloud as a function of time, that is, measuring the temporal structure of the cloud. While this "AC" measurement provides significantly more information, the DC measurement is useful in an extremely low signal environment for simplicity and the fact that it allows for filtering of high frequency noise.

While the DC measurement does not reveal the temporal structure of the cloud, it can show the dependence of average density on total beam current and fill pattern. To carry out the DC measurement the following setup was used. High voltage power supplies located in a spur adjacent to the tunnel were used to bias the grids and collectors (as opposed to the batteries used at other facilities for similar measurements). The length of cable from the power supplies to the RFAs is about 60 feet. Power supplies have the advantage of being readily adjustable to allow future fine tuning of the grid potentials to optimize collection. In these preliminary tests, the retarding grids of all three RFAs were biased simultaneously, and the collector and focusing grid of each RFA, which were ganged together for this test, were biased independently. The current gathered on the collector and focusing grid is measured with a shunt on the negative terminal of the power supply (i.e. in the L3 spur rather than at the RFA). Following aggressive low-pass filtering the shunt voltages go to the inputs on a differential instrumentation amplifier with a gain of 50 and a second stage with a gain of 20. The large shunt resistor required to read out such small signal currents means that even very small current leaks in any of the components can produce sizable offsets. Furthermore, very high frequency EMI is prone to be rectified and further contribute to offsets. Though this arrangement is less than ideal for noise considerations, it is necessary during development due to the infrequency of machine access during CLEO running.

Measuring the AC signal can be challenging because the current pulses that occur as each bunch passes are very small, very short, and accompanied by abundant high frequency EMI. In CESR, bunches are roughly 33 picoseconds long ($1\ \sigma$) and 14ns apart. A substantial portion of the signal extends into the GHz range; thus, both wide bandwidth and high gain are required. The readout circuit used in this case, based on a design in use at the LANL-PSR, consists of an AC coupled op-amp current to voltage converter followed by several gain stages and a cable driver. This amplifier was originally conceived for much larger signals than were eventually observed in L3, so as a first step we attempted to detect train-by-train structure, which requires far less bandwidth. In the configuration of the amplifier shown in the figure, gain and bandwidth are limited by the I-V stage. Minimizing capacitance on the amplifier input is critical and requires mounting the amp as near as possible to the RFA. The RFA and cable stub still have enough capacitance to cause the amplifier to oscillate, so a feedback capacitor must be included for stabilization. As the feedback resistor, which determines the voltage for a given current input, grows, the stabilizing capacitor must grow as well to preserve decent pulse response. Boosting both the resistor and the capacitor, however, limits bandwidth. The gain and driver stages are current feedback amplifiers, for which gain and bandwidth can to an extent be varied independently, with a bandwidth of 140 MHz.

The setup used for the AC measurement was as follows: The amplifier, along with a power supply and transformer, was mounted in a Bud box and suspended from the pipe to minimize input cable length. The bias voltage power supplies were located in the L3 spur as was the oscilloscope used to read out the amplifier (cable length to the RFA was again $\sim$60 feet). In addition to the configuration shown in the figure, the amplifier was tested with the bandwidth limited to $\sim$15MHz to suppress noise. In neither case was a signal detected that resembled bunch or train passage or that could be altered by changing the grid biases. Substantial interference apparently associated with the quadrupole power supplies was observed, but there is enough time (several turns) to measure the cloud between these pulses. While there is room to improve the cabling scheme, it is clear that there is not sufficient signal to carry out a single pass AC measurement.

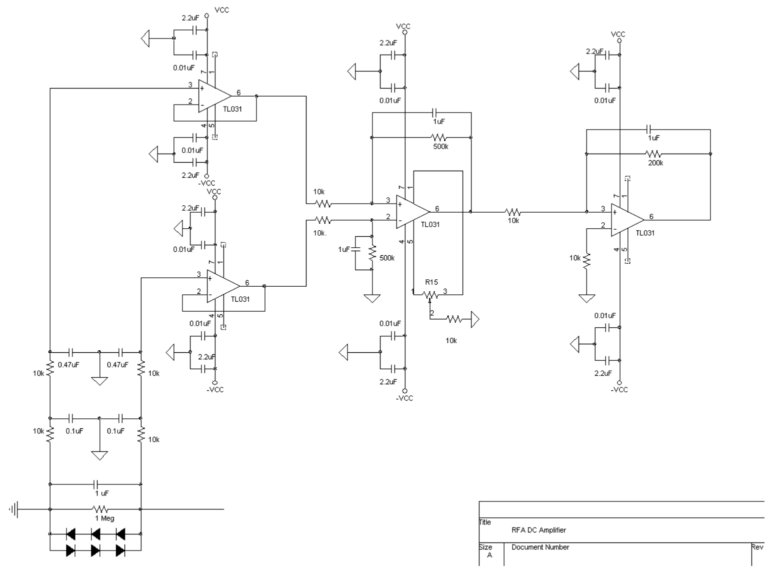


Figure 2: A schematic of one channel of the DC amplifier. As a result of the large capacitor, the shunt behaves as a short in the case of a short pulse input. The filters are susceptible to passing high frequency signals if the filter capacitors are not matched well. The sensitivity to mismatches might be reduced with the inclusion of a capacitor directly across the differential inputs. Offset trim is achieved with a trimmer potentiometer on the differential stage. The thermal drift, which can be considerable, might be mitigated by replacing the potentiometer with metal film resistors.

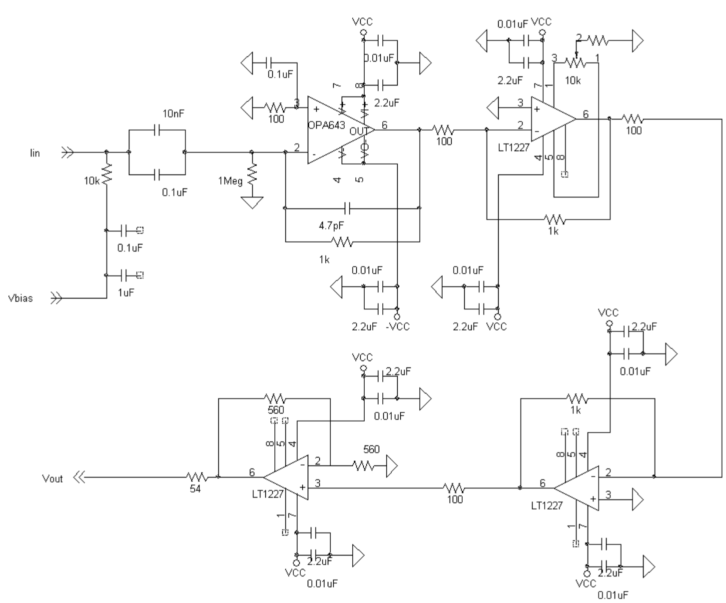
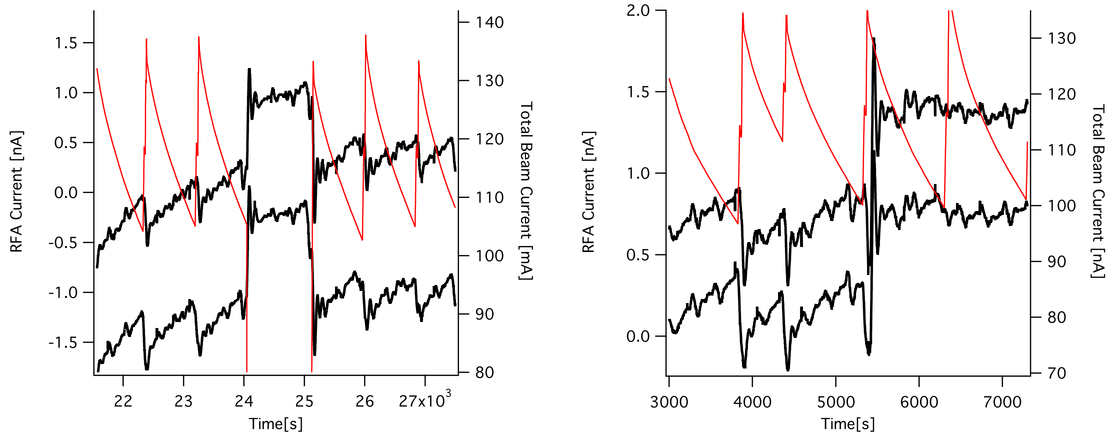


Figure 3: A schematic of the DC amplifier.

	$I_{RFA} : I_{beam}$ [pA/mA]	ΔG1[nA]	ΔBeam off [nA]
Bottom outside	14.1(1)	.72(3)	1.45(3)
Inside	12.0(1)	.78(3)	1.28(1)

Table 1: Data taken under colliding conditions



(a) RFA signal behaves reasonably during filling and when the beam is dumped. The lower trace is the output of the bottom outside RFA, and the middle trace is the output of the inside RFA.

(b) G1 is biased to -150V suppressing a substantial fraction of the signal.

Figure 4: Data taken under CLEO colliding conditions.

Results

The DC measurement was carried out under both CLEO colliding conditions and single species beam. During CLEO running, the beam is comprised of nine trains of three bunches amounting to a total current of about 130 mA. The beam is topped off every ∼30 minutes, over which interval the current decays to ∼95mA. Thus, it is possible to observe the dependence of the electron cloud on total current without dedicated machine studies. As is evident in Figure 4(a), the signal on the RFA varies in coincidence with the fill cycle and follows the decay of the beam current. When the beam is dumped, the signal diminishes and levels out. The difference in the RFA signal between a full fill and no beam is a maximum possible collected current. It is not immediately clear that this current can all be attributed to cloud electrons being collected as opposed to beam related EMI. When the repeller is biased to -150V the signal is suppressed such that the difference in signal observed at full fill with the grid on and off is somewhat smaller than the maximum difference. Since biasing the grid blocks electrons but not EMI, some portion remaining offset may be due to interference. However, with the repeller on the signal is insufficient to resolve the ∼25% change expected to accompany filling, so contributions from EMI and higher energy electrons cannot be distinguished.

It is perhaps also possible to notice variance in response to positron and electron currents between the RFAs. When the beam is topped off positrons are injected first, then followed by electrons. As each species of particle is injected, some of the current of the other species is lost. Figure 4(a) shows beam and RFA currents during a typical fill. As positrons are injected and electrons are lost the current collected by the bottom outside RFA increases (i.e. the signal goes more negative) while the current collected on the inside RFA decreases slightly. When electron injection begins and positrons are lost, the current collected by the bottom outside RFA decreases, again despite the increase in total current.

During machine studies the electron cloud was measured under single species conditions. Due to difficulties with positron injection, data was only gathered for an electron beam. The machine was filled with a single train of 1.2 mA electron bunches with 14 ns spacing. Bunches were added five at a time and

Table 2: Single beam data. These measurements are consistent with the previous observation that the inside RFA is more sensitive to electrons and the bottom outside RFA to positrons.

	$I_{RFA} : I_{beam}$ [nA/A]	ΔG1[nA]	ΔBeam off [nA]
Bottom outside	2.3	0.27(2)	0.26(7)
Inside	8.8	0.74(2)	0.68(8)

the beam and RFA currents were recorded every two seconds. Upon completion of filling, the retarding grid (G1) was biased at -150V. G1 was then returned to 0V and the beam was dumped.

While it is very difficult to directly measure the time dependent behavior of the electron cloud without a larger signal, some information can be obtained by measuring and comparing the DC currents for trains of different lengths. This was carried out for an electron beam during machine studies on 8/14/07. Due to problems with injection we were not able to attempt measurements with positrons. To mitigate the oscillations due to AC line transients caused by a nearby air conditioner, the compressor was deactivated for a portion of this test. While this was effective in eliminating noise, the rise in temperature was sufficient to induce substantial drift and required that the air conditioning be turned back on for the rest of the test. As in the measurements taken during CLEO running, we found that a retarding voltage of -150 V was sufficient to suppress most of the signal.

Conclusion

Planar retarding field analyzers have been installed in L3 and appear to be functioning. Prototype readout electronics have been built and tested. An electron cloud appears to exist in the L3 straight, though it is small enough to allow only time averaged current measurements. Though some minor issues remain to be addressed with the DC amplifier, measurements taken with this equipment so far have been broadly consistent with expectations. The return to CHESS operating conditions may provide enough additional illumination to improve the measurements taken thus far.

References

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