Measurements of Electron Cloud Growth and Mitigation in Dipole, Quadrupole, and Wiggler Magnets

J. R. Calvey, W. Hartung, Y. Li, J. A. Livezey¹, J. Makita², M. A. Palmer³,
D. Rubin

*Cornell Laboratory for Accelerator-based Sciences and Education, Cornell University,
Ithaca, New York, USA, 14853*

Abstract

Retarding field analyzers (RFAs), which provide a localized measurement of the electron cloud, have been installed throughout the Cornell Electron Storage Ring (CESR), in different magnetic field environments. This paper describes the RFA designs developed for dipole, quadrupole, and wiggler field regions, and provides an overview of measurements made in each environment. The effectiveness of electron cloud mitigations, including coatings, grooves, and clearing electrodes, are assessed with the RFA measurements.

1. Introduction

The electron cloud effect, in which a high density of low energy electrons builds up inside a vacuum chamber [1], has caused operational difficulties at a number of past and present accelerators [2], and is expected to be a limiting factor in next generation machines [3]. As part of the CESR Test Accelerator (CESRTA) program at Cornell [4], the Cornell Electron Storage Ring (CESR) was instrumented with a number of electron cloud detectors [5–9], including retarding field analyzers (RFAs) [10]. Previous papers have discussed the design of RFAs for measurements in magnetic field free regions [5]; and described the use of simulations to quantify the electron emission properties of different cloud mitigating coatings tested in these regions [6]. This paper will summarize results obtained from RFAs located in dipoles, quadrupoles, and wigglers.

¹Present address: Department of Physics, University of California, Berkeley, CA, USA, 94720

²Present address: Department of Physics, Old Dominion University, Norfolk, VA, USA, 23529

³Present address: Fermi National Accelerator Laboratory, P.O. Box 500, MS 221, Batavia, IL, USA, 60510

Electron cloud buildup has been measured in dipole and wiggler fields at SLAC [11], KEK [12, 13], INFN [14], and CERN [15, 16]; and in quadrupole fields at LANL [17] and LBNL [18]. At CESR we have worked to replicate and expand on these measurements, with the goal of providing specific recommendations for cloud mitigations in the International Linear Collider [3] damping ring (ILC DR), as well as deepening our understanding of cloud dynamics in magnetic fields.

1.1. Retarding Field Analyzers

A retarding field analyzer consists of three main components [10]: small holes drilled in the beam pipe to allow electrons to enter the device; a “retarding grid,” to which a voltage can be applied, rejecting electrons with less than a certain energy; and a positively biased collector, to capture any electrons which make it past the grid. If space permits, additional (grounded) grids can be added to allow for a more ideal retarding field. In addition, the collectors of most RFAs used at CESR are segmented transversely to allow characterization of the spatial structure of the cloud build-up. Thus a single RFA measurement provides information on the local cloud density, energy, and transverse distribution.

1.2. Experimental Sections

There are four main electron cloud experimental sections of CESR that contain RFAs in magnetic fields. These are:

- An detector inside a CESR dipole in the B12W arc section.
- A chicane of four dipole magnets, each containing an RFA, located in the L3 straight.
- An instrumented quadrupole (Q48W), also in L3.
- Three superconducting wigglers, each containing 3 RFAs, in the L0 straight.

The properties of each instrumented chamber are listed in Table 1. Fig. 1 shows the locations of these experimental sections in the CESR ring; more details on each location are given below.

Figure 1: Present layout of the CESR ring. Electron cloud detectors in magnetic fields have been installed in L0, B12W, Q48W, and L3.

Table 1: List of RFA locations. The “Chamber” column refers to the base material; some locations have tested one or more mitigations. The vacuum chambers at all locations are 5 cm in height by 9 cm in width, with the exception of the circular chambers, which are 4.5 cm in radius.

Location	Magnet	Field Strength	Chamber
L0	Wiggler	1.9 T (peak)	Rectangular Cu
12W	CESR Dipole	0.079 T (2.1 GeV) - 0.201 T (5.3 GeV)	Elliptical Al
L3	Quadrupole	3.7 T/m (2.1 GeV) - 7.4 T/m (5.3 GeV)	Circular Al
L3	Chicane Dipole	0 - 0.1460 T	Circular Al

1.2.1. B12W and L3 Dipole RFAs

In the presence of a dipole magnetic field, an electron will undergo helical motion, spiralling around the field lines. For a standard dipole magnet in an accelerator (with strength ~ 1 kG), a typical cloud electron (with energy ~ 10 - 100 eV) will have a cyclotron radius on the order of a few hundred μm . In other words, the motion of the electron will be approximately one dimensional, along the direction of the dipole field. This “pinning” of the motion to the field lines results in an electron cloud buildup that is both qualitatively and quantitatively different from the field free case.

To study cloud buildup in such an environment, a thin RFA was designed to fit inside a CESR dipole magnet (Section 2.2), and installed in the 12W section of CESR. The magnetic field at this location depends on the beam energy: 790 G at 2.1 GeV, 1520 G at 4 GeV, and 2010 G at 5.3 GeV. The chamber is made of uncoated (6063) aluminum.

Figure 2: PEP-II 4-dipole magnet chicane and RFA-equipped vacuum chambers.

69 Additionally, a chicane of four magnets designed at SLAC [11] was installed
 70 in the L3 straight (Section 2.3). The field of these magnets can be varied over
 71 the range of 0 to 1.46 kG, which allowed for the study of the effect of dipole field
 72 strength on cloud dynamics, without affecting the trajectory of stored beams.
 73 A photo of the chicane is shown in Fig. 2.

74 1.2.2. *Q48W Quadrupole RFA*

75 As in the dipole case, cloud electrons in a quadrupole will be constrained
 76 to spiral along the field lines. However, the non-uniform character of the
 77 quadrupole field can lead to unexpected behavior. Of particular interest is
 78 long term cloud trapping. To investigate these effects, a thin RFA was built to
 79 fit inside the Q48W quadrupole in CESR (Section 2.4).

80 1.2.3. *L0 Wiggler RFAs*

81 Wigglers are an important component of next generation lepton colliders, as
 82 they greatly increase the radiation damping of the beam [3]. The high rate of
 83 photon production in wigglers, combined with the complex three dimensional
 84 nature of their magnetic fields, makes electron cloud buildup inside them a
 85 serious concern [19].

86 In 2008, the L0 straight section of CESR was completely reconfigured for the
 87 CEsrTA program. The CLEO detector was removed, and six superconducting

Figure 3: Superconducting wigglers in the L0 straight.

wigglers were installed (Fig. 3). The wigglers are 8-pole super-ferric magnets with main period of 40 cm and trimming end poles, and were typically operated with a peak transverse field of 1.9 T, closely matching the ILC DR wiggler requirements. Three of these wigglers were instrumented with RFAs (Section 2.5).

1.3. Cloud Mitigation

Evaluating the effectiveness of cloud mitigations in different magnetic field environments is a major component of the CESR-TA program. Mitigations tested include:

- TiN coating [20–23], which reduces the secondary emission yield (SEY) of the coated chamber.
- Longitudinal grooves [13, 24–26], which (in a dipole field) intercept electrons produced on the wall before they can drift to the center of the chamber.
- A clearing electrode [12, 14, 27], which pulls electrons toward the chamber wall, away from the beam.

Table 2: RFA styles deployed in magnetic fields in CESR. See [11] for more information on the chicane dipole RFAs.

Type	No. of Grids	No. of Collectors	Grid Type
CESR dipole	1	9	Etched
Chicane dipole	3	17	Mesh
Quadrupole	1	12	Mesh
Wiggler	1	12	Etched, Mesh

2. Instrumentation

RFAs in each field region had to be specially designed to fit inside the narrow magnet apertures. A thorough account of the design and construction of these detectors can be found in [4]; here we provide an overview. The key parameters of each RFA type are listed in Table 2.

2.1. General Design Considerations

With the exception of the chicane dipole RFAs, which were designed at SLAC [11], the detectors detailed below shared several design features:

- A 3:1 depth to diameter ratio was chosen for the vacuum chamber holes, to shield the detectors from direct beam signal.
- Because of the narrow apertures available inside the CESR magnets, only a single retarding grid was used, with the vacuum chamber serving as ground.
- The electron collector pads were laid out on copper-clad Kapton sheet using standard printed circuit board fabrication techniques.

Two different styles of retarding grid were used in the CESR RFAs (Table 3). The first type was made of photo-chemically etched 0.15 mm-thick stainless steel (SST), with an optical transparency of approximately 38%. The grid holes have a bi-conical structure, with 0.18 mm diameter and 0.25 mm spacing. To reduce secondary emission, the grids were coated with approximately 0.3 μm of gold.

The second style of grids was made with electroformed copper meshes, consisting of 15 μm wide and 13 μm thick wires with 0.34 mm spacing in both

Table 3: Grid types used in CESR RFAs. Note that “transparency” refers to the optical transparency.

Type	Transparency	Material	Thickness
Etched	38%	Gold coated SST	150 μm
Mesh	92%	Gold coated Cu	13 μm

transverse dimensions. They have an optical transparency of approximately 92%. The meshes were also coated with gold ($\sim 0.3 \mu\text{m}$) via electroplating. Both grid styles were used in the wiggler RFAs; Section 2.5 below discusses the merits of each style.

2.2. CESR Dipole RFA

This RFA style was specifically designed for use inside the 12W CESR dipole, with only 3 mm available between the magnet and beam aperture. As shown in Fig. 4, the RFA housing is machined from a separate block of 6061 aluminum welded to the cutout on top of the beam pipe. The lower face of the RFA housing matches the curvature of the beam pipe aperture, while the upper face is divided into three flat sections, with each section tilted so that the wall thickness is similar. There are three collectors in each section, for a total of nine. Each section has a single retarding grid, made of etched stainless steel. Arrays of 0.75 mm holes were drilled through the 2.5 mm thick beam pipe wall (maintaining the $\sim 3:1$ ratio described above). There are 44 holes per collector. This style of RFA was also deployed in a field free region [5].

2.3. Chicane Dipole RFAs

The design of the 4 dipoles of the SLAC chicane is shown in Fig. 5. The chicane beam pipe is partitioned into 4 vacuum chambers for testing different electron cloud mitigation techniques. One chamber is bare aluminum, two are TiN coated, and one is both grooved and TiN coated. The grooves are triangular with a depth of 5.6 mm and an angle of 20° . Each test chamber is equipped with an RFA and is surrounded by a chicane magnet.

Figure 6 shows the structure of the chicane RFAs. Because there was no aperture limitation for these magnets, the RFAs were designed with three (high

Figure 4: RFA design detail for a CESR dipole chamber.

150 efficiency) grids, with a generous 5 mm spacing between each grid. The retarding
 151 voltage is applied to the middle grid. The field of the chicane dipoles can be
 152 varied from 0 to 1.46 kG, though most of our measurements were done in a
 153 nominal dipole field of 810 gauss.

154 2.4. Quadrupole Instrumentation

155 The design of the quadrupole RFA beam pipe is illustrated in Figure 7. This
 156 detector follows the curvature of the circular beam pipe, covering 78° , including
 157 one of the quad pole tips. There are 1740 beam pipe holes, which are grouped
 158 into 12 angular segments, matching the 12 RFA collector elements on the flexible
 159 circuit. The beam-pipe-quadrupole assembly and angular coverage of the RFA
 160 are shown in Figure 8.

161 2.5. Wiggler Instrumentation

162 Three of the L0 wigglers (Section 1.2.3) were equipped with RFAs. Each
 163 instrumented wiggler has three detectors: one in the center of a wiggler pole
 164 (where the field is mostly transverse), one in between poles (where the field
 165 is mostly longitudinal), and one in an intermediate region (where the field is

Figure 5: PEP-II 4-dipole magnet chicane and RFA-equipped vacuum chambers. Top: top view. Bottom: side view.

Figure 6: Four RFAs were welded onto the chicane beam pipes. Left: Cross-sectional view. Right: photograph of the assembled RFA in its aluminum housing.

Figure 7: Exploded view of the structure of the RFA within a CESR quadrupole beam pipe. Major components include: (1) Aluminum beam pipe with cooling channels; (2) RFA housing and wiring channels; (3) Retarding grids, consisting of high-transparency gold-coated meshes; (4) RFA collector flexible circuit; (5) Stainless steel backing plate; (6) Wire clamps; (7) RFA vacuum cover with connection port; (8) Electric feedthrough.

Figure 8: Left: Quadrupole with RFA beam pipe (left). Right: RFA angular coverage.

manifestly three dimensional, see Fig. 9). The RFAs each have one retarding grid and twelve collectors; there are 240 beam pipe holes per detector.

The design of the wiggler RFAs was especially challenging. An exploded view of the wiggler RFA beam pipe assembly is shown in Fig. 10. Because the collector flexible circuit has a temperature rating of 220° C, all the welding near the RFA had to be completed prior to the installation of the collector. To allow for this requirement, a “duck-under” channel was created beneath the stainless steel flexible disk, which was later welded to the wiggler insulation vacuum vessel. After all welding was complete (except for the final RFA vacuum cover), the collector flexible circuit was fed through the “duck-under” channel to the RFA portion of the beam pipe. The construction of these chambers was done in collaboration with LBNL and KEK, and is described in more detail in [4] (Section 2.2.3.3).

The first generation wiggler RFAs were equipped with low-transparency stainless steel grids (see Table 3). However, as described in Section 3.3.3, secondary emission from these grids lead to a significant interaction between the electron cloud and the RFA, complicating the interpretation of the measurements. Consequently, in the second generation of wiggler chambers, the grids were changed to high-transparency copper meshes.

The use of high efficiency grids effectively solved the grid emission problem. However, in one of the RFAs (in the longitudinal field of the grooved chamber) the grid shorted to one of the collectors, preventing us from performing voltage scans with this detector. Instead, we modified the electronics board so that the grid was powered by the collector power supply, to allow for passive data collection with the RFA.

Over the course of the CESR-TA program, four different RFA-instrumented wiggler beam pipes have been constructed, each incorporating a different electron cloud mitigation mechanism. The first two chambers, installed in fall 2008, were bare Cu and TiN coated Cu. The TiN coating was applied (via DC sputtering) at SLAC. In summer 2009, a chamber with triangular grooves on the bottom was constructed. Finally, in 2010 we installed a chamber with a clear-

Figure 9: Three RFAs are built into each wiggler RFA beam pipe. A plot of the magnetic field along the wiggler (red line with blue dots) is superimposed on the drawing of the wiggler. The RFAs are located at three strategic locations.

Figure 10: Exploded view of a wiggler RFA beam pipe assembly. The key components are: (1) beam pipe top half, housing the RFAs; (2) RFA grids (see upper right inset); (3) RFA collector; (4) RFA connection port; (5) RFA vacuum cover; (6) Flexible disk, which attaches the beam pipe to the wiggler vacuum vessel. The “duck-under” channel, through which the kapton flexible circuit is fed after all heavy welding is complete, is shown in Detail B.

Table 4: Locations of instrumented wiggler chambers

Dates	1W	2WA	2WB
11/08 - 6/09	-	Cu	TiN
7/09 - 3/10	Cu	TiN	Grooves
4/10 - 12/10	Cu	TiN	Electrode
1/11 - present	Cu	Grooves+TiN	Electrode

ing electrode. Additional information about the grooved and clearing electrode wiggler chambers can be found in Appendix A.

These four chambers have been rotated through the three available locations in L0, to directly compare the effectiveness of each mitigation in identical photon environments and beam conditions. The locations are nicknamed “1W”, “2WA”, and “2WB” (ordered from upstream to downstream for the clockwise-travelling positron beam). Table 4 gives the location of each instrumented wiggler chamber throughout the CESRTA program. Note that in January 2011, the grooved chamber was coated with TiN, and installed at 2WA.

3. Measurements

Most of the data presented here are one of two types: “voltage scans,” in which the retarding voltage is varied (typically from +100 to −250 V or −400 V) while beam conditions are held constant, or “current scans,” in which the retarding grid is set to a positive voltage (typically +50 V), and data are passively collected while the beam current is increased. The collector was set to +100 V for all of our measurements, to capture any secondary electrons produced on it. The RFA signal is expressed in terms of current density in nA/mm², normalized to the geometric transparency of the RFA beam pipe and grids. In principle, this gives the time averaged electron current density incident on the beam pipe wall.

3.1. Dipole Measurements

Fig. 11 shows retarding voltage scans done with the CESR dipole RFA under standard CESRTA conditions, at two different beam energies. The beam condi-

Figure 11: CESR dipole RFA voltage scans: 1x45x1.25 mA e^+ , 14ns. Top: 2.1 GeV (790 gauss); Bottom: 5.3 GeV (2010 gauss). The central collector is no. 5, and the chamber is made of uncoated aluminum.

tions are given as “1x45x1.25 mA e^+ , 14 ns.” This notation, which will be used
 throughout this section, indicates one train of 45 bunches, with 1.25 mA/bunch
 (1 mA = 1.6×10^{10} particles), with positrons and 14 ns spacing. At both en-
 ergies, one can see a strong multipacting peak in the central collector, aligned
 with the horizontal position of the beam. This is where cloud electrons receive
 the strongest beam kicks, and generate the most secondaries. The measured
 energy distribution is qualitatively very different for the two beam energies, an
 effect which was not observed in other detectors. This discrepancy is due to the
 fact that the RFA efficiency depends on the magnetic field strength (which in
 turn depends on the beam energy in the CESR dipoles), as will be discussed in
 Section 3.1.2.

Figure 12: Chicane dipole RFA voltage scans: 1x45x1.25 mA e+, 14 ns, 5.3 GeV, 810 gauss. Top: Aluminum chamber; Bottom: TiN-coated chamber. The central collector is no. 9.

231 Voltage scans done under similar conditions in the chicane RFAs are shown
 232 in Fig. 12. In the aluminum chamber, we again observe a strong multipacting
 233 peak. However, in the TiN coated chamber, where the SEY is much lower, the
 234 peak is greatly suppressed, and the overall signal is much lower. The variation
 235 in signal across the collectors in this measurement is most likely due to an
 236 azimuthal variation in the photon flux.

237 3.1.1. Bifurcation of Central Peak

238 For high bunch currents, we have observed a bifurcation of the central mul-
 239 tipacting peak into two peaks with a dip in the middle. This is demonstrated in
 240 Fig 13, which shows the signal in the aluminum chamber chicane RFA vs beam
 241 current. Bifurcation occurs when the average energy of electrons in the center

Figure 13: Bifurcation of peak cloud density in a Al chicane dipole: 1x20 e+, 5.3 GeV, 14 ns.

of the beam pipe is higher than the peak energy of the SEY curve, so that the location of the effective maximum yield is actually off center [11]. The higher the bunch current, the further off center these peaks will be. Voltage scans done with high beam current (see Fig. 14), also clearly show this effect.

3.1.2. Dependence of RFA Signal on Dipole Field Strength

The strength of the magnetic field can have a significant effect on dipole RFA measurements. Fig. 15 shows a series of voltage scans performed with the aluminum chicane RFA, under the same beam conditions, with different dipole field values. In the TiN coated chamber, the signal increases with field strength. This is because as the field is increased, the cyclotron radius of the electrons becomes smaller, so they can more easily pass through the beam pipe holes. This results in a higher effective RFA efficiency [28]. The same effect is observed in the aluminum chamber at high retarding voltage. However, the total signal in the aluminum chamber actually decreases with field. At very high fields, the motion of the electrons becomes almost completely one dimensional, and the RFA begins to deplete the cloud directly under the beam pipe holes. This effectively makes the detector less sensitive to multipacting, since electrons will not be able to collide with the vacuum chamber multiple times before being absorbed.

Figure 14: Chicane RFA voltage scan at high beam current: 1x20x5 mA e+, 5.3 GeV, 14 ns. Bifurcation is clearly visible.

261 Notably, simulations indicate that the cloud development is almost com-
 262 pletely insensitive to field strength for the range of fields shown in Fig. 15.
 263 This means that the difference in RFA signal is purely a detector effect. More
 264 detailed simulations are required to confirm that the efficiency and depletion
 265 effects described above quantitatively explain what we measure.

266 3.2. Quadrupole Measurements

267 A typical quadrupole RFA measurement is shown in Fig. 16. We observe
 268 high current on the collector lined up with the quad pole tip (no. 10), and little
 269 current on the other collectors. This suggests that the majority of the cloud is
 270 streaming between the pole tips, guided by the quadrupole field lines.

271 One particular area of concern for quadrupole magnets is the potential for
 272 long term ($> 1 \mu\text{s}$) cloud trapping. Since the RFA provides a time integrated
 273 measurement, it is not ideally suited for addressing this question, though data
 274 taken as a function of bunch spacing is consistent with a long time scale for
 275 cloud development [29]. More direct evidence of quad trapping has come from
 276 measurements done with a time resolved electron cloud detector [30].

Figure 15: RFA voltage scans for different chicane field strengths. Top: TiN coated chamber. Bottom: bare Al chamber. Beam conditions are 1x20x2.8 mA e⁺, 14 ns, 5.3 GeV.

Figure 16: Quadrupole RFA voltage scan: 1x45x1.25 mA e⁺, 5.3 GeV, 14 ns.

277 3.3. Wiggler Measurements

278 Fig. 17 shows a typical voltage scan done in the center pole RFA (see Fig. 9)
279 of a Cu wiggler chamber, for a 45 bunch train of positrons at 1.25 mA/bunch,
280 14 ns spacing, and 2.1 GeV. The signal is fairly constant across all the collectors
281 at low retarding voltage, but does become peaked in the center at high volt-
282 age. There is also an anomalous spike in current at low (but nonzero) retarding
283 voltage. Since the RFA should simply be collecting all electrons with an energy
284 more than the magnitude of the retarding voltage, the signal should be a mono-
285 tonically decreasing function of the voltage. So the RFA is not behaving simply
286 as a passive monitor. This effect is discussed in detail in Section 3.3.3)

287 A voltage scan done in the intermediate field RFA under the same beam
288 conditions is shown in Fig. 18. Typical of measurements with this detector, we
289 observe complex (and unphysical) behavior as a function of retarding voltage.
290 These measurements are not currently well understood. Modeling of cloud de-
291 velopment at this location (requiring a fully three dimensional simulation) is a
292 potential future area of research.

293 During normal wiggler operation, no signal was ever observed in the RFAs
294 located in the longitudinal field region. This means that no electrons in the
295 cloud had sufficient transverse energy to cross the longitudinal field lines and
296 reach the vacuum chamber wall. Fig. 19 shows the signal in a longitudinal field
297 RFA (in the uncoated copper wiggler), as a function of magnetic field strength.
298 The signal is effectively gone by 1000 gauss, well below the 1.9 T full field value.
299 However, simulations have indicated that cloud could be trapped near the beam
300 at these locations [19].

301 3.3.1. Grooved Chamber Measurement

302 Fig. 20 shows an example voltage scan from the grooved chamber. The
303 width of the collectors (1.5 mm) is comparable to the distance between peaks of
304 the grooved surface (1 mm), so each collector will sample either two peaks, or
305 two valleys. Since the valleys are more effective at intercepting electrons than
306 the peaks, we observe alternating high and low signals in the collector currents.

Figure 17: Cu wiggler pole center RFA measurement: 1x45x1.25 mA e+, 2.1 GeV, 14 ns.

Figure 18: Cu wiggler intermediate field RFA measurement: 1x45x1.25 mA e+, 2.1 GeV, 14 ns.

Figure 19: Cu wiggler longitudinal field RFA signal as a function of wiggler strength: 1x45x.75 mA e+, 2.1 GeV, 14 ns.

307 Note that this implies that the effective SEY of the grooves varies significantly
 308 across the chamber.

309 3.3.2. *Clearing Electrode Scan*

310 Fig. 21 shows the result of varying the clearing electrode voltage on the
 311 center pole RFA. The signal is reduced by an order of magnitude with only
 312 +50 V on the electrode, and continues to decrease with higher voltage. Using a
 313 negative voltage actually slightly increases the RFA signal, because the electric
 314 field is pushing electrons into the RFA.

315 3.3.3. *Anomalous Enhancement*

316 As described in Section 3.1.2, dipole field strength can have a significant
 317 effect on the RFA efficiency. At very strong fields, unphysical features begin
 318 to appear in the data, due to an interaction between the RFA and the cloud it
 319 is measuring. One example of such an interaction can be seen in the top plot
 320 of Fig. 22. It shows a voltage scan done with an RFA in the center pole of a
 321 wiggler (in effect a 1.9 T dipole field). Here one can see a clear enhancement in
 322 the signal at low (but nonzero) retarding voltage. The spike in collector current
 323 is accompanied by a corresponding dip in the grid current, suggesting that the
 324 grid is the source of the extra collector signal.

Figure 20: Grooved wiggler pole center RFA measurement: 1x45x1.25 mA e+, 2.1 GeV, 14 ns.

Figure 21: Clearing electrode scan: 1x45x1 mA e+, 2.1 GeV, 14 ns.

Figure 22: Top: Anomalous enhancement in center pole wiggler data. Bottom: The adjacent wiggler chamber, with high transparency grid, does not show this effect. Beam conditions are 45 bunches, 1.25 mA/bunch, e+, 2.1 GeV, 14 ns. Note that there are 12 collectors, so collector 6 is one of the central ones.

More detailed analysis [31, 32] has shown that the enhancement is caused by a resonance between the bunch spacing and retarding voltage, enabled by the fact that the electron motion is essentially one dimensional. In short, secondary electrons produced on the grid will be accelerated by the retarding voltage, out the same beam pipe hole the original electron entered. If the secondary electron is near the center of the chamber during a bunch passage, it will receive a large beam kick, resulting in a high SEY. Thus an artificial resonance between retarding voltage and bunch spacing is created.

At high beam currents, this effect can become quite significant. However, it was effectively cured by switching to a high efficiency retarding grid in later wiggler chambers (see Fig. 22, bottom).

4. Mitigation Comparisons

Several different electron cloud mitigation techniques have been tested at CESR-TA, in dipole, quadrupole, and wiggler environments. The results shown in this section represent the state of the chambers after beam conditioning (see [33–35] for a discussion of this effect).

4.1. Dipole Mitigations

Fig. 23 shows a current scan comparison between three of the chicane RFAs. We observe a large difference between uncoated and coated chambers. At high beam current, the TiN coated chamber shows a signal smaller by two orders of magnitude than the bare Al chamber, while the coated and grooved chamber performs better still.

A similar comparison, done with an electron beam, is shown in Fig. 24. Here we observe a threshold current, at which the aluminum chamber signal “turns on,” and shows a dramatic increase with current. This threshold occurs when the kick from the electron beam on low energy cloud particles near the vacuum chamber (which drives them back into the wall) is strong enough to result in significant secondary emission. The threshold is not observed in any of the chambers with mitigation, where the secondary emission yield is below unity even at high incident energies.

Figure 23: Dipole RFA mitigation comparison, 1x20 e+, 5.3 GeV, 14 ns, 810 gauss.

Figure 24: Dipole RFA mitigation comparison, 1x20 e-, 5.3 GeV, 14 ns, 810 gauss.

Figure 25: Quadrupole mitigation comparison, 1x20 e+, 5.3 GeV, 14 ns.

4.2. Quadrupole Mitigation

Fig. 25 shows a comparison of a bare aluminum quadrupole chamber with the TiN-coated chamber that replaced it. The effect of the TiN coating was to reduce the electron cloud signal by well over an order of magnitude.

4.3. Wiggler Mitigations

As described in Section 2.5, cycling the location of the different wigglers has allowed us to compare the RFA response with different mitigation techniques at the same longitudinal position in the ring. Fig. 26 compares the average collector current (in the center pole RFA) vs beam current for different mitigation schemes, at both the 2WA and 2WB locations. These locations have slightly different photon fluxes, but as the TiN coated chamber has been installed in both, it can be used (roughly) as a reference. Note that TiN coating by itself does not appear to lead to a reduction in the wiggler RFA current relative to bare copper. This may be due to a reduced sensitivity to SEY at high field, as explained in Section 3.1.2.

Grooves do lead to an improvement, and TiN coated grooves are better still. The chamber instrumented with a clearing electrode shows the smallest signal by a wide margin, improving on TiN by approximately a factor of 50. The electrode was set to 400 V for this measurement. Note that, while TiN is used primarily to reduce secondary emission, both grooves and electrodes will work

Figure 26: Wiggler RFA mitigation comparison: 1×45 e+, 2.1 GeV, 14 ns. Top: 2WA location, bottom: 2WB location. The 2WB location is further downstream in the wiggler straight, and therefore has a slightly higher photon flux.

375 equally well on primary and secondary electrons. This is important for regions
 376 that see a large amount of synchrotron radiation, such as a wiggler straight.

377 5. Conclusions

378 Retarding field analyzers have been installed throughout the CESR ring, in
 379 dipole, quadrupole, and wiggler field regions. Each location presented unique
 380 design challenges. In particular, designing detectors which fit inside the narrow
 381 magnet apertures was non-trivial.

382 A large quantity of electron cloud data has been collected at each location.
 383 To summarize:

- 384 • Dipole data shows a strong multipacting peak aligned with the beam,

385 where secondary emission is highest. At high beam currents, this peak
386 bifurcates into two.

- 387 • The quadrupole data is strongly peaked in the collector aligned with the
388 pole tip, where electrons are guided by the quad field lines.
- 389 • The center-pole wiggler data shows an anomalous peak at nonzero retard-
390 ing voltage, caused by secondary emission from the retarding grid. This
391 problem was solved by using a high efficiency grid.

392 Several different cloud mitigation schemes have been tested. We observe
393 that:

- 394 • TiN coating is effective at suppressing cloud growth in a dipole field. TiN
395 coated grooves show even better suppression.
- 396 • TiN coating is also effective in a quadrupole.
- 397 • In a wiggler, the clearing electrode chamber showed the lowest electron
398 cloud signal.

399 In general, we have found that the cloud dynamics, most effective mitigation,
400 and limitations of our detectors all depend on the type and strength of the local
401 magnetic field. Our results have been incorporated into the proposal for the ILC
402 damping ring [36]; we expect that they will also be of use in other accelerators.

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415 **Appendix A. Wiggler Mitigation Details**

416 *Appendix A.1. Grooved Chamber*

417 Using grooved surfaces to lower effective SEY is a well-known [13, 24–26]
418 passive technique to suppress electron cloud growth in a magnetic field. We
419 studied the effects of grooved chambers by constructing an RFA-equipped wig-
420 gler chamber with a grooved insert installed on the bottom surface, as shown in
421 Fig. A.27.

422 The implementation of a grooved surface in a copper vacuum chamber was
423 found to be quite challenging. First, it was determined (through test machining)
424 that the copper extrusions used for the wiggler beam pipe were fully annealed,
425 and too soft for machining the tiny groove geometry. Thus the grooves were ma-
426 chined in a separate copper plate of full-hard temper, which was electron-beam
427 welded into the vacuum chamber. Additionally, it was too costly to machine
428 grooves for the entire length of the chamber. Thus, for the experimental tests,
429 a grooved plate of sufficient length to span the RFAs was used.

430 The geometry and dimensions of the grooves are shown in Figure A.27,
431 Detail F. Cuts at a 30° angle were made on both ends of the groove plate and
432 on the beam pipe wall (shown in Detail D), which provide a smooth transition
433 from the flat surface to the triangular groove tips in order to minimize higher
434 order mode loss (HOML).

435 The triangular grooves were made with a milling technique using specially
436 designed cutters. A small radius of the tips and valleys are desirable for max-
437 imum suppression of secondary emission [24]. We found that we could achieve
438 tip and valley radii of approximately $25\ \mu\text{m}$ and $60\ \mu\text{m}$ respectively, which was
439 satisfactory for our purposes.

440 The wiggler beam pipe assembly, containing the grooves and their asso-
441 ciated RFAs, was successfully operated from July 2009 through March 2010,

Figure A.27: Wiggler RFA beam pipe with a groove plate welded to the bottom beam pipe.

442 accumulating total beam doses of approximately 940 Amp·hr. After removal,
 443 the grooves were inspected for damage (from over-heating), but none was found.
 444 The chamber was then TiN coated, and re-installed in L0. The TiN deposition
 445 was undertaken in two stages, with the titanium cathodes shifted transversely
 446 to minimize the geometric shadowing of the steep grooves. The estimated TiN
 447 film thickness was 150 to 500 nm, based on the on-line measurements of a
 448 QCM (Quartz Crystal Micro-balance) and the off-line measurements of witness
 449 coupons. Close-up optical inspection of the grooves was done after the TiN coat-
 450 ing. Figure A.28 shows typical inspection images of a portion of the grooves
 451 before and after the TiN coating. Although the camera did not possess sufficient
 452 acuity to resolve the fine features of the sharp tips/troughs, no obvious signs
 453 of over-heating or damage to the grooves were visible. The image also showed
 454 relatively uniform TiN coating, with no significant shadowing within the groove
 455 troughs.

456 *Appendix A.2. Clearing Electrode*

457 In April 2010, a clearing electrode, shown in Fig. A.29, was installed on the
 458 bottom of an RFA-equipped wiggler chamber. The structure of the electrode

Figure A.28: The grooves of the wiggler beam pipe were inspected optically. Left: Before TiN coating; Right: After TiN coating.

Figure A.29: Photograph of the clearing electrode and contact button in the wiggler beam pipe.

equipped chamber is diagrammed in Figure A.30.

The clearing electrode forms a thin stripline, consisting of an insulating alumina layer (~ 0.2 mm thick) deposited on the copper beam chamber, and a conducting layer of tungsten (~ 0.1 mm thick, deposited on the alumina) as the electrode. The area of the alumina ceramic layer was larger than that of the electrode, so that the required DC voltage could be applied to the electrode in vacuum. These two layers were deposited via a thermal spray technique developed at KEK [12], and were tightly bonded to the copper chamber. Tungsten was chosen as the electrode material owing to its good thermal and electrical

468 properties, in particular its small thermal expansion rate. The insulation resis-
469 tance between the electrode and the copper chamber was about 5 M Ω (in dry
470 air), and the electrode is capable of withholding DC voltages above 1 kV.

471 The clearing electrode has a width of 40 mm, and extends for 1.09 m
472 along the bottom of the vacuum chamber. To minimize higher order mode
473 loss (HOML), the ends of the electrode are tapered at a 42° angle down to a
474 3 mm radius at its tip. The high voltage (HV) connection is made by a coaxial
475 line coming through a port located underneath one of the tapered ends of the
476 electrode. The electrical connection is made via a convex button washer (with
477 26 mm diameter) on the top of the electrode, as shown in Figure A.30. The con-
478 nection was designed to make the inner surface (visible to the beam) as smooth
479 as possible, while keeping a secure electrical contact. Although the effects of
480 the low profile of the discontinuity, the tapered ends of the electrode and the
481 hidden HV connection have not been calculated in detail, they are expected to
482 produce a HOML parameter of less than a few times 0.001 V/pC for the 7 to
483 10 mm bunch length of CESR. Any heating from the wall currents flowing on
484 the surface of the electrode is easily handled by conduction to the beam pipe
485 through the thin alumina dielectric layer, which has good thermal conductivity.
486 Thermocouples mounted on the bottom beam pipe near the electrode assembly
487 have detected no increase in heating due to HOML during operations. A de-
488 tailed account of the impedance characteristics of the clearing electrode is given
489 in [4].

490 The clearing electrode was operated from April to December 2010, accu-
491 mulating a beam dose in excess of 1000 Amp·hr. In January 2011, a visual
492 inspection of the electrode and the electrical contacts was done. Both were
493 found to be in excellent condition with no sign of arcing or overheating. The
494 electrode chamber has remained in CESR for three years since then, with no
495 noticeable degradation of performance.

Figure A.30: Wiggler RFA beam pipe with clearing electrode assembly. Top: sectional view of the clearing electrode as seen from above. Bottom left: sectional view of the clearing electrode and the HV input port. Bottom middle: detail of HV port. Bottom right: exploded view of HV port; electrical contact is made with a vented screw (1), an aluminum alloy button (2), insulation spacers made of PEEK (3A, 3B), a stainless steel spring washer (4), and a tapered copper pin (5).

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