SUPPRESSING ELECTRON CLOUD IN FUTURE LINEAR COLLIDERS*

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Abstract

Any accelerator circulating positively charged beams can suffer from a build-up of an electron cloud (EC) in the beam pipe. The cloud develops through ionization of residual gases, synchrotron radiation and secondary electron emission and, when severe, can cause instability, emittance blow-up or loss of the circulating beam. The electron cloud is potentially a luminosity limiting effect for both the Large Hadron Collider (LHC) and the International Linear Collider (ILC). For the ILC positron damping ring, the development of the electron cloud must be suppressed. This paper discusses the state-of-the-art of the ongoing SLAC and international R&D program to study potential remedies.

INTRODUCTION

Beam-induced multipacting, which is driven by the electric field of successive positively charged bunches, arises from a resonant motion of electrons that have been initially generated by photons, by gas ionization, or by secondary electron emission from the vacuum chamber wall. These electrons are occasionally getting kicked by the circulating beam to the opposite wall, thence producing secondary electrons. The electron cloud density depends on characteristics of the circulating beam (bunch length, charge and spacing) and the secondary electron yield of the wall from which the electrons are generated. The space charge from the cloud, if sufficiently large, can lead to beam instability and losses ultimately causing a reduction in the collider luminosity. The electron cloud effect has been observed at many storage rings [1] and it is an issue for future machines aiming at higher beam intensity.

The damping rings (DRs) design options for the International Linear Collider have a circumference of 17 km, 6 km or 3 km. A reduction in circumference will increase the average current, which could make electron cloud effects more severe.

LINEAR COLLIDER DESIGN

Damping Rings

Damping rings are necessary to reduce the emittances produced by the particle sources to the small values required for the linear collider. A summary of the main parameters of the damping ring is given in Table 1. A conceptual layout of the ILC positron damping ring [2] is shown in Fig.1, with the long straight section, injection/ejection sections, wigglers, and RF placed in the main linac tunnel. Actually, the 17km DR main damping ring stores 2820 bunches with a 20 ns bunch spacing.

Table 1: Parameters for possible ILC damping rings. Beam sizes are shown for the arcs.

Circumference [m]	17000	6114	3067
Energy [GeV]	5.0	5.0	5.0
Bunch charge [10^{10}]	2.0	2.0	2.0
Bunch spacing, ns	20	6	3.6
Beam sizes $\sigma_{x,y}$ [μm]	103, 7.3	98, 6.8	76, 5.5
Bunch length [mm]	6.0	6.0	6.0
Energy spread [10^{-3}]	1.3	1.5	1.2
Synchrotron Tune	0.07	0.034	0.026
Vacuum beam mater.	Al	Al	Al
Arc pipe sizes, [mm]	22x18	--	--

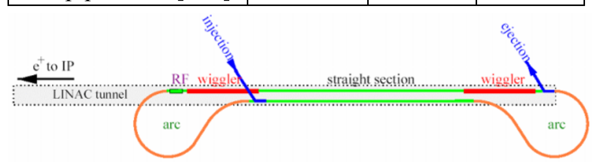

Figure 1. ILC 17 km "dogbone" DR layout and electron cloud levels colour code.

The DR vacuum chambers are in aluminum.

SECONDARY ELECTRON YIELD SEY

Parameters determining the cloud formation are the secondary electron yield (SEY or δ), which is the number of secondary electrons generated per incident electron, and the energy spectrum of the secondary emitted electrons. Typically a peak SEY value is δ_{max}~3 for an as received aluminum etched material, see Fig. 2. An electron reflectivity at low electron energy is assumed to be ~50%, or δ(0)=0.5 in simulations.

The SEY of technical surfaces has been measured in the past at SLAC [3,4], at CERN [5,6,7] at KEK [8] and in other laboratories [9,10,11,12,13,14]. Technical surfaces have an SEY higher than the pure material because they are oxidized. The SEY model used for the simulations is shown in Fig. 3.

SEY Threshold and Requirements

In the arcs and wigglers sections of all the DR options an electron cloud is expected with a high density even at low SEY values listed in Table 2 and 3 and 4 and shown in Fig.4. An electron cloud in the long straight sections can be prevented with a surface peak SEY below 1.9 [15,16,17], which is a safe margin provided a good coating.

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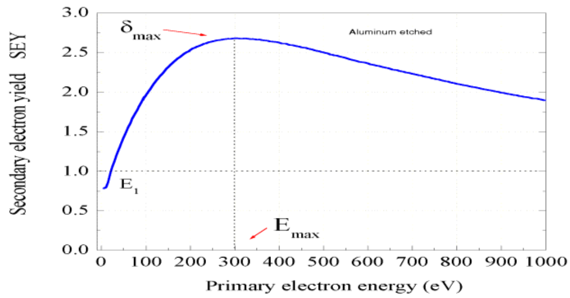

Figure 2. Typical SEY for as-received Al etched.

Simulations also show that ionisation of residual gases is not sufficient to trigger an electron cloud in the Low Emittance Transport (LET) lines to the IP due to the large 337ns and 176ns bunch spacing. Nonetheless, photoelectrons still need to be included in simulations for the LET and further investigations are needed.

Table 2: SEY (δ_{max}) thresholds for the electron cloud development in the ILC damping rings from simulations with an increased chambers size with radius=22mm.

params	17 km	6 km	3 km
Long straight sec.	1.9-2.0	n.y.	n.y.
Arcs bends w antech.	1.3	1.1	1
Wiggler sections	1.3	n.y.	n.y.

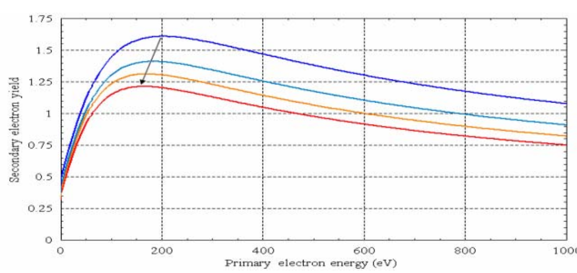

Figure 3. SEY model used in the simulations. Note the shift of the energy at which the peak occur with SEY, similar to conditioning measured in accelerator *in situ* [18].

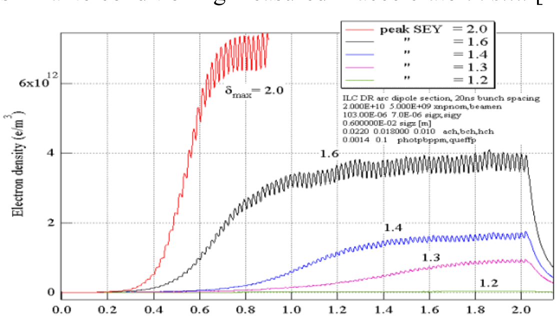

Figure 4. Evolution of the cloud density [m^{-3}] in arc bends with an antechambers design. Threshold is for δ_{max}~1.3.

SINGLE-BUNCH INSTABILITY

If the electron cloud density ρ_e exceeds a certain threshold a head-tail instability may induce beam blow-up and losses eventually reducing the collider luminosity.

We computed the single-bunch instability cloud density thresholds for the different DR options, see Table 3 and

Table 3: Neutralization levels and single-bunch instability electron cloud density thresholds for various DR options.

Circumference	17 km	6 km	3 km
Neutralization ρ_e [10^{12} m^{-3}]	0.8	6.0	15
Simulated ρ_e in arcs δ_{max}=1.4	0.4	8.0	17
SB: ρ_e threshold [10^{12} m^{-3}]	0.2	1.0	3.0
Neutral. / SB threshold	4.0	6.0	5.0

ref. [19]. The cloud density thresholds for the instability are a factor ~5 below the neutralization levels.

SEY EXPERIMENTAL SETUP

At SLAC, a dedicated laboratory system is setup to measure the SEY of vacuum chamber materials. The system used to measure SEY at SLAC as shown in Fig. 5. Details on the experimental system and methodology can be found in [4]. Other laboratory systems at CERN, KEK, and Frascati [6,8,14] differ slightly in the measurement setup but are based on the similar following concept.

The measurement chamber has two electron guns and a soft X-ray source. One electron gun (energy, 1-3 keV) is used for SEY and SEM, and the other is a "flood" gun for electron conditioning. The SEY (δ) is defined by

$$\delta = 1 - I_T/I_p \qquad (1)$$

where I_p is the primary electron current and I_T is the total current measured on the sample ($I_T = I_p - I_{SE}$). I_{SE} is the secondary electron current leaving the sample target.
The SEY curves were obtained with a primary electron beam impinging at 23° from normal incidence or at 0° normal incidence.

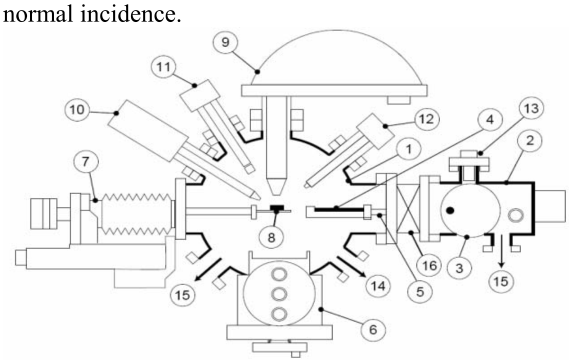

Figure 5. SEY experimental setup, SLAC [21].

R&D EFFORT TO REDUCE THE SEY

Why Not Just Aluminum?

As-received aluminum has a high SEY as shown in Fig. 2 and conditioning by electron bombardment, is not completely effective as shown Fig. 6. Measurements performed at SLAC and CERN confirm that the electron conditioning effect on aluminum reduces the SEY down to not lower than δ_{max}~2, as needed [20, 21]. Thus,

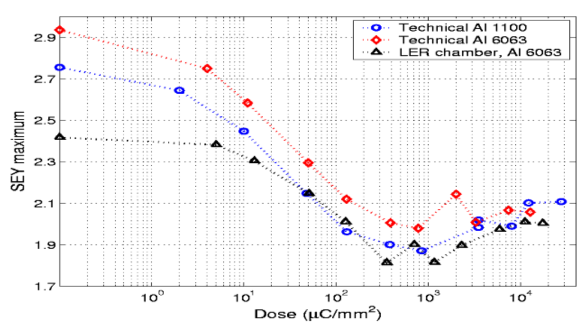

Figure 6. Electron conditioning effect on the SEY for aluminium, SLAC. The electron conditioning is not sufficient to lower the aluminum SEY as needed [21].

Aluminum is not attractive as a vacuum chamber material to avoid electron cloud in particle accelerators.

Drastic Reduction of the SEY: Grooved Surface

A metal surface with a new specially designed grooved profile [22, 23] is under study. Such a surface is expected to reduce the escape probability of secondary emitted electrons, reducing considerably the effective SEY. Simulations estimates show a reduction of the secondary yield by a factor of 2.

Copper and aluminum samples with triangular and rectangular grooved surface profile have been fabricated to test the SEY reduction indicated by simulations. Measurements of triangular grooved samples show a good reduction of the secondary electron yield of ~30% [4,21].

Very promising results come from the rectangular groove concept as shown in Fig. 7 and 8 with an effective peak SEY δ_{max}~0.65 to be compared to the flat smooth surface of the sample at δ_{max}=1.65. These measurements were performed in a field free region.

Following these highly promising results, we are planning to install a 6 m long section to test the groove concept with dedicated chambers equipped with proper electron diagnostics [24] in the PEP-II Low Energy Ring (LER) accelerator.

Since the electron cloud is an issue mainly in dipoles and wiggler sections of the ILC DR, we performed a simulation of the possible trapping due to a triangular or rectangular groove profile.

The dynamics of a 300 eV electron in the 0.19 T vertical magnetic field of the 17 km DR arc bend is shown in Fig. 9. The groove spacing and height is choosen to be comparable with the Larmor radius of a 200 eV electron, energy corresponding to the SEY peak for a smooth surface. The SEY of a rectangular groove compared with a smooth surface is shown in Fig. 10. In this particular set of simulations, we assumed a groove period and depth of 0.25 mm and groove width of 0.025 mm. For this first set of simulations, we also assumed that electrons have equal energy in the three directions of motion.

Triangular grooves are not as effective in dipole field [23].

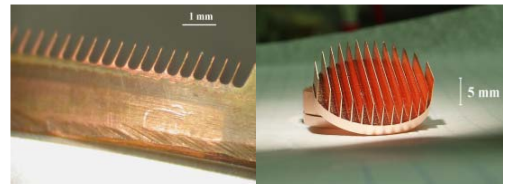

Figure 7. Samples with two different rectangular groove profiles, 1 mm or 5mm depth.

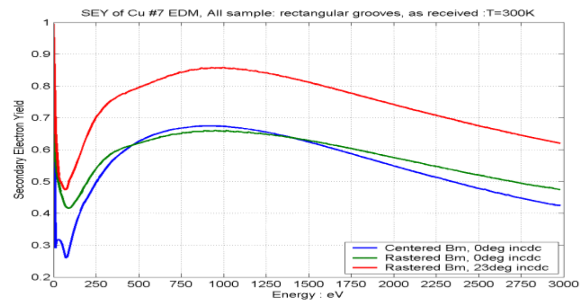

Figure 8. Measured SEY for a rectangular groove Cu sample at different angles. The smooth part of the sample has a δ_{max}=1.65.

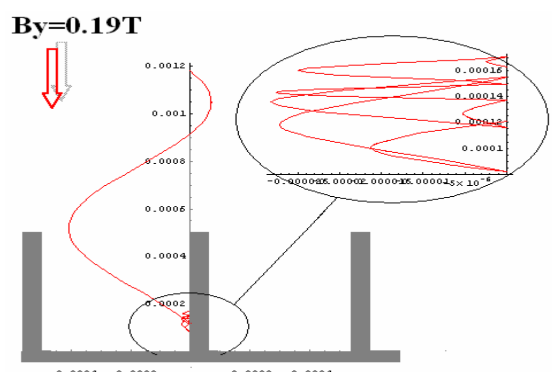

Figure 9. Electron dynamics in proximity of a rectangular groove surface in the presence of a dipole magnetic field. The electron is absorbed.

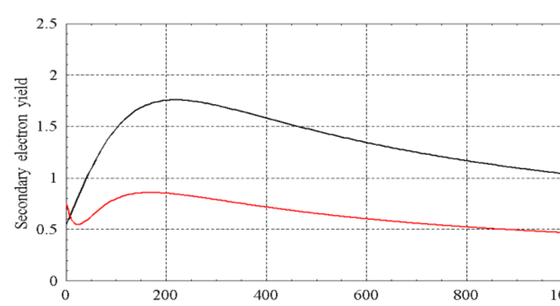

Figure 10. Simulated SEY for a smooth (above) and for a rectangular grooved surface (below) in a dipole field.

An irregular surface may excite wake fields during the passage of the bunch.

Simulation results using MAFIA [25] indicate that wake fields are not excited during the beam passage. Very small losses come from the step transition from the

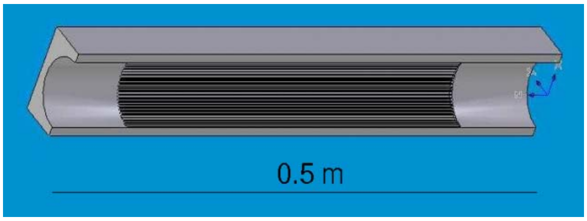

Figure 11. Modelling of a chamber with groove profile for wake field simulations with MAFIA [25].

smooth surface to grooved surface with loss factor estimated at 1.5E-04 V/pC.

RESULTS: THIN FILM COATINGS

Electron Conditioning, Bake and Related Evolution of the SEY

TiN coating is commonly used to mitigate multipacting in accelerator and storage ring structures. The SEY of as received TiN may vary between 1.5 to 2.5 [3,4]. Electron bombardment or conditioning is effective to reduce the SEY of thin film coating surfaces as shown in Fig.12.

These results are in agreement with data obtained elsewhere at other energies [26], and thus within this energy range, there is a weak dependence with the conditioning electron beam energy.

Electron conditioning may be explained by the electron stimulated desorption removal of oxides and hydroxides from the surface and by a carbon layer increase at the electron impinging location, this latter was confirmed by independent laboratory measurements [8,27].

An alternative SEY-reducing coating to TiN is sputter-deposited TiZrV non-evaporable getters (NEG). NEG, when activated shows a drastic reduction of its SEY, refs. [4,7]. The initial δmax, as received, is 2 and decreased upon activation to 1.2.

It is also interesting to follow the behaviour of the SEY curves when the sample is exposed to a residual gas background in the high 10^{-10} Torr scale for an extended period of time. The SEY of the previously conditioned surface increases to higher SEY values with time, as shown in the bottom Fig.12.

In the CERN-LHC, an experiment was carried out at the Super Proton Synchrotron (SPS), where a section of the machine was replaced with a TiZrV NEG-coated chamber [28]. After cycles of activation and saturations, no EC developed, suggesting that the SEY should be <1.4.

Questions about the durability of thin film coatings subject to electron, ion and photon bombardment during accelerator operations remains open and needs to be still answered.

REMEDY PERSPECTIVES

Electron conditioning of TiN and TiZrV/Al NEG is efficient at reducing the SEY of the surface below 1.2. These results are very encouraging for choosing thin film coatings as a solution for suppressing the EC. An additional advantage of the NEG is the pumping capability following its activation in a UHV system.

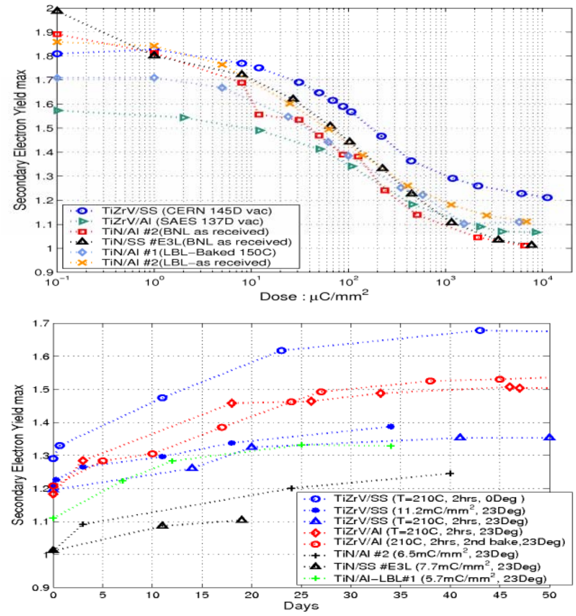

Figure 12. Electron conditioning (above) and SEY increase due to recontamination effect (below) of TiN and NEG thin film coatings.

Nevertheless, in an accelerator environment, the electron cloud itself is providing the necessary conditioning of the vacuum chamber walls. When the SEY decreases, the efficiency of the electron conditioning will decrease as well (fewer electrons, slower conditioning), reaching a limit where the recontamination from the accelerator vacuum dominates, thence making the EC re-appear.

In a dynamic vacuum, the contribution of photon [29] and ion conditioning could be the key to preventing the re-increase of the SEY. Coated samples will be arranged in a dedicated chamber located in a high synchrotron radiation region. This will also allow to studying the durability of thin film coatings in an actual accelerator environment.

In some locations, the as received SEY of TiN or TiZrV NEG will not be low enough for operation.

Combining a rectangular grooved surface with TiN or TiZrV coatings, could be a viable solution. Simulations show that a rectangular grooved surface is also effective in dipole magnetic fields. A grooved pattern increases the chamber exposed surface by a factor ~2 and an increase in residual gas pressure should be expected.

Grooved chambers will be installed in the straight sections in PEP-II.

Ion-conditioning is also under study. Solenoid can be applied in the magnetic free regions of a damping ring. Furthermore, simulations show that increasing the chamber aperture is beneficial in reducing the cloud density in the damping ring.

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Table 4 lists the electron cloud expectations in the DR and the actually suggested possible remedy.

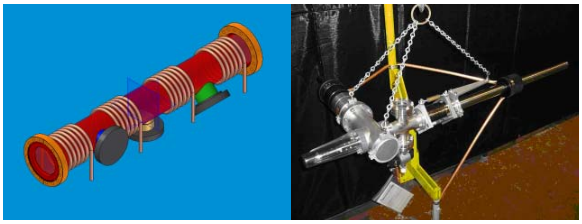

Figure 13. R&D program, SLAC. chambers with thin film coated samples installation in the PEP-II LER.

INTERNATIONAL EFFORT

The electron cloud is an issue for many different facilities and there is a broad international effort on simulations, beam measurements and finding mitigation strategies. SLAC, LBNL and KEK are collaborating with USC, CERN, DESY, Frascati and other laboratories. Status of the electron cloud R&D program for the Linear Collider in the different laboratories includes:

R&D at SLAC. Laboratory SEY measurements. Projects: installation in the PEP-II LER of chambers with rectangular grooved profiles, and chambers with thin film coated samples.

R&D at KEK. SEY laboratory measurements of electron conditioning and coatings studies. Installation of dedicated chambers and electron detectors in the KEKb positron ring.

R&D at CERN. A large number of electron detectors have been installed in quadrupoles, dipoles and field free regions of the SPS ring, the LHC pre-injector. Laboratory SEY measurements. R&D is focused on reducing the electron cloud effect in the LHC.

R&D at LANL. Electron trapping mechanism in quadrupole field and development of novel electron diagnostics.

R&D at Frascati. Lately, an electron cloud formation in Daϕne is suspected. Possibility of important measurements to localize the possible formation of electrons, in particular, in wiggler and dipole regions. Most of the ring is made of aluminum vacuum chambers.

CONCLUSIONS

The electron-cloud effects through the Damping Rings to the Interaction Point of the Linear Colliders have been evaluated. The build-up of the electron cloud will be prevented by treating the vacuum chambers and increasing the chamber radius. Investigations of surface treatments include: measurement of the secondary electron yield of TiN and TiZrV NEG thin film coatings, testing the effectiveness of electron or ion conditioning, fabrication of very promising specially grooved chamber surfaces and development of a novel TiCN alloy.

Demonstration chambers will be installed in PEP-II.

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Table 4: ILC 17 km DR. Electron cloud expectations and suggested possible remedy, assume aluminum chambers.

Sections	Electron cloud	Possible remedy
Arcs	Expected high	Coating + rect. groove
Wigglers	Expected high	Coating + rect. groove
Long straights	Preventable	Coating

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