Electron Cloud Modeling for CesrTA

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Plans for the conversion of the Cornell Electron Storage Ring (CESR) to a test accelerator (CesrTA) for the International Linear Collider damping rings have prompted a program of study attempting to characterize the electron cloud effect in CESR. This paper addresses the use of the ECLOUD simulation program for this purpose and provides some initial sets of input parameters that seem to fit experimental data.

I. INTRODUCTION

In recent years much work has been done on the design and planning of the International Linear Collider (ILC). As a lepton collider, the ILC will be able to explore with more clarity physics revealed by the Large Hadron Collider (LHC), up to center of mass energies of 0.5-1 TeV.

One of the limiting factors of the ILCs performance will be the ability of its damping rings (DR) to maintain stable operation at the emittance levels required for the ILC's desired luminosity. A key contributor to this limitation is the electron cloud effect (ECE), which is known to exist in high-intensity accelerators [1]. As bunches of particles pass through the ring they generate large numbers of electrons, which arise primarily from either photoelectron generation from synchrotron radiation or from ionization of the residual gas in the beam chamber. The cloud of electrons that forms may introduce several types of instabilities to the system, such as coupled-bunch instabilities or single bunch head-tail effects, and it may also interfere with beam diagnostics as an additional source of noise. The ECE is also an important contributor to emmitance blow-up in the damping rings, limiting the possible achievable luminosity.

Since the ECE is a limiting effect in the ILC's operation, it is a high priority to understand the parameters surrounding the build up and decay of the cloud, as well as to search for ways that may help to reduce its impact on diagnostic equipment and beam dynamics. It is for this end that it has been proposed that CESR be converted to a test accelerator (CesrTA) for the ILC's damping rings [2]. It is hoped that CesrTA can be used to investigate and characterize the ECE in conditions similar to the ILC DR, as well as look into ways to mitigate the effect. This paper is primarily concerned with determining the parameters that best characterize the ECE in the CESR environment.

II. ELECTRON CLOUD MEASUREMENTS IN CESR

In April of 2007, experiments were done in CESR to indirectly measure the buildup and decay of the electron cloud through beam position analysis [3]. One of the effects of the electron cloud is that it focuses the beam, causing a shift in the tune. Since this shift

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is proportional to the density of the electron cloud [8], a measurement of the tune-shift will indicate the strength of the EC present in the beam chamber. A 10-bunch train of positrons was run at an energy of 1.9 GeV with a bunch current of 0.75mA. The tunes of the individual bunches are calculated by fast Fourier transform of the beam's position over multiple turns, as measured by beam position monitors. Figure 1 shows the tune shifts of each bunch relative to the first bunch; the first ten bunches are the primary train and the following points are witness bunches, each stored and measured individually, trailing the train at various distances. The decay constant associated with the tune-shift, and likewise of the electron cloud as well, is approximately 170ns. Understanding the conditions behind this value is a major goal of this research, and it is this objective that is the principle subject of the following sections.

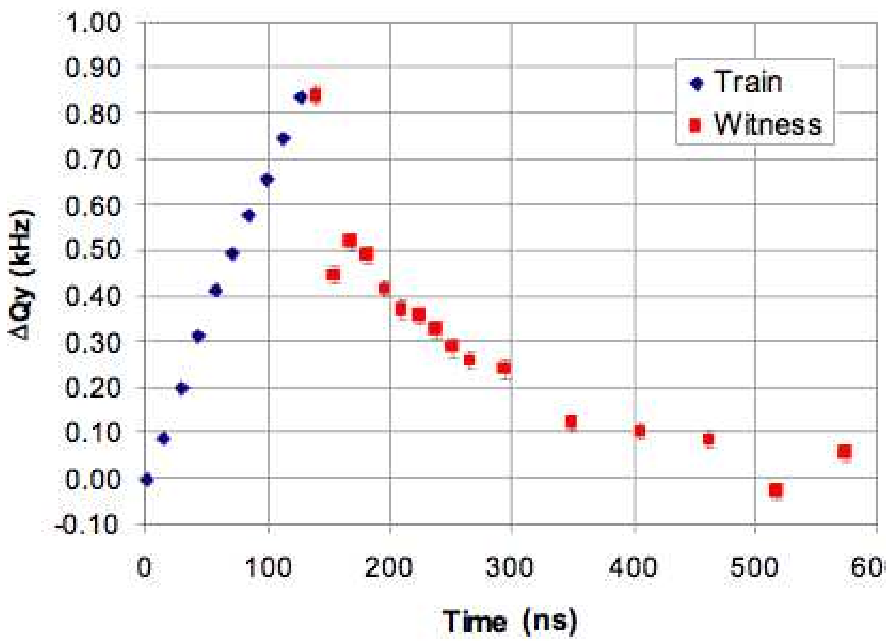

FIG. 1: Tune shift measurements (relative to the first bunch) of a 10 bunch train, with trailing witness bunches. Each witness bunch is the result of an individual measurement following the train. An exponential decay can be seen in the measurements of the witness bunches, and the time constant associated with this decay is approximately 170ns. [Image from Cornell Electron Cloud Group]

III. ECLOUD SIMULATION PROGRAM

The primary tool used to investigate the generation of the electron cloud was the simulation program ECLOUD, developed at CERN [4–7]. This program models the electron cloud as macro-particles, each of which may represent upwards of a million electrons, and it allows for the variation of a multitude of input parameters, only a few of which will be touched on here.

The majority of the parameters dealt with in this work concern the production of primary and secondary electrons at the beam walls, though ECLOUD also has the capability to simulate different beam configurations, i.e. bunch spacing, bunch current, beam size, etc. Though not discussed here, these values may be an important topic of future work.

One important input parameter of the ECLOUD program is the primary photoelectron emission yield (`peeff`, refers to the name of the variable within the program). This is the number of photons generated per bunch particle per meter multiplied by the yield of the beam pipe material. If a 2GeV beam generates 260 photons during one turn and the yield of the chamber walls is 0.1, then for CESR (which has a circumference of 768m) we can expect a value for `peeff` on the order of 0.03 photoelectrons per bunch particle per meter [8]. The simulations here assume a more conservative default value of 0.01. There are a number of other parameters governing the energy distribution of these photoelectrons, but these values were not investigated. A Gaussian distribution is used, with a peak at 7eV and a σ of 5eV.

Another parameter relevant to the generation of the photoelectrons is `refl`. Representing the reflectivity of the chamber wall, `refl` is the percentage of generated electrons that are distributed around the entire cross-sectional circumference of the beam pipe. The remainder of the electrons are created in a narrow strip along the outside wall of the chamber. For example, if `refl` is zero all photoelectrons will be generated on the outside wall, and none anywhere else. Since in a dipole chamber the motion of the electrons is heavily restricted to the vertical direction, this is an important parameter governing the overall distribution of the electron cloud in the beam pipe.

The secondary emission of electrons plays a key role in determining the lifetime of the cloud. The secondary emission yield, or how many secondaries are generated for an incident electron, is a function of incident electron energy (for more information on this function see Ref. [7]), and is handled through several parameters. One of these parameters is `yim`, which indicates the maximum value of the secondary emission yield. It occurs at some energy specified by `yemax`, and typical values for `yim` range from 1.0 - 3.0, depending on the material and treatment of the beam chamber. Typical values for `yemax` are from 150eV to 300eV [9].

The final important variables considered are `ibend`, a switch which chooses the type of magnetic field modeled, `bfield`, which sets the strength of the field, and `ibeam`, which turns on beam-cloud interaction.

The ECLOUD simulation was used to model a situation close to that described above (Fig. 1), in which 10 bunches travel with a beam energy of 2.085GeV and a bunch current of 1mA (1.5E10 particles per bunch).

IV. MODELING

A quantitative description of the simulation output was desired in order to better compare and contrast different situations, so an analytic model was introduced that describes the EC build up and decay. The idea behind the model is that of repeating steps and decays, and this gives an equation for the number density of the EC of the form

$$y(t) = \sum_{\nu=0}^{N_b-1} \Delta \cdot h(t - T\nu) \cdot e^{-\frac{t-T\nu}{\tau}} \tag{1}$$

where N_b represents the number of bunches in the train, T is the bunch spacing, $h(t)$ is the Heaviside step function, Δ represents the number of electrons added to the cloud by each bunch, and τ is the decay constant of the electron cloud.

Here it is assumed that each bunch contributes a *fixed* amount to the EC density, Δ, and that it decays away according to a *fixed* time constant, τ, also referred to as the lifetime of the cloud. The generation and dissipation of the electron cloud can then be described as a function of these two variables, Δ and τ.

With this analytic model we can assign numerical values to the ECLOUD simulations, i.e. the values of the parameters Δ and τ. In order to do this it is necessary to fit the model to the simulation output. Mathematical programming software was used for this purpose, and the method for doing this will be described here.

As part of its output, ECLOUD creates a data file containing the number density of electrons at discrete time steps in the evolution of the simulation. After the simulation has run this data is imported into the mathematical analysis program and, since it consists of around 30000 points and requires too much time to process in the following steps, it is cut down by taking every 10th point. A normalized error function as a measure of the fit against a set of simulation output $f(t_i)$ was calculated as

$$E(\tau,\Delta) = \frac{\sum_i \left(f(t_i) - y(t_i,\tau,\Delta) \right)^2}{\sum_i f(t_i)^2} \tag{2}$$

An analytic solution for Δ as a function of τ can be found by minimizing Eq. 2 with respect to Δ ($\frac{\partial E}{\partial \Delta} = 0$) and solving. This results in:

$$\Delta(\tau) = \frac{\sum_i f(t_i)}{\sum_i \sum_{\nu=0}^{N_b-1} e^{-\frac{t_i - T\nu}{\tau}}} \tag{3}$$

Substituting this into (2) effectively reduces the situation so that it may now be described by a single parameter, τ. All that is required now is to find the value for τ that minimizes (2) for any given set of data. Though there are routines within the mathematical analysis software that do optimization of this kind, in the interest of time, and because we are looking for variations in the lifetime greater than one nanosecond in magnitude, it was enough to plot (2) at integer values (in units of nanoseconds) for τ and locate the minimum.

V. PARAMETER SEARCH

With this framework for a quantitative analysis of the ECLOUD output, we can look at the effects that various parameters have on the lifetime and try to determine what set of values best represents the environment in CESR.

As was mentioned above, ECLOUD modeled a situation in which there are 10 bunches at 2.085GeV traveling with a bunch spacing of 14ns. Figure 2 gives a representative plot of the density information for these parameters. Figure 3 shows the fit that Eq. 1 gives, along with the simulation output, for a similar representative situation.

Many ECLOUD jobs were run, and several general trends were noticed in the dependence of the lifetime on key parameters. For instance, as `yim` increases, so does the lifetime (Figure 4); the lifetime will also increase if `yemax` is decreased. These trends can be understood by considering that they both effectively increase the number of secondary electrons emitted, which in turn means that electrons are not absorbed as quickly into the wall, resulting in a prolonged life of the cloud.

The dependence of the lifetime on the `refl` parameter, which can vary between 10 and 100, was noticed to plateau at the high end of the range (Figure 5). Thus, there seems to be

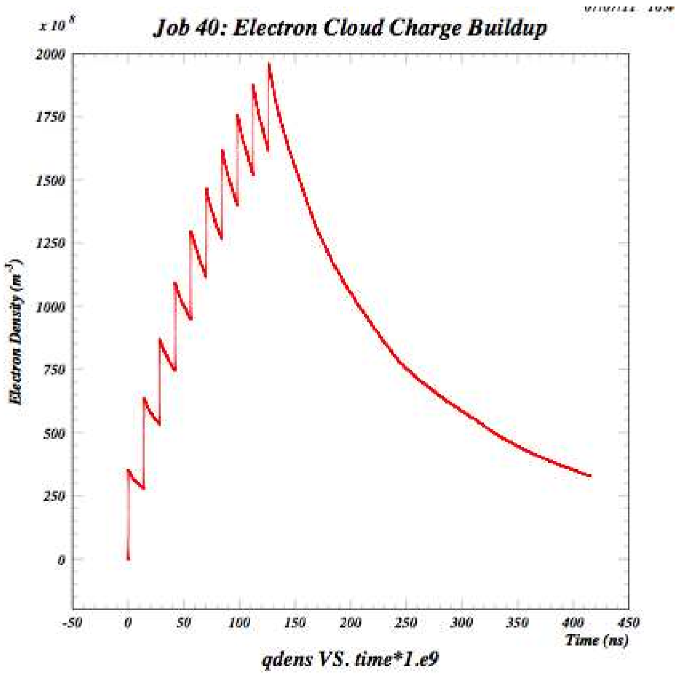

FIG. 2: A representative plot of the output of the ECLOUD simulation program. On the y-axis is electron number density, and on the x-axis is time. This particular situation models: an infinite dipole, `peeff` $= 0.01$, `refl` $= 80$, `yim` $= 1.4$, `yemax` $= 170eV$.

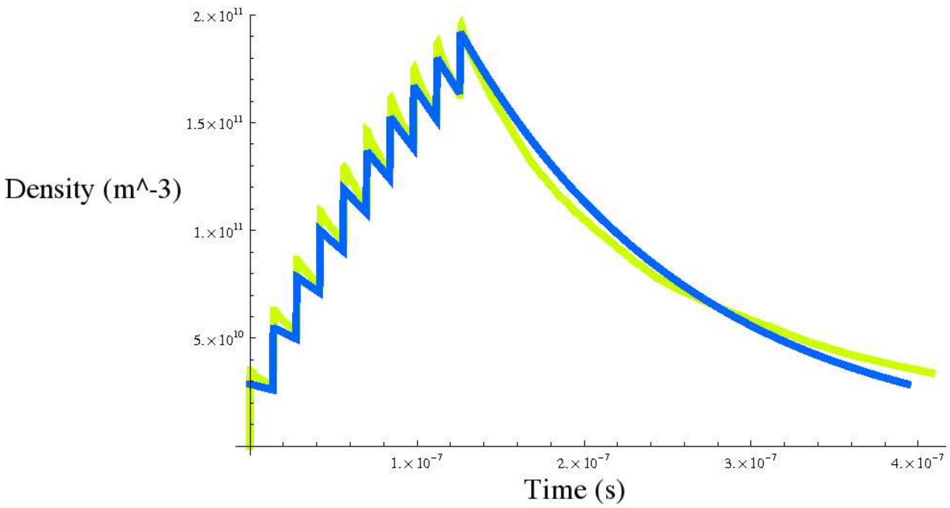

FIG. 3: A representative plot of fitting equation 1 to simulation output. The green plot is the density data that the simulation outputs, and the blue is the model.

very little change in the lifetime when varying `refl` between 60 and 100. A higher reflection parameter means that a greater portion of electrons will be towards the center of the pipe, where they have a greater distance to travel to the walls and may also be trapped by the passage of the positron bunches, though the reason for the plateau that is seen is not well understood.

As can be seen in Figure 6, the lifetime of the cloud seems to decrease with an increasing

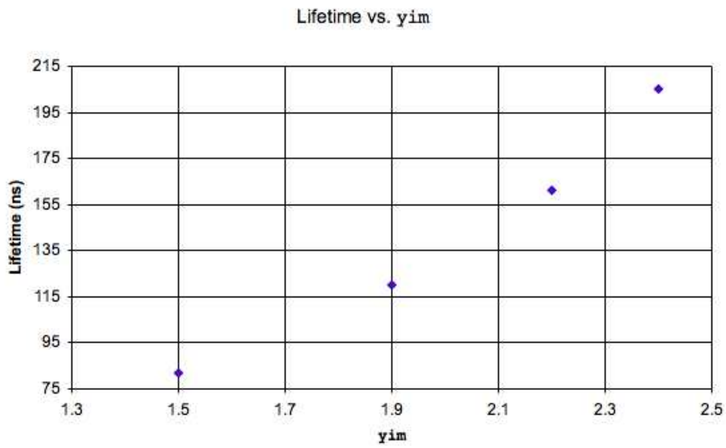

FIG. 4: The dependence of the lifetime on `yim`. The other parameters are held as such: 800 gauss dipole, `peeff` $= 0.01$, `refl` $= 80$, `yemax` $= 300eV$.

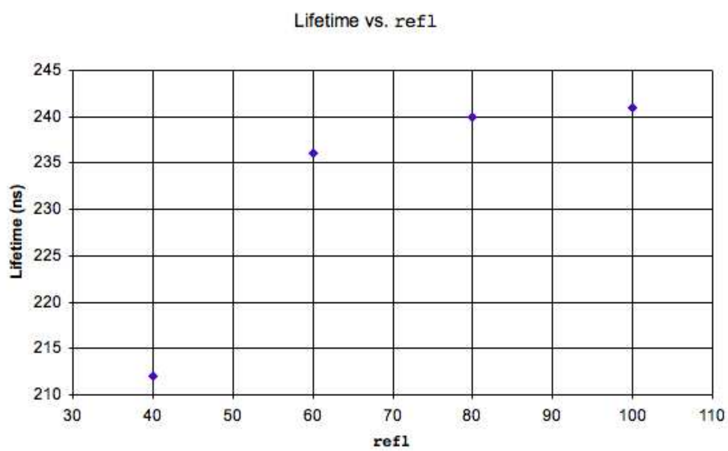

FIG. 5: The dependence of the lifetime on the strength of the dipole magnetic field. The other parameters are held as such: infinite strength dipole, `yim` $= 1.8$, `peeff` $= 0.01$, `yemax` $= 170eV$.

strength of the dipole magnetic field. The reason for this may be that weaker fields allow for more horizontal motion, and with a greater range of motion the electrons will not strike the wall as frequently.

The effect of the `ibeam` parameter (as will be discussed) is that turning it on seems to increase the lifetime of the cloud. With beam-cloud interaction turned on the electron cloud will feel a kick from each bunch that passes by; this kick will increase the average energy of the cloud, and a more energetic cloud will be able to generate more secondary electrons.

An attempt was made to find a set of parameters that gave a reasonably close fit to the experimental measurements described above (Fig. 1). With as many input parameters as ECLOUD takes, there are actually many sets of parameters that give results similar to the data, so it is important to make sure that they are all set to realistic values and are as accurate as possible. While searching for a set of parameters that gave a lifetime approximately equal to that of the measurements, many adjustments had to be made after changing an

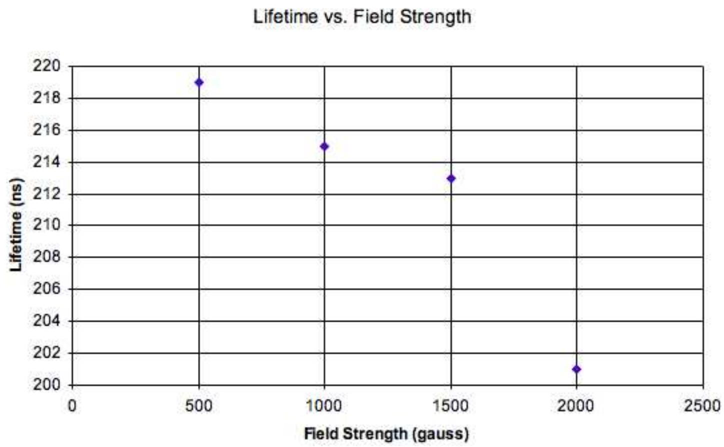

FIG. 6: The dependence of the lifetime on the strength of the dipole magnetic field. The other parameters are held as such: `yim` $= 1.5$, `peeff` $= 0.01$, `refl` $= 80$, `yemax` $= 170eV$.

incorrect parameter. Examples include: switching on beam-cloud interaction (`ibeam` $= 1$), switching from an infinite dipole (`ibend` $= 1$) to a dipole with a field strength of 800 gauss (`ibend` $= 18$, `bfield` $= 0.08$), and changing `yemax`. These adjustments are summarized in Table I.

TABLE I: Parameter Adjustments - The corrections indicate an important difference between that job and the one previous. The value for `peeff` is 0.01 for all the jobs in this table.

Job Name	Field Strength (gauss)	`yim`	`refl`	Lifetime (ns)	Correction
job52	infinite	1.6	60	174	-
job65	infinite	1.6	60	204	`ibeam` $= 1$
job67	infinite	1.5	80	168	-
job93	800	1.5	80	212	changed dipole type
job127	800	1.5	80	82	`yemax` = 300eV, from 170eV
job130	800	2.2	80	161	-

VI. DISCUSSION

Though a set of parameter values has been found that matches reasonably well with the measurements it is by no means *the* descriptive set of CESR conditions. Since there are so many potential sets that fit, it is necessary to trim down the range for each parameter for which it is possible - this may be done through materials research, data from other accelerators, or measurements made in CESR itself. The variables that most likely will need refinement are `peeff`, `yemax`, and `yim`. In this work these parameters had a relatively large range of potential values, and changes over these ranges considerably alter the simulation output and electron cloud lifetime. The more restricted these parameters are the easier it will be to find a parameter set of best fit. That said, since the data was modeled by a set of parameters containing realistic values, the use of ECLOUD for further modeling in CESR looks very promising.

VII. ACKNOWLEDGMENTS

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