Computational Analysis of CesrTA Electron Cloud-Induced Tune Shift Effects with POSINST

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Electron clouds pose a significant problem for high-energy lepton colliders, including the proposed International Linear Collider. The Cornell Electron Storage Ring Test Accelerator is able to study the dynamics of such clouds by measuring their effect on the tune of particle bunch trains. Key parameter values characterizing electron clouds can be estimated using numerical simulations of the observed tune shift. The POSINST electron cloud simulation suite was used in conjunction with a six-dimensional variant of Newton's method to better determine the value of parameters including the peak secondary electron emission yield and the incident energy of peak yield. The most influential parameters appear to be the energy at which the secondary yield peaks and the secondary emission yield at that peak. Simulations suggest optimal values of 270-310 eV and 2.3 for these parameters respectively.

I. INTRODUCTION

The Cornell Electron Storage Ring Test Accelerator (CesrTA) currently serves as a test bed for the damping rings of the planned International Linear Collider. The position of CesrTA as an electron-positron storage ring enables it to conduct studies exploring phenomena unique to such machines. Among the primary goals of CesrTA is the characterization of electron clouds that form within the beam pipe of the accelerator, and how the effects of such clouds may be effectively mitigated. As accelerators move into domains of progressively higher energy a greater understanding of such effects will become significant to the advancement of particle physics and x-ray imaging, among other fields.

Electron clouds of some magnitude are present in virtually all accelerators, with the problem becoming especially acute for positron beams. This is a consequence of both their charge and comparatively small mass. As positrons emit synchrotron radiation, electrons are released from the wall of the CesrTA beam pipe via the photoelectric effect [1]. These freed electrons are subsequently accelerated by the positrons traveling around the synchrotron, sometimes causing them to collide a second time with the beam pipe wall and release additional electrons. This process continues indefinitely, resulting in the buildup of an electron cloud that can disrupt accelerator function. The effects of electron clouds are strongly dependent on the material composing the beam pipe wall. This analysis focuses nominally on a beam pipe wall composed of aluminum.

The degree to which the CesrTA beam has been affected by electron clouds can be indirectly observed by measuring the tune shift for each consecutive bunch composing a train of particles moving through the ring. A train of particles moving through the ring will oscillate horizontally and vertically about its nominal path due to misalignments in the CesrTA bending magnets. The number of oscillations a particular bunch undergoes when traversing the ring is its tune. The rate of electron cloud formation can be inferred by measuring the shift in tune for each bunch in a given train [2]. Numerical simulations of the resulting data then permit the partial determination of certain parameters affecting the electron cloud formation and dissipation rate, in addition to an estimate of the electron cloud density encountered by each progressive bunch.

II. COMPUTATIONAL METHODS

Data taken from beam position monitors located around the CesrTA ring between 2008 and 2012 yield spatial information about the positron bunches as they travel around the ring. Applying a fast Fourier transform to these data yields a estimate for the tune of a given bunch. Repeating this for each bunch in the train and subtracting from the tune of each bunch that of the first bunch, assumed to have a tune shift of zero, yields the tune shift as a function of bunch number over the entirety of the bunch train. Analysis of the tune shift can then yield further insight into the growth and decay of the electron cloud. Measuring the tune shift of witness bunches sent through the beam pipe after the main bunch train has passed allows for an additional characterization of the dissipation of the electron cloud. This analysis focused specifically on the vertical tune of the beam.

The data resulting from these measurements can be compared directly with numerical simulations. Key parameters determining both the rate of growth and impact of electron clouds on beam quality can then be estimated by comparing collected tune shift data to simulated output over a range of potential parameter values. The electron cloud simulation suite POSINST was used in conjunction with the program SYNRAD3D. SYNRAD3D generates the spectrum of synchrotron radiation emitted by the particle bunches composing the train as they travel around the accelerator. POSINST then computes the evolution of the electron cloud density in the beam pipe as the bunch train travels through the CesrTA ring based on both this radiation spectrum and the user-input values of parameters characterizing the accumulated electron cloud. The POSINST simulation suite assumes linear behavior for the variables relevant to our analysis. The Cornell batch node system was utilized to run many simulations in parallel. Many simulations were split into sections and later recombined due to restrictions placed on the duration of time for which a single simulation may run in an effort to reduce statistical error. A Mathematica script was then used to calculate the tune shift of each bunch in the train based on the simulated electron cloud.

Six primary parameters serve to characterize the build-up and dissipation of the electron cloud in this model. The CesrTA ring can be approximated as a series of drift chambers and dipole bending magnet sections. The first two parameters of interest are the quantum efficiency of the beam pipe wall in the drift chambers and dipoles respectively. The quantum efficiency is defined as the probability that a given photon incident on the beam pipe wall will release a photoelectron, or primary electron. The nominal values for drift chambers and dipoles are 0.08 and 0.10 respectively.

The third and fourth parameters concern the production of secondary electrons. The positron bunches circulating about the CesrTA ring accelerate the primary electrons resulting from photoemission, forcing them to collide with the beam pipe wall. When this collision occurs it is possible for an additional electron, or secondary electron, to be emitted. When secondary emission occurs the number of emitted secondary electrons is a function of the incident electron energy. Both the peak value of this secondary electron yield (SEY) and the incident energy for which it occurs are key parameters of interest. The peak SEY and incident energy for electrons at this peak are nominally 2.0 and 310 eV respectively for aluminum.

Alternatively, an electron incident on the beam pipe wall may scatter elastically from the wall or interact with the beam pipe material and later rediffuse. The percentage of electrons that are elastically scattered is also a function of incident electron energy. An incident energy exists at which the percentage of elastically scattered electrons is maximized, with the total percentage falling to zero at both very high and low energies. The percentage of electrons that are elastically scattered at this maximum is a parameter of key interest. The nominal peak percentage of elastically scattered electrons is 0.5. The percentage of incident electrons that are rediffused is also a function of incident electron energy, asymptotically leveling-off to a certain percentage at high incident energies. This asymptotic value is the sixth parameter of interest. Its nominal value for aluminum is 0.19.

It is experimentally and computationally well documented that these parameters are strongly correlated with one another, compounding the existing difficulties inherent in locating global extrema in a six-dimensional space [3]. A higher-dimensional variant of Newton's method was implemented in MATLAB to more efficiently minimize the reduced chi-squared values of the simulated fits to the measured tune shift data. A column vector β giving the recommended change in each parameter to minimize the reduced chi-squared value associated with the fit of the simulation to a certain data set is given by [4]:

$$\beta = (X^T W X)^{-1} X^T W y, \tag{1}$$

where W is a diagonal square matrix containing the reciprocal variance in the tune shift of each particle bunch, X is the Jacobian matrix associated with changing each of the six parameters, and y is a column vector containing the initial user-input parameter values. The optimal parameter can then be found by iteratively applying this algorithm and fitting the results to measured tune shift data.

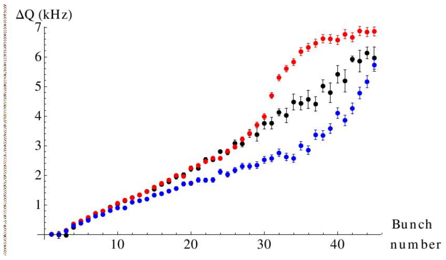

FIG. 1: Tune shift vs. bunch number for parameter sets 1 (blue) and 2 (red) to a data set (black) featuring a 2.1 GeV 45-bunch positron train with 0.75 mA/bunch spaced at 4 ns. The parameter sets are associated with reduced chi-squared values of 22.0 and 13.0 respectively.

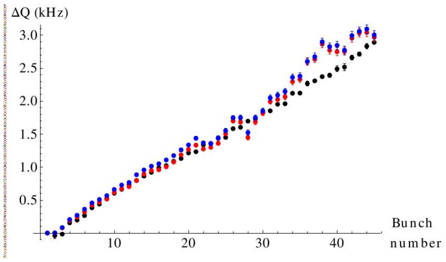

FIG. 2: Tune shift vs. bunch number for parameter set 2 (red) with a similar run (blue) relative to a data set (black) featuring a 5.3 GeV 45-bunch positron train with 0.75 mA/bunch spaced at 4 ns. In the blue fit the drift quantum efficiency has been elevated from 0.083 to 0.10. The blue perturbed fit has an associated reduced chi-squared value of 17.5, increased compared to 10.0 for the main red fit.

III. RESULTS

Parameter set 1 in Table I shows the best-performing parameter set in use prior to the implementation of SYNRAD3D, while parameter set 2 is the best-performing parameter set obtained with the use of the six-dimensional

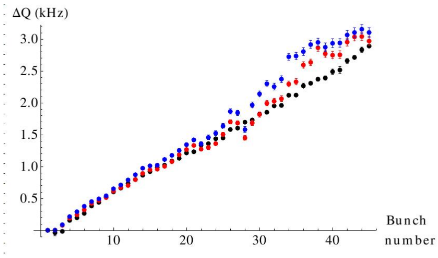

FIG. 3: Tune shift vs. bunch number for parameter set 2 (red) with a similar run (blue) relative to a data set (black) featuring a 5.3 GeV 45-bunch positron train with 0.75 mA/bunch spaced at 4 ns. In the blue fit the dipole quantum efficiency has been elevated from 0.13 to 0.16. The blue perturbed fit has an associated reduced chi-squared value of 28.3, increased compared to 10.0 for the main red fit.

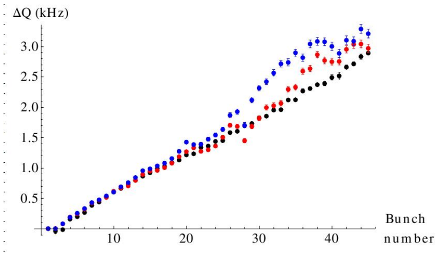

FIG. 4: Tune shift vs. bunch number for parameter set 2 (red) with a similar run (blue) relative to a data set (black) featuring a 5.3 GeV 45-bunch positron train with 0.75 mA/bunch spaced at 4 ns. In the blue fit the peak SEY has been elevated from 2.3 to 2.5. The blue perturbed fit has an associated reduced chi-squared value of 40.4, increased compared to 10.0 for the main red fit.

Newton's method in conjunction with SYNRAD3D. The third parameter set listed is a minor perturbation on the second, and was partially used to examine the degree of correlation between the relevant parameter values. Parameter set 2 was tested against a collection of data sets at beam energies of 2.1 GeV, 4.0 GeV, and 5.3 GeV. Simulated bunch train configurations included 10-, 20-, and 45-bunch trains, with bunch current ranging between 0.50 and 1.00 mA/bunch. Bunch spacings of 4, 8, 14, and 20 nanoseconds were analyzed. Data taken from positron beams dominated the simulated data, though a small quantity of electron beam data was examined as well.

TABLE I: Best Parameters Sets Before and After SYNRAD3D Implementation

Parameter Set	1	2	3
Drift QE	0.08	0.083	0.08
Dipole QE	0.10	0.13	0.12
SEY at Peak	2.0	2.3	2.2
Energy at Peak SEY (eV)	310	290	279
Fraction Elastic Scatter	0.5	0.42	0.4
Fraction Rediffused	0.19	0.20	0.19

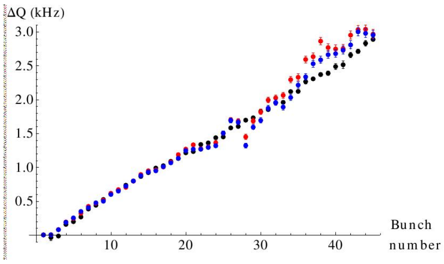

FIG. 5: Tune shift vs. bunch number for parameter set 2 (red) with a similar run (blue) relative to a data set (black) featuring a 5.3 GeV 45-bunch positron train with 0.75 mA/bunch spaced at 4 ns. In the blue fit the incident energy of peak SEY has been elevated from 0.083 eV to 0.103 eV. The blue perturbed fit has an associated reduced chi-squared value of 8.0, decreased compared to 10.0 for the main red fit.

Figure 1 plots tune shift versus bunch number for data taken from a 45-bunch, 0.75 mA/bunch, 2.1 GeV positron beam spaced at 14 ns and the fitted output from parameter sets 1 and 2. In this example parameter set 2 is associated with a reduced chi-squared value of 13.0, while the fit of parameter set 1 is associated with a reduced chi-squared value of 22.0. Figures 2-7 show parameter set 2 fitted to a 5.3 GeV 45-bunch positron beam with 0.75 mA/bunch spaced at 4 ns, along with a similar fit in which one of the six key parameters has been increased by approximately twenty percent. The associated chi-squared value of the fit increases for all but one of the perturbed fits. These figures illustrate the susceptibility of the simulation results to minor changes in the given parameter values.

Figure 8 shows a 4.0 GeV 20-bunch positron beam with 0.75 mA/bunch spaced at 20 ns, followed by 8 witness bunches. It is fitted to both a simulation using parameter set 2 and parameter set 3, a minor perturbation on this parameter set. The calculated reduced chi-squared value for the current parameter set is 8.5 for the main bunch train and 2.1 for the witness bunches. Simultaneously, the perturbation is associated with a reduced chi-squared of 2.2 for the main bunch train and 15.1 for the witnesses.

IV. DISCUSSION

Analysis of the simulation output given in Figure 1, and similar data sets, suggests that the use of SYNRAD3D is beneficial in trying to locate the optimal parameter values to accurately describe the largest set of data possible. Furthermore, the improvement of simulation agreement with existing data over a number of iterations of the modified Newton's method suggests that an iterative approach of this kind can be effective in both automating the simulation process and in using computational resources more efficiently. Figures 2-7 illustrate how small changes in each of the six parameters worsen agreement between simulation and measurement for this

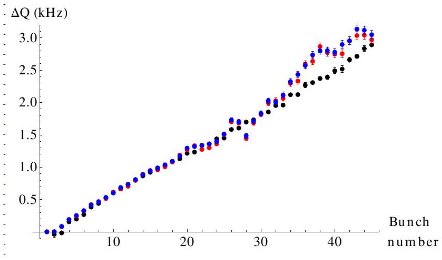

FIG. 6: Tune shift vs. bunch number for parameter set 2 (red) with a similar run (blue) relative to a data set (black) featuring a 5.3 GeV 45-bunch positron train with 0.75 mA/bunch spaced at 4 ns. In the blue fit the percentage of incident electrons undergoing elastic scatter has been elevated from 0.42 to 0.47. The blue perturbed fit has an associated reduced chi-squared value of 11.7, increased compared to 10.0 for the main red fit.

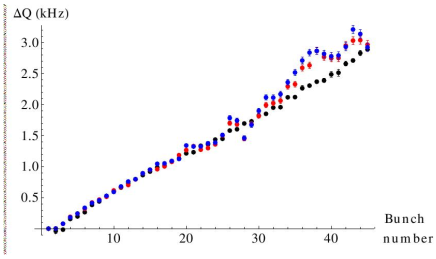

FIG. 7: Tune shift vs. bunch number for parameter set 2 (red) with a similar run (blue) relative to a data set (black) featuring a 5.3 GeV 45-bunch positron train with 0.75 mA/bunch spaced at 4 ns. In the blue fit the aympototic percentage of incident electrons undergoing reidffusion has been elevated from 0.20 to 0.24. The blue perturbed fit has an associated reduced chi-squared value of 15.6, increased compared to 10.0 for the main red fit.

particular data set, indicating that Newton's method has been at least partially successful in identifying a local minimum in parameter space. The only key simulation parameter for which the Newton's method techniques failed to produce consistent results was the incident electron energy at which peak SEY production occurs. Calculated results generally ranged between 270 eV and 310 eV.

A central problem impeding greater understanding of the electron cloud parameter values is the strong correlation between the six primary values. Figure 8 shows how a small perturbation in each of the six parameter values simultaneously significantly affects agreement between the simulation output and measured tune shift data. Additionally, the nature of this technique makes it difficult to distinguish global from local minima within parameter space. Further questions exist regarding the disparity between the simulated peak SEY of 2.3 and recent experimental measurements suggesting a value of approximately 1.5. Future analysis of a greater number and diversity of data sets will be required to address these persisting concerns.

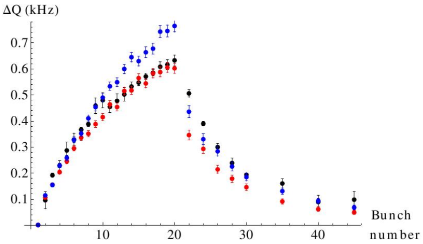

FIG. 8: Tune shift vs. bunch number for parameter sets 2 (blue) and 3 (red) to a data set (black) featuring a 4.0 GeV 20-bunch positron train with 0.75 mA/bunch spaced at 4 ns followed by 8 witness bunches experiencing the dissipation of the electron cloud. Parameter set 2 has an associated reduced chi-aquared fit parameter of 8.5 for the initial 20 bunch train and 2.2 for the witnesses, while parameter set 3 records 2.1 and 15.1 for the initial 20 bunch train and witnesses respectively.

V. ACKNOWLEDGMENTS

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