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ELECTRON CLOUD SIMULATIONS FOR THE LOW-EMITTANCE UPGRADE AT THE CORNELL ELECTRON STORAGE RING

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Abstract

The Cornell Electron Storage Ring operations group is planning a major upgrade of the storage ring performance as an X-ray user facility. The principal modification foresees replacing the former e^-e^+ interaction region with six double-bend achromats, reducing the emittance by a factor of four. The beam energy will increase from 5.3 to 6.0 GeV and single-beam operation will replace the present two-beam e^-e^+ operation. The initial phase of the project will operate a single positron beam, so electron cloud buildup may contribute to performance limitations. This work describes a synchrotron radiation analysis of the new ring, and employs its results to provide ring-wide estimates of cloud buildup and consequences for the lattice optics.

INTRODUCTION

The Cornell Electron Storage Ring (CESR) serves as the X-ray source for the Cornell High Energy Synchrotron Source (CHESS). At present, CESR operates at 5.3 GeV with counter-rotating electron and positron beams. This two-beam operation limits CESR performance in emittance, beam lifetime, and beam current. An upgrade to single-beam operation has now progressed to the engineering and prototyping phase. The CHESS X-ray end stations will all be oriented to align with the on-axis positron beam. The positron beam energy will be increased from 5.3 to 6.0 GeV, and the normalized emittance will be reduced by a factor of four. One-sixth of the CESR storage ring, including the former interaction region for the CLEO experiment, will be replaced by six double-bend achromats, each equipped with two conventional combined-function magnets providing dipole fields of 6.4 kG and quadrupole fields of 8.8 T/m gradient [1], and with Cornell Compact Undulators (CCUs) [2]. The synchrotron radiation from this new section requires extensive additional shielding to enclose the ring throughout the large CLEO experimental hall. It will also present an additional source of electron cloud buildup, and since initial operation will be with a single positron beam, it is important for the vacuum chamber design to estimate the effect of the cloud on the beam optics. Here we present a synchrotron radiation analysis of the ring, electron cloud buildup modeling, and estimates for electron-cloud-induced betatron tune shifts.

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SYNCHROTRON RADIATION ANALYSIS OF THE UPGRADED LATTICE

The vacuum chamber design in the modified south arc section of the CESR ring foresees a small vertical dimension of 5 mm in the CCUs, and a 100-mm horizontal dimension with the beam 25 mm from the outer wall, thus providing a 50-mm antechamber for electron cloud suppression. Outside of the CCUs, the vacuum chamber will be nearly elliptical with vertical side walls, as in most of the CESR ring, but reduced by a factor of two, so 45x25 mm rather than 90x50 mm. This vacuum chamber model has been implemented in the Bmad synchrotron radiation analysis [3] of the lattice. Figure 1 compares the rates of photons incident on the vacuum chamber wall in the downstream 50 m of the upgraded lattice to the rates in present operation. In contrast to the upgraded lattice, there is very little radiation in the first 15 m at present. The radiation from the combined-function bends illuminates both the bends themselves and the downstream quadrupoles and CCUs.
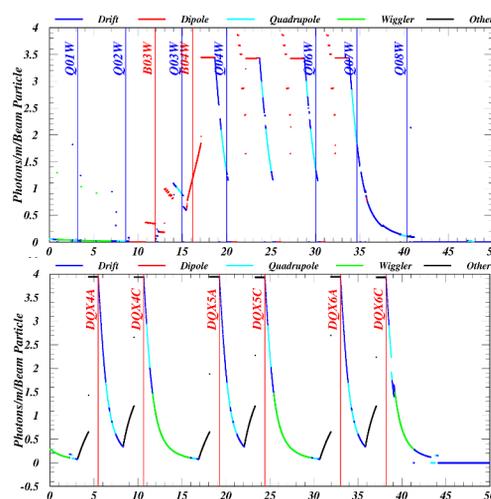

Figure 1: Calculations of synchrotron radiation incident on the vacuum chamber walls in the downstream 50 m of the modified section of the CESR ring. The upper plot shows the rates during present CHESS operation. The lower plot shows the rates expected for the upgraded lattice.

The modeling methodology for estimating coherent betatron tunes shifts employs the element-type ring occupancy fractions and the element-type-averaged rates, beta functions and beam sizes, as described in Ref. [4]. Inclusion of the field-free and dipole regions of the CESR ring suffice to accurately model present tune shift measurements. We include the combined-function magnet and CCU regions in the calculations for the upgraded lattice in order to assess

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their relative contributions. Table 1 shows that the average rate in the combined-function magnets is a factor of two higher than in the CESR dipoles (an important motivation for this study), while the average horizontal beta function is much lower.

TUNE SHIFTS IN CHESS OPERATING CONDITIONS

The cloud buildup modeling employs the code ECLOUD [5, 6], which includes models for photoelectron generation kinematics, for time-sliced macroparticle tracking in the 2D electrostatic fields sourced by the beam and the cloud, and 3D tracking in magnetic fields, as well as a detailed model of the secondary emission process (SEY) at the vacuum chamber wall. The SEY model is parameterized in the manner described by Furman and Pivi [7]. Simulations are performed for the magnetic field environment of each element type. The coherent tune shifts for each bunch are derived from the horizontal and vertical cloud spacecharge field gradients integrated over the longitudinal and transverse bunch charge distributions.

In order to ensure a reasonable starting point for the simulations, we performed measurements of coherent tune shifts in 2016 CHESS operating conditions using the pinging method described in Ref. [4] for a 20-bunch train of 14-ns-spaced bunches, each comprising 3.2×10^{10} positrons. The ECLOUD input parameters for the photon scattering rate in the beampipe (reflectivity), quantum efficiency, photoelectron energy distributions and SEY were adjusted to achieve the degree of consistency with the vertical tune shift measurements shown in Fig. 2. These tune shifts are to be compared to the revolution frequency of 390 kHz. We
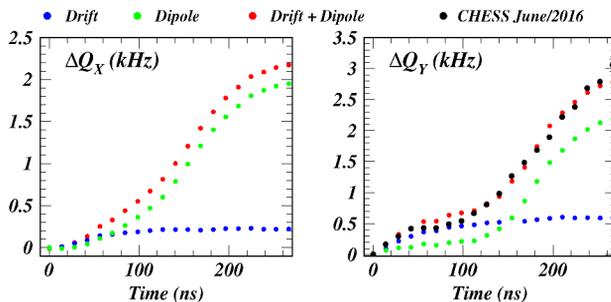

Figure 2: Modeled and measured (black points) tune shifts for a 20-bunch train of 5.3 GeV positrons with population 3.2×10^{10} e$^+$ in the CHESS operating optics. The bunch spacing is 14 ns. The revolution frequency is 390 kHz. At this bunch population one observes that the contribution of the dipole regions increases during the train passage relative to that from the field-free regions.

emphasize that the importance of the contribution from the dipole regions of the ring means that horizontal tune shift measurements using the pinging method are compromised by the pinning of the cloud to the vertical field lines. Consequentially, the model calculation cannot be validated using this measurement method. While we include the modeled

horizontal tune shifts for comparison, our conclusions are based solely on the vertical tune shift modeling.

The model tuned to the 20-bunch-train results was then applied to the bunch pattern used in two-beam CHESS operations The positron-beam-generated cloud is disrupted by the electron beam in ways we find difficult to estimate. Our intention in applying the tuned model to the two-beam e$^+$ bunch pattern is to establish a benchmark with which to compare our estimates for the tune shifts in the upgraded CESR configuration.

The positron bunch pattern in two-beam operation consists of five trains of either 3 or 4 bunches situated around the ring so as to maximize separation from the counter-rotating e$^-$ beam. The relatively few bunches means that a bunch population of 8.8×10^{10} is required to reach the full positron operating current of 100 A. Figure 3 shows the model results for the tune shifts at each 2-ns-spaced bunch position, though only the circled positions carry charge in both operations and in the model. The fact that the tune
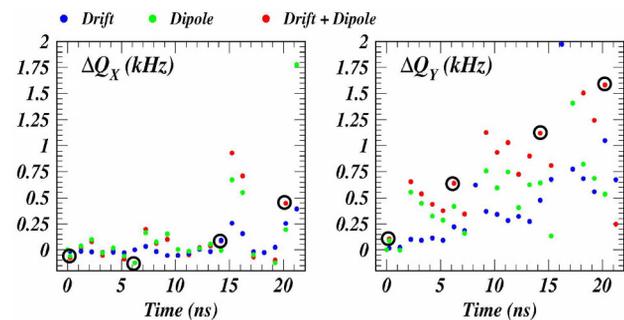

Figure 3: Modeled coherent tune shifts for the positron bunch pattern presently in use for two-beam CHESS operation with 6-8-6-ns spacing in a train of four bunches. The bunch population is 8.8×10^{10}. Only the circled bunch positions are filled during operation, and in the model; the simulation calculates tune shifts for the other positions as if they were filled.

shifts calculated for the unfilled bunch positions are so large and variable testifies to the highly dynamic nature of the cloud during the train passage. The conclusion we draw from these calculations is that we can reasonably expect stable operation in the upgraded CESR operations if the tune shifts are limited to a level below that shown in Fig. 3.

TUNE SHIFTS PREDICTED FOR THE UPGRADED CESR/CHESS LATTICE

The design current for the upgraded CESR/CHESS lattice is 200 mA. There are 183 14-ns-spaced bunch positions in the 768-m ring circumference with 2.56 μs revolution period. In the interest of limiting electron cloud buildup we have chosen to fill the ring with seventeen 70-ns-spaced trains consisting of five bunches each, resulting in a specified bunch bunch population of 3.8×10^{10} e$^+$. The left plot of Fig. 4 shows the modeled electron cloud density averaged over the beampipe cross section for the conditions of the measurements in Fig. 2 in the case of the 2.0-kG dipole

Table 1: Table of Element-Type-Averaged Quantities used as Input to the Electron Cloud Buildup Simulations

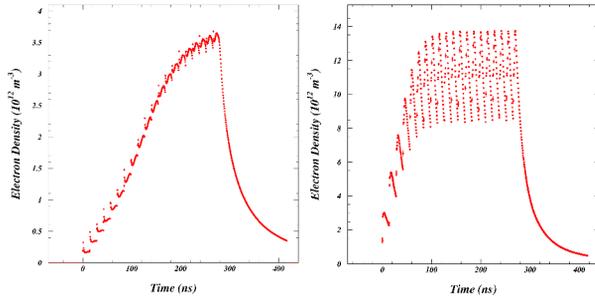|	Element type	Total length (m)	Ring fraction (%)	$<\beta_X>$ (m)	$<\beta_Y>$ (m)	$<\sigma_X>$ (mm)	$<\sigma_Y>$ (mm)	Average photon rate γ/m/positron
Present CHESS conditions	Dipole	475.5	61.6	15.4	20.5	1.444	0.139	1.048
	Drift	188.5	24.4	17.9	21.3	1.493	0.138	0.696
Upgraded CHESS conditions	Dipole	440.0	57.0	13.4	21.2	0.870	0.077	1.145
	Drift	181.5	23.5	16.7	20.0	0.882	0.072	0.749
	C-F magnet	28.2	3.7	1.8	15.9	0.218	0.069	2.149
	CCU	25.5	3.3	10.9	3.2	0.568	0.031	0.409

Figure 4: Modeled electron cloud density averaged over the beampipe cross section. The left plot shows the result for the conditions of the tune shift measurements in Fig. 2 in the case of the dipole field, which is the primary contributor to the tune shift late in the train. The right plot applies the model to the the combined-function magnetic field in the CESR/CHESS upgrade lattice for the bunch population of 3.8×10^{10} e$^+$ chosen to provide 200-mA beam current in seventeen trains of five bunches each. The higher average rate of photon absorption in the combined-function magnets results in an increase in the cloud density of a factor of four and earlier saturation.

magnetic field in CHESS operating conditions. The right plot shows for comparison the cloud density calculated in a south arc combined-function magnet in the upgraded lattice. The high photon absorption rate (2.149 vs.1.048 γ/m/e$^+$) results in an increase in the maximum density reached in a 20-bunch train from 3.5×10^{12} m^{-3} to 14×10^{12} m^{-3}. This comparison illustrates our initial concern for the contribution to coherent tune shifts by cloud buildup in the south arc region of the CESR/CHESS upgrade.

The contribution of the high cloud density in the combined-function magnets is mitigated by the low ring-occupancy fraction of 3.7% and, for the case of horizontal tune shift, by the low average beta function value of 1.8 m. Figure 5 shows the tune shifts predicted by the model for the CESR/CHESS upgrade, and the relative contributions of the field-free, 2.2-kG dipole, combined-function and CCU sections of the ring. Despite the low ring-occupancy fraction of the combined-function magnets, their contribution to the vertical tune is comparable to that of the dipole and field-free regions of the ring. The horizontal tune shift is due predominantly to the dipole regions of the ring, as in present CHESS conditions. We also conclude that the small, 5-mm vertical height of the CCU vacuum chambers does not result in intolerably high cloud densities. Most importantly, by limiting the train length to five bunches, the max-
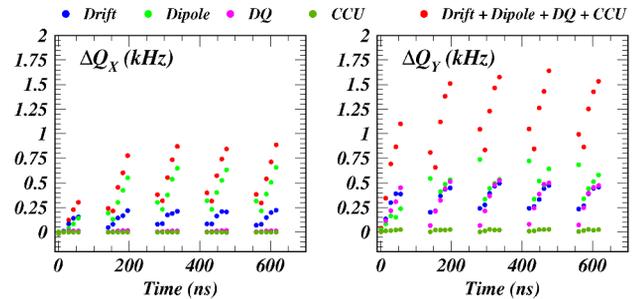

Figure 5: Model predictions for the coherent tune shifts in the 6 GeV, 200-mA operating conditions of the CESR/CHESS upgrade.

imum tune shifts are limited to values less than 1.8 kHz, comparable to those observed in present CHESS conditions. This study thus provides assurance that performance limitations associated with electron cloud buildup will be no worse than in present CHESS operating conditions. Taken together with the advantages of single-beam, on-axis operation, we can reasonably expect stable, reliable operating conditions for the CESR/CHESS upgrade.

SUMMARY

We have performed analyses of the synchrotron radiation patterns for the present 5.3 GeV operating conditions of the Cornell Electron Storage Ring (CESR) as a light source for the Cornell High-Energy Synchrotron Source (CHESS), and extended them to the optics and modified vacuum chamber design of the 6-GeV CESR/CHESS upgrade. These calculations are applied to electron cloud buildup modeling, which is tuned to reproduce 2016 measurements of coherent tune shifts in present CHESS operating conditions. The tuned model is then used to calculate the magnitude of tune shifts to be expected during 200-mA upgraded operation with seventeen trains of five positron bunches each. We determine that performance limitations due to electron cloud buildup can be expected to be no more severe than during present CHESS operations, despite unusually high cloud densities in the combined-function magnets. Our calculations are based on the beam-processed aluminum vacuum chamber surface properties typical of the present CESR ring, so we conclude that special cloud mitigation techniques such as grooves or coatings will not be necessary in the new south arc region of the ring. Operation of the upgraded CESR ring for CHESS is scheduled to begin during the summer of 2018, providing 20-150-keV X-ray beams for about 1300 user visits per year.

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