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CESR UPGRADE AS A HIGH-ENERGY, HIGH-BRIGHTNESS X-RAY LIGHT SOURCE*

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Abstract

The Cornell Electron Storage Ring (CESR) operates most of the year as the Cornell High Energy Synchrotron Source (CHESS). CESR was originally designed and operated as an electron/positron collider, circulating high-emittance beams in order to maximize luminosity. Beam lines were developed to extract x-rays from both electron and positron beams. The two beams share a common vacuum chamber, and are electrostatically separated to avoid collisions. The requirement to store counter-rotating beams significantly constrains the storage ring optics, limiting emittance and, beam current, and bunch distributions. The proposed upgrade eliminates two-beam operation in favor of a single optimized on-axis beam. Several new undulator-based beam lines are planned. The horizontal emittance is reduced in steps, first from 90 nm to 20 nm at 5.3 GeV, and then in a ring-wide upgrade to as low as 300 pm at 6 GeV. The low-emittance optics are based on multi-bend achromats with combined function bends. The details of the optics, apertures, and magnet parameters are presented.

INTRODUCTION

The Cornell Electron Storage Ring (CESR) is a 768-meter e^+/e^- storage ring, with operating energies 1.8–5.3 GeV. Originally developed to operate parasitically while CESR collided electrons and positrons for high energy physics [1,2], CHESS takes advantage of the counter-rotating beams, with seven lines illuminated by light from the positron beam and four from the electron beam. With the conclusion of the particle physics program in 2008, CESR continued to circulate both species of particles, in order to feed the existing CHESS beam lines.

Maintenance of two-beam operation places a long list of constraints on the optics [3,4], including minimum achievable emittance, and injection efficiency. Top-off injection is limited to a single species as the single synchrotron injector is shared by both electrons and positrons.

Here, a proposal is outlined that optimizes performance with a single beam, and that can accommodate additional insertion devices. All CHESS beam lines would be reconfigured to accept an undulator source, and all beam lines would be oriented in the same direction. The same sextant where the beam lines are located is also the source of a disproportionate fraction of the total emittance. Reconfiguration of the lattice in this sextant with double-bend achromat (DBA) cells thus allows re-orientation of the beam lines as well as a substantial reduction of the horizontal emittance.

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PROPOSED UPGRADE

CESR presently uses a FODO-style lattice, with a long straight section for the former CLEO detector. The strong dipoles required for bending into the CLEO straight presently contribute ≈ 60% of the radiation integral I_5, and thus dominate the horizontal emittance.

The proposed upgrade replaces one sextant of the lattice centered at the CLEO straight with six double-bend achromat (DBA) cells. Between each DBA there will be a four-meter zero-dispersion straight for insertion devices. Figure 1 demonstrates how the new layout will remove the CLEO detector straight, following the arc of the ring more continuously. The change in CESR will mandate removing part or all of the CLEO detector that remains in the experimental hall.

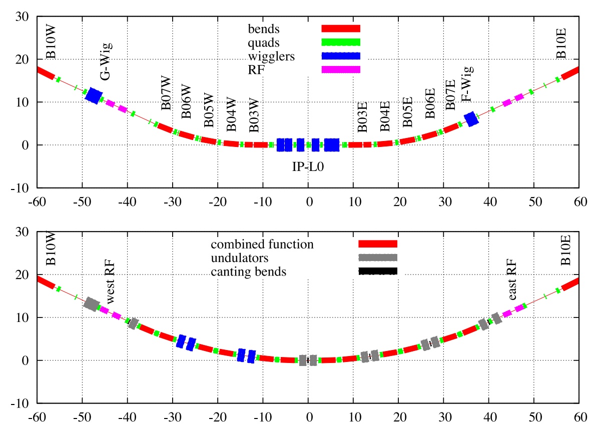

Figure 1: Top: existing user area layout. Bottom: proposed change to user area, removing the CLEO detector straight. All counter-clockwise beam lines will be replaced with clockwise-facing lines, and all beam lines will utilize undulator sources.

Twiss parameters are shown for one DBA cell in Fig. 2, and for the entire ring in Fig. 3. Magnet parameters for one DBA cell are shown in Table 1. Dipoles in the DBA cells will be combined-function dipole-quadrupoles, contrasting with the fixed-purpose dipoles presently installed throughout CESR. Two of the three quadrupoles in each DBA will reuse existing magnet stock. As with the rest of CESR, all quadrupoles in the upgraded region will be independently powered in order to retain flexibility in the optics.

An unusual feature of the proposed lattice is a lack of sextupoles in the DBA sextant. CESR does not presently have sextupoles through this sextant, relying on sextupoles in the remaining 5/6 of the ring to compensate chromaticity and nonlinear dynamics. Dynamic aperture is > 20σ of the stored beam.

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Table 1: DBA Magnet Specifications. k_1 is evaluated for 6.5 GeV.

Magnet	#/cell	L [m]	B_0 [T]	B_1 [T/m]	k_1 [m^{-2}]
Combined-Function Dipole	2	3.036	0.5357	-5.522	-0.25467
Quadrupole 1	1	1.0	n/a	18.469	0.851
Quadrupole 2	2	0.6	n/a	24.393	1.125

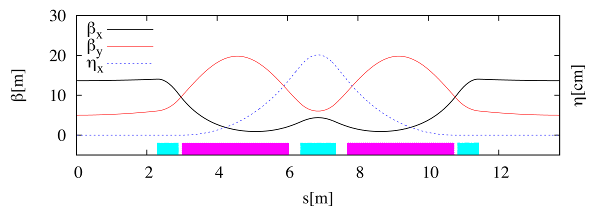

Figure 2: Lattice parameters for one proposed DBA cell. Quadrupoles are shown in cyan, and combined-function dipoles in purple. There are no sextupoles in this sextant of the storage ring.

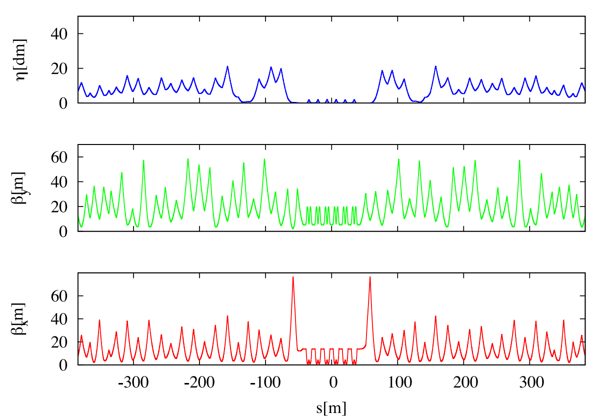

Figure 3: Lattice parameters for the proposed modification. The upgraded sextant is centered at $s = 0$.

A summary of parameters in the old and new lattice is shown in Table 2. In the new configuration, the DBA sextant only contributes 6% of I_5.

Table 2: Lattice Parameters for Present and Proposed Configurations

Parameter	Present	Proposed
Circumference [m]	768.438	768.439
Energy [GeV]	5.289	6.5
Species	e^+/e^-	e^-
Current [mA]	200×200	200
Emittance [nm·rad]	101.7	34
α_c [–]	9.168×10^{-3}	5.677×10^{-3}
Bunch Length [mm]	15.8	22.3
Energy Spread [–]	6.5×10^{-4}	1.1×10^{-3}
# Beam lines	11	10
# Undulator Beam lines	4	10

The modified ring will operate with a single on-axis beam for x-ray users, rather than the present electrostatically-separated two-beam mode. Single-beam operation allows for a more uniform bunch spacing with more bunches and smaller charge per bunch, increasing the beam lifetime, increasing injection efficiency, and reducing current-dependent instabilities. Although the majority of beam lines (7 out of 11) are oriented in the positron direction, there is strong motivation to use electrons for light source operations–electron cloud, positron converter reliability, and positron production rates, to name a few. As such, single-beam operation will be with electrons. Positron capabilities would be retained for accelerator physics studies.

The polarity of the synchrotron booster and all CESR magnets will be reversed, such that electrons will circulate clockwise rather than counter-clockwise. All counter-clockwise-oriented beam lines will subsequently be reversed or replaced.

Note again that the decrease in emittance arises from two factors: discontinuing two-beam operations (and thus large-amplitude pretzel orbits), and reconfiguring one sextant of the storage ring lattice. The remaining circumference of the ring is inaccessible for users, as it is underground. If the remaining five-sixths of the ring were upgraded to a theoretical minimum emittance (TME)-style lattice, the horizontal emittance at 6.5 GeV would reduce to 325 pm. This is beyond the scope of the proposed upgrade, but remains an option for the future.

USER BENEFITS

All beam lines in the upgraded machine will use adjustable-phase out-of-vacuum CHESS Compact Undulators (CCUs) [5]. Parameters for the CCU design are summarized in Table 3. A pair of canted CCUs will be placed in each 4 m straight.

Table 3: Parameters for the 7 mm Gap Out-of-vacuum CHESS Compact Undulators (CCU)

Parameter	Value
Total Length [m]	1.523
Period [mm]	28.4
# Periods	52
Magnet Pole Gap [mm]	7
Vacuum Chamber Aperture [mm]	4.5
Magnet Material	NeFeB
B_z [T]	0.952
k-value	2.52

X-ray performance before and after the proposed reconfiguration is shown in Fig. 4. Users presently on lines with a bend source will see an increase in brightness of four orders of magnitude; users presently on undulator beam lines will

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see an increase of up to 10 times the present flux at high energy (50-100 keV).

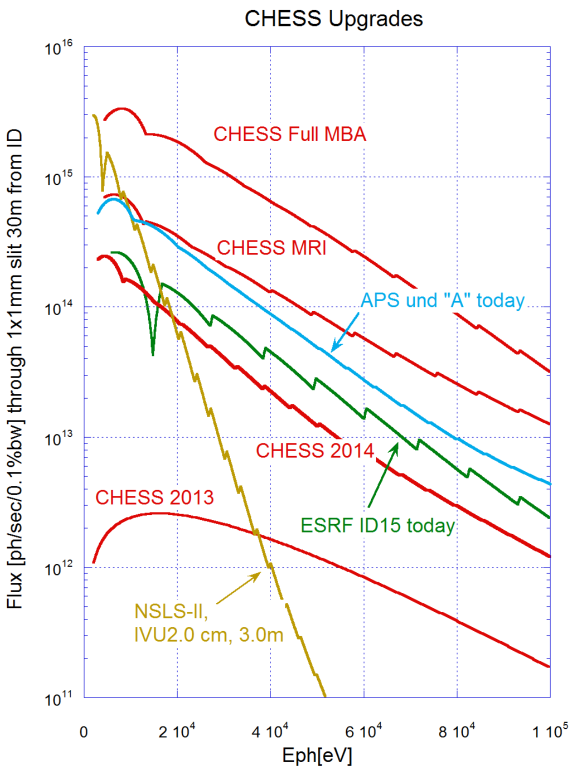

Figure 4: X-ray performance before and after the proposed upgrade. "CHESS 2013" refers to the CHESS 50-pole wiggler; "CHESS 2014" is for the current installation of a 1.5 m CHESS Compact Undulator (CCU). "CHESS MRI" is this proposal. "CHESS Full MBA" is the resulting flux if the remaining 5/6 of the ring (underground, and inaccessible to users) were upgraded to a TME-style arc cell.

In the present configuration, each undulator is a source for two beam lines: one electron and one positron. In the upgraded lattice, every beam line will have an independently-tunable source, allowing further flexibility for users.

Without an opposing beam circulating, users will also benefit from decreased top-off duration, improved reliability, and full 200 mA performance.

IMPACT ON CESRTA PROGRAM

With the reconfigured storage ring, CESR Test Accelerator (CesrTA) [6] low-energy (2.085 GeV) conditions will also see a reduction in horizontal emittance, from 2.6 nm to 1.5 nm, even with the removal of two of the twelve CESRc damping wigglers placed in zero-dispersion straights.

The CesrTA program relies on comparisons between electron and positron conditions in CESR. Positron production and injection will be retained after the upgrade, though positrons will circulate opposite of their historical orientation. A new positron snout to direct the linac beam into the synchrotron will be necessary in order to retain positron capabilities.

At present, dispersion in the cavities is of order 1 m. The coupling of longitudinal and horizontal motion significantly increases the projected horizontal beam size [7]. In the proposed single-beam lattice, there is zero dispersion in the RF straights, thus enhancing low emittance performance.

During operation of the storage ring for CesrTA experiments, the undulator magnets are removed but the undulator vacuum chambers (3 m long and 4.5 mm full vertical aperture) remain. The CesrTA experimentalists have so far been able to adjust to the reduced aperture.

TIMING AND COMMISSIONING

The upgrade proposal allots 8 months for installation, with another 12 weeks for commissioning. Anticipated installation would begin at the end of Q2 in 2016.

In 2014-15 CESR has commissioned two-beam operations with two out-of-vacuum CCUs installed (4.5 mm chamber aperture), with 120 mA per beam. It is believed that beam current is presently limited by a wakefield instability caused by scrapers used to mask injection radiation on the undulators. By replacing the scrapers with a properly tapered fixed-aperture collimator, stable beam currents of 150 mA per beam are anticipated. As such, the small apertures required by the CCUs are not expected to be problematic from an operational perspective.

A new optics correction algorithm has been developed in anticipation of operation with the combined-function dipoles. The algorithm is an extrapolation of the low-emittance tuning method used in CesrTA [8, 9], based on betatron phase measurements from resonant excitation. With proper alignment, vertical emittance around 10 pm should be achievable.

SUMMARY

The upgrade presented here provides a substantial increase of up to four orders of magnitude in brightness for CHESS users at a minimal cost, when compared with a ring-wide overhaul. This would greatly simplify operations by eliminating the requirement of electrostatically-separated counter-rotating beams. The upgrade will require replacing one sextant of the CESR lattice and upgrading or replacing 2/3 of the beam lines, and mandates the removal of part or all of the CLEO detector. Positron capabilities will be retained for accelerator physics studies.

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