# CESR LOW EMITTANCE UPGRADE WITH COMBINED FUNCTION BENDS*

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## *Abstract*

The Cornell Electron Storage Ring is the laboratory for the CESR Test Accelerator damping ring R&D program, and the source of x-rays for the Cornell High Energy Synchrotron Source. A peculiarity of the layout of the storage ring is that horizontal emittance is generated predominantly by the strong bends in the sextant of the ring that was designed with a long straight to accommodate the interaction region required when the machine operated as an electron-positron collider. By reconfiguring that single sextant (L0) we reduce the emittance by 50% to 25 nm-rad at 5.3 GeV for x-ray production and with damping wigglers to 1.5 nm-rad at 2.1 GeV for investigations of low emittance phenomena. The 35 m radius of curvature, 3.2 meter long dipoles are refitted as combined function (vertically focusing) magnets to create simple achromats. The connecting zero dispersion straights can accommodate as many as six, 3 meter long undulators, in addition to six superconducting damping wigglers. By virtue of reducing horizontal emittance and energy spread at 2.1 GeV, the reconfiguration enhances the sensitivity of CESR to the emittance diluting effects that are the subject of the CesrTA study. At the same time, operation as a light source is significantly improved with lower emittance, and as many as six new undulator beam lines.

The reconfigured hard bend region can be the basis of a global upgrade of the storage ring. By extending the conversion of single function to combined function magnets to all of the ring dipoles, we reduce the horizontal emittance at 5 GeV (for x-ray operation) to $\sim$ 1nm-rad and at 2 GeV (for damping ring studies) to less than 80 pm-rad, well into the parameter space of the worlds most brilliant x-ray sources and ambitious positron sources.

## INTRODUCTION

The proposed rearrangement of the layout and optics in the CESR flares is the basis for a possible optimization of the storage ring for operation of the CHESS x-ray source and CesrTA R&D[1]. By refitting the hard bends as combined function (vertically focusing) magnets and careful matching to the CESR arcs, it is possible to achieve relatively low emittance, and to accommodate as many as a total of six undulator beam lines. Changes to the CESR layout are limited to the region south of the RF straights. The permanent magnet wiggler beam lines are preserved. With the elimination of the horizontal separator in the east, the F-line wiggler could be replaced with a $\sim$5 m long undulator. In the west, the RF cavities could be translated a couple of meters to the south, making space for a 5 m undulator feeding the G-line x-ray experimental area. There are additionally 4 new 6 meter long, zero dispersion straights, separated by $10^o$ of bend, that could be fitted with undulators. The configuration is compatible with an ongoing CesrTA low emittance program, as there is space for damping wigglers, as well as undulators in the zero dispersion straights. Horizontal emittance at 5.3 GeV is 25 nm-rad, and at 2 GeV with damping wigglers, $\epsilon_x \sim 1.5$ nm-rad.

## STORAGE RING OPTICS

In order to save space for undulators, vertical focusing is incorporated into the hard bends. The existing 8 hard bends, and the 2 each soft bends and quarter normal bends that together provide the $51.3^o$ of bend from west to east RF straights, are replaced with 10 equal strength combined function bends, with length $l = 3.238$ m (same as the existing hard bends), bending radius 35.97 m (as compared to the current hard bend radius $\rho = 31.65$ m) and $k = -0.1056 \text{ m}^{-2}$. The pole faces of the existing magnets can be modified to produce the required gradient as shown in Figure 1.

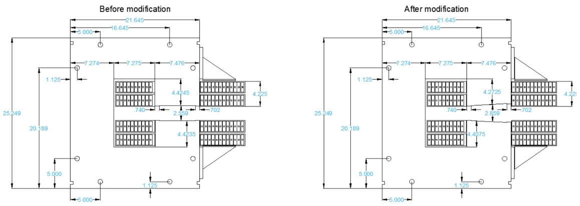

Figure 1: The cross section of the hard bend dipole is shown on the left, and with the pole face modified to provide a vertically focusing gradient on the right.

Nine horizontally focussing quadrupoles are required, five with ($k = 1.29 \text{ m}^{-2}$, and $l = 60$ cm), and four with ($k = 0.62 \text{ m}^{-2}$, and $l = 60$ cm) We propose to build a longer (1 m quadrupole) , for the very strong quadrupoles described above using our inventory of quad laminations to lengthen existing 60 cm quadrupoles. The layout and optical functions extending through the reconfigured southern sextant, are shown in Figs. 2 and 3.

The match to the arcs is shown in the plot of the twiss parameters for the entire ring in Figure 2. The lattice parameters are summarized in Table 1. The lengths of the drifts in the reconfigured hard bend region can easily be adjusted to preserve the ring circumference.

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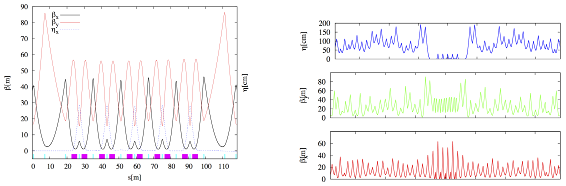

Figure 2: (Left)Optical functions through L0. The light blue rectangles represent quadrupoles and the purple, combined function bending magnets. There is zero dispersion in the RF straights, and zero dispersion in the four straight sections between the pairs of bends. (Right)Twiss parameters for the entire ring. The reconfigured sextant is at $-60 < s < 60$ m in the right plot.

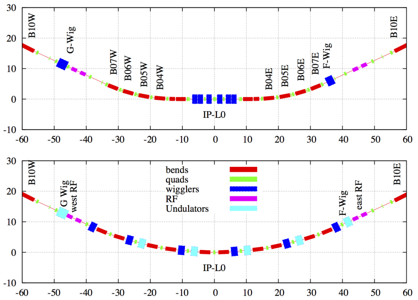

Figure 3: L0 layout. At the top is the existing layout of the sextant that once housed the CLEO colliding beam detector. Existing x-ray wiggler beam lines are indicated, as are the superconducting damping wigglers. The bottom figure shows the proposed layout including additional undulators. There is zero horizontal dispersion in all of the insertion straights. (Beam goes from right to left)

## *Error tolerance*

We have grown accustomed to the flexibility afforded by independent control of all of the storage ring quadrupoles. By including the vertical focusing as part of the bends we can no longer correct focusing errors by simply adjusting the appropriate quad. Furthermore, we are unable to trim the hard bends with backleg windings, to correct the orbit, as any change in field will also change focusing. But the relatively high density of horizontal quadrupoles provides significant leverage for compensating nearby errors. Indeed, the density of adjustable quadrupoles is no different than in the existing layout. We have shown that the lattice can be readily adjusted by varying the quadrupoles, to compensate the focusing of six 1.9 T damping wigglers at 2.085 GeV, located as shown in Figure 3. A more detailed analysis of error tolerance is required to determine how many corrector magnets (dipole and possibly quadrupole) are needed. We are also investigating the possibility of including trim windings on the pole faces of the hard bend magnets for fine adjustment of dipole, quadrupole and sextupole components[2].

Table 1: Lattice parameters (Values in parenthesis are with 11 damping wigglers at 1.3 T for 2.1 GeV and 1.9 T for all other energies. ) (Beam Power [kW]) = (Synchrotron Radiaiton Loss/Turn[MeV]) X (Beam Current [mA]). Bunch length and synchrotron tune assume an RF accelerating voltage of 6MV at 500MHz

| Energy[GeV] | 5.289 | 6.5 | 2.1 |
|---|---|---|---|
| $\epsilon_x$[nm-rad] | 25.5(13.0) | 38.8(23.5) | 4.0(1.5) |
| $\epsilon_y$[pm-rad] | 50(25) | 60(40) | 2(2) |
| Current [mA] | 500 | 200 | 500 |
| Bunches | 600 | 600 | 600 |
| $Q_x$ | 15.86 | 15.86 | 15.86 |
| $Q_y$ | 7.26 | 7.26 | 7.26 |
| $Q_z$ | 0.0364 | 0.0328 | 0.0579 |
| $\tau_x$[ms] | 24(12) | 13(7.8) | 388(97.2) |
| $\tau_y$[ms] | 27(12.6) | 14(8.3) | 427(99.5) |
| $\tau_z$[ms] | 14(6.5) | 7.6(4.3) | 226(5.0) |
| $\alpha_p$ | $5.7 \times 10^{-3}$ | $5.7 \times 10^{-3}$ | $5.7 \times 10^{-3}$ |
| $\sigma_E/E[\times 10^{-4}]$ | 6.2(10.9) | 7.5(11.5) | 2.4(6.4) |
| $\sigma_l$[mm] | 11.8(20.9) | 16.0(25.4) | 2.9(7.7) |
| $\Delta E$/turn [MeV] | 1.0(2.) | 2.3(4.0) | 0.025(0.11) |
| Beam Power [kW] | 500(1000) | 460(800) | 12.5(55) |

## *Wigglers*

Note that each zero dispersion straight is split by a quadrupole into two 3.45 m drifts. One could imagine placing a 3 meter long undulator in one of the drifts, and a superconducting wiggler in the other. The wigglers could be used for ultra-low emittance operation for CesrTA or possibly for low energy operation of CHESS. In summary, the lattice can accommodate as many as 6 undulators and 6 superconducting wigglers in the L0 sextant in addition to the 6 wigglers now in the arcs.

Figure 4: At present CHESS x-ray are generated by counterrotating electron and positron beams. In the proposed reconfiguration x-ray lines are all illuminated by radiation from a single beam traveling counterclockwise. A possible layout of undulator beam lines and accompanying experimental stations in the reconfigured machine are shown.

## CESRTA

As shown in Table 1, the proposed configuration yields horizontal emittance of 1.5 nm-rad at 2.1 GeV assuming 11 wigglers operating at 1.3 T. This compares to 2.5 nm-rad in the current CesrTA low emittance optics where we use 12 wigglers at 1.9 T. In addition to the smaller horizontal emittance, the energy spread is reduced in the new layout from 0.081% to 0.064% and the bunch length from 10.6 mm to 7.7 mm, as a result of the lower wiggler field. Furthermore, as there is zero dispersion in the RF cavities, coupling of longitudinal and transverse motion is much smaller than in the standard CesrTA optics. This distortion of the bunch phase space complicates the interpretation of IBS measurements. The new layout would provide an opportunity to measure collective effects with significantly smaller emittance, (both transverse and longitudinal) and where there is no distinction between normal mode and projected emittance.

We estimate the capital cost for rebuilding the single sextant of the storage ring to be less than \$4 M and that the work could be completed in about nine months of down time[1].

## PENULTIMATE CESR

The reconfiguration of the hard bend region described above can be the basis of a global upgrade of the storage ring. By extending the conversion of single function to combined function magnets for all of the ring dipoles, we reduce the horizontal emittance at 5 GeV (for x-ray operation) to $\sim$ 1nm-rad and at 2 GeV (damping ring studies) to less than 80 pm-rad, well into the parameter space of the world's most brilliant x-ray sources and ambitious positron sources. The concept is to split the arc dipoles that are now paired with a single coil to form a 6.6 m chevron, into two 3.3 m rectangular bends, and then to modify the poles to include both horizontal de-focusing, quadrupole and sextupole components. The arc cell and a first approximation of the ring optics is shown in Figure 5. The dynamic aperture at 5.3 GeV is shown in Figure 6 where the vertical chromaticity is compensated by the sextuple component of the combined function bends and the horizontal chromaticity by the sextupole adjacent to the quadrupole. (The layout shown in Figure 5 is a simplification insofar as there is no match to the injection lines). Parameters of the "Penultimate CESR" ring are shown in Table 2 for various beam energies.

The proposed reconfiguration of the full ring requires splitting the existing "chevron" bend magnets, modification of the magnet poles to include gradient and sextupole, and construction of new coils compatible with the shorter length. The quadrupoles can be reused without modification. The sextupole magnets have only about 85% of the strength required to compensate chromaticity at 5.3 GeV. Some modification of the poles, and/or coils would be required. The estimated capital cost of the upgrade is \$25 M [1].

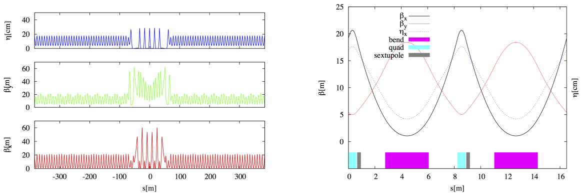

Figure 5: (Left)Penultimate CESR optics. The reconfigured sextant is at the center of the figure. (Right) Arc cell. The bend magnet includes vertically focusing quadrupole and sextupole components. The discrete quadrupole and sextupole are both horizontally focusing.

Table 2: Lattice parameters for Penultimate CESR. $Q_x$= 35.13 and $Q_y$=11.29. There are 600 bunches spaced 4ns apart. Numbers in parenthesis are with damping wigglers.

| Energy[GeV] | 5.289 | 6.5 | 2.1 |
|---|---|---|---|
| $\epsilon_x$[nm-rad] | 1.2 | 1.9 | 0.21(0.075) |
| $\epsilon_y$[pm-rad] | 1 | 1 | 1(0.5) |
| Current [mA] | 300 | 150 | 500 |
| $Q_z$ | 0.01 | 0.0091 | 0.016 |
| $\tau_x$[ms] | 11.1 | 6.1 | 197(67) |
| $\tau_y$[ms] | 16.1 | 9.0 | 297(75) |
| $\tau_z$[ms] | 10.4 | 5.9 | 199(40) |
| $\alpha_p[\times 10^{-4}]$ | 4.36 | 4.36 | 4.36 |
| $\sigma_E/E[\times 10^{-4}]$ | 8.2 | 9.76 | 3.1(7.0) |
| $\sigma_l$[mm] | 4.4 | 5.7 | 1.0(2.3) |
| Energy loss/turn [MeV] | 1.7 | 3.7 | 0.036(0.142) |

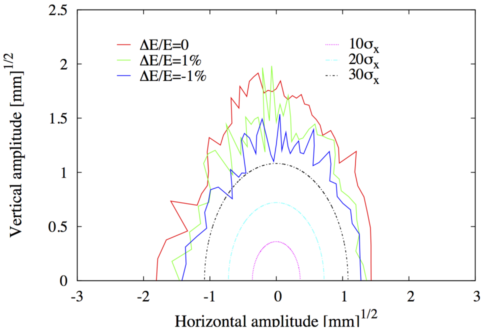

Figure 6: Penultimate CESR dynamic aperture. Lines indicate maximum initial amplitude that survives more than 1000 turns.

## REFERENCES

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[2] A. Mikhailichenko, "On the Possibility of Flat Pole Magnet Modification into a Magnet with Variable Gradient," CBN 13-4, January 2013