

# MINIMIZATION OF EMITTANCE AT THE CORNELL ELECTRON STORAGE RING WITH SLOPPY MODELS

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## Abstract

Our current method to minimize the vertical emittance of the beam at the Cornell Electron Storage Ring (CESR) involves measurement and correction of the dispersion, coupling, and orbit of the beam and lets us reach emittances of 10 pm, but is limited by finite dispersion measurement resolution. For further improvement in the vertical emittance, we propose using a method based on the theory of sloppy models. The storage ring lattice permits us to identify the dependence of the dispersion and emittance on our corrector magnets, and taking the singular value decomposition of the dispersion/corrector Jacobian gives us the combinations of these magnets which will be effective knobs for emittance tuning, ordered by singular value. These knobs will permit us to empirically tune the emittance based on direct measurements of the vertical beam size. Simulations show that when starting from a lattice with realistic alignment errors which has been corrected by our existing method to have an emittance of a few pm, this new method will enable us to reduce the emittance to nearly the quantum limit, assuming that vertical dispersion is the primary source of our residual emittance.

## INTRODUCTION

The Cornell Electron Storage Ring (CESR) is a 768 m circumference storage ring at Cornell University using electron and positron beams of up to 5.6 GeV. Among other uses, it is a testbed for beam dynamics relevant to damping rings of future linear colliders, including low-emittance tuning. It is instrumented with roughly 100 Beam Position Monitors (BPMs) and a large number of independently-controllable corrector magnets, of which 85 (the vertical kickers and skew quadrupoles) are useful for reducing the vertical emittance. Currently, we minimize the vertical emittance at CESR by identifying and correcting the sources of emittance, such as dispersion and coupling, enabling us to obtain vertical emittances of order 10 pm. The effectiveness of this method is limited by finite dispersion resolution, forcing us to take a different approach in order to proceed further [1].

One method is to make use of sloppy models. These are models which nominally depend on a large number of parameters, but, if we transform to a basis of eigenparameters, the corresponding eigenvalues show an exponential falloff when written in decreasing order [2, 3]. Therefore, only a few of these eigenparameters will be sufficient to describe most of the behavior of the system. In our case, these sloppy eigenparameters will be various linear combinations of the corrector magnets which affect our vertical emittance. To obtain improved emittances, it would be useful to identify

which combinations of our corrector magnets have the largest impact on the emittance. We may then adjust those magnet combinations by hand and monitor the vertical emittance directly in order to bring further reductions in emittance. This is similar to the RCDS method successfully employed at SLAC by Huang *et al.* [4, 5].

The utility of the eigencombinations depends on our ability to monitor vertical emittance and closed orbit. CESR is equipped with an xray beam size monitor that provides real time measurement of the vertical beam size with resolution corresponding to emittance 0.5 pm-rad. A visible light interferometer measures horizontal beam size. The closed orbit is continuously monitored with the 100 distributed beam position monitors referred to above.

## PROCEDURE

To first order, the vector of dispersions measured at each of our  $N$  BPMs,  $\vec{d}$ , will be equal to  $J\vec{c}$ , where  $\vec{c}$  is the vector of our  $M$  corrector magnets and  $J$  is the  $N \times M$  dispersion/corrector Jacobian matrix. This may be found from simulations of the ideal CESR lattice using the BMAD accelerator-simulation program. [6] We may take its singular value decomposition (SVD) in order to identify its right singular vectors,  $\vec{v}_i$ , which correspond to different magnet combinations, and their associated singular values, which tell us their effectiveness at changing the dispersion. Since our vertical emittance is strongly dependent on the vertical dispersion, we expect that these magnet combinations should give us large emittance effects as well. We may check that this model shows sloppy behavior by examining the singular values of our dispersion/corrector Jacobian, which are plotted in Fig. 1. We immediately see that the singular values drop roughly exponentially, indicating that this model is sloppy.

To evaluate the effectiveness of these sloppy directions, we used BMAD simulations. We generated a lattice with random magnet alignment errors consistent with our measurement resolution in CESR. We then applied our standard emittance tuning procedure including measurement errors corresponding to our BPM resolution, obtaining a few pm emittance. [1] At this point, we applied our sloppy model algorithm by sequentially varying each of our magnet combinations found above in order of decreasing singular value to obtain a minimal emittance. We repeated this procedure for an ensemble of 83 misaligned lattices to obtain a sense of the utility of our method. We see in Fig. 2 the mean emittance across our ensemble of lattices after tuning different numbers of singular directions. Note that we are able to reduce the emittance by a factor of 3 with just 10 magnet combinations, and by more than a factor of 5 with 25 such

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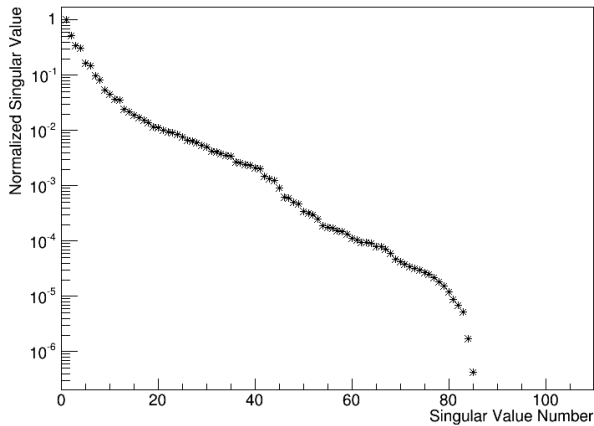


Figure 1: Singular values of the dispersion/corrector Jacobian. Note the large drops in singular value.

combinations. The vertical emittance has a quantum limit of 0.25 pm.

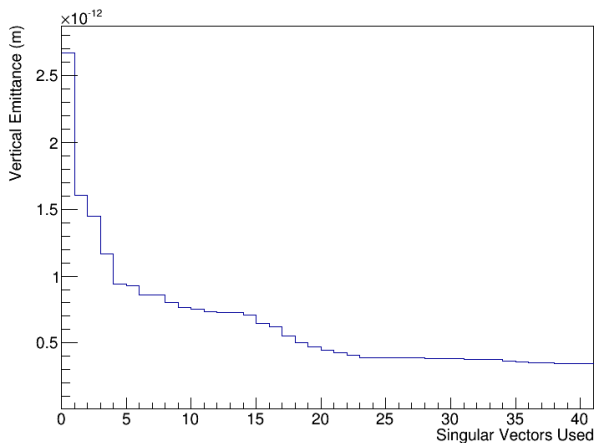


Figure 2: Vertical emittance as a function of singular vectors used to minimize it. Although we have 85 corrector magnets, only 10 combinations are needed to reduce the emittance by more than a factor of 3.

### Orbit Correction

Although this procedure vastly improves our vertical emittance, it also creates severe orbit distortions, as may be seen in Fig. 3. We therefore wish to find some way to preserve most of our gains in emittance while at the same time preventing large changes in the orbit. We found that this may be most easily accomplished by finding new magnet combinations which reduce emittance while avoiding excess harm to the orbit. We can take the SVD of the orbit/corrector Jacobian, which gives us the magnet combinations,  $\vec{u}_j$ , which have the largest effect on the orbit. We may then form new magnet combinations as  $\vec{w}_i = \vec{v}_i - \sum_{j=0}^K (\vec{v}_i \cdot \vec{u}_j) \vec{u}_j$ , subtracting off the projections of our old magnet combinations onto

the  $K$  magnet combinations having the greatest effect on the orbit. Setting  $K$  to 25 and using our same methods as before, we see emittance drops similar to what we had previously, but with much less harm to the orbit. See Fig. 4 and 5.

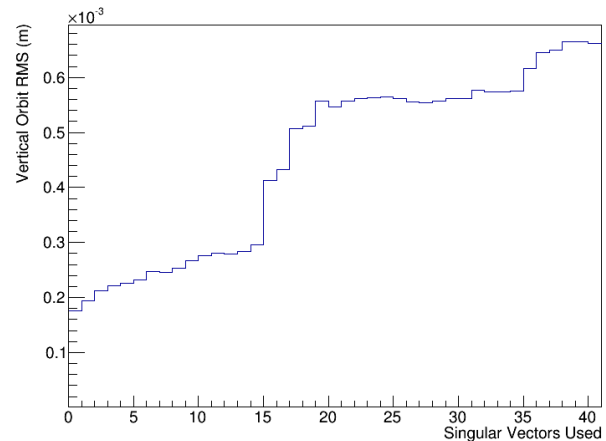


Figure 3: Vertical orbit RMS as a function of number of singular vectors used. We see an increase by nearly 100 microns if we use ten singular vectors, and 400 microns if we use 25.

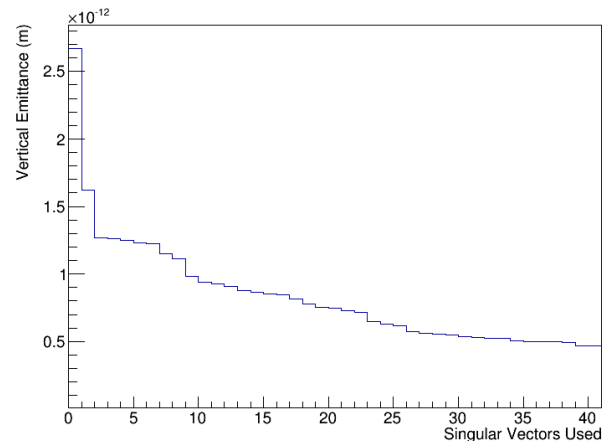


Figure 4: Vertical emittance as a function of modified singular vectors used to minimize it. We see improvements comparable to those in Fig. 2, when we made no attempt to minimize orbit changes.

### FUTURE WORK

Although this process works well in simulation, it will be necessary to try it in a real machine. We will therefore make these magnet combinations real knobs which we can turn at CESR and try the procedure. We also note that the vertical emittance in simulation with realistic misalignments (a few pm) is less than in the real ring (ten pm), so there is some as-yet unknown source of vertical emittance. It will be

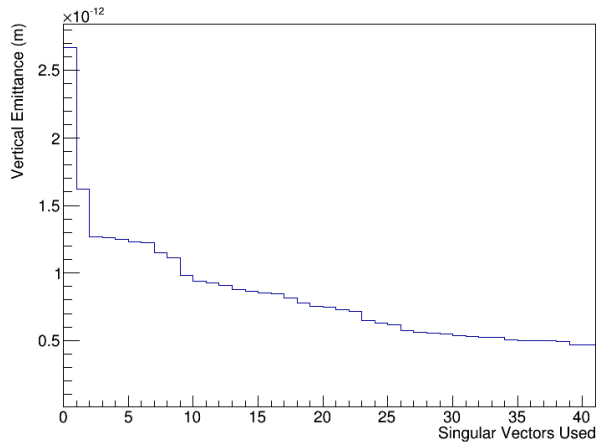


Figure 5: Vertical orbit RMS as a function of modified singular vectors used. We see gains of only a few tens of microns, which is a large improvement over the several hundred micron errors from our previous method.

interesting to see to what extent our tuning procedure will mitigate that error.

## CONCLUSIONS

We have found that, although the vertical emittance of the CESR beam depends on a large number of magnets, we should be able to reduce it using good combinations of correctors. These may be obtained from the SVD of the dispersion/corrector Jacobian, and corrected by subtracting components of the singular vectors of the orbit/corrector Jacobian. The resulting emittance is reduced by a factor of three when using 25 such singular vectors, while the orbit only gets worse by a few tens of microns. This procedure may be easily applied online to the accelerator by manually

tuning each of our magnet combinations in sequence until we reach a minimal emittance.

## ACKNOWLEDGMENTS

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