USING HIGH PRECISION BEAM POSITION MONITORS AT THE CORNELL ELECTRON STORAGE RING (CESR) TO MEASURE THE ONE WAY SPEED OF LIGHT ANISOTROPY

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Abstract

The Cornell Electron Storage Ring (CESR) has been equipped with a number of high-precision beam position monitors which are capable of measuring the orbit of a circulating beam with a precision of a few microns. This technology will enable a precision measurement of deviations in the one-way speed of light. An anisotropic speed of light will alter the beam momentum as it travels around the ring, resulting in a change of orbit over the course of a sidereal day. Using counter-circulating electron and positron beams, we will be able to suppress many of the systematics such as those relating to variations in RF voltage or magnet strength. We show here initial feasibility studies to measure the stability of our beam position monitors and the various systematic effects which may hide our signal and discuss ways in which we can minimize their impact.

INTRODUCTION

The isotropy of the speed of light forms a cornerstone of modern physics. However, theories of quantum gravity suggest that this symmetry may not hold exactly, so it is possible that the speed of light may not be wholly isotropic. Although very good measurements have been done on the two-way speed of light, accurate measurements of the one-way speed are significantly more difficult. A recently proposed way to precisely test the isotropy of the one-way speed of light is to examine the behavior of counter-circulating electrons and positrons in the Cornell Electron Storage Ring (CESR) [1,2]. If the speed of light is anisotropic, the relationship between velocity and momentum will be direction-dependent. Particle momenta will vary around the storage ring, causing the orbits to vary over the course of a sidereal day. The fractional change in orbit is enhanced by a relativistic factor of γ^2 relative to the the fractional change in the speed of light. Since we are using 5.3 GeV beams, this means that we may obtain a limit of the speed of light anisotropy of one part in 10^{16} with an orbit measurement accurate to one part in 10^8. To reduce systematics, we will look at the difference between the positron and electron orbits. Any change in the operating parameters of the accelerator will result in different orbit shifts for the two species only insofar as the electrons and positrons have different energies at different parts of the ring, and so will be greatly suppressed. Meanwhile, our signal will be enhanced because, if the energy of the electrons is increased in one part of the ring due to a speed of light anisotropy, the positron energy will be reduced by the same amount since they are traveling in the opposite direction.

We present here a number of studies in simulation and actual experiment. We first use BMAD, an accelerator simulation program, to simulate a signal from the speed of light anisotropy as well as the effects of changes in dipole strength or RF voltage [3]. We next examine data taken at CESR where we put electron and positron beams in the ring and changed the RF voltage. Finally, we observe the stability of the beam position monitors (BPMs) and see that there is a current-dependent effect. Simulations show that this may be due to some current-dependent gains in the BPM buttons.

ACCELERATOR LATTICE

Single counterrotating bunches of electrons and positrons collide at diametrically opposed interaction points in the storage ring. A colliding beam lattice was designed to minimize the effect of the collisions on both closed orbit and lifetime. The strength of the beam-beam collision is characterized by the tune shift parameter $\xi = \frac{N}{2\pi\gamma}\frac{\beta_i}{\sigma_i(\sigma_x+\sigma_y)}$, where $i = x, y$ gives the horizontal and vertical tune shifts respectively. Since $\sigma_x >> \sigma_y$, we minimize vertical tune shift by minimizing β_y. Horizontal beam size is given by $\sigma_x = \sqrt{\epsilon\beta_x + (\eta\delta)^2}$. To minimize horizontal tune shift, we minimize horizontal beta and maximize emittance and horizontal dispersion. The relevant lattice parameters at the two interaction points are given in Table 1. The beam energy is 5.3 GeV. The beam position monitors are most accurate in the current range of 0.5-1.0 mA/bunch. Beam beam parameters at the two interaction points (IP) in the table are computed for $N = 10^{10}$ particles per bunch (0.6 mA).

Table 1: Beam Parameters at Interaction Points

IP	β_x (m)	β_y (m)	η_x (m)	$\xi_x \times 10^{-3}$	$\xi_y \times 10^{-3}$
south	6.1	3.94	0.99	1.66	4.86
north	5.5	4.38	1.00	1.51	5.04

The beam-beam parameter is well below the limit measured at all electron-positron colliders. Because the electrons and positrons do not collide head-on as a result of the energy scallop, and perhaps other effects, there the beam-beam kick may introduce a current dependent distortion of the closed orbit. This effect is shown in simulation to cause orbit shifts at the micron level.

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BACKGROUND SUPPRESSION

We used BMAD to simulate a signal from a speed of light anisotropy by changing the energy of the beam by a direction-dependent factor of $1 + 10^{-4}\cos(\theta)$, where θ is the angle between the direction of the beam and east. We have plotted the difference between electrons and positrons of the orbit change due to an anisotropic speed of light (the difference of differences) as Fig. 1.

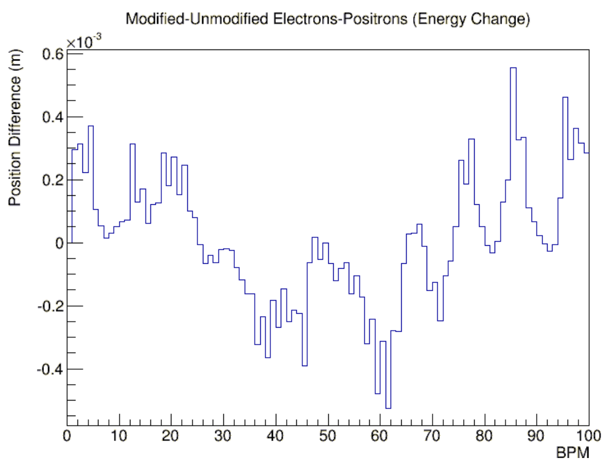

Figure 1: Difference in electron and positron orbit changes when changing energy sinusoidally around the ring with amplitude one part in 10^4.

We wish to compare this to the change in orbit differences if we change the dipole strengths by a similar amount. Figure 2 shows this resulting change if the dipole strengths are altered by one part in 10^4. We see immediately that we are only 400 times more sensitive to the speed of light anisotropy signal than to a dipole error. However, if we take the Fourier transform for each plot, we obtain Fig. 3 for the case of an anisotropic speed of light and Fig. 4 for the case of a dipole drift. We note immediately that there is a large spike at the revolution frequency in the former case, but not in the latter. If we examine only this peak, we are 5 thousand times more sensitive to a change in particle momentum due to a speed of light anisotropy than to a comparable change in dipole field.

We also worry that an antisymmetric change in RF voltage will give a signal resembling a speed of light anisotropy, since that will artificially boost the energy of one particle species and lower it in the other. We therefore simulated such a change in the RF cavity voltages antisymmetrically between east and west and found that we are 30 thousand times more sensitive to a speed of light anisotropy than to such an RF voltage change at a similar level. We tested this by injecting single electron and positron bunches in CESR, and changing the RF voltages antisymmetrically after about ten minutes, then returning them to their nominal values. We have plotted in Fig. 5 the orbital frequency component of the FFT of the positron-electron orbit difference as a function of time, and can see clearly the times when we changed the RF and when we changed it back. The observed change agrees

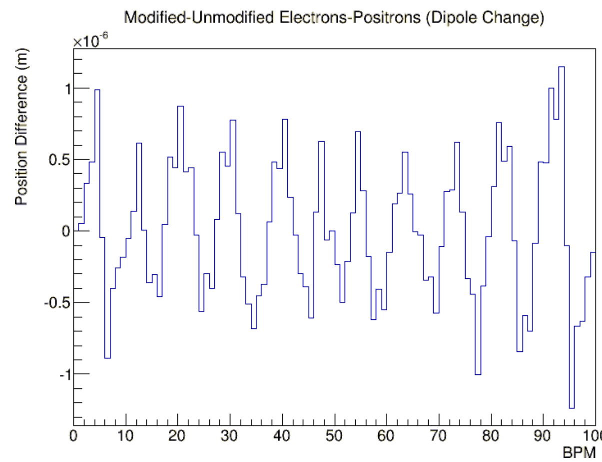

Figure 2: Difference in electron and positron orbit changes when changing dipole strength by one part in 10^4.

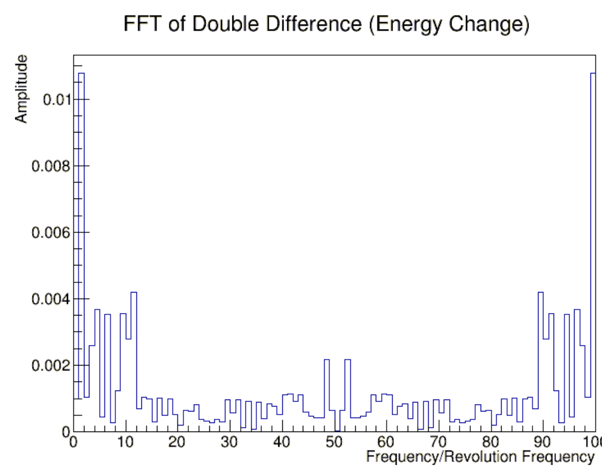

Figure 3: FFT of difference in electron and positron orbit differences due to sinusoidal energy change of amplitude one part in 10^4.

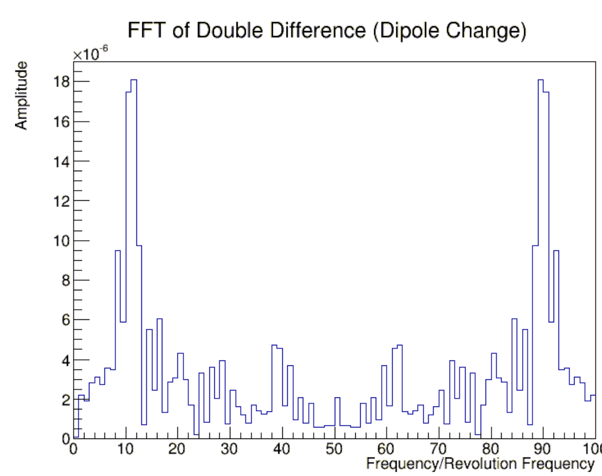

Figure 4: FFT of difference in electron and positron orbit differences due to dipole strength change of one part in 10^4.

well with simulation and is the sort of signal we would expect if the particle momenta changed by 3 ppm due to a speed of light anisotropy. However, we note that there is a similar change in the FFT value during the first part of the run, when we were not changing anything. This will severely limit our experimental sensitivity if uncorrected and we will discuss it further in the next section.

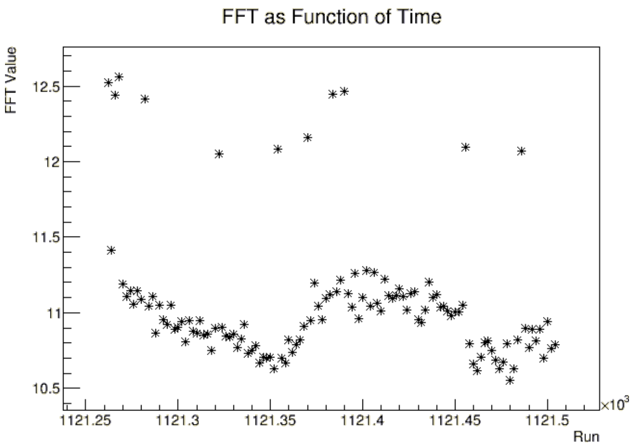

Figure 5: Plot of FFT value at the revolution frequency for difference between electron and positron orbits as a function of time. We are clearly able to pick out the time when we had the RF cavity voltages shifted to a different value (runs 112136 - 1121450). However, there is a similar change at the start of data-taking, when we were not doing anything, which would dramatically reduce our sensitivity if we do not have it under control.

BPM STABILITY

The stability of our BPMs is of very great importance for detecting a speed of light anisotropy, since any drift in measurements over the course of data-taking would greatly contaminate our signal. We suspect that the BPM instability described above is due to some current-dependent effect, since it appeared to be stronger in cases when the current of our beam was changing more quickly.

To further investigate this, for each BPM in the ring we recorded the difference between the electron and positron orbits for each run and plotted this as a function of time. These data are displayed in Fig. 6 for one particular BPM during a period of changing beam current, and we see that the electron/positron position difference changes by several tens of microns. This is much larger than the few micron precision obtainable with a constant beam current.

Our BPM button gains were calibrated using a procedure developed by David Rubin and Jim Shanks and described in [4]. However, this calibration was only performed for one value of the beam current, so the BPM buttons may have some current-dependence in their gains. We therefore performed a fit to the data to determine what values for a drift, if any, would give us our signal if the electron/positron position difference was roughly constant. As seen in Fig. 6, such a fit is possible. Moreover, it only requires gain drifts of roughly one percent or less, which is certainly plausible.

We will therefore perform our gain calibration at various beam currents in order to determine whether such a drift in gains actually exists.

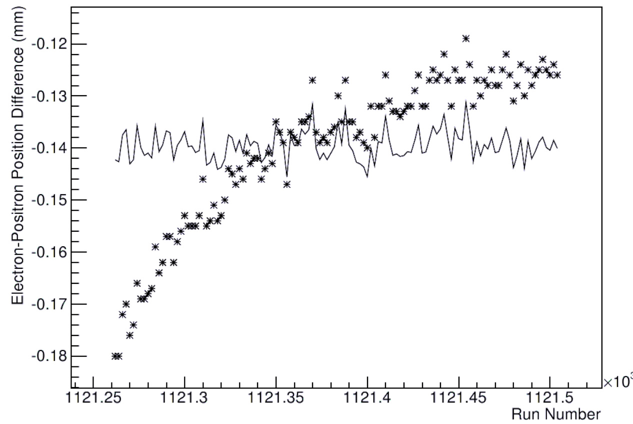

Figure 6: Electron/positron orbit difference at BPM 17 as a function of time. The points show the measured data, while the line shows the resulting orbit difference if one corrects for a hypothetical current-dependent gain. We see that such a current-dependent gain would explain our measured orbit change.

CONCLUSIONS

We see that effects of changes in dipole strength and RF cavity voltage are significantly weaker than corresponding changes in the particle momentum throughout the ring as may be expected due to an anisotropic speed of light. The simulations for the RF case agree well with what had been seen in the data. However, BPM stability presents a major problem, and will severely harm the precision of our experiment if not accounted for. We see that permitting our BPM buttons to have a small current-dependent gain will largely explain the problem. We will therefore recalibrate our BPMs at a number of different currents to measure this effect.

ACKNOWLEDGMENTS

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