COLLISIONS OF RESONANTLY COUPLED ROUND BEAMS AT THE CORNELL ELECTRON-POSITRON STORAGE RING (CESR)

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Abstract

As a first step toward testing the proposed "Möbius" scheme[1], we used existing CESR elements to collide round, rather than flat, beams. The tune shift parameter, ξ, was inferred from the beam profiles and current, was compared to the tune shift of the coherent beam-beam π mode, and was corroborated by luminosity measurement. Values of ξ up to 0.09 were achieved without significant lifetime reduction.

1 INTRODUCTION

For round beams ($\epsilon_x = \epsilon_y = \epsilon, \beta_x^* = \beta_y^* = \beta^* \rightarrow \sigma_x^* = \sigma_y^* = \sigma^*$), the well known expressions for the tune shift parameter and the luminosity, written in terms of the emittance, $\epsilon = \sigma^2/\beta$, become

$$\xi = \frac{r_e}{4\pi\gamma e f}\frac{I}{\epsilon}, \quad L = \frac{I^2}{4\pi e^2 f \beta^* \epsilon} = \frac{\gamma}{e r_e}\frac{\xi I}{\beta^*}, \tag{1}$$

where I is the current per beam. For a given ξ, L for a round beam is twice as large as for a flat beam; moreover, there is hope of achieving higher values of ξ with a round beam[2]. For dissimilar beams, equation (1) for the luminosity becomes

$$L = \frac{I_+ I_-}{2\pi e^2 f \beta^* (\epsilon_+ + \epsilon_-)}. \tag{2}$$

Simulations of round beams in collision show considerable promise, especially in the "Möbius" scheme proposed by Talman[1].[1] If a CESR lattice is tuned to the coupling resonance ($Q_x - Q_y = \text{integer}$), sufficient x-y coupling can be achieved using existing skew quadrupoles in CESR to make equal transverse emittances, $\epsilon_x = \epsilon_y$. The present interaction region (IR) quadrupoles can produce $\beta_x^* = \beta_y^*$, but only for relatively large values of β^*. While this limits the luminosity attainable with round beams, it does not prevent large ξ, which is independent of β^*; thus the present experiment focuses on ξ, rather than luminosity.

Since the bunch currents were sometimes not equal and the beam-beam blowup was often not symmetrical during these experiments, we consider separately the tune shift parameter experienced by each beam:

$$\xi_\pm = \frac{r_e}{4\pi\gamma e f}\frac{I_\mp}{\epsilon_\mp}. \tag{3}$$

A weak-strong unbalance can entrench itself if the stronger beam, by producing a large ξ, blows up the weak beam and thus reduces the ξ that it experiences itself.

During collisions there are two primary coherent modes of beam motion, analogous to the normal modes of coupled pendulums. One mode has the same frequency as single beam motion. The other mode, called the π mode, is shifted to a higher frequency. The relationship between the tune shift of the coherent beam-beam π mode, ΔQ_π, and the tune shift parameter, ξ, is

$$\cos 2\pi(Q_o + \Delta Q_\pi) = \cos 2\pi Q_o - 2\pi\lambda\xi_{\text{av}} \sin 2\pi Q_o, \tag{4}$$

where $\xi_{\text{av}} = \frac{1}{2}(\xi_+ + \xi_-)$. For an (unrealistic) linearized interaction, $\lambda = 2$. For more realistic models of round Gaussian beams, Yokoya and Koiso[3], and independently Alexahin[4], find $\lambda = 1.21$, assuming $\epsilon_+ = \epsilon_-$ and $I_+ = I_-$. The derating factor λ has not been derived for the case of unequally blown up bunches.

2 EXPERIMENTAL CONDITIONS

2.1 Machine Conditions

The design parameters for the round beam lattice are shown in table 1. The fractional tunes match the optimum operating point as found in simulation studies.[2] At the outset of the experiment, the betatron phase advance around the ring was measured and corrected[5] to conform to the design parameters. The resulting β functions agreed with the design values to within about 5%.

Table 1: Lattice parameters for round beam experiment.

Tunes	Q_x = 10.77 Q_y = 9.77
IP β-functions	$\beta_x^* = \beta_y^*$ = 0.30 m
IP dispersion	$\eta_x^* = \eta_y^*$ = 0.0 m
Emittances	$\epsilon_x = \epsilon_y$ = $\frac{1}{2}\epsilon_{x,\text{flat}}$ = 62.0 nm-rad

* Work supported by the National Science Foundation.

[1] A complete test of the "Möbius" insert requires considerable hardware effort, namely the installation of $45°$ rolled quadrupoles and stronger interaction region (IR) quadrupoles to produce small β^*. The experiments described in this paper were intended to test some aspects of round beam collisions before this hardware was available. A Möbius section has since been installed and awaits testing. Optics with smaller β^* will become available after the planned installation of superconducting IR quadrupoles in 1998.

[2] In a few tune scans done in the weak/strong regime, deterioration of beam-beam performance was seen at an average fractional tune of about 0.8, in rough agreement with predictions for the simulations. All results reported here are for collisions at the design tune.

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The CLEO detector solenoid was left at its usual field of 1.5 T, and compensation of this field was achieved by rolling quadrupoles on either side of the interaction point (IP) by small angles (minimum tune separation < 0.002). After that, a pair of skew quadrupoles was powered to produce the intended transverse coupling, which splits the observed tunes into upper and lower normal modes, where the tune split is a measure of the coupling strength. During these experiments, the tune split was typically 0.012. We collided single bunches of electrons and positrons. At the crossing point on the opposite side of the ring, the electron and positron bunches were separated vertically with an electrostatic bump.

2.2 *Diagnostics*

Existing monitors, which image synchrotron light onto a linear CCD photodiode array, were used to monitor the vertical profile. The output of these profile monitors was digitized and later fitted to a Gaussian plus a linear background, an example of which is shown in figure 1. Inferring the absolute vertical emittance, $\epsilon_y = \sigma_y^2/\beta_y$, requires knowledge of the optical magnification of the synchrotron light monitor and of β_y at the source point of the synchrotron light. These parameters are somewhat uncertain, as evidenced by the unequal values of ϵ_0 measured for positrons (51 ± 2 nm-rad) and electrons (61 ± 2 nm-rad). We normalize the scale factors to bring both values of ϵ_0 to their average, 56 nm-rad.[3] No horizontal scanners were available. The horizontal emittance was assumed to equal the vertical emittance due to the substantial coupling; this is consistent with the shape of the light image as seen on a TV monitor.

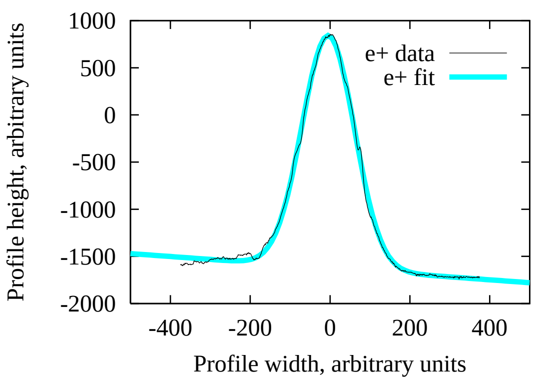

Figure 1: An example of the digitized beam profile and the Gaussian fitted to it. In the digitizer units, $\sigma = 58.6$, which corresponds to $\epsilon = 67.5$ nm-rad.

The coherent mode frequencies were monitored by a spectrum analyzer connected to pickup electrodes. During collisions the two coupled transverse modes and the corresponding coherent beam-beam π modes were easily identifiable in most cases. During most runs the π mode shift was slightly different for the two coupled modes, as shown in figure 2. The reason for this is not known. For calculating ξ, the average of the two tune splits, $\overline{\Delta Q_\pi}$, was used.

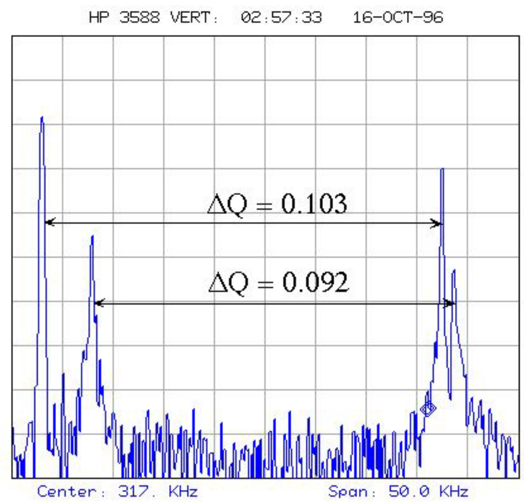

Figure 2: Spectrum of colliding beams showing all four modes. The average tune split seen here, $\overline{\Delta Q_\pi} = 0.098$, was the maximum tune split achieved.

During two runs, the luminosity was measured by the standard method using CLEO endcap detectors to monitor Bhabha scattering.

3 RESULTS

3.1 *Beam Blowup*

An important effect of the beam-beam interaction is the increase of the colliding beam emittance over that of the unperturbed single beam. If this blowup increases more quickly than proportionally to the current, then further gains in tune shift cannot be made by increasing the current. Figure 3 shows the emittance blowup factors for each beam, $b_\pm \equiv \epsilon_\pm/\epsilon_0$, as a function of the tune shift parameter experienced, $\xi_\pm$. The electrons are consistently blown up more than the positrons, an (unexplained) tendency also observed during flat beam operation of CESR. As the upper limit of these curves was approached ($\xi_- \to 0.09$), it became progressively harder to bring the beams into collision without loss; however, once in collision the beam lifetimes did not differ significantly from the pre-collision lifetimes. Furthermore, over the range of our data ($I_{\mathrm{per\ beam}}$ up to 22 mA), no limiting tune shift saturation is evident.

3.2 *π Mode Tune Shift*

For each run we compared the observed tune shift, $\overline{\Delta Q_\pi}$ to the value calculated from our measured ξ_{av} via equation (4). Unfortunately, the applicable derating factor λ has not

[3] Equality of positron and electron emittances to within 1% was confirmed by inserting scrapers into the vertical aperture until the beam lifetime of a single bunch of positrons or electrons reached a predetermined value.

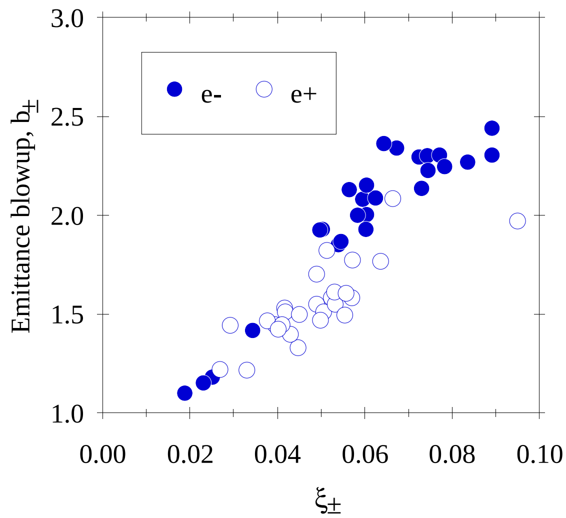

Figure 3: The emittance blowup of each beam, $b_{\pm}$ as a function of the tune shift parameter which it experienced, $\xi_{\pm}$.

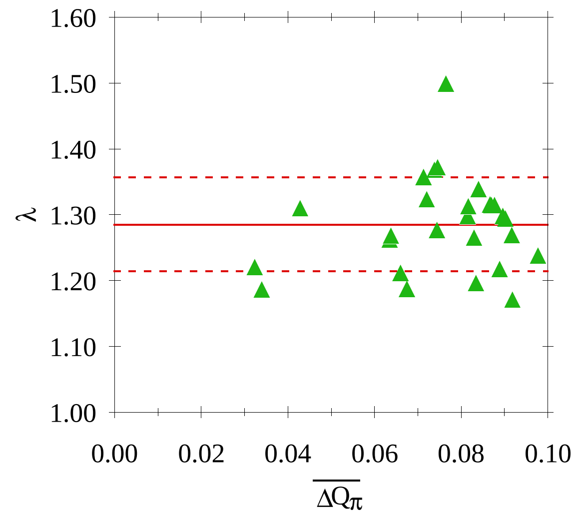

Figure 4: The calculated factor λ vs. ΔQ_{π}. $\lambda_{\rm av} = 1.28 \pm 0.07$ is indicated by the horizontal lines.

been derived for the case $\epsilon_+ \neq \epsilon_-$. Figure 4 shows that our results correspond to values of λ in the range 1.28 ± 0.07.[4]

3.3 Luminosity

As a further consistency check, the luminosity as measured by the CLEO endcap detector was recorded during two runs, and the beam profiles and currents were recorded several times during those runs from which the theoretical luminosity was calculated. Table 2 shows that there was good agreement between the measured luminosity and the luminosity predicted by equation (1).

Table 2: The luminosity calculated from I and ϵ and the measured luminosity at different times during two runs.

$I_{\rm per\ beam}$ in mA ($\pm$ 2%)	L in 10^{31} cm^{-2} s^{-1} Calculated ($\pm$ 10%)	Measured ($\pm$ 5%)
19.5	0.95	0.97
21.6	1.10	0.95
21.1	1.12	1.06
19.1	0.95	0.93

[4]For round beams with unequal currents per beam (but equal emittances), Yokoya and Koiso[3] find that λ increases from 1.21 to 1.28 as the current ratio becomes 2:1. Had we chosen to normalize our emittances to the lattice value ($\epsilon_0 = 62$ nm-rad), we would have obtained $\lambda = 1.43$; normalizing to the scraper result ($\epsilon_0 = 51$ nm-rad) would have yielded $\lambda = 1.18$.

4 CONCLUSION

These experiments demonstrate the feasibility and promise of collisions of beams made round via strong coupling. Tune shift parameters of the same order ($\xi \rightarrow 0.09$) as those in simulations were reached with only moderate emittance blowup and without significant lifetime reduction.

5 REFERENCES

[1] R. Talman, Phys. Rev. Lett., v. 74, p. 1590 (1995).

[2] S. Krishnagopal and R. Siemann, *Proc. 1989 IEEE Part. Accel. Conf.*, p. 836 (1989).

[3] K. Yokoya and H. Koiso, Part. Acc., v. 27, p. 181 (1990).

[4] Y. I. Alexahin, "On the Landau Damping and Decoherence of Transverse Dipole Oscillations in Colliding Beams," CERN-SL-96-64 AP (1996).

[5] D. Sagan, D. Rubin, and S. Greenwald, *Proc. EPAC '96* (1996).