Operation of CESR with Permanent Magnet Interaction Region Quadrupoles*

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Introduction

The Cornell Electron Storage Ring is a 768 m circumference electron positron collider which operates in the 10 GeV center of mass energy region of the Υ resonances. We have modified CESR by inserting strong permanent magnet quadrupoles close to the two interaction points. The additional focussing permits a reduction in the beta function at the interaction points, β_v^*, from 3 cm in our previous "mini-beta" configuration to 1.5 cm in our present "micro-beta" configuration.

The quadrupoles are embedded in the interaction region particle detectors with the inner faces only 64 cm from the interaction points. This is possible because of the compactness of the quadrupoles, and, in the South interaction region, because the rare-earth-cobalt (REC) permanent magnets are not affected by the 10 kG axial magnetic field of the CLEO detector.[1]

CESR has operated with the micro-beta configuration for about 1/2 year. We report on the initial operation and on measurements of luminosity performance as β_v^* approaches the bunch length.

Configuration of the South Interaction Region

Installing quadrupoles within the detectors introduced many problems involving mechanical support of and access to the storage ring and detector components. We summarize the configuration of the South interaction region with the aid of fig. 1.

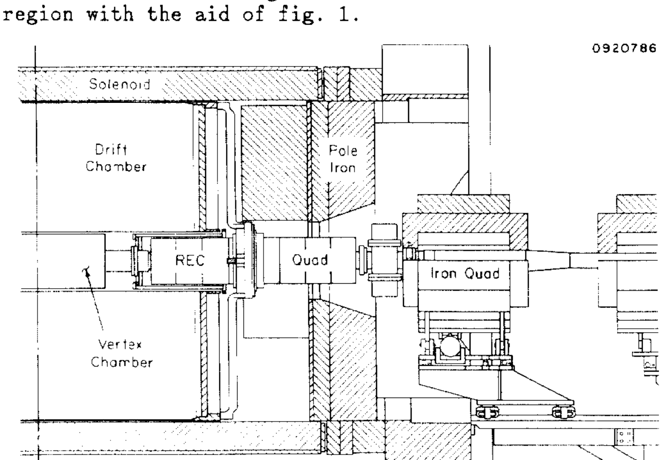

Fig.1: Configuration of the South Interaction Region

1. A vertex detector drift chamber sits at the center of the 34 cm bore of the large drift chamber. It is mounted on a Beryllium vacuum chamber with 11 cm diameter and 0.5 mm wall thickness; both are supported by a 30 cm diameter aluminum tube extending out to the drift chamber endplate.
2. The 10 cm diameter vacuum chambers through the REC quadrupoles include a synchrotron radiation mask 60 cm from the interaction point and water cooling circuits which stabilize the temperature of the quadrupoles and remove heat from beam induced wall currents in the chamber. The outer knife edge flange is designed with a split bolt ring so that the vacuum chambers can be installed along with the vertex detector but without the quadrupoles; the 450 kilogram quadrupoles are slipped on afterwards.
3. The vertically focussing REC quadrupoles are mounted directly outside the vertex chamber, with their inner faces 64 cm from the interaction point. They are supported by tubes containing bearings which permit rotation of the quadrupoles to partially compensate the coupling of the vertical and horizontal betatron motion caused by the 10 kG field of the detector solenoid. The tube is in turn supported by four lightweight aluminum legs which bolt to the heavy end ring of the drift chamber, which bears on the inner wall of the cryostat for the superconducting solenoid.
4. Outboard of the REC quadrupoles are short lengths of vacuum pipe containing synchrotron radiation masks, luminosity monitors, and ion pumps. The masks (with a horizontal aperture of +-2.5 cm) intercept direct radiation from the nearby soft bend magnets (B=1.2 kG) and scattered radiation from the more distant hard bend magnets (B=5 kG). The luminosity monitors sit in the horizontal narrows of the mask and view the interaction point through the horizontally defocussing field of the REC quadrupoles. The field extracts Bhabha scatters with horizontal angles down to about 10 mr, thus providing a rate of 150 counts/10^{31} cm^{-2}. The luminosity monitors use BGO crystals with photodiode readout to provide a compact assembly which is insensitive to magnetic fields.

The sputter-ion vacuum pumps are mounted top and bottom. They use Co_5Sm magnets to provide a 4 kG magnetic field which permits use of smaller pump cells and thus higher capacity/volume. The cells are formed by stacks of perforated stainless steel plates; the measured pumping speed is 45 liters/sec for each unit.
5. Beyond this vacuum chamber is an electrically powered quadrupole, also vertically focussing, which serves as a vernier to the REC quadrupole and permits changing the beam energy from about 4.3 to 6.0 GeV. This, and the horizontally focussing quadrupole beyond it, are mounted on Thomson bearings since they must be rolled back when the pole-tip iron is pulled out to permit access to the drift chamber face and the electronics mounted there.

The electrically powered quadrupoles are also rotated as part of the compensation of solenoid induced coupling. Rotation angles are typically 20 to 40 mr and must be accurate to 1 or 2 tenths of a mr. The angles are set by stepping motors and monitored by bubble levels with electrical readout which are temperature stabilized by small thermoelectric junction devices.

Performance of Components

1. In both the North and South interaction regions the diameter of the beam pipe at the interaction point was decreased from 15 cm (in the mini-beta configuration) to about 10 cm, permitting detectors to be placed closer to the interaction point but prompting the concern that background rates from beam halo or synchrotron radiation might not permit useful operation of the detectors. Synchrotron radiation background is in fact somewhat reduced; we observe no chamber current attributable to X-rays up to 5.5 GeV beam energy. Background from beam halo is also lower, by roughly a factor of three, probably in part because of the shielding provided by the massive REC magnets.
2. Another concern has been that the support of the REC quadrupoles would not be sufficiently stable, which could result in unpredictable changes in the closed orbit of CESR; the magnification factor for maximum

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closed orbit distortion caused by a transverse displacement of the quadrupole is about 50. We find, after the rather large perturbation of removing and replacing the iron pole-tips of the CLEO detector, that vertical orbit ripple is typically several mm, which is easily removed with our vertical orbit correctors.

3. Performance of the luminosity monitors is described in reference 2. On several occasions radiation from injection losses has darkened the BGO crystals and we have observed recovery of the light output to previous levels over a period of several days.

4. The electrical bubble levels are described in reference 3. We have observed drifts at the level of 1/4 mr and occasionally larger which we do not understand so that the levels, while useful, may not be a complete solution to our requirements for monitoring the quadrupole angles.

Performance of CESR

Before installation, the quadrupole fields of the REC magnets were cross-calibrated at the 0.1% level with those of our electrically powered arc and interaction region quadrupoles, and lattices for CESR were calculated using this calibration. Because the REC magnets are not identical in strength (variations are about 1/2%) we modified the power supplies for our electrically powered interaction region quadrupoles so that quadrupoles on opposite sides of the interaction region could be run at different strengths to compensate the REC asymmetry. The beam optics measured for the micro-beta lattices are close to design values, with only small changes required to bring β_v and β_h within 5% of design values at most positions in the ring.

For the past three years CESR has operated with three bunches each of electrons and positrons.[4] The bunches are separated at crossing points in the arcs so that collisions occur only at the two interaction points, and the maximum current/bunch is normally limited by the beam-beam interaction. For initial micro-beta operation, three bunch operation was continued and interaction region parameters were set to duplicate our previous mini-beta optics, with β^*_v=3 cm, β^*_h=0.8 m, and η^*_h=0.7 m. Luminosity performance was similar although we were limited to slightly lower bunch currents by RF cavity problems. After the tests described below we switched to a lattice with β^*_v=2cm. The result has been an increase in specific luminosity, as summarized in table I, but a reduced maximum bunch current compared to the 3 cm lattices for our mini-beta configuration, so that the integrated luminosity is about the same. During most of our recent operation the luminosity in the North Area, which contains a non-magnetic detector, has been 10-25% higher than in the South area. We attribute the difference to incomplete compensation at the South interaction point of the coupling caused by the CLEO solenoid; the difference has been decreased by operator tuning of skew and rotating quadrupoles and we are improving our diagnostic capabilities so that we can make better corrections.

Table I

Luminosity Performance at 5.18 GeV

Lattice	β^*_v	Peak current per bunch	Luminosity 10^{31} cm^{-2}/sec	Pb^{-1} per IR/day
Mini-β	3.2 cm	12.5 ma	2.5	1.2
micro-β	3.0 cm	10.0 ma	2.1	0.9
micro-β	2.0 cm	10.0 ma	2.5	1.3

Dependence of Luminosity on β^*_v

With the REC quadrupoles in place we can easily vary β^*_v between 1.5 and 5 cm. If the beam emittance were constant and the bunch length much smaller than β^*_v, luminosity would be proportional to $\beta^{*-1/2}_v$. Neither of these conditions is valid. The vertical beam emittance, for bunch currents of more than a few milliamps, is controlled by the beam-beam interaction. CESR has usually operated with a roughly constant vertical beam-beam linear tune shift of 0.02, corresponding to a vertical beam emittance which grows linearly with beam current. A constant tune shift gives $L \alpha \beta^{*-1}_v$.

In addition, the rms bunch length in CESR is 2.2 cm, or approximately equal to β^*_v, at our usual synchtrotron tune of 19 kHz. This means that interactions between the bunches take place at longitudinal positions where β_v is significantly higher than β^*_v, which results in a loss of luminosity due to the increase in the average height of the bunches during the collision. Also, for a fixed vertical emittance the average tune shift will be larger than for a very short bunch, and the beam emittance may grow in compensation; this would cause a further decrease in luminosity. Finally, it has been suggested that excitation of synchrobetatron resonances by the beam-beam interaction for particles with large energy oscillations should result in decreased beam lifetimes and hence lower maximum stable beam currents.[5]

We have measured the luminosity performance for lattices with β^*_v = 1.5,2.0,3.0,and 5.0 cm, at a constant bunch length of 2.2 cm. β^*_h was 1.05 m and the energy dispersion, η^*_h, 0.70 m. Tunes were close to our normal operating values, with ν_v=9.36, ν_h=9.39, and ν_s=0.05 . The CLEO solenoid was turned off to eliminate the need for compensation of coupling, and small focussing corrections were made to each lattice to ensure that the measured optics were close to design values. We monitored the North and South luminosities and also the beam-beam tune split as observed on spectrum analysers looking at signals from beam position monitors in CESR. The general procedure was to optimize luminosity in each lattice using small adjustments of the betatron tune and of skew quadrupoles which control residual coupling in the ring, and to measure luminosity and tune shift vs. current. Bunch current limits were observed as rapidly decreasing lifetimes and reduced operating space in the betatron tune plane for colliding beams.

The results have been analysed[6] and are summarized in fig. 2. Figure 2a shows the luminosity vs. bunch current for the different lattices. The highest luminosity is achieved with β^*_v =2 cm, although higher bunch currents are possible at 3 and 5 cm. Reducing β^*_v from 2 to 1.5 cm does not result in an increase in specific luminosity. We also noted at 1.5 cm reduced beam lifetimes, higher rates in the experimental detectors, and reduced operating space in the tune plane. Thus the best luminosity performance is for β^*_v almost equal to the bunch length, and for β^*_v/σ_z= 0.7, performance is significantly degraded.

In fig. 2b we plot for each point in 2a an <u>effective</u> linear vertical tune shift, DQV, calculated from the measured luminosities and β^*_v as DQV= $(r_e/2\gamma)\beta_v L/I$. For a very short bunch length this is the linear tune shift, with constant DQV corresponding to $L\alpha\beta^{*-1}_v$. DQV falling with decreasing β^*_v, as observed, parameterizes the loss of luminosity compared to β^{*-1}_v. In figure 2c we have recalculated these points, dividing out the luminosity decrease calculated from the hourglass shape and from the emittance growth needed to maintain a constant average tune shift. The calculations assumed Gaussian distributions for the transverse and longitudinal bunch shape. It appears that these factors completely account for the decrease in luminosity.

The accompanying decrease in maximum stable beam current is expected, but we do not have quantitative predictions for this effect.

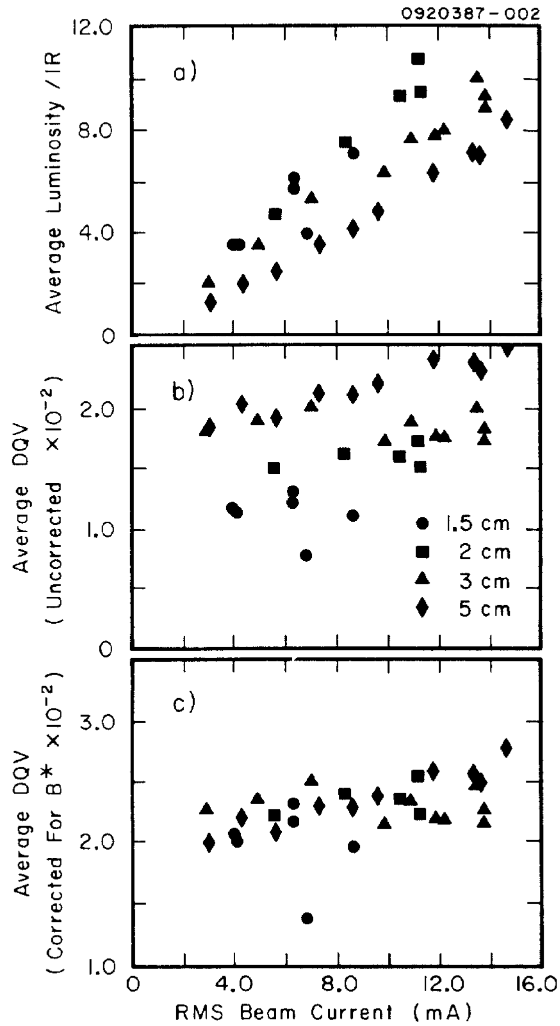

Fig.2: a) Luminosity vs. bunch current for β_v^*=1.5,2.0,3.0, and 5.0 cm. b) DQV vs. bunch current, and c) DQV corrected for geometric luminosity loss and tune shift enhancement.

Further Plans

Obviously, shortening of the bunch is crucial to exploitation of the micro-beta optics. CESR now uses a single 14 cell 500 MHz cavity which provides 3 MV/turn; a second cavity will decrease the bunch length by a factor of 1.4 . We plan to add an additional RF cavity to CESR (and in the past ran tests with two cavities in CESR) but have encountered severe problems with the cylindrical alumina window which couples RF power into the high vacuum of the cavity. Window failures seem associated both with the fundamental power entering the cavity and with higher frequency modes excited by the bunches as they traverse the cavity. Thus the problem is exacerbated by higher bunch currents, and by bunch shortening, which increases the higher mode power.

We are now operating in CESR a cavity with a modified window design in which corona rings on the high vacuum side of the window have been eliminated, and have some evidence that the tolerance for large bunch currents is much improved.

The bunch may also be shortened by raising the horizontal tune of the storage ring since the momentum compaction, α_p, varies inversely with ν_h. We have made a test in which ν_h was raised from 9.4 to 13.4 and observed a large degradation in luminosity performance consistent with dynamic aperture limitations caused by the strong sextupoles required for chromaticity correction. Operation at ν_h=11.4 may be practical and would significantly reduce the RF power required to achieve a shorter bunch length.

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Footnotes

1. S.W. Herb, submitted to this conference
2. G. Bobbink et al., submitted to this conference
3. J. Kirchgessner and S.W. Herb, submitted to this conference
4. R. Littauer,IEEE Trans.Nucl.Sci.,Vol NS-32,No.4,1985
5. S. Peggs, IEEE Trans.Nucl.Sci. Vol NS-30,No.4, 1983
6. D.H. Rice, CON 87-3 (CESR Operations Note, 1987)