OPERATION OF CESR AS A LOW EMITTANCE X-RAY SOURCE*

E.B. Blum
Cornell University
Ithaca, New York 14853

The Cornell Electron Storage Ring was operated with a horizontal emittance of 65 nm-rad to produce hard x-rays from an undulator. Because all of the storage ring quadrupoles are individually powered and under software control, hardware modifications were not needed to reduce the emittance from its usual value of 166 nm-rad during colliding beam operation. Up to 35 mA could be stored in a single bunch and a total of 115 mA was stored in six bunches. A vertical emittance of less than 1 nm-rad was observed at low currents. The undulator did not significantly affect the behavior of the beam in the storage ring.

Lattice Design and Performance

The Cornell Electron Storage Ring (CESR) normally operates at an energy between 4.7 and 5.5 GeV to provide colliding beams for high energy physics research. Synchrotron radiation from the electrons in CESR is also used parasitically, for experiments at the Cornell High Energy Synchrotron Source (CHESS). During the spring of 1988, the CESR lattice was adapted to produce low emittance electron beams for the dedicated operation of a hard x-ray undulator.[1]

The undulator was inserted in the CESR straight section that is upstream from one of the CHESS x-ray beam lines. Synchrotron radiation is usually supplied to this line by a seven pole wiggler that was removed to make room for the undulator. An electrostatic separator, used during colliding beam operation to deflect the electron and positron beams onto distinct orbits, was also removed from this straight section. A storage ring energy of 5.437 GeV, where injection conditions were well established from previous high energy physics running, was chosen for the initial operation. On-energy injection into CESR was used throughout the experiment.

During high energy physics operation, the horizontal emittance of the electron beam in CESR, 166 nm-rad, is too large to produce high brightness radiation from the undulator. The emittance was reduced to 65 nm-rad by increasing the horizontal tune of the storage ring from 9.38 to 15.42 and the vertical tune from 9.36 to 12.35. This could be done without making any physical modifications to the storage ring magnets or power supplies because all of the quadrupoles in CESR, except the nonadjustable permanent magnet quadrupoles nearest the interaction points, are individually powered and under software control. One additional quadrupole was added next to the undulator to create an insertion with nearly constant values of β in each plane. A second quadrupole was added on the opposite side of the storage ring to preserve its symmetry. Zero dispersion in the undulator insertion was also desired in the lattice design. The lattice functions chosen are shown in Fig. 1.

Once injection was established, the β functions were measured at each quadrupole in the storage ring by varying the strength of the quadrupole and observing the effect on the tune. The quadrupoles were then adjusted to bring the measured values of β into conformance with the design. Particular care was taken with the beta function in the undulator. The measured and design values of the lattice functions at the end of the quadrupoles at each end of the undulator insertion are listed in Table 1.

Besides the desired reduction in emittance, a number of other effects also resulted from increasing the tune of the storage ring. The momentum compaction α_p was reduced from .0157 to .0063, thus reducing the required radio frequency accelerating voltage from 6.4 to 3.9 MV/turn. This allowed the removal of one of the RF cavities from the ring. Less desirably, the strength of the sextupoles needed to correct the natural chromaticity of the storage ring approximately doubled. The properties of the normal high emittance lattice and the low emittance undulator lattice are compared in Table 2.

The horizontal size of the electron beam was measured by scanning the visible light component of the synchrotron radiation from a ring dipole magnet across a narrrow, vertically oriented charge coupled device (CCD) detector using a mirror. The shape of the beam was roughly Gaussian with $\sigma = 1.08$ mm. At the source of the light, $\beta_x = 15.3$ m, and the contribution to the size of the beam from its energy spread is negligible. The measured

Table 5.1

Undulator Insertion		
	Design	*Measured*
$\beta_{x,\text{upstream}}$	19.82 m	21.20 m
$\beta_{x,\text{downstream}}$	19.14 m	20.20 m
$\beta_{y,\text{upstream}}$	5.01 m	4.47 m
$\beta_{y,\text{downstream}}$	4.77 m	5.14 m
$\eta_{x,\text{upstream}}$	0.1186 m	
$\eta_{x,\text{downstream}}$	0.0754 m	

Table 5.2

Storage Ring Parameters		
	Normal Lattice	*Low ϵ Lattice*
Energy E_0	5.437 GeV	5.437 GeV
Revolution Frequency f_0	390.139 KHz	390.139 KHz
RF Frequency f_{RF}	499.768 KHz	499.768 KHz
Horizontal Emit. ϵ_x (design)	166 nm-rad	65 nm-rad
Vertical Emit. ϵ_y (measured)	8 nm-rad	<1 nm-rad
Horizontal Tune Q_x	9.38	15.42
Vertical Tune Q_y	9.36	12.35
Natural Vert. Chromat. ξ_x	-36.88	-26.04
Natural Horiz. Chromat. ξ_y	-21.41	-37.30
Horiz. Sextupole Strength M_x	.1439	.3268
Vert. Sextupole Strength M_y	-.3306	-.5698
Synch. Oscillation Freq. f_s	24 Khz	11.8 KHz
Energy Spread σ_ϵ/E_0	6.32×10^{-4}	6.32×10^{-4}
Momentum Compaction α_p	.0157	.0063
Bunch Length σ_L	2.0 cm	1.6 cm
Number of RF Cavity Cells	28	14
RF Voltage V_0	6.4 MV	3.9 MV
RF Power (no beam)	230 KW	150 KW
Synch. Rad. Energy Loss U_0	1.15 MeV/turn	1.15 MeV/turn
Number of Bunches	7 $e^+ \times 7$ e^-	1-7 e^-

---

* Supported in part by the U.S. Department of Energy and the U.S. National Science Foundation.

CH2669-0/89/0000-0473$01.00©1989 IEEE

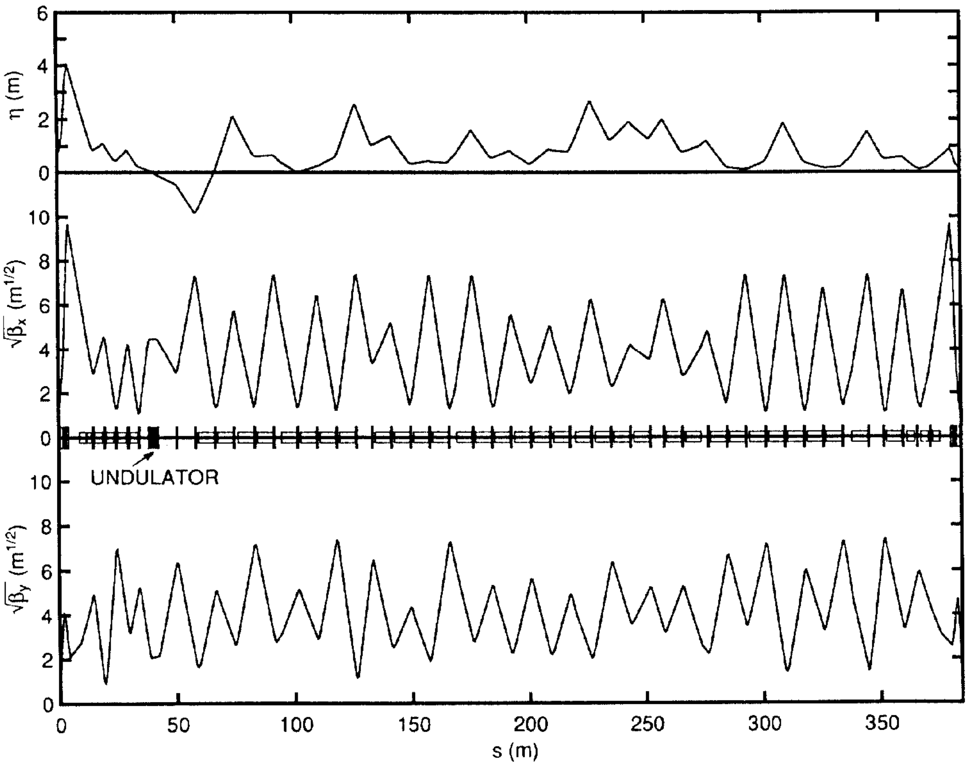

Fig. 1. CESR low emittance lattice.

beam size therefore corresponds to a horizontal emittance of

$$\epsilon_x = \frac{\sigma^2}{\beta_x} = 76 \text{ nm-rad.}$$

Given the uncertainty in the angular orientation of the CCD detector and in the magnification of the optical system, this is consistent with the design value of 65 nm-rad.

The vertical beam size was obtained from a Gaussian fit to a scan of the vertical profile of the visible synchrotron light obtained with a position sensitive CCD. Before the measurement, the coupling between the horizontal and vertical components of the electron beam motion was minimized by adjusting the skew quadrupoles in the storage ring, thereby minimizing the vertical beam size. The accuracy of the meaurement was limited by the 150 μm resolution of the optical system.[2] The smallest observed profile had a value of $\sigma_{\text{meas}} = 190$ μm. Subtracting the optical resolution in quadrature results in a vertical beam size $\sigma = 116$ μm which together with $\beta_y = 13.97$ m at the the source point corresponds to a vertical emittance of .96 nm-rad. Frequent adjustment of the skew quadrupoles was required to maintain this vertical emittance. Typically, the vertical emittance was somewhat greater than 1 nm-rad. The vertical emittance was unaffected by the amount of beam stored until the current exceeded 20 mA/bunch with the emittance increasing rapidly beyond this current (Fig. 2).

The best injection rates, > 10 mA/min/bunch, were comparable to the best rates achieved with the normal high emittance lattice. The injection rate as well as the life-time of the stored beam was very sensitive to the precise value of the vertical tune. Harmful resonances were found with a spacing corresponding to one-third of the synchrotron oscillation frequency. These may have been due to third order synchrobetatron resonances driven by the strong sextupoles required but no detailed measurements were undertaken. The injection rate was also extremely sensitive to the strength of the sextupoles. Increasing the chromaticity much beyond zero quickly hurt injection and it was not possible to store the beam when the chromaticity was negative. All of these effects were exacerbated when the beam energy was increased to 6 GeV where a slightly different lattice was used to compensate for the weaker focusing from the permanent magnet quadrupoles. Given the short time available for dedicated undulator operation, no effort was devoted to understanding the 6 GeV performance and 5.437 GeV beams were used for undulator operation.

The largest current stored in a single bunch was 35 mA. Beyond that, further injection was prevented by a beam instability. The nature of the instability was not investigated. Up to seven equally spaced bunches were stored at one time. Under those conditions, the life-time of the stored beam would often deteriorate rapidly, possibly because of ion trapping. This was prevented by storing only six bunches with a gap corresponding to the missing seventh bunch. The maximum current stored under these conditions was 115 mA which was lost when the power to the RF accelerating cavity was inhibited by a protective interlock. Operationally, 80 mA currents could be easily stored. The beam life-time at these currents was from 200 to 300 minutes.

Interaction with the Undulator

The undulator had no important effect on the performance of the storage ring. Its installation produced no operationally significant change in the orbit, tune, coupling, or chromaticity, and use of the trim magnets that were installed to correct the integrated dipole error in the undulator was not required. The undulator produced an orbit error of less than ±0.5 mm in the horizontal plane and ±0.06 mm in the vertical.These are much smaller than the deviations that remain after other orbit errors are corrected. Analysis of the closed orbit distortion produced by the undulator shows that it can be caused by the dipole errors at the undulator location listed in Table 3. These are compared with the maximum error that was permitted in the specification for the undulator.

An attempt was made to measure the effective sextupole

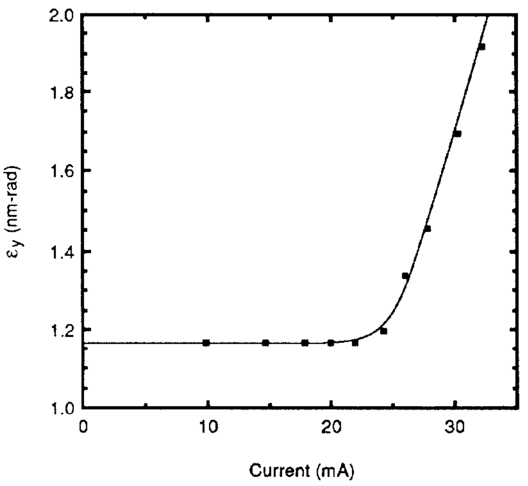

Fig. 2. Vertical emittance growth with current.

component of the magnetic field of the undulator by measuring the horizontal and vertical tunes as function of the horizontal position of the beam in the undulator. The experiment was repeated with the undulator gap set to 2.4 cm and 1.5 cm, corresponding to peak undulator fields of 0.19 and 0.45 Tesla respectively. The position was varied using a four element orbit bump and measured with beam detectors at each end of the undulator. The results are plotted against the average beam position in the undulator in Fig. 3. Any sextupole component in the undulator field would change the slope of the lines when the undulator field is changed as the gap is opened but no appreciable change is seen. Its sextupole component is too small to measure by this technique.

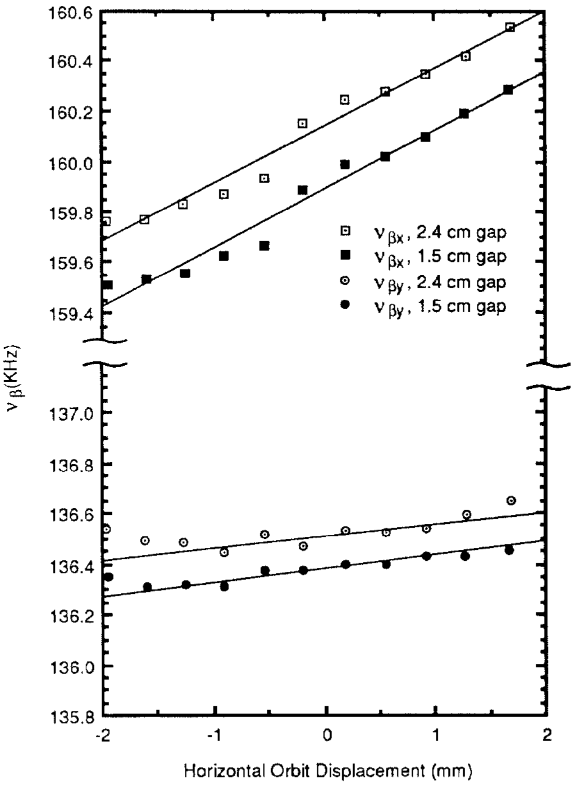

Fig. 3. Betatron frequencies vs. beam position in undulator.

The constant tune shifts between open and closed gap conditions in Fig. 3 can not result entirely from a quadrupole component in the undulator field because both the horizontal and vertical tunes move in the same direction as the gap is opened. Part of the tune shift as well as all of the slope of the lines results from a change in the orbit around the ring introduced by the orbit bump. The erroneous hypothesis that all of the horizontal tune shift is produced at the undulator location requires an integrated quadrupole field of 3.9×10^{-4} m^{-1} corresponding to a gradient of .35 Gauss/cm from a 2 m long quadrupole.

The skew quadrupole component of the undulator was studied by measuring the change in coupling introduced by closing the undulator gap from 2.4 cm to 1.5 cm.[3] The integrated skew quadrupole component measured by this technique is approximately 4.7×10^{-5} m^{-1}.

The measurements described have shown that CESR can provide low emittance electron beams for use with an undulator but the true test of the performance of CESR as a low emittance x-ray source lies in the quality of the x-rays from the undulator. The undulator produced a radiation spectrum with distinct peaks through the seventh harmonic and an observed brightness in the third harmonic of 8.2×10^{14} photons/sec-.1%bandwidth-mm^2-mrad^2-mA at 13 KeV, thus demonstrating the suitability of CESR as a source of high quality undulator radiation.

Table 3

Dipole Errors		
Plane	*Measured*	*Specified*
Horizontal	338 Gauss-cm	< 400 Gauss-cm
Vertical	< 81 Gauss-cm	< 100 Gauss-cm

References

1. P.J. Viccarro, et. al., "The Performance of an APS Prototype Hard X-Ray Undulator at CHESS", these proceedings.

2. S.V. Milton, M.S. Thesis, Cornell University (1988).

3. The technique used was described by M. Billing, I.E.E.E. Trans. Nucl. Sci., vol. NS-32, p.2246, 1985.