EXPERIMENTAL CHARACTERIZATION OF A PEP LOW EMITTANCE LATTICE[0]

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Abstract

Parameters of a successfully-implemented low-emittance lattice for PEP II are presented. Measurements of beta-functions, dispersion functions, and emittance, and their agreement with theory, are summarized. At 7.1Gev, the emittance was 5.3 ± 0.8 π-nm-rad for the normal configuration and 3.8 ± 0.5 π-nm-rad for a modified-damping-partition configuration.

Low Emittance Lattices

The December 1987 run of a modified PEP ring (PEP II) was made with several lattices, two designed for colliding-beam use, and two designed to achieve low emittance. Because of PEP's large bending radius (about 165m), it is capable of achieving emittances as small as or smaller than that to be achieved by rings now in the design and construction stages that are being planned specifically for synchrotron radiation production. PEP is also suited to the introduction of damping wigglers to reduce the emittance even further (by about a factor of 10, for 200m of wigglers [2]), and can run at energies up to 15 Gev.

Parameters of two of the lattices used for the December 1987 run are listed in Table 1. The important feature of the low-emittance lattice, PEP-29, is the high horizontal tune, ν_x, of 100° per FODO cell compared to about 60° per cell for the 4cm colliding-beam lattice. This is brought about by increasing the quadrupole strength in the arcs, with the additional result that the normally high horizontal dispersion function, η_x, in the arc bending magnets is substantially reduced. This leads to reduced quantum excitation due to synchrotron radiation in the bending magnets, and hence to reduced equilibrium emittance.

Graphs of β_x, β_y, and η_x are shown in the figures for one sextant of the ring. PEP II does not have six-fold periodicity as did PEP I; a special insertion in region 2 has reduced the periodicity to one-fold. Let 'M' stand for the magnet sequence in the mini-beta section that extends from z=0 to the symmetry point at z=183m in the figures, and let 'N' stand for the normal sequence from z=183m to z=366m, starting at the symmetry point and ending with the interaction point. Then the full PEP magnet arrangment is

$$M\ N\ \bar{N}\ N\ \bar{N}\ N\ \bar{N}\ N\ \bar{N}\ N\ \bar{N}\ \bar{M}$$

where a bar indicates a reversed-order sequence.

Because PEP is a colliding-beam storage ring, it must have the capability to focus the beam to small dimensions at the interaction regions. PEP II is a modified PEP ring in which new quadrupoles have been added in region 2 to achieve β_y^*=4cm (compared to 11 cm for the PEP I ring). This will increase the luminosity for colliding-beam experiments by a factor of about 2.75. In order to achieve this β_y^* it is necessary to employ very strong quadrupoles around the interaction point, and since one must leave a free space of about 10m total length for the detector, β at these insertion quarupoles will become very large (see figure).

Since the dispersion function in the arcs was reduced by a factor of two to achieve the low emittance, the effectiveness of the chromaticity-correcting sextupoles has also been reduced by that factor. Doubling the strength of the sextupoles would lead to a serious reduction in the dynamic aperture. In order to drastically reduce the chromaticity, the normal point-focus optics across the interaction points was changed to parallel-focusing optics, thereby cutting the vertical linear chromaticity by a factor of about 2. One disadvantage of this is a slightly reduced horizontal aperture, due to increased β_x at aperture-limiting synchrotron radiation masks in the insertion regions.

In the course of the run it was found that the current threshold for the single-bunch transverse instability was noticeably lower in the on-energy low-emittance lattice than it was in the colliding-beam lattices. This is thought to be due to the high β in the low-emittance lattice (relative to the colliding beam lattice) in certain regions that contain high-impedance objects, namely RF cavities in the straight sections adjacent to the interaction points and synchrotron radiation masks near the interaction points themselves. A modified low-emittance lattice, one with smaller β_x in these regions, was implemented, and the current threshold increased significantly (from about 1.5mA per bunch to about 2.5 mA per bunch). More detail is in reference 3. (Results that follow are for the unmodified, on-energy low-emittance configuration unless otherwise noted.)

Since the emittance depends inversely on J_x, the damping partition number for the horizontal motion, the emittance can be decreased by increasing J_x from its usual value of 1. Such an emittance reduction was implemented by changing the RF frequency in order to change the beam energy relative to the magnet settings. A change of +4.5 kHz was used, resulting in a reduction in the beam energy by 1.27%, J_x≈2.1, and emittance ε_o ≈ 3.7nm-rad, the latter two values being those calculated by lattice codes. The reduction in the emittance is not as great as might be expected from the magnitude of the change in J_x, due to mismatched horizontal η and β.

Measurement of Beta-functions

To confirm the model of the lattice, measurements were made of β_x and β_y at the insertion region quadrupoles and at the region 2 quadrupoles outside of the regular arcs. The method uses the well-known equation for the perturbation of the tune due to a quadrupole error[4], namely, $4\pi\Delta\nu = -\int\beta(s)\Delta k(s)ds$, where $\Delta k(s)$ is the quadrupole error or perturbation in the ring magnets as a function of distance s around the ring. By changing the current in a specific quadrupole (or group of quadrupoles) and measuring the resultant changes in the vertical and horizontal tunes, one can obtain the average β in that quadrupole (or group of quadrupoles).

Results (for the low-emittance configuration) for the Q1 insertion quadrupoles, for which the measurement resolution was the greatest, were $(\Delta\beta_x/\beta_x)_{rms}$ ≈ .13 and $(\Delta\beta_y/\beta_y)_{rms}$ ≈ .19, with resolutions of about .08 and .07 respectively, where $\Delta\beta/\beta \equiv (\beta_{meas} - \beta_{theory})/\beta_{theory}$. Since

$$(\Delta\beta(s)/\beta(s)) \approx 2^{\frac{1}{2}}(\Delta\beta/\beta)_{rms}\cos(p(\phi(s)-\psi))$$

(where p is the nearest integer to 2ν, φ varies from 0 to 2π around the ring, and ψ is an arbitrary phase offset), one can conclude that the rms fractional error in β is about the same for all points in the ring, which allows one to put a rough upper limit of the β error at points in the ring where β cannot be measured directly (e.g., at an undulator beamline).

The probable variation Δα in α at any point can be deduced using $\alpha \equiv -\beta'/2$. From this one obtains (upon averaging over ψ)

$$(\Delta\alpha(s))_{rms} \simeq (\Delta\beta/\beta)_{rms}(1+\alpha^2)^{\frac{1}{2}} \quad ,$$

where by $(\Delta\alpha(s))_{rms}$ it is meant the rms value of $\Delta\alpha$ at any point s, subject to variations in ψ.

Measurement of the Dispersion Function

The dispersion function η gives the closed orbit for a particle of some momentum p other than the design momentum p_o, via $x_{co}(s)=\delta\eta(s)$, where $\delta = (p-p_o)/p_o$. For an average energy error δ_{ave} the centroid of the beam has a deviation from the design orbit of $x_{co}=\eta\delta_{ave}$. Thus, to measure η one need only change the energy of the beam without changing fields in the magnets and the subtract the orbit so obtained from an orbit taken with no energy deviation.

The energy error is realized by adjusting the RF frequency of the cavities. For $\gamma>>1$, $\Delta L/L = \alpha\delta$, where α is the momentum compaction factor[4] and $\Delta L/L$ is the fractional change in the length of a particle's closed orbit. Since particles must stay in synchronism with the RF fields in order to acquire, on average, no more energy from the RF per turn than is lost to synchrotron radiation, changing the RF frequency forces the particles to travel paths of different lengths. Hence, $\Delta L/L = -\Delta\omega/\omega$, and $\delta = -\Delta\omega/(\omega\alpha)$. If the momentum compaction is assumed to be known from computer calculations, then by varying the RF frequency one can vary the energy by a known amount.

The perturbation $\Delta\eta \equiv \eta_{theory} - \eta_{meas}$ in the dispersion function is given approximately by

$$\Delta\eta(s) \simeq \sqrt{E\beta(s)}\,\cos(n(\phi(s)-\psi))$$

and

$$\Delta\eta'(s) \simeq \sqrt{E/\beta(s)}\,(\,\sin n(\phi(s)-\psi) - \alpha(s)\cdot\cos n(\phi(s)-\psi)\,)$$

where E is a constant and n is the integer nearest to ν. Data taken during the experiment and knowledge of β allows one to estimate that $E_x \simeq 1\times10^{-4}$m (for the x plane) and $E_y \simeq 4\times10^{-4}$m (for the y plane) for the on-energy running of December 18th, and $E_x \simeq 2\times10^{-3}$m and $E_y \simeq 4\times10^{-5}$m for the off-energy running of December 20th. This allows one to estimate the maximum error in η at places where there are no position monitors available to measure the off-energy closed orbit.

The probable variations in $\Delta\eta$ and $\Delta\eta'$ can be deduced averaging over ψ to obtain

$$(\Delta\eta)_{rms} \simeq (E\beta/2)^{\frac{1}{2}} \qquad (\Delta\eta')_{rms} \simeq [E(1+\alpha^2)/(2\beta)]^{\frac{1}{2}}$$

Measurement of the Emittance

There is a 2m, 52-pole undulator in the straight section SYM1 of PEP[7]. Two imaging modes are available, "angular" and "spatial". Angular imaging involves allowing the photon beam to propagate freely to a screen; the image thus formed depends primarily on the angular distribution of the source, hence the name. Spatial imaging involves inserting a pinhole between the source and image planes, resulting in an image that depends primarily on the spatial distribution of the source. Table 2 gives relevant parameters of the beamline.

By making both angular and spatial scans in both the horizontal and vertical directions, one can get data allowing the calculation of the total emittance ε and the emittance coupling κ, in terms of which the horizontal and vertical emittances are $\varepsilon_x=\varepsilon/(1+\kappa)$ and $\varepsilon_y=\kappa\varepsilon/(1+\kappa)$. There are many complications in this calculation that make simple treatments inaccurate. Reference 5 contains the details of the analysis. Here, we simply report the results in Table 3.

Table 2—Parameters of the PEP-1B Beamline

Undulator:

2.002m long, 26 periods, 77mm period, gap of 44 to 120mm, fields of .1 to 2.2kG , ends at SYM1.

Interior pinhole:

33.78m from SYM1, radius a=0.0625mm , removable.

Scanning aperture:

56.91m from SYM1, square of width 2w=0.2mm .

Lattice functions at SYM1:

on-energy: β_x=26.37m η=.534m β_y=5.29m $\eta'_x=\alpha_x=\alpha_y=0$

off-energy: β_x=27.39m η=.303m β_y=6.33m η'_x =−0.009 $\alpha_x=-\alpha_y$=0.045 δ = −1.27%

Table 3—Measured, Theoretical Emittances & Couplings at 7.1Gev

Lattice	Emittance (π-nm-rad) Theoretical	Measured	Coupling
On-energy	6.4	5.3 ± 0.8	0.04 ± 0.02
Off-energy	3.7	3.8 ± 0.5	0.015 ± 0.008

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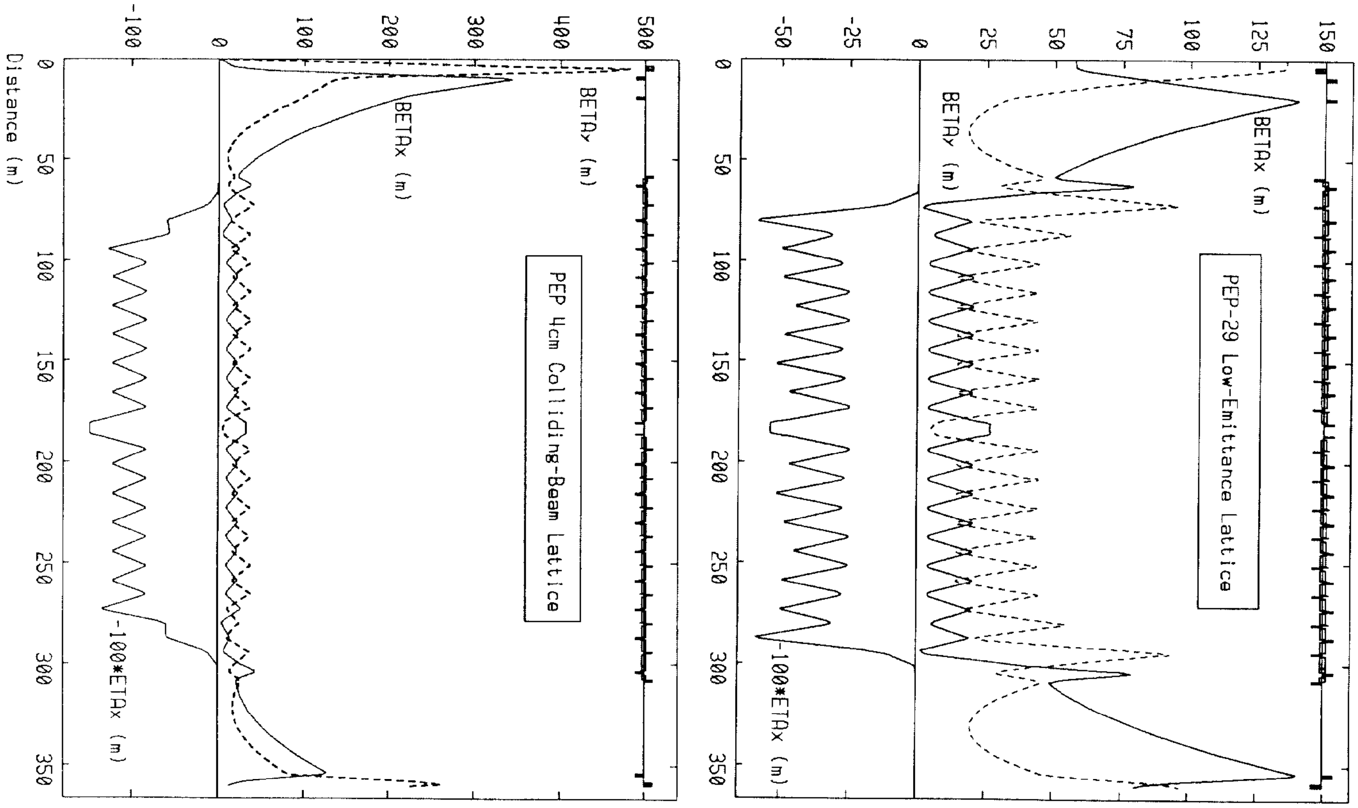

Table 1--Configuration Parameters at 7.1 Gev[6]

		PEP 29	4cm
Emittance:	ε	6.4 π nm-rad	27.7 π nm-rad
Tunes:	ν_x	29.28	21.28
	ν_y	13.20	18.22
Phase Advance in Arcs:	ψ_x	100° per cell	56° per cell
	ψ_y	33° per cell	34° per cell
Lattice Functions in Arcs:			
	β_x	4→21 m	10→23 m
	β_y	14→44 m	17→37 m
	η	0.25→0.53 m	0.8→1.2 m
Momentum Compaction:	α	0.00097	0.00256
Synchrotron Tune*:	ν_s	0.041	0.067
Bunch-length*:	σ_z	3.91 mm	6.34 mm
Interaction Region 2:	β_x	57.2 m	1.00 m
	β_y	134.1 m	0.04 m
	η	0	0
Other IR's:	β_x	79.3 m	4.50 m
	β_y	96.6 m	0.18 m
	η	0	0
Linear Acceptance:	A_x	11.3 mm-mrad	27.7 mm-mrad
	A_y	5.0 mm-mrad	5.8 mm-mrad
Energy Spread:	σ_δ	0.047 %	
Damping Times:	τ_x, τ_y, $2{*}\tau_s$	76.9 msec	

*Assuming 30MV RF.