THE CENTER-OF-MASS ENERGY OF PEP-II*

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Abstract

The PEP-II B-factory is designed to operate at a center-of-mass energy (E_{cm}) of 10.58 GeV, the mass value of the upsilon 4S resonance. It is important to set and maintain the E_{cm} to the peak of this resonance in order to maximize the production of B mesons that enable the BaBar detector to measure CP violation. There are several elements in the determination of the beam energies. Aside from the strength of the main bending magnets, there is a contribution to the beam energy from horizontal correctors. In addition, the frequency of the RF system also influences the ring energies by controlling the closed orbit circumference. The low-energy ring (LER) in PEP-II has a wiggler magnet for emittance control that also contributes to the beam energy of the LER. We discuss these aspects of beam energy determination and the algorithms used to monitor the beam energies.

1 INTRODUCTION

The PEP-II asymmetric-energy e^+e^- collider [1] consists of two separate storage rings, one for the 8.9 GeV electrons and one for the 3.1 GeV positrons. The two beams are brought into a head-on collision with strong horizontal dipole permanent magnets located ±0.21 cm from the Interaction Point (IP). Figure 1 shows a layout of the PEP-II rings and describes some of the ring features. Table 1 lists some of the PEP-II parameters that are used in beam energy calculations.

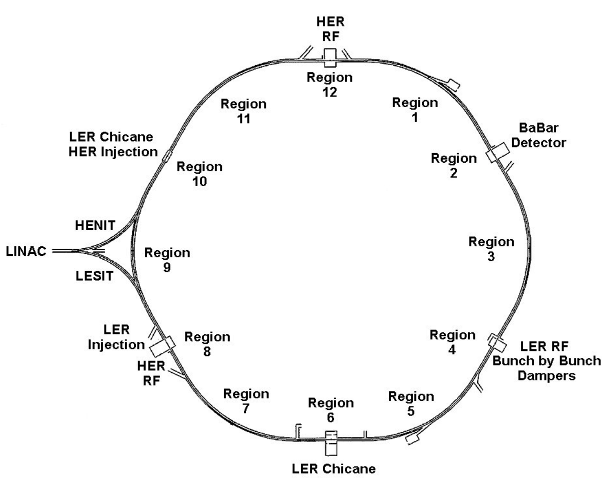

Figure 1. Layout of the PEP-II rings. The odd numbered regions are arc sections and the even numbered regions are the straight sections.

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Table 1.
Some parameters used in determining the beam energies.

PEP-II Parameter	HER	LER
Design beam energies	8.9732	3.1186
Number of bend magnets	192	192
B·dl (Tm) for each magnet	0.98063	0.34042
Number of x correctors	146	162
Design RF frequency (MHz)	476	
Number of RF buckets	3492	
Ring circumference (m)	2199.318	
Momentum compaction (α)	2.41×10^{-3}	1.23×10^{-3}

2 BEAM ENERGY DETERMINATION

In an ideal ring, the beam energy is determined by setting the sum of the angles of the main bending magnets equal to 2π. So we have:

$$E_{beam}\,(\mathrm{MeV}) = c\,(\mathrm{m/s})\cdot 10^{-6}\sum \frac{B\cdot dl\,(\mathrm{Tm})}{2\pi} \quad (1)$$

For an ordinary ring there are at least two more energy terms: 1) the correction to the energy from the horizontal correctors and 2) the frequency of the RF system.

2.1 Corrector term to the energy

Horizontal correctors can contribute to the energy by adding (or subtracting) to the total B·dl for a ring. One might think that just adding up the corrector strengths is all that is needed. However, this is not quite right. In order for a corrector to contribute to the beam energy the corrector must be in a dispersive region. In general, a corrector kick just generates a closed betatron oscillation around the ring and therefore should not contribute to the energy since half of the time the beam is outside the central orbit and half the time inside. The corrector does contribute when the dispersion at the corrector is nonzero by the following formula[2]:

$$\frac{\Delta E}{E} = -\frac{\theta_{corr} D_{corr}}{l\alpha} \quad \text{where} \quad (2)$$

θ_{corr} = angular kick from the corrector
D_{corr} = dispersion at the corrector (m)
l = ring circumference (m)
α = ring momentum compaction

Therefore the correction to the beam energy from the horizontal correctors is weighted by the dispersion at the corrector. We use the model dispersion function to calculate the horizontal corrector contribution to the energy.

2.1 Frequency of the RF system

The frequency of the RF system controls the circumference of the closed orbit by defining a fixed path length around the ring that is an integral number of RF cycles or "buckets". There is also a geometric circumference defined by the centers of the quadrupoles around the ring. The frequency that produces a closed orbit that agrees with the geometric orbit given by the quadrupoles we define as the central frequency of a ring. Frequency deviations from this central frequency result in energy changes since any new orbit will be off-axis in the quadrupoles and the added bending fields experienced by the beam in these quadrupoles changes the total B·dl and hence the beam energy. The change in energy due to changing the RF frequency is expressed by the following formula: [3]

$$\frac{\Delta E}{E} = -\frac{1}{\alpha}\frac{\Delta f}{f} \qquad (3)$$

where α is the ring momentum compaction.

In a similar fashion any attempt to change the path length of the beam also results in an energy change since the RF system maintains a constant path length. So we have:

$$\frac{\Delta E}{E} = \frac{1}{\alpha}\frac{\Delta l}{l} \qquad (4)$$

where l is the ring circumference.

The central frequency is found by measuring the average offset of the x bpms around the ring as a function of RF frequency and finding the frequency where the average offset is zero. Fig 2 shows the data for a few frequency scans for PEP-II.

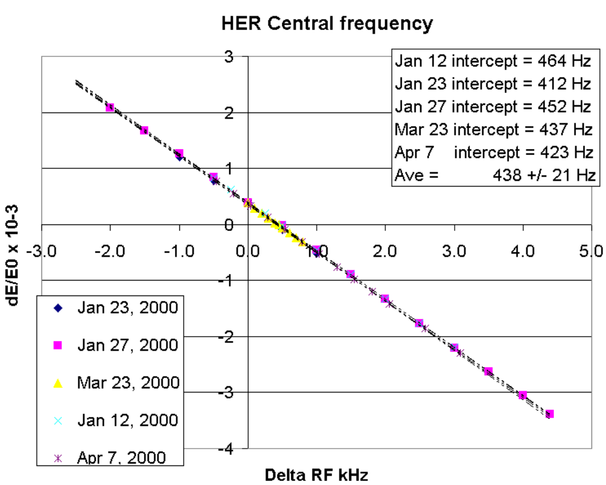

Figure 2. Plot of 5 frequency scans of the HER from Jan. to Apr 2000. The scans are very reproducible and the slope agrees with the expected momentum compaction value in table 1.

3 THE WIGGLER MAGNET OF THE LER

The LER has a series of alternating-field horizontal bend magnets that make up a wiggler section in region 6 of the PEP ring (see fig 1). The wiggler is designed to increase the emittance of the LER, but it also affects the beam energy. The path length inside the wiggler section increases by 1.485 mm when the wiggler is energized. Using eq. 4 we get a 1.7 MeV change in the LER energy. At first, it was thought that this was the only change to the energy that came from turning off the wiggler. However, when we turned off the wiggler section in March of last year we were surprised to discover that we were no longer on the peak of the 4S mass but had shifted about 5 MeV above the peak value. Closer inspection of the lattice, and in particular, of the dispersion function in the wiggler section revealed the missing energy term. It was thought that though there is nonzero dispersion in the wiggler section the wiggler fields alternate in sign so any energy term from treating the wiggler like a corrector would cancel. However, the wiggler fields are very high and it turns out that the design dispersion through the wiggler section has a slight slope so the cancellation is not complete. Table 2 shows the wiggler section values and the net change in energy due to the small slope in the dispersion. The 3.5 MeV change in the LER beam energy from this term accounts for the missing 5 MeV in the Ecm.

Table 2. Design parameters for the LER wiggler section.

	D (m)	L (m)	B (T)	B.dl (Tm)	E (MeV)
BW1-	-0.638	0.225	-1.8	-0.405	28.63
BW1+	-0.651	0.225	1.8	0.405	-29.22
BW2+	-0.647	0.225	1.8	0.405	-29.04
BW2-	-0.634	0.225	-1.8	-0.405	28.46
BW1-	-0.637	0.225	-1.8	-0.405	28.59
BW1+	-0.651	0.225	1.8	0.405	-29.22
BW2+	-0.647	0.225	1.8	0.405	-29.04
BW2-	-0.634	0.225	-1.8	-0.405	28.46
BW2+	-0.63	0.225	1.8	0.405	-28.28
BW2-	-0.618	0.225	-1.8	-0.405	27.74
BW1-	-0.621	0.225	-1.8	-0.405	27.87
BW1+	-0.634	0.225	1.8	0.405	-28.46
					-3.50

4 CENTER-OF-MASS HISTORY

Figure 3 shows some of the history of the E_{cm} for PEP-II. The plot is the reconstructed history using the

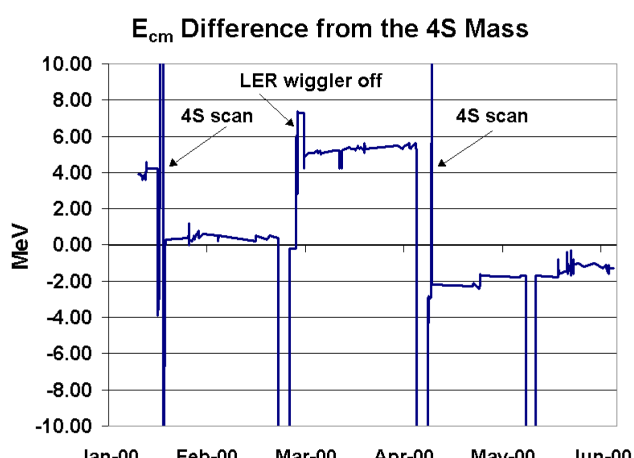

Figure 3. Reconstructed history of the Ecm value for PEP-II from Jun 1999 to Jun 2000.. The large changes (> 10 MeV) in Ecm denote off resonance running or energy scans.

algorithms mentioned in this paper. It also includes a correction to the Ecm after the April 4S scan. We discovered last July that the scan done in April had not come out with the correct set point for the mass peak and moved the E_{cm} up 2.1 MeV to get back on top of the peak. The April scan had occurred when we were having trouble with RF power supplies and we had switched several stations on and off during the scan. Section 6 of this paper talks more about the effects changing RF stations in the HER has on the E_{cm}. Since July of last year PEP-II has been within 1 MeV of the peak

5 THE INTERACTION REGION

The interaction region straight is the most complicated part of the PEP-II accelerator. The two beams are brought into collision by steering the LER down through a vertical step to the level of the HER. In addition, the LEB goes through several horizontal bend magnets as it travels down and up again. Moreover, the beams are coupled in this region the solenoidal field of the BaBar detector. The local coupling is not fully corrected until the beams are back into the arc sections on either side of the interaction region. All of these features make it difficult to calculate contributions to the beam energies from elements in this area. The vertical step in the LER introduces vertical dispersion. This dispersion can contribute to the energy of the beam if there are nonzero vertical correctors in this region. However, the coupled beam makes it difficult to decide how much of the horizontal and vertical dispersion at any given point should be used in the energy calculation. We have not yet developed a satisfactory method to account for possible energy contributions in this section so the current calculations exclude the interaction region straight. This may account for a discrepancy we have with the absolute beam energy values. Using the methods outlined above, we find beam energies that produce a center-of-mass energy of 10594 MeV, 14 MeV above the value of the mass of the upsilon 4S. To account for this difference the LER beam energy would have to change by 8 MeV. The discrepancy is large but we have seen from the wiggler straight that several MeV corrections can occur when relatively large magnetic fields are involved and there are several large bending magnets in this region.

6 THE RF SYSTEM

There is one more contribution to the energy that has been investigated. As the beam goes around the ring, the energy loss from synchrotron radiation in the arcs is made up in the RF cavities. Therefore the location of the cavities with respect to the interaction point leads to the beam energy at the IP not being the same as the average energy of the beam. Figure 4 illustrates this for the HER.

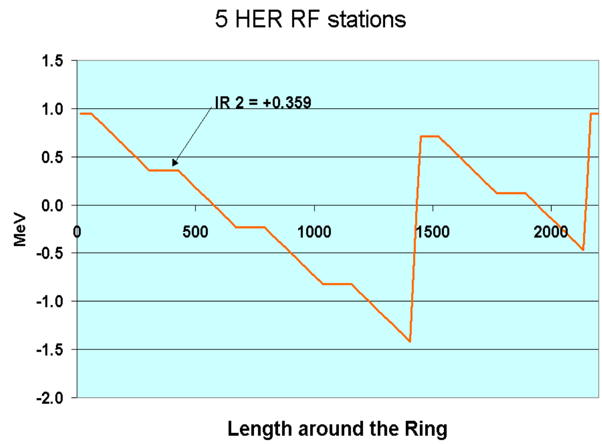

Figure 4. Plot of the beam energy for the HER as a function of location around the ring. The RF stations are in the straights where energy is added to the beam.

This effect was very important for the LEP machine at CERN [4]. However, for PEP-II, the difference is quite small (> 0.5 MeV). Even when PEP-II ran with fewer stations, the change in the Ecm at the IP remained below our tolerances. These small differences can become important when the detector is scanning the 4S peak. Small changes in Ecm can make a big change in the hadron rate when one is on the slope of the peak.

7 SUMMARY

The determination of the energies of the PEP-II beams employs basic algorithms to account for changes in the RF frequency and for contributions from the horizontal correctors. The method has been very successful in maintaining the Ecm of PEP-II on top of the peak of the 4S resonance. There is however, an inconsistency in that the calculated beam energies do not match the known mass of the 4S resonance. At this point, we attribute the discrepancy to the fact that the interaction region straight, which has coupled beams throughout the straight, is not used in the energy calculation.

We also use confirming evidence from the BaBar detector that we are indeed on the peak of the 4S mass.

8 REFERENCES

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[4] Proceedings of the 4th Workshop on LEP Performance, Chamonix, Jan. 17-21, 1994, pg 341.