Monitoring System to Permit Accurate Alignment of Beams at Collision in CESR*

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Abstract

Colliding beams in a storage ring should be aligned, in position and angle, to within a small fraction of the beam dimensions. Errors may be corrected by the use of appropriate steering elements (in CESR, electrostatic separators). In view of the small beam size, measurement of the misalignment needs to be highly accurate. In the system used at CESR, the orbits of e^+ and e^- are measured simultaneously, to reduce the effect of small orbit fluctuations with time. In addition, the signals are processed in an automatic gain control (AGC) system which extracts the e^-/e^+ pulse height ratio, with the e^+ pulses being brought to a fixed level. When the beams are coincident, the e^-/e^+ pulse height ratios will be identical on all four buttons of the beam position monitor (BPM). The AGC technique reduces the errors produced if the orbit is not well centered between the pickup buttons.

Introduction

The closed orbits of counterrotating beams in a shared magnetic guide field will coincide, provided that the beams have everywhere the same energy. Perfectly aligned head-on collisions—required to maximize luminosity and reduce beam-beam blowup—might thus be thought to occur automatically. However, residual beam-beam misalignment at the interaction point (IP) can arise from orbit effects due to the rf acceleration system [1]. More importantly, in a ring (such as CESR) which incorporates electrostatic deflectors, or in a collider using two separate guide fields, beam alignment at collision needs to be enforced by deliberate adjustment, using appropriate differential steering elements.

The problem lies in the *measurement* of the alignment error. In principle it would suffice to use the luminosity itself as an indicator; in practice, statistics make this process slow and the many parameters which affect luminosity are not distinguished. A sensitive measurement of orbit alignment at the IP is thus desirable. The system used at CESR is separate from the general orbit-monitoring equipment because a much higher accuracy is required, albeit only in a small section of the ring and only as regards the relative orbits for e^+ and e^-.

Available Sensors

Relative position and angle information is needed for the two beams at the IP. However, the BPMs are at some distance from this point and orbit reconstruction is thus needed. The corresponding trajectories are shown in figure 1, in each case scaled to represent a misalignment which is a small fraction of the natural beam size: at the IP the initial displacement or angle is set equal to 0.1σ, an error of this order being considered at the threshold of significance. Typical values of σ are $\sigma_x \approx 420\mu m$ and $\sigma_y \approx 5.6\mu m$ in displacement, and $\sigma_{x'} \approx 410\mu rad$ and $\sigma_{y'} \approx 310\mu rad$ in angle. The permissible error is much smaller for vertical than for horizontal orbit separation, due of course to the much smaller vertical beam emittance ($\epsilon_y \approx 0.01\epsilon_x$ with $\epsilon_x \approx 1.8 \times 10^{-7}m$).

A single pair of monitors has been used, placed symmetrically on either side of the IP at BPM3 E/W. Our choice optimizes the signal produced by a vertical orbit difference Δy, which is the most difficult to detect; moreover, BPM3 happens to be preferable for practical reasons. Different pairs could be used to maximize the observable orbit error for different parameters ($\Delta x, \Delta y, \Delta x', \Delta y'$), but if the instrumentation can in fact resolve Δy adequately, it should also be sufficient for the other errors.

Energy Difference

Measuring projected trajectories and inferring the beam alignment at the IP is subject to error unless the two beam energies are equal, which is true only if the rf acceleration is effectively symmetrical about the IP. For significant time periods CESR has operated with only a single rf cavity; this gave rise to a fractional $e^+ - e^-$ energy difference at the IP of $\delta \approx 2 \times 10^{-4}$. Under normal conditions—two symmetrically placed cavities—a (much smaller) residual unbalance can still be present.

A nonzero δ falsifies the reconstruction of the relative $e^+ - e^-$ orbits only if the trajectories suffer deflections be-

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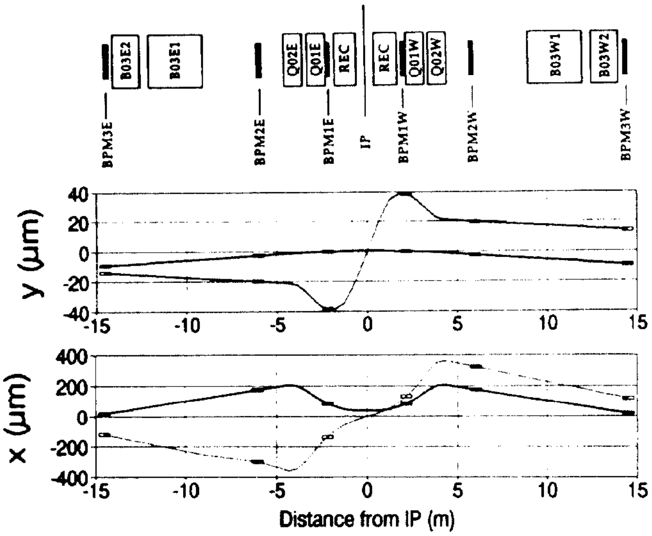

Figure 1: Trajectories with misalignment errors of 0.1σ in displacement and angle. The error values used are: $\Delta x = 42\mu m$, $\Delta y = 0.56\mu m$, $\Delta x' = 41\mu rad$, $\Delta y' = 31\mu rad$.

tween the IP and the BPM in use. As seen from fig.1, two weak guide-field bends at $B03E/W$ (about $20mrad$ each) intervene just before BPM3. For the worst-case $\delta \approx 2 \times 10^{-4}$ they separate two perfectly aligned e^+ and e^- trajectories by $22\mu m$ horizontally at BPM3. This approaches the level of our permissible error, but a correction can be made if ever CESR is operated with only a single rf cavity. Beyond BPM3, however, there are much stronger dipoles and all further BPMs are eliminated from consideration.

Trajectory deflection occurs also if the orbit is not centered in the quadrupoles or the experimental solenoid. Passing a quadrupole of focal length f with an offset x_0 from its magnetic center is equivalent to a dipole deflection of x_0/f. The effects of such deflections have been tracked, in both planes, for all lenses; and offsets of the order of $1mm$ produce at most $4\mu m$ of trajectory separation, again for the single-cavity extreme. In practice such errors should be negligible.

Signal Processing

From fig.1 the required detection sensitivity can be read for relative-orbit measurements at BPM3; the resolution should be within $20\mu m$ horizontally and $10\mu m$ vertically. Despite the unfavorable location of BPM3 for detecting horizontal errors, the vertical requirement is still the more stringent. Given the signal amplitudes at the four buttons (b1 ... b4), the x and y coordinates of the bunch centroid are found from the usual difference/sum algorithm; e.g., $x = X_0(b_2 - b_1 + b_4 - b_3)/(b_2 + b_1 + b_4 + b_3)$, and similarly for y. With the geometric scale factors, X_0 and Y_0, of order $25mm$, the individual button signals must be measured with fractional uncertainties below 4×10^{-4}. Brief ($< 200ps$), bipolar signals are not easily measured with this accuracy.

CESR button signals are usually monitored by diode peak rectification; we have found this to yield the best signal-to-noise ratio. With e^+ and e^- beams simultaneously present, their respective signals could be separated by time gating. However, such gates require very stable synchronization. We prefer, instead, to separate the signals by their *polarity*. To this end, the pulses must first be shaped so as to exhibit a marked asymmetry; then the undershoot from one polarity will not interfere with pulses of opposite sign, provided the e^+ and e^- bunch charges are not too different. This shaping is done by a length (about $100ns$) of lossy cable (RG174/U).

The rectifier outputs are passed through low-pass filters and measured by 16-bit dual-slope integrating digitizers which average over about 0.3 s. These digitizers are synchronized so that the e^+ and e^- readings apply to the same time period; any common orbit fluctuation, due for example to drifts in magnetic steering elements, is thus eliminated.

It would be unrealistic to require precise centering of the orbits within the BPMs; but it is only necessary that the relative $e^+ - e^-$ error vanish, i.e., that the orbits for the two species be off-center by the same amount. The pulses from the four buttons are thus not necessarily equal; however, the four e^- signals should fall into the same pattern as the four e^+ signals. To detect this equality of pattern with high precision, an AGC loop (fig.2) is closed around the processor. By controlling an electronic attenuator, this loop brings each e^+ output, in turn, to a standard reference level, thus making all four e^+ outputs equal. The e^- signals, passing through the same attenuator, will then also all deliver equal outputs, provided they were originally in the same pattern as the e^+ pulses.

In this system, the peak rectifiers serve only to detect equality of signal levels; their actual (nonlinear) transfer function is irrelevant. By the same token, any incidental attenuation which may be introduced by the coaxial relay applies equally to e^- and e^+ and is thus eliminated from consideration. Evidently, the electronic attenuator now becomes the critical element: its treatment of e^- and e^+ pulses must be even-handed. This requires not only insensitivity to pulse polarity and time sequence, but also similar attenuation at the (possibly different) absolute levels for the two species of signals. Though bench measurements can quantify attenuator performance in these respects, ultimately the most sensitive test is to operate the system under various conditions and observe what errors, if any, are produced.

Results

Two diagnostic tests were performed: (1) The relative-orbit readings were taken with a fixed attenuator (-12dB)

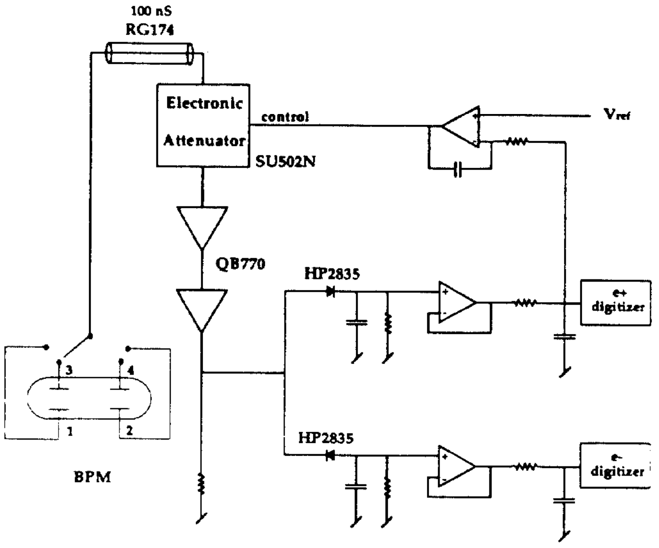

Figure 2: Schematic diagram of the AGC circuit

inserted into the signal path, thus forcing the electronic attenuator into a different region of operation. (2) By the use of an inverting transformer, the roles of e^+ and e^- channels were exchanged, thus also reversing the time sequence of the AGC-stabilized and the companion pulse. These perturbations produced variations in the indicated relative orbit at BPM32, taking into account the resulting sign change, of at most $+/-10\mu m$.

In CESR luminosity runs, the relative-orbit measuring system has been used, in conjunction with horizontal and vertical electrostatic separators, to bring the beams into precise alignment at collision. Maximum luminosity occurs with zero displacement error at the IP, within a few μm. However, the machine appears to prefer a vertical *angular* misalignment (fig.3), with the angle seeming to depend on beam current. Work is proceeding to detemine whether this indication is an instrumentation error or whether it corresponds to some physical effect in the ring.

References

[1] R. Littauer,"Orbit and Tune Effects of RF Conditions", CBN88-4, CESR internal report.

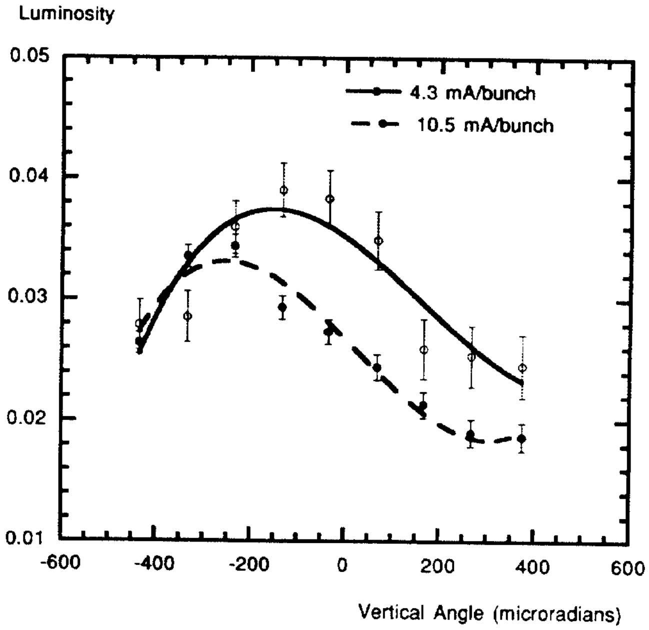

Figure 3: Plot of luminosity vs. relative vertical angle at two different beam currents