LOW EMITTANCE TUNING WITH A WITNESS BUNCH *

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Abstract

Electron positron damping rings and colliders will require frequent tuning to maintain ultra-low vertical emittance. Emittance tuning begins with precision beam based measurement of lattice errors (orbit, transverse coupling, and dispersion) followed by compensation with corrector magnets. Traditional techniques for measuring lattice errors are incompatible with simultaneous operation of the storage ring as light source or damping ring. Dedicated machine time is required. The gated tune tracker (the device that drives the beam at the normal mode frequencies) and the bunch-by-bunch, turn-by-turn beam position monitor system developed at CESR are integrated to allow synchronous detection of phase. The system is capable of measuring lattice errors during routine operation. A single bunch at the end of a train of arbitrary length, is designated as the witness. The witness bunch alone is resonantly excited, and the phase and amplitude of the witness is measured at each of the 100 beam position monitors. Lattice errors are extracted from the measurements. Corrections are then applied. The emittance of all of the bunches in the train is measured and the effectiveness of the correction procedure demonstrated.

INTRODUCTION

Ultra-low vertical emittance is essential to achieve high luminosity in electron/positron colliders. In a linear collider, the sources of the low emittance beams are the damping rings. The vertical emittance specification for the International Linear Collider is 2pm-rad (at 5GeV) [1]. In circular colliders, the equilibrium emittance of the electron and positron storage rings likewise determines the luminosity. In SuperKEKB the vertical emittance target is 1.5pm-rad (7GeV) [2].

The principle source of vertical emittance in collider damping rings is misalignment of the guide field magnets. Transverse coupling is generated by tilted quadrupoles, and vertical dispersion by tilted dipoles and displaced quadrupoles. Low emittance tuning is the procedure to minimize the effects of the misalignments. The sources of dispersion and coupling are determined with beam based measurements. Corrector magnets are then deployed to compensate those sources. The emittance targets for both ILC and SuperKEKB have been achieved in storage rings (mostly light sources) with emittance tuning [3] [4].

Traditional emittance tuning procedures require dedicated machine time for the beam based measurements. Instrumentation has been developed at CESR for beam based measurements based on a single witness bunch, and thus allow continuous monitoring of coupling, betatron phase advance, dispersion, and orbit during normal operation. Lattice parameters are measured and corrector strengths adjusted without interruption. The witness bunch (perhaps the bunch at the end of a train) is resonantly excited at horizontal, vertical and, in principle, longitudinal normal mode frequencies, and the turn by turn position of the bunch measured at each of the 100 beam position monitors (BPMs) in the storage ring. The phase and amplitude of the response at the resonant frequencies characterizes the lattice functions.

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BEAM BASED MEASUREMENT OF LATTICE PARAMETERS

The lattice properties are determined by measuring the linear mapping (transfer function) between BPMs. The mapping is extracted from measurements of a large number of non-degenerate trajectories. In the orbit response method (ORM) [5] [6], the distinct trajectories are generated by varying the strength of horizontal and vertical dipole correctors to create a matrix of position versus corrector. Typically there are many more measurements than BPMs and the system is overconstrained. The matrix is inverted by singular value decomposition to yield transfer functions. The ORM method is very powerful and can provide information about the calibration of the dipole correctors and beam position monitors as well as the linear transfer function from one BPM to the next. However, the measurements are incompatible with normal operation. Dedicated machine time is needed to make the orbit measurements. The measurements can be time consuming, as each steering must be varied sequentially and orbits collected at each step. Finally, the measurement time will scale with the circumference (or at least the number of beam position monitors and corrector magnets) of the ring.

In a storage ring equipped with BPMs capable of turn-by-turn position measurements, the set of non-degenerate trajectories can be collected much more quickly. A bunch can be excited simultaneously at the three normal mode tunes (horizontal, vertical, and longitudinal) by fast kickers, with width less than the minimum bunch spacing. (Two tune trackers are presently implemented in CESR, thus limiting simultaneous measurement to two of the three planes.) In CESR the bunch-by-bunch feedback kickers are used to drive the beam. As long as the betatron and synchrotron tunes are non integer, each turn will provide a distinct trajectory and each is recorded by the BPMs. The linear mapping between BPMs is extracted from the trajectory data as before. The signal noise is reduced by filtering the data at the normal mode tunes. In particular, an amplitude and phase is identified at each of the four BPM electrodes, for each of the normal mode tunes. Horizontal, vertical, and longitudinal betatron amplitude and phase advance is reconstructed. Vertical (horizontal) motion measured at the horizontal (vertical) tune corresponds to transverse coupling [7]. Vertical (horizontal) motion at the synchrotron tune gives the vertical (horizontal) dispersion. The reference phase and frequency for each of the normal modes is provided by a tune tracker [10].

TUNE TRACKER

In the CESR storage ring, the transverse tunes continuously vary by several times their natural width. Hence, synchronous beam excitation is impossible without active feedback control. The digital tune tracker consists of a direct digital frequency synthesizer which drives the beam through a transverse kicker [8], and is phase locked to the detected betatron signal from a position detector. This ensures synchronous excitation, and by setting the correct locking phase, the excitation can be tuned to peak resonance. The fully digital signal detection allows a single bunch amid a long train to be synchronously driven.

Position and Phase Detection

The position signal is taken from a set of microstripline electrodes, which are separated into amplitude and displacement signals with a network of sum and difference combiners. The core of the digital processor is implemented with and LSI logic array which performs both logic and memory functions. The difference signal is digitized with a 16 bit ADC timed to the peak signal amplitude, and the signal from the selected bunch is latched for one turn. The latched amplitude signal is digitally mixed with a sinusoidal representation of the betatron drive signal. This produces a vector representation of the phase difference between the synthesized betatron drive and the actual betatron motion of the beam. The digital multiplication of the betatron signal with a sinusoidal representation of the betatron motion eliminates harmonics of the betatron signal so that the instrument is insensitive to nonlinear detector response. The demodulated position signals are filtered in a pair of single pole IIR (infinite impulse response) filters. Only one of the filtered signals is used to represent betatron phase error, and the other is only used to reconstruct signal amplitude.

Betatron Frequency Synthesis

The DDS (direct digital synthesizer) consists of a phase register which is incremented by the frequency command at the 23.8MHz clock rate, a sinusoidal lookup table and a 16 bit DAC. Adjustments of drive phase and amplitude are effected by changing the contents of the RAM, and the 16 bit output resolution gives sufficient dynamic range for all applications without the need for analog attenuation. The betatron drive signal is coupled to the beam with the existing feedback kicker, which allows the isolated drive of a single bunch in the 14 ns spacing configuration. In closer bunch configurations, there is some crosstalk of the drive signal to bunches adjacent to the one selected for phase locking.

Loop Closure

The phase locked loop requires a proportional channel and an integrating channel. The proportional channel shifts the betatron frequency command by an amount proportional to phase error. This is necessary to maintain loop stability, and to give the loop sufficient agility to track the tune fluctuations of the storage ring in real time. The integrating channel increments the frequency command on every revolution by an amount proportional to phase error. This is necessary to bring the phase error to zero, and thus provide a stable phase reference for lattice measurements. Signal acquisition is shown in Fig. 1. The phase lock is accompanied by a large increase in the amplitude. Once locked, the fit is refined by sweeping the drive phase. Results of the phase centering sweep are shown in Fig. 2.

The DDS phase register value is latched once per accelerator revolution, and the phase is sent by a parallel digital link to the clock modulator for the CESR BPM system[3]. The BPM clock modulator imposes both the vertical and horizontal phase values from the two tune trackers on the BPM clock using a pulse width modulation system. The individual BPM modules then extract the phase values and use them to reconstruct the betatron drive signal, in order to synchronously detect betatron phase at each BPM station.

WITNESS BUNCH

Storage ring light sources and damping rings typically operate with trains of closely spaced bunches. Low vertical emittance is essential to achieving high luminosity and brilliance. Emittance is diluted by magnet misalignment at the level of tens of microns (offset) and micro-radians (tilts) and is thus sensitive to environmental noise, temperature, etc. The digital tune tracker and turn-by-turn, bunch-by-bunch position monitors allow the possibility of continuosly measuring lattice functions with the witness bunch as probe. The tune trackers lock onto the witness bunch, (here the last bunch in the train), and the beam position monitors measure its turn-by-turn position, from which lattice errors are extracted.

The witness bunch is driven to large amplitude ($\sim$ 10 times the characteristic beam size). As a result of the motion, its vertical emittance is increased, so that it is not useful for producing luminosity or a brilliant x-ray beam. However, the emittance and motion of the other circulating bunches is unaffected. An example of a 10 bunch train with trailing witness is shown in Figs. 3 and 4. Bunches are spaced 14ns apart. Fig. 3 shows the root mean square of the turn-by-turn centroid position of each of the bunches, measured at one of the beam position monitors. The rms bunch motion of bunch 10 is increased an order of magnitude for both horizontal and vertical motion. The vertical size of each of the bunches, measured with the turn-by-turn and bunch-by-bunch x-ray beam size monitor [11], appears

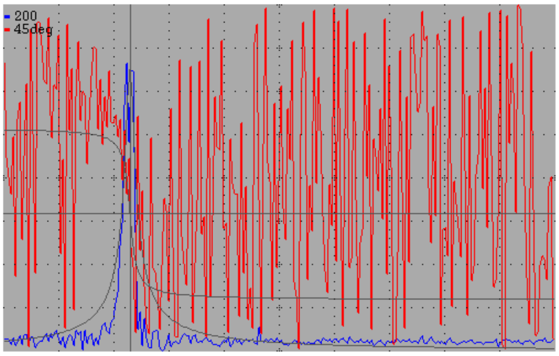

Figure 1: Frequency sweep over 10kHz. The tune tracker acquires a betatron signal by sweeping the drive frequency through a band and recording betatron amplitude and phase. Blue trace is amplitude and red trace phase response shown with fitted Lorentzian.

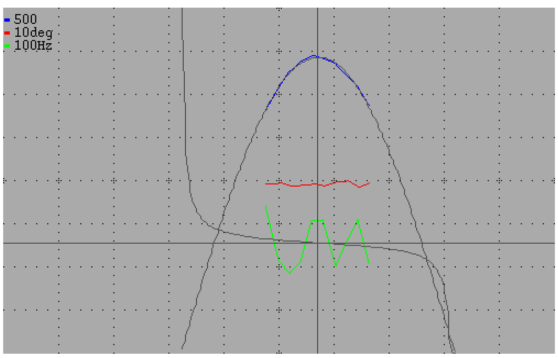

Figure 2: Phase sweep and fit. Amplitude (blue), phase error(red), DDS frequency(green)

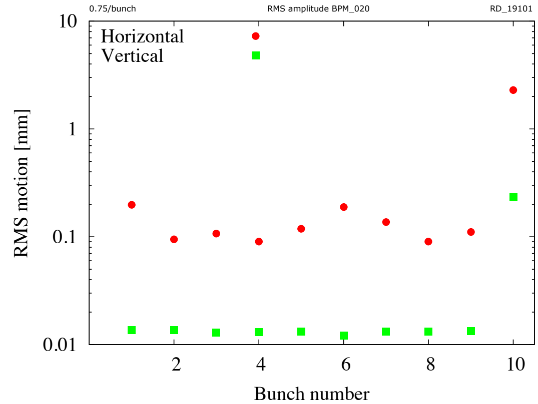

Figure 3: Standard deviation of the turn-by-turn position. The 10 bunches are spaced 14ns apart. The tune tracker is locked to the last bunch in the train, driving it at the horizontal and vertical betatron tunes.

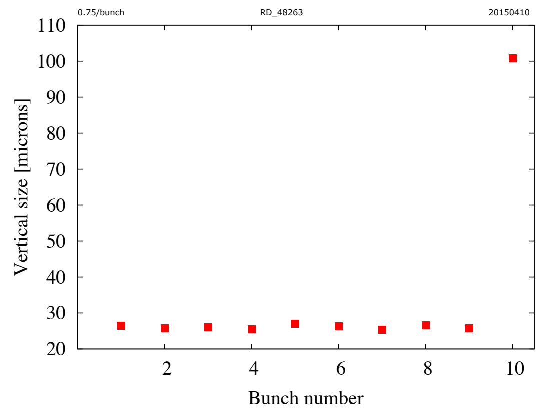

Figure 4: The vertical size of each of 10 bunches in the train, measured turn-by-turn and bunch by bunch with an xray-beam size monitor. The plotted size is a 100 turn average.

in Fig. 4. The effect of the tune tracker is to increase the vertical size of bunch 10 from 25 to 100 microns.

The betatron phase and amplitude and the transverse coupling, given by the measured turn-by-turn position of the witness, is shown in Fig. 5. The change to corrector strengths required to compensate the measured phase and coupling errors are computed and implemented. The effectiveness of the corrections is evaluated in a subsequent measurement (not shown). The nine leading bunches are unaffected.

CONCLUSION

High performance colliders that rely on ultra-low emittance damping ring sources may benefit from continuous monitoring and correction of lattice errors. The digital tune tracker and beam position monitor electronics developed at CesrTA for CESR allow manipulation of a witness bunch to measure betatron phase advance, transverse coupling and dispersion, in addition to orbit, without effecting the emittance or position of the other bunches.

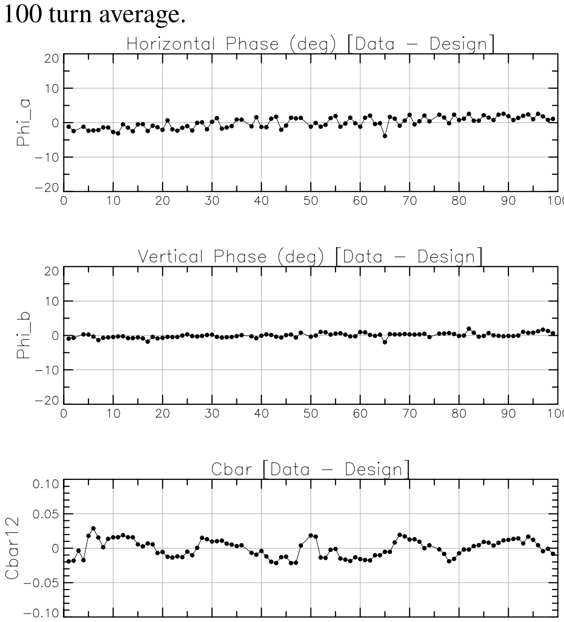

Figure 5: The turn-by-turn position of the witness bunch, measured at each of 100 beam position monitors, is used to determine betatron amplitude and phase advance.

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