TECHNICAL REPORT

Instrumentation for the study of low emittance tuning and beam dynamics at CESR

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Abstract: The Cornell Electron-positron Storage Ring (CESR) has been converted from a High Energy Physics electron-positron collider to operate as a dedicated synchrotron light source for the Cornell High Energy Synchrotron Source (CHESS) and to conduct accelerator physics research as a test accelerator, capable of studying topics relevant to future damping rings, colliders and light sources. Some of the specific topics that were targeted for the initial phase of operation of the storage ring in this mode for CESR as a Test Accelerator (CesrTA) included 1) tuning techniques to produce low emittance beams, 2) the study of electron cloud development in a storage ring and 3) intra-beam scattering effects. The complete conversion of CESR to CesrTA occurred over a several year period, described elsewhere [1–3]. In addition to instrumentation for the storage ring, which was created for CesrTA, existing instrumentation was modified to facilitate the entire range of investigations to support these studies. Procedures were developed, often requiring coordinated measurements among different instruments [4]. This paper describes the instruments utilized for the study of beam dynamics during the operation of CesrTA. The treatment of these instruments will remain fairly general in this paper as it focuses on an overview of the instruments themselves.

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Their interaction and inter-relationships during sequences of observations is found in a companion paper describing the associated measurement techniques. More detailed descriptions and detailed operational performance for some of the instrumentation may be found elsewhere and these will be referenced in the related sections of this paper.

**Keywords:** Instrumentation for particle accelerators and storage rings - high energy (linear accelerators, synchrotrons); Hardware and accelerator control systems

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1 Introduction and overview

The initial phase of the CesrTA project was defined as having a set of specific goals for accelerator physics research and development:

- The investigation of instrumentation and methodology to systematically reduce the vertical emittance of the stored beam [5].
The study of the effects on the stored positron beam due to electron clouds (EC), produced by synchrotron radiation-induced photoelectrons. The goal is to 1) characterize and quantify the production mechanisms, 2) compare these with computer simulations, 3) develop methods to mitigate the EC effects, [6–8] and 4) study the related beam dynamics and instabilities [9].

The measurement and characterization of the intra-beam beam scattering effects as they lead to emittance enlargement [10–12].

The diverse objectives of the CesrTA project described above require a wide array of operating conditions, summarized in table 1.

| Parameter                              | Specification                        |
|----------------------------------------|---------------------------------------|
| Circumference                          | 768.438 m                             |
| Energy                                 | 1.5–5.3 GeV                           |
| RF frequency                           | 500 MHz                               |
| Typical Betatron tunes ($Q_x$, $Q_y$)  | (14.57, 9.62)                         |
| Synchrotron tune                       | 0.018–0.072                           |
| Single-bunch current                   | 0.1–10 mA/bunch                       |
| Number of bunches                      | 1–640                                 |
| Bunch spacing                          | multiples of 4 ns or 14 ns            |
| Typical beam dimensions (H, W, L)     | (20–100 µm, 500 µm, 10–20 mm)         |

To meet these goals a number of instruments in CESR required significant upgrades or complete development of new designs and subsequent implementation. The general description of these instruments, which are required during coordinated measurement sequences, are described below in the following broad categories:

- A major upgrade to the beam position monitor (BPM) system, which replaced an older relay-based position monitor system with individual readout modules for each BPM capable of turn-by-turn and bunch-by-bunch trajectory measurements for bunches spaced as closely as 4 nsec.

- The installation of positron and electron vertical x-ray beam size monitors (xBSMs) designed for turn-by-turn and bunch-by-bunch beam size measurements for 4 nsec spaced bunches.

- Implementation of a visible-light beam size monitor (vBSM) to measure the horizontal beam size for either positron or electrons, including the addition of optical elements to allow streak camera measurements of either positron or electron bunches.

- Development of software to extract bunch-by-bunch tunes utilizing the new modules for the beam position monitors and a second method, which employed video gating of signals from a few beam position monitors from the older relay system.
• An upgrade for the tune tracker, a device containing a feedback loop to phase lock the betatron tunes of a bunch, using either a shaker magnet or stripline kicker. This device allows the measurement of the betatron phase advance and the horizontal-to-vertical coupling of CESR permitting their correction.

• Installation of a new beam-stabilizing feedback system, which damps 4 nsec-spaced bunches for horizontal, vertical and longitudinal motion.

In addition these instruments utilize existing pulsed magnets or stripline kickers to excite dipole motion of the beam. Each of these systems will be discussed in the following sections.

Note that this paper is a companion to the set of papers describing the general modification of CESR’s infrastructure to create the test accelerator CesrTA [1–3]. This paper is the concluding document in preliminary conference papers describing the instrumentation, required for the CesrTA Project in publications from workshops [13] and accelerator conferences [14–16] and within the CesrTA Phase 1 Report [4].

2 Beam position monitors

An upgraded beam position monitor system that provides high resolution measurement capability has been designed and deployed. This system is capable of turn-by-turn measurements of individual bunches within bunch trains with spacings that are multiples of either 4 nsec or 14 nsec. The system provides the ability to make closed orbit, betatron phase, coupling and dispersion measurements via synchronous detection of a driven beam.

2.1 System requirements

The primary operational requirements for the new CESR BPM (CBPM) system are summarized in table 2, and include:

• The ability to operate with counter-rotating beams of electrons and positrons in a single vacuum chamber for the synchrotron light two beam operation for CHESS;

• High resolution for low emittance optics correction and tuning;

• Turn-by-turn readout capability for multiple bunches to support beam dynamics studies;

• Capability for digitizing single species bunch trains with bunch spacing as small as 4 nsec and dual beam digitization for bunch trains with 14 nsec spacing.

The need for dual beam operation of the system places a unique constraint on the CESR BPM specifications. Since the relative arrival time of the bunches from the two beams varies widely from location to location around the ring, standard RF processing techniques to optimize resolution and minimize timing sensitivity cannot be applied to the full system. As a result, the CESR design utilizes peak sampling with a high bandwidth digitizer and incorporates hardware and software design features to optimize the system timing performance.
Table 2. CESR BPM module requirements [23]

| Parameter                                         | Specification |
|---------------------------------------------------|---------------|
| Front End Bandwidth (for 4 ns bunch trains)       | 500 MHz       |
| Absolute Position Accuracy (long term)            | 100 µm        |
| Single Shot Position Resolution                    | 10 µm         |
| Differential Position Accuracy                     | 10 µm         |
| Channel-To-Channel Sampling Time Accuracy          | 10 psec       |

2.2 System implementation

The CESR BPM system, described elsewhere [23], consists of a network of local sensors and processors. Each location has four beam buttons arranged in a mirror symmetric fashion, providing relative amplitude signals for a processing module. All modules share a common controls database, timing and synchronization controls, and networked data storage. This allows for accelerator-wide coordinated measurements.

3 Beam size monitors

Vertical and horizontal beam size measurements are made utilizing the xBSM and vBSM, respectively. These systems can operate in parallel so that the combination of vertical and horizontal beam sizes can be acquired simultaneously. In addition the vBSM has a π-polarization operational mode that allows it to measure vertical beam size.

3.1 X-ray beam size monitors

During the conversion of CESR to operate for CesrTA research, two xBSMs detectors were added to CHESS x-ray extractions lines with synchrotron radiation (SR) source points located in two Hard Bend magnets (38 m bending radius), one for positrons and the other for electrons. The one-dimensional monitors produce the vertical beam profile turn-by-turn for bunches spaced as closely as 4 nsec. The processing software fits the vertical beam size and vertical position turn-by-turn allowing the averaging the vertical beam size independent of vertical dipole motion of the beam. Beam size measurements may be acquired on the same turns for each bunch in trains of bunches with arbitrary spacings. This system is described in detail elsewhere [17, 18].

3.2 Visible light beam size monitor

The two visible light beam size monitor ports were installed in the L3 straight section of the storage ring. An overview of the vBSM system is shown in figure 1. The vBSM ports are placed symmetrically at east and west ends of the straight section in order to image visible synchrotron light from the electron and positron beams, respectively. The visible SR from bending magnets (140 m bending radius) is reflected by a Beryllium mirror located inside the vacuum chamber, which directs the light out of the chamber through a vacuum window and into an optics box. On exiting the vacuum window, the SR photons pass through an iris with an adjustable aperture into the optics
The optics box contains several sets of double slits with different slit spacings and orientations for interferometric measurement of vertical or horizontal beam size. The slits are followed by a focusing lens. The light is then reflected by multiple mirrors, overhead, across the tunnel and eventually through the wall from the accelerator tunnel to an optical table in an experimental hall. At this point the light has traveled 27 m from the source in the bend magnet. The path of the light, from vacuum window through tunnel wall, is indicated in figure 2. On the optical table in the experimental hall, the SR light passes through a second lens, a polarizer, a bandpass filter and is finally incident on a CCD camera. A beam splitter can be placed in the path to direct a fraction of the light into a streak camera in order to measure the bunch length. The vBSM system is explained in detail in [19].

![Figure 1. Schematic of the L3 vBSM.](image)

### 4 Tune and motion detection

The variation of the tunes of individual bunches within trains of bunches or of a witness bunch, following a train of bunches, carries information about the electron cloud density. Different methods have been employed to measure the tunes of the bunches during the beam dynamics studies.

#### 4.1 Tune and motion detection for multiple bunches by turn-by-turn trajectory measurements

A simple method for determining the tunes for each bunch in a train of bunches is to use a subset of the complete number of CBPM modules to measure the beam position turn-by-turn for each bunch. The data is read out from the CBPM modules and written into a raw data file. Each BPM’s position data is then analyzed offline by performing a Fourier transform, which yields the spectral lines of the beam’s transverse motion. This method is most often used in conjunction with a kicker that deflects all of the bunches within the train on a single pass (see section 5.2).
4.2 Tune and motion detection by single bunch spectrum measurements

A second method for detecting the tunes of a single bunch within a train of bunches is shown in the block diagram in figure 3. This detection method makes use of one of a few BPM detectors, which are still connected to CESR’s original relay-based BPM system processors. The signal from one BPM button is routed via coaxial relays to one of the analog processors, where fixed gain amplifiers and/or attenuators may be inserted in the signal path to maintain the peak signal level within a factor of five over a wide range of currents. After the gain adjustment the signal passes along to an RF gating circuit, which is triggered by signals from CESR’s fast timing system. This allows the gating of the signal from a single bunch, sending it to a peak rectifier circuit (with approximately a 700 MHz bandwidth) and then routing its video output to a spectrum analyzer in the Control Room. This hardware has a much better sensitivity than the CBPM; it is the only position monitoring system at CESR capable of observing head-tail motion of bunches.

The timing aperture for the gating circuit was measured by sweeping the gate delay for the signal coming from a single bunch to observe the signal amplitude vs. gate delay and the results are displayed in figure 4. A second method for observing the signal crosstalk between bunches is seen in figure 5. This plot is obtained by shaking the beam vertically and observing the spectrum analyzer’s signal amplitude as a function of gate delay. This second observation gives the base timing aperture as 7.5 nsec wide, giving more than 20 dB isolation of the signal crosstalk from adjacent 4 nsec-spaced bunches and a signal isolation of greater than 50 dB for 14 nsec-spaced bunches.
Figure 3. Block diagram of a betatron tune receiver using the relay BPM system.

Figure 4. Relay BPM processor’s gate timing aperture as measured with the video signal in the Control Room having a 77 mV DC offset due to the peak rectifier circuit.

Figure 5. Relay BPM processor’s gate timing aperture as measured by driving a single bunch vertically and measuring its response vs. gate delay.
4.3 Single bunch tune measurements to establish the operating point in the tune plane

The initial setup of the storage ring operating point in the tune plane at the beginning of a set of dynamics measurements requires the determination of the betatron and synchrotron tunes, which are routinely performed by measurements with a single stored bunch. The betatron tune instrumentation configuration, which is capable of detecting the beam’s tune in both planes, is shown in the block diagram in figure 6. In this mode the single bunch is excited with the relatively narrow bandwidth shaker magnets (see section 5.3) and detected with a swept spectrum analyzer. For synchrotron tune measurements the RF accelerator system’s phase command is modulated and the energy oscillation is detected using the orbit’s dispersion in one BPM detector.

![Block diagram of an narrow-band tune receiver.](image)

**Figure 6.** Simple block diagram of a narrow-band tune receiver, shown in the mode where it can detect both the horizontal and vertical betatron tunes.

5 Beam excitation

To measure the tune spectra of bunches it is necessary to observe them undergoing coherent motion. In some cases their self-excitation is sufficient for a good tune measurement, but in other cases the beam must be driven with some type of dipole kicker to cause the beam to undergo centroid motion. There are three types of dipole kickers used in CESR.

5.1 Pinger magnets

A pinger magnet is used to create a single impulse deflection for the beam. There are three pingers installed in CESR: two are horizontal and one is vertical. A horizontal pinger is shown in figure 7 and is a pair of single-turn ferrite-core magnets, which surround a Kovar-coated ceramic vacuum chamber. The horizontal pingers are excited using a thyratron with an approximately square pulse, having a flattop region about 2 µsec long, where the circulation time for CESR is 2.56 µsec. This is more than long enough to excite all bunches in one train with the same deflection angle. The pulse shape for the vertical pinger has a different waveform, since the magnet is constructed in a ferrite box structure with two 2-turn windings; the magnet is driven with a half sine-wave pulse of approximately 2.5 µsec duration. The pingers can be triggered via CESR’s Fast Timing System at repetition rates up to 60 Hz and the triggers can be synchronized with the CBPM turn-by-turn and bunch-by-bunch data acquisition. Because of its half sine-wave shape, for the excitation of a train of bunches the vertical pinger is timed to have the bunches in a train arrive at the time for them to straddle the peak of the pinger’s deflection.
5.2 Stripline kickers

The second type of deflection element is a stripline kicker, which is utilized for beam dynamics measurements in the configuration shown in figure 8. There are two stripline kickers installed in CESR, one horizontal and one vertical, and serve as are the deflectors for the transverse dipole bunch-by-bunch beam stabilizing feedback systems for the ring. The kickers are shorted at one end, with a transit time of 3.5 nsec, and are excited with 200 W-150 MHz bandwidth RF amplifiers. The kickers have an impedance of 50 $\Omega$ and are constructed from OFHC (oxygen free, high thermal conductivity) copper sheet. As a part of the transverse feedback system for 14 nsec-spaced bunches, the amplifiers are modulated with 14 nsec single period sine-wave, producing an approximately constant (±5%) deflection to the beam for about 3.5 nsec. The crosstalk of this stripline kicker to adjacent bunches is less than $-40$ dB for 14 nsec-spaced bunches. Each feedback modulator has an external modulation input and when it is enabled, the input will allow the deflection of any combination of 14 nsec-spaced bunches. For beam dynamics measurements, the stripline kickers are most often used to deflect individual bunches within the train. For detailed tune shift measurements, another method excites the first bunch at the same time one of the later bunches is being excited; this allows accurate accounting for the difference in tunes between the lead bunch and the measured bunch when drifts in the accelerator tunes are present.

5.3 Shaker magnets

For completeness there is a third type of deflection component in the storage ring. This is low-frequency shaker magnet, a multi-turn coil wound around a H-frame ferrite core surrounding a metalized coated ceramic vacuum chamber. Although this shaker magnet does not have sufficient
bandwidth to excite motion of individual bunches and is therefore not in use during beam dynamics measurements of trains of bunches, it is still important for the detection of the tunes, when CESR conditions are re-established at the beginning of each extended measurement period.

6 Digital tune tracker

Numerous storage ring diagnostic procedures require synchronous excitation of beam motion. Some examples are the lattice betatron phase advance measurement [20] and BPM button-by-button gain calibrations [21], which involve synchronous detection of the driven betatron motion. In CESR the transverse tunes can vary continuously by several times their natural width. Hence, synchronous beam excitation is impossible without active feedback control. The digital tune tracker [22] consists of a direct digital frequency synthesizer, which drives the beam through a transverse kicker, and is phase locked to the detected betatron signal from a BPM. This ensures synchronous excitation and, by setting the correct locking phase, the excitation can be adjusted to be at the betatron tune’s resonant peak. The fully digital signal detection allows selecting a single bunch within a long train to be synchronously driven, which permits lattice diagnostics to be performed including collective effects. An overall block diagram of the tune tracker is shown in figure 9.

The tune tracker operates at a clock frequency of 71.4 MHz, corresponding to 14 nsec bunch spacing. This clock is used for beam sampling, filtering, and synthesis of the betatron drive signal. Since only a single bunch is to be used for phase locking, the instrument can select any bunch from within any pattern of stored bunches.

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 difference signal is digitized with a 10 bit ADC, which is timed to peak signal amplitude, and the signal from the selected bunch is latched for one turn. As shown in figure 10 the latched amplitude signal is digitally mixed at 71.4 MHz with two square wave representations of the betatron drive signal at quadrature phases. This produces a vector representation of the phase difference between the
synthesized betatron drive and the actual betatron motion of the beam. The betatron clock is represented as square waves to eliminate the need for real-time multiplication. The demodulated position signals are filtered in a pair of single pole infinite impulse response filters. One of the filtered signals is used to represent betatron phase error and the other is only used to reconstruct signal amplitude.

The direct digital synthesizer (DDS) consists of a phase register, which is incremented by the frequency command at the 71.4 MHz clock rate, a sinusoidal lookup table implemented in a high-speed cache RAM and a 14 bit DAC. Adjustments of the drive phase and amplitude are effected by changing the contents of the RAM with the 14 bit output resolution giving sufficient dynamic range for all applications without the need for analog attenuation. The betatron drive signal is coupled to the beam via the feedback kicker, which allows the isolated drive of a single bunch in the 14 nsec spacing configuration. For 4 nec-bunch spacings, there is −20 dB crosstalk of the drive signal to bunches adjacent to the one selected for phase locking, due to the modulator waveform shape and the 3.5 nsec stripline kicker length.

Figure 9. Overall block diagram of the tune tracker. The phase-lock block diagram is detailed in figure 10.

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 the 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.

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 CBPM system, [23, 24]. 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 drive signals (typically at one of the three normal mode dipole frequencies: horizontal and vertical betatron modes or the synchrotron oscillation mode),
which is used to synchronously detect corresponding phase at each BPM station. The synchronous phase measurement is used to determine the phase advance between BPM stations, and hence the phase function of the entire lattice, while the relative phase of horizontal and vertical motion at each BPM is used to extract coupling information [20].

The operating configurations of the tune trackers, including center frequencies, gains, and filter settings, are saved and restored along with the storage ring configuration. This gives a high probability of a successful phase lock with minimal adjustment. The signal acquisition and locking functions can be operated through a graphic user interface and the same functions can be executed automatically by other system processes using control system subroutines.

The tune tracker can initially acquire a betatron signal by sweeping the drive frequency through a band, typically 20kHz wide, and recording betatron amplitude and phase error relative to the DDS. A fit of center frequency, center phase, peak width, and peak amplitude is then automatically computed to match a Lorentzian resonance model, where the phase shifts by $\pi$ as the excitation frequency sweeps across resonance.

Only a rough fit is possible to the tune of an unlocked beam because of the tune noise of the storage ring, which is approximately a few hundred Hertz. Acquisition of phase lock, seen in figure 11, is accompanied by a large increase in betatron amplitude. Once phase lock is established, a fine fit to the resonance can be done by sweeping the betatron drive phase, and recording betatron amplitude and drive frequency. A fit of the same four parameters is automatically performed using the Lorentzian model by the same method described above. This consists mainly of fitting the amplitude to a cosine function, and gives the closest possible approach to the resonance peak.

7 Beam stabilizing feedback systems

Three Dimtel iGp-1281F signal processor systems have been added to the CESR ring to supplement existing feedback systems. Prior to this CESR operated exclusively with 14 nsec, multiple bunch,
Figure 11. Time sweep showing the acquisition of the lock condition for the tune tracker. The blue trace is the betatron amplitude (arbitrary units). The red trace is the betatron phase error (10 degrees per division.) The green trace is the direct digital synthesizer frequency offset (100 Hz per division.) The time scale is approximately 0.4 sec per division. Note that the tune tracker is following the frequency shifts of the betatron tune after the lock condition is established.

turn-by-turn feedback [25]. The 14 nsec system was designed for and constrained by having electrons and positrons in the ring simultaneously. The Dimtel systems add faster processing capability to the same detection and kicker hardware to provide independent feedback for all bunches in a single electron or positron beam with spacings down to 4 nsec. This gives CESR the flexibility to transversely and longitudinally stabilize bunch trains with a bunch spacing of any integer multiple of 2 nsec greater than 4 nsec.

7.1 14 nsec feedback system

The 14 nsec feedback system [25] uses a standard set of four CESR beam position buttons as the input. Pairs of button signals are connected to hybrid combiners which output both the sum and difference of the two signals. The vertical feedback system uses the signals from combining the top and bottom button signals together, thus yielding a difference signal which is sensitive to vertical position. Likewise, the horizontal system uses the difference of the combined inner and outer button signals. The sum of all four button signals is used as the longitudinal system input. The horizontal system block diagram is nearly identical to the vertical system block diagram and can be seen in figure 12.

Signals are acquired at 71.4 MHz by a direct sampling 10 bit analog to digital converter (ADC). This rate allows sampling at the traditional CESR bunch spacing of 14 nsec. Longitudinal signals are processed with displacement or phase detection, sample and hold, displacement or phase offset correction, and filtering circuits. Transverse signals are filtered then sampled in a digital signal processor (DSP.) The output is the beam error signal represented by a ±500 mV analog signal that is updated every 14 nsec [26].
For the transverse systems, the error signal is modulated into a bipolar pulse. The pulse is amplified by an ENI3200L 200 watt power amplifier with bandwidth from 250 kHz to 150 MHz. The amplified pulse is sent to a 1.16 m stripline kicker.

The longitudinal error signal is amplified by a 1 kW solid state amplifier. The signal is transmitted to the beam through an 1142 MHz resonant frequency cavity kicker. The cavity kicker has three coupling ports for drive and three coupling ports for load, for a total of six ports. The cavity has a loaded $Q$ of about 14 and a field decay time of 3.9 nsec [25]. A block diagram overview of the longitudinal system is in figure 13.

The 14 nsec feedback system is controlled through the CESR control system multi-port memory (MPM). The MPM allows many devices to share a memory space. The DSPs access the shared memory for information on the gains and delays necessary for different CESR ring configurations.

7.2 4 nsec feedback system

The pre-existing feedback system described above was augmented to provide stability for bunches spaced down to 4 nsec by adding three Dimtel iGp-1281F signal processors [27], one each for horizontal, vertical and longitudinal dipole modes of oscillation. The processors use the same beam
input signals as the 14 nsec feedback system as well as the same stripline and cavity kickers. A block diagram of the iGp is in figure 14.

The new signal processors operate at 500 MHz and acquire the input signals with 1.26 GHz bandwidth with high speed 8 bit ADCs. The signals are processed by a dual-port memory field programmable gate array (FPGA) for control computations including applying a finite impulse response (FIR) filter with up to 16 taps. A high speed DAC drives the output signal with 12 bit resolution, a rise time under 250 psec and a fall time under 350 ps.

The FPGA is controlled by an embedded EPICS input-output controller (IOC). The IOC is connected to the FPGA by universal serial bus (USB) and to the CESR control system via Ethernet [28]. Computing scripts and display screens on the CESR control system are used to control the parameters of the signal processor and to acquire and analyze data. An additional software EPICS IOC running on the CESR control system and a service program provide an interface from the CESR MPM to the iGp devices.

Completely configurable bunch control allows the setting of any combination of the 1281 available 2 nsec RF buckets in CESR for feedback or excitation. The iGp has the ability to resolve individual bunches, however, the system is limited by the electrical length of the stripline kickers and the field decay time of the cavity kicker to provide differing feedback kicks 4 nsec apart.

**Figure 13.** System overview of the longitudinal 14 nsec feedback.
Figure 14. System overview of the Dimtel iGp 4 nsec signal processor.

Figure 15. A drive-damp measurement with the horizontal 4 nsec feedback off (black trace) and on (blue trace.)
7.3 Feedback system results

The Dimtel iGp upgrade proved successful in stabilizing either electron or positron beam (separately) in a wide array of bunch patterns and spacings. For example, at 5.3 GeV the single bunch damping in the horizontal system is shown in figure 15. In this drive-damp measurement, the beam is driven at horizontal betatron frequency for 3 msec and then allowed to damp. The black curve shows the natural damping without any horizontal feedback. The blue curve shows the result with the 4 nsec feedback on. The feedback drops the maximum excitation by about 15 dB and the beam is damped back to its noise floor within 500 µsec. The resulting damping times are approximately 9 msec without feedback and less than 0.32 msec with feedback.

8 Summary

This paper describes the instrumentation, which has been developed or modified for use in the CesrTA program for the investigation of storage ring beam dynamics. In particular these studies have focused on the methods for low emittance tuning of the beam, on the causes for intra-beam scattering of single bunches and on the production of ECs, produced by photo-electrons from synchrotron radiation and secondary emission, and their interaction with bunches within trains. A companion paper describes how this instrumentation is used for coordinated beam dynamics measurements.

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