DEVELOPMENTS IN BEAM INSTRUMENTATION AND NEW FEEDBACK SYSTEMS FOR THE ILC

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Abstract

The baseline configuration of ILC accelerator was discussed and described in the baseline configuration documents (BCD)[1]. The detailed discussion and design are still on-going towards reference design report (RDR). To address and to demonstrate realization of these instrumentation, many development activities on BPMs, laser wire, and fast feedback in Europe, US, and Asia are going on using several test facilities. This paper introduces the specification of ILC beam instrumentation appeared in BCD, and describes its developments status. The critical items and its R&D program to support BCD and RDR are especially outlined.

INTRODUCTION

The ILC instrumentation and control system is an highly automated feedback system maximizing luminosity stably. The sophisticated integration of basic monitors, orbit control, LLRF control of various acceleration system and beam generation control is the major target. The beam instrumentation which supplies precise beam information with enough high bandwidth is required. There are four types of basic monitors: position (BPM), intensity (toroid), profile and loss (BLM). From the monitor point of view, the ILC is divided into two sections, the 'damped beam' section (damping rings - beam dumps), and the injector system (upstream of the damping rings, including injection into the rings). Typical beam sizes and required position resolution in the damped beam are around a few microns to ~0.1 microns. And they are 2 to 3 order bigger in the other section. Monitor R&D for damped beam is needed to provide confidence for the BPM and profile monitor systems.

The most critical beam instrumentation is the BPM system. The requirements to the BPM will be met by precision RF cavity BPM's. The second critical system is the damped beam profile monitor. The system validates the performance of the low emittance transport. For the most part, these monitors will be based on 'laser-wires'. A laser-wire consists of a 90 degree Compton scattering chamber where a finely focused, very high power pulsed laser is used to sample the particle beam density. Although laser-wires have been built and successfully tested in all three ILC regions, these systems still need more development and require constant handling by experts. The laserwire system will be used to evaluate the luminosity and will be necessary tools in the low emittance transport.

Beam-based dynamical feedback control is essential for high performance and high luminosity. Beam based feedback systems will stabilize the electron and positron orbits in the damping rings and trajectories throughout the machine, and keep the collision stably. In this paper, only beam-based feedback systems which consist of beam position monitors (bpms) and fast feedback kickers are discussed.

ILC INSTRUMENTATION BCD

BPM for Main Linac

Main linac BPM is required substantial R&D. Main linac BPMs will be placed at each of the approximately 800 quadrupoles in the cryomodules of the two main linacs. The specification appeared in BCD are; it has 60-70mm aperture with 0.5micron resolution with less than 10microns stability over cryomodule thermal cycling. They shall report the position of each bunch in every bunch train. In particular during fabrication and assembly they must be cleanable with standard techniques like ultra-high purity pressurized water to prevent contamination into the accelerating cavities.

There are two candidate solutions for the beam position pickup sensor. Both are based on resonant cavities. The "conventional cavity" BPM relies on dipole modes of a pillbox resonant cavity. The "re-entrant cavity" BPM relies on the dipole resonant mode of a coaxial resonator where the beam duct is the center conductor

Cavity BPM: Cavity BPM usually pick up a dipole mode with common-mode free coupling to external electronics. The signal produced at the output coupler is proportional to the product of beam charge and beam position. Cavity BPMs show extremely good resolution and stability. There are many examples studied at KEK ATF and at SLAC FFTB. These feature dipole-mode couplers that reject the cavity monopole modes. This reduces the dynamic range required to achieve sub-micron resolution and is thought to yield excellent accuracy and stability. At C-band frequency, resolution in the 20 nm range or better have been reported. Centering stability better than ±50 nm over 2 hours has also been observed. However we are not aware of a common-mode-free cavity BPM that has been qualified for use in a cryogenic clean environment.

Re-entrant Cavity BPM: These are RF BPMs using coaxial resonant modes in a shorted coaxial structure. They have proven cryogenic and cleanroom compatibility as demonstrated in the TTF cryomodule. The signal at the output couplers have considerable common-mode signal. Careful monopole mode cancellation is required here; much of it is accomplished externally by RF hybrids in the processor electronics. More R&D is required to demonstrate required resolution and stability.

BPM for Beam Delivery System

Beam Delivery System (BDS) BPMs must have resolution significantly better (around 250nm) than half the beam size to keep beam position jitter less than it. The stability is required less than 10micron for long term, especially less than 1 micron for energy spectroscopy. Cavity BPMs are favored for most of the BDS BPMs for resolution, accuracy, and stability. The intra-train IP feedback BPMs are exceptions; these are likely to be stripline BPMs for ease of low-propagation delay processing, and for the 2 milliradian crossing angle scheme, the possibility of directional beam pickups.

A potential problem arises from the beam halo generated in the collimators. The BPMs will measure the position of the sum of beam core and halo position weighted by their relative intensities, while for optics tuning and feedbacks the core position is the relative quantity. Dedicated studies of these effects are required to estimate the magnitude and potential risks of this effect.

Beam Profile Monitor System

In the damped beam section, the beam profile monitors are based on ‘laserwires’. A laserwire uses a finely focused, high power laser beam to sample the particle beam density in the same way like a wire scanner. However, the operational issues of a laserwire are more complex because of laser control, laser focusing, laser profile, pulsed laser timing and etc. The laserwire has the added advantage that there is no added material inside the vacuum chamber. This reduces the risk of contamination to the nearby cavities. In the damping ring, a synchrotron radiation by an interference technics or by using zone plates in X-ray wavelength region will be used for a profile monitor.

In the baseline configuration, the total number of laserwire systems per side is 9. They are in 1) the damping rings, 2) the ring to BC transport, 3) between the two BC stages, 4) the BC to main linac transport, 5) within the main linac (3 sets; at the 10%, 25% and 50% energy gain locations), 6) at the entrance to the beam delivery and 7) within the beam delivery, downstream of the collimation systems. With the exception of the damping ring laserwire, each laserwire system has 3 to 5 interaction chambers distributed along a fraction of a betatron cycle, extending perhaps 40 meters, depending on the beam optics. Each interaction chamber has a focal system for x and another for y and may have a ‘u’ scan direction also, for monitoring x y coupling. The damping ring only has two interaction chambers, one for a dispersion - free and one for a non-zero dispersion region. The main linac laserwires use a modified inter-module insert that allows ‘warm access’ to the vacuum chamber. The total number of interaction chambers, for both sides of the ILC is 70. It is important to note that a single laser may feed many IP’s through the use of an extended laser transport system. The number of lasers for the ILC laserwire system should be 12 or less (total for both sides).

The performance requirements for the laserwire profile monitors are typically within 10% error for emittance measurement (5% beam size). The system in the damping ring and the system at the entrance to the beam delivery should be 2x better than that. R&D is required to show the performance.

Beam-based Feedback Systems

Beam-based feedback systems which are discussed in this paper employ instrumentation such as bpms and fast kickers. Other (non-beam based) feedback systems, such as cavity temperature control are considered out of scope for this section. Beam based feedback systems will stabilize the electron and positron orbits in the damping rings and trajectories throughout the machine. It will also be used to correct for emittance variations, and for measurement & correction of dispersion in the Main Linac. A summary of anticipated beam-based feedback loops are followings; for Damping Ring, 1) Injection trajectory control, 2) Dynamic orbit control, 3) Bunch-by-bunch transverse feedback, 4) Extraction orbit control, for Ring-to-Main Linac (RTML) 5) Pre-Turnaround emittance correction, 6) Turnaround trajectory feed-forward, 7) Post-Turnaround emittance correction, 8)Beam energy at bunch compressor (two stages), for Main Linac 9) Dispersion measurement and control, 10) Beam energy (several cascaded sections), for positron source 11) Beam energy at undulator, for Beam Delivery System 12) Trajectory feedback from pulse to pulse, for Interaction Point, 13) Trajectory feedback from pulse to pulse, 14) Trajectory feedback within bunch-train.

Most of the feedbacks are relatively low correction rates and the distributed nature of many of the monitors and actuators, they will be integrated into the controls infrastructure as the 5Hz feedback systems in a synchronized way. On the other hand, dedicated local systems are required for intra-bunch feedback systems that must operate at the bunch rate of ~3MHz, such as the RTML turnaround trajectory feed-forward control, and intra-bunch trajectory control at the IP. The most difficult challenges is the bunch-by-bunch trajectory feedback system in the beam delivery system. The developments are required for high precision measurement at 3MHz bunch rate, fast (low latency) processing, and for fast kicker systems. Integrated simulations of the linac and BDS trajectory feedback systems show that, for noisy sites, these systems recover only of order 20% of the nominal design luminosity. The problem is serious in y where the beam is of order 5 nm in size. For collision optimization, and luminosity stabilization, an intra-train (bunch-to-bunch) feedback system should be implemented in the interaction region. The BPM sensor will be placed several metres downstream of the IP to record the trajectory of the outgoing bunches, and the correcting kicker will be placed several metres upstream of the IP to correct the trajectory of the incoming bunches. Such a system can ‘lock in’ within the first 100 bunch crossings to achieve roughly 80% of luminosity attainable if the beams were in perfect collision.

BEAM POSITION MONITOR DEVELOPMENTS

CEA Re-entrant BPM Development [2]

The re-entrant BPM developed by CEA was installed in ACC1 on TTF2 and held several beam calibration measurement. A new version of BPM which will be installed near ACC7 on TTF2 is now on going. The RF cavity is fabricated with stainless steel and has a small size (170mm of length, 78 mm for the beam pipe and 152 mm of diameter) as shown Figure 1. The antennas are assembled to the cavity by a conflat gasket, and keep the conditions of ultra-high vacuum. To ensure electrical conduction, a RF contact in CuBe was welded in the coaxial cylinder part.

Figure 1: BPM Cavity and one of its feedthrough.

With the new design, the feed-throughs are made simpler and more robust to avoid rejection by cool down qualification test. Since this new design has no resonant mode, the feed-throughs moved from 31.5 mm in the re-entrant part, to have a higher Q and therefore a longer signal in time. With this movement, the monopole and dipole signals are more clearly distinguished and the rejection of the monopole signal become better. One of the biggest problems on the cavity in ACC1 was the cleaning. To be used in a clean environment at cryogenic temperatures, twelve holes of 5 mm diameter were drilled at the end of the re-entrant part. Cleaning tests were successfully preformed at DESY and validated the system for the cleaning. In the test at ACC1, the rejection of the monopole mode is done by three steps. One is made by the new hybrid coupler, the second with the pass band filter, which rejects the monopole mode on the delta channel and the third with the synchronous detection. The digital electronics is used for the sampling, the calibration of the system. The resolution of around 1 micron, and having a centering accuracy better than 1 micron were achieved.

3.3. SLAC Main Linac BPM R&D at ESA [3]

As a development of Main Linac BPM, a slot couple cavity BPM at S-band frequency were designed and fabricated. The slot on the beam pipe is intended to use high pressure water rinsing of cavity and waveguide inside to avoid contamination flow into SC cavities. The beam test of this monitor using 3 BPMs in one set has being done at SLAC End Station A (ESA). Preliminary result on a resolution was 0.8 micron at 1.4E10 electrons beam.

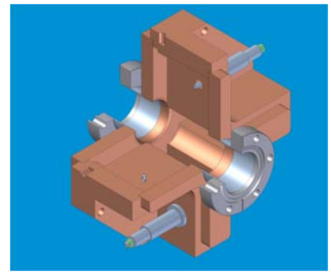

Figure 2: Cavity BPM with Slot Coupled Waveguide.

SLAC/LLNL nm-BPM System at ATF [4]

The SLAC/LLNL nm-BPM system is aiming for achievement of nm resolution to be used in ILC beam delivery and everywhere other than BDS. The system consist of three BINP BPMs which are rigidly mounted inside an alignment frame on six variable-length struts to move the BPMs by small amounts in x, y, z, yaw, pitch, and roll, with avoiding relative movement by mechanical vibration. The alignment frame and movers are designed and built at LLNL. The three BPMs system is located in the ATF extraction line. The resonant frequency of the dipole TM110 mode was 6426 MHz. The cavities have two orthogonal slots corresponding to x and y which couple only dipole mode and reject the monopole mode. The reference cavity is sitting downstream of the system. Single bunch 1.5Hz extractions from the ATF ring were used for the tests. The SLAC developed electronics to process the raw signals from the BPMs use double down conversion technique from 6426 MHz down to 26 MHz, and digitizer of 14 bit and 100 Megasamples per second. The digitized data are fit to sinesoidal function with exponential decay, and get amplitude and phase. They are converted to I and Q components, and then converted to position and tilt signal with careful calibration and correction procedure. The demonstrated best resolution is approximately 16 nm for short interval data, over a dynamic range of ±20 μm. Recent study on cylindrical metrology frame newly installed in its outside for measuring mechanical stabilities of BPMs each other shows 16.4nm rms spread for y movement of center BPM, where their intrinsic system noise is 5nm.

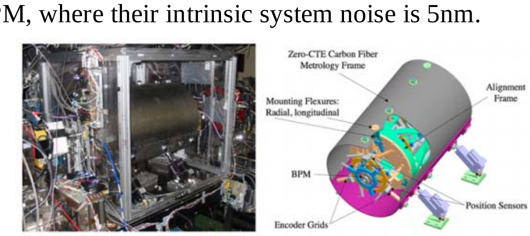

Figure 3: SLAC/LLNL nm-BPM System.

KEK nm-BPM System [5]

With the same motivation and target as SLAC/LLNL nm-BPM, but using active feedback mover to stabilize BPM's relative mechanical movement, KEK nm-BPM system are constructed and installed at about 5m downstream from SLAC/LLNL BPM system. Active stabilization consists of elastic hinge mover driven by piezo actuator for x, y, yow, pitch, position detector of optical interferometer only for y direction. Stabilization feedback acts only for y direction. BPM cavity has design of 4 symmetry slot coupling and reference cavity installed to the sensor cavity body in adjacent. The resultant performance was not so good, because of rf interference between sensor cavity and reference cavity caused strange response in output signal by change of beam position. The signal outcome was 5 times less than BINP cavity, because of less coupling of feedthrough antenna. The interference problem was cured by de-tuning of reference cavity putting metal piece in it. The detection electronics is not digital acquisition. The single stage down conversion from 6551MHz to 714MHz is used for successive phase detection by down converted reference signal. The final detected pulse signal has single polarity. It is integrated by charge ADC module. The phase detector can also output 90degree out of phase signal, that is Q signal. After several R&D and improvement, the best resolution achieved is 17nm, exactly the same as SLAC/LLNL system. It is also confirmed that the active stabilization system reduces 20nm movement down to less than 5nm.

KEK IP-BPM R&D [6]

For R&D on ILC final focus system realizing scaled beam line at ATF, ATF2 beam line is now under construction. Position stability at interaction point which is point of 37nm focused beam size in vertical, is one of study item. Very high resolution BPM with less sensitive to angle jitter is required. In order to avoid x-y coupling, rectangular cavity shape with different resonant frequency for x and y is selected. The frequency is 5.7GHz for x and 6.4GHz for y. The sensitivity is designed to have twice much for x and 4 times much for y compared with BINP BPM by lowering Qext. Cold model for two cavities in one block is fabricated as shown in figure 4, and beam test is under way.

Figure 4: Cold model of IP-BPM system.

BEAM SIZE MONITOR DEVELOPMENTS

ATF DR Laser-wire [7]

The laser wire developed for ATF damping ring is the CW laser wire formed inside of optical cavity with feedback actuated by piezo to keep its resonance on and off repeatedly. Use of low power solid-state laser brought us compact and cost-effective instrumentation, however, leads several challenge required for signal-to-noise ratio problem. The on and off of feedback by sinesoidal modulation on reference signal gives us an elimination of slow drifted background, and good for enhancement of small gamma signal coming from collision. DR laser wire uses 532nm, 300mW YAG laser excited by laser diode, and 99.9% reflectivity optical resonator. 5micron waist size is used for beam scan of about 5micron beam. The monitor used for emittance measurement for single bunch and 20 multibunch, and for damping time measurement also. To get more spatial resolution, use of dipole mode laser wire was developed by introducing small perturbation into optical cavity. The laser wire size itself was increased to 9.6micron, however, the sharpness of each peak was increased. 4.3micron beam size measurement is clearly demonstrate its high resolution of 2micron.

ATF DR X-ray SR Monitor [8]

For emittance monitor in a damping ring, a synchrotron radiation profile monitor using X-ray wavelength focus lens of the FZP (Fresnel Zone Plate) has been designed and constructed at KEK-ATF damping ring. The transverse image of beam at bending field is twenty times magnified by the two FZPs and detected on the X-ray CCD camera. The expected spatial resolution is less than 1 micron. By applying mechanical shutter, the shutter opening time was reduced less than 1ms and the existing 100Hz beam vibration could be neglected on the beam profile measurement. Additionally, the X-ray pinhole mask was installed in one of focal point to reduce the background component of the transmitted X-rays. The typical measured sizes are 50micron horizontal and 7micron vertical. The monitor is used in ATF operation routinely, and used in damping time measurement for wiggler studies. It is very useful and necessary technology for ILC damping rings.

RHUL Laser Wire at PETRA and ATF [9]

The fast scanning Laser-wire (LW) is a candidate of ILC profile monitor. The group of John Adams Institute of RHUL and Oxford university is developing LW by Electro-optic (EO) techniques which has running at a rate of ~100 kHz will provide information about the particle beam size in about one hundred different positions along the train. Such high frequencies might be reached by exploiting the EO effect, where a refractive index change is induced by an applied electric field. Among several EO materials, LNB crystal is selected to start the experimental investigation. Also test of prism optics for study of laser beam distortion has being done. As a step of R&D, 532nm wave-length of laser wire scanned by piezo-driven mirror are installed in PETRA and KEK ATF. Beam profiles with 60 to 70microns size were obtained at PETRA for 7GeV, 7.7nC positron beam. Similar experiment is on-going at ATF to try to measure few micron beam size which is compatible to ILC size. Figure 5 shows image of laser focusing chamber used at ATF, green laser is coming in to f/2 lens system to make few micron size wire.

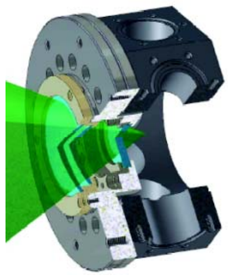

Figure 5: An Image of Laser Wire Chamber at ATF.

Laser Interference Monitor for ATF2 [10]

Beam profile scanner by laser interference pattern which was developed at FFTB by T. Shintake succeeded to measure 60-70nm size. The monitor is now upgrading to use for 37nm beam size measurement at ATF2 focal point. The change of laser wavelength from 1064nm to532nm is pushing a resolution to about half. Making phase feedback of laser using interference fringe and its detection through pin hole, will make fringe stabilized less than 10nm. This will be great improvement to avoid mechanical vibration effect observed at FFTB. Development is also being done for gamma detector. To avoid shower like background, several type of detector are under test, such as multi material cherenkov detector or multi-layer inorganic scintillator. The monitor is now under development by University of Tokyo and KEK collaboration.

BEAM FEEDBACK DEVELOPMENTS

5.1 FONT4 at ATF [11]

The FONT collaboration of Oxford university, QMUL, Daresbury, SLAC and KEK pursues the Interaction Point (IP) feedback system development. In the series of development, very fast BPM processor with small latency were tested at NLCTA and ATF as FONT1, FONT2 and FONT3 experiments. The FONT4 devise is designed for beam parameter of cold machine. The 1ms train, with 300ns bunch spacing, allows the latency requirements to be greatly relaxed and ideally suited to digital processing techniques which would support the use of more sophisticated algorithms to recover an even greater proportion of the luminosity. The FONT4 system is under testing at ATF, where the installation of a new fast extraction kicker will give an ILC-like time structure to the beam in the extraction line, with 150 ns bunch spacing, initially with 3 bunches per train and later up to 20 bunches. A modified FONT3 front-end BPM processor is used to supply the analogue position signals to the digital processor inputs. The digital processor board (shown in figure 6) using a Field Programmable Gate Array (FPGA), of which the Xilinx Virtex 4 has been selected. The aim of FONT4 is to provide stabilization of the third bunch at the micron level, which is a future requirement for ATF2. Currently the test of the front-end BPM processor and the digital board is underway using ATF beam.

Figure 6: FPGA Board developed for FONT4.

SUMMARY

A required ILC instrumentation has been described in BCD for its performance, locations and required number of monitors. Achievement and status of major monitor developments, which will support BCD are briefly summarized.

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