

## BEAM INSTRUMENTATION EXPERIENCE AT ATF\*

Yosuke Honda, High Energy Accelerator Research Organization (KEK), Tsukuba, Japan  
ATF International Collaboration

### Abstract

With its low-emittance stable electron beam, ATF in KEK has been an unique facility to develop various beam instruments. This paper reviews some of those devices that are used in the operation, were tested in the past, and being under development.

### INTRODUCTION

Accelerator Test Facility (ATF) in KEK is a test accelerator to produce a high quality electron beam required in ILC. It consists of an injector linac, a damping ring (DR) and an extraction line. Beam energy is 1.3 GeV, nominal beam charge is  $1 \times 10^{10}$  e/bunch, and pulse repetition rate is 1.56 Hz in the usual operation. There are three types of operational modes, a single bunch mode, a multi-bunch mode of 20-bunches with 2.8 nsec bunch spacing, and a 3-bunches mode with 150 nsec spacing.

The damping ring reduces transverse emittances of the beam down to 1.5 nm-rad and 6 pm-rad in horizontal and in vertical plane, respectively ([1]). Emittance tuning procedures are routinely performed applying corrections to reduce dispersions and couplings based on beam orbit measurements around the DR. The emittance realized in the DR can be measured by three types of monitors, SR-interferometer, X-ray SR imaging monitor and Laserwire monitor. The typical dimensions of the damped beam are 100  $\mu\text{m}$  in horizontal, 10  $\mu\text{m}$  in vertical, and 8 mm in longitudinal.

After beam reaches to the equilibrium in the DR, it is kicked out to the extraction line. The emittance in the extraction line is measured with wire-scanners. The extracted low-emittance beam has been useful to test various devices, such as cavity BPMs, laser-wire, ODR, OTR and fast feedback system (FONT). Recently, most of the beam operation shifts are devoted for development works of these new instruments.

It is scheduled to extend the extraction line for building a test beam line for ILC final focus (ATF2 [2]). Its construction will start in the summer of 2007. Monitors to be used in ATF2 are also being tested.

This article reviews development works of various instruments in ATF. In the following, the instruments are categorized into four sections, beam position monitors, beam size monitors, bunch length monitors, and beam control.

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### BEAM POSITION MONITORS

Beam position is the most essential information. Single shot pick-up BPMs are used for usual operation. Recently, lots of works were done on cavity BPMs using the extracted beam. In the new beam line of ATF2, cavity BPMs will be used as main monitors for operation.

#### *Pick-up BPM*

The diameter of the beam duct is 24 mm in the most part of the beam line. Button type pick-ups are used in the DR, and strip-lines are used in the linac and in the extraction line. In order to quickly measure beam positions in shot-by-shot basis, a single-shot wide-band detection system was developed. The band width of the processor reaches up to 1 GHz, which almost covers the spectrum of the signal after transported to the outside of the tunnel. Bi-polar signals from pick-ups are clipped into uni-polar signals with a diode detector, then they are recorded by 14 bit charge sensitive ADCs. Each channel of the processors was calibrated using a dummy pulse distributed to all channels at the same time. The resolution reaches to 2  $\mu\text{m}$  at  $10^{10}$  e/bunch beam intensity.

#### *Damping ring BPM upgrade*

In order to realize further small vertical emittance, tests to improve the DR BPM by replacing it to a narrow-band system have started. Heterodyne receivers following narrow-band BPFs are installed closely to the pick-ups. On board processors with digital waveform recorders process signals of every beam revolutions. It is expected to have 100 nm resolution with 500 nm accuracy in a machine cycle.

#### *Cavity BPM*

Electro-magnetic modes in a cavity-like structure on beam ducts are excited by the beam passage. Among the various resonant modes, transverse dipole modes are useful to measure the beam positions because their field strength are proportional to the product of beam charge and the beam offset with respect to the electrical center. The beam signal is read out through a selective coupler which couples only with the dipole mode. Its strong and narrow-band signal enables us to measure the beam position with  $\sim$ nano-metre resolution. Mechanical rigidness and reliability of the electric center are also advantages of cavity BPMs. This types of BPMs are expected to play important roles in ATF2 and future accelerators.

Signal strength depends on the choice of cavity frequency. Considering the relatively long bunch length, C-band frequency was estimated to be the most sensitive in our case. All types of cavity BPM developed in ATF use 5.7~6.5 GHz.

*nano-BPM* Three-BPM method is an usual technique to study very high resolution BPMs. A triplet of BPM are supported by a rigid frame so that the relative position of the three to be mechanically stable. Because of the very high resolution, the measurable range of the BPM is limited. A precise mover system is needed to align the BPMs in a straight line within  $10\ \mu\text{m}$ . Two of the three are used to monitor the beam orbit and they predict the beam position at the remaining BPM. Comparing the actual measurement with the prediction, resolution of the BPM can be estimated. Two sets of BPM triplet systems have been developed in the extraction line. Figure 1 is the one with parallel-link movers (upstream). A fast digital waveform recorder samples the down-converted BPM signals. Using an analysis procedure of fitting or digital down-conversion, the data is converted to beam positions. The other one (downstream) has active stabilization movers using sensors with optical interferometers. As for the electronics, this system uses a fast analogue electronics which directly rectifies the signal into beam positions. Figure 2 shows the data taken by the latter system. Calibrating the scale by moving one of the BPM with known amount, the residual between the measurement and prediction can be estimated. Both of the systems have proved position resolutions smaller than 20 nm. ([3]).

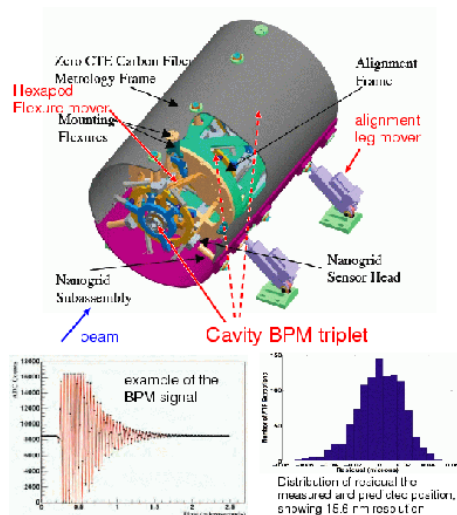


Figure 1: nano-BPM triplet system in the upstream.

*ATF2-BPM* Reliable beam position control within a few  $\mu\text{m}$  accuracy is required along the final focus beam line of ILC and ATF2. Figure 3 is the cavity BPM to be attached on quadrupole magnets of ATF2 ([4]). It is a cylindrical cavity read out from four symmetric ports of waveguides

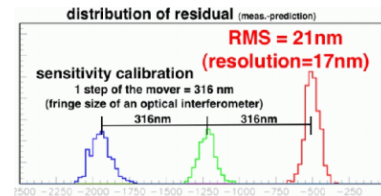


Figure 2: Result of the system in the downstream.

coupled with slots. The front end electronics to down-convert the signal into 20 MHz is also developed. An on-line calibration/analysis system to extract beam positions has been developing.

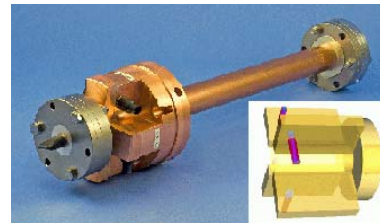


Figure 3: ATF2-BPM.

*IP-BPM* One of the major goals of ATF2 is to demonstrate stabilization of the beam position at the focal point (the virtual interaction point, IP) within a few nanometer. An ultimately high resolution cavity BPM located at the IP (IP-BPM) is necessary to prove it. Due to the special beam optics at the IP, several special considerations were needed in designing IP-BPM. To reduce the signal originated by the angle of the beam orbit, the length of the cavity in the beam direction was shorten compared with other cavity BPMs. To be free from cross-coupling between the dipole modes of different directions, the cavity has a rectangular shape with dipole mode frequencies 714 MHz apart. Tests in the extraction line has started recently (Figure 4).

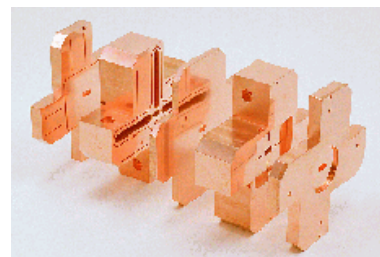


Figure 4: Structure of IP-BPM.

## BEAM SIZE MONITORS

Beam size measurements are important to estimate transverse emittances. High resolution beam size monitors are needed especially for the vertical beam size. To separately

measure bunches in the multi-bunch beam, the monitors have to have a good time resolution.

### X-ray SR Monitor

Imaging its source point on a screen, synchrotron radiation (SR) can be used to measure the beam profile. Since the beam size in the arc sections of the DR is too small to image with a visible light due to the diffraction limit, we have developed an X-ray optical system as shown in Figure 5 ([5]). SR from a bending magnet is first reflected by a monochromator of Si crystal to choose 3.24 keV X-ray, then transported through a magnification optics which consists of two Fresnel Zone Plates (FZP). It was designed to realize a  $\times 20$  magnified image of the source on an X-ray CCD camera. This monitor can measure beam size as small as  $5 \mu\text{m}$  with  $1 \mu\text{m}$  resolution, and is now routinely used in beam operation.

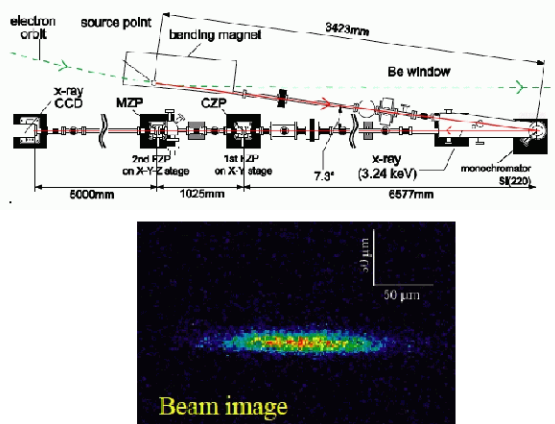


Figure 5: X-ray SR Imaging system.

### SR Interferometer

Spatial coherence of SR can be used to estimate its source size. SR of visible light region is transported to a double-slit interferometer as explained in Figure 6 ([6]). Visibility of the interferogram is a good measure to tell the beam size, the smaller is the beam size, the larger is the visibility. This monitor can measure  $5 \mu\text{m}$  beam size with a carefully tuned system.

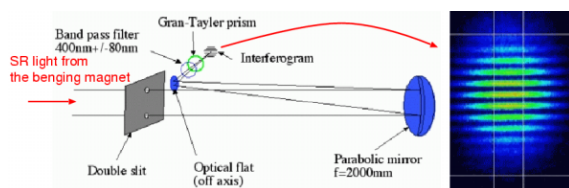


Figure 6: SR Interferometer system

### Laserwire monitor

To reliably measure beam emittances in DR, a direct way to measure the beam size was developed ([7]). This monitor uses a thin laser beam to scan the electron beam in the transverse direction. Compton scattering produces gamma rays in the forward direction of the electron beam. Since the flux of the gamma ray is proportional to the convolution of the beam profile and the laser profile, the beam profile can be obtained by scanning the laser across the beam. To be able to measure a small beam size, laser beam has to be well focused. A cw laser of 532 nm wavelength is injected into a high finesse optical cavity of nearly concentric configuration to stably realize such a small spot while enhancing the effective laser power by  $\sim 1000$  times. By identifying the bunch number with the incoming timing of the scattered gamma rays, this monitor can separately measure each bunch of the multi-bunch beam at the same time. This monitor can measure  $5 \mu\text{m}$  beam size with a good accuracy since the laser spot size is known precisely. Since it takes  $\sim 5$  minutes to complete a scan, accurate beam orbit monitoring to remove the effects of beam position drift is necessary to further improve the system.

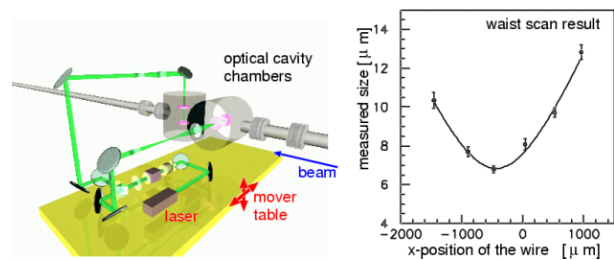


Figure 7: Laserwire system in the DR

### Laser-wire system in the extraction line

To apply the laser wire technique in a single path beam line, a different approach of laser system has been developing in the extraction line ([8]). A laser beam is focused with a specially designed lens system to have a  $\sim \mu\text{m}$  spot size, and is used to scan across the electron beam. To obtain enough signal in single collision, a pulsed laser of high peak power is necessary. Timing system is also important to establish a stable collision. Because this is a non-invasive method to measure the beam and a laser target is never damaged by high intensity electron beams, laserwires are expected to become main beam size monitors in ILC. The collision chamber shown in Figure 8 has been installed and tests are underway. Figure 9 is an example of the beam measurement.

### Wire scanners

The emittances of the extracted beam are usually measured by a wire scanner system. Tungsten wires of  $10 \mu\text{m}$  diameter are installed in horizontal, vertical, 45 degree and

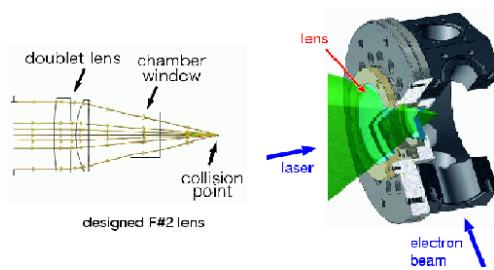


Figure 8: Lens and the collision chamber of the laser-wire system.

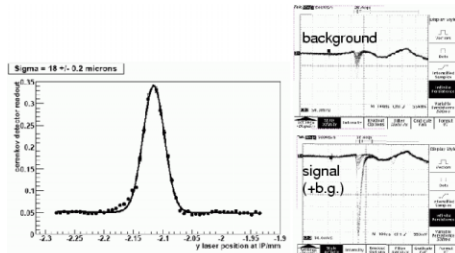


Figure 9: Example of test data by the laser-wire system.

10 degree direction in a scanning system ([9]). The horizontal (vertical) wires are used to measure the vertical (horizontal) beam size, and the angled wires to estimate the beam tilt. An air-Cherenkov detector placed downstream measures the flux of the gamma ray produced in the collision of the wire and the beam. There are 5 sets of the wire scanners in the dispersion-free section of the line to calculate emittances by measuring development of the beam size along the phase advance. Although it can measure beam size as small as  $3 \mu\text{m}$ , the resolution of the emittance measurement is limited by residual dispersions in the extraction line.

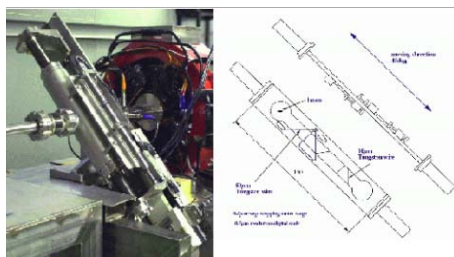


Figure 10: Wire scanner system

*OTR monitor*

A beam profile monitor to be able to measure beam spots as small as  $5 \mu\text{m}$  with the optical transition radiation (OTR) was developed in the extraction line. Radiation of visible light is emitted from a polished plane of a beryllium target. In order to image the radiation that has an opening angle of  $\sim 1/\gamma$  without aberrations, a high NA lens system to magnify the source image is needed. Although it successfully

proved the expected resolution, the target could not tolerate the high intensity beam for a long enough time.

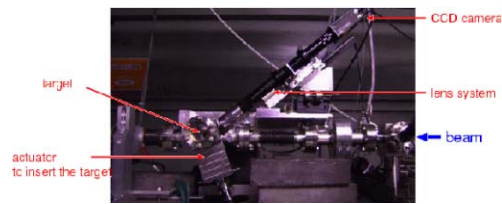


Figure 11: OTR monitor.

*ODR monitor*

A beam size monitor based on the optical diffraction radiation (ODR) has been developed in the extraction line ([10]). ODR is a kind of wake-fields generated by a passage of a beam near a conductive object. A metal plate with a slit is installed in the beam line with 45 degree angle to the beam. When an electron beam passes through the slit, radiations of visible light are emitted toward perpendicular direction of the beam from both edges of the slit. They generate an interference pattern of double peak in its angular distribution as shown in Figure 12. The beam size can be estimated from the contrast of the pattern. A low-noise cooled CCD camera detects the image of the radiation shot by shot. This monitor can measure beam size as small as  $15 \mu\text{m}$ . Flatness of the target, controlling beam position in the slit, and shielding the background of synchrotron lights from magnets in the upstream are important to do a reliable measurement.

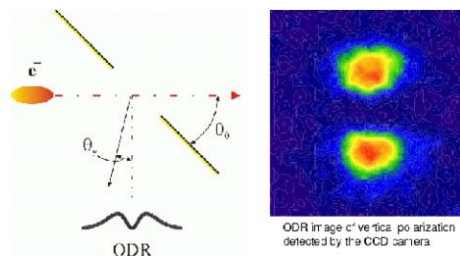


Figure 12: ODR system.

**BUNCH LENGTH MONITORS**

Bunch length and longitudinal motion of bunches are useful to investigate impedance and instabilities in the DR. The injected bunch length from the linac of 10 psec is lengthened to  $\sim 25$  psec in the equilibrium of the DR.

*SR measurement with a streak camera*

Time structure of electron bunch is imprinted in the time structure of the SR. SR light from a bending magnet of the DR is transported to a streak camera. It converts the light into photo-electrons, and projects the time axis into

a transverse profile as an image. This system is also used to measure longitudinal motion of the bunch circulating in the DR with a synchronized scanning setup to the beam revolution.

### Pulsed laser system

Using the technique of the optical cavity developed for the laserwire monitor, an optical cavity for a mode-locked pulse laser of 357 MHz was developed and installed in the same way as the laserwire. Since the round-trip time of the optical cavity is made exactly the same as the bucket spacing, timing of the laser can be synchronized to the DR bunches. The shorter pulse length ( $\sim 7$  psec) of the laser than the electron beam enables us to obtain longitudinal bunch shape by scanning the relative phase between the beam and the laser.

### CSR monitor

Short bunched beams in the first few turns after DR injection emit a coherent synchrotron radiation (CSR) of THz region (shown in Figure 13). In order to study the properties of CSR a transport line for the radiation and a schottky barrier diode detector is installed at the end of the straight line of the DR. Since the strength of the coherent radiation strongly depends on the peak intensity of the bunch, it might become a good tool to check the bunch length of the incoming beam.

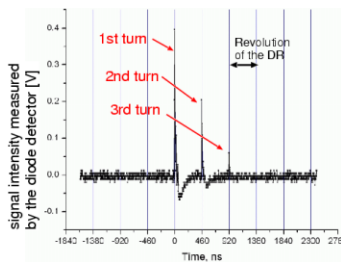


Figure 13: CSR signal in the first few turns in the DR.

### Energy spread monitor

The beam energy spread is converted to the beam size at a high dispersion location. There is a screen monitor of phosphor plate at a designed high dispersion region of the extraction line where the horizontal beam size is dominated by the dispersion effect. Energy spread monitor has been a useful tool to measure the strength of the intra-beam scattering (IBS). The larger the energy spread, the stronger the IBS (*i.e.* the smaller the vertical emittance).

## BEAM CONTROL

Not only measuring the beam, but also acting on it is important to realize a high quality beam. Works to develop the feedback/feedforward system are underway in the extraction line.

### FONT

In order to realize stable beam collision in ILC and stabilization in the virtual IP of ATF2, a beam position feedback/feedforward system has been developing. It consists of a strip-line BPM, a fast BPM processor board, and a strip-line kicker to give a correction on the beam orbit.

**FONT3** At the first stage of this experiment in ATF, we developed the system for the multi-bunch beam of 20-bunches train ([11]). Developing a fast analogue BPM processor, a feedback system with small total latency (23 nsec) was realized. It demonstrated stabilizing the beam position of the later part of the train using the measurement in the first part of it (Figure 14).

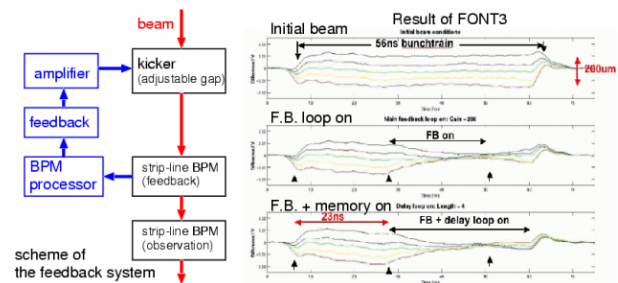


Figure 14: Result of FONT3.

**FONT4** Since the bunch spacing specified for ILC is  $\sim 300$  nsec, the very fast BPM processor is not necessary. Given time is long enough to design the system with a digital processors which should have more redundancies. A processor board using a Field Programmable Gate Array (FPGA) has been developed for the tests with 3-bunches mode in ATF.

## SUMMARY

Development of beam monitors has been an important theme to realize the high quality beam in the ATF. Lots of beam instrumentation works have been done with its international collaboration.

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