INSTRUMENTATION FOR THE ATF2 FACILITY

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Abstract

ATF2 is a final-focus test beam line that aims to focus the low emittance beam from the ATF damping ring to a vertical size of about 37 nm and to demonstrate the nanometer level beam stability, using numerous advanced beam diagnostics and feedback tools. These tools have been developed through R&D at the previous ATF extraction line, and applied for the ATF2 beam line. Further improvements will be continued in parallel to the commissioning of the nanometer beam focus. Present status of the instrumentation of ATF2 facility is reported in this paper.

INTRODUCTION

An important technical challenge of future linear collider projects such as ILC [1] or CLIC [2] is the collision of extremely small beams of a few nanometers in vertical size. This challenge involves three distinct issues: creating small emittance beams, preserving the emittance during acceleration and transport, and finally focusing the beams to nanometers before colliding them.

The Accelerator Test Facility (ATF) at KEK was built to create small emittance beams, and has succeeded in obtaining emittances that almost satisfy ILC requirements [3]. The ATF2 facility, which uses the low emittance beam extracted from the ATF damping ring (DR), was constructed to address the last two issues [4].

ATF2 is a follow-up of the final focus test beam (FFTB) experiment at SLAC [5]. The optics of the final focus section is a scaled-down version of the ILC design. The local chromaticity correction scheme should be tested here. The value of β_y and hence the vertical beam size at the optical focal point, referred to as interaction point (IP) by analogy to the linear collider collision point, are chosen to yield a chromaticity of similar magnitude as in the ILC final focus. For the energy and emittance of the ATF beam and given the distance L* between the last quadrupole and the IP, this leads to a vertical beam size of about 37 nm. Therefore the two challenging goals for ATF2 are well defined; one is the achieving of the 37 nm vertical beam size at the IP, and the other is a demonstration of the stabilization of beam in a few nanometer level. They will be addressed sequentially in 2010, and in 2012, correspondingly.

Unlike the case of a linear collider where the measurement of luminosity and electromagnetic interactions between the colliding beams provide information on their respective sizes and overlap, ATF2 is a single beam line. Measuring transverse beam sizes at the IP requires dedicated beam instrumentation, notably a laser interferometer-based beam size monitor (BSM) [6]. To measure the beam orbit and maintain the beam size with feedback, the beam line magnets are equipped with submicron resolution cavity beam position monitors (BPM) and are placed on mechanical movers. Both BSM and BPM measurements are essential to implement the tuning methods for the first goal.

The intra-train feedback system has been developed to correct the impact of fast jitter sources such as the vibration of the magnets in the final focus section. This system is essential for the second goal.

BEAM SIZE MONITORS

Interference fringe monitor

Measurement of the vertical beam size, not only for the goal value of 37 nm but also for that of less than 1 micron, is a key part of the ATF2 program. A beam size monitor based on the laser interference fringes, so called Shintake monitor is installed. A beam size is measured through the modulation of the inverse Compton signals by changing the relative position of the electron beam and the interference fringes. Schematic of the interference fringe monitor system for ATF2 is shown in Figure 2. The main optical table is installed to form interference fringes just on the ATF2 focal point (IP). A dipole magnet located at the downstream of IP separates the electron beam and the Compton gamma rays.

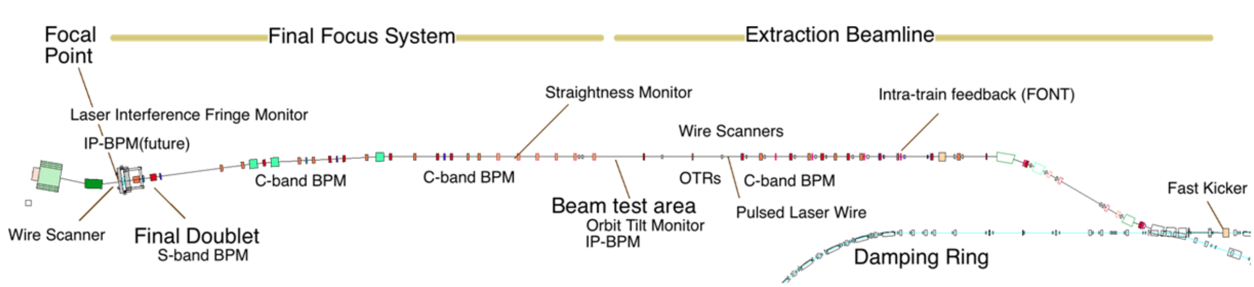

Figure 1: The major beam instrumentations in the ATF2 beam line.

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Several improvements from the FFTB system are applied for the ATF2 system [7]. To have a sufficient sensitivity to the beam size measurement at ATF2, the second harmonic of an Nd:YAG laser, 532 nm, is used while the wavelength of 1064 nm of Nd:YAG laser was used at FFTB.

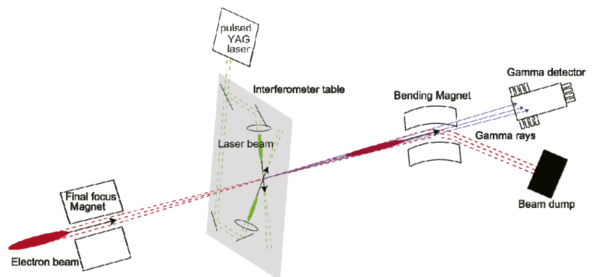

Figure 2: Schematic of the laser interferometer at ATF2.

To achieve wide dynamic range and to measure σ_x and σ_y independently, an optical path switching mechanism is implemented. Using this, crossing angles of 174˚, 30˚ and a variable mode from 8˚ to 2˚ can be selected for σ_y measurement. Measurable beam size ranges from 20 nm to 5 μm, which has an overlapping range with traditional wire scanners whose measurable range is down to several micron.

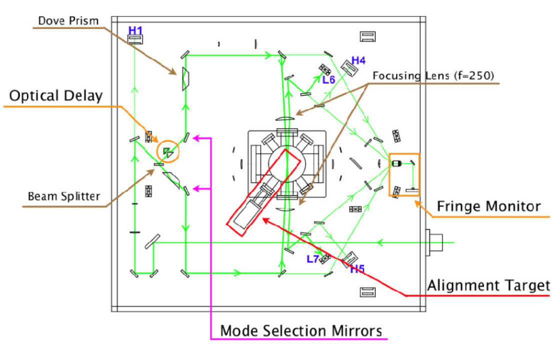

Figure 3: Layout of the main optical table of the interferometer.

The variable optical delay line on one of the split laser paths is installed to control the phase of the interference fringe. It consists of a piezoelectric stage and prisms. Two lasers create the interferometer fringe at IP and are transported into the phase monitor where a second interference fringe is created for monitoring and feedback.

The detector for the inverse Compton gamma-ray located a few meters after the IP after a dipole magnet consists of multiple layers of CsI(Tl) crystal scintillators with photomultiplier tubes. This multiple-layer structure is chosen to distinguish the contribution of background photons using the energy difference.

The commissioning of the ATF2 Shintake monitor has been started since the end of 2008 with a single laser mode (laser wire mode). The interferometer mode has been started in November 2009, after increasing the laser power and modifying tools to adjust the laser and the electron beam by taking into account the experience from single laser mode. The first measurement of the vertical beam size by the fringe scan was shortly achieved with a laser crossing angle of 2˚.

An example of a laser-fringe scan for vertical beam size measurement is shown in Figure 4. It gives a vertical beam size of 860±40 nm, using a laser crossing angle of 4.1 degrees [8,9].

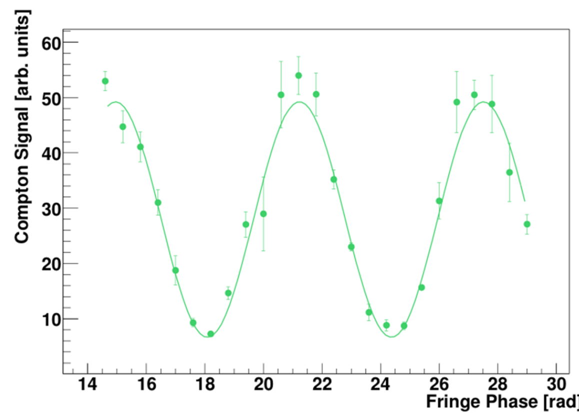

Figure 4: Compton signal of the laser interference fringe monitor at ATF2.

Pulsed Laser-wire system in the extraction line

The ILC and other electron accelerators require beam size measurements of order μm for emittance measurement. The aim of the pulsed laser-wire project is to develop a system capable of reliably measuring an electron beam of order one micron in vertical size with a non-destructive method. A laser beam is focused with a specially designed f/2 lens system to have an order μm spot size, and is used to scan across the electron beam. The various optical focusing and operation schemes have been tested on the prototype system located at the ATF extraction line.

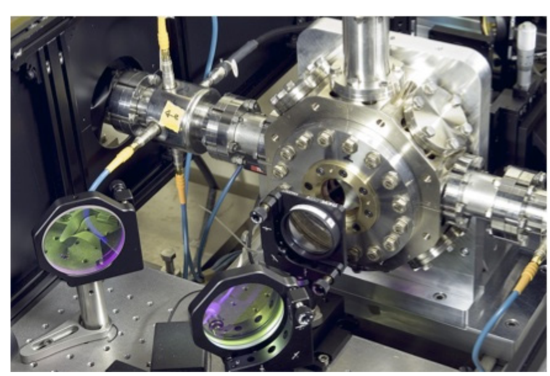

Figure 5: The beam line device of the pulsed laser wire at the ATF/ATF2.

During ATF operation the smallest electron beam size was obtained as 4.8 μm while the estimated laser size was between 2.1 and 3.1 μm [10]. The system has been recommissioned in the ATF2. A further improvement for ATF2 is the inclusion of an OTR target in the system for collision optimisation and cross calibration [11]. The R&D to achieve a ~μm laser-wire system is ongoing at the ATF2 beam line.

Multi-OTR monitors

A beam profile monitor to be able to measure beam spots as small as 5 μm with the optical transition radiation (OTR) was developed in the previous ATF extraction line [12]. Application of the multiple OTR monitors for the ATF2 beamline has been designed to realize the fast emittance measurement [13]. Four OTR monitors with the improved resolution of about 2 μm will be installed soon to assist the programs at ATF/ATF2.

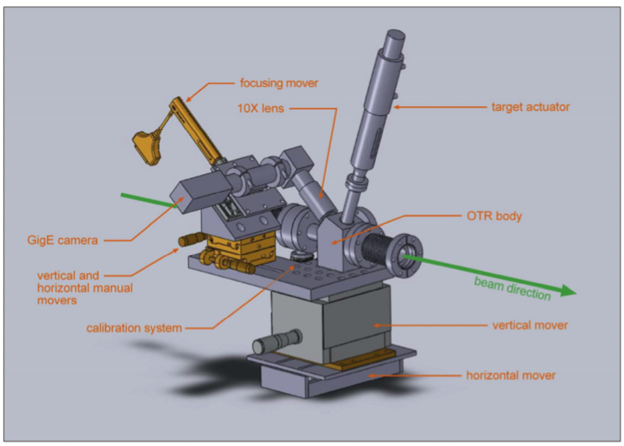

Figure 6: OTR monitor for the ATF2 beam line.

BEAM POSITION MONITORS

Electro-magnetic modes in a cavity-like structure on the beam pipe are excited by the passage of a charged beam. Among the various resonant modes, transverse dipole modes are useful to measure the beam position because the excited field strength is proportional to the product of a beam charge and a beam offset with respect to the electrical center. The beam signal is read out through a rectangular waveguide coupler that selectively couples only with the dipole mode. The strong and narrowband signal enables us to measure the beam position with order nano-meter resolution. Mechanical rigidity and reliability of the electric center are also advantages of cavity BPMs. The RF signals from these cavities are typically downmixed either to baseband in homodyne electronics or to some low (~20 MHz) frequency for digitization by a transient waveform recorder.

Developments towards nano-meter resolution cavity BPMs were carried out in previous ATF extraction line. Signal strength depends on the choice of cavity frequency. Considering the relatively long bunch length, C band frequency (~6.5 GHz) was estimated to be the most sensitive in ATF. The Three-BPM method is a usual technique to study very high resolution BPMs. 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 was estimated. Two sets of BPM triplet systems, based on the different mechanical stabilization ideas, were developed. They showed the consistent results, for example, the demonstrated position resolution was 15.6 nm and a tilt resolution was 2.1 μrad, over a dynamic range of approximately 20 μm [14].

Cavity BPM for ATF2 beam line

Based on the results of the above prototypes, further improvements were implemented for the ATF2 BPMs [15]. The resonant frequency of the cavity and the isolation between horizontal and vertical modes were tuned efficiently using tuning pins brazed on the cavity rim instead of a conventional tuning plunger. Offset between electrical and mechanical centers could be reduced by tuning within ±5 um, the isolation tuned better than 50 dB, and the 100 nm resolution of the cavity BPM for ATF2 has been proved through the beam tests.

In the diagnostic, matching and final focus section of ATF2, except for the final doublet magnets, every quadrupole and sextupole magnet is instrumented with these C-band (6.422 GHz) BPMs, with 34 units in total, shown in Figure 7.

Cavity BPMs for the final doublet magnets, four in total, require an inner diameter of 40 mm for the enlarged beam size before the focal point of ATF2. These BPMs were designed by scaling the C-band BPM [16]. The resonant frequency is selected as S-band (2.888 GHz).

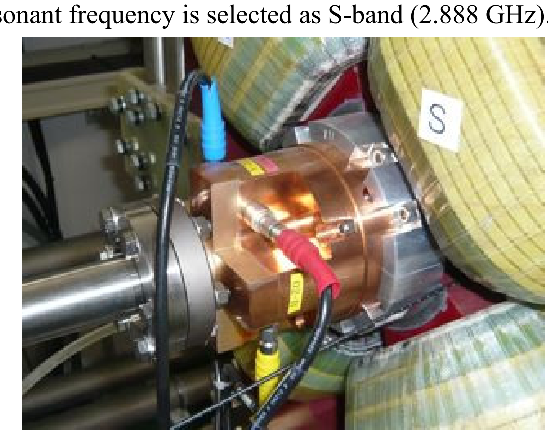

Figure 7: C-band Cavity BPM and quadrupole magnet on the ATF2 mover.

In addition to these BPMs (i.e., position-sensitive dipole cavities), four C-band and one S-band monopole cavities (reference cavities) are installed to monitor beam charge and beam arrival phase for dipole cavities.

The readout and controls of the ATF2 BPM system has also been developed based on the experience of the prototype R&Ds. All BPMs (S and C-band) are processed using a single stage image-rejection mixer and amplifier circuits. The resulting IF is approximately 25 MHz for all cavities, which is subsequently digitized by 100 MHz, 14-bit VME-ADC system. The waveforms are processed in real-time to produce position signals using an EPICS software package. The tone calibration system is attached to monitor the overall electronics and algorithm health without a beam in ATF2.

The digitized output IF signals are again digitally downmixed to baseband and the amplitude and phase information extracted and calibration factors applied to calculate a positions [17]. A BPM resolution is computed by determining the linear correlations between position readings from the other BPMs and predicted position at that BPM, using a singular value decomposition technique. The resolution of the C-band BPMs with 20 dB attenuators is between 200 nm and 1.2 μm. The resolution variation is due to gain variations in the mixer electronics and unevenness in the local oscillator power delivered to each BPM. This will be corrected in the near future so the BPM system will have a nominal resolution of 200 nm. Without attenuators the best C-band resolution is 27 nm, consistent with the 200 nm for BPMs with attenuators.

The S-band cavities suffer from x-y cross coupling 30 dB larger than the C-band cavities. This has caused problems in the BPM use, with the resolution is currently between 5 and 10 μm, but there are further complications causing systematic effects.

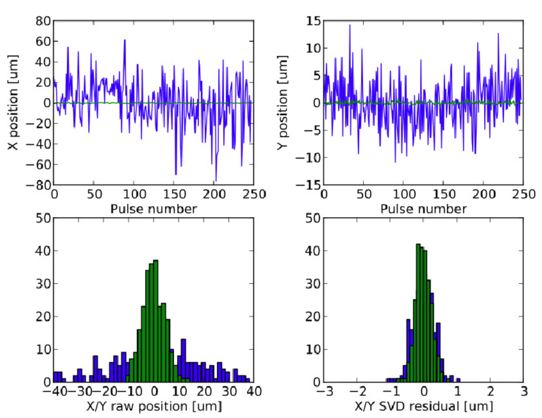

Figure 8: Example resolution determination for a C-band BPM with a 20 dB attenuator. Top-left : Horizontal raw and corrected position. Top-right : Vertical raw and corrected positions. Left bottom : Raw positions. Bottom right : Corrected residuals

Cavity BPM for ATF2 focal point

The cavity BPM with an ultra-fine resolution for the ATF2 focal point has been developed in the previous ATF extraction line [18]. The goal resolution is a challenging value of 2 nm. This special BPM will provide a direct demonstration of beam position stability at the IP, tracks the beam trajectory during beam size measurements to correct the effects of position jitter, and produces a feedback signal to stabilize the beam orbits of the following bunches.

The rectangular shape, as shown in Figure 9, isolates two dipole mode polarizations in the orthogonal directions and the thin cavity reduces the sensitivity to trajectory inclination. A position resolution of 8.7 nm was achieved with a prototype BPM for a beam intensity of 0.7×10^{10} e/bunch with a dynamic range of 5μm. A modified BPM to operate with a low Q-value to enable the bunch-by-bunch position measurement for the multi-bunch beam with bunch spacing of 154 ns, was successfully developed [19]. Improvements on the readout electronics have been continued to achieve the 2 nm resolution [20].

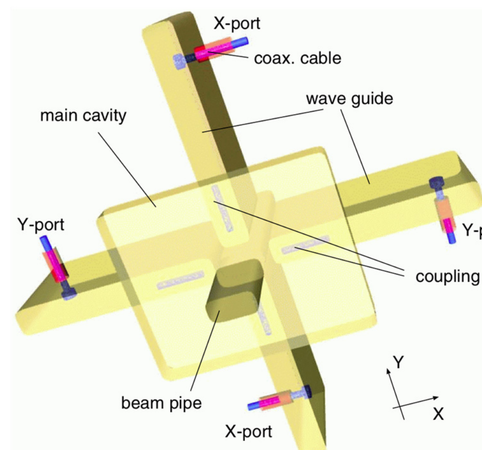

Figure 9: IP-BPM design.

BEAM FEEDBACK

FONT (Feedback on Nanosecond Timescales) is an experimental program to test a very fast orbit feedback which is applied within a bunch train. This technology is vital in order to realize stable beam collisions in ILC, as well as stabilization in the virtual IP of ATF2.

Critical issues for the intra-train feedback performance include the latency of the system, as this affects the number of corrections that can be made within the duration of the bunch train, and the feedback algorithm. Previously all-analogue feedback system prototypes, in which the aim was to reduce the latency to a few tens of nanoseconds, were developed and the total latencies (signal propagation delay + electronics latency) were achieved as 67ns (FONT1), 54ns (FONT2) and 23ns (FONT3) [21].

The use of a digital processor will allow for the implementation of more sophisticated algorithms which can be optimized for possible beam jitter scenarios at ILC. This approach is now possible for ILC given the long, multi-bunch train, which includes parameter sets with c. 3000/6000 bunches separated by c. 300/150ns respectively.

The ATF damping ring can be operated so as to provide an extracted train that comprises 3 bunches separated by an interval that is tuneable in the range 140 - 154 ns. FONT4 has been designed [22] as a bunch-by-bunch feedback with a latency goal of less than 140ns. This allows measurement of the first bunch position and correction of the second and third bunches. The correction to the third bunch is important as it allows test of the 'delay loop' component of the feedback, which is critical for maintaining the appropriate correction over a long ILC bunch train.

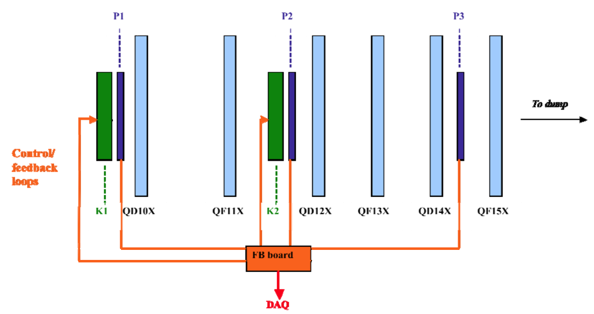

Figure 10: Schematic of the FONT system at ATF.

The FONT5 system in the ATF2 extraction line consists of two stripline kickers and three stripline BPMs. Figure 10 shows the schematic of the ATF2 system. The digital electronics based on a Virtex5 FPGA are reprogrammable allowing flexible feedback configurations and the total feedback system latency is less than 140ns. Commissioning is complete, and a coupled feedback system of two loops correcting both position and angle jitter in the vertical plane has been successfully demonstrated. The position jitter was reduced from 2.1 μm to 0.4 and 0.8 μm for the 2nd and 3rd bunches respectively in the FONT-P2 BPM, which is expected to give around 2.6 nm jitter when extrapolated to the IP as shown in Figure 11 [23].

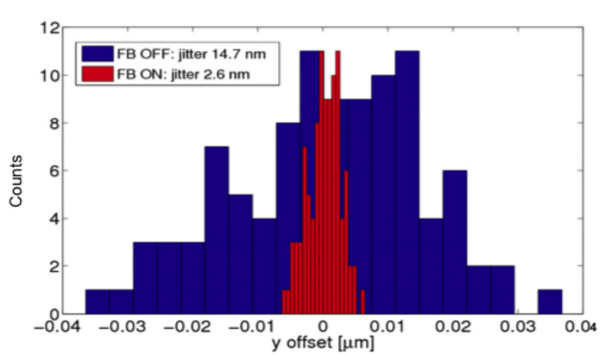

Figure 11: Expected position jitter correction by FONT feedback system at ATF2 IP.

Although current operation is with only 3 bunches in a train, it is planned in future to operate ATF2 with the fast kicker system which extracts trains of 30 bunches with a bunch spacing of 154 or 308 ns; the design allows for this upgrade.

OTHERS

A laser interferometer straightness monitoring system has been installed at the middle of the final focus system [24]. It will eventually correct the measurement of the C-band BPM used for the feedback for mechanical motion or vibrations. A beam orbit tilt monitor using a monopole cavity has also been developed to improve the IP beam stability [25].

SUMMARY

A variety of beam instruments have been developed at ATF/ATF2. The cavity BPMs with a nanometer level resolution, the beam size monitor based on the laser interference fringe, cavity BPMs and the fast intra-train feedback system are essential tools to realize two major goals at ATF2; achieving the 37 nm vertical beam size and establishing a few nm level beam-position stabilization.

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