

## ATF2 COMMISSIONING

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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 beam size of about 37 nm, and at the same time to demonstrate nm beam stability, using numerous advanced beam diagnostics and feedback tools. The construction has been finished at the end of 2008 and the beam commissioning of ATF2 has started in December of 2008. ATF2 is constructed and commissioned by ATF international collaborations with strong US, Asian and European participation.

### INTRODUCTION

An important technical challenge of ILC [1] is the collision of extremely small beams of a few nanometers in size. This challenge has three distinct issues: creating small emittance beams, preserving the emittance during acceleration and transport, focusing the beams to nanometers and colliding them. Accelerator Test Facility (ATF) at KEK [3] was built to create small emittance beams, and has succeeded in obtaining an emittance that almost satisfies the ILC requirements. The ATF2 facility [2], which uses the beam extracted from ATF damping ring, was constructed to address two major challenges of ILC: focusing the beams to nanometer scale using an ILC-like final focus and providing nanometer stability.

The two ATF2 goals, first one being achievement of 37nm beam size, and second being achievement of nanometer scale beam stability at IP, will be addressed sequentially, in 2010, and in 2012, correspondingly.

Achievement of the first goal will require development of the methods to implement and verify the design optics, requiring development of tuning methods to cancel lower order correlations and higher order unwanted aberrations in the beam. The ATF2 beamline, in addition to the final focus, includes a diagnostics section for measurements and correction of the beam at the entrance to the final focus. ATF2 being a single beam line, achievement of the

first goal will also require use of an interferometer-based beam size monitor (BSM, also called Shintake monitor). To measure the beam orbit and maintain the beam size with feedback, the beamline magnets are equipped with sub-micron resolution cavity-BPMs and are placed on movers. Tuning methods will be established based on BSMs as well as BPM measurements.

Table 1: Comparison of ATF2 and ILC parameters

Parameters	ATF2	ILC
Beam Energy, GeV	1.3	250
$L^*$ , m	1	3.5-4.2
$\gamma\epsilon_{x/y}$ , m <sup>2</sup> rad	3E-6 / 3E-8	1E-5 / 4E-8
IP $\beta_{x/y}$ , mm	4 / 0.1	21 / 0.4
IP $\eta'$ , rad	0.14	0.094
$\sigma_E$ , %	~0.1	~0.1
Chromaticity	~1E4	~1E4
$n_{\text{bunches}}$	1-3 (goal A)	~3000
$n_{\text{bunches}}$	3-30 (goal B)	~3000
$N_{\text{bunch}}$	1-2E10	2E10
IP $\sigma_y$ , nm	37	5

To this moment, ATF2 construction has been completed and beam commissioning began in December 2008, focusing on the first goal. In parallel, studies and hardware development toward the second goal are ongoing. These include characterization of the site and beamline stability, development of nano-BPM to be installed at IP, FONT (Feedback On Nanosecond Timescale), an interferometer to monitor the position of FD with respect to IP, and nanosecond rise-time kickers.

ATF2 is a model for a future ILC collaboration, constructed by in-kind contributions, and commissioned and operated by an international team of researchers from

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many institutions. Planning and coordination of commissioning activity is of crucial importance. Organization of the ATF collaboration and commissioning efforts are described in [3]. The commissioning strategy is designed to use the large international contribution to ATF2 commissioning efficiently. The operation time is

split to give 50% for ATF2, 30% for Damping Ring related (ATF) R&D (including the injector), and 20% for maintenance and upgrades, which ensure richness of the overall program while providing sufficient time for commissioning.

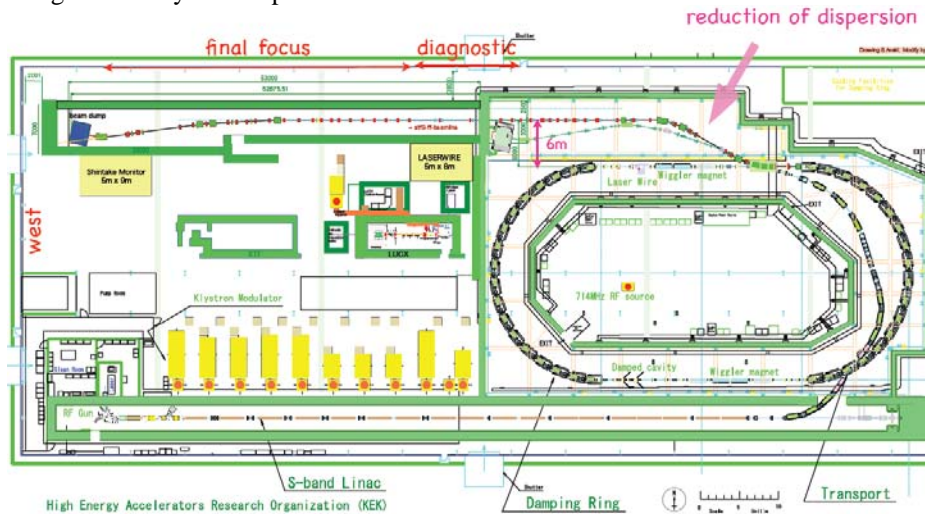


Figure 1: Layout of ATF damping ring and ATF2 final focus facility.

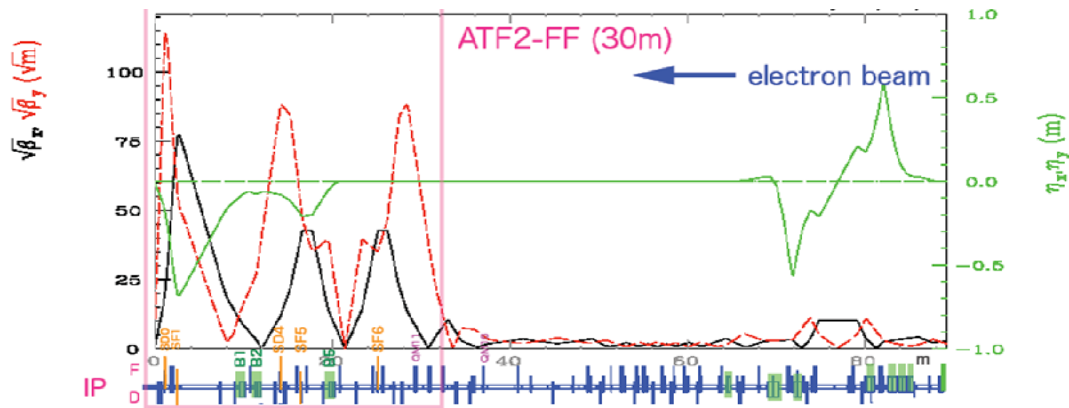


Figure 2: Optics of ATF2, starting from (on the right) extraction point from the ATF damping ring.

## COMMISSIONING STATUS

Since the beginning of commissioning at the end of December 2008, three commissioning runs were performed, with typical duration of three weeks for each run. The December 2008 pilot run was performed with large IP beta optics and semi-ballistic trajectory and was focused on establishing the beam to the beam dump, minimizing beam losses and passing the radiation inspection. The very first tests of the hardware and tuning software as well as commissioning and background characterization for BSM, started during this run. The January 2009 run was focused on continuation of hardware commissioning and fast kicker study. The February-March 2009 run was performed with large IP beta function (8cm beta-Y\*), and with all ATF2 magnets switched on for the first time. Hardware commissioning continued, and the laser wire mode of the BSM was

commissioned. An example of horizontal beam size measurement is shown in Figure 3. The beam tuning tools (extraction dispersion and coupling correction, IP scans, Twiss function, emittance determination and Beam Based Alignment) were verified and started to be used for setting up the beamlines. The most recent April 2009 run focused on continuation of optics and tuning tools verification and start of commissioning of an interferometer mode of BSM. Commissioning status of individual systems is described below.

### Beam Size Monitor

The beam size monitor is based on inverse Compton scattering between the electron beam and the laser interference fringe. Energy of the generated gamma-rays through the process is relatively small when compared to the typical background energy. To estimate the signal intensity from the high energy background effectively,

multilayered detector and shower shape analysis are adopted. The laser wavelength is 532 nm, the 2nd harmonics of Nd:YAG laser, which makes suitable fringe pitch to measure the target vertical size of 37 nm. Four crossing modes are designed to cover the required dynamic range, widened to several microns for the initial beam study. In addition, a laser wire mode is prepared for horizontal size measurement.

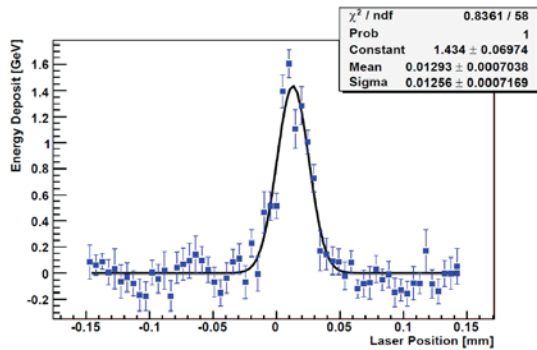


Figure 3: Convolved horizontal size of 13 microns measured by BSM in laser wire mode in March of 2009.

The system was designed at the University of Tokyo. It was shipped to KEK in spring, and installed to the beam line during the summer shutdown in 2008. The commissioning started with laser wire mode in the winter. Figure 3 shows an example of laser wire mode data, with measured convolved horizontal size of 13 microns, consistent with the designed waist size of the laser wire and with the beam size of about 10 microns, as also confirmed by the measurements with the post-IP wire scanner. Commissioning of the 8 deg. mode, one of the four crossing mode, is now continuing.

### Cavity Beam Position Monitors

The ATF2 beam line is instrumented with 32 C-band and 4 S-band cavity beam position monitor systems. In addition to the dipole cavities there are 4 C-band and 1 S-band reference cavities to monitor beam charge and beam arrival phase. In the diagnostics and final focus section every quadrupole and sextupole is instrumented with a high resolution BPM. The C-band position-sensitive cavities are centred with respect to the quadrupole magnet centres using a special mounting fixture. The S-band cavities are mounted on the same magnet mover stage. The cavity design, fabrication and performance during ATF2 commissioning are described in more detail in [4,5,18]. The cavities are cylindrical resonant cavities, with rectangular waveguide couplers to select the dipole, position sensitive, mode. The cavity output is filtered, mixed, amplified and filtered again to produce an intermediate frequency between 20 and 25 MHz. The down-converted signal is acquired using 100 MHz, 14-bit digitizers with a VME interface. The dipole signals are processed using a digital down conversion algorithm running on a dedicated CPU. The data is acquired, the processing algorithm controlled and position data distributed via an EPICS channel access application.



Figure 4: View of the ATF2 beamline.

The ATF2 commissioning work has been focused on BPM calibration and usage of the BPM system for beam based alignment (BBA) and final focus dispersion measurement. Two types of calibration were required, quadrupole mover calibration and ballistic beam deflection (for BPMs that are not mounted on a quadrupole with a mover system). The mover calibration consisted of moving each quadrupole in steps of 100  $\mu\text{m}$  over a total range 400  $\mu\text{m}$  whilst recording the cavity response for 10 machine pulses at each position. The dynamic range of the cavity system was found to be greater than the stroke of the quadrupole mover system ( $\pm 1.5 \text{ mm}$ .) The resolution of the C-band system is about 1  $\mu\text{m}$  at this moment, although a full analysis with beam motion jitter subtraction has yet to be performed.

### Flight Simulator Beamline tools

The successful tuning of the ATF2 beamline will rely on many automated software tools. The existing ATF control system is based on V-system. To enable international collaborators to contribute to the development and implementation of these tools the "Flight Simulator" software environment was designed and constructed. This is a "portable" control system for the ATF2 that allows code development and checkout offsite and additionally provides the framework for integrating that code into the operational ATF2 control system through an EPICS interface. Code is developed through the native Lucretia [13] package and also through various supported "add-on" packages such as MAD8, PLACET and SAD. Code developed through the flight simulator is used in the ATF2 control room alongside tools developed through the existing V-System interface. Tools currently in use include: EXT coupling correction; EXT dispersion measurement and correction; EXT and FFS orbit monitoring and steering; IP sextupole-based tuning knobs; BPM tools (orbit plotting, reference save/restore system. Offline calibration of stripline

BPMs), watchdog tools (beam orbit in critical apertures monitoring, operating magnet strengths, online optics checks, model response matrix), magnet standardisation, BBA (Quad shunting to get BPM-Quad offsets, Sextupole BBA to get Sext-BPM offsets), orbit bump tools.

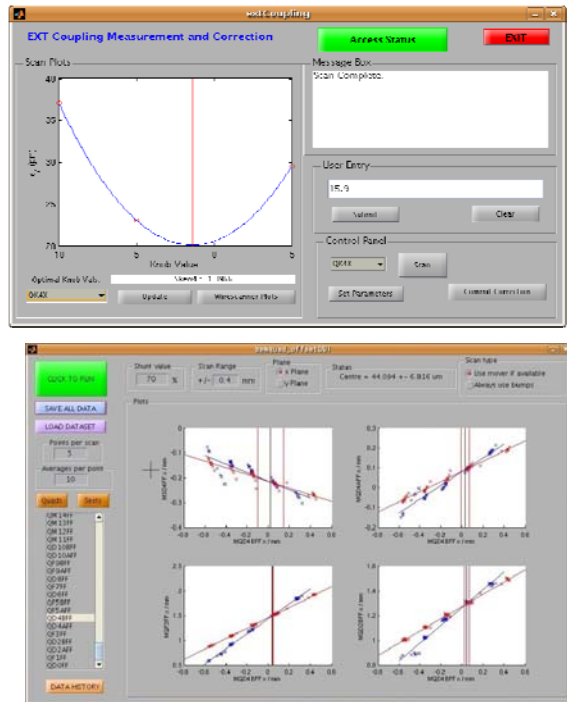


Figure 3: Flight simulator beamline tools in action: coupling correction, beam based alignment.

### Beamline instrumentation

Instrumentation equipment, of the previous beamline, (Strip-line BPMs, ICTs, OTR, Screen profile monitors and wire scanners), are re-used in the new beamline, especially before the final focus section. There are 5 wire scanners with 10 $\mu$ m tungsten and 7 $\mu$ m carbon wires at the diagnostic section in the upstream of the final focus system as shown in Fig.1. They are used to measure the horizontal and vertical emittances of the extracted beam from DR. An additional wire scanner is located just downstream of IP and has carbon wires of 5 $\mu$ m diameter and the tungsten wires for optics tuning. Screen monitors are located right after the extraction in the middle of the beamline, before and after the final doublet system. A beam loss monitor using optical fibers is installed along the beamline and used to identify the location and quantity of beam loss.

### Magnets and magnet movers

The ATF2 beam line, from an extraction point from the ATF ring to the final focal point, is about 90m long. It contains 64 room-temperature magnets. The 7 dipole magnets, 3 septa, 49 quadrupole magnets, 5 sextupole magnets and several corrector magnets came from a variety of sources. Some were newly designed and fabricated, and the others were taken from old KEK and SLAC beam lines. Three dipole magnets, in the final focus section, were designed at SLAC, fabricated and

magnetically measured at IHEP, China. 27 quadrupole magnets were designed at SLAC and KEK, fabricated at IHEP and magnetically measured both at IHEP and KEK. 20 quadrupole magnets, 4 dipoles and 3 septa of various styles were re-used from the old ATF extraction beam line. The 2 styles of sextupole magnets were re-used from beam lines at SLAC. The final doublet system at the end of the beam line consists of two modified quadrupole magnets and two modified sextupole magnets from SLAC. Their special support system is described below.

The old KEK dipole and quadrupole magnets are fixed on steel or stainless steel supports, which are bolted to the floor. Their vertical and horizontal positions and tilts are manually adjusted with adjusting bolts. The FF magnets are fixed on concrete supporting blocks which are fixed firmly to the floor with adhesive polymer concrete. Their vertical and horizontal positions and tilts are also manually adjusted with screw bolts during alignment.

All the ATF2 magnets, especially those in the final focus area, must be very mechanically stable. This requirement influenced the design of their supports and, anticipating the gradual movement of the supports and magnets caused by thermal variations or slow ground motion, 20 quadrupole magnets and 3 sextupole magnets in the final focus area were put on remote-controlled 3-axis movers, recycled from the FFTB at SLAC. Each mover has three camshafts which allow adjustment in horizontal and vertical position (with precision of 1-2  $\mu$ m) as well as rotation angle (tilt, with precision of 3-5  $\mu$ rad). The camshaft driving motors are controlled through a CAMAC mover module. The potentiometer read backs of the camshaft rotation are read out through an ADC. There are also 3 Linear Voltage Differential Transformers on each mover magnet support plate which are read out via CAMAC modules. The interface to these modules is provided by an EPICS control system running in the CAMAC crate controller.

Magnet production and refurbishment was carried out from mid 2005 through mid 2008. Installation and alignment of all magnets were performed in 2007 and 2008. Most magnets have alignment reference holes on top of the magnet, and the magnets from SLAC have tooling balls. The reference hole positions on the new quadrupoles were measured relative to the center of the magnetic field during the field measurement at KEK, and these offsets were corrected during the magnet alignment process. Alignment precisions of 0.1mm in position in three directions and 0.1 mrad in roll angles have been achieved. The installation and commissioning of the magnets has proceeded smoothly. The magnets fit in with all the other beam line components as designed, and run with the predicted cooling water temperature increases. The magnets' integrated strength data have been translated into controlling polynomials in the new power supply controlling software, and their specified strengths were reached precisely. The final alignment of the FF magnets is to be achieved through the beam-based alignment process that has been successfully tested.

## Laser Wire

A laser wire system was developed at ATF extraction line between 2005 and 2008; the hardware system and beam operation results are described in details in [6,7,8]. The aim of the laser wire project is to demonstrate a 1  $\mu\text{m}$  electron beam size measurement. At the end of ATF operation in 2008, the laser wire group achieved a minimum beam size measurement of  $2.91 \pm 0.15 \mu\text{m}$  [9]. The laser wire system has been moved to a new location within ATF2 at 48 m from the IP at end of the diagnostics section. At this location the normal ATF2 electron beam optics generates a beam size of  $142 \times 27 \mu\text{m}$ , which can routinely be measured during ATF2 operations. The commissioning during the 2008/09 operations year focused on testing a dedicated electron beam optics required for small electron beam size, laser wire tests and minimisation of backgrounds to the Compton signal. In April 2009 tests a beam size of below  $30 \times 3.2 \mu\text{m}$  was confirmed using 1 m downstream wire scanner with similar background conditions as observed at the old ATF extraction line laser wire. The expected focus at the Laserwire location is  $20 \times 1.5 \mu\text{m}$ .

## Final Doublet Integration and Commissioning

The final doublet (FD) section is composed of 2 quadrupoles and 2 sextupoles (QD0, SD0, QF1, SF1). These magnets needed a support that guaranteed a 6 to 7nm jitter tolerance between QD0 and the Interaction point (IP) materialized by the BSM. The significant frequency range for the study is between 0.1Hz (due to the beam repetition rate) and 100Hz (where ground motion becomes negligible). A rigid support (vs. active support) was chosen taking into account that the coherence length at ATF2 is about 4m [10] which is more than the distance separating FD from the IP. A rigid honeycomb table from TMC was chosen and it was fixed with beeswax with good transmission of vibrations and ease of removal [11]. The FFTB movers were adapted to meet the 1.2m beam height. Vibration measurements with the support fixed to the floor and all magnets and movers installed were performed to validate the choice of the rigid support. Before the final installation, effects cooling water in FD magnets were confirmed not have any effect on the relative motion between FD and the IP [12]. Quadrupole relative motion due to cooling water is less than 0.1nm. The whole system was sent and installed at KEK in September 2008. Additional vibration measurements were performed on site and the results and tolerances are shown in Table 2. The rigid support installed at ATF2 is well within tolerances.

Table 2: Vertical motion of BSM to QD0 and QF1

Tolerance (nm)	Meas. QD0 (nm)	Meas. QF1 (nm)	Absolute (nm)
7 (QD0), 20(QF1)	5.1	6.5	212.6

## ATF2 OUTLOOK

While the present ATF2 efforts of the ATF collaboration are focused of the first goal, the hardware developments for the second goal are proceeding, which include: a) the Monalisa interferometer system [17], for measurements of the FD position with respect to the BSM; b) the FONT feedback [19]; c) the nanometer resolution IP BPM.

The near future plans, after the main goals of ATF2 have been achieved, include tests of low beta function configuration (four times smaller than ATF2 nominal), as suggested by CLIC colleagues [14]. These plans also include tests of the superconducting final doublet [15], built according to ILC direct wind technology, which will allow to study FD stability with beam.

The much longer term and tentative plans, after 2012, include an optional photon facility, which would include laser and optical cavities for photon linear collider and generation of photon beam, and eventually a possible strong QED experiments with laser intensity of  $>10^{22} \text{ W/cm}^2$ , for studies of the Unruh radiation [16].

## CONCLUSION

ATF collaboration has completed construction of ATF2 and has started its commissioning. Hardware for the second ATF2 goal is being developed. The collaboration is developing the near and long terms plans for ATF2.

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