Aiming for Nanobeams

Accelerator Test Facility
ATF

ACCELERATOR TEST FACILITY

The International Linear Collider and the Accelerator Test Facility (ATF)

The Accelerator Test Facility is dedicated to the study of ultra-low emittance beams, one of the most important aspects of the International Linear Collider (ILC). In order to discover new elementary particles and study their properties, ILC will accelerate electron and positron beams to an energy greater than 250GeV. The beam will be accelerated using two superconducting linear accelerators that face each other, each 10 km long, (one for electrons, the other for positrons). The total site length will be 45 km. At the interaction point, the opposing electron and positron beams, as they collide, will be tightly focused to a tiny spot of 300 nm wide and 5 nm high. Beam acceleration through the linacs to their collision at the interaction point will occur at a repetition rate of 5 Hz. Stable, ultra-low emittance beams are a "must" at the ILC to reliably provide and maintain beam collisions. ATF aims to help scientists establish the production techniques of such high-quality beams. Highly sophisticated beam transport lines will also be built near the interaction point of the ILC, with very strong, superbly mechanical stable, precision final focus magnets. ATF2, a new extension of ATF, attempts to address the technical challenges associated with such tight beam focusing.

The superconducting International Linear Collider

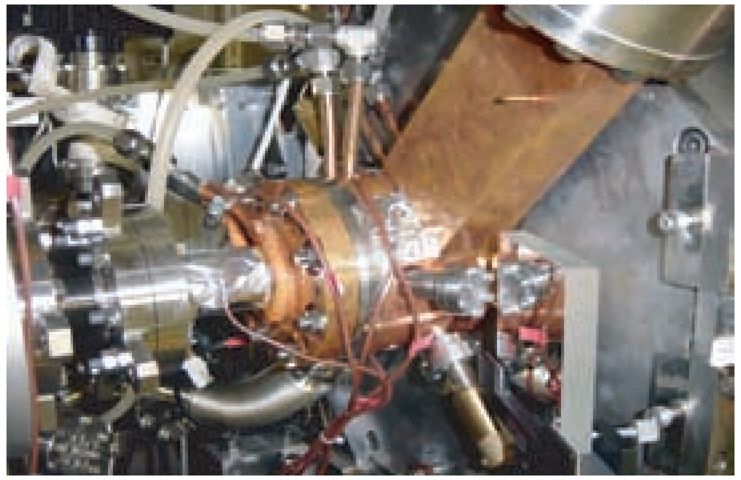
Performance of the ATF Accelerator

The ATF is a model of the injector accelerator complex of the electron side of a linear collider. It consists of an electron gun, a 1.5 GeV linac, a 1.5GeV damping ring (small beam storage ring), and an extraction line for beam diagnosis. Initial work on ATF began in 1990. Following the commissioning of the 1.5 GeV linac, operation of the damping ring began in 1997, and the beam emittance goal was achieved in 2001. Presently the ATF provides scientists with world-class high quality beam for studies of advanced beam handling techniques, dedicated to the ILC.

Performance		
Beam energy:	1.28	GeV (in normal operation)
Beam intensity in the single bunch mode:	2.0×10^{10}	electrons per bunch
Beam intensity in the multibunch mode:	0.7×10^{10}	electrons per bunch × 20 bunches
Beam repetition:	0.8 – 6.3	Hz
Emittance in X direction (in the limit of zero beam intensity)	1.0×10^{-9}	rad.m (at 1.28GeV)
Emittance in Y direction (in the limit of zero beam intensity)	4.0×10^{-12}	rad.m (at 1.28GeV)
Typical beam size:	$70\mu m \times 7\mu m$	(rms horizontal × rms vertical)

Photocathode RF gun

The electron beam at ATF is produced by the electron gun, located at the far upstream end of the injector. An RF photocathode gun is presently deployed (prior to this, a thermionic electron gun was in service until Summer 2002). Pulsed laser light is directed onto a cesium-telluride photocathode to obtain the electrons. High quality beams with a wide variety of intensity and bunch patterns are available by suitably choosing the sequence of laser pulses. A typical beam has a bunch length of 10 ps, 1.0×10^{10} electrons per bunch, 20 bunches of 2.8 ns spacing, and is produced with repetition rates ranging from 0.8 to 6.3 Hz.



The photocathode RF gun

The injector linear accelerator

The damping ring injector is a 90 m-long linear accelerator (linac), driven by pulsed 2856MHz radio-frequency (RF) power. The linac consists of seventeen 3 m-long accelerator structures. Ten 80 MW klystrons produce the needed pulsed power (4.5 µs pulse width). This RF power is time-compressed into ~400MW, 1 µs by using a pulse compression system, known as SLED, and distributed to the accelerator structures. The ATF injector linac provides an average accelerating gradient of 26 MV/m, about twice as high as that of standard linear accelerators. The beam energy at the linac exit is ~1.28 GeV.

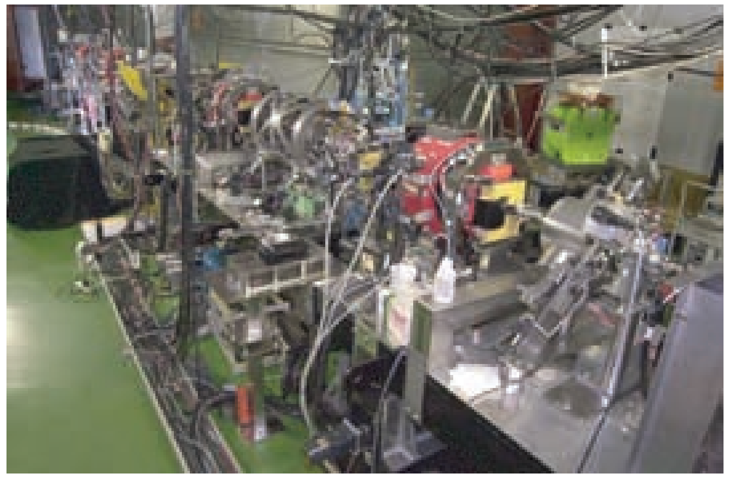
Accelerating structures of the linear accelerator

Damping ring

The electron beam from the injector is injected into a storage ring called a "damping ring". During the time the beam is stored in the damping ring, 100~450 ms, the process of "radiation damping" the beam emittance is reduced and approaches an equilibrium value (equilibrium emittance). The beam is then extracted. A damping ring design must both minimize the equilibrium emittance and the damping time. The magnets in the ring arc sections are laid out expressly to achieve small equilibrium emittance. Wiggler magnets are introduced in the straight sections to shorten the damping time. Precise control of the beam orbit is also critical for minimizing the beam size. A set of high-speed, high-resolution, beam position monitors (96 units) have been installed for this purpose.

An arc section of the damping ring.

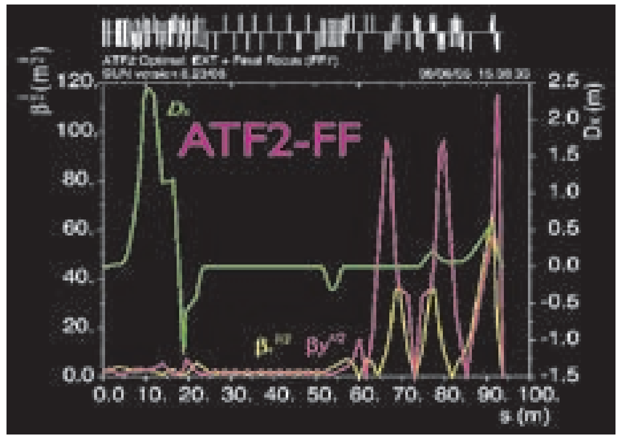
The diagnostic line for the extracted low emittance beam



Beam extraction line

The realization of an ultra-low-emittance beam by a damping ring relies on many factors, including precise alignment and excitation of the magnets and the precise correction of the beam orbit. High precision magnet alignment is an important achievement of ATF. The excitations of the magnets are cross-calibrated by measuring the beam responses that occur. High-resolution beam position monitors (BPMs) with sophisticated signal processing electronics circuits are employed. The beam is then extracted from the damping ring, using fast kicker magnets and DC septum magnets, onto the extraction line where beam monitor devices are used for high precision beam property measurements.

The ATF2 plan: realization of the nanobeam



Planned beam optics

Near the collision point of the ILC special beam optics will be used to squeeze the beam down to a few nanometers, making a 'nanobeam'. In order to test and develop those optics and the stabilization of the beam at the nanometer-level, a new beam line extension of the existing ATF extraction line is scheduled to be built. This is the ATF2 plan. A laser monitor capable of precise nanobeam measurements, a high-resolution beam position monitor able to determine the beam position within nanometers, and a beam orbit feedback system able to maintain the beam position within nanometers will be developed.

International collaboration in beam development

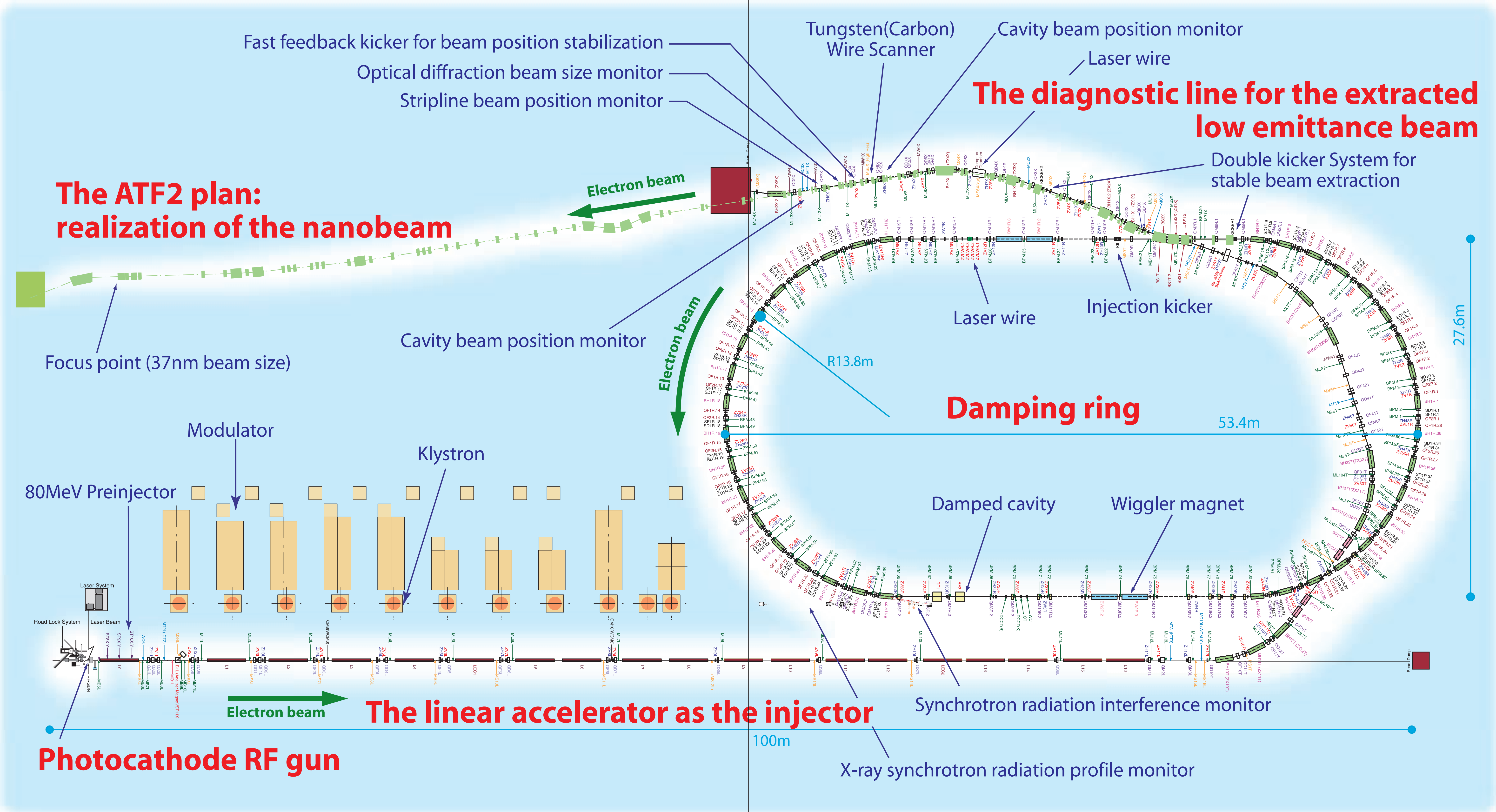
A beam research and development meeting

In the past decade, the construction and operation of the ATF has been led by Japanese scientists and collaborators from overseas universities and laboratories. The collaborators from outside Japan typically stay for one week and up to several months at a time, to install the new hardware or software and to participate in beam operation and studies. This cooperative R&D style is a fundamental driving force behind our successful research.

The recent launch of the new ATF2 project has triggered us to augment our international collaboration in a more systematic and project-oriented manner. Our international cooperation on the design, construction, and beam development is hoped to provide a model for collaboration on the International Linear Collider project.

International collaboration: BINP, BNL, Cambridge University, CERN, Cornell University, DESY, DL, FNAL, IHEP, Laboratoire de L'accelerateur Lineaire - LAL, LBNL, LLNL, NSC KIPT, PAL, PSI, QMUL, RHUL, SSRL, SLAC, Tomsk, UC Berkeley, UCL, University of Notre Dame, Oxford University.

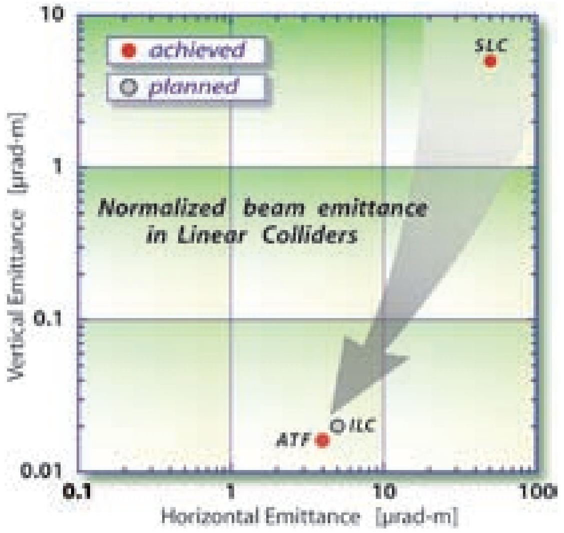
Domestic collaboration: Osaka University, Kyoto University, JAEA, Kobe University, Shinshu University, JASRI, Seikei University, The Graduate Universi ty for Advanced Studies, University of Tokyo, Institute for Solid State Physics of the University of Tokyo, Tokyo Metropolitan University, Science University of Tokyo, Toho University, Tohoku University, Tohoku Gakuin University, Nagoya University, Hiroshima University, Yokohama National University, RIKEN, Waseda University.



Accelerator Test Facility for ILC

The Achieved Emittance in ATF (normalized emittance).

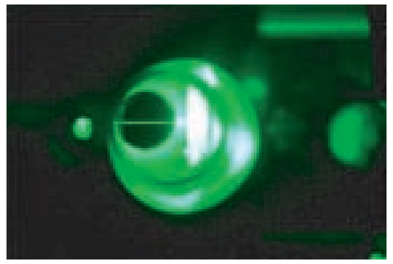
Emittance is a technical term for the phase-space extent of a distribution of particles within a beam, roughly corresponding to its spatial divergence. A low emittance beam can travel a long distance without diverging. The SLC at SLAC was the first linear collider in the world which tackled the challenge of handling very low emittance beams. (operation of SLC was terminated in 1998). Emittance specifications for the ILC are even more demanding; one tenth or less horizontally, and one hundredth or less vertically, than at SLC. As shown in the graph, ATF surpassed these goals in 2001-2002.



The Beam Monitors under Development at ATF

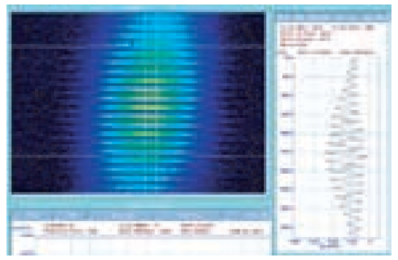
Laser wire

The laser wire monitor is an instrument for measuring very small, low emittance beams by detecting the Compton-scattered photons from the interaction of the electron beam with tightly focused laser light. The light from a low-power semiconductor laser (CW) is focused and amplified within an optical resonator formed by concave mirrors, creating a “laser wire” with a width of approximately 7 μm. By placing the laser wire over the beam, and by measuring the flux of photons while transversally scanning the laser wire across the beam path, electron beams as small as 5 μm can be measured.



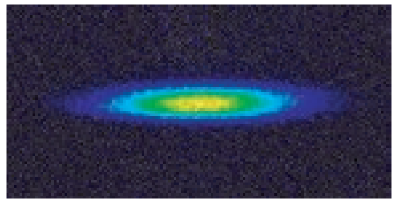
Synchrotron radiation interference monitor

Charged particles, including electrons and positrons, emit synchrotron radiation (SR) when their trajectories are bent by dipole magnets. The spatial and temporal distributions of SR carry a wealth of information on the beam size. However, the diffraction effect, whose magnitude is determined by the wavelength and opening angle of SR light, limits the resolution in a telescope measurement (e.g. ~50 μm in case of visible light). A method, developed at ATF, to resolve this problem is to use a novel double-slit interference technique which allows the performance of a visible light telescope to be extended by a factor of 10. We have used this device to measure beam sizes as low as 5 μm.



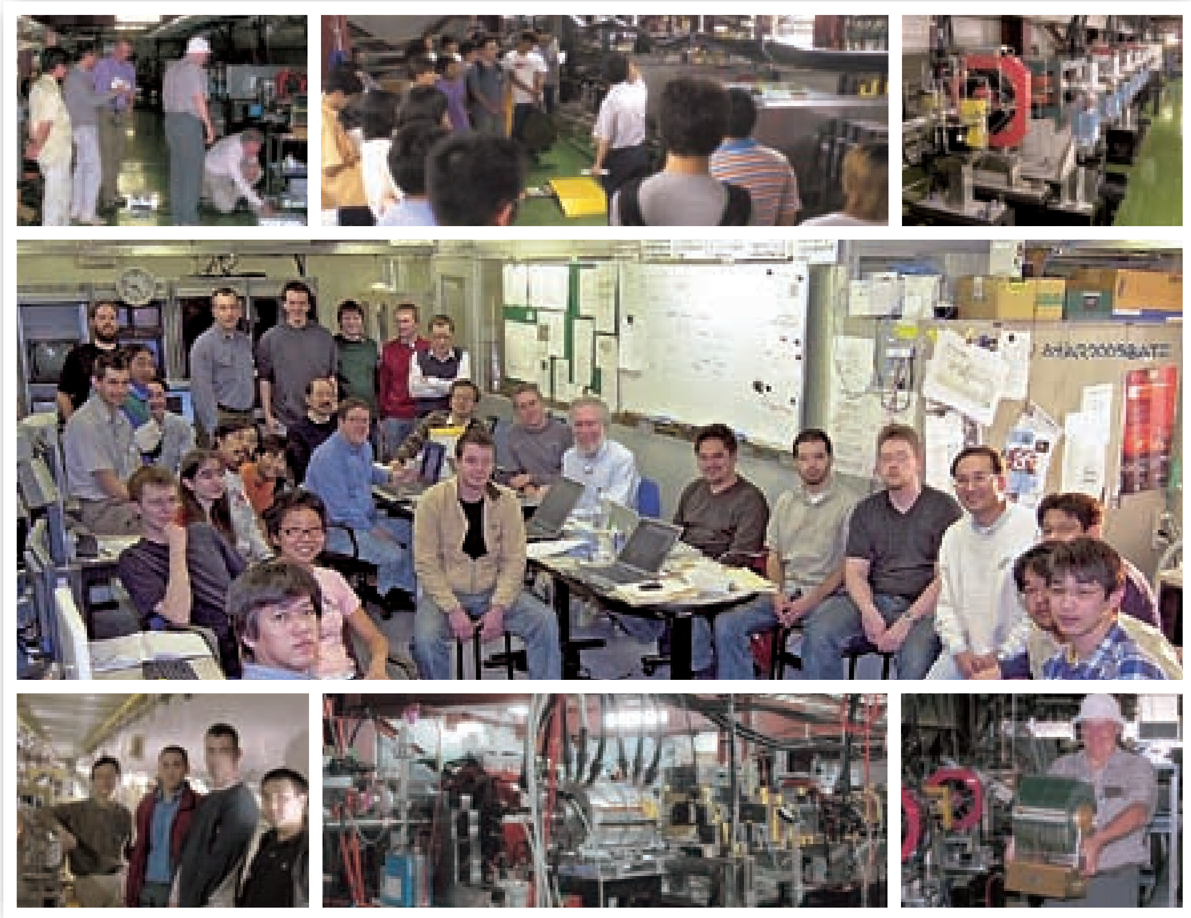
X-ray synchrotron radiation monitor

Another new method, developed at ATF for high resolution beam size measurements, is to use the X-ray component (3 keV range) of SR. An X-ray telescope has been realized by a combination of zone plates, which act as lenses, and a precision X-ray CCD camera. An excellent resolution of 2 μm has been achieved for beam size measurements. In addition, this monitor has the outstanding capability of obtaining a two-dimensional image of the beam in a single shot.



Cavity beam position monitor

Passage of the beam through a metallic box (cavity) excites an electro-magnetic field. The strength, the frequency, and the pattern of the excited field are determined by the beam intensity, its position, and the cavity shape. Thus, by carefully crafting an optimized cavity design, a very high precision beam position monitor (BPM) can be realized. The picture shows a “cavity BPM” which has been developed at ATF and PAL. There, the TM_{110} mode excited in a cylindrical cavity is used. The strength of the TM_{110} signal is zero when the beam passes through the exact center of the BPM, and it grows linearly in proportion to the beam offset. A resolution of 20 nm has been demonstrated in an actual beam test using a similar cavity BPM.



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