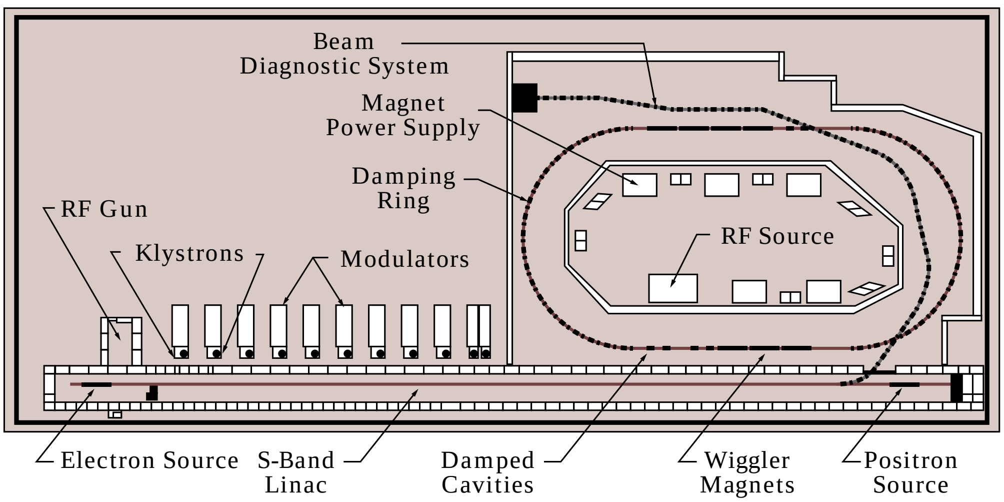
The JLC Accelerator Test Facility

by SEIGI IWATA

ONE OF THE MOST important experimental issues confronting physics today is the search for and study of the Higgs boson and other very heavy particles thought to be responsible for imbuing quarks, leptons, and gauge bosons with their various masses. This research can be done most effectively and efficiently at a high energy electron-positron collider. Thus the Japanese high energy physics community chose the construction of a large linear collider (called the Japan Linear Collider, or JLC) as its highest-priority project for the future. Research and development toward the design of such a machine has occurred at KEK for more than a decade. Two major areas of current accelerator R&D at KEK include the technologies needed to generate high-quality beams in an injector complex and high-power microwave technology required for the main linear accelerators.



Layout of the Accelerator Test Facility built at KEK as a prototype injector system for the JLC. Accelerator physics research is being conducted on this facility by an international collaboration with the goal of developing the technology of ultralow-emittance beams.

Because its particle bunches encounter another bunch only once, a linear collider must achieve very narrow beams (several nanometers thick for the JLC) at the interaction point in order to provide sufficiently high luminosities required for the intended physics research. Therefore KEK physicists made key contributions to the Final Focus Test Beam project at SLAC, which succeeded in squeezing a 50 GeV electron beam down to a thickness of only 60 nanometers. Its advanced magnet system performed as designed by Katsunobu Oide, while Tsumoru Shintake pioneered a new technique to measure such narrow beams using laser interference fringes.

One major improvement remaining to be demonstrated before a TeV linear collider can be built is the quality of the beams entering the final focus system. They must be sufficiently narrow and have small enough angular divergence so that the final focus magnets can compress the beams down to nanometer thicknesses. The injector systems must generate such high-quality beams and the main linacs must accelerate them to their final energies while maintaining the beam quality.

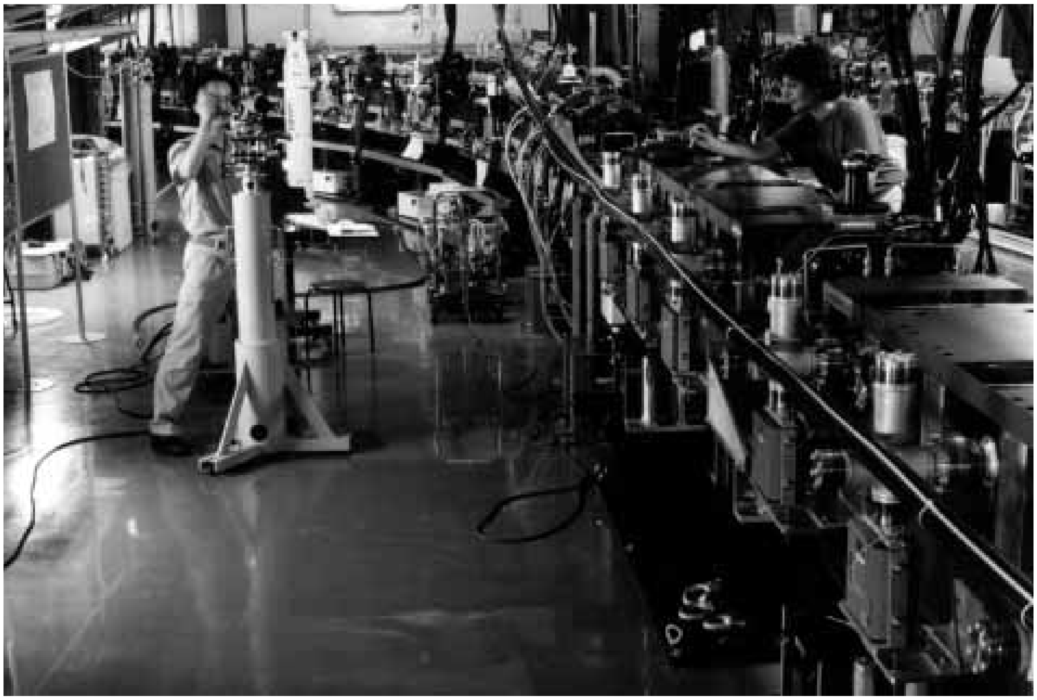
Clearly the injector system will be a key part of the JLC, determining the ultimate performance of its colliding beams. The KEK Accelerator Test Facility (ATF) was constructed in a large hall about the size of a football field; its purpose is to pioneer the state-of-the-art techniques needed to generate multibunch beam with unprecedentedly low emittance. (This is the conventional measure of beam quality, representing a one-standard-deviation divergence from the forward direction in the velocity vectors of individual particles in each bunch.) The principal components of the ATF are an electron source, a 1.54 GeV injector linac (operating at a microwave frequency of 2.9 gigahertz), an injection beam transport line, a 1.54 GeV damping ring, and an extraction line. In addition, various diagnostic instruments are included to measure beam performance. Much of the work on the ATF—from its design to current operations and research—has been done as an international collaboration with SLAC, PAL (Korea), IHEP (China), DESY (Germany), CERN (Europe) and BINP (Russia). In addition, university teams from Tohoku, Tohoku-Gakuin, Tokyo-Metropolitan, Tokyo-Science, Yokohama-National, Nagoya and Kyoto have been playing an increasingly important role in the project.

Since its speedy commissioning in autumn 1995, the injector linac has served as a facility for studying high-power microwave technology as well as production, acceleration, handling, and monitoring of various kinds of electron beams. It now routinely operates at an accelerating gradient of 30 MeV per meter—almost *twice* that of the Stanford Linear Collider and TESLA Test Facility. As an injector to the damping ring, this linac must generate a beam that is stable in energy, intensity, trajectory and size. Most of the early R&D work concerned improvements on these aspects. A drift in beam energy was suppressed by introducing an energy-feedback system based on information about the beam position at the transport line, and by stabilizing the temperature of the cooling water used in some of the klystrons. In addition, physicists and engineers have completed a systematic investigation of the stability of individual accelerator elements.

Another important goal was to show that one can stably compensate for the energy spread caused by the effects of multibunch beam loading. When a sequence of closely spaced bunches traverses an accelerating structure, each bunch carries away a small amount of electromagnetic energy; latecomers therefore suffer from successively larger losses in acceleration. In order to compensate for these deficits, two short accelerating structures with slightly offset resonant frequencies were included in the linac. The bunches passing through them are accelerated on the slope of the traveling electromagnetic wave—not its crest—in such a way that later bunches are accelerated more strongly. Tests performed with trains of 20 bunches spaced 2.8 nanoseconds apart successfully reduced the bunch-to-bunch energy spread to only 0.3 percent, thus verifying that this frequency-shift method works well in practice. Another way to compensate for beam loading is to feed amplitude-modulated microwave power into ordinary accelerating structures; preliminary tests have shown that this principle works well, too.

The goal of the damping ring is to generate a beam with ultralow emittance within a storage time brief enough to handle the successive beam trains coming from the injector linac. Circulating electrons (and positrons) exhibit oscillatory transverse motions known as betatron oscillations. Upon deflection by bending magnets, these particles emit synchrotron-radiation photons, thus losing a bit of their longitudinal and transverse momentum. But in passing through accelerating cavities every orbit, they regain the longitudinal component, thus narrowing the beam ever so slightly. After many orbits, the subtle imbalance between these losses and gains lowers the emittance exponentially to an equilibrium value independent of initial conditions.

The ATF damping ring was designed to reach a very low equilibrium emittance—about a *hundredth* that of conventional storage rings and a tenth that of advanced synchrotron-light sources. Eight multipole wiggler magnets were included in the ring to boost radiation damping by forcing the beam to oscillate in short steps. All round the ring's 140 meter circumference there are many



A portion of the Accelerator Test Facility Damping Ring. High precision alignment of individual components is important, although an automatic beam-based alignment system will ultimately be used.

small magnets in addition to the wigglers and microwave cavities. Its vacuum chambers have inner diameters as small as 24 millimeters in the arc sections and only 12 millimeters high at the wigglers—considerably smaller than the dimensions of conventional storage rings. But they are still large compared to the dynamic beam aperture arising due to nonlinear effects in an ultralow-emittance ring. Highly sophisticated beam control is naturally called for in such a situation, and the present ring is equipped with almost a hundred button-electrode systems to measure the bunch positions at every turn.

A team of physicists led by Junji Urakawa commissioned the ATF damping ring (see photograph above) in January 1997. After dealing with initial hardware problems, they established a sequence of successful operations from injection of a beam into the ring, its storage with the microwave cavities on, and extraction from the ring. So far, they have attempted only single-bunch operation at about 1 Hz repetition rate. Serious accelerator-physics research began six months after commissioning ended. To model the ring precisely, physicists conducted a systematic study in which they gave the beam small electromagnetic kicks and measured corresponding changes in the downstream orbit; the latest measurements agree well with calculations. These data are then used to adjust the field intensity of individual magnets. An automatic optimization procedure, using a similar beam-based alignment appoach, is about to become effective. Emittance damping times of 19 milliseconds (horizontal component) and 30 msec (vertical) have been observed with the wigglers off, in good agreement with design values. The damping time is expected to drop to 10 msec or less with the wigglers turned on.

A conventional synchrotron-light monitor was sufficient for measuring the beam profile in early stages of the research. But as machine tuning improved, this approach had to be abandoned due to the limited capability of such a monitor. As the beam gets very small, on the other hand, its synchrotron light begins to reveal a spatial coherence corresponding to the decreasing source size. Thus Toshiyuki Mitsuhashi developed and introduced a synchrotron-light interferometer that records the interference fringes formed behind a double slit. The size of the source is deduced from how the fringe contrast varies with the slit separation. So far the beam size has been measured (at a specific point in the ring) to be 39 μm wide and 15 μm high, compared with 40 μm and 6 μm expected from beam optics and the design emittance. Therefore the ring has essentially reached its design goal of 1 nm-rad—at least as far as the horizontal emittance is concerned. This conclusion was confirmed by measurement of an extracted beam, after correcting for beam jitter and spurious dispersion. The vertical emittance should be substantially smaller, as it is primarily determined by betatron coupling associated with magnet misalignments. Current estimates of this emittance, based on the beam-size measurement mentioned above, are about four times larger than the design value, although with a fairly large uncertainty.

After the first, hectic year of research at ATF, physicists have come close to achieving the ultralow-emittance beam needed for the JLC. At the same time, it has become increasingly clear that, even with a well-designed accelerator, stability and resolution are key issues. After scheduled improvements in these aspects, single-bunch operations will continue for some time before we move on to multibunch operation. Our immediate objectives are to achieve reliable, high-precision, one-shot and turn-by-turn beam measurements and to reach ultralow vertical emittance.