Physics Nobel Prize awarded for microscopies old and new

The 1986 Nobel Prize in Physics has been awarded for two profound advances in the history of microscopy, separated by half a century. Both involve imaging with electrons to achieve resolutions far beyond the capability of optical microscopy. But there the resemblance ends.

Half the prize was awarded to Ernst Ruska "for his fundamental work in electron optics and for the design of the first electron microscope" in the early 1930s. Ruska, who was 80 years old on Christmas Day, is the retired director of the Institute of Electron Microscopy of the Fritz Haber Institute in West Berlin. The other half of the 1986 prize went to Gerd Binnig and Heinrich Rohrer "for their design of the scanning tunneling microscope" at the IBM Zurich Research Laboratory. This collaborative work began when Binnig joined Rohrer's Zurich group just after getting his PhD in 1978 at the Wolfgang Goethe University in Frankfurt.

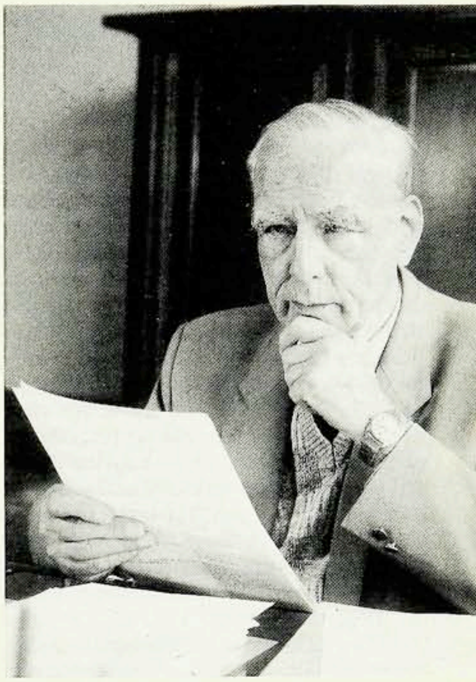
The transmission electron microscope developed by Ruska and his colleagues is very similar in concept to an ordinary optical microscope, except that the illuminating light and glass lenses are replaced by an electron beam and electromagnetic lenses. The best point resolution achieved by such microscopes nowadays is about 2.4 Å. The scanning tunneling microscope, on the other hand, bears little resemblance to any optical instrument, or even to the scanning electron microscope. A fine probing stylus scans across the surface to be imaged in a raster pattern, separated from the surface by only 10 Å. Applying a voltage across this tiny gap causes a tunneling electron current to flow between the probe and surface. It is the extreme sensitivity of this "vacuum tunneling" current to the distance between the surfaces that permits the instrument to resolve surface features with an astonishing vertical resolution of about 0.1 Å.

The beginnings of electron microscopy owe much to the efforts made in the 1920s to perfect the cathode ray oscilloscope. Oscilloscopes were much in demand at the time for the monitoring of undesirable surges in power plants and other high-voltage facilities. As work progressed on concentrating the "writing spot" where the electron beam hits the fluorescent tube face, it slowly became clear that the "concentration coil" that did the work was in fact a lens, in very close analogy to optical lenses. It followed that if one could make an electron lens of sufficiently short focal length, one could probably devise a multiple lens system that would yield high magnification—an electron microscope.

Ruska, born in Heidelberg in 1906, began work on the oscilloscope problem in 1928 as an engineering graduate student under the direction of Max Knoll in the Study Group for Very High Voltage Installations at the Berlin Institute of Technology. Ruska was to investigate the "bundling" of electron beams in the coaxial magnetic field of the oscilloscope's short coil, as well as bundling in electrostatic fields. As Ruska describes it in his published reminiscences[1] of the early days, "Although as prospective engineers we were supposed to be solving technical problems, my supervisor Adolf Matthias was sympathetic when we wanted to pursue physics problems."

Ruska's task was to "find a calculation scheme that would enable us to design the optimum oscilloscope." The crucial parameters were the electron density and diameter of the writing spot. Practical considerations dictated exploitation of the nonuniform magnetic field of a short coil rather than a uniform field, which could only be produced by much larger coils.

There was, however, in the literature "no clear account of the mode of action of such coils." In particular, no one had written of the imaging capability of such coils before Hans Busch, at Jena, undertook a mathematical analysis of the problem in 1927. In the approximation that the coil length is small compared with its distance from the cathode source and screen, Busch calculated that all electron trajectories in a narrow bundle should intersect at a focus beyond the coil field, and that the object and image distances are given, in terms of an effective focal length, by the simple formula of geometrical optics.

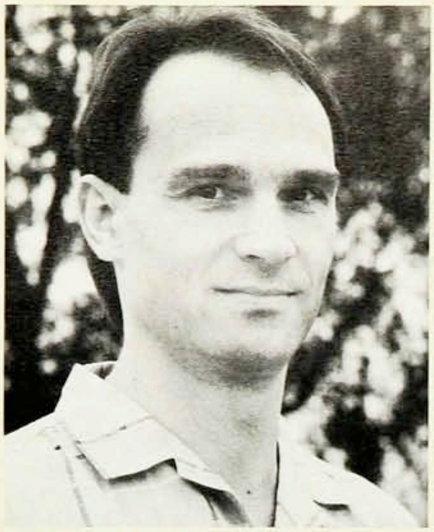


RUSKA

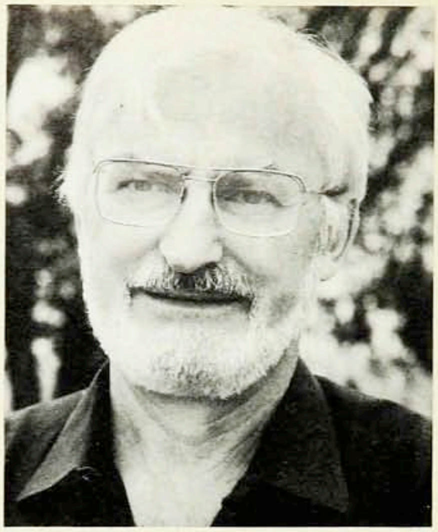
Going back to data he had taken 16 years earlier, Busch was disappointed to find that the magnification implicit in his lens formula did not agree with the old data. Ruska comments that Busch's coil was "not really short enough to accord with the approximations of the theory.... It remains a matter of speculation whether this held Busch back at this stage from suggesting new possibilities ... that could be realized by optical imaging."

The apparent inconsistency of Busch's theory with his old magnification data "was the stimulus urging me to check the new lens theory with a short-coil arrangement permitting more accurate measurements than had hitherto been possible." The results, contained in Ruska's 1929 *Studienar-*

0031-9228 / 87 / 0100 17- 07 / $01.00



BINNIG



ROHRER

beit (a prerequisite to the master's thesis), were in much better agreement with the theory. But discrepancies remained, which Ruska attributed to the fact that he was using a gas discharge tube with a cold cathode rather than the thermionic cathodes "that were only just becoming known." In a gas discharge tube the electron beam has a sizable energy dispersion.

Because Knoll was also interested in electrostatic lenses, he and Ruska set out to test the electrostatic calculations of Busch. The predicted electrostatic focusing was verified, but the image distortions they observed "made it seem to us more fruitful to concentrate on magnetic lenses."

"The economic situation having worsened considerably, it was not possible for me to find a paying position at the institute or in industry after I completed my master's thesis in 1930, so I was happy to take an unpaid position at the institute, where I could continue with the electro-optical investigations I had begun," Ruska writes. Early in 1931 he put together a two-stage apparatus with two short coils along the electron beam path. In front of each was a chamber for inserting apertures (at anode potential) to be imaged, and between the two coils was a spherical electrostatic condenser lens. The apertures were covered with fine mesh grids to serve as interesting and hardy imaging objects. "We were astonished, and of course delighted, to see how good these images were, particularly when the apertures were imaged at high magnification."

The combined action of the two focusing coils and the defocusing condenser, it turned out, yielded precisely what one would expect from the corresponding laws of light optics. In this case, however, one had an extra continuous degree of freedom in addition to image and object distance. One could vary the focal lengths of these magnetic lenses simply by changing the coil currents. In April 1931, having obtained their first sharp two-stage image with a total magnification of 4×4, Knoll and Ruska began to discuss whether it might be possible to exceed the diffraction-limited resolution of optical microscopes with an electron microscope. De Broglie's theory and the Davisson–Germer verification of the wave properties of electrons were not yet known to them, Ruska tells us, but "we took it as highly probable, in view of the minute size of the electron corpuscle, that a fundamental resolution limit would only arise at distances small compared with interatomic spacing in solids."

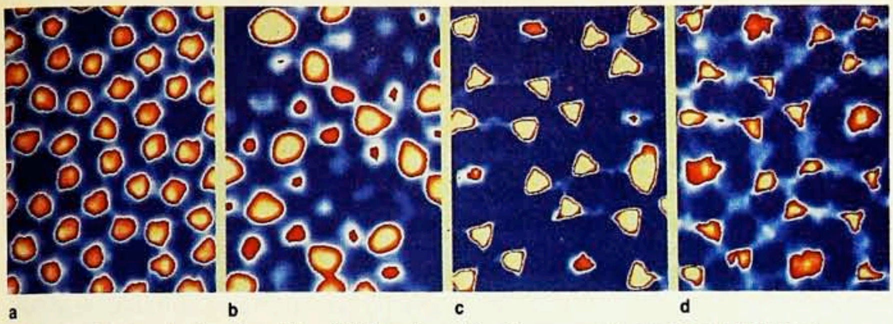
Announcing Ruska's two-stage results in a lecture two months later, Knoll avoided the term "*electron microscope* for fear of being accused of showmanship," Ruska recalls. "We, as engineers, did not learn about de Broglie waves till the middle of 1932.... I have a lively memory, even today, of my first discussion with Knoll about this new kind of wave, for I was at first disappointed that once more the resolution would be limited by a wave phenomenon. But I was quickly heartened when I had satisfied myself that these waves [for electron energies on the order of 100 keV] must be five orders of magnitude shorter than light waves."

Just five days before Knoll's June 1931 lecture, Reinhold Rüdenberg at Siemens had applied for several patents relating to multistage magnetic and electrostatic magnification. "Several weeks earlier," Ruska writes, "we had shown Rüdenberg's Siemens colleague Max Steenbeck our experimental arrangements and imaging results." This sequence of events has led to unpleasant insinuations of plagiarism, vigorously denied by George Siemens[2] and Rüdenberg's son Gunther, who told us that Rüdenberg began this work when Gunther's younger brother contracted polio in 1930, motivated by the desire to make visible the submicroscopic (viral) agent of this devastating disease. There is no dispute that Ruska and Knoll built the first electron microscope, Rüdenberg's work remaining entirely conceptual and unpublished before his departure from Germany after the Nazi accession in 1933. Siemens's possession of these first patent applications played a considerable role in Ruska's decision at the end of 1936 to carry out the development of a prototype commercial electron microscope at Siemens.

In their next paper, which showed that their electron images of metal grids were yielding the same detailed features they got with a light microscope, Knoll and Ruska invoked the de Broglie wavelength to point out that an electron microscope could, in principle, reach a resolution of 2.2 Å. "Half a century later this has in fact been realized," comments Ruska. "But at that point, the highest magnification we had observed was 400×. An electron microscope had indeed been realized, but better-than-light resolution seemed, to many experts in 1932, an illusory pipe dream."

Pole-piece lens. To challenge the light microscopes, Ruska needed, first of all, electron lenses of very short focal length. For a coil with a given number of ampere turns, Ruska concluded from Busch's formalism, one would get the shortest focal length by concentrating the field within the smallest axial length. To this end Ruska and his colleague Bodo von Borries developed the first "pole-piece lens," a design that, in its essence, remains indispensable in present-day electron microscopes. They encased the coil in iron, leaving only a short ring-shaped gap inside the coil. On each side of the ring gap they extended the iron casing into a funnel-shaped pole piece. The axial magnetic field was thus strongly concentrated in the few millimeters between the opposing circular pole faces. The development and investigation of the optical properties of the pole-piece lens were the subject of Ruska's PhD thesis, completed in August 1933, by which time the group had attained a focal length as short as 3 mm. High magnification was now very much in prospect. This time Ruska and von Borries had taken the precaution of applying promptly for a patent.

To make the electron microscope into a generally useful instrument, one still had to answer several questions. It had been shown that solid metal aperture edges and grids were faithfully imaged



Various electronic bonds at the (111) surface of a silicon crystal are seen by Robert Hamers and IBM colleagues (*Phys. Rev. Lett.* **56**, 1972, 1986) with a scanning tunneling microscope, as the instrument's voltage and polarity are varied. **a:** At +2 volts (electrons flowing into the silicon sample) we see effectively the surface atoms themselves in their reconstructed 7×7 configuration. **b:** At −0.35 V we see the least tightly bound electrons, the "dangling bonds" extending outward from these surface atoms. **c:** At −0.8 V the more tightly bound electrons from the dangling bonds of the next atomic layers become visible. **d:** At −1.7 V we also begin to see the wispy white connections that indicate the "back bonds" to the bulk silicon atoms.

with good contrast. But what about thin specimens essentially transparent to electrons? Would they exhibit adequate contrast in the absence of electron absorption? Furthermore, could such specimens withstand the high electron beam intensity required for the very high magnification necessary to challenge the hegemony of the light microscope? These questions were crucial to applications in biology and medicine.

Remaining at the institute for the remainder of 1933 with a modest short-term grant arranged through the good offices of Max von Laue, Ruska worked on these questions, having built a new electron microscope with a magnification of 1200×. In particular, he convinced himself that the image contrast obtained with thin specimens was due to the scattering of transmitted electrons rather than to absorption. Because Coulomb scattering off nuclei transfers very little of the electron beam energy to the specimen, "one could nurture the hope that [sufficiently] thin specimens could be imaged with good contrast without being heated."

At the end of 1933, with no prospect of further support, Ruska left the institute to work in industry on television technology, as Knoll had done the previous year. But he stayed in close touch with the continuing work being done by Heinz-Otto Müller and Friedrich Krause, two students at the institute who were investigating the applicability of the instrument he had built to biological specimens. For the next three years Ruska and von Borries, encouraged by the interest of his physician brother, Helmut Ruska, in submicroscopic disease agents, expended considerable effort in trying to convince various organizations (I. G. Farben, Krupp, Zeiss, Siemens and the Kaiser Wilhelm Society, among others) to support the industrial development of a better-than-light electron microscope.

Resistance to the idea that electron microscopes might be useful centered on questions of biology and medicine. It was widely believed that if cells had substructures much smaller than optical wavelengths, these would be moving too rapidly to be studied. And there remained the question of distortion of biological samples by the electron beam and the required vacuum environment. In a 1936 public lecture, Ruska was able to show a few images of diatoms, cells and fibers at magnifications ten times greater than one could get with the best light microscopes. But these specimens had indeed all been carbonized or otherwise damaged in the electron microscope. "These objections could not yet be deprived of their force."

Ladislaus Marton, who began building electron microscopes of modest magnification at the University of Brussels in 1932, attacked the carbonization problem by impregnating biological samples with heavy metals. "Let it burn, but let us look at the cinders," is the slogan Denis Gabor, another pioneer of the field, ascribes to Marton. It would be a while before Marton and Ruska could demonstrate that with sufficiently thin samples one could get adequate contrast without burning.

Finally at the beginning of 1937, Ruska and von Borries began their work at Siemens, joined by Müller, brother Helmut and theoretical physicist Walter Glaser. In a disused small-arms factory in Berlin they set up the Siemens Laboratory for Ultramicroscopy. Early the next year two commercial prototype instruments were in experimental operation. With an imaging length of 80 cm, the instruments provided a maximum magnification of 30 000× and point resolution of 13 nm—20 times better than the diffraction limit of a light microscope.

"Now, for the first time, it was possible to work reliably with an electron microscope," Ruska tells us. By the end of 1939, thousands of micrographs of various specimens had been made. Twenty papers had been published on submicroscopic biological structures. Because the ordinary microtomes then available did not provide sufficiently thin slices for electron microscopy, most of this early biological work was done with intrinsically thin samples—detached single cells or tissue components dispersed by ultrasonics.

Just as the Siemens electron microscope was ready for mass production, with a point resolution of 7 nm, the war began. The Berlin ultramicroscopy laboratory continued its research work until it was largely destroyed in an air raid in the summer of 1944. In the meanwhile, electron microscopy had spread as far as North America and Japan.

The scanning tunneling microscope, invented by Binnig and Rohrer, is the first device to exploit the quantum phenomenon of vacuum tunneling. The history and recent triumphs of this extraordinary new instrument for the study of surfaces were described in considerable detail in our August issue (page 26).

Vacuum tunneling of electrons between separated metal surfaces is conceptually one of the simplest of quantum tunneling phenomena. But in practice it proved one of the most difficult to demonstrate. It is much easier to separate two conductors by interposing a thin material interface than it is to hold them a few angstroms apart, across a vacuum gap, with any assurance that they will not inadvertently touch because of vibrations or protuberances.

When Binnig joined Rohrer's group at IBM after completing his PhD thesis in 1978 on tunneling in superconductors, there was as yet in the published literature no systematic demonstration of the steep exponential dependence of current on separation that would serve as a clear signature of vacuum tunneling. "When you work in tunneling, you always have vacuum tunneling in the back of your mind," Binnig told us. "It's an old dream." Binnig and Rohrer set out to demonstrate vacuum tunneling, and to exploit it.

Because of its very steep distance dependence, vacuum tunneling is an extremely local phenomenon. Increasing the gap by an angstrom reduces the tunneling current by an order of magnitude. "We didn't at first think of imaging," Binnig recalls. "We thought vacuum tunneling would provide a good, highly localizable surface probe. But after a few days we came to the idea of scanning. And then you have a microscope."

The probe turned out to be even more local than their fondest hopes. Employing stylus tips with curvature radii on the order of a thousand angstroms, Binnig and Rohrer had expected a horizontal resolution of about 50 Å—not nearly good enough to resolve individual atoms. But when they started scanning, they certainly did see atoms. "We had thought this kind of resolution would require a big effort," Binnig told us. "But we got atomic scale resolution more or less as a gift."

The gift comes from the fact that these 1000-Å tips are inevitably rough on a smaller scale, with accidental protuberances serving as tips only a few atoms wide. With these protuberances doing the probing, the scanning instruments achieved a horizontal resolution of about 4 Å very early on. Now it's down to 1 Å. In recent months the IBM Zurich group has been replacing these fortuitous probing tips with monatomic tips carefully created by field-ion microscopy techniques devised by Hans-Werner Fink. The end of the tip is the world's smallest manmade pyramid: three layers consisting respectively of seven, three and finally one single atom. Putting the last single atom in place is "a miracle," says Rohrer.

The successful demonstration of vacuum tunneling by Binnig and Rohrer in 1981 and the early scanning work (PHYSICS TODAY, April 1982, page 21) involved a vacuum environment and a very elaborate system for the suppression of vibrations, neither of which is required any longer in the present generation of much smaller scanning tunneling microscopes, designed for great rigidity. Their original apparatus was magnetically levitated on a superconducting lead bowl resting on a heavy stone slab atop a bed of inflated rubber tires.

Lacking this high degree of vibration suppression a decade earlier, Russell Young, who invented a very similar surface-imaging device at the National Bureau of Standards (see the letter on page 11), was unable to control gap size sufficiently at very small separations to demonstrate the steep current vs distance signature of vacuum tunneling. Nor could he scan surfaces in the tunneling mode. But Young was able to observe the evolution from the field-emission regime to vacuum tunneling in curves of current against voltage for several fixed spacings. In 1976 William Thompson at IBM also came close to providing a clear demonstration of vacuum tunneling. Finally, in 1977, Clayton Teague, who worked with Young at NBS, was able to demonstrate vacuum tunneling from the dependence of current on separation and voltage, with a non-scanning device built specifically for that purpose. But that work was not published (outside of Teague's PhD thesis) until last year.[3]

Young's "topografiner," developed in the early 1970s at NBS, was in a many ways a precursor of the scanning tunneling microscope. (See PHYSICS TODAY, November 1971, page 42.) With its probe separated from the surface under study by about 200 Å and rather high voltage, the instrument operated by field emission rather than vacuum tunneling. But its piezoelectric horizontal and vertical drive mechanisms for surface scanning prefigured the STM, although it did lack the rigidity of the three-legged piezoelectric drive design so essential to the success of the later Zurich instruments. In 1972 the NBS management made the portentous decision to terminate further work on the topografiner.

The fourth-generation scanning tunneling microscope recently developed at IBM Zurich is "about the size of a fingertip," Rohrer told us. It can be operated on an ordinary table, without any special vibration protection. As one miniaturizes the microscope, he explained, the vibrational eigenfrequencies of the structure become ever higher. So with a pocket-sized instrument one gets only high-frequency noise, which is trivial to filter out. Banging into the table is no problem, because the apparatus responds rigidly to such low-frequency disturbances. The relative positions of probe and specimen remain fixed.

Recent generations of the STM operate at ambient pressure rather than in vacuum. Paul Hansma (University of California, Santa Barbara) has in fact recently achieved atomic resolution in scanning tunneling microscopy of graphite surfaces under water. "In moderate vacuum," Rohrer explains, "you get a few atoms per second hitting the active area of the sample. And that makes visible noise." At ambient pressure, on the other hand, it's billions of atoms per second "and that averages out nicely. It's so fast you see no effect, no distortion. We've found from experience that ordinary atmosphere is not only acceptable, it's in fact better than vacuum in many respects."

Vacuum also poses particular problems for the study of biological materials. It robs them of their water films, distorting them and perhaps interfering with the conduction mechanism necessary for the maintenance of a tunneling current. The STM was originally thought to be suitable only for the study of electrically conducting specimens. "One of the surprises," Rohrer told us, "is that many biological samples conduct well enough to let us do scanning tunneling microscopy. We don't really understand this unexpected conduction mechanism yet. It may be very local. But it lets us use the instrument for biology."

"The real breakthrough in biological exploitation is yet to come," says Binnig. "But the potential is very high." To this end Binnig is developing the "atomic force" scanning microscope, a cousin of the STM designed for nonconducting samples. In this instrument the probe is drawn toward the surface by van der Waals and other such forces. The probe sits at the end of a cantilever, whose minuscule deflection is monitored by a vacuum tunneling current at its other end. Binning began this work while visiting Calvin Quate's laboratory at Stanford. Quate was the first of the many outside researchers who have now taken up the Binnig–Rohrer STM with great enthusiasm.

The superb vertical and lateral resolution of the STM owe much to the exquisitely sensitive piezoelectric drives that move the probe in three orthogonal directions over the surface contours of the specimen. One can control the motion of these drives to 10^{-4} Å. But when Binnig and Rohrer began their work, it was not clear whether this could be done continuously and reproducibly—without jumps or hysteresis. The IBM group was making novel demands on piezoelectric microdrive systems. "We were relieved to find that the motion is indeed continuous and absolutely reproducible," Rohrer recalls.

There was, however, a problem of reproducibility in the early days. "Every surface we looked at in those days was unaccountably rough," Binnig told us. "But then when we waited awhile and looked again the landscape had become smooth." What was happening, they soon realized, was that the probe was inadvertently coming in contact with the surface and scratching it. While they waited before looking again, thermal shift brought a clean new landscape under the probe. Eventually they learned how to avoid this

1986 Nobel Prize in Chemistry

The 1986 chemistry Nobel Prize, which went to Dudley R. Herschbach, Yuan T. Lee and John C. Polanyi for the study of reaction dynamics, will be covered in this department in a forthcoming issue.

touching, and how to repair the probe *in situ* by evaporation when touching had not been avoided.

Spectroscopy. The STM is not simply a topographical imaging device. "Now we can also see the *color* of the atoms," Binnig stresses. This new and highly promising enterprise is, in effect, scanning tunneling spectroscopy: In the imaging mode one simply scans with a fixed voltage while a feedback mechanism raises or lowers the probe to maintain a fixed tunnel current over a bumpy landscape. But one can also examine the dependence of tunneling current on the probe voltage at each point on the surface. (See the figure on page 19.) These voltage–current curves are indications of the species and bonding of surface atoms and molecules, and of the band structure of the substrate. A local thin layer of NiO_2 on a nickel substrate, for example, shows up as a prominent peak in dI/dV near 0.8 volts. Small islands of oxide, easily seen this way, are hardly noticeable on a simple STM topographic image.

Simply by reversing the polarity of the voltage between probe and specimen, Randall Feenstra and his colleagues at the IBM Thomas J. Watson Research Center (Yorktown Heights, New York) have demonstrated that the STM can clearly distinguish between the different atomic species on the surface of a diatomic crystal. In gallium arsenide, for example, the gallium atoms acquire the preponderance of empty electron states. Thus if the STM voltage polarity is such that the probe is the cathode, tunneling will occur only into the electron-poor Ga sites. Reversing the STM polarity, one sees tunneling electrons emerging only from the electron-rich As sites (see cover).

"We can also use the STM as an *active* instrument," Rohrer stresses, "to perform a variety of local modifications on microelectronic devices." Other device applications would include detailed probing of local voltages. "We can really see exactly where the current is flowing, where the voltage drops are. I think the STM will become very important for the development of microelectronic devices."

Rohrer got his PhD in 1960 at ETH, the Swiss Federal Institute of Technology in Zurich, working on the pressure and volume effects of superconductivity. Since 1963 he has been at IBM in Zurich, where Binnig joined his group in 1978. "The STM is just beginning to do science," says Binnig. "The technique is now more or less developed. The important thing is to apply it for doing science. It's like a baby at the moment. There'll be some surprises."

—Bertram Schwarzschild

References

1. E. Ruska, *The Early Days of Electron Lenses and Electron Microscopy* (translated by T. Mulvey), S. Hirzel Verlag, Stuttgart (1980).
2. G. Siemens, *History of the House of Siemens*, vol. II (translated by A. Rogers and L. Hole), Karl Alber, Freiburg (1957), p. 193.
3. E. C. Teague, J. Res. Natl. Bur. Stand. **91**, 171 (1986).

Tristan e^+e^- collider in Japan yields 50 GeV center of mass

Tristan, an electron–positron collider at KEK, the National Laboratory for High Energy Physics at Tsukuba, Japan, achieved collisions with 25 GeV in each beam in mid-November. At that time the maximum luminosity was $2.6\times10^{29}/cm^2$ sec. This center-of-mass energy of 50 GeV makes Tristan the world record holder for electron–positron collisions, at least until the SLAC Linear Collider starts colliding-beam trials, scheduled to begin next month. SLC will have 50 GeV in each beam.

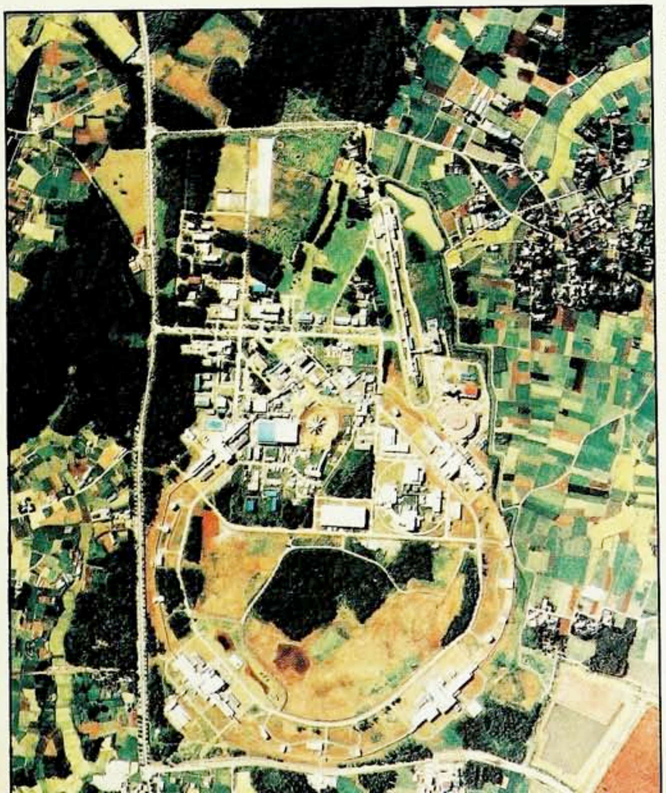
The SLAC Linear Collider, the first single-pass collider ever built, is expected to be ready for physics experiments early in May if all goes well in initial tests. Meanwhile, the CERN Large Electron–Positron collider, also with 50 GeV in each beam, is scheduled to operate in March 1989.

Until Tristan came on the air, the highest-energy e^+e^- colliders were PETRA, at DESY in Hamburg, which has operated as high as 23.5 GeV per beam, and PEP at SLAC, which has operated at 15 GeV per beam.

During a visit to KEK on 10 November, we chatted over green tea with KEK director Tetsuji Nishikawa, Tristan project director Satoshi Ozaki and other members of the KEK staff about the initial tests of Tristan. KEK, a two-hour automobile ride from downtown Tokyo, is in the midst of Tsukuba, the academic city that is also the home of many research institutes, government agencies and the University of Tsukuba.

Ozaki, a high-energy physicist who spent many years at Brookhaven, had returned to Japan to head the Tristan construction, which began in November 1981. He was pleased that Tristan was behaving so well so soon after the accelerator builders were ready to attempt e^+e^- collisions.

Its design luminosity is $2\times10^{31}/cm^2$ sec, but achieving a factor of only 100 lower so soon after start-up is impressive. By mid-December Tristan had an average luminosity of $1\times10^{30}/cm^2$ sec. Both electrons and positrons are accelerated to 2.5 GeV by a 400-meter linac (which has been operating since 1982 as the injector for



Aerial view of Tristan site in Tsukuba, Japan. The 400-meter linac injects 2.5-GeV electrons and 2.5-GeV positrons into the main ring, whose circumference is 3018 meters. In the main ring the electrons and positrons are each accelerated to 25 GeV and allowed to collide.