TESLA
The Superconducting Linear

by REINHARD BRINKMANN

Superconducting niobium cavities offer an alternative path to a TeV linear collider. Extensive R&D on this approach has stimulated the conceptual design of such a machine.

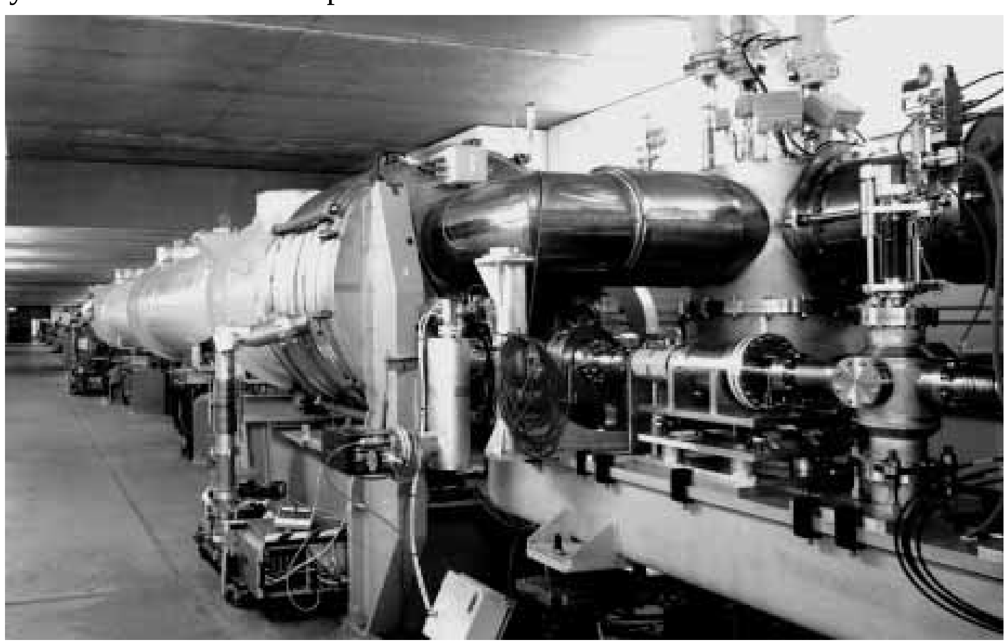
SEVERAL FUNDAMENTAL PROBLEMS of particle physics concerning the high-energy behavior of matter are expected to be solved—at least in principle—by studying collisions of particles at energies almost an order of magnitude higher than those reached by accelerators operating today. The next step in this direction will be the Large Hadron Collider, a proton-proton storage-ring collider being built as an international effort at the European laboratory CERN in Geneva. But there now is widespread agreement that this machine should be complemented by other colliders in which leptons—in particular electrons and positrons, but eventually perhaps muons—annihilate, allowing a cleaner study of the reaction products.

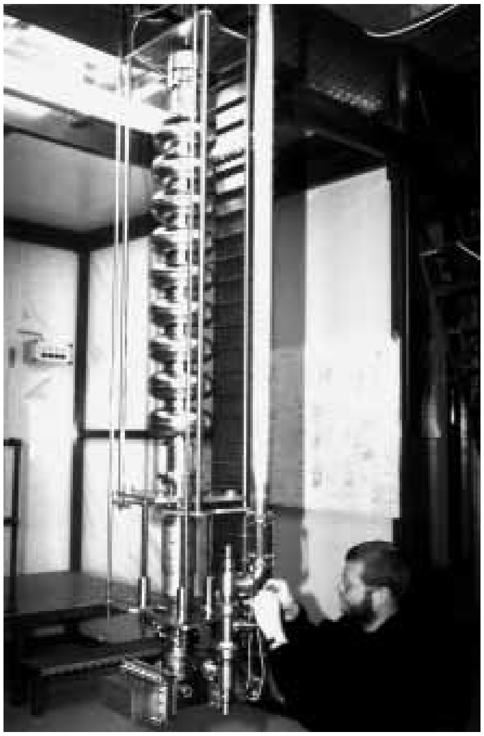
To reach the required energies with electrons and positrons, a pair of linear accelerators firing at one another seems to be the most feasible technical solution. Storage rings for such light particles are limited in energy because of their energy losses due to synchrotron radiation. Studies of various linear-collider designs are being pursued at several laboratories as described by Gregory Loew and Michael Riordan in the Winter 1997 *Beam Line*, Vol. 27, No. 4. One of these approaches is the TESLA concept, or "TeV-Energy Superconducting Linear Accelerator," which should initially reach a collision energy of at least 500 GeV. The TESLA project is being pursued by a broad international collaboration coordinated at DESY in Hamburg; more than thirty

Collider

institutions from China, Finland, France, Germany, Italy, Poland, Russia, and the United States are participating in it.

THE TESLA CONCEPT is based on superconducting cavities made of niobium metal and operating at superfluid helium temperature (2K). The energy losses in the walls of such superconducting microwave cavities are extremely low, leading to a ratio of the stored power to the power lost by damping, the so called "quality factor," of the order of 10^{10}—a *million* times higher than in a normally conducting, room-temperature copper cavity. This allows one to operate a superconducting linear accelerator at a relatively low frequency (1.3 GHz for TESLA) and with long pulses that can be generated by a low-peak-power microwave source. A high efficiency of power transfer to the beam is possible. And, at the lower frequency, the wakefields induced by the beam in the surrounding structures are small while the required alignment tolerances are quite moderate (0.5 mm for the cavities). All this makes a superconducting linac





TESLA nine-cell niobium cavity ready for installation in the vertical test cryostat for performance testing. (Courtesy DESY)

Assembly of the first string of eight TESLA cavities in the clean room at the Test Facility. (Courtesy DESY)

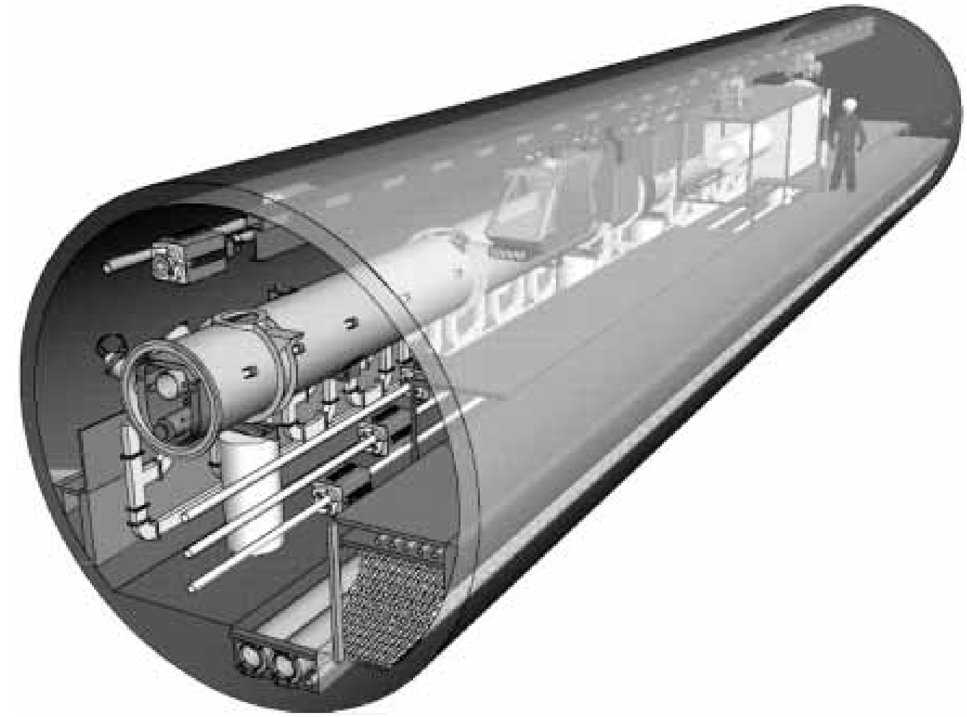
ideal for accelerating a beam of extremely good quality—with small transverse dimensions and angular divergence ("low emittance") and with a low energy spread, that is exactly what is required for a high-performance linear collider. Consequently, there is in principle also a strong potential for TESLA to achieve high collision rates, corresponding to a luminosity of as much as $3\text{–}5\times10^{34}$ cm^{-2}s^{-1}, as compared with 3×10^{30} achieved so far on the Stanford Linear Collider at 50 GeV beam energy and about 5×10^{31} on the LEP collider at CERN at 90 GeV. This potential high performance of TESLA coincides with a low background environment and good energy resolution for particle-physics experiments.

But there is also a major challenge: superconducting accelerator systems are known to be expensive. The TESLA collaboration has set an ambitious goal for reducing the cost per megavolt (MV) of accelerating voltage by a factor of 20 compared to what has so far been realized at existing large-scale installations (such as Jefferson Lab and in the superconducting cavities of the LEP ring). The goal is $2000 per megavolt, to be achieved by increasing the accelerating gradient fivefold in comparison with the 5–6 MV/m typical of existing facilities, and by reducing the cost per unit length by a factor of four. In order to demonstrate that this goal can be reached, an aggressive R&D program was launched in 1992.

The TESLA Test Facility, or TTF, has been set up at DESY to serve as a focus for R&D on high-performance superconducting cavities. It includes a fully operational linac in order to perform an integrated system test of all components as they would be used in a future collider. Developments at the TTF will also provide a basis for a complete cost estimate for a 500 GeV machine.

In the test facility the complete infrastructure for processing nine-cell niobium cavities (see top left photograph), as they are obtained from industrial production, is already available. Steps toward achieving high-performance cavities include the required chemical treatment, high-pressure rinsing with ultrapure water and heat treatment up to 1400˚C. Each cavity undergoes performance tests with continuous-wave as well as pulsed-mode microwave excitations. Strings of eight cavities are assembled under clean-room conditions (bottom photograph) and mounted into cryogenic modules. In May 1997 the first module of this type was completed and installed in the test linac (photograph on previous page). Within a few days of commissioning of the accelerator, an average accelerating gradient of 16.5 MV/m was demonstrated with an electron beam passing through the cavities. In addition to this encouraging start, test results for cavities from the continuing industrial production show a further performance improvement. The best performance to date was obtained with a nine-cell cavity in pulsed-mode operation (as required for TESLA), reaching a gradient of 33 MV/m at a quality factor of 4×10^9.

Assembly of two more accelerator modules with eight cavities each is in progress, with installation into the linac scheduled for autumn 1998 and February 1999. By that time we expect to accelerate a beam with a gradient of 25 MV/m. The R&D program towards even higher gradients will continue. The theoretical limit for niobium cavities is about 55 MV/m; single-cell cavities have attained 40 MV/m in tests at Jefferson Lab and KEK. Therefore the TESLA team is confident that operation of a superconducting linac above 30 MV/m will eventually be feasible.



Artist's conception of the main TESLA linac in a 5 meter tunnel.

A COMPLETE DESIGN of the overall layout for TESLA as a next-generation linear collider facility has been developed and documented in an extensive report published in the spring of 1997. The two volumes of this report, titled "Conceptual Design of a 500 GeV e^+e^- Linear Collider with Integrated X-Laser Facility," (available as ECFA-Report 1997-182 and as DESY Report 1997-048), include discussions of the physics involved and the experimental detectors required. In addition to the main linacs, the report details subsystems such as the required particle sources, bunch compressors and damping rings, and the final-focus system needed to compress the beams at the interaction point. An alternative S-band linear collider (considered as a backup solution) is also discussed, as well as a superbrilliant X-ray laser facility.

The site length of 32 km permits a total collision energy of 500 GeV, assuming an accelerating gradient of 22 MV/m. All subsystems of the machine have been designed so that an energy of 800 GeV can be reached with improved cavity performance at a gradient of 34 MV/m. Within the TESLA collaboration there is broad agreement that the site of the next linear collider should be adjacent to an existing high energy physics laboratory; this will provide significant advantages with regard to both the cost and the construction time required for such a facility.

As the coordinating laboratory of the collaboration, DESY has begun to investigate in detail the possibility of constructing TESLA adjacent to its own Hamburg site (which, however, does not rule out other options). The geographical conditions are favorable along a 32 km line stretching northwest from DESY (see illustration on page 25). The machine would sit in a tunnel 15–20 meters underground, very similar to the 6.3 km HERA tunnel. At the electron- positron collision point near Ellerhoop (16 km from DESY) a central site would accommodate the experimental hall for the particle-physics detector and additional infrastructure, as well as the user facility for the X-ray free electron laser.

The proposed TESLA site lies mostly in the "land" of Schleswig-Holstein and in part on territory of the city of Hamburg. The political authorities of both regions and the involved communal administrations have all given their support to the project; they have been very cooperative in investigating the feasibility of the required construction.

The direction of the linac has been chosen such that it connects tangentially to the HERA ring, thus allowing the possibility of a linac/ring electron-proton collider option at a collision energy 3–4 times the present HERA energy (300 GeV). Furthermore, part of the TESLA linac could serve as an injector for HERA's electron ring, which would be converted into a pulse stretcher to provide a continuous electron beam at 15–25 GeV for nuclear-physics experiments.

The proposed TESLA facility includes a coherent X-ray source in the angstrom wavelength (10^{-8} cm) range; it would serve a broad scientific user community and continue a long DESY tradition of providing experimental facilities for both elementary-particle and synchrotron-radiation research. The X-ray free-electron laser would be able to deliver an extremely high photon flux with a time resolution on the order of 100 femtoseconds and a peak brilliance that exceeds by ten orders of magnitude that of the most advanced synchrotron-radiation sources in existence today.

The first ideas about generating coherent X-rays from a high-energy electron beam using self-amplified spontaneous emission in the framework of a free-electron-laser concept were developed at Stanford University using part of the SLC linac. The TESLA superconducting linac should deliver a particularly good beam quality for this application. The idea is to extract an electron beam from the linac (generated by additional microwave pulses) at various energies (15–50 GeV) and transport it to the central experimental site at which the X-ray user facility is located.

A free-electron-laser test facility using the TTF linac is now under construction at DESY. First tests at a beam energy of about 400 MeV and a wavelength of 40 nanometers will start in the spring of 1999. Further extension to energies over 1 GeV beam energy and 6 nanometers wavelength is planned for subsequent years; operation as a pilot user facility is scheduled to begin in 2001.

IN CONCLUSION, the TESLA collaboration has worked out a complete design for a next-generation electron-positron collider based on superconducting linac technology. Our team is convinced that the excellent performance achievable with this approach justifies the considerable R&D on superconducting cavities. The progress at the TESLA Test Facility justifies our optimism that the necessary cost and performance goals can be reached. Within the next two years a comprehensive technical proposal, including a cost estimate, will be completed. Approval of TESLA as an international project can be envisaged for the year 2002 at the earliest. DESY will be prepared to offer a suitable site for this future facility.

For readers wishing more information on ***TESLA****, the following URL may be helpful:*

http://www-mpy.desy.de/desy-acc.html#LC