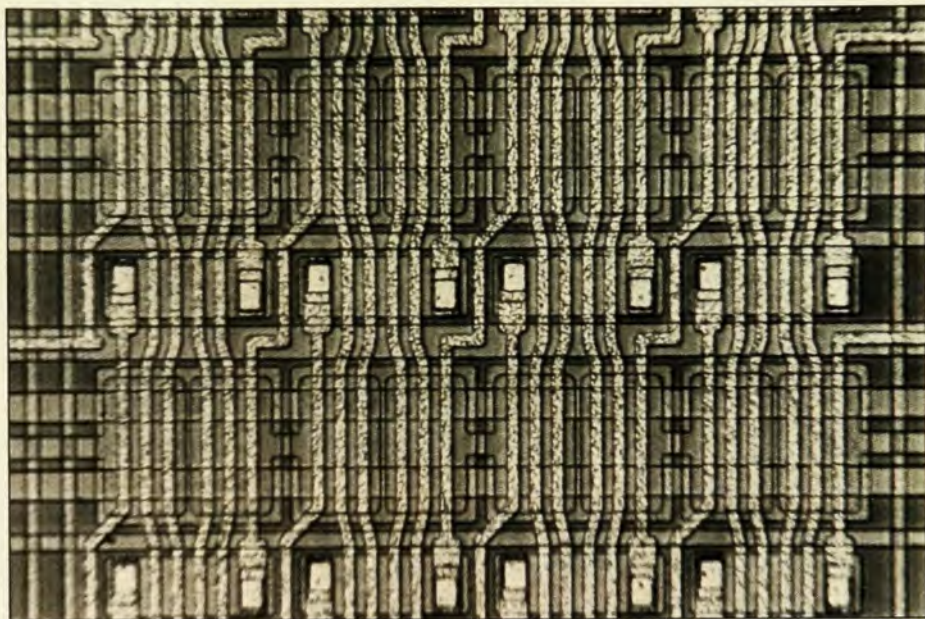


search & discovery

Josephson-junction logic and memory circuits

The superconducting tunnel effect predicted by Brian Josephson in 1962 is looking increasingly promising for another very practical application—as logic and memory circuits for computers. Josephson-junction circuits are capable of high switching speeds (50–100 picosec have already been obtained). And because such circuits operate at voltages comparable to the superconducting energy gap, the heat generated is typically microwatts, thousands of times lower than high-speed transistor circuits. The diminished heat-removal problem allows one to pack the Josephson circuits much closer than semiconductor circuits. Once high switching speeds are achieved, this packability becomes extremely important because then the major limitation on computer speed is how fast the electrical signal takes to move from one circuit to another.

Recently, groups at the IBM Research Center in Yorktown Heights, N.Y. and Zurich, Switzerland and at Bell Laboratories in Murray Hill, N.J., announced new results on making high-speed Josephson circuits that might be suitable for computer applications. IBM reported its results at the International Solid-State Circuits Conference in San Francisco in February. Both IBM and Bell Labs described their results at the Conference on



Photomicrograph shows 16 memory cells in an experimental Josephson-junction memory chip built at IBM Zurich lab. The device is used to test elements of a prototype 16 000-bit memory chip.

Future Trends in Superconductive Electronics in Charlottesville, Va. this March.

Other groups working on Josephson logic and/or memory circuits (now or in the past) include Texas Instruments, Sperry Research Center, Aerospace Corp,

Hughes Research Laboratories, the National Bureau of Standards, the University of California at Berkeley, Fujitsu Laboratories in Kawasaki, Japan, and Nippon Telegraph and Telephone in Musashino, Japan.

continued on page 19

Experimenters build detectors for PEP turn-on in 1979

Construction of the Positron-Electron Project at SLAC is in full swing, and the \$78-million facility is expected to operate in October 1979. PEP will have 18-GeV positrons colliding with 18-GeV electrons in six interaction regions.

Meanwhile, both the first and second rounds of experimental approvals have been made. Four different detectors were approved in the first round: PEP-4, the Time Projection Chamber (TPC), PEP-5, General Survey of Particle Production (Mark II), PEP-6, Lepton/Total-Energy Detector (MAC) and PEP-9, PEP Forward Detector Facility (Two-Gamma). PEP-4 and PEP-9 will share a single interaction region and exchange data in real time. Three interac-

tion regions will be used to house these experiments.

The second round of experimental approvals consists of PEP-12, the High-Resolution Spectrometer, PEP-14, the Free Quark Search, and PEP-2, the Monopole Search. These detectors will occupy the remaining interaction regions. When PEP begins operating for physics experimentation, it is expected that Mark II, the Monopole Search, MAC, and possibly the Free Quark Search will be ready to go.

The German counterpart of PEP, the Positron-Electron Tandem Ring Accelerator, is now nearing completion at the Deutsches Elektronen Synchrotron in Hamburg. Its parameters are very simi-

lar. PETRA will operate for experiments with 18-GeV electrons and 18-GeV positrons colliding (PHYSICS TODAY, June 1976, page 17). Start-up is officially scheduled for this September, but DESY is hopeful that PETRA will begin running this summer, more than a year before PEP.

After successful positron injection tests through one-eighth of the ring in mid-1977, early in January electron injection tests were performed, and single bunches were guided through one-fourth of the PETRA ring in the opposite direction. Since then, almost all the magnets have been delivered to the site. Equipment is being installed in three out of the four experimental halls; the fourth hall is al-



Construction of the ring tunnel at PEP, an 18 GeV $\times$ 18 GeV electron-positron storage ring. Because of the variation in height of the terrain, parts of the ring enclosure are tunneled, parts are poured-in-place concrete. The interior of the tunnel walls is "shotcrete" and will be only slightly more regular in surface than they appear in this photograph. The ring has a 710-m. diameter.

most completely ready for occupancy.

PETRA will operate with 15–18 GeV in each beam in the first stage. Plans are to increase beam energy in a second stage to 23 GeV by increasing the rf power and the number of accelerating cavities. At 18 GeV, PETRA's designers expect to have a luminosity of $10^{31} \text{ cm}^{-2} \text{ sec}^{-1}$ and at 15 GeV to reach a maximum luminosity of $10^{32} \text{ cm}^{-2} \text{ sec}^{-1}$. One early experiment at PETRA will search for new resonances and interference effects between weak and electromagnetic interactions.

Cornell University is converting its 12-GeV electron-synchrotron facility to a colliding-beam facility with a storage ring called "CESR" with 8-GeV electrons and 8-GeV positrons (PHYSICS TODAY, August 1977, page 20). CESR is scheduled to operate on or before October 1979. In Novosibirsk, USSR, VEPP-4 is being built. It will have 7–8-GeV electrons and 7–8 GeV positrons colliding in a device that might operate this year. SPEAR at SLAC operates at 4.0 GeV/beam. DORIS at DESY is being upgraded to reach 5 GeV in each beam to look for upsilon resonances. An energy of 4.7 GeV in each beam has already been achieved.

PEP has a ring whose major diameter is 710 m, and along its circumference are six bending arcs and six long straight sections. The two-mile SLAC linac injects electrons and positrons into the storage

ring. The vacuum chamber is maintained at 10^{-8} torr, and beam lifetimes of several hours are expected. PEP designers anticipate a luminosity of $10^{31} \text{ cm}^{-2} \text{ sec}^{-1}$ at 4–18 GeV with a peak of $10^{32} \text{ cm}^{-2} \text{ sec}^{-1}$ at 15 GeV.

Commenting on the anticipated luminosity figures, Gerard K. O'Neill (Princeton University), who pioneered the storage-ring concept as early as 1956 told us, "All the way from the first small electron-electron storage rings through to the latest and largest electron-positron rings, the history of storage-ring development shows that it is very difficult for the designers to predict accurately what the luminosity will be. For this reason, it's generally recognized that it's not worthwhile to dwell too closely on estimates of the best possible luminosity, but rather to make sure that the experiments being designed can still do good physics over a wide range of luminosities. It's with that approach over the past 20 years that these machines have been so extraordinarily successful and productive."

PEP designers, to sustain the maximum circulating beam current of 54 milliamps in each beam at an energy of 15 GeV, will use about 6 MW of rf power. SLAC has developed a special high-power klystron for this purpose; the tubes have delivered 500 kW output power at an efficiency of 63%—the best combination of

efficiency and power achieved anywhere, according to Helmut Wiedemann of PEP.

PEP project director John Rees told us that because of the heavy rains in the Bay Area in December and January, conventional construction was delayed. He still hopes that the tunnel will be finished in October, and that the first new buildings will be occupied at the same time. Tunnel drilling has begun and is proceeding on schedule (see photo). The magnet assembly factory is operating and will reach a peak production rate of three magnets per day. The project was originally scheduled to be finished April 1980. Now SLAC and Lawrence Berkeley Laboratory, who jointly manage the project, hope to advance the completion date by six months, but only if Congress allows the Department of Energy to spend some of the \$78 million earlier than anticipated.

(While excavations are under way, a variety of fossil remains from marine animals have been turned up by professional paleontologists from the US Geological Survey in Menlo Park and by amateur paleontologist Adele Panofsky, wife of Wolfgang Panofsky, SLAC's director. During the original digging to build SLAC in 1964, the site yielded the fossil of a *Paleoparadoxia*, an extinct sea mammal the size and shape of a hippopotamus.)

The first-round detectors were selected in April 1977 by the SLAC and LBL directors, on recommendations made by a committee of 15 physicists from many different laboratories. And in January of this year, the second-round detectors were chosen.

Time Projection Chamber. The most novel of the first-round detectors is the Time Projection Chamber, a joint effort of LBL (where David Nygren is the spokesman and Jay Marx is deputy spokesman), UCLA, Yale University, University of California at Riverside and Johns Hopkins University. TPC is to share an interaction region with PEP-9, a joint effort of the University of California at Davis, San Diego (where George Masek is spokesman) and Santa Barbara.

The Time Projection Chamber is a cylinder divided into two cylinders by a thin membrane that serves as a negative high-voltage electrode; hence the electric field is aimed oppositely on the two sides. A magnetic field is applied along the axis. Each end cap of the cylinder has six sectors, each with about 200 sensing wires. Because of the reversed electric field in the two halves of the chamber, electrons produced by ionization drift away from the membrane toward one of the end caps. The parallel electric and magnetic fields keep the electrons in fairly straight trajectories. At the end of their drift, the ionization electrons are collected by the sensing wire to produce a signal.

TPC gives three-dimensional tracking,

momentum measurement and particle identification. To obtain the location, the path in two dimensions is given by the sequence of hit-locations along the sensing wires at the end caps. The third dimension comes from measuring the time it takes electrons from different parts of the track to arrive at the respective wires that record them. To obtain momentum, TPC uses a solenoidal magnetic field. Resolution is expected to be better than 1% at 1 GeV.

For particle identification, TPC measures the amount of ionization that occurs at each of about 200 different points along the track. The amount of ionization produced for a given length of ionization is a function of both momentum and mass. It is fairly simple to distinguish electrons from pions, kaons and protons with the same momentum. But the differences among pions, kaons and protons are much smaller, and they change in a complicated way as momentum is varied. By sampling the ionization so many times, the experimenters hope to obtain statistically significant particle identification. It is this feature that is most exciting but has not yet been completely tested. Nygren told us the group expects to get better than 2.5% resolution in dE/dx (energy loss).

When TPC starts running (planned for March 1980), Nygren hopes it will be able to detect as many as 15 to 20 particles from a single event. Photons will be detected by shower counters surrounding TPC and muons identified by their penetration of about 1 meter of iron. The group would like to be able to observe the particles within so-called "jet structure," first believed to have been observed at SPEAR. Such a jet structure is a tightly collimated set of particles produced in electron-positron annihilation. The experimenters hope to search for new particles, to study weak interactions, quantum electrodynamics and the properties of hadrons produced by PEP.

PEP-9, the Forward Detector Facility, will surround TPC like a pair of bookends to provide coverage of events in which particles emerge at small angles with respect to the beam. Moving in towards the interaction region, there are a muon identifier, a composite shower-counter system, septum magnet and a series of drift chambers.

Mark II. The other two first-round detectors are expected to be operating when PEP turns on. In fact, the Mark II is already running at SPEAR. It is a substantially improved version of the Mark I, which was used to discover the psi particle. Mark II is again a SLAC (spokesman is Rudy Larsen) and LBL (spokesman is John Kadyk) collaboration.

Mark II does tracking and momentum measurements with a set of cylindrical drift chambers immersed in a solenoidal magnetic field. The shower counters, used to identify electrons, positrons and

gammas, are contained in an eight-sided structure surrounding the solenoid coil. There is also an end-cap shower counter to detect particles emitted at small angles to the beam. The shower develops in a series of lead sheets alternating with lead collection strips (instead of sensing wires), and the ionizing medium is a liquid-argon bath (rather than the more common mixture of gases). The ionization electrons produced in the argon generate proportional signals in the strip sensing elements; the signals are analyzed to determine direction and energy of the initiating particle. To identify charged hadrons, the chief method used is time-of-flight.

Magnetic Calorimeter. PEP-6, known as MAC (for Magnetic Calorimeter), is being built by a collaboration among the University of Colorado, Northeastern University, Stanford/SLAC, the University of Wisconsin (spokesman Richard Prepost) and the University of Utah.

MAC is a 4π lead-iron detector optimized for use in muon physics, new-particle searches, total-energy measurements for both charged and neutral hadrons, and total cross-section measurements. The detector combines hadron and shower calorimetry with a solenoidal inner detector and a toroidal magnetized-iron muon spectrometer.

In its center is a hadron tracking system consisting of a multilayer drift chamber inside a 5–10-kG aluminum solenoid. Surrounding the solenoid is a shower detector that is a six-sided structure with 30 alternating layers of lead and proportional wire chambers for electron and photon detection.

Beyond the shower detector is a 550-ton hadron calorimeter consisting of a six-sided central section and planar end-cap sections, each of 30 layers of magnetized iron interleaved with proportional chambers. Identification of muons is made by penetration of the segmented iron, and muon momenta are measured both by the toroidal magnetic field of the iron and the inner solenoid. In addition the calorimeter provides total energy and position information for both charged and neutral hadrons in each event.

In the second-round experiments, PEP-12 is a collaboration among Argonne National Laboratory (Malcolm Derrick, spokesman), Indiana University, the University of Michigan (Donald Meyer, spokesman) and Purdue University. PEP-14 is a collaboration among LBL, Northwestern University, Stanford and the University of Hawaii. PEP-2 is a collaboration between Berkeley and SLAC.

PEP II. Even though PEP is not finished yet, SLAC and LBL are already dreaming how to upgrade its energy eventually. Three main possibilities are being considered:

► to increase maximum energy from about 18 GeV to 24 GeV per beam by

adding more rf power and more accelerating cavities of conventional design,

► to increase maximum energy from about 18 GeV to 30 GeV per beam by developing and installing superconducting cavities,

► to add a separate storage ring (with superconducting magnets) for 200-GeV protons, thus allowing electron-proton collisions.

—GBL

Josephson junctions

continued from page 17

The work at IBM started in 1965 with one man—Juri Matisoo, who reported building some simple switching circuits in 1966. His first measurements showed switching times of single junctions of less than 800 picosec, "practically dc by today's standards," Matisoo notes. These early devices were so-called "in-line devices," consisting of a traditional Josephson sandwich—a superconductor, thin insulating layer and then a superconductor. The Josephson junction acts as a gate (closed or open), which is controlled by the magnetic field of a control line, making a three-terminal device.

After three or four years of solo research by Matisoo, Wilhelm Anacker at IBM became interested in using the devices for high-speed computer technology, and a larger effort was mounted. By now roughly 50 IBM scientists and engineers are doing full-time research on the devices.

The present IBM devices are superconducting quantum interference devices, SQUID's. A one-junction interferometer is a ring with a single junction, and a two-junction interferometer is a ring with two junctions. The latter are used for relatively low-speed memory applications. For high-speed memories (less than about 1-nanosec access time) and for logic circuits, IBM uses three-junction interferometers instead of in-line Josephson junctions. These employ a figure-eight arrangement introduced by Hans Zappe of IBM Yorktown Heights, in which the junctions are at the intersection of the rings and directly opposite on either ring.

The switching time of the logic circuits is equal to the product of the capacitance and the characteristic impedance of the output transmission line, Matisoo noted. With in-line junctions, to make the device sensitive to small control currents, the junction area had to be quite large, causing the capacitance to be large, and thus also the switching time. With three-junction interferometers, the capacitance is reduced while at the same time one has sufficient field sensitivity so that switching can be controlled by a relatively small current.

At the San Francisco meeting, Mel Klein, Dennis J. Herrell and Arthur Davidson (Yorktown Heights) reported