the room-temperature region.

The Cornell group plans to use standard iron quadrupoles with windings of aluminum or copper operating at less than 20 kG and with a pole tip field of a few kG. For electron storage rings, bending and focusing magnets need not be superconducting because the required fields are so low, compared to those in proton devices. The LEP magnets produce a field of 1-2 kG and are in fact to be two-thirds concrete: C-shaped steel laminations would be stacked, and instead of filling the space with iron, CERN plans to use concrete, which is cheaper and makes the magnet more rigid.

Two of the interaction regions are planned to have high luminosity with four meters of clear space for experiments, that is no magnets for 2 meters on either side of the crossing point. The other two interaction regions would have 6 meters of clear space, and correspondingly lower luminosity.

Inspired by recent success at PETRA, the e^+e^- device at DESY, with "mini-β insertions," Cornell is working on a design to bring its focusing magnets even closer to the crossing point, so that focusing is tighter, producing a denser beam. Tigner told us the optimal size for the depth of focus is the length of the beam. This summer the group designed an interaction region with a clear space of 1 meter on each side. In this interaction region Cornell might use superconducting quadrupoles inside the detector, because the pole-tip field is 40 kG and the magnet size must be small.

The design luminosity for CESR II was 3×10^{31} cm^{-2}sec^{-1} for 4-meter straight sections. With 2-meter straight sections and a superconducting magnet, triple that luminosity could be expected based on the experience at PETRA. The value reached at PETRA for the envelope function, β, at the crossing point is 5–7 cm. CESR II would lower β to 1 cm.

Another possible problem with all kinds of rf cavities, McDaniel told us, is "multipactoring." In this process a single electron, perhaps originating from ionization of the residual gas in the cavity from field emission, may be driven into the cavity wall to release additional electrons by secondary emission. These are then drawn away from the wall by the alternating electric field and upon later reversal of the field are driven back to the wall again, producing still more secondary electrons. Repetitive cycles lead to a secondary emission cascade. This multipactoring can reduce the almost infinite Q (stored energy divided by input per energy per cycle) to a low value, making the cavity go normal. To lower multipactoring, Cornell is etching grooves in the face of the muffin cup. This July, with such grooved cavities, the Cornell group got an accelerating field of 8 MeV/meter, far better than the design field of 3 MeV/meter.

Work at other labs. A group at CERN is working on superconducting rf cavities, which would eventually be added to LEP to raise its energy from its full-scale operation with 90 GeV/beam to 130 GeV/beam. This group contains physicists from Karlsruhe, Orsay, Genoa and the Technische Hochschule in Wuppertal. This fall the group will put a superconducting cavity into PETRA. KEK is also looking into superconducting rf cavities to be added later to Tristan.

The High-Energy Physics Lab at Stanford has been operating a high-duty-cycle superconducting electron linac that recirculates the beam, each time picking up more energy, with a total of about 100 MeV after three or four passes. The HEPL-type cavities operate at 1300 MHz, L band. A group at the University of Illinois has used the HEPL-type cavities to do nuclear-physics experiments at energies of the order of hundred MeV. Unlike storage rings, these linacs do not have problems with shock excitation from the passage of large bunch, but they do not achieve the high electric field gradients (tens of MeV/meter) originally anticipated, Tigner told us. Such high field gradients are not required for storage rings, because the cavities are used over and over as the beam circulates in the ring.

Two groups are making superconducting postaccelerators for heavy nonrelativistic particles; the postaccelerator follows a tandem electrostatic accelerator, which permits one to retain high beam quality and raise the energy. A Stony Brook–Caltech group is using lead-plated copper cavities (operating at 150 MHz) while a group at Argonne uses niobium cavities (at 92 MHz). Both groups use a modular construction, allowing portions of the accelerator to be used while others are not installed. Florida State University is planning to add two Argonne modules to its existing tandem to double its beam energy.

A group from Wuppertal and Darmstadt is planning to make an electron accelerator that is a hybrid between a synchrotron and a linac; it will use S-band superconducting cavities (instead of the L band cavities used by HEPL). This higher frequency appears to improve performance. —GBL

Superconducting cyclotrons

The impending completion of a 500-MeV superconducting heavy-ion cyclotron at Michigan State University—first beam is expected in September—is indicative of two important trends in nuclear physics. Although very few data exist at present on collisions of heavy ions at beam energies between the nuclear Fermi energy (about 36 MeV per nucleon) and the GeV regime of relativistic energies, it is generally believed that this "intermediate" region will soon provide much enlightenment about the properties of nuclear matter. Secondly, there is a growing consensus that superconducting cyclotrons are a particularly efficient and cost-effective way of attaining this region of heavy-ion beams.

A few months ago a ground-breaking ceremony was held at Michigan State's National Superconducting Cyclotron Laboratory, to mark the beginning of construction on a building to house an 800-MeV superconducting cyclotron and its experimental areas. This "Phase II" cyclotron is scheduled for completion in 1984. The "Phase I" 500-MeV machine will then serve as an injector into the 800-MeV cyclotron, providing heavy-ion beams with energies up to 200 MeV per nucleon. In the meanwhile, the 500-MeV machine, standing alone, will accelerate light ions to 80 MeV per nucleon, and heavy ions (out to copper) to 10 MeV per nucleon.

The National Superconducting Cyclotron Laboratory, so designated in 1979, is a national user facility. It expects to issue a call for experimental proposals for the Phase I cyclotron as soon as the first beam tests have been completed in September. The director of NSCL is Henry Blosser.

"We're in a race with Chalk River, to see who will have the world's first superconducting cyclotron in operation," Walter Benenson, associate director of NSCL, told us. The Chalk River Laboratory, in Ontario, is building a superconducting cyclotron to serve as a booster, or "after-burner," for their tandem Van de Graaff accelerator. The Canadian tandem-cyclotron coupled system will accelerate heavy ions to a maximum of about 50 MeV per nucleon. Blosser credits the Chalk River group with being the first to realize the feasibility and economic desirability of building superconducting cyclotrons for heavy-ion physics.

The Michigan State machines are essentially conventional cyclotrons, except that their bending magnets are superconducting. They can therefore be made smaller, and can operate with much less power than room-temperature cyclotrons of comparable energy. Their 50-kilogauss bending fields—more than three times the intensity of the magnetic fields in conventional cyclotrons—will permit the Phase I and II accelerators to have outer diameters of only ten and fourteen feet, respectively.

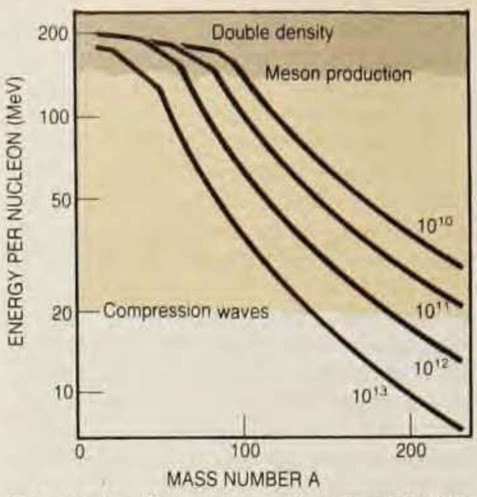
By way of comparison, the GANIL system, a pair of coupled room-temperature cyclotrons now under construction in France (PHYSICS TODAY, March, 1976, page 20), will require three times the linear dimensions of the Michigan State pair to achieve heavy-ion beam energies up to 100 MeV per nucleon, at considerably higher cost than the estimated $35 million construction cost of the NSCL Phase I and II machines.

Another important advantage of superconducting cyclotrons, Benenson told us, is that one can know beforehand what magnetic fields one is going to get, without having to build a scale model. To achieve precise magnetic fields in a room-temperature cyclotron, where iron saturation effects are complex, one usually has to map the field produced in a scale model, modify the pole pieces and then map the model field again. This arduous procedure is not necessary for a superconducting cyclotron because the iron is fully saturated, making the design calculations of the magnetic field much simpler and more reliable.

The superconducting magnet of the Phase I cyclotron has been operating successfully as a prototype for the past two years. Its niobium–titanium coils are run at 4.5 K. After a number of recent modifications, the magnet is now being cooled down again, and final field maps are being made.

The achievement of higher energies in heavy-ion accelerators depends crucially on the attainment of high ionic charge states. The highest energy that a given cyclotron bending field can keep in orbit goes as q^2/A, the square of the particle charge divided by its atomic weight. The conventional rating of the Phase I cyclotrons as a "500-MeV" machine means that it can maintain a heavy ion in orbit up to an energy of 500 MeV$\times q^2/A$. Alpha particles, for which $q^2/A = 1$, would then be able to reach 500 MeV, except that focusing problems prevent one from accelerating faster, lighter ions with the full 50-kG field. To achieve the highest possible charge states for the ions to be accelerated, a Philips ion gauge source at the center of the Phase I cyclotron produces a very hot, high-voltage gas discharge. It is the development of such ion sources over the past decade that has made possible the acceleration of heavy nuclear species.

The Phase I cyclotron will accelerate alpha particles to 80 MeV per nucleon. The beam energy per nucleon decreases with increasing atomic weight, falling to about 10 MeV per nucleon for copper. When Phase II



Beam intensity contours (ions/sec) for the Michigan State coupled-cyclotron accelerator, showing dependence on mass number and energy per nucleon. Threshold energies are indicated for nuclear compression waves and multimeson production. Collisions at about 200 MeV per nucleon produce twice normal nuclear density.

comes into operation in about four years, the beam of the 500-MeV cyclotron will be injected into the center of the 800-MeV machine through a stripping foil. The foil will strip off enough electrons from the injected beam to increase its charge state by a factor of two to four. The 800-MeV cyclotron will thus be able to produce beam energies of 200 MeV per nucleon for ions lighter than calcium. As the mass increases (ultimately one hopes to accelerate uranium), the beam energy falls to 20 MeV per nucleon.

The primary physics interest of heavy-ion beams at intermediate energies is the study of nuclear matter under conditions very different from those ordinarily obtaining in nuclei. By getting well above the Fermi energy (the typical energy of nucleons bound in a nucleus), one can circumvent the Pauli exclusion principle and achieve unusually high densities of nuclear matter for brief periods in collisions. It has been conjectured that nuclear matter may exhibit phase transitions at high density. In sufficiently energetic collisions of heavy ions one measures the bulk properties of nuclear matter: compressibility, tensile strength, thermal conductivity and the like.

Collisions at energies in the range of a few hundred MeV per nucleon are also expected to produce nuclei with neutron/proton ratios very different from the stable isotopes and their neighbors. There are expected to be about 5000 such nuclear species "far from stability" with lifetimes long enough to permit their study. They should provide an important test of current nuclear theory. "It's easy to calculate the first excited state of O^{20}," Benenson points out. "But can we get it right for O^{26}?" One may even be able to test astrophysical conjectures in the laboratory by briefly simulating the nuclear-matter density of neutron stars.

The Michigan State cyclotrons will also permit the study of nuclear deformations at very high spin. Furthermore, although the NSCL machines will be used primarily for heavy-ion physics, they will also accelerate alphas for the production of the recently discovered proliferation of giant nuclear resonances.

Other accelerators. The Berkeley Bevalac, with a maximum energy of 2 GeV per nucleon, has for years had a monopoly in the field of relativistic heavy-ion beams, where the physics is quite different from the intermediate-energy regime. It can get down to 50 MeV per nucleon, but beam quality at energies so far below its design energy has not been good. LBL is planning a major modification of the Bevalac vacuum system to improve performance at intermediate energies.

Oak Ridge is taking a different approach to the achievement of intermediate-energy beams. Its Holifield Heavy-Ion Facility consists of a large tandem Van de Graaff (built by the National Electrostatics Corporation) injecting into the old Oak Ridge ORIC cyclotron. The system will reach energies somewhat lower than the NSCL coupled-cyclotron configuration. But Oak Ridge should achieve higher beam intensities for low-melting point metals, Benenson told us, while Michigan State will have the edge for noble-gas ions. The Holifield Facility is just now becoming operational.

The old CERN synchrocyclotron has just completed its first year as a heavy-ion machine, accelerating carbon ions to 86 MeV per nucleon. The CERN group is hoping to get up to neon in the near future. Texas A&M is currently building a superconducting cyclotron similar to the NSCL 500-MeV machine, to serve as an afterburner for a smaller room-temperature cyclotron. The cyclotron group in Milan is building a superconducting cyclotron, while Dubna in the Soviet Union has opted for a large room-temperature heavy-ion accelerator. In Germany, Belgium, France and the Netherlands, advanced ion sources are being installed in existing cyclotrons, to bring them up to intermediate energies for heavy-ion beams.

—BMS

in brief

The shaping and polishing of the 2.4-meter mirror for the Space Telescope, scheduled for launch in 1985, has been completed at the Danbury (Conn.) facility of Perkin-Elmer. Production of the mirror blank began at Corning in 1977, using Corning's Ultra-Low-Expansion glass. □