a report on the International Conference on

SECTOR-FOCUSED CYCLOTRONS

By David J. Clark

THE conventional cyclotron, pioneered by Lawrence in the 1930's, is limited in energy by contradictory requirements for the magnetic field. To provide beam stability in the direction of the magnetic field, the field must decrease with radius. But to keep the beam in phase with a constant-frequency dee voltage, the field must increase with radius as the particle mass increases. In a conventional machine, the first requirement is satisfied and phase loss of the beam has limited the energy of protons from this first-generation cyclotron to about 15 MeV, but it has been pushed as high as 22 MeV by the Oak Ridge group.

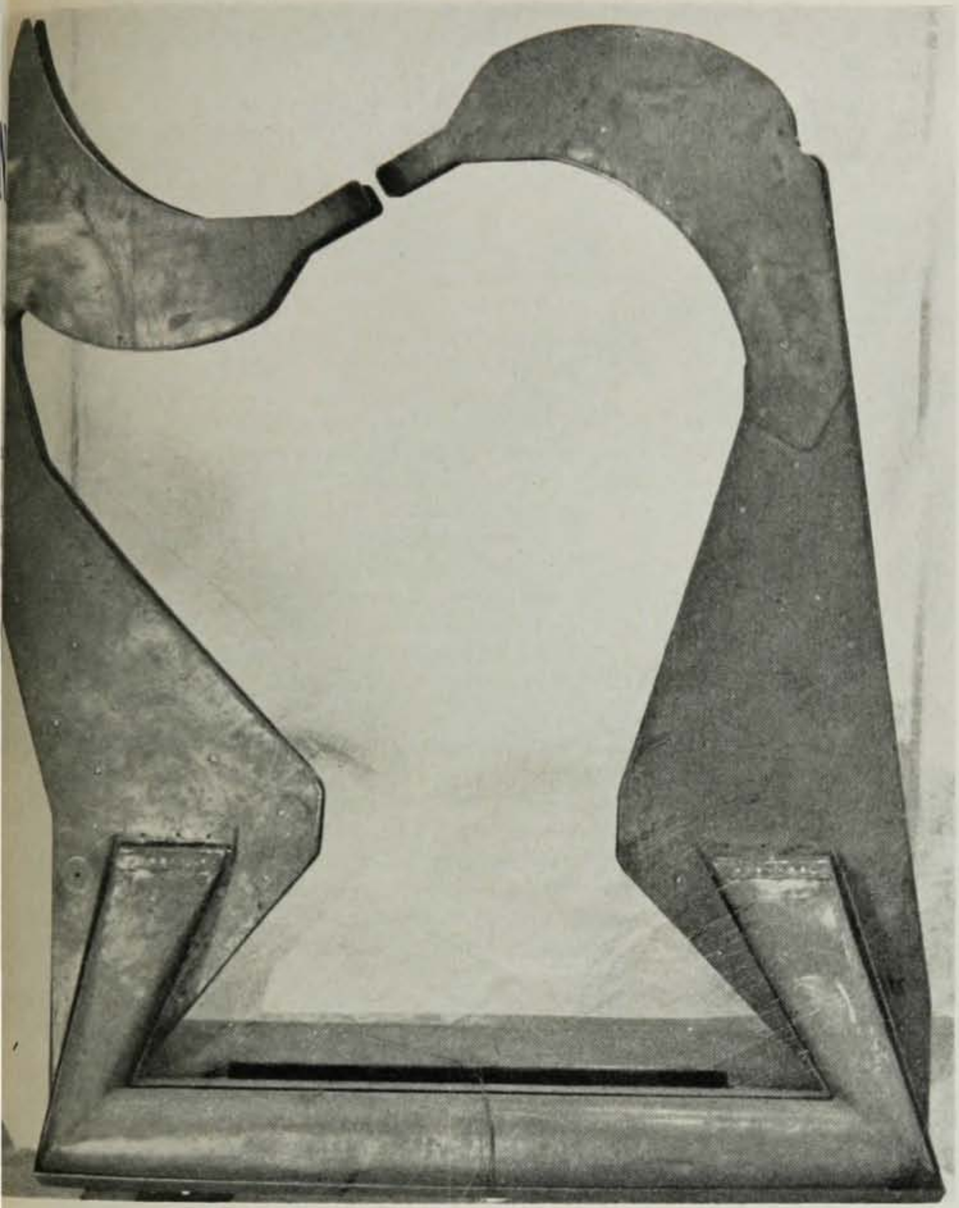
The discovery of phase stability by Veksler and McMillan in 1945 allowed the phase requirement to be satisfied by modulating the dee frequency. In this scheme, the particles automatically adjust to the proper phase while being accelerated. The maximum energy of the synchrocyclotron, the second generation of cyclotrons, is limited mainly by economic factors to around 700 MeV. However, the gain in energy is made at a sacrifice of beam intensity, since the synchrocyclotron operates on a duty cycle of a few percent of that of the conventional cyclotron.

As far back as 1938, a suggestion was made by Thomas [1] on how to satisfy both focusing and phase requirements and retain a 100-percent duty cycle. He suggested having a magnetic field which increased with radius to satisfy the phase requirement. The axial defocusing due to the rising average field would be compensated by strong and weak sectors of "hills" and "valleys" in the field, which would act like lenses to focus the beam axially. His idea was not used by cyclotron designers until 1950–52 when several 3-sector electron-model cyclotrons were built [2] at Berkeley. They used iron poles and accelerated electrons to $\beta = v/c = 0.5$, corresponding to 150 MeV protons. Thus, the third generation of cyclotrons, the sector-focused type, was born. In 1955, the Midwestern Universities Research Association (MURA) group [3] showed that spiral sectors would give more axial focusing than the straight sectors of Thomas. In 1957, the Oak Ridge National Laboratory (ORNL) put into operation a 4-sector Thomas-type electron-model cyclotron.[4] It was an air-core machine accelerating electrons to $\beta = 0.7$, corresponding to 350-MeV protons. Electron models clearly showed the feasibility of constructing high-energy proton cyclotrons. After 1958, when the first Thomas proton cyclotron was placed in operation at Delft, The Netherlands,[5] interest grew rapidly in this field and many laboratories throughout the world began planning the construction of sector-focused cyclotrons. The first of the spiral-sector variety of these machines came into operation at Dubna, USSR,[6] where a 6-sector machine accelerated deuterons to 12 MeV, and at Harwell, where 4-MeV protons were produced. The first spiral-ridge proton cyclotron in the US was operated at Illinois in early 1960 as a modification of their conventional cyclotron.

Ideas for the design and construction of spiral-ridge cyclotrons were shared at a Conference on Sector-Focused Cyclotrons in February 1959 at Sea Island, Georgia. Since that time, many laboratories have become interested in such machines, and it was felt that another conference would be useful. This year's International Conference on Sector-Focused Cyclotrons was sponsored by the International Union of Pure and Applied Physics and the University of California at Los Angeles and was supported by the US Atomic Energy Commission and the Office of Naval Research. Byron T. Wright, professor of physics at UCLA, was chairman of the Organizing Committee. The dates were set for April 16–20, 1962. Accommodations for the delegates were provided at Hershey Hall, a student dormitory on the campus. Here, private or double rooms were provided and meals were served during the conference. It was only five minutes' walk from the residence hall to the lecture hall in the chemistry building. The delegates numbered 178 scientists and engineers from fourteen countries.

The conference opened with a banquet on the evening of April 16 at the UCLA Faculty Center. This was an enjoyable affair preceded by a social hour, where newly arrived delegates from laboratories throughout the world could get acquainted and renew friendships. The after-dinner speaker was Arthur H. Snell, who presented a nostalgic and amusing talk, with slides, on "Recollections of the Radiation Laboratory". There were ten delegates in the audience who had worked at

The author recently received his PhD in physics from the University of California at Los Angeles. He is now at the Rutherford High Energy Laboratory, Harwell.



The work of art at left is the dee structure of the spiral-ridge cyclotron which was designed and built by physicists at the University of California at Los Angeles.

Berkeley with Lawrence in the thirties in what later became known as the Old Radiation Laboratory.

The conference sessions began the morning of April 17th, and continued with two sessions a day at 9:00 AM and 2:00 PM through the afternoon of April 20th. There were no concurrent sessions. A 20-minute coffee break in the morning and afternoon provided time for relaxation and discussion during the sessions. A free afternoon was scheduled on April 19th to allow an outing in the fine Southern California spring weather to such attractions as Disneyland, Marineland or the nearby institutions, the California Institute of Technology and the University of Southern California. The UCLA Cyclotron Laboratory, another five-minute walk from the lecture hall, was open for tours between sessions.

ON the first morning of the conference, there were reports on the design and operation of most of the currently operating sector-focused cyclotrons. J. R. Richardson described UCLA's fixed-energy, 49-inch, 50-MeV spiral-ridge proton machine which has been in operation since November 1960. Its cost was relatively low: $400 000 including materials, labor, building, and shielding, but no external-beam-handling magnets. Its interesting feature is its dee-in-valley design, described by K. R. MacKenzie later in the conference. The strange shape of the dee system (above) drew considerable interest among the delegates and MacKenzie said the present system may be entered in an art exhibit after a new high-power system is installed. This design allows a hill gap of only one inch producing 25 kilogauss there, and an average field of 19 kilogauss.

This design gives a maximum energy for a given magnet size but only 10-percent energy variation.

W. B. Powell talked about the 40-inch Thomas cyclotron at Birmingham which produces 11-MeV deuterons and heavier particles. It uses ion injection through a hole in the yoke at 10 kilovolts. The present beam current is about 50 microamperes. This type of injection would be very useful for acceleration of polarized ions. Powell also described phase measurements on the beam.

The preliminary operating characteristics of the Berkeley 88-inch spiral-ridge cyclotron were given by E. L. Kelley. This project followed its construction schedule very closely, beginning in January 1958. A beam was obtained in December 1961. It will produce variable-energy protons to 50 MeV, deuterons to 60 MeV, and heavy ions. During the tune-up period, the beam intensity is being held down to about 10 microamperes. Beam pictures, taken to evaluate the axial betatron frequency, were shown. Beam-phase measurements made by C. G. Dols were reported later in the conference. An interesting feature of the 88-inch cyclotron is the variation of radio frequency by moving panels, rather than by a movable short along the dee stem. This was reported by B. H. Smith in a later session. Richardson of UCLA mentioned some experiments he

D. Clark, A. Galonsky, R. S. Livingston, and J. R. Richardson mix machine talk and coffee.

and H. Willax of Berkeley tried on beam deflection on the Berkeley cyclotron. Using the available harmonic coils, all of the beam was deflected without axial loss, but quality was poor and azimuthal spread large since the coils were not at the optimum radius and no magnetic channels were used.

The next paper on the first morning was given by R. E. Worsham, describing Oak Ridge's ORIC. This is a 76-inch variable-energy, variable-particle spiral-ridge machine giving up to 80-MeV protons. This machine came into operation just before the conference on March 18th. Just as at Berkeley, the large amount of careful planning paid off with the beam being accelerated to full radius almost immediately. Currents of 250 microamperes have been obtained so far at maximum radius. The threshold dee voltage is 13 kV, indicating good trimming of the magnetic field and at least 450 particle turns. Phase measurements were made by W. M. White by a capacitive pick-up near the beam. As Worsham pointed out, this cyclotron is 90 degrees out of plumb with the rest of the world, having a vertical magnet gap, following the tradition of the 86-inch cyclotron at Oak Ridge. This design has the advantage of better mechanical stability of the dee. However, D. Judd pointed out that there is the disadvantage of external beam dispersion in two planes instead of one, after passing through bending magnets.

Next came a description of the University of Colorado's 52-inch variable-energy spiral-ridge machine. It will accelerate 30-MeV protons and 20-MeV deuterons. This cyclotron just made it under the wire by producing a beam about a week before the conference. But in that week some amazing results were produced. J. J. Kraushaar described the "early period" of operation. The beam came to maximum radius with only a factor-of-2 loss in intensity. M. E. Rickey told of the events in the "later period" of operation. A 1-microampere beam of negative ions was accelerated to full radius, then stripped of electrons by an aluminum-oxide foil, and brought outside the magnetic field. R. Smythe "accentuated the negative" by putting a block next to the source to stop positive ions. Some stripping cross section calculations made in 1956 by B. T. Wright of UCLA had indicated that acceleration of negative ions to modest energies is feasible. The Colorado group is the first to exploit successfully the acceleration of negative ions. The success depends partly on having a good vacuum in the machine, 10^{-6} mm or less being desirable.

This development produced much discussion among the delegates. It provides a simple method of solving the extraction problem, which gets increasingly difficult at higher energies and beam intensities. Apparently, the only fundamental limitation on this idea is the break-up of H^- ions caused by $\mathbf{v} \times \mathbf{B}$ forces of the magnetic field at high fields and velocities. For example, an evaluation by D. Judd [7] shows that, at 25 kilogauss, break-up will occur at approximately 50 MeV. At the energies which meson factories require, the break-up field would be quite low, and the magnets would, therefore, be very large. However, for the majority of spiral-ridge cyclotrons operating or planned, this $\mathbf{v} \times \mathbf{B}$ break-up would not be troublesome. This concluded one of the most interesting sessions of the conference.

In the afternoon session and those on following days, many other ideas were described both by those who are planning cyclotrons and by those having operating machines. Many of the ideas were mentioned recently in *Physics Today*.[8] There were 56 oral papers and 15 more submitted for inclusion in the Proceedings, which will be published as an issue of *Nuclear Instruments and Methods*. Twenty-two laboratories were represented in the papers. Only a few of the ideas which were not included in the previous article will be mentioned here.

Verster talked about the Philips variable-energy, vari-

Delegates to the 1962 International Conference on Sector-Focused Cyclotrons

able-particle machine to be completed in 1963 for Saclay. It will give 25-MeV protons. A floating-wire technique was used to find the magnetic median plane within 1 mm. The cost is approximately $1 million.

K. G. Standing told of his "red-hot" shims, a method of adjusting the magnetic field in the Manitoba cyclotron. He plans to use shims of invar on the poles. Each shim group will be heated to several hundred °C by internal piping. This will vary the permeability and thus control the magnetic field in the vicinity. Standing feels that this type of arrangement will be more efficient than the conventional current-carrying coils.

J. D. Lawson of the Rutherford High Energy Laboratory at Harwell, England, described some studies on a projected 70-inch variable-energy, variable-particle cyclotron. The maximum proton energy would be 50 MeV. Studies are being made on electrostatic regenerative extraction.

There were a number of papers on orbit theory and computer techniques. The active group at Michigan State, under H. G. Blosser and M. M. Gordon, showed the results of extensive computer runs on orbit stability and magnetic-beam extraction. H. L. Hagedoorn of Philips and F. Fer of Orsay talked on orbit theory. R. N. Bassel of Oak Ridge described programs used in the design of ORIC. A. Garren of Berkeley discussed trim-coil settings and electrostatic-deflector calculations. N. F. Verster talked about computer programs at Philips and G. Parzen described a MURA program to study orbit stability. These theoretical studies, many using high-speed digital computers, are extremely important in predicting beam characteristics in possible magnetic-field configurations during the design stage.

There was a session on the central region where the combination of electric and magnetic fields makes exact computer analysis rather difficult.

On April 18 and 19, there were sessions on "meson factories". J. R. Richardson, the chairman of the first session, outlined the scope of the topic. He pointed out that the energy range to be discussed would be 25–1000 MeV and the intensities would be 100 to 10 000 times those presently available, or up to a milliampere of beam current. The questions to be answered are:

(1) Do the likely research results justify construction?
(2) How does the AVF cyclotron compare with other accelerators?
(3) What are the broad features of the design?

R. P. Haddock of UCLA opened the sessions with a summary of the present data on meson production. He then noted a number of experiments which would require AVF cyclotron beam intensities.

Next, L. Smith of Berkeley talked on comparison of accelerator types. In his opening remarks, he noted that 800 MeV would be much better than 400 MeV for π-meson production and that less than 10 microamperes of current should be allowed to produce activity within the machine. He then gave a very interesting comparison of accelerators which could compete with AVF cyclotrons as meson factories. He pointed out that the

FM cyclotron can produce 10 microamperes of 600–800-MeV protons and the duty cycle possibly can be increased to 100 percent by stochastic modifications. But extraction is difficult. The alternating-gradient synchotron will give 10 microamperes at a 10-percent duty cycle at a cost of 7 or 8 million dollars for a 700-MeV machine. Here, extraction is relatively easy. The FFAG type of machine would produce 100 microamperes. A 750-MeV machine would cost about 10–12 million dollars, but extraction is very difficult. The AVF cyclotron would give 100–1000 microamperes at 100-percent duty cycle and extraction is again difficult. There, the cost would be about 5 million dollars for 400 MeV and 10–12 million dollars for 800 MeV. Last, Smith mentioned the linear accelerator, which he said is capable of producing 100 microamperes at a 1–10-percent duty cycle. The extraction, of course, would be trivial. A linac would be the most costly of the group, at about 15–17 million dollars for 800 MeV.

R. Wallace of Berkeley considered shielding and activation problems in meson factories. He assumed 100 microamperes of 600-MeV protons in the external beam. Thirty-five feet of concrete would be needed to reduce the radiation to the industrial tolerance level 50 feet from the target during operation. Problems associated with activation of the machine and its surroundings are severe, but not insoluble.

The plans at ETH in Zurich were discussed by J. P. Blaser. They would work with AEG in Germany to build a 6-sector 430-MeV machine. They plan to use two 90-degree dees operated on the second harmonic of the particle frequency. N. Vogt-Nilsen discussed CERN's studies on a 6-sector meson factory. The Oak Ridge design for an 800-MeV meson factory was presented by R. S. Livingston. The energy would be chosen so that the $v_R = 2$ resonance would occur at the extraction radius so the beam could be deflected magnetically. According to calculations by Gordon and Welton, a 4-cm turn separation could be obtained for extraction after 14 turns in a perturbing bump.

The AEG thinking on a 400–450-MeV machine was explained by W. Müller. In this energy range, 6 sectors would be desirable since, with 3 or 4 sectors, important resonances occur at 190 MeV and 240 MeV, respectively. A transition to 3 sectors near the center could be made to provide more flutter there. The cost was estimated at 5–6 million dollars.

J. R. Richardson described some of his ideas on a conceptual design. For a 700-MeV machine, the center field would be 6 kG. The dee-in-valley system is used, with the dees extending over the hills in the central region. An interesting feature is that no return path would be used in the magnet yoke.

The Oak Ridge electron analogue of an 800-MeV proton cyclotron has been in operation since August 1961. It was described by J. A. Martin. Its field of 41 gauss is provided by an iron-free coil system. The beam has been accelerated through the $v_R = 2$ resonance, a ticklish operation. A total of 2600 particle turns has been obtained, compared to only 800 necessary in the proton-machine proposal. R. J. Jones made some interesting remarks on a knob-twiddling experiment on this machine. The 29 circular coils and 8 sector coils were placed at random settings by Martin. Then Jones came along and proceeded to tune up the cyclotron by knob-twiddling and watching a beam-current meter. This took about 8 hours to get the beam to full radius, and demonstrated that tune-up could be accomplished without the help of computer calculations.

During the session on "diverse topics" on April 20th, R. J. Burleigh of Berkeley gave an entertaining talk on cost and manpower estimates for the 88-inch cyclotron. He pointed out that, in estimating the cost of a project, one should use as a guide the cost of similar projects in the past, and then allow for increases in prices since that time. However, many people prefer the "factor method", according to which one computes a "reasonable price" and then multiplies by a suitable factor, such as 2, 3, or e. This is often a successful method, because everyone knows that a project cannot be built for a reasonable price.

There were several informal evening sessions covering related topics. W. M. Brobeck chaired a session on radiation-damage problems inherent in these high-flux cyclotrons. The Berkeley 88-inch cyclotron uses metal gaskets for the less accessible seals because of the greater resistance of inorganic materials to radiation damage. L. C. Teng of Argonne led a group discussion on polarized ion beams.

L. Rosen of Los Alamos was chairman of a third session on planned experiments with the new sector-focused cyclotrons. Many experiments were mentioned in the energy range of 10–100 MeV. There are the nucleon-nucleon experiments, including *p-p* and *n-p* scattering and the many types of polarization experiments which will become practical with the high beam intensities expected. Then there are nucleon-nucleus elastic and inelastic scattering and reactions, especially involving polarized beams or targets. Heavy-ion work can also be done with many of the versatile cyclotrons coming into operation. Nuclear spectroscopy will also be important, with the emphasis on high-precision determination of energy levels.

There was general feeling at the conclusion of the conference that a large amount of design and construction work on sector-focused cyclotrons has been completed and much is yet to come. Of 41 projects brought to the attention of the conference, 11 machines are in operation, 12 more under construction, and the remainder in various stages of planning and design.

References

1. L. H. Thomas, Phys. Rev. **54**, 580 (1938).
2. E. L. Kelley, et al., Rev. Sci. Instr. **27**, 493 (1956).
3. K. R. Symon, et al., Phys. Rev. **103**, 1837 (1956).
4. H. G. Blosser, et al., Rev. Sci. Instr. **29**, 819 (1958).
5. F. A. Heyn and K. K. Tat, Rev. Sci. Instr. **29**, 662 (1958).
6. V. I. Danilov, et al., Proc. Int'l Conf. on High-Energy Accelerators, p. 221, CERN, Geneva (1959).
7. D. L. Judd (private communication).
8. A. I. Yavin, Physics Today, May 1962, p. 19.