THE AVF CYCLOTRONS

An informal account of one physicist's European and North American tour in search of first-hand information on a new breed of medium-energy cyclotrons

By ***Avivi I. Yavin***

HAVING recently completed an eight-week trip to AVF (Azimuthally Varying Field) cyclotrons, I have found that many people are greatly interested in this field. Many laboratories are either discussing the attractiveness of medium-energy accelerators or are already debating what kind to get and how to go about it. Unfortunately, there is insufficient direct cooperation among the various laboratories, and up-to-date information on accelerator subjects is rarely found even in print. I hope therefore that the present report on my trip may serve as a guide to cyclotron physicists, and bring the subject to the attention of physicists generally, some of whom may, sooner or later, be faced with the issue of obtaining AVF cyclotrons for their laboratories.

What is an AVF cyclotron, and in what respect is it different from the "conventional" cyclotron? The condition for acceleration of ions with mass m and charge e in a cyclotron is that the frequency ν_{rf} of the accelerating voltage on the "dees" is made equal to the frequency ν_i of the circulating ions in the magnetic field B. This so called "resonance condition" is given by $\nu_{rf} = \nu_i = eB/2\pi mc$, where c is the speed of light. Since $m = m_0/(1 - v^2/c^2)^{\frac{1}{2}}$ where m_0 is the rest mass of the ion and v its velocity, B should be made "isochronous", that is,

$$B(r) = \frac{B(0)}{(1 - v^2/c^2)^{\frac{1}{2}}}.$$

On the other hand, focusing in the axial direction (the direction perpendicular to the plane of motion) requires that $\partial B/\partial r < 0$. The two requirements are obviously incompatible, since, for an isochronous field, $\partial B/\partial r > 0$. This incompatibility sets a limit to either the energy or the intensity of the conventional cyclotron. Whenever a high intensity is required, the cyclotron is built as a CW (continuous wave or fixed frequency) machine and $\partial B/\partial r$ is set negative. This allows simultaneous acceleration of many groups of ions separated by a time interval $1/\nu_{rf}$; however, in each turn the ions suffer a phase lag, and at a specific turn they reach the energy in which this phase lag is 90° and acceleration stops. For a high energy requirement, the cyclotron rf frequency is modulated to follow the relativistic increase in mass, but the intensity of these frequency-modulated cyclotrons is severely reduced, since only one group of ions can be accelerated for each cycle of the modulation.

A high-intensity and high-energy cyclotron was proposed in 1938 by Prof. L. H. Thomas, who suggested the separation of the isochronism condition from the focusing condition, requiring the radial dependence of B to satisfy only the isochronism condition. He proposed to achieve axial focusing by the introduction of azimuthal variation in the magnetic field. Since the orbit of an ion moving in an azimuthally varying field is scalloped rather than circular, a radial velocity component appears and interacts with the azimuthal component of the magnetic field in the region between the strong and weak fields. The resulting axial force is always directed towards the median plane, so that axial focusing is achieved. An azimuthally varying field cyclotron is sometimes called a sector-focused or strong-focusing or FFAG (fixed field alternating gradient) cyclotron. Additional axial focusing can be obtained by making the magnetic sectors spiral, and the cyclotron is then called spiral ridged.

A national committee composed of physicists has proposed the setting up of an AVF cyclotron in Israel. The author was charged with finding out what has been already achieved with regard to beam characteristics of AVF cyclotrons, and what is expected in the future. The committee also wanted to know costs and

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whether it was advisable to design and construct the machine in Israel, or whether it was preferable to purchase it abroad, and if so, where.

The account which follows describes my findings on a trip to cyclotron centers. Unique observations made in each laboratory will be emphasized rather than a general coherent picture presented.

ON such a trip one is interested in examining in each laboratory the essential parameters of the machine (e.g., energies, particles to be accelerated, profiles and azimuthal behavior of the magnet, rf design, power consumed) and also the initial cost and operating budget and the time schedule. One also hopes to get answers to questions such as: Why did you decide on a cyclotron and not, say, a Van de Graaff? Why did you decide on your particular model? Are you satisfied now with your choice and progress? If you had to start all over again, what would you do differently? Before one asks these questions one probably has the feeling that people will not be too happy with their choice and progress, and that given a second start would make several new choices. It was therefore both surprising and gratifying that except for one laboratory in which the director was not sure whether his choice of number of sectors was best, all other laboratories were happy with their choice and progress, and, given a second start, would build essentially the same machines. One shrugs away thoughts about the need to exercise objectivity and feels that this proud and contented attitude indicates that cyclotron physicists enjoy their work and that most AVF machines are going to be good.

In talking to so many people in this one line of work one wondered how they felt about other projected machines. Being faced with the need to recommend one or two models (and perhaps one or two firms to build the selected model), the question is very significant in this context. Most people felt that all machines being constructed now were going to operate well, but seemed to reserve the highest praise for the amount of design and model work which has gone into the 88-in cyclotron in Berkeley.

Another point to be considered is the question of what help one might expect from the laboratory whose machine will be copied. Here, opinions were unanimous. Practically everybody offered all possible help, ranging from blueprints to engaging our people to enable them to gain experience. In some cases it was even proposed that we should move to the offerers' laboratory site and construct a machine alongside theirs. What better indication of scientific cooperation is needed?

The first lap of the tour carried me to the Federal Institute of Technology, in Zurich. Here in ETH I found that Prof. J. P. Blaser's group is planning to construct a 450-Mev CW spiral-ridge cyclotron which will provide an intense beam of pions. Prof. Blaser will probably have a commercial company construct most of the machine for him, but his group will assist in the design. The cyclotron will probably have one dee and he thinks it will be placed in the valley between ridges. The unique feature is the design of the yoke. It is expected to be 1 m thick and will extend 360° so that the whole magnet, including the pole pieces, will look like a symmetric fountain or an "anti-doughnut". The yoke will also serve as a vacuum chamber and a radiation shield. With all the ingenuity of the idea one somehow has the feeling that it would be rather hard to get to the center of the machine to do field measurements, or even to fish out a screw which is liable eventually to drop there from somewhere. I believe that CERN is considering converting their 600-Mev synchrocyclotron to a 450-Mev CW machine. If and when both projects materialize, Switzerland will no more be known as the land of the Alps, but as the land of the 450-Mev CW cyclotrons.

The Philips Company of Eindhoven will shortly deliver a 25-Mev cyclotron to Saclay. Prof. J. Thirion, who is in charge of the cyclotron project at Saclay, believes that the machine is going to perform well. A lot of time is devoted meanwhile in the cyclotron laboratory of Saclay to polarized-ion sources, and when this is achieved this laboratory will be among the first in the world to couple such sources to a cyclotron and accelerate polarized ions. The unique feature which strikes one when one looks at the Philips design is the grounding of the dees with "spiders" outside the vacuum. One should note that 25-Mev cyclotrons might soon have to compete with 20–30-Mev tandem Van de Graaffs which are rushing over the horizon.

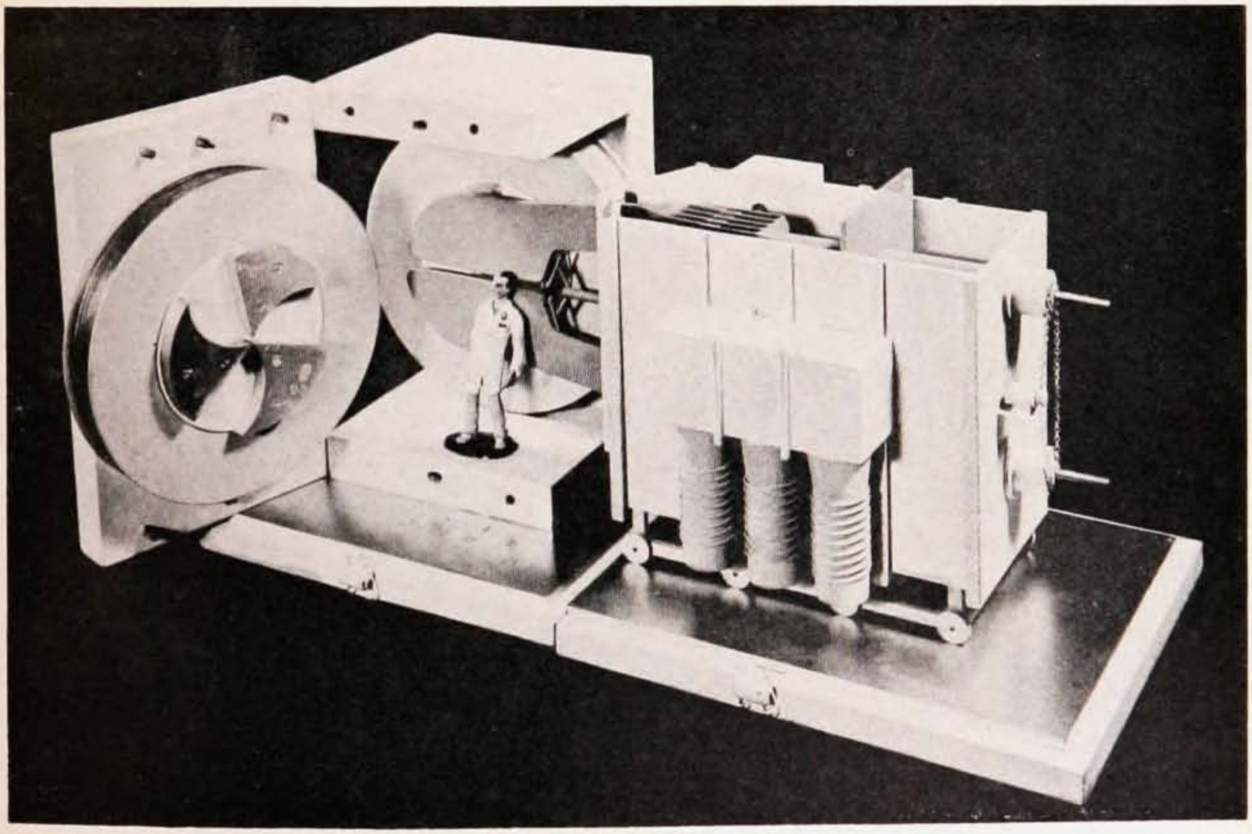
At Orsay one is impressed by the large number of accelerators ranging from a 300-kev positive-ion accelerator to a 1-Bev electron linear accelerator. People at Orsay are now planning to add two AVF cyclotrons to their 1937 "conventional" cyclotron. The one AVF machine, under the direction of Prof. M. Langevin, will accelerate light ions (protons up to 20 Mev) and will be ready by 1964; the other, under the direction of Prof. Cabrespine, will be a 2-m diameter heavy-ion accelerator (N^{4+} from 13 Mev to 90 Mev) and will be ready by 1963. There is an interesting and unique piece of design in the pole pieces of the 2-m cyclotron. Ni-Fe alloy will be used at small radii, and then will be gradually changed to Fe and finally to Fe-Co alloy. Calculations indicate that it would be possible to vary the profile of the field this way, using the various degrees of saturation of the alloys to achieve required isochronous fields at all energies. Fine adjustments will be made with valley coils.

A trip to Delft and Prof. F. A. Heyn's accelerator laboratory is an unforgettable experience. In one corner of a hall one sees a Thomas cyclotron, probably the first Thomas cyclotron which worked. Mainly due to small dee-voltages, no beam is extracted. Although the cyclotron is a CW machine, it is pulsed in order to reduce the beam and lower the background. In the main part of the hall one sees a 1-Bev proton synchroton which, it must be admitted, is the prettiest synchroton yet seen. This machine was built under Prof. Heyn's direction for the purpose of educating students in accelerator physics. It is very inexpensive, but unfortunately there is not much room around the machine for experiments.

The Karlsruhe Institute in Germany is having a three-sector Thomas cyclotron built by AEG. The very unique feature of their machine is that it has three dees connected at the center. Among other advantages, this design allows for three simultaneous ion clouds in each turn and it improves the duty cycle of the machine. The machine will be tuned with a servomechanism which senses the phase difference between the pulse of the ions and the rf voltage of the dees. It is a constant-energy 50-Mev deuteron cyclotron.

I left Europe after learning about quite a few other laboratories which were trying hard to get money to build cyclotrons. Upon arriving in the United States, I found in Washington that there were three laboratories in that area which wanted AVF cyclotrons.

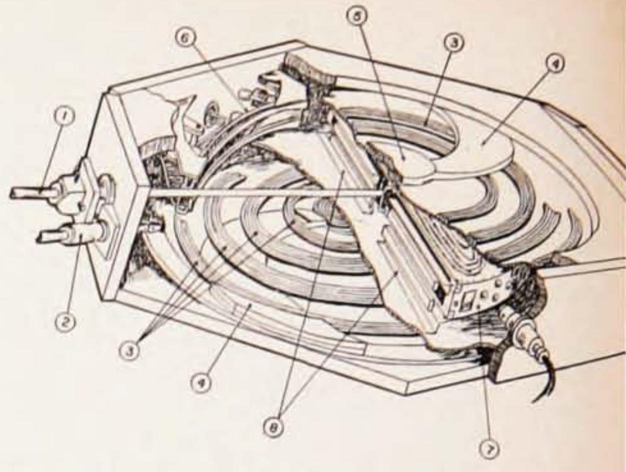
Oak Ridge National Laboratory already has two cyclotrons: a 63-in machine which accelerates mostly heavy ions and uses one of the many calutron magnets, and an 86-in proton cyclotron which accelerates protons to 23 Mev and probably is the most effective machine in the world for isotope production. The laboratory has proposed the acquirement of an 850-Mev CW cyclotron for protons, and work is being done on an electron model to investigate crossing of resonances and extraction. About three years ago, the laboratory undertook to build the ORIC (the Oak Ridge relativistic isochronous cyclotron). Dr. R. S. Livingston, who is among other things also the director of the project, is certain that they are building the best possible machine for the given 76-in magnet. The machine, which is almost completed, will accelerate various light and heavy ions (protons up to 75 Mev) and will be a powerful research tool. Three rather than four sectors were chosen in order to bring the AVF focusing closer to the center, and the magnetic field changes azimuthally from 8 to 22 kilogauss. Part of the azimuthal variation of the magnetic field (flutter) is achieved by valley coils, although it seems that ridge coils would be more efficient. This is not a spiral-ridge machine in the usual sense, and the curvature of the sector edges, or rather the flaring out of the ridges, is used to achieve the radially increasing magnetic field (when averaged over the azimuth). The amount of model work and field measurement is very impressive and the building is beautiful. The laboratory will have every experimental facility which a physicist might want, and one sees that it is well planned. When one thinks



Model of ORIC, the relativistic isochonous cyclotron at Oak Ridge National Laboratory, showing the three-sector magnet pole tips and the dees with one of the resonant circuits.

of the design, one feels that the Oak Ridge group is very ambitious in trying to get 75-Mev protons out of a 76-in magnet and also have the possibility of accelerating heavy ions, but the impression is given that the goal will probably be achieved after a reasonable amount of struggling. (It should be noted also that a trip to Oak Ridge is usually very gratifying. It involves a visit to an interesting scientific laboratory, located in a beautiful part of the country, and having in it not only good scientists, but also very hospitable ones!)

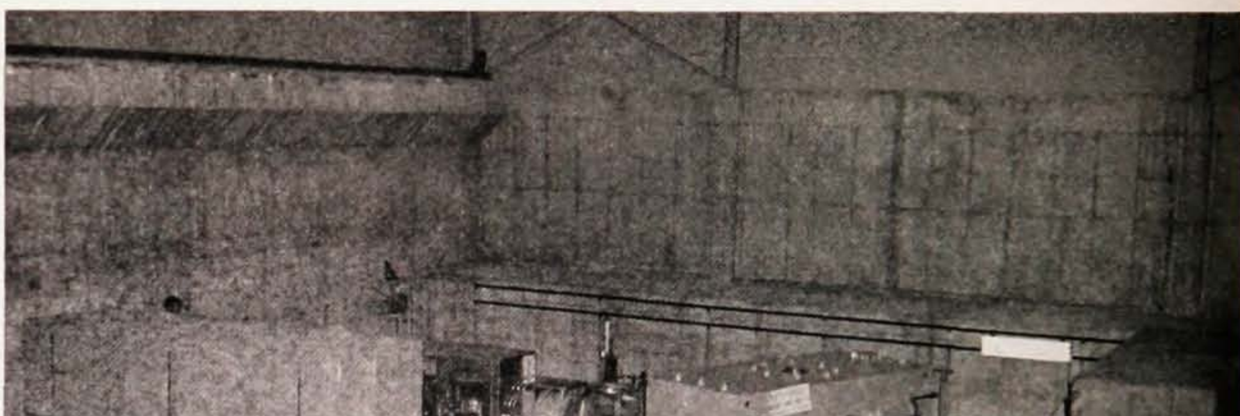
The Illinois cyclotron has been remodeled under the direction of Prof. J. S. Allen and is now a four-sector spiral-ridge cyclotron. It already accelerates protons, deuterons, and alphas with a maximum energy for protons of 15 Mev. The internal beam reached 3 ma at extraction, but this beam was too much for the deflector-septum, so lower internal beams are used, and out of 200 μa of circulating beam are extracted 40 μa. The energy can be easily varied over a range of 6–12 Mev, the changes being made in few minutes from the control room. The beam has been shown to be very well focused vertically, with a vertical focusing frequency equal to that predicted in preliminary design calculations. The cyclotron has one dee and a dummy dee, and five concentric trimming coils. There is a beam-analyzing magnet in the external system and a



Cutaway view of the acceleration chamber of the University Illinois cyclotron, showing (1) ion-source assembly, (2) b probe, (3) field-correction coils, (4) spiral shims, (5) iron dis the center, (6) electrostatic deflector, (7) dee, and (8) dummy

broad range magnetic spectrograph installed on a 5-in gun mount for energy analysis of reaction particles.

The University of Colorado is completing now a four-sector spiral-ridge cyclotron which will accelerate protons up to 30–35 Mev. Prof. D. Lind, the director, feels that it will be a good machine, and there is little doubt that he is right. The unique feature is the design of the water-cooled coils which are imbedded



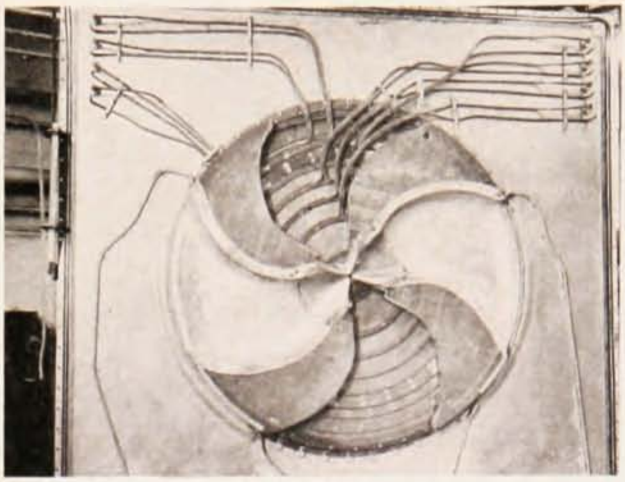
The low-energy, four-sector, spiral-ridge cyclotron at the University of Colorado at Boulder. Bird's-eye view at a late stage in the construction shows the arrangement of some of the installed shielding in the cyclotron area.

in the shims. The Colorado group made a thorough study of the first few turns of the beam, and are probably going to use electrostatic deflection at least in the beginning. The septum will be made of copper with tungsten sprayed on it. The acceleration is against the spirals, and close to the extraction radius Prof. Lind is planning to add some iron near the median plane. This will help increase the amount of isochronism and will reduce the sudden increase of the axial-focusing frequency due to the fall off of the magnetic field. It will also help extraction by making the fall off of the fringing field steeper. The machine is elevated, and the external beam is far from any heavy concrete structure to lower the neutron background. One of the most attractive features of this machine is its modest price. The whole machine plus buildings and equipment cost less than $2 million. The energy is low and there is some danger that in a few years tandem Van de Graaffs will compete with it strongly.

Shown above are three of the four spiral shims designed for the University of Colorado cyclotron.

It is a pleasure to visit the new UCLA cyclotron and see how Profs. R. Richardson, K. MacKenzie, and B. Wright can build a very inexpensive constant-energy AVF cyclotron with the help of only two students and two technicians, and no engineers. Many components are home made. The machine has two dees in the valleys between the spiral ridges. This allows for four accelerations per turn and requires less power. The gap is very small and the field very high (up to 25.5 kgauss in the ridges). A lot of thought and ingenuity has gone into the design; if one wants to find exact drawings one is referred to the University of Manitoba or to Berkeley, since people from these two laboratories came down to Los Angeles and made the only complete set of drawings of the machine.

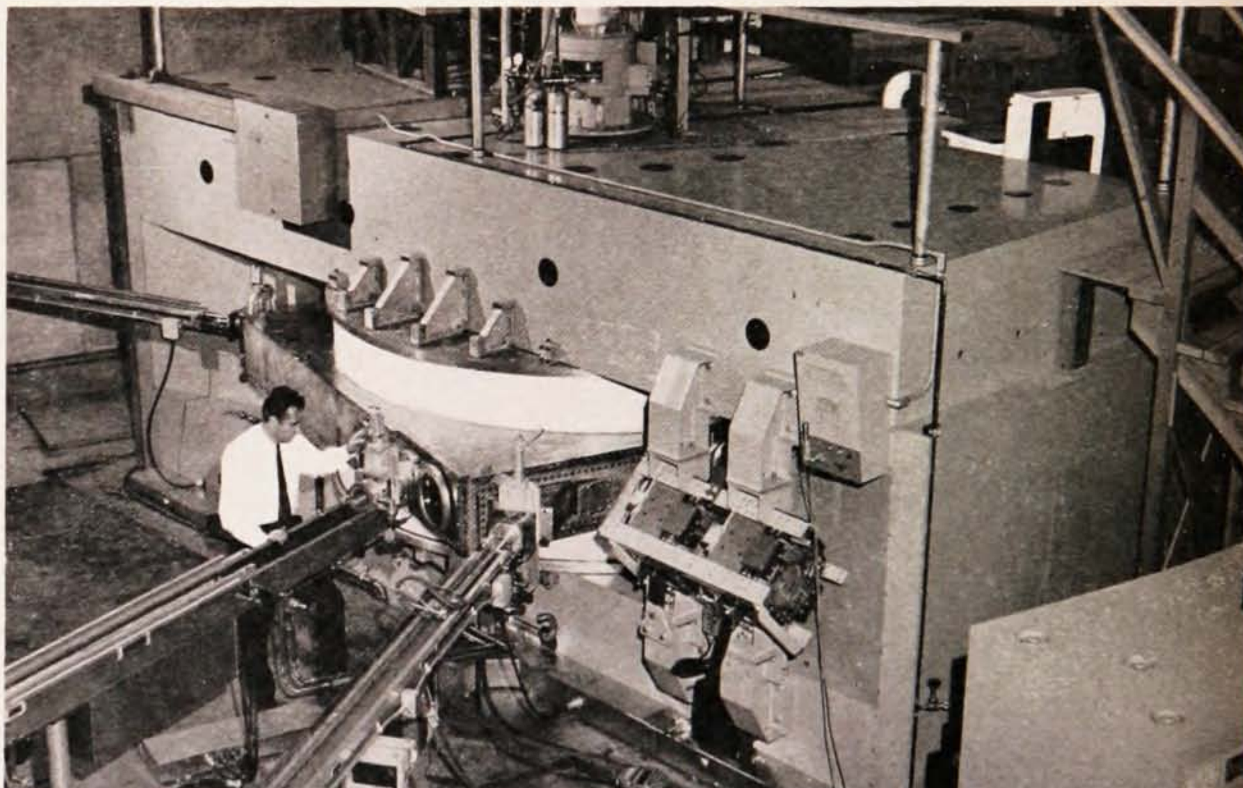
Physicists Byron T. Wright and J. R. Richardson are shown above with the constant-energy AVF cyclotron which they and their colleague Kenneth R. MacKenzie designed and constructed at the University of California at Los Angeles.



At left, a view of the four spiral shims used in the acceleration chamber of UCLA's recently completed machine.

The spirit of optimism is well reflected by their proposal for extraction. The DGIIW method is proposed. For those who do not know the meaning, they explain: "Don't Get In Its Way!". The machine is low in intensity and constant in energy, so its use will be limited to some extent, but its builders are justifiably proud of their contribution to the art.

The Lawrence Radiation Laboratory is now completing the 88-in spiral-ridge machine. It is a well-designed and powerful machine, and is expected to be one of the best in the world. Over one million dollars have already gone into engineering design and computation, and recent field measurements indicate that the computer can predict the necessary field to a great accuracy. This is a single-dee (no dummy dee) machine, with three sectors. The energy is varied easily and continuously. It was designed to yield up to 60-Mev deuterons, and this energy was chosen to allow production of all isotopes with long enough lifetime to be detected. Unfortunately, the machine will accelerate protons only up to 50 Mev, mainly because of lack of flutter, although the magnetic rigidity is adequate for 115 Mev. This can be improved by an additional expenditure of several hundred thousand dollars, but this expenditure has not yet been approved. There are many unique and well-



The 88-inch spiral-ridge cyclotron at the University of California's Lawrence Radiation Laboratory in Berkeley. Elmer Kelly, physicist in charge of the machine, is shown at left in this LRL photograph, which was taken last January.

engineered features of this machine, such as the use of water-cooled coils made with an insulator sandwiched between two concentric copper tubes, or the use of large metal gaskets. Other features worth mentioning are the mercury diffusion pumps, which will eliminate formation of oil films on targets, and the unique rf system which will allow changing the frequency without moving "spiders". The computing team at Berkeley has recently had several successes outside their laboratory. It was able to find the reasons for two blowups of the beam in UCLA, which were then easily cured. One of the blowups was caused by a large first harmonic, which increased the radial oscillations into the region in which the axial-focusing frequency was half the radial one (the Walkinshaw resonance), and the other was caused by the large second derivative of the flutter.

The state of Michigan has an AVF cyclotron being constructed under the direction of Prof. W. C. Parkinson in the University of Michigan, and another AVF machine is proposed by Prof. H. G. Blosser for Michigan State University.

The University of Michigan machine is an 83-in spiral-ridge cyclotron. It is constructed to act mainly as a deuteron machine for the energy interval 15–40 Mev. Most of the effort was put into getting a well-resolved beam, and this is reflected in the proposed budget, in which the expenditure for the machine proper is expected to be only fifteen percent of the total cost. The cyclotron has two dees with four dee-stems, so that a half-wave mode is formed. The external system consists of five magnets: a cascade of two magnets precedes the target and a cascade of three magnets is used to analyze the reaction particles. A highly resolved beam is expected to impinge on the targets and the design calls for an energy resolution of 10^{-4} for the reaction particles. The AVF cyclotron will be housed in one wing of a U-shaped building; the other wing will house the old cyclotron which will be moved from its present location at Randall Hall.

Michigan State University has an interesting proposal and an excellent team headed by Profs. Blosser and M. M. Gordon, but up till now they have not been able to get money for the machine. Most cyclotron physicists hope that they are given a chance to build their machine, since a tremendous amount of original work is put into the design. The MSU team deserves credit for developing the system of resonant extraction and fitting it theoretically to AVF cyclotrons. In their laboratory, they do model work and calculations, and are generously willing to help other laboratories with field-shape and extraction problems. They seem a little optimistic when they talk about getting a 3-ma extracted beam with $\Delta E/E = 1/1500$, but they feel that they are right and their computations support their expectations.

Prof. K. Standing in Manitoba is constructing a UCLA-type cyclotron at very moderate cost. It will be mainly a proton cyclotron, accelerating protons to energies from 12.5 Mev to 50 Mev. His group is considering varying the energy by changing the pole pieces, but is not yet sure that this method will be used. The general feeling is that the Manitoba cyclotron will be an inexpensive but powerful machine and one which is appropriate for small universities.

MANY other laboratories are planning to obtain AVF cyclotrons. In the United States, I heard of proposals for such machines at Argonne National Laboratory and the Naval Radiological Defense Laboratory; in Europe, physicists at Grenoble, Milan, and Groningen are interested. There are people who want to build a cyclotron in North Africa, and in Australia, and national committees in Japan and India have proposed national cyclotrons for their respective countries. There are also several machines which are either constructed or planned in Russia, and perhaps also others of which the author has not yet learned.

There are at least five firms which are interested in constructing AVF cyclotrons. They are: CSF in France; Philips in Holland; AEG in Germany; and Brobeck & Associates and Hughes Aircraft in California.

Despite the great efforts being invested in AVF cyclotron construction and design, there are still many unsolved problems in the field. Among the many problems which still have to be satisfactorily solved, five will be mentioned here:

1. The control of the phases of the ions injected from the ion source.
2. The stabilization of the cyclotron parameters and especially the dees voltage to achieve constant orbits.
3. The problem of extraction.
4. The development of sources of polarized ions and the coupling of such sources to the planned cyclotrons.
5. The improvement of the poor (1%–5%) duty cycle which is caused by ion bunching and extraction conditions.

The great interest in AVF cyclotrons, as well as the large number which are already in various stages of construction, seems to call for cooperation and coordination. This is especially true because of the large expenditure involved and because of the many unsolved problems which still exist. An international conference on sector-focused cyclotrons was held in February 1959 in Sea Island (see *Sector Focused Cyclotrons*, Nuclear Science Series, Report No. 26, by F. T. Howard) and a second conference is planned for April 1962 at UCLA. However, I feel that the situation calls for more explicit efforts and more formal cooperation. One possible avenue would be the establishment of a regular summer school. Another would be the creation of an international center for cyclotron studies, to be located preferably in a laboratory which will soon have an operating AVF cyclotron. Either or both of these avenues would provide for the continuous and coordinated efforts to improve the performance of AVF cyclotrons.