SESSION I: ORBIT CALCULATIONS AND MAGNETIC FIELD DESIGN

SUMMARY

It is not possible to give a simple and concise summary of the information presented at this first session for several reasons. The session was long, and a great variety of topics were covered, some of which were essentially experimental and therefore not directly related to field design and orbit calculations. The discussions were vigorous and far-reaching, a circumstance which greatly increased the usefulness of this session to the participants. It is hoped that the account which follows will assist the reader to locate the material in which he may be interested amongst the fourteen papers, and the numerous remarks in three discussion periods, that together comprise the published record of this session.

The first four papers, broadly speaking, dealt with general problems and discussed them in general terms. Richardson described a simplified approach to the problems of orbit theory in relatively small machines, which avoids the complexity of resort to a digital computer but yields reasonable accuracy for most purposes. He illustrated his results by describing the UCLA design for a 50-Mev proton cyclotron of four-fold symmetry with high magnetic field (up to 25 kg) and small magnetic gap. A point of special interest was his consideration of the correction of errors in phase in an optimum way by use of a minimum number of concentric trimming coils on the pole faces. Powell next presented a similarly simplified discussion of orbit properties in the Birmingham radial-sector cyclotron which had a similarly small gap but a lower magnetic field (up to 19 kg), together with a description of the principal features of this machine. Cohen's discussion concerned the line of reasoning used at Oak Ridge to determine how to assign the principal parameters (number of sectors, magnet gap, and angle of spiral) so as to achieve suitable orbit stability. The behavior in the central region was crucial in these considerations, particularly since the large gap desired (about 7.5 in.) prevents reliance on flutter focusing near the center; valley coils were felt to be helpful, and three-fold symmetry was decided on to minimize complications in the central region and to facilitate deflection for which this choice was felt to offer advantages. King drew attention to a comprehensive Harwell report on measurements of magnetic fields produced by rectangular ridge structures and discussed in detail the application of this data to the design of sector-focused cyclotron fields. He illustrated these techniques by describing model and design work for a 400-Mev machine at the University of Florida. In one case a transition from 3-fold to 6-fold symmetry at an intermediate radius was considered.

The first general discussion followed these four papers. Some remarks were made concerning the relative accuracies of approximate analytical treatments and the so-called smooth approximation. A number of comments were made on the general subject of magnet gaps. It was noted that the financial cost of a larger gap was generally not a large fraction of the cost of a cyclotron project, but also that in at least some machines the useful beam required only a very small axial space, and that phase slip may be larger with large gaps in spite of the larger r-f voltages that could be sustained in these larger gaps. The writer feels that this question was not settled and that the determination of a suitable gap is still a matter of design judgment on which different groups will continue to reach different decisions. It is worth remarking that the smallest gaps seem always to be found on converted magnets in which the freedom to enlarge them is absent and/or in which a large increase in energy is hoped for from the conversion. In addition to the question of magnet gaps, remarks were made about the various possible radial variations of isochronous fields near the c3nter in machines with different numbers of sectors. The isochronous field may actually decrease near the center of a machine with three-fold symmetry due to the rapid rise of flutter with radius. Some interesting remarks were made concerning the differences between the behavior of a small ordinary cyclotron and the central region of a sector-focused cyclotron; the two situations vary considerably in several details.

The second group of papers started with a presentation by Heyn of design and performance data on the 12-Mev cyclotron at Delft, which is the first sector-focused machine for protons to come into operation. Particular interest attached to a description of an anomalous highly eccentric beam of low energy particles which was observed under some circumstances, but could be eliminated by increasing the magnetic field at the center. It may have been related to asymmetries in the r-f electric field. The next four contributions dealt with rather general studies, by analysis and by digital computation, of a variety of orbit properties in cyclotron fields. Parzen presented some rather general and complicated analytical formulas for the various quantities of interest, including nonlinear stability limits for the important resonances, together with a discussion of the relative importance of the various terms and of comparisons between his results and those of other techniques. Smith traced the Berkeley theoretical program through the arly stages of simplified theory such as that of Richardson, on to general analytical orbit work like Parzen's and then to detailed work on digital computers using MURA and ORNL codes. Detailed comparisons among the numerical work with different codes and the evaluation of analytical formulas were presented, including work on the stability limits at resonances. The numerical agreement was adequate in most cases. Welton next gave a detailed description of the philosophy of cyclotron orbit work at Oak Ridge and of the ORNL codes which are available. With the best of these, for an IBM 704 computer, one can obtain the complete properties of an orbit in six seconds, starting from a specification of the magnetic field by giving field values on a mesh of points. These values could have as their source either an analytical representation of the field or a set of measurements in a model magnet. Symon next described the MURA codes that have been developed over a period of years for purposes somewhat more general than cyclotron design. They form a connected set by which magnetic pole shapes, field values, and orbit properties may all be inter-related in a comprehensive way. In the discussion following this group of contributions it was brought out that for many cyclotron problems, especially those with relatively complicated fields derived from model magnets, the Oak Ridge codes are the fastest available, being designed especially for this task. It was encouraging to hear from the three groups (Berkeley, MURA, and Oak Ridge) that have constructed sector-focusing electron accelerators that generally satisfactory agreement between observed and pre-calculated orbit properties has always been found.

The last group of contributions to this session dealt largely with specific topics or with particular machines. Blosser discussed the machine being planned at Michigan State University, with particular emphasis on the $\frac{3}{3}$ resonance. It was encouraging that his studies showed the stability limits to be equally satisfactory for 50-Mev protons and for non-relativistic C^{4+} ions, since the distance off resonance is largely determined by flutter rather than by the relativistic mass increase in a machine of three-fold symmetry. Gordon presented his work which first showed in a definitive way that adequate stability could be obtained in machines with three-fold symmetry. His calculations indicated that axial stability near deflection was actually better for N = 3 than for N = 4. Terwilliger described orbit studies for a four-sector, tight spiral machine for 40-Mev deuterons. For such machines the "smooth approximation" results seem quite reliable as judged by digital work with the MURA codes. Special attention was given to nonlinear axial motion effects, coupling resonances, and unwanted first harmonic perturbations, and it was concluded that this tight spiral design was quite reasonable. Lind described experimental and calculational work on the first few turns of the University of Colorado cyclotron. The space dependence of the r-f electric field was found from a model and approximated by analytical functions. Calculations of radial and axial motion then led to numerical estimates of the phase space injected, of the amplitude of radial oscillation to be expected at the deflector, and of phase bunching as well as of axial electric focusing.

All of those present were charmed by the gracious acknowledgment by Prof. Thomas of the appreciation of his pioneering work in this field and of the widespread developments which have flowed from it in recent years. His remarks which followed drew attention to the possible advantages, in computing nearly-periodic orbits, of applying computational methods long known in celestial mechanics by which one extrapolates forward by several cycles, rather than by small steps along the orbit.

In the last general discussion of the session, attention was drawn to the importance, in using the smooth approximation for non-scaling fields, of using a proper definition of the field exponent. Boyer described measurements in the central region of the Los Alamos cyclotron which showed that only a very small range of phases and of axial aperture was occupied by that part of the beam which was accelerated in a way suitable for deflection. In additional discussion of central region problems, Blosser emphasized the importance of locating a defining aperture at an antinode of phase focusing and at a node of radial betatron focusing in order to obtain the best usable beam with a minimum of unwanted particles.

In general summary, it appears that, in aggregate, a great volume of work on orbit calculations and magnetic field design has now been accomplished and that the general procedures to be followed in such work are now well established. The publication of these proceedings will be of great value in helping those who are newer to this field to get in touch with the workers who are familiar with these techniques so as to avoid unnecessary duplication of effort in designing new machines. However, it will be some time before this body of lore will be so standard and so codified as to present only routine problems in development. In particular, the central region in sector-focused cyclotrons needs additional effort, both computational and empirical, before one can say that an optimum design can be predicted in advance. The same is true of beam extraction techniques which were discussed in another session.