THE DESIGN OF HIGH ENERGY ACCELERATORS

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In opening this talk on new ideas for accelerating machines I believe it is appropriate to express our respect for the high degree of imagination shown and the thoroughness of the detailed analyses made by those now working in the field of high-energy machine design. In recent years we at Berkeley have been primarily concerned with the design of lower-energy cyclotrons and linear accelerators, and with the problems of learning to make the most useful tool possible of our 6-Bev proton synchrotron known as the Bevatron. One of our occupations has been the development of the liquid hydrogen bubble chamber, which is to be discussed next week. Our chief concern with machines of higher energy than the Bevatron has been the attempt to keep abreast of developments by other groups. During the last year the possibility of studying the application of the newer ideas to machines in the 100-Bev range has been discussed informally and some thinking along these lines has been done. Nothing like a study comparable to those of the Brookhaven, CERN, or MURA groups has, however, been made at Berkeley in recent years. This paper, therefore, must be based on our considerations of the ideas of other rather than on the results of studies such as you have heard from other speakers.

In the advance of accelerator design, three directions can be recognized. These are toward higher energies, higher currents, and higher ratios of observable information to background. While higher energy obviously opens unknown territory which has proved extremely fruitful in the past, the other two directions of development should not be overlooked. Significant discoveries are almost sure to result from observing effects now too weak to be detected and from making more accurate measurements of quantities already known approximately. The cost of machines intended to improve the measurements in energy ranges already entered is less than whose purpose is to extend the high-energy frontier, but the degree of care and refinement required in their design may be considerably greater.

General problems of a large accelerator project

Many difficult problems face those concerned with the design of an accelerator intended to be appreciably better in some aspect of performance than the existing machines. First in the planning of a new machine should be the selection of an objective of sufficient importance. Construction times for large machines are from four to eight years, which is long to maintain the enthusiasm of the staff. The objective should be one that does not decrease in importance during this waiting period. Another basic problem is that of reaching the best balance between cost and confidence in meeting the specified performance. There are many design parameters whose variation in one direction increases confidence and in the other decreases cost. The price of what is considered the necessary degree of confidence will depend on how much extrapolation is made beyond existing knowledge, how well the theory used is believed to apply, and how serious might be a failure to meet the expected performance. Confidence can be increased sometimes at small cost in time or money by the construction of models to verify important assumptions, or by the construction of the final machine in such a way that its basic parameters may be changed after completion. Both were done in the case of the Bevatron, where a quarter-scale model was built to verify the stability of the accelerating beam, and where the final machine was designed to permit an exchange of energy for aperture at a small fraction of the total construction cost. It seems reasonable to take some risk in relying on future technical developments where it is felt that progress is to be expected. Complication in an accelerator should not be cause for too much concern so long as the individual elements are basically reliable. Dependence on a single unreliable element can be far less satisfactory than dependence on a great network of many reliable ones. Simplicity is a virtue in itself, but complication per se should not cause one to abandon an objective that cannot be reached without it.

Design study for a large synchrotron

At Berkeley we plan to make a rather detailed study of the design of a machine for the next step in energy above that of the CERN and Brookhaven synchrotrons. Although this work has not really begun there has been some preliminary thinking, and discussion of the possible features of such a machine, that may be of interest to report.

We have been considering the alternating-gradient synchrotron in particular, and with reference to the factors determining the cost. The magnet and its power supply
will certainly make up the largest part of the cost and will also determine the cost of the building. In the Bevatron the magnet with its power supply amounted to 55 percent and the building to 20 percent of the cost of the project.

The cost of the magnet can be separated into the cost of the core and that of the coil and excitation equipment. For a constant current density the cost of copper and power equipment will both vary approximately as the square of the gap height and directly with the energy. The optimum current density is determined mainly by the relative cost of copper and power, and is not very sensitive to the size of the magnet. The cost of the iron will vary approximately as the aperture area times the energy. The total cost then can be expected to vary directly with the energy and between the first and second power of the aperture height, for the same aperture shape. These rules, of course, assume that generally similar types of magnets are being compared. With a constant ratio of aperture height to radius the cost of the magnet and power supply then will vary between the square and the cube of the final energy.

We would hope to look into other designs in addition to the C-type ironcore magnets now planned for the AGS machines. Air-core magnets, although removing the limit on flux density set by saturation of the iron, have not looked attractive to us in the past and we do not hold much hope that they would look better for larger machines. However, there are attractive features to the separated-function machine studied at Princeton University, in which the focusing and bending are done by separate magnets. The symmetry of the quadrupole focusing magnets would indicate that closer tolerances might be held on the uniformity of the gradient, and that mechanical alignment might be improved over that of the C design. It should also be easier to obtain the necessary uniformity in bending magnets having uniform fields. With the separated function scheme it would be expected that the turning magnets could operate at much higher fields than would be possible with the conventional C magnets. This would, of course, be necessary to make up for the presence of the straight focusing magnets in the ring. Poleless magnets of rectangular cross section have been built which appear suitable for fields up to 22 kilogauss. An attractive feature of the separated-function design is that large changes in the focusing strength can be made by replacing bending magnets with focusing magnets, or vice versa. Thus some additional flexibility is provided that could prove valuable if it is desired to change the focusing strength after test operation. If it is found that weaker focusing can be used some of the focusing magnets can be replaced with bending magnets to permit an increase in energy without change of the radius of the ring. It is also possible to consider arrangements in which combines focusing and bending magnets alternate with magnets which only focus or bend the beam. We hope to learn how the costs of these various arrangements compare.

It may be possible to take more advantage of the contraction of the beam with increasing energy than has been done in the past. Two machines might be used in tandem, the low-energy machine having a large aperture and the high-energy machine a smaller one which would be adequate after the contraction that would occur in the first stage. For this scheme to be practical the losses in deflection and injection must be small. This might be achieved if the beam could be transferred from one machine to the other on a single turn by suddenly changing the magnetic field over a small region. The saving in cost of a two-stage over a single-stage system for very high energy appears to be large.

As the size of the aperture is the principal cost-determining parameter that can be varied for a machine of a given energy, the possibilities for its reduction must be thoroughly considered. Considering the requirements of injection, it appears that as the size of the machine increases it will be possible to make some reduction in the relative aperture. If the charge accelerated per pulse is to be constant, the cross section of the injected beam need not increase as the size of the synchrotron increases. In fact, as the size increases the injection energy will probably increase and the size of the injected beam will decrease due to its improved ratio of longitudinal to transverse momentum. As the absolute size of the injected beam is one of the factors determining the synchrotron aperture, the absolute size of the aperture need not increase with energy quite as fast as does the radius. In other words, the acceptance of the synchrotron does not have to increase as the size increases, whereas it would increase if the relative aperture were held constant.

The recent developments in high-current linear accelerators make comparatively large beams possible even with single-turn injection. Extrapolation of the performance of the linear accelerator now in operation at the Livermore branch of the Radiation Laboratory indicates that a proton current of 150 milliamperes could be obtained at 100 Mev through a 3-inch-diameter bore with a maximum half angle of 0.0025 radian. This corresponds to $10^{12}$ protons injected in a single turn with a machine of 5000 ft circumference, about 1000 times the charge now being accelerated by the Cosmotron and the Bevatron.

A means of multiple turn injection for the AGS machine has recently been suggested*. Molecular hydrogen ions would be sent into a part of the orbit where a high gas pressure was maintained. A fraction of the injected ions would break up into protons while passing through the gas. The geometry would be arranged so that the protons, having half the radius of curvature of the molecular ions, would be caught in the equilibrium orbit. The protons would necessarily be scattered on subsequent passes through the region of high gas pressure but it appears possible that more charge might be captured in this manner than with single turn injection. Injection by this method would pro-

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* I have since learned that a similar study has been made by Prof. P. B. Moon at the University of Birmingham.
bably proceed for several seconds before the magnetic field of the synchrotron started to rise.

One of the most important parameters affecting the aperture is the focusing strength. Reduction of the aperture by increase of the n value is limited by the increasing sensitivity to misalignments of the magnets and the difficulty of avoiding resonances. The usual method of providing for accurate alignment of a machine is to build the most permanent foundation possible and to locate the magnets as accurately as possible on the foundation by conventional surveying methods. If misalignment is suspected the magnet positions must be resurveyed and readjustments made if necessary. As this process would consume many weeks for a large machine, a considerable error in alignment must be allowed in order to avoid spending too much time on corrections. Another approach would be to correct the alignment automatically and almost instantaneously by a servo position control on each magnet. If this could be done, no allowance for motion of the foundations would be needed. The use of methods other than optical surveying might also provide better mechanical alignment. An alignment scheme bases on these ideas might be the following. Levels at three points on each magnet would be determined from a liquid surface. Corrections would have to be made for tidal motion, but these appear accurately predictable. Horizontal displacements would be determined from a series of wires stretched along chords of the magnet circle. Each end of each wire would be attached to a magnet. The intermediate magnets would carry electrical pickup devices that would determine their positions with respect to the wire. As the wires would overlap around the circle, the positions of the pickups would provide the information on the departures of all the magnets from the true circle. With many individual magnets, as many be required for a high-energy machine, hundreds if not thousands of readings would be continuously produced. Reduction of these readings to the required motions of the magnets to bring them back into line would require automatic computing methods. As it seems unnecessary to go all the way in correcting the alignment automatically it should be sufficient to provide the operator with the errors in position of the equilibrium orbit and the necessary readjustments. These motions would then be made by motor-driven jack screws. A function of the computer would be to determine the Fourier components of the alignment errors and the minimum number of adjustments to make the necessary correction. Experiments indicate that the position of a stretched wire can be determined electrically to better than one mil and the height of a liquid surface can be determined to similar accuracy by electric methods.

The position of the orbit is, of course, affected by variations in the magnetic field as well as by mechanical alignment errors. If the latter were reduced by an order of magnitude the magnetic errors would have to be examined in much greater detail than has been done at our laboratory to date.

To permit stronger focusing and still avoid resonances, we have also been considering the possibility of servo control of the focusing strength. The problem here seems to be to obtain a continuous indication of the betatron oscillation frequency. One method by which this might be done is to modulate the focusing periodically at a low frequency, say 10 kc, and to observe the corresponding pulsation in the size of the beam. The phase relation between the pulsation signal and the modulating component of the focusing strength would give the direction in which to correct the focusing. As the modulating frequency is accurately known, it may be possible to pick up small variations in the beam amplitude in spite of the background of noise and the effects of other oscillations. If necessary, the modulating frequency could be varied during the acceleration to keep it away from the frequencies of other existing oscillations. This method would require that the focusing be set slightly off the value giving the minimum beam size, in order to obtain a monotonic relation between size and focusing strength.

In studying the extension of the AGS design to higher energies, we would expect to make considerable use of automatic computing machines. One subject of investigation would be the periodic structure of the magnet; how the focusing, defocusing, bending, and straight sections should be arranged. The criterion would be the required aperture, and the independent variables would include the injection conditions, focusing strength, alignment tolerances, and frequency errors. Another machine problem would be determination of the cost of the accelerator, given the energy, aperture, dimensionless magnet characteristics as determined from model tests, repetition rate, and other pertinent variables. The unit costs of magnet core, coils, and power supply (the last a function of peak and average power and stored energy) obtained from our own manufacturers' estimates would be used. The cost calculations can be usefully made only after the physics of the proposed design is understood.

The intersecting-beam machine

Very little thought has been given to intersecting-beam machines at Berkeley as the ideas that may make the method practical have appeared so recently. Storing a large number of particles at maximum energy appears necessary to a practical system, and the most crucial problem seems to be that of adding more charge without losing too much of the charge already stored. I am afraid we have little to contribute to the ideas on how this might be done, but we believe that the difficulties are of the sort that can be overcome by the application of technical effort. Assuming the problem of accumulating the high-energy beam to be solved, one arrangement for the machine would be three rings of magnets, each ring touching the two others. One ring would be the pulsed accelerator, while the others would be fixed-field storage magnets. The accelerator would inject alternately into each of the storage rings and the high energy beams would interact
where the storage rings touched. Deflection from the accelerator ring could be done efficiently in a single turn if a portion of the magnetic field could be rapidly pulsed off. One might think of providing the storage rings with accelerating electrodes to keep the beam bunched about an equilibrium phase angle. Additional beam could be injected when the bunch was away from the injection position without disturbing the beam already stored. Some experiments on beam stacking in the 184° inch cyclotron at Berkeley have been made by Drs. Crawford and Stubbins in which they found it possible to store the charge of from five to seven beam pulses. Losses due to scattering and to the disturbing radio frequency dee voltage were measured. Further experiments will be made when the cyclotron is again in operation.

Two requirements for the development of intersection-beam machines seem clear. One is the production of the high circulating charge required in a single machine of appropriate energy. The other is invention and analysis of all the possible methods of storing the beam. One may hope and expect that these objectives will be vigorously pursued.