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SUPER-ENERGY ACCELERATORS

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Summary

Alternating gradient synchrotron design can be extrapolated in a relatively straightforward way to larger circumference and higher particle energy. This means of increasing available energy is more attractive economically than any other accelerating system that has been suggested. Since increased energy makes it possible to uncover new phenomena as well as extend knowledge of effects presently known, a number of groups in the United States and Europe are intensively developing design studies of synchrotrons up to as large as 1000 GeV. This paper is a review of the work of these various groups, with particular emphasis on a 200-GeV study at the Lawrence Radiation Laboratory which will soon be presented to the Atomic Energy Commission.

Background and History

The possibility of building proton accelerators in the multihundred-BeV range has been with us for quite a long time. As soon as the strong-focusing principle was discovered (1950, 1952) it was realized that it could be used for as high an energy as anyone might dare to suggest. Little was done about this fact in the mid-fifties for a variety of reasons. The 25- and 30-BeV machines at CERN and Brookhaven, respectively, were still under construction and an extrapolation by a factor of ten or so seemed too risky without a direct demonstration of their utility. The MURA group was developing the FFAG principle, which promised much higher intensity at presently available energies; a lengthy debate was in progress among high energy physicists as to whether higher energy or higher intensity would be the better next step. In addition, invention was in the air, stimulated largely by interesting suggestions from the Soviet Union, and accelerator designers were groping for new principles which would yield a more economical or more compact machine.

By 1960-61, the situation had changed substantially. The 25- and 30-BeV machines were in operation, and not only had they provided verification of the strong-focusing principle, but also they were proving to be much easier to run and much more flexible for experimental use than the older weak-focusing machines. None of the suggestions of new principles had panned out and, indeed, it no longer seemed so important to reduce the capital cost of the accelerator. The investment in auxiliary facilities and in a 10- to 15-year experimental program is the dominant expense in producing results, so that the prime requirements for the accelerator are reliability, ease of handling, and flexibility to meet changing experimental demands. It is difficult to imagine a device superior to the alternating-gradient synchrotron in these respects; even regarding intensity it has the property of providing an increase with increasing size.

Enthusiasm mounted rapidly for getting on with the next step in energy. By the middle of 1962, the government was faced with requests from Berkeley and Brookhaven for authorization of serious design studies of super-energy accelerators, and simultaneously with a construction proposal from MURA for a high-intensity 10-BeV FFAG accelerator. A panel (known as the Ramsey panel, after its chairman) was convened to formulate a long-range plan for high-energy physics and to make recommendations concerning the immediate requests. In April, 1963, the panel's report became public; in particular, it supported higher energy as the most important goal, and recommended that Berkeley undertake the design and construction of a proton synchrotron of about 200 BeV, while Brookhaven should contemplate a 600- to 1000-BeV machine to come along 5 or 6 years later. The AEC immediately authorized the two laboratories to proceed as recommended, thus officially launching the design study which is described below.

Since that time other panels and committees have touched on high-energy physics, by and large endorsing the two-step approach recommended by the Ramsey panel. In March of 1965, the AEC submitted to Congress the government's proposed long-range program. It specifies that the 200-BeV complex designed by Berkeley should be constructed as a National Facility, to be completed by 1973, and that exploratory studies should continue, leading to design of a 600- to 1000-BeV accelerator to be completed in 1980. The latter work would presumably be carried out mostly by Brookhaven, with some contribution from Argonne National Laboratory.

Plans of this sort are not unique to the United States. In western Europe, the CERN laboratory has proved to be a great success, not only as an experiment in international collaboration, but also as one of the world's most important contributors to the advancement of physics. Europe has had its fair share of panels and committees in recent years, leading to much the same conclusion as ours — that new accelerators at higher energy are necessary for the further development of the field. In December, 1964, the CERN staff submitted to its governing council a design study for a 300-BeV accelerator, and discussions are now under way concerning sites and financing. In the Soviet Union, preliminary studies have been made of 500- and 1000-BeV machines; however, the country is currently occupied with construction of a 70-BeV synchrotron, and apparently plans for the next step have not reached the level of urgency felt here and in western Europe. There has also been talk from time to time of the three continental blocs' collaborating in a single super-energy laboratory, but that possibility seems remote at present.

Design Studies

General Considerations

Work on a 600- to 1000-BeV accelerator has not yet come to focus on a specific design, but continues to be fairly speculative (see, for example, paper D-8 by G. Parzen, at this conference). On the other hand, the design studies for a 300-BeV machine by CERN and for a 200-BeV machine by the Lawrence Radiation Laboratory are more or less complete. The remainder of this paper is devoted to a description of those machines. The similarity between them is not entirely coincidental, for there has been a considerable amount of contact between these laboratories and with Brookhaven in recent years in the form of exchange of ideas and personnel. In fact, the differences between the designs give a measure of the arbitrariness in the choice of some parameters.

Table I is a list of the principal parameters of the two machines. The mode of operation is as follows: the protons are first accelerated to an energy of 200 MeV in a 200-Mc Alvarez-type linear accelerator. They are then injected into a rapid cycling synchrotron (called the "booster") and accelerated to an energy of 8 BeV. By means of fast kicker magnets they are than extracted in a single turn and injected into the main ring, in which the magnetic field has an appropriate dc value and in which the rf cavities are energized to keep the particles bunched within a length equal to the circumference of the booster. This process is then repeated, with each new batch of 8-BeV protons being deposited in a empty sector of the main ring; when the main ring is entirely filled, its magnetic field starts to rise and all the protons are accelerated to peak energy. The method sounds complicated, but the kicker magnets are comparable to ones used on the present machines, and the only really new feature is the need to synchronize rf frequency and phase at the moment of transfer. Since the injection energy for the main ring must, for various reasons, be quite high, the only serious alternative would be a multi-BeV linear accelerator, which is itself still more complicated and expensive.

Magnet Configuration

The dependence of the basic orbit properties on length, gradient, and number of magnets and the disposition of field-free regions is well known, and the new designs depart from orthodoxy in only one respect. A few years ago, T. L. Collins pointed out that it was possible to introduce much longer field-free regions than previously realized without increasing the required magnet aperture. In its simplest form, the trick is to break the magnet structure apart between a focusing and a defocusing magnet and insert two quadrupoles of such a strength and location that the transverse oscillation of an entering particle is changed in phase but not in amplitude while traversing the special section. An open stretch 100 feet or more in length between quadrupoles is quite easily achieved this way; more complicated inserts can include much longer runs if desired. This invention has been a godsend to super-energy accelerators because a lot of space is needed for accelerating rf stations and for devices to bring the very stiff extracted beams clear of the downstream magnet structure. Both machines include 12 of the simple two-quadrupole inserts; the LRL design is somewhat better optimized for length of the open region.

An inovation which has been enormously useful in magnet design work is the extensive use of large computers to calculate field distributions and magnetic characteristics of proposed steel and copper configurations, including saturation effects. This procedure largely replaces the older one of fabricating a series of model magnets, though of course it will still be necessary to verify the results with a final model or prototype. The proposed LRL magnet, for example, runs well into saturation in some parts of the yoke to reach 15 kG at the equilibrium orbit, but the computations are precise enough to form the basis for engineering design and cost analysis.

rf Systems

In this area we find what is perhaps the most striking difference between the two machines. CERN proposes a traveling-wave accelerating structure, linac style, at 180 Mc, while LRL favors more conventional ferrite-tuned cavities at 50 Mc. There are arguments for and against each method, but it is certainly not obvious at this stage of investigation that one is better than the other.

The rf system for a super-energy accelerator is a problem quite different than for present accelerators. For the same repetition rate of the main magnet, the required energy gain per turn increases as the square of the radius. In the LRL design, a peak voltage of 7 MV per turn is to be supplied by 42 cavities; thus each cavity must produce twice the voltage of the entire rf system of the Brookhaven 30-BeV machine. In order to keep the total power in hand, the accelerating structure must be high-Q, which is relatively easy to achieve because of the small frequency range required ($\approx$0.5%). In the LRL design, the Q value, including ferrite, should be about 15 000 — this makes for a total power of about 1 mW skin loses and 1 MW beam power at design intensity of 3×10^{13} protons per pulse (1/3 ampere circulating current). The beam-induced voltage on a floating cavity would be several times the required accelerating voltage, which indicates that beam-cavity interactions must be carefully considered. The present philosophy is to retain the high Q to minimize the amount of expensive high-power hardware, and to handle beam-loading problems by suitable low-power trickery, the details of which have still to be worked out.

Experimental Areas

The super-energy accelerators will make extensive, if not exclusive, use of external proton beams extracted either by fast kicker magnets or by a slow resonant build-up of betatron oscillations. This mode of operation will minimize the problem of induced radioactivity in the accelerator tunnel, permit greater flexibility for running simultaneous experiments and changing experimental setups, and provide good access to secondary beams emitted in the forward direction from external targets. This third point is important because we know from a combination of laboratory and cosmic-ray experience that for 200- to 300-BeV primary energy, the secondaries will be confined to a forward core of a few milliradians half-angle. The extracted proton beams will be transported by quadrupoles and bending magnets to a series of target stations, from which points the experimental setups will diverge. Most of the experimental runs should be less than a quarter mile in extent; however, some, such as those involving 100-BeV separated beams, will require a mile or more. Thus an experimental hall is quite out of the question and the experiments will stretch across open terrain with occasional temporary housings for special equipment and portable substations for electrical power.

Accelerator Housing

The housing for the accelerators will be much like the present ones, with some important differences forced by the great circumferential length and the anticipated high level of radiation. In the LRL design, the primary shielding material will be earth, 20 to 30 feet deep, on top of the housing, sloping laterally as steeply as soil conditions will permit. As much equipment as possible will be located on the surface above the accelerator for ease of access and protection from radiation. The concrete of the housing itself will be loaded with boron to suppress induced activity from slow neutrons. This feature should make most of the ring liveable when the machine is off, but it will be necessary to provide some remote handling devices in target and beam-extraction areas. Self-propelled cars, probably on rails, will be used for maintenance and trouble shooting, since access points large enough to admit bulky equipment will be about 3/8 mile apart. These access points pose a knotty design problem because of the extensive earth shielding; in the present concept, they require elevators, bulky shielding doors, and other unpleasant features.

Site

In the CERN study, a hypothetical hard rock site has been assumed, whereas LRL chose to consider as a specific example for detailed investigation, an inactive army base situated in the Livermore valley. In fact, a final choice of site has not yet been made either in the United States or in Europe. At present, attempts are being made to establish a general list of criteria for site selection, which would serve as a basis for evaluating available locations.

Conclusion

It has not been possible, within the space and time allotted to this paper, to do more than touch briefly on some of the features of the next generation of accelerators. There is, regrettably, almost no published material available at this early stage which can provide more detail. If all goes well, the next two years will be devoted to the evolution of a final design; the great interest which the general public and the technical community are displaying will surely cause the work to be well documented.

Table I. Parameters for LRL and CERN designs

Parameter Main Synchrotron	LRL	CERN	
Energy	200	300	BeV
Intensity	3×10^{13}	3×10^{13}	protons/pulse
Repetition rate	30	24	pulses/minute
Diameter	4500	8000	feet
Magnetic field	660 to 15 000	350 to 12 000	gauss
Weight of magnets	17400	23 700	tons
Average magnet power	12	26	MW
Radio frequency	52	184	Mc/sec
Beam aperture	5×12	6×10	cm^2
Length of long straight sections	112	95	feet
Booster synchrotron			
Energy	8	8	BeV
Intensity	4×10^{12}	2.5×10^{12}	protons/pulse
Repetition rate	18	20	cycles/second
Diameter	647	660	feet
Magnetic field	520 to 7000	510 to 7000	gauss
Weight of magnets	1500	970	tons
Radio frequency	29.6 to 52	104 to 183	Mc/sec

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