

# DESIGN CONCEPTS FOR ULTRA-HIGH ENERGY SYNCHROTRONS

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## I. INTRODUCTION

The principle of resonance acceleration of Wideroe and Lawrence, the principle of phase-stable acceleration of Veksler and McMillan, and the principle of alternating-gradient focusing of Courant, Livingston and Snyder, and Christofilos, have been joined in a most felicitous combination to make possible the giant synchrotrons at CERN and at the Brookhaven National Laboratory—accelerators both esthetically pleasing and functionally gratifying. These 25 to 30 Gev accelerators have not, however, extended to the limit the capabilities of the basic principles. Drawing on the experience gained in the construction of these newest machines, we can now contemplate accelerators of ever higher energy.

One may well ask whether accelerators of still higher energy will serve usefully the purposes of research in particle physics. This important question will no doubt receive—and should receive—much attention in colloquia other than this one. I believe that the consensus will be that they will do so.

The most straight-forward and economical path to the attainment of higher energies appears, at this time, to be the A. G. synchrotron, although other methods are, or may be, possible. Novel principles of acceleration, such as those presented at our earlier conferences by Veksler and by Budker, may one day lead to new approaches, but have, unfortunately, not yet fulfilled this promise. High-energy interactions can also be achieved in colliding beam devices, but these will complement and not substitute for beams of high laboratory energy.

## II. EXTENSION OF AGS MACHINES TO HIGHER ENERGIES

Once the mental adjustment is made to the fact that absolute size is no impediment, the A. G. synchrotron is an obviously open path to very high energies. During the past two years an ever increasing amount of effort has been given to the consideration of possible designs of proton synchrotrons of ultra-high energy (U.H. E.)—energies from 100 to 1,000 Gev. One effort, on the west coast—primarily, at the California Institute of Technology and at the Lawrence Radiation Laboratory—has considered machines with energies from 100 to 300 Gev. A second, and more recent, effort at the Brookhaven National Laboratory has considered synchrotrons of energies from 400 to 1,000 Gev as a possible international project. Both of these efforts have relied extensively on the collaboration of accelerator specialists throughout the United States, particularly from workers at the Argonne National Laboratory, the Cambridge Electron Accelerator, Midwestern Universities Research Association, Yale University and the University of California at Los Angeles. A particularly intense activity has been going on during the last summer at the studies organized at the Lawrence Radiation Laboratory by Lloyd Smith and at Brookhaven National Laboratory by John Blewett. In this report I shall try to summarize the status of the design concepts which have evolved from all of these national efforts.<sup>1</sup>

The general result of the considerations to date is that proton synchrotrons with energies up to 1,000 Gev—and even higher—are technically feasible; that they will be relatively straight-forward extensions of existing practice; and that they will be expensive. With a few

notable exceptions, a large part of the recent design effort has involved attempts to determine an "optimum" choice of the many parameters which enter into the design specifications, usually with a strong emphasis on economic factors. An U.H.E. accelerator will, very likely, be one of the most expensive instruments ever contemplated for purely basic research. It is appropriate that the greatest yield, in terms of ultimate utility for research, be obtained for the national—or international—resources which will be expended.

In the following, I shall treat in turn the problems of the guide field, the aperture, magnet alignment, injection and intensity, acceleration, and the experimental characteristics. When it is useful to give quantitative examples I shall choose quantities approximately applicable to a 300 Gev and to a 1,000 Gev design.

#### A. The Guide Field

It is a testimony to the careful work of the designers at CERN and Brookhaven that all of the suggested designs of U.H.E. machines provide orbit characteristics which resemble closely those of the existing large proton synchrotrons. For a general discussion, such as this, we may characterize synchrotron orbits by three basic parameters: the radius of the orbit  $R$ , the "size" parameter; the gradient strength  $k$  ( $=n/R=1/\ell_o=dB/BdR$ ), the focusing "strength" parameter; and  $\Phi=\sqrt{n}L/R$ , the orbit form parameter (where  $L$  is the length of the typical magnetic focusing element). These three parameters can be chosen more or less independently, and suffice to describe the gross characteristic of the guide field design.

The radius  $R$  is evidently determined by the realizable maximum field in the magnet. There seems to be general agreement that iron magnets in A.G. synchrotrons can be efficiently used to fields of 10 to 15 kilogauss. The magnetic radius is then determined to be about 800 meters (300 Gev), or 2,500 meters (1,000 Gev). The requirements for field-free sectors for additional facilities—injection, acceleration, targeting, etc. result in an increase in average radius by a factor of about 1.3. The overall diameters become about 2 kilometers (300 Gev) or 6 kilometers (1,000 Gev). (See Table 1.)

TABLE I

The Guide Field

		300 Gev	1,000 Gev
Size	$R$	800 meters	2,500 meters
	$D$	2 Km	6 Km
Form	$\Phi$	1.2	
	or $\mu$	$\pi/4$	
Strength	$k=n/R$	4 to 8/meter	
	or $n$	2,500	20,000
	or $\ell_o=1/k$	12 to 25 cm.	
Radial Aperture		5 to 8 cm.	

The magnitude of these numbers requires some psychological adjustment. They also imply large expenses for real estate, for tunnels, for control and communication and for transportation. Any possibility of a significant reduction in scale is intriguing. One thinks immediately of the high-field superconductors. Christofilos<sup>2</sup> has suggested a design of a superconductor guide field which would operate at 30 kilogauss. It is not clear, at this date, whether the great technical uncertainties of the new cryogenic techniques, as well as other disadvantages, are adequately compensated by a reduction in scale by a factor of 2 or 3.

The orbit form parameter  $\Phi$  is fairly well determined to be about 1.2 (corresponding to  $\mu=\pi/4$ ) by the general exigencies of A.G. orbits. Second-order refinements of a final design will determine the precise value. No new developments have emerged here. The geometrical form of the orbits will resemble those of the existing machines.

It remains to choose the focusing strength parameter  $k=n/R$ . There is greater latitude of choice here, and many opinions exist. In the first place, there is a limiting gradient strength which depends inversely on the dimensions desired for the aperture. On the other hand, the aperture required depends on  $k$  as well as on many other variables. Strong focusing (large  $k$ ) may pose problems in magnet design and assembly, and augment the alignment difficulties. Weaker focusing emphasizes field inhomogeneities, and increases the aperture required for betatron oscillations, and particularly that for energy oscillations. The latter in turn depend on the parameters of the rf system. The dependence on  $k$  of the various factors

mentioned (assuming a constant  $\Phi$ ) is shown in Table II.

TABLE II

Effect	$k$ -dependence*
(1) Aperture required for:	
(a) Alignment error.....	$k^{1/4}$
(b) Field error.....	$k^{-3/4}$
(c) Given acceptance.....	$k^{-1/4}$
(d) Energy spread.....	$k^{-1}$
(2) Possible aperture**.....	$k^{-1}$
(3) Space-charge limit.....	$k^{1/2}$
(4) Allowable gradient error.....	$k^{3/4}$
(5) Maximum "free" section.....	$k^{1/2}$

$$* k = nR = 1/\ell_0 = \frac{1}{B} \frac{dB}{dr}$$

\*\* For a given  $\Delta B/B$  across the aperture.

The range of dependences in the Table illuminates the problem of choosing an "optimum" value for  $k$ . The Cal. Tech. group has considered, primarily, values of  $k$  near 8 meter<sup>-1</sup>. This figure corresponds to a magnet pole profile which is geometrically similar to that of A.G.S. but reduced in linear scale by a factor of 3. The Brookhaven group has considered mainly values of  $k$  around 4 or 5 meter<sup>-1</sup>, which makes for a relatively flatter pole profile. More work is required before final choices can be made.

## B. The Aperture

It seems to be apparent to all that injection should occur at fields of 100 gauss or more. Injection energies are then 3 to 10 Gev.<sup>3</sup> Several advantages accrue from high injection energies. In particular, the damping of lateral phase oscillations in the preaccelerator allows reasonable intensities to be reached with rather small betatron oscillations. The aperture is determined in large part, rather, by the need to contain the excursions of the closed orbit which arise from magnet placement and field errors which are also expected to be less at high injection fields. Radial apertures of from 5 to 10 cm seem quite feasible for synchrotrons of from 300 to 1,000 Gev.<sup>3</sup> Figure 1 shows a possible magnet cross section for a 300 Gev synchrotron. Cross sections of the Cosmotron and A.G.S. magnets are shown for comparison.

## C. Magnet Alignment

The A.G.S. and the C.P.S. were constructed with specified magnet placement errors of 0.05 cm with respect to an ideal design orbit. The

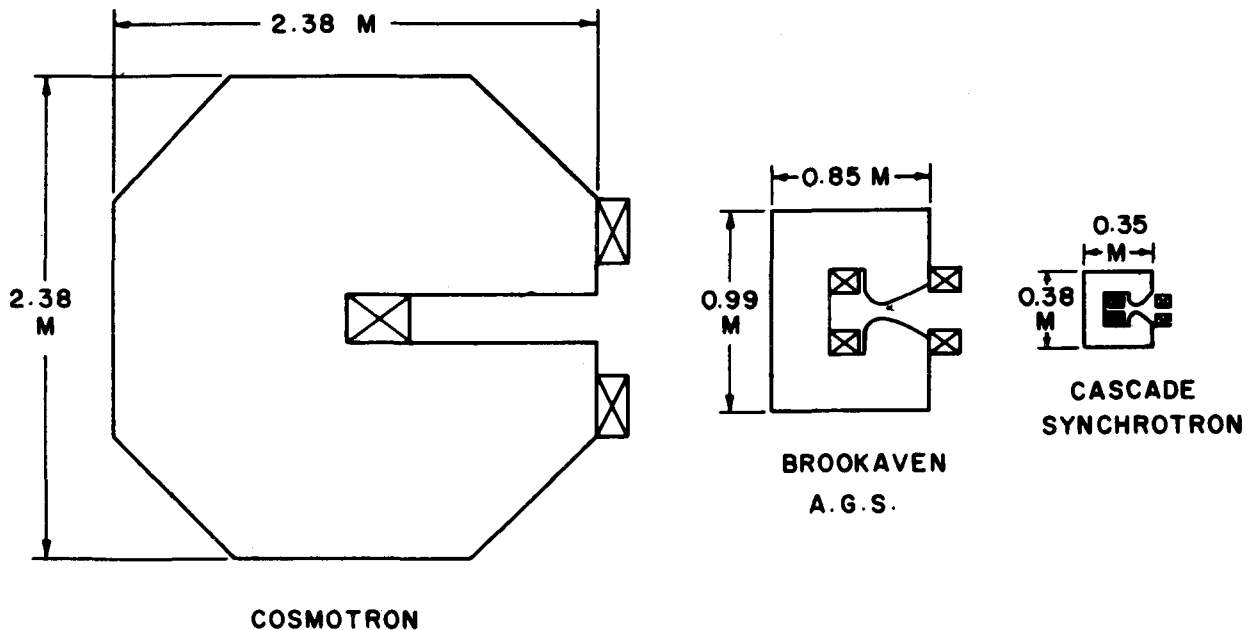


Fig. 1 Magnet cross sections for proton synchrotrons.

problem of achieving such accuracies on a scale 10 or 30 times larger is a formidable one. The A.G. guide field acts, however, somewhat as a pipe. If the magnet deviates from its ideal figure *in a smooth way*, the particles will follow the magnet. The serious misalignments are only those in the *relative* position of nearby magnets. The California groups have been investigating alignment schemes which will measure continuously the short-range, relative alignment of the magnet sections. A precision of better than 0.01 cm does not appear to be difficult over distances of 20 meters or more. The aperture requirement for orbit excursions which arise when the short-range, relative alignment method is used have been evaluated by E. Courant (B.N.L.)<sup>4</sup> and by J. Mathews<sup>5</sup> (California Tech.). Their work gives the interesting result<sup>6</sup> that the "local" survey produces no greater beam excursions than an "absolute" survey provided only that the base line of the local survey is at least as long as the reduced wavelength ( $\lambda = R/\nu$ ) of the betatron oscillations.

Reduced wavelengths will be from 30 to 100 meters. Optical or other alignment methods can give accuracies of 0.01 cm or better over such distances. These accuracies result in aperture requirements of a few centimeters. Total apertures of about twice that consumed by magnet misalignments are typically chosen, that is, radial apertures of 5 to 8 cm and vertical apertures of 3 to 4 cm.

With short-range magnet alignment procedures, it becomes possible to consider continuous, automatic monitoring of the magnet alignment, and, if necessary, frequent readjustment of magnet positions. If these possibilities are exploited fully, the restrictions on site selection become much less severe. Almost any geologic base is satisfactory. Also, one may expect significant economies in the magnet foundation.

#### D. Injection

The magnetic measurements at CERN and at Brookhaven show that A.G. magnets in U.H.E. synchrotrons will have satisfactory fields as low as 100 gauss. Injection at lower fields would be possible only with large correc-

tions for remanent fields and gradients. Injection energies of several Gev are, therefore, desirable. When the 300 Gev synchrotron was suggested two years ago, the 50 Mev linear injectors at CERN and Brookhaven were not yet in operation; an extrapolation of linear accelerator techniques to the Gev region seemed premature. It was proposed,<sup>7</sup> therefore, that a 10 Gev A.G. Synchrotron be used as an injector. The construction of such an injector would be straight-forward. The problem of transfer of the beam from the injector synchrotron to the main synchrotron has been considered by R. L. Walker<sup>8</sup> at California Tech., and it appears to present no particular difficulty.

The synchrotron injector has one obvious difficulty: after transfer to the main guide field the beam occupies a small fraction— $\frac{1}{30}$  to  $\frac{1}{50}$ —of the circumference of the larger ring. Although intensities of several times  $10^{12}$  protons per second can be reached in this way, intensities larger by an order of magnitude or more could be obtained if the full circumference were filled. The small circumferential filling will also give a low effective duty-ratio for the high energy beams, a serious disadvantage for counting experiments.

Several possibilities exist for providing injection into the full circumference of a U.H.E. synchrotron: (1) An A.G.S. operating at a higher pulse rate, say 10 pulses per second; (2) An F.F.A.G. synchrotron operated at high pulse rates; or (3) A linear accelerator. With the first two methods, the main guide field would be held at its injection value for a second or more and 10 to 50 pulses from the injector would be inserted, in a suitable azimuthal sequence, and/or with energy stacking, into the main accelerator. The latter would then execute its acceleration cycle. A linac would, instead, be able to fill the ring with a single long pulse. Any of these methods could give intensities of  $10^{13}$  or more protons per second.

The apparent advantage of the linac is somewhat misleading. Although the beam does occupy the complete circumference, the high phase bunching in the normal linac would produce an average azimuthal filling factor not too different from a single-turn synchrotron injector. L. Teng<sup>9</sup> of the Argonne Laboratory has proposed a linac variant in which the later

stages are operated at an unstable phase to produce phase debunching. Such a device will probably give an average azimuthal filling factor of 5 or so times larger than would be possible with a single-pulse synchrotron injector.

The space-charge-limited intensity of the main accelerator may be  $10^{14}$  protons per pulse or larger. Beams of even as high as  $10^{15}$  protons appear to be possible if means are provided to remove neutralizing ions created by the beam (which would give rise to a relativistic pinch), and if optimum azimuthal filling is obtained. These maximum possible intensities will be reached (if desired) only if sophisticated injection schemes are employed. High-current sources ( $> 100$  ma), high-current linac, multi-turn injection, and beam stacking may be necessary. Kjell Johnsen<sup>10</sup> (at the Berkeley Summer Study) has shown that a high-pulse-rate linac of moderate intensity could provide  $10^{14}$  protons per pulse in a 300 Gev accelerator by exploiting the high momentum compaction to stack 10 or more pulses at injection.

The unexpected high intensities (due to high injection energy) mean that U.H.E. synchrotrons are potentially also high-intensity machines. With intensities of  $10^{14}$  protons per second at 1,000 Gev the energy in the beam is 16 megajoules! Such beam powers pose problems in targeting, in shielding, and in radioactive contamination of the accelerator. Induced radioactivity is already a noticeable problem with accelerators which have beam powers of a few kilowatts. Much study will be required before we understand how to cope with megawatt beams, and the solutions may be expensive. Yet one will always be reluctant to place arbitrary limits on the possible—at least eventual—intensity.

A linear accelerator injector, or an F.F.A.G. injector, would imply larger extensions from existing practice than a synchrotron injector, even one with a pulse rate of several per second, and would probably be significantly more expensive. Much study is, however, now being devoted to the design of Gev proton linacs by groups at BNL, LRL, and at Yale. (Lloyd Smith has reported in detail on this work at an earlier session of this Conference.) The decision on the form of the injector for a U.H.E.

synchrotron will depend on future technical developments, and on further analyses of the required characteristics and expected costs. The importance of these analyses is emphasized by the fact that the costs of the injector may amount to one-third or one-half of the cost of the main accelerator itself.

### E. Acceleration

The required rf accelerating voltages of U.H.E. synchrotrons increase as the square of their energy, if the acceleration time is held fixed—usually at about one second. The total accelerating voltages required are about 10 Mv for 300 and 90 Mv for 1,000 Gev. (Compare 130 kv for the 30 Gev accelerators).

Fortunately, the relativistic injection energies ameliorate greatly the rf problem. The frequency range of the rf systems is at most a few percent and may be as low as 0.5 percent for the highest contemplated injection energies.

If high-Q systems are used, the total rf power dissipated in them is proportional to  $E^2/zT^2$  (Table III) where  $E$  is the final particle energy,  $T$  is the acceleration time, and  $z$  is the specific shunt resistance of the structure (defined as the ratio of the square of the effective electric field in the rf structure to the power loss per unit length) under the assumption of a given peak magnetic field and a constant fraction of the circumference devoted to accelerating structures. Very efficient high-frequency structures (e.g. iris loaded waveguides) may be expected to have a  $z$  of about 20 megohms per meter and are single frequency devices. The rf power requirements (during acceleration) computed for such a structure are 50 kw for 300 Gev and 1.5 Mw for 1,000 Gev, and are certainly lower limits to the actual power requirements. The shunt resistance of the rf structures of the C.P.S. are about 5 kilohm/meter. Power requirements for such structures (which have a 3:1 frequency range) would be 4,000 times greater!

It is clear that rf systems with a small frequency range, with a high effective shunt resistance and with a low unit cost must be developed. Several methods are being considered, and so far appear to be possible candi-

dates. We list them in order of the likely power requirements:

- (1) Constant frequency, phase jump (Robinson, CEA)<sup>11</sup>
- (2) Mechanically tuned (Schnell, CERN and LRL)<sup>12</sup>
- (3) Variable reactance (Kearns, LRL)<sup>13</sup>
- (4) Off resonant (MacKenzie, Schnell, Symon)

TABLE III

Approximate RF Requirements		
	300 Gev	1,000 Gev
Effective volts.....	10 Mv	90 Mv
Length available.....	100 m	300 m
Minimum peak power*.....	50 kw	1.5 Mw
Probable peak rf power.....	1-2 Mw	10-20 Mw
Beam loading (10 <sup>13</sup> protons).....	0.5 Mw	1.5 Mw

$$P \propto E^3 / zT^2$$

$$z = \frac{(\text{Effective electric field strength})^2}{\text{Power per unit length}}$$

\* For  $z=20$  megohms/meter.

Among these methods the ultimate choice will depend strongly on economic analyses, as well as on a choice of the frequency desired. Frequencies from several tens of megacycles to several hundred megacycles per second—harmonic numbers of 1,000 to 10,000—give the most reasonable compromise between phase acceptance and the radial amplitudes of energy oscillation.

The ingenious method of rf acceleration proposed by Robinson of C.E.A. warrants special mention. Robinson proposes that the accelerating sections shall consist of iris loaded traveling waveguides (such as those used in electron linacs) operated at the highest frequency permitted by the required aperture—say 500 Mc. The filling time of reasonable lengths of such a guide is a small fraction ( $\frac{1}{3}$  or less) of the revolution time of the protons in the synchrotron. Robinson realized that this short filling time permits the *phase* of the rf energy in the guide to be adjusted each revolution so as to match the phase of the particle bunches, while still maintaining a unique frequency for the rest of a rotation time. Detailed analyses by Robinson have shown that stable acceleration is achievable with this “phase jump” method and that economies in rf power result.

Typical rf power requirements for U.H.E. accelerators are estimated at the order of one or more megawatts for 300 Gev (not necessarily the minimum possible power) and 10 megawatts or more for 1,000 Gev. These powers apply to losses in the accelerating structures alone. If proton intensities of greater than 10<sup>12</sup>/sec are obtained, beam loading of the rf system will become a problem. Beam interaction with the accelerating structures not only increase the rf power requirements, but can also introduce instabilities in the energy oscillations. The latter problem requires further study.

The high-frequency rf systems, although attractive in some respects, introduce a possible disadvantage. Beam control of the accelerating system becomes difficult. The period of the phase oscillations becomes only a few times the rotation period and it is possible that instabilities may arise in the lateral focusing.

### III. UTILIZATION OF HIGHER ENERGY MACHINES

The utilization of U.H.E. accelerators poses some special problems. The identification of particles and interactions at hundreds of Gev will require the refinement of current techniques and the development of new ones. A study at B.N.L. by L.C.L. Yuan and his collaborators<sup>14</sup> has indicated the directions in which these developments may proceed, and has concluded that useful experimentation at these energies is certainly feasible. The production of pure particle beams (beam separation) appears to be the most formidable one, and may well be intractable.

Perhaps the two most important ways in which an U.H.E. synchrotron will differ from the existing machines are that it will be possible to produce well collimated beams of secondary particles of rather high intensity, and that the characteristic production angles will be small. At 300 Gev, for example,<sup>15</sup> even with only 10<sup>12</sup> protons per second in the primary beam, secondary beams of pions through reasonable beam-forming systems will have intensities of 10<sup>10</sup> per second at 20 Gev and 10<sup>8</sup> per second at 100 Gev. In the same beams the anti-proton intensity will be equal to or greater than the pion intensity! The intensities at 20 Gev are higher

than would be expected at even a few Gev from accelerators of 10 to 15 Gev designed specifically for high intensity.

The most striking characteristic of secondary particle production at these energies is that the typical production angles are less than a degree, in general, and only a few milliradians for the highest energies. Extraction of the secondary beams from the synchrotron at such small angles poses special problems.

A suggestion by T. Collins<sup>16</sup> of C.E.A. provides a means of obtaining exceptionally long field-free sectors which will aid greatly in targeting for small angle beams. (See Fig. 2.) Collins shows that a focusing period of the magnet can be replaced by a straight orbit segment occupied only in part by quadrupole lens systems for maintaining unchanged the overall optical property of the section. With this system magnet-free sectors as long as one-half of the focusing period can be obtained. For the machines under consideration free sectors of 20 to 70 meters are possible. With such free-sector lengths, particles emitted at angles as small as  $\frac{1}{2}$  degree can be removed before encountering any further magnetic fields or magnet yokes.

A refinement suggested by Kerth of L.R.L. consists of providing a distortion of the orbits in the long free-sector to aid in the extraction of particles produced at zero degrees.

Small angle beams have an additional serious consequence, particularly with machines of large radius. The emerging beams remain close to the guide magnet for long distances. It appears, at first sight, that large quantities of movable shielding will be required, together

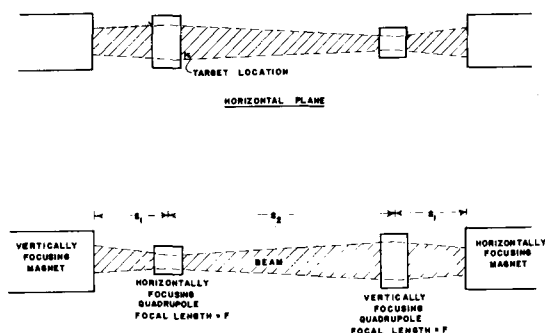


Fig. 2 Long free section in which a magnet period is replaced by a pair of quadrupoles.

with the appropriate handling equipment. The costs are frightening, and one ruefully contemplates the accelerator being idle for a large fraction of its existence while shielding is being adjusted.

Two proposals have been made to avoid this difficulty. One suggests that permanent channels be set up for the primary beam, and that all secondary beams be produced at points outside the main shielding walls. During the setup time of a particular secondary beam, the primary beam would be switched to another channel. The practicability of such a scheme depends on the development of slow beam extraction techniques of high efficiency and good beam quality. Preliminary investigations by Courant<sup>17</sup> (B.N.L.) and by Lambertson<sup>18</sup> (L.R.L.) indicate that extraction efficiencies of 30 percent or more may be possible.

Tom Collins of C.E.A. has proposed an alternative scheme in which the main accelerator magnet would be provided with "sidings" or duplicate paths, (Fig. 3) at each of several (say 4) parts of the circumference. By suitable electrical control, the circulating beam could be arranged to pass either on an "inner track" within the primary shielding, or along an "outer track" which passes out through the primary shielding and runs parallel to the main track for a short distance before returning to the "main track". All targeting would occur on the outer tracks. During the setup of an experiment the beam would be accelerated past that area on the inner track, and would be used for experiments at some other "siding".

#### IV. AN ELECTRON ACCELERATOR

M. S. Livingston and the C.E.A. group<sup>19</sup> have considered the interesting possibility of incorporating an electron accelerator in the tunnel which would be provided for a U.H.E. proton synchrotron. They have shown that the maximum electron energy for a given ex-

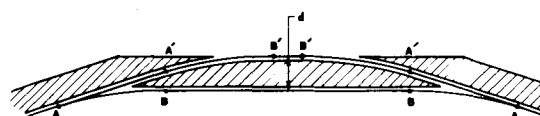


Fig. 3 Beam siding.

penditure of rf power is obtained if 1/3 of the circumference is devoted to acceleration structures and 2/3 to magnetic guide field. The peak electron energy is then determined by the power one is willing to expend. Taking 20 Megawatts as a practical maximum (the power expected to be consumed by the proton synchrotron) it is found that electrons of 70 Gev can be accelerated in a companion machine to the 1,000 Gev accelerator. (The electron radiation loss in this case is 1.5 Gev per turn!)

The compatibility of the two machines and of the associated research programs in such a dual-purpose facility certainly needs further study.

## VI. CONCLUSION

In summary, we can now see clearly the possibility of accelerators with energies 10 or more times higher than the largest existing machines. I am confident that increased experience with the present machines will point to the desirability of a step upward into this new energy range.

The currently available baricentric energies are barely 3 times the rest energy of the nucleons involved. An increase of this excess to a factor of 10 or 15 will surely open an interesting new area in particle physics. I look forward to hearing at one of our Conferences in the future—say in the early 1970's—the exciting announcement of the successful operation of a new ultra-high-energy synchrotron.

## V. COSTS

The C.P.S. and the A.G.S. cost about one million dollars (25 million Swiss Francs) per Gev. The cost per unit energy for U.H.E. machines can be expected to be significantly less. First, the increased size is accomplished mainly by an increased number of units of the machine. The design and engineering costs which are relatively fixed become a smaller fraction of the total production cost. The economies of "mass production" are realized. Second, the refinements of design have led to a

smaller magnet aperture with consequent reduction in the unit costs of power, cooling, vacuum, and rf equipment. Estimates of the costs of 300 Gev and 1,000 Gev synchrotrons have been made which indicate that the cost per unit energy will probably be about \$0.5 million per Gev, or \$150 million for 300 Gev, and \$500 million for 1,000 Gev. (The costs may be higher or lower than these figures depending on the intensity goal chosen.) These costs include the machine and basic facilities but do not include, of course, all of the necessary eventual complement of experimental equipment.

## REFERENCES

1. The preparation of this paper was greatly helped by the extensive report of the Brookhaven Study: "Design Study for a 300-1000 Bev Accelerator" which was prepared under the direction of John P. Blewett, Brookhaven National Laboratory, August 28, 1961. (The report contains a valuable bibliography).
2. N. CHRISTOFILOS, Internal Report, Lawrence Radiation Laboratory, 1961.
3. See, e.g., L. SMITH "Factors Influencing Choice of Aperture and Injection Energy in an A-G Synchrotron". Lawrence Radiation Laboratory Internal Report, LS-2 (revised in LS-4), Nov. 1960. See also Ref. 7, below.
4. E. D. COURANT, "Magnet Position Errors in Large A-G Synchrotrons", Brookhaven Internal Report, IA-3, August, 1961.
5. J. MATHEWS, "A study of the Second Difference Method for Radial Magnet Alignment," Caltech Synchrotron Lab. Report, August 1961, in press.
6. M. SANDS, "Remarks on the Alignment of Large A-G Synchrotrons", Brookhaven Internal Report IA-MS-1, August, 1961.
7. M. SANDS, MURA Internal Report No. 465, June 1959, and "A Proton Synchrotron for 300 Gev", Caltech Synchrotron Laboratory Report CTSL-10, Sept. 1960.
8. R. L. WALKER, "Beam Transfer in a Cascade Synchrotron", Caltech Synchrotron Lab. Report CTSL-16, Jan. 1961.
9. L. C. TENG, "Proposal of Using the Accelerating RF for Beam Bunching or Debunching", Paper in Session V-1, this Conference.
10. K. JOHNSEN, "Intermediate Stacking in a 1000 Gev Synchrotron", Brookhaven Internal Report IA-KJ-1, Aug. 1961.
11. K. W. ROBINSON, "Acceleration of Protons at Constant Frequency by Phase Shifting", Cambridge Electron Accelerator Internal Report CEA-82, Dec. 1960.

12. W. SCHNELL, "Mechanically Tuned RF Systems" Lawrence Radiation Laboratory Internal Report WS-2, Sept. 1961.
13. Q. KEARNS, "Main Ring RF Systems", Lawrence Radiation Laboratory Internal Report QK-1, March 1961.
14. "Experimental Program Requirements for a 300-1000 Bev Accelerator" Brookhaven National Laboratory, Aug. 1961.
15. H. TICHO, "Secondary Particle Intensities from a 300 Gev Synchrotron", Univ. of Calif. at Los Angeles, Technical Report, No. 1, April 1961.
16. T. C. COLLINS, "Long Straight Sections for A-G Synchrotron", Cambridge Electron Accelerator Report CEA-86, July 1961.
17. E. D. COURANT, "Beam Extraction from a 1000 Bev A-G Synchrotron", Brookhaven Internal Report IA-EDC-44, Aug. 1961.
18. G. LAMBERTSON, "A Slow Beam Extractor for the A-G Synchrotron", Brookhaven Internal Report IA-GRL-1, Aug. 1961.
19. T. COLLINS, et al., "Large Orbit Electron Synchrotrons", Cambridge Electron Accelerator Report CEA-38, July 1961.

## DISCUSSION

L. C. TENG: I think your estimate of 20 percent of filling factor for the linac injector is probably a little pessimistic. If we have the rf frequency matched in these two machines and use the method of unstable phase matching, I think we can get fairly close to 100 percent, by that I mean 100 percent of the available rf bucket size in the ring.

M. SANDS: My feeling from the analyses done to date is that the nonlinear problems haven't been looked at sufficiently closely to be able to say that you can get that large a debunching factor, but it would be good if you can. Do you think so?

L. C. TENG: Yes.

K. R. SYMON: I just want to make a comment with regard to the question of comparing secondary beam intensities at various primary energies. If one looks at the total number of secondaries of a given kind that are produced per unit solid angle and at very high energies, this number is much larger than at lower energies. This is partly because of an increased multiplicity but that factor is not very large. The main effect comes from increased collimation of the secondary beams. However, if one looks at secondaries of a given energy, and of course one chooses an energy which is within the reach of a lower-energy accelerator, then a little thought will show that the difference between low and high primary energies is very small, if there is any. The reason is that the collimation depends on the energy of the secondary beam, not on the energy of the primary beam, because it is the transverse momentum which is constant. Since the multiplicity is not going up very rapidly and the secondary particles are spread out over a larger

energy range, it is not at all clear whether the number per unit solid angle of secondaries, for a fixed energy secondary, goes up or down. If you study the calculations which various people have made on this effect, you find it to be true that, if you compare secondary energies at say 30 and 1,000 Bev, looking at secondaries of a few Bev, there is no significant difference between the number produced per unit solid angle at the two different primary energies. So, if one looks at the total number of secondaries, there is a big gain, but if one is just looking at the secondary energies that one would produce, say with a 30 Gev machine then, for the same intensities, one doesn't get any more, or not strikingly more, at higher energies.

M. SANDS: That would be true if the typical transverse momentum of particles of each energy were 0.3 Gev/c. In this case, the advantage of higher primary energies comes only from the increase in multiplicity.

R. F. MOZLEY: Do you have any estimates of the total cost of the machine including the fencing and the problems of the target area and things of this nature, I mean taking the whole thing into account?

M. SANDS: My talk was on general principles and the general principles of the experimental area haven't yet been sufficiently refined to make a cost estimate.

J. RAINWATER: Yesterday it was indicated that the supporting personnel to run the machine and for set-ups would probably be about 300 for a 30 Bev machine. Is this expected to go up linearly or do you have any thoughts on this matter?

M. SANDS: Almost everything goes up at least as fast as the square root of the energy. Numbers between 1,000 and 2,000 have been suggested as possible numbers for the total staff.

W. K. H. PANOFSKY: I would like to make one cautionary remark on costs which is based on bitter experience. If you start duplicating things, which of course we are doing to a violent extent in the planning for the 2-mile accelerator, there is, of course, the economy of mass production; at the same time there are many factors going in the opposite direction which, at least according to experience during the last year, tend to more than offset it. One is that the reliability requirements increase. Another is, that the question of instrumentation appears, to us at least, to go up faster than linearly. Again, taking a very elementary point of view, the number of pieces of information you need, if you want adequate instrumentation, goes up linearly; in addition, the distance you have to transmit this information also goes up. This you can counteract by more complex things about information storage and multiplexing, and so forth, but this again leads to increased costs. However, when we combine these factors with the increased inefficiency of large organizations, we think it probable that the scaling law, in our case at any rate, would go faster than linearly and that the cost per Mev of the large linac is apt to be considerably higher than that of the smaller.

M. SANDS: I think that what you say about instrumentation is particularly true of linacs where the complexity of the individual piece is large. I think there is a significant qualitative difference between the complexity of a single piece of a proton synchrotron and a single piece of an electron linac, and whether the same laws will apply is certainly not clear to me.

I meant to answer one problem posed by Hine this morning. He brought up the question of the aperture requirements for targeting. The typical scattering angle varies inversely as the energy, and the amplitude of the scattering oscillations goes as the wavelength times the scattering angle. The wavelength goes as the square root of the energy, the angle goes down as the energy, so that the typical amplitude required for targeting goes as one over the square root of the energy. Going up a factor of 10 in energy, one could come down a factor of 3 in aperture and be just as well off as he is with the present 30-Bev machines. So this is not an argument against small aperture machines. Unfortunately, the typical production angle goes as one over the energy also. So, for the same reason, the typical lateral distance a particle goes after having been produced also goes down as one over the square root of the energy. Thus, if we have an aperture of  $\frac{1}{3}$  the Brookhaven or CPS size, we'd be just as badly off as they are for small angle particles. Therefore, I think the arguments are both in favor of smaller apertures and/or more refined targeting techniques, some of the ones I mentioned—the long straight section, the zero-degree extraction, for example.

C. A. RAMM: With reference to the problems of stability of the machine that Dr. Sands touched upon, I would like to make a comment to support him in his belief that they are not overwhelming. The machine at CERN has never been realigned since installation; I believe the same is true of the Brookhaven AGS. It is known by now that there are errors of alignment of about 1 mm in both, but in neither is the error serious enough to cause much trouble. It is interesting to examine to what extent these errors would affect a 300 Gev machine. My colleague at CERN, Gunther Plass, has calculated this for a 300-GeV machine with the same distribution of alignment errors as now exist in the CERN-PS. He finds that the large machine would have a displacement of the closed orbit at maximum of only 5 cm. This is a magnitude of error which could easily be removed by realignment.

It may be useful to observe that although, in the CERN machine, every effort was made to make the magnet as uniform as possible, and successfully, no magnetic measurements were made in situ. The added complication of such a measuring program was not considered necessary. However, when one considers what has happened in the CERN machine and extrapolates the figures to a possible future machine, this omission might not be tolerable. Although the present magnet units are very uniform, the assembled system should be slightly asymmetric with respect to the horizontal plane, albeit uniformly. This particular point should be taken into account when present data are extrapolated in design considerations for future machines.