LINEAR ACCELERATOR INJECTORS FOR PROTON SYNCHROTRONS

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1. Introduction

This paper has two objectives: first, a demonstration that the linear accelerator is a suitable injector for proton synchrotrons in the Bev region and, second, a presentation of the more important aspects of linear accelerator design and performance. The latter topic will be covered by descriptions of existing and proposed machines, particular attention being given to the proposed Brookhaven linear accelerator with which the author is most familiar.

2. Possible injectors for high energy proton synchrotrons

The injection energy for a proton synchrotron is usually fixed between a lower limit set by the magnet design group, and an upper limit set by the injection group. The lower limit corresponds to a minimum magnetic field of the order of 100 gauss below which eddy currents, remanent magnetic fields, and initial transients make field correction unreasonably difficult. In the machines in the 1-3 Bev range, the available injection techniques permitted a comfortable margin above the minimum field near 100 gauss; but, as the 25-Bev region is approached, difficulties and costs associated with proton injectors and with the inflection of the proton beam into the synchrotron have forced the injection field down to approximately 100 gauss.

With increasing final energy of proton synchrotrons, the injection energy has increased from 460 Kev in the Birmingham 1-Bev machine through 3.5 Mev in the Brookhaven Cosmotron, to 10 Mev in the 6-Bev Bevatron and in the 10-Bev synchrotron in the Soviet Union. For the CERN and Brookhaven 25-Bev machines, the injection energy will be 50 Mev.

The injector for a proton synchrotron should deliver a beam of several milliamperes, of the order of 1 cm. in radius 1 milliradian in angular spread and with an energy spread of 2 or 3 parts in 1000. Only two types of injectors merit serious consideration for energies above 5 Mev. The cyclotron in either the classical or the f-m version has been used or proposed in several cases. The quarter-scale model of the Bevatron used cyclotron injection, the Canberra air-core machine will have an 8-Mev cyclotron injector, cyclotron injection will be used in the Delft synchrotron, and other proposals for cyclotron injectors are heard from time to time. Improved methods for collimating external cyclotron beams will, no doubt, encourage further consideration of these ideas. On the whole, however, the difficulty of ejecting a clean, well-focused beam of high intensity from a cyclotron militates against its use and results in a marked preference for the other candidate, the linear accelerator. In machines aimed at proton energies of 6 Bev, or higher, the linear accelerator has been chosen in four out of the five cases.

3. The Bevatron injector

The first successful use of a linear accelerator, as an injector for a proton synchrotron, was in the Bevatron in 1954. The Bevatron injector accelerates protons from 500 kev to 10 Mev and is similar, in its basic electrical and mechanical design, to the original Berkely 32-Mev linear accelerator designed several years earlier by Alvarez and his associates. Its general features are indicated in fig. 1.

Protons, originating in a cold-cathode ion source, are accelerated to 500 kev by a Cockcroft-Walton cascade

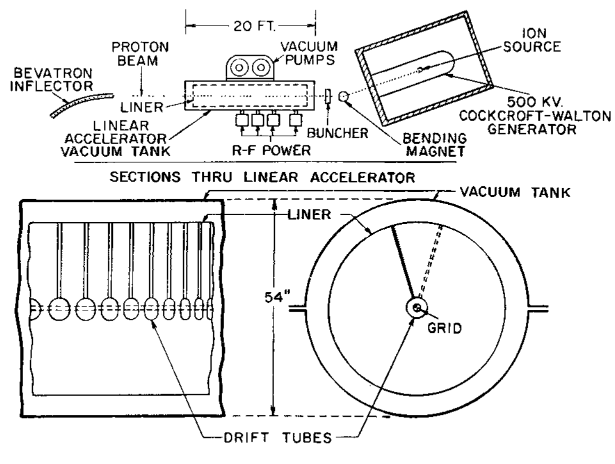

Fig. 1. Bevatron injection system

rectifier set. They then enter the so-called "buncher" in which they traverse an axial electric field having the same 200 Mc/sec frequency as the field in the linear accelerator proper. A drift space of 1 m. is included in which the protons bunch themselves around the correct accelerating phase. Inclusion of the buncher results in an increase, by a factor of about three, in the phase acceptance and, consequently, in the intensity of the linear accelerator.

The linear-accelerator tank, itself, is a resonant cavity about 6 m. long operating in the TM_{010} mode; the primary axial electric field is in phase from one end of the tank to the other. At its proper phase, this field accelerates the protons; at other phases, the proton bunches are shielded from the field as they pass through the so-called "drift tubes".

The radiofrequency resonator is a sheet-copper structure built by an aircraft company which used the specialized construction techniques developed by the aircraft industry. The drift tubes are hung inside this structure on radial pipes which do not perturb the TM_{01} field pattern appreciably because no field components exist parallel to their axes. The resonator, or "liner" with its drift tubes is enclosed in a steel vacuum tank split along a horizontal plane into an upper and a lower half so that it can be opened like a seashell.

The operating frequency for the accelerating field is determined by certain geometrical considerations. Firstly the drift-tube aperture must be large enough to accommodate the proton beam which is of the order of 2 cm. in diameter. Secondly, if the drift tube is not materially longer than its aperture, the protons will not be well shielded from the field during its phase reversal, the gap coefficient will decrease and the efficiency of the machine will drop. Since in one cycle at 200 Mc/sec, a 500-Kev proton travels 4.5 cm., and this distance is a measure of the length of drift tube plus accelerating gap, it is evident that frequencies above 200 Mc/sec will not be suitable for use with 500-Kev protons. Use of lower frequencies, on the other hand, will increase the diameter of the resonator in inverse proportion to the frequency. Although frequencies in the 50 Mc/sec range are proposed for heavy-ion linear accelerators in the United States it does not seem reasonable to go below 200 Mc/sec for the acceleration of protons.

To maintain the electric fields which will accelerate protons to 10 Mev in 6 meters, very powerful radiofrequency sources are required. Although the Q factor of the cavity is about 90,000, the r-f power dissipation in the cavity is still about 500 kw. This power is supplied at four r-f stations by three triode oscillators and one loosely coupled pre-exciter. The latter is an amplifier which builds up power in the cavity at the correct mode and forces the r-f field through the so-called "multipactor region"—a low-field region in which stray electrons take exactly an odd-integral number of half periods of the radiofrequency to travel from one drift-tube face to the next. When this occurs, secondaries travel back along the original path and liberate more secondaries in a sort of chain reaction which eventually can lead to breakdown. This phenomenon occurs not only between drift tubes but also in other regions of the resonant structure. It has been found that the system can be driven through this region by a pre-exciter into a safe region of high fields where resonance of this sort no longer occurs.

When the correct radiofrequency field is established, an injected beam of protons will undergo a selection process similar to that which takes place on injection into a synchrotron. Bunches of protons will be accepted by the machine and will be accelerated with oscillations, in phase and position, similar to the phase and radial oscillations which occur in the synchrotron. Unfortunately, the protons which are stable in phase are unstable in radius. This is easily understood from the fact that protons are focused in the converging field pattern at the downstream end of each drift tube and then defocused as they enter the diverging field pattern at the upstream end of the next drift tube. Since phase stability occurs when the field between drift tubes is rising, the defocusing action is stronger than the focusing action and the beam is subjected to a strong and continual defocusing action which would destroy it in a very short distance. This effect has been compensated in the Berkeley linear accelerator by the inclusion of grids in the upstream ends of all drift tubes. This prevents the field pattern from diverging and provides a net focusing action. As a solution of the problem it leaves something to be desired, however, since the grids intercept a large fraction of the beam. When the grids are reduced in structure to a couple of thin strips of tungsten so that less beam is intercepted, they begin to constitute rather poor lenses with aberrations so large that protons are again lost in large numbers. It has not been possible to design focusing grids which do not reduce the beam, by a factor of at least five, in a 10-Mev accelerator.

After leaving the linear accelerator, the beam from the Bevatron injector passes through several focusing quadrupoles and enters the electrostatic field which inflects it into the Bevatron vacuum chamber.

The basic parameters of the Bevatron injector may be summarized as follows:

Injecting energy	460 Kev
Final proton energy	9.9 Mev
Frequency of accelerating field	202.5 Mc/sec
Q of resonant system	90,000
Radiofrequency power dissipated	500 kw
Equilibrium phase	about 25° before peak of r-f wave
Length of vacuum tank	6.05 m.
Diameter of vacuum tank	1.37 m.
Pressure in vacuum tank	2×10^{-6} mm. Hg
Length of liner	5.55 m.
Diameter of liner	1.076 m.
Number of drift tubes	42
Length of first drift tube	3.7 cm.
Length of first accelerating gap	1.3 cm.

Diameter of first drift tube . . .	14.1 cm.
Length of last drift tube	15.7 cm.
Length of last accelerating gap .	5.2 cm.
Diameter of last drift tube . . .	6.4 cm.
Duration of radiofrequency pulse	700 microseconds
Duration of proton pulse	500 microseconds
Best injected current at 460 kev .	6 milliamps.
Best output current at 9.9 Mev .	400 microamps.
Diameter of accelerated beam . .	less than 2 cm.
Angular spread of accelerated beam	$\pm$ 0.0015 radians
Energy spread in accelerated beam	less than 30 kev

4. Linear accelerator injector for the Brookhaven alternating-gradient synchrotron

a) Basic parameters

In the opinion of the Brookhaven magnet group, the field in the synchrotron magnet will not reach a sufficiently stable configuration for injection at fields less than about 100 gauss. At this field the injection energy is about 50 Mev. Higher injection energies would be desirable from the point of view of the magnet designers, but inflection considerations (to be discussed by later speakers) indicate that injected proton beams of energies above 50 Mev would introduce problems in the inflection system which are very unpleasant. In the Brookhaven design the inflector plates must be charged to about plus and minus 100 kV and must be discharged in less than one microsecond for 50 Mev injection. There appears to be very little range for compromise in this problem and the choice of 50 Mev for injection is almost automatic.

Since the multiple-turn injection used in conventional synchrotrons is no longer possible and the duration of the injection pulse must be less than the duration of one revolution (about 7 microseconds), it will be desirable to inject a beam of as high a density as possible. If milliamperes of current are desired, very little loss can be tolerated in the linear accelerator and it seems important to replace the conventional system of grid focusing by a system which does not introduce aberrations and which does not intercept a large fraction of the beam during acceleration. Several methods for focusing have been studied and will be discussed below.

Although it is tempting to decrease the operating frequency below that of the Bevatron injector to enter the range where transmitting tubes with higher power ratings are available, it was finally concluded that the increased diameter of the machine and the difficulties of aligning drift tubes at the ends of long stems would more than offset the expected difficulties in power generation at 200 Mc/sec. Consequently the Brookhaven machine will be designed for operation at 200 Mc/sec.

The injector must have a very high order of reliability since its breakdown will stop operation of a large and expensive machine. It should be very conservatively designed with respect to electric fields so that breakdown will be avoided. Accordingly, these fields have been held at, or below, those in the Bevatron injector with the result that the overall length of the 50-Mev accelerator will be about 33 m.

Advantages of simplicity in design, construction, and operation of the machine attend the use of a single tank for the whole machine, rather than the several tanks that have been used, for example, in the research machine at the University of Minnesota. The problems of r-f moding and stability, which are associated with a long tank, must be controlled by a conservative design of the radiofrequency system and by attention to the temperature stability of the tank.

These considerations and many others have led the Brookhaven group to the design described below.

b) The pre-injector

Although injection at several Mev from an electrostatic machine would simplify the low-energy end of the linear accelerator, several disadvantages accrue from this choice. The worst disadvantage is associated with the necessity for enclosing such a pre-injector in a pressure tank. During the early trial period, each minor change or repair to the ion-source assembly involves several hours of removal of high-pressure insulating gas, removal of a large and heavy tank, drying and repressurizing the tank. The space available in this type of pre-injector for ion sources of large or unconventional form is seriously limited. Finally, the energy spread at the exit of the linear accelerator, which is a rising function of value of the injection energy, would be too large to be accepted by the synchrotron. Consequently, we have chosen to inject into the linear accelerator at a proton energy of 750 Kev from a Cockcroft-Walton set which will be operated at atmospheric pressure.

We have placed an order for such a set with the Philips Company of Eindhoven, Holland. This set will be of conventional design and will use selenium rectifiers. It will include a cascade-generator stack and a filter stack and will be capable of supplying over 5 milliamps at the operating voltage. This high current capability is advantageous because currents of the order of 1 milliampere, through high-voltage resistor chains, can be used for voltage monitoring and voltage distribution along the accelerating column.

c) Choice of radiofrequency accelerating system

Although the radiofrequency system of the Berkeley linear accelerators is apparently quite satisfactory, it was felt, at Brookhaven, that a preliminary study of alternative systems might result in an improved design. In any case, it seemed that a study of different systems would be valuable education for our group which had had no previous linear-accelerator experience. The objectives of this study were possible improvements in mechancial design, possible use of traveling waves instead of the conventional standing wave system, and possible improvement in power consumption. Power consumption is best described in terms of a quantity known to linear-accelerator designers as the shunt impedance. Its value is given by the ratio:

$$\frac{(\text{Proton energy gain per meter, in volts})^2}{(\text{Radiofrequency power dissipation per meter, in watts})}$$

This ratio has the dimensions of ohms per meter, and should be as high as possible. For the 32-Mev linear accelerator at Berkeley and for the Bevatron injector the shunt impedance is about 30 megohms per meter.

Travelling-wave helix types of accelerating systems present the advantages of small dimensions and relatively high shunt impedance but are difficult to construct mechanically and do not permit the inclusion of small focusing units. Since these systems have been studied in detail by Johnsen, both in Bergen and with the CERN group, and since the CERN group has decided against their use, no further study of helix systems was undertaken at Brookhaven.

A new system usable with either traveling waves or standing waves is shown in fig. 2. This system has been named the "interdigital" system because it consists of

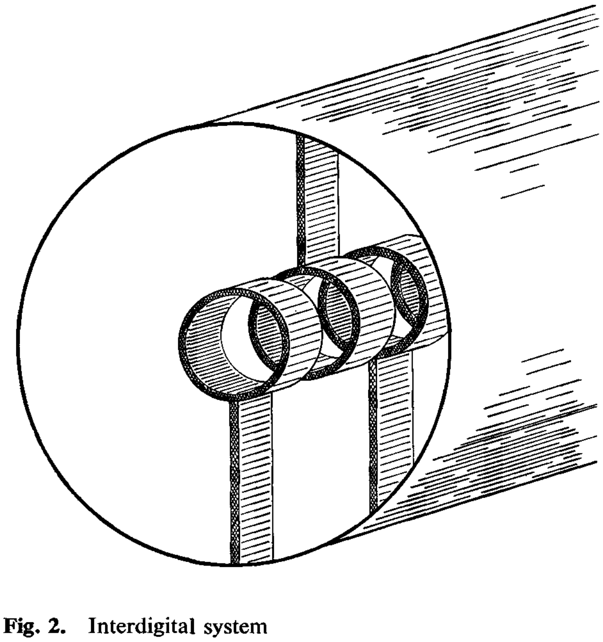

Fig. 2. Interdigital system

drift tubes connected alternately to opposite sides of a cylindrical wave guide. In this structure, each half of the waveguide remote from the axis supports a TE_{01} field mode. The protons travel from one gap to the next in approximately one half of an r-f cycle instead of a full cycle as in the Berkeley machines. The waveguide is loaded by the drift-tube structure to the extent that its diameter is reduced to less than half of the diameter of a machine of the Berkeley type operating at the same frequency. In the low-energy range, up to about 10 Mev, model tests showed that this system has a shunt impedance about twice as high as that of the Berkeley system. For higher energies it drops rapidly until, at 50 Mev, the shunt impedance has fallen to about half of that of the Berkeley system. For a 10 or 20-Mev linear accelerator this would apparently be a system worthy of further consideration. For the 50-Mev machine, however, its overall shunt impedance is lower than that of a machine of the Berkely type; accordingly, it has been abandoned for our purposes.

A third possible system is shown in fig. 3. For obvious reasons this is known to us as the "organ-pipe" system. This is a traveling-wave system in which it is easily possible

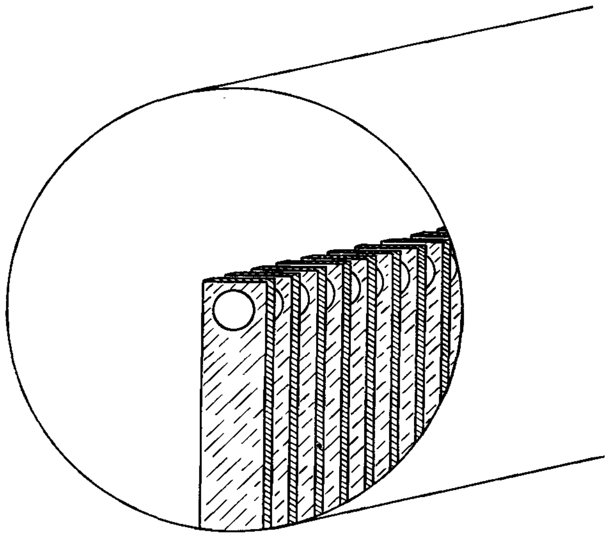

Fig. 3. "Organ-Pipe" system

to decrease the phase velocity of the traveling wave to match proton velocities in our range. This system has been analyzed theoretically and experimentally and it is found that the field pattern is strongly localized around the series of stubs which protrude from one side of the cylindrical container. The fields decrease, roughly exponentially, with distance from the stubs; thus, the fields at the container walls are small and introduce very small losses. In the neighborhood of the stubs remote from their ends, the fields have the peculiar feature that both magnetic and electric fields, parallel to the stubs, are zero. In this *region there is no Poynting vector and energy propagation* takes place only in the region around the stub ends. The stub length is slightly less than a quarter wavelength. Phase velocity, down the array, varies very rapidly with stub length, thus, the phase velocity can be varied from that of a 750-Kev proton to that of a 50-Mev proton by a change in stub length of only about 20 per cent. Losses in this system are primarily due to the currents flowing along the stubs. In the region around 50 Mev, it appears that this system would have a shunt impedance materially higher than that of the Berkeley system. At lower energies, however, the losses increase because so many stubs must be included per wavelength to establish the field pattern. Consequently, it was concluded that this system is appropriate for energies in the range above 50 Mev and further study of it has been abandoned for this application.

A fourth system, proposed by Christofilos, is illustrated in fig. 4; he has succeeded in deriving an analytical solution for the field patterns in cavities of the form shown. The

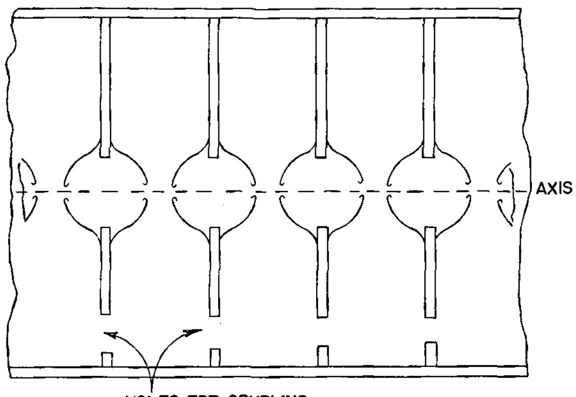

Fig. 4. Christofilos multiple cavity system

procedure involves the synthesis of a field pattern and computation of the cavity shape which supports the assumed fields. This is also a traveling-wave system. Energy flows from one cavity to the next through holes whose diameter can be adjusted to give the correct phase to the successive accelerating gaps. The ability to adjust phase in this fashion would make it possible to make large numbers of successive cavities identical except for the coupling holes and would introduce some mechanical simplification. However, the shunt impedance of this system is always less than that of the Berkeley system.

The fifth, and final, system evolved from Christofilos' cavity calculations. He observed that a special case of the field pattern exists in which the protuberance on the cavity wall has a normal incidence with the wall. In this case the wall can be omitted and the system reduces to the Berkeley system except that the drift-tube shape has become approximately elliptical. The drift-tube diameter has been increased in a region where high losses are experienced in the Berkeley design and the overall shunt impedance of the new system is higher by about 20 per cent than that of the Berkeley system. In the enlarged drift tubes, more than adequate space is available for focusing means and for water cooling. With these drift tubes it is possible to include the whole 50-Mev accelerator in a tank of constant diameter. Since, moreover, the theoretical analysis gives a complete picture of the field patterns everywhere in the accelerator, this design has been chosen for the radiofrequency system of the Brookhaven machine. The shapes of the drift tubes are now being computed by the UNIVAC at New York University; hand computation would involve about one week per drift tube and 124 drift tubes are needed in the accelerator. The method of computation is included in a later paper by Christofilos.

d) *Mechanical design of linear-accelerator tank*

The separation of radiofrequency cavity and vacuum tank, that has been conventional in linear accelerators, introduces mechanical and electrical complexities which should be removable by a combination of the two structures. The Brookhaven linear accelerator will be constructed in sections about 3 meters long. Each section will be a heavy steel pipe about 1 meter in diameter lined with a layer of copper about 6 mm. thick. Flanges on the ends of the sections will make possible the assembly of all of the pipes into a machine 33 m. in length. Details of construction are shown in fig. 5. The ends of the tank sections will be supported on linear bearings so that part

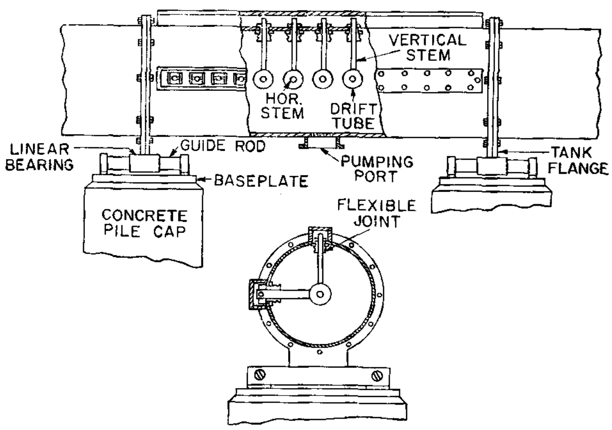

Fig. 5. Brookhaven linear accelerator injector for A.G.S.

of the tank can be moved in the axial direction to permit removal of any tank section. The bearings, in turn, are mounted on pile caps which cover the tops of steel piles driven 12 meters into the Long Island sand.

The drift tubes are supported from adjustable structures on the outside of the tank wall. Each drift tube has two supports: a relatively heavy horizontal pipe of the order of 3 cm. in diameter, and a light vertical tension member about 1 cm. in diameter. Drift-tube supports are arranged so that each drift tube can be adjusted in position and then maintained in its final alignment by introduction of shims. It is hoped that each drift tube can be aligned and maintained in a position which is within 0.2 mm. of its correct position.

The shape and construction of an individual drift tube is shown in fig. 6. Each drift tube is cooled by water which flows in through one drift tube support and out through the other support. Fig. 6 shows the location, inside the drift tube, of the focusing magnet structure to be discussed in Section 4f below.

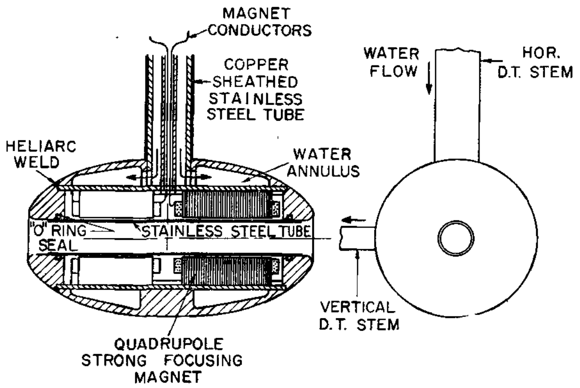

Fig. 6. Brookhaven linac injector drift tube

The temperature of the tank will be held constant to about 0.1 °C by a thermostatically controlled water-cooling system. By this means it should be possible to obtain preliminary tuning of the tank to resonance at the design frequency and a preliminary suppression of unwanted modes to the extent that servo-controlled tuning will not be necessary. A number of tuners will be included, probably in the form of spheres movable along a tank radius, but no automatic position controls will be added unless operation shows that they are necessary in spite of the tank's temperature control.

e) *Radiofrequency power supply*

In all proton linear accelarators built, thus far, one of the worst problems has been the radiofrequency oscillator or amplifier system to supply the pulsed power of hundreds or thousands of kilowatts required to excite the resonant structure. In the Brookhaven case, about 2.5 Megawatts of power will be required at a frequency of 200 Mc/sec. The only suitable power tube which is commercially available in the United States is the 250-kW Eimac 3W10000A3 triode or its tetrode version, the 4W20000. These are the tubes which have been used with the Berkeley accelerators. The Brookhaven machine will be designed so that it can use these tubes if necessary. In all probability, the triodes will be used as amplifiers so that the tank can be driven at its correct resonant frequency without the moding difficulties to be expected with self-excited oscillators. Also, an amplifier system should avoid the hazards associated with the multipactor region.

If proton currents of milliamperes are successfully injected and accelerated, changes in resonant frequency due to beam loading may be experienced. These can be observed by the resultant phase shift between tank fields and driving voltage and the information can be fed back into the driving oscillator to restore it to the correct frequency.

It is hoped that the radiofrequency problem will be reduced to more manageable proportions by the development of a 5-Megawatt 200 Mc/sec klystron. Experts in the klystron field are sure that this development can be successful. Therefore, we are negotiating a contract for the development of such a klystron and anticipate that its delivery time will permit its inclusion in the final machine.

f) *Radial focusing*

With the decision to abandon grid focusing, we have initiated studies of several other kinds of focusing. Pulsed, axial, magnetic fields from solenoids embedded in the drift-tube structure, and various types of electric and magnetic alternating-gradient focusing have been considered. All of these methods are sensitive to mechanical misalignments.

In a pulsed solenoid system, fields of the order of 20,000 gauss are necessary. Power dissipation is high enough that the windings must be water cooled. Stray fields around the rather heavy water-cooled leads to such solenoids would make precise alignment of the resultant field very difficult.

Electrostatic alternating-gradient focusing would require voltages on quadrupole electrodes of the order of 20 kV with attendant hazards of electrical breakdown.

Magnetic alternating-gradient focusing requires field gradients, at the low-energy end of the accelerator, of the order of 6000 gauss per cm. diminishing rather rapidly to about one tenth of that value at the high-energy end.

Although other systems have been studied and modeled, it now appears that magnetic alternating-gradient focusing

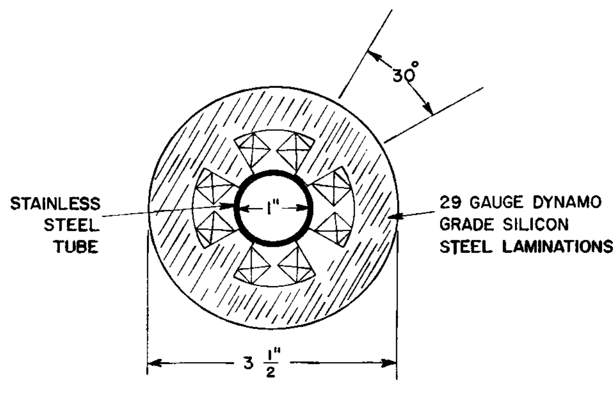

Fig. 7. Pulsed quadrupole magnet

is the most satisfactory choice. A number of experiments have been performed on permanent-magnet quadrupoles and it has been shown that good quadrupole fields can be attained by suitable magnetization of rings of permanent-magnet materials. The best material for this purpose is Ferroxdur, or one of its commercial variants. In this material, the highest gradients attained were of the order of 1000 gauss per cm., thus, the use of permanent-magnet quadrupoles would necessitate a decrease in the rate of proton acceleration at the low-energy end of the machine. However, further consideration of permanent magnets was stopped when it was concluded that orbit computation could not be accurate enough to establish the most desirable field gradient. Therefore, in view of the necessary variability and of the desirability of maintaining a uniform rate of acceleration throughout the length of the accelerator, pulsed quadrupole magnets have been chosen for the focusing system.

Both iron-core and air-core quadrupoles have been investigated and the final choice has not yet been made. Fig. 7 is a sketch of our present iron-core quadrupole design. Methods have been evolved for thorough exploration of the magnetic field pattern, and the pole shape of the magnets will undergo modification to give minimum field distortion at the operating fields. In magnets of the size necessary at the low-energy end of the accelerator, it has been shown that field gradients of 10,000 gauss per cm. are relatively easily attainable. We are indebted to the CERN group for a great deal of our design information.

The magnetic axis of the pulsed quadrupoles can be located by magnetic measurement to within about 0.05 mm. J. G. Cottingham has pointed out that the location of this axis, when the quadrupole is mounted in the drift tube in the final machine, can be checked by observation of the deflections of an unaccelerated 750-Kev proton beam when each magnet is pulsed individually. Experiments on the effects of pulsed quadrupole misalignments on a 100-Kev proton beam have been made at Brookhaven, and have shown that quadrupole alignment to 0.1 mm. is possible from observations of this type.

g) *Proton dynamics in the linear accelerator*

The stable phase in the Brookhaven linear accelerator will be 25° before the peak of the radiofrequency wave. Approximately four complete oscillations, in phase, will occur between injection and 50 Mev; during this period the amplitude of the oscillation will be damped by a factor of about five. A 10-degree error in phase, at injection, will result in an energy spread, near injection, of about 2 per cent; at 50 Mev, this energy spread will have been damped to about 0.2 per cent. Larger initial phase errors will result in correspondingly higher final energy errors.

With the proposed alternating-gradient focusing, beginning with field gradients of about 5000 gauss per cm. and ending with field gradients of about 1/10th this amount, the radial oscillation will have a slightly lower frequency than the phase oscillation.

Position errors of x cm. in the focusing magnets will result in deflections of the protons from the beam axis, at the Nth drift tube, by amounts of the order of $\sqrt{N}\,x$. Since misalignments of the order of 0.3 mm. are expected in the drift tube positions, the drift-tube aperture will be gradually increased along the machine. From the 750-Kev injection point to 1.5 Mev, the aperture will be 1.27 cm.; from 1.5 Mev to 3.0 Mev, the aperture will be 1.90 cm.; from 3.0 Mev to 6.0 Mev, the aperture will be 2.54 cm.; and from 6.0 Mev to 50 Mev, the aperture will be 3.18 cm.

The proton orbits to be expected are discussed in more detail in a subsequent paper by Lloyd Smith.

h) *Buncher and debuncher*

As in the Bevatron injector, a proton buncher will be included between the 750-Kev pre-injector and the entrance to the linear accelerator. This will be a cavity located at the exit of the Cockcroft-Walton accelerating column and distant 2.7 m. from the entrance to the linear-accelerator tank. In this cavity, the protons pass a gap across which is maintained a 200 Mc/sec voltage of about 5000 volts, peak. As the protons travel through the 2.7-m. drift space, the accelerated protons overtake the decelerated protons and, if the buncher signal has been correctly phased, the protons enter the linear accelerator bunched around the equilibrium phase. This should result in a gain, by a factor of the order of three, in proton acceptance by the linear accelerator.

The debuncher, proposed by K. Johnsen of CERN, performs the inverse function for the 50-Mev protons after acceleration. The well bunched beam, from the linear accelerator, drifts for a distance of about 12 m. during which the protons with too high energies move away from the protons with too low energies. The beam then passes through a gap across which a correctly phased 200 Mc/sec voltage, of about 700 kV, will act to reduce the energy spread by a factor of about three. This will yield a final beam whose energy spread is well within the $\pm$ 0.3 per cent that is considered to be suitable for injection into the synchrotron. The debuncher may include two gaps in a configuration similar to that surrounding the last two accelerating gaps in the linear accelerator.

i) *Building and linear accelerator location*

The linear accelerator injector for the Brookhaven alternating-gradient synchrotron will be located almost diametrically opposite the target building. This location has been dictated primarily by the terrain—at this point a minimum of excavation will be required for the linear accelerator building. This building will consist of a tunnel about 10 m. wide and 40 m. long which encloses the linear accelerator proper, and a house at the head of the tunnel about 18 m. by 21 m. which will enclose the 750-Kev pre-injector, the control room and several shops and laboratories.

The axis of the linear accelerator lies approximately on an extension of the synchrotron straight section in which injection is to take place. Between the output end of the linear accelerator and the inflection system of the synchrotron, the proton beam must travel a distance of about 40 m.

The building is scheduled for completion during the summer of 1957. Installation of linear accelerator components will proceed immediately thereafter and it is hoped that the machine can be ready for its first tests during 1958.

j) *Brookhaven Linear-Accelerator Group*

About ten physicists and engineers have been active in the design of the Brookhaven linear accelerator. Dr. Lloyd Smith, on leave from the Berkeley Radiation Laboratory, Mr. N. C. Christofilos and Dr. J. W. Bittner have made many contributions to all aspects of the machine design. The radiofrequency group includes Mr. J. G. Cottingham, Mr. S. Giordano and Mr. J. D. Kiesling. Mr. I. Polk is in charge of all phases of mechanical design and Mr. J. Spiro is responsible for wiring and control systems. Much of the early work on the focusing quadrupoles was done by Mr. A. Vash.

5. The CERN linear accelerator

Since the same limitations apply to magnet design in Geneva and at Brookhaven, it is not surprising that the CERN group has also chosen to inject at 50 Mev into their proton synchrotron. The basic parameters of the CERN and Brookhaven machines are very similar. Both machines have 200-Mc accelerating fields, both machines are approximately 30 m. long, and both machines use Cockcroft-Walton cascade generators for pre-injectors; the CERN pre-injection is at 500 Kev whereas the Brookhaven pre-injection is at 750 Kev.

In mechanical design the machines are quite different. The CERN group has chosen to take advantage of a linear-accelerator design project at Harwell and has been able to place orders with the same firm that is fabricating components for Harwell. The CERN machine will be constructed in three tanks. The first, in which acceleration takes place from 0.5 to 10 Mev, will be about 6 m. long; both the second, 10 to 30-Mev tank and the third, 30 to 50-Mev tank will be about 11 m. long. Each vacuum tank is split in the horizontal plane into half-cylinders just as in the Berkeley machines. The radiofrequency resonant structure is a separate liner also similar, in basic design, to the liners in the Berkeley machines.

Radiofrequency power will be supplied by triode amplifiers now under development in France. These amplifiers will be driven through two stages of German tubes by a modified 800-watt television transmitter. Servo-controlled tuners, in the tanks, will keep them resonant at the applied frequency.

Focusing in the second and third tanks will be by D.C. quadrupole magnets. The first tank was originally designed for grid focusing but will probably be converted to pulsed quadrupole-magnets. Because of the lower injection energy, somewhat higher field gradients will be required at the 500-Kev end of the machine than at the injection end of the Brookhaven machine. The required gradients of 10,000 gauss per cm have already been achieved in bench tests by the CERN group which has also developed ingenious and precise methods for locating the axis of magnetic symmetry to a precision of better than 0.1 mm.

The CERN machine will not be discussed in detail since more authoritative information can be obtained by a visit to the CERN linear-accelerator group at the CERN site in Meyrin.

6. Conclusion

Several other proton or heavy-ion linear accelerators exist or are under construction. It is the author's understanding that a linear accelerator injector for a 10-Bev proton synchrotron is now in operation in the USSR. This machine has similar ratings to the Bevatron injector. It is to be hoped that further details of its design and construction will become available at this meeting. Heavy-ion linear accelerators are under construction at Berkeley and at Yale University. Lower-energy linear accelerators, designed for operation at high intensity, have been constructed and operated at the Livermere Laboratory of the University of California. The successful operation of these various machines, and the general agreement with theoretical predictions, leads to the conclusion that the design principles of proton linear accelerators are well established. Many improvements both in mechanical and electrical design have still to be made, but it seems that no serious difficulty should be experienced in the use of the proton linear accelerator as an injector for proton synchrotrons. It should be quite possible to achieve proton currents of many milliamperes at energies up to several hundred Mev whenever these are required.