Proton Linear Accelerators for Nuclear Research, and the A.E.R.E. 600 MeV Project.

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1. – Introduction.

A certain proportion of our work at Harwell is devoted to fundamental research, and we already have one high energy machine which is used in a part of this programme. This is the 110-inch synchrocyclotron, which has been operating for nearly 5 years, producing 175 MeV protons. When planning our future programme we took into account the existence of CERN, with its plans to construct a 25 GeV proton synchrotron and a 600 MeV synchro-cyclotron, in addition to the national requirements of the United Kingdom itself. In these circumstances, with access by British physicists to particles of the highest energies assured by our participation in CERN and with a considerable variety of accelerators already existing in Great Britain, we were attracted by the possibilities offered by a large proton linear accelerator. Such a machine would be designed to give high intensity of real events in the experiments, and would be complementary to the CERN programme and to our own existing facilities.

In what follows it is the intention to discuss the project in general terms and from the point of view of the user of the machine and not the constructor. We assume that protons are required, and do not attempt to discuss the relative merits of protons and electrons in nuclear physics.

2. – General Features of Linear Accelerators.

The linear accelerator has certain obvious advantages over other type of machines:

1) There is no beam extraction problem, so that flexibility and high intensity should be assured.

2) The machine can be built in stages, and can be extended to higher energies if the nuclear physics situation appears to justify this at any time.

We first have to consider the energy range in which a linear proton accelerator appears to be a sensible proposition. This is largely an economic question; economics rather than technology have for some time determined the useful energy range of large accelerators. The cost of high energy accelerators may be summarised very roughly as follows in Table I.

TABLE I.

Large synchrocyclotron ($\sim$ 600 MeV)	\$ 8.00 per keV
(The cost of a synchrocyclotron varies non-linearly with energy)	
Conventional proton synchrotron	\$ 3.00 per keV
Large alternating-gradient proton synchrotron . .	\$ 1.00 per keV

The cost of a large proton linear accelerator is not yet known with any accuracy, but it may be assumed to be of the same order as that of a synchrocyclotron of the same energy — perhaps somewhat higher. In the present stage of development the A.G. proton synchrotron is the best machine for the highest energies, and we have to compare the proton linear accelerator with the synchrocyclotron, in the energy region of a few hundred MeV.

3. – π-Meson Physics.

If we are correct in assuming that π-mesons are closely concerned with the nature of nuclear forces, we shall need to compile a great deal of precise experimental data on the particles for a long time to come. Two kinds of experiments are involved:

1) *Studies of production phenomena.* We have to determine production cross-sections, angular distributions, energy dependence, and so on. These are « primary beam » experiments and the intensity of existing machines appears to be sufficient for such work.

2) *Experiments in which π-mesons are the bombarding particles.* Here we are concerned with such quantities as differential scattering and reaction cross-sections of nucleons and nuclei, and we have first to produce the π-mesons in nucleon-nucleon collisions. These are « secondary beam » experiments, and the intensity offered by existing machines is insufficient for really precise work. There is a case for building an accelerator with an increased useful yield of π-mesons.

3˙1. *Meaning of « useful yield ».* – We always mean number of particles $cm^{-2} s^{-1} MeV^{-1}$ entering the experimental equipment, with the proviso that the total number per second per MeV interval must also be large, since a large flux in a vanishingly small area is not useful! We need for precise experiments:

a large number of events to observe . . . .   *good statistics*
small energy spread, since most of the phenomena
   which we investigate are energy dependent . . .   *good spectrum*
a well-collimated beam, since most of the phenomena
   which we investigate are dependent upon the angle
   of observation with respect to the beam . . . .   *good geometry*

4. – Comparison of Proton Linear Accelerator and Synchrocyclotron.

4˙1. *Experiments in which an external beam must be used.* – The flux of protons, available as a collimated beam in a well-shielded enclosure, reported from various cyclotron laboratories, varies over the range

$$10^5 \div 10^7 \text{ protons } cm^{-2} s^{-1} .$$

A proton linear accelerator giving a mean current of 1 µA, which is a typical internal beam current for a synchrocyclotron, in an area of 5 cm² would give a useful flux of

$$\sim 10^{12} \text{ protons } cm^{-2} s^{-1} .$$

There would therefore be an enormous gain, by at least a factor 10^5, over *present* synchrocyclotron yields. For example at 450 MeV where the cross-sections have been determined, the reaction

$$p + p \to \pi^+ + d$$

would yield a flux of π^+-mesons in an experimental target of

$$\sim 4 \cdot 10^5 \pi^+ \ cm^{-2} s^{-1} ,$$

with good energy resolution. Corrected for energy spread, this represents an improvement by nearly a factor 10^4 over existing π^+ yields.

The external beam of synchrocyclotrons may be greatly improved if a new method, not yet fully tried, should prove successful. The expected maximum improvement is by about a factor 100. Moreover, the optics of beam focusing devices could undoubtedly be improved. But even allowing an additional factor 100 for improved focusing, and both these estimated possible factors

of improvement are optimistic, the external beam of the proton linear acce-
lerator would still be greater by one or two orders of magnitude (*).

The final comparison would depend upon the relative beam currents of
proton linear accelerators and synchrocyclotrons after continued development
of both types of machine but the linear accelerator would always produce a
much higher ratio of real events: background events since the whole beam
would be available externally.

4·2. *Experiments in which the internal beam of the synchrocyclotron may be
used.* – All synchrocyclotron experiments with beams of high energy neutrons
are performed with the internal beam, since the highest possible intensity is
required. There would be two advantages to be gained by using a proton linear
accelerator:

i) *The energy distribution would be better*. The energy spread (width at
half height) of the beam of a high energy linear proton accelerator would be
about 1%, whereas the internal synchrocyclotron beam has a spread of 5-10%
as a result of radial oscillations of the protons. Smaller energy spread has been
achieved with synchrocyclotrons, but only with great loss of intensity. Hence
there would be a larger yield per unit energy interval of the high energy neutrons.

ii) *The background radiation would be lower*. All the protons in the synchro-
cyclotron, except for the small number (a few per cent) which make nuclear
interactions in the internal target, stop somewhere inside the machine and
produce unwanted neutrons. The beam of the proton linear accelerator could
be brought intact through a hole in a shielding wall, passed through the target
and led away for a considerable distance before being stopped. Moreover it
should be possible to bring experimental apparatus much closer to the neutron-
producing target, since there are no magnet poles and coils to intrude. A
factor of at least 10 should be gained, in useable intensity, by the use of a
linear accelerator producing the same beam current as a synchrocyclotron.

The internal synchrocyclotron beam is also much used in experiments with
π-mesons, and at present time fluxes $10 \div 1000$ π^--mesons cm^{-2} s^{-1} are
available, the value in this range depending upon the meson energy.

It is estimated that 1 μA of protons at 450 MeV, from a linear accelerator,
would produce from a carbon target a flux $\sim 10^5$ π^--mesons cm^{-1} s^{-1} with a
similar energy spread to that at present available in the synchrocyclotron meson
beams. The gain is simply due to better geometry. The mesons produced by
a synchrocyclotron have to travel rather a long distance from the internal

(*) *Note added in proof.* – The regenerative beam extraction system has now been
put into operation at Liverpool, with spectacular success. 2% of the internal beam
of the Liverpool synchrocyclotron is now available externally.

target to the experiment, passing through the fringing field of the magnet on the way. Some focusing is produced by the fringing field, but only over a rather small solid angle. Undoubtedly this focusing could (and should) be improved; perhaps it would pay to use specially shaped magnet pole pieces near the internal cyclotron target. Nevertheless it appears to us that the linear accelerator, for the same beam current, would always have a useful factor in hand, and the factor of improvement over existing sources of π^--mesons is very striking. For π^+-mesons the gain is very great. π^+-mesons are rather weakly produced by the internal beam of the synchrocyclotron since they must be emitted near the backward direction; for the same reason they have rather low energy.

These considerations, together with the possibility of future extensions, have led us to make a serious study of high energy proton linear accelerators.

5. – Fundamental Difficulty of the Proton Linear Accelerator.

It is well known that phase stability of the particles in a linear accelerator, with respect to the accelerating RF field, requires that the particles be accelerated in an electric field rising with time (or, in the case of a travelling wave, ahead of the wave crest). This condition is also the condition for radial electric defocusing of the particles by the RF field. No high energy accelerator has a hope of success unless it is operated in conditions of directional and phase stability. There is no serious stability problem with linear electron accelerators, since at extreme relativistic velocities, which occur at quite low electron energies, the radial and longitudinal oscillations virtually disappear. With protons, however, we are dealing with, « slow » particles throughout the accelerator, in the energy range which we are considering here. Moreover, long RF wavelengths have to be used with slow particles, for reasons associated with transit time and the minimum hole size required for the particle beam. For protons of a few MeV, the minimum wavelength is about 1 metre, whereas the electron accelerator can use a wavelength of 10 cm.

These facts explain the comparative neglect of the proton linear accelerator and the success of the electron linear accelerator (notably at Stanford University, where 600 MeV electrons have been produced with good yield). The biggest proton linear accelerator at present operating is the 32 MeV machine constructed some years ago at the University of California by ALVAREZ and his collaborators. A bigger machine, for 68 MeV, is nearing completion at the University of Minnesota. The Alvarez machine produces a mean current of a few tenths of a microampere, with an energy spread of about 100 keV and with very good collimation. 85% of the beam passes through a 3 mm

aperture, with an angular divergence of 10^{-3} radian. The corresponding proton flux is very high, about $2 \cdot 10^{13}$ protons cm^{-2} s^{-1}.

5˙1. *Solution of the focusing problem by Alvarez.* – The Alvarez accelerator consists essentially of a long cylindrical resonator excited in the E_{010} mode at about 200 MHz, and the protons are accelerated by the longitudinal electric field along the axis. Many RF cycles are occupied in the passage along the resonator, and axial drift tubes are introduced to shield the particles from the reverse half-cycles of the electric field. In this mode of operation the particles travel the distance between the centres of successive drift tubes in one RF cycle. The electric field distribution in the accelerating gaps between the drift tubes is distorted, to produce an inward radial component for focusing, by placing a conducting grid of high transparency across the entrance of each drift tube. Foils were originally used but they had to be very thin in order to avoid excessive loss of particles by scattering, and they were destroyed by sparking.

5˙2. *Focusing in a large machine.* – The grids could not be used in a very long machine, with hundreds of drift tubes, since the resulting exponential loss of beam current would be prohibitive. It appears from work done by BELL at Harwell that foils of 10 times the thickness used by ALVAREZ could be used from 50 MeV upwards, without excessive loss due to scattering. It is not known whether the foils would successfully resist damage by RF sparking but they might be placed well inside the drift tubes, shielded from the RF field, and made to carry a suitable DC potential for focusing. Other methods have been considered by various people. An intense axial beam of electrons could be used to introduce charge on the axis (CHICK and PETRIE) but this method has not yet been tried. A 1 ampere beam of 75 keV electrons would be needed to focus 22 MeV protons, and the method does not appear promising for very large linear accelerators. In another method the proton beam would be made to spiral around a charged axial conductor.

The most promising method at present appears to be alternating gradient focusing, similar to that planned for the big proton synchrotrons. Quadrupole electrostatic or magnetic lenses would be placed inside the drift tubes, with electrodes or pole pieces arranged to produce zero field on the axis of the drift tube and constant field gradients, equal in magnitude and opposite in sign, across two perpendicular planes crossing on the axis. These would be similar to the quadrupole correcting lenses proposed for the proton synchrotron, and would be mutually oriented in successive drift tubes in such a way as to produce the desired radial dynamics of the particle motion. The electrodes or pole pieces would be shaped in section as rectangular hyperbolae, and adjacent poles would have opposite polarity. Magnetic focusing appears

to be preferable, since there are no breakdown problems and the field may be progressively reduced along the accelerator, as $1/v$. The gradient required is of the order of 1 kilogauss per cm, which is easily obtainable.

As with the proton synchrotron, it is necessary to study the changes in radial motion induced by random misalignment of the magnetic centres and by non-linearities in the focusing fields. The problem should be less serious here, since each particular disturbance is encountered only once, but it appears to be necessary to align the magnetic centre-lines of the lenses to within a few thousandths of an inch. This will not be easy.

6. – Radiofrequency Problems.

A 600 MeV proton linear accelerator will need 100/150 MW of peak RF power at a relatively long wavelength ($\sim$ 1 metre), and the provision of suitable power sources obviously constitutes one of the major problems. In the interests of reliability and simplicity it is desirable to use a fairly small number of individual sources, so that valves capable of giving at least 1 MW each are required. Suitable valves are not yet commercially available, and a valve development programme is an essential part of a big proton linear accelerator project. Maintenance of the correct RF phase along the whole accelerator, within narrow limits, is necessary in order to preserve phase stability for a useful fraction of the injected particles, and this involves the use of power amplifiers rather than oscillators. Elaborate tuning and phase-shifting devices, automatically controlled, are needed, and close dimensional tolerances and temperature control of the RF-heated surfaces have to be maintained.

There are also RF structure problems. The Alvarez structure is very efficient at low particle velocities, but becomes less efficient as the drift-tube dimensions and resonator diameter are changed to take account of the increasing particle velocity. Ultimately a resonance effect in the drift tubes causes very high RF losses, at about $v/c = 2/3$ with the geometry usually adopted. It is necessary, therefore, to change to a different structure at some stage, and a suitable energy at which to make this change appears to be about 150 MeV. The structure used at the higher energies would have dividing walls at the centre of each drift tube, so that it would take the form of a series of individual « pill-box » resonators. In order to reduce multiplicity of components and power sources, many of these unit cells would be contained in a single tank excited by a single RF source. The aperture of the drift tubes would be too small to provide sufficient RF coupling between the individual unit cells, and some form of coupling through the dividing walls would have to be devised. One structure which may be suitable is the π-mode structure, where it is known that sufficient coupling can be achieved by placing loops in each unit

cell, adjacent loops being connected together through a hole in the dividing wall. In the π-mode structure the protons travel the distance between centres of adjacent drift tubes in one half of the RF cycle. A structure operating in the $\pi/2$ mode could be operated in either resonant or travelling wave form, and in either case we believe that sufficient coupling between unit cells could be achieved simply by cutting holes in the dividing walls. A choice between these three structures can only be made after careful studies of power losses, liability to RF breakdown, optimum section length, feedback problems (in the case of travelling wave system), dimensional tolerances, and so on. Such studies are being made at Harwell, both experimentally and theoretically.

7. – Outline of the Harwell Project.

The Harwell project is still in an early stage, but the main characteristics can be discussed in general terms. Injection will be at 0.5 MeV, the protons being produced by an RF ion source and accelerated by a potential difference obtained from a Cockcroft-Walton generator. The usual system of electrostatic lenses is incorporated, and it is anticipated that several milliamperes of protons in the pulse will be produced within the acceptance conditions of the linear accelerator. Suitable ion sources and focusing systems have been built and tested.

The first linear accelerator tank, 20 feet long, will be very similar to the Bevatron injector at Berkeley and the first tank of the Minnesota accelerator. It will be of Alvarez type and will use grid focusing initially, because at these low velocities the drift tubes are extremely short and therefore contain little space for focusing magnets, and because the defocusing forces are stronger at the lower velocities. The second and third tanks will each be 40 feet long and will each add 20 MeV to the proton energy. They will also be of Alvarez type, but will use alternating gradient focusing provided by electromagnets inside the drift tubes. The resonant frequency of these three tanks will be nominally 200 MHz.

After the third tank, i.e. at an energy of 50 MeV, it will be an advantage to reduce the wavelength. The phase oscillation amplitudes will have diminished sufficiently by this time to ensure that no particles will be lost from the stable bunches if the wavelength is halved (in an ideal machine with no phase « jitter »), and the use of the shorter wavelength enables the diameter of the resonators to be halved. Since the vacuum envelopes of the early resonators will be about $4 \div 6''$ in diameter, the saving achieved in this way will be considerable. A further advantage is that it is found that a higher accelerating rate may be used at the shorter wavelength, without risk of breakdown. The next series of tanks, then, will operate at approximately 400 MHz.

They will still be of the Alvarez pattern, and this system will continue until an energy of about 150 MeV has been reached.

Beyond 150 MeV it will be necessary to change the structure for one with dividing walls, for reasons already discussed. However, the wavelength will remain the same, and from this point on the tanks will be identical save for a slow change of the dimensions of the unit cells to account for the increasing velocity of the protons.

The 10 MeV tank is now completely designed, and all important physical characteristics and much engineering design have been established for the second and third tanks. The main features of that part of the machine from 50 MeV to 150 MeV are settled, and serious engineering design will start soon. Beyond 150 MeV the basic physics is well understood, and experiments and calculation have been under way for some time to establish the main features of a practical machine.

In all the waveguide work, and also in the work which is proceeding on modulators, controls and general RF problems, we are collaborating with Messrs. Metropolitan-Vickers who will manufacture the appropriate equipemnt.

The valve programme has to be divided into two parts on account of the change of wavelength at 50 MeV. Rather little power will be required at 200 MHz (about 4 or 5 valves), and our valve development group will produce grounded-grid triode power amplifier valves of a type which they are now developing. A similar type of valve of modified design suitable for operation at 400 MHz with a power output of $1 \div 2$ MW peak, is being developed for us by the English Electric Valve Company. Finally, we are collaborating with a group at London University who are developing a $1 \div 2$ MW klystron for operation ad 400 MHz. A choice will ultimately be made between these two 400 MHz valves.

The overall design parameters of the accelerator are listed in Table II.

TABLE II.

Final proton energy	600 MeV
Mean beam current	1 µA
Duty cycle	1 %
Pulse duration	50 Hz
Length	270 m

It is intended to instal beam bending stations at intervals, so that protons of intermediate energy may be extracted. Shielding will be by earth banks, and the site has been chosen to allow extension to several times the length corresponding to 600 MeV.

The project is being approved in stages, so that at present we are engaged in a large scale exercise to determine whether a 600 MeV proton linear acce-

lerator of acceptable reliability and output is economically feasible. Certainly there appear to be no fundamental scientific objections to the construction of such an accelerator, and we are convinced of the advantage to nuclear physics which would result from its satisfactory operation.

One remark may be made on the subject of electron machines. In the region of a few hundred MeV, 1 proton is the equivalent of approximately 2 000 electrons in terms of useful meson production per unit interval of meson energy. Electron linear accelerators are easier to build than proton machines, and indeed may be the machines of the future even for the very highest energies when electrons are specifically required, but for the particular purpose which we have in mind the proton linear accelerator appears to be a much better proposition, despite the difficulties.