Multi-GeV Electron Linear Accelerator

At the CERN accelerator conference in June 1956 a paper speculating on the multi-GeV possibilities of electron linear accelerators was read by R. B. Neal of Stanford University. Recent discussions with University representatives have aroused interest in this subject at A.E.R.E. and Mullett in HAG/Gen/1 has made some comments on the Stanford work. It is the purpose of this note to consider the project of building a multi-GeV electron linear accelerator in the light of the present state of technological development in this field.

1. Wavelength Choice

Two arguments are usually advanced in favour of an increase in operating wavelength from 10cm to 20 or 30 cms, one concerning the accelerating structure and one the R.F. source. For the accelerating structure itself an increase in wavelength could lead to a reduction in production costs if it enabled a simpler method of fabrication to be used. Off-set against this reduction would be the increase cost of the vacuum system and some ancilliary components. The percentage saved on the total cost of the machine by a change of wavelength is unlikely to be greater than 10% even assuming that no development charges are involved.

The argument for longer wavelength R.F. sources rests on the possibility of obtaining higher powers and greater reliability. Peak R.F. power scales as λ^3 or for a fixed operating voltage as λ^2. Alternatively for a given R.F. power and operating voltage the current density on the cathode varies as λ^{-2}. Against this the pulse length used must increase as $\lambda^{3/2}$ because of build-up time in the accelerating structure.

The increase in size with wavelength makes manufacture more difficult and this is quite an important factor when production in quantity is involved. Failures of klystrons at Stanford indicate the importance of residual vapours present in the vacuum system. In this connection sealed off valves would seem to offer a decided advantage over continuously pumped valves. With the present techniques available a sealed off valve on 10 cms would be more easily manufactured than one for the same power on 20 or 30 cms.

However even if one accepts these arguments for an increase in wavelength the advantages to be gained have to be weighed against the knowledge and experience already accumulated on the present wavelength. New valves and new structures would take time to develop and could easily add 1-2 years to the time schedule.

2. Klystron Power

The Stanford klystron is capable of giving 30 M.W. of R.F. power and is run reliably at 10 M.W. in the 650 MeV accelerator at a pulse rating of 2 μsec 60 cycle. The cathode area is about 50 cm^2 and the lower rating is obtained for an input of about 240 K.V. 120A. Each 10' section of the 650 MeV accelerator is fed with 10 M.W. and the acceleration rate with 100 mA beam loading is 3 MeV/ft. A lower rate of about 1.5 MeV/ft is proposed for multi-GeV machines bringing down the power to 2.5 M.W. per 10' section for 50 mA beam current.

In considering klystrons for powers of the order of 50 M.W. the main advantage to be gained is in the reduction in the number of valves used. This should lead to a design of machine requiring less maintenance provided the same order of reliability holds for the higher power components used. It should also be possible to cheapen the cost of R.F. by using larger units of power.

However in deciding what size of klystron to use in a projected accelerator we are again greatly influenced by what is available at the present time. To develop a klystron and associated equipment for 50 M.W. R.F. power would certainly take at least 2-3 years. As 10-20 M.W. would seem to be the maximum power required at a single feed point in the accelerator klystrons for powers greater than this would require to use power dividing networks and high power phase adjusting sections.

Considering the total number of klystrons used in the accelerator the interval between servicing and the time spent in changing valves are the important points. Using a large number of small valves it would be possible to provide stand-by ~~kly~~ klystrons at intervals along the accelerator which could be switched in as soon as a failure occurred. With fewer large valves involving power-dividers and phasers this would not be so practicable. A life of 2000 hours between servicing would make it reasonable to use about 20 valves. Assuming that cathodes could be replaced in the sealed-off valves then batch changing would be economical and enable this number to be increased to about 50 valves.

Stanford are now able to operate reliably with 22 valves the average life being 1000-1500 hours. With sealed-off valves a reasonable target would be 5000 hours and comparable reliability should be possible with an accelerator using 50-60 valves.

3. Power to Length Ratio

The Stanford study shows that the minimum total cost for the accelerator is attained when the power dependent costs are equal to the length dependent costs.

Because the variation in total cost is only 25% for deviations from this optimum of 2 to 1 there is considerable latitude in the choice of power to length ratio.

Most electron linear accelerators in Britain have used rates of acceleration of 1 - 1.5 MeV per foot and under these conditions very satisfactory operation of the accelerating structure has resulted. Invariably the components giving most trouble has been the R.F. source and this has been the limitation in most accelerators designed to date.

There is consequently a very strong argument in favour of using a low rate of acceleration and thereby reducing the amount of R.F. power required. As reliability and cheapness of R.F. power should improve with experience gained on the accelerator it would always be possible to increase the rate of acceleration and hence the final en energy by adding R.F. at a later date.

A Proposed Project

Stanford now have considerable experience in operating a high energy linear accelerator. Although Britain has pioneered much of the work in this field the first accelerator using more than one R.F. source is only due to come into operation this year. This will use six 6 M.W. klystrons and is designed for 25 MeV energy and a high beam current of ~ 750 mA.

If we are to keep to the front in this work then another linear accelerator project should be started forthwith. This could have a fairly modest target as a first objective but be so sited and designed that it could be subsequently extended to at least 10 GeV.

The following is a proposal for a three stage programme which could be started as soon as a decision to build had been made. It assumes that a site with a straight run of at least a mile is available.

Stage I.

A 1000' length of accelerator is constructed to produce an energy of 1.5 GeV for a total R.F. power of 250 M.W.. This power will be supplied by 50 sealed-off klystrons working at 5 M.W. R.F. output on a wavelength of 10cm. At this stage a duty cycle of 0.1% with 5 μsec pulses at 200 ~ could be used in order to give a high intensity. The total A.C. power would be about 1.5 M.W..

Experimental work would then be started using the 1.5 GeV electron beam while construction of the second stage proceeded.

Stage II.

The accelerator is now extended for a further 4000' to give an energy of 7.5 GeV for 1200 M.W. of power. 60 Klystrons of a sealed-off design to give 20 M.W. power would be used. To keep the mean power consumption down the duty cycle would be reduced by dropping to 50 ~ instead of 200 ~.

Experimental work at 7.5 GeV can now be carried out while preparations for stage three are made.

Stage III

For stage III more power is supplied to the accelerator to increase the accelerating rate and hence the final energy. This could be done progressively with a final target of 15 GeV for which 5000 M.W. would be needed. Assuming that klystron reliability had improved considerably it would be possible to envisage using as many as 250 20 M.W. klystrons for the full energy. The mashine could be operated at energies intermediate to 7.5 and 15 GeV by either switching off klystrons or turning down the power from each. Failure of a klystron would not put the machine off the air but merely reduce the energy until the total power was restored by turning up the power to the remaining valves. The machine would be so designed that servicing of a klystron could be done while the machine was in operation.

Time Scale

Stage I could be started right away fot it is designed around existing components, the 6 M.W. sealed-off klystron and a 12.5 M.W. modulator using a large hydrogen thyratron. A construction time of 2½-3 years would be required. Simultaneously a 20 M.W. sealed off version of the Stanford klystron would be developed to be ready for production in quantity before the end of this period.

Stage II will require a similar period for completion, the effort having been stepped-up to deal with the increased size of the project.

Stage III would be introduced over a period of 2-4 years adepending on the urgency of increasing the energy.

The production of a 1.5 GeV electron beam in 3 years time would be a very useful addition to high energy machines in Britain and is a worthwhile target in itself. With the increase to 7.5 GeV the machine would be a serious competitor to the 6 GeV electron synchrotron under design in America and a further 2-3 years is not an unreasonable target for this extension. Both target dates involve the organising of industrial effort to produce the components on a large scale and with the bulk of the design work already existing this should be possible.

Cost

It is difficult to estimate the cost of this accelerator using the costs of smaller accelerators as a basis. Usually these have been made for special requirements and the total cost has included a lot of ancilliary equipment. However some prices are available for the component parts of the 45 MeV 100 mA accelerator constructed at Harwell. Based on these it would seem reasonable to cost a 20' run of accelerator complete with vacuum system, focusing coils and mounting arrangements at £20,000. The cost of a 5 M.W. R.F. unit comprising modulator power supply and klystron should not exceed £10,000, making a total of £30,000 for a 30 MeV section.

If now these units are produced in quantity and some simplications introduced it should be possible to manufacture 50 for less than £1,000,000. The building and shielding for the 1.5 GeV 1000' long accelerator would cost about £200,000.

In stage II the accelerator costs /MeV should drop due to improvements in production efficiency and a reduction in cost / M.W. by using larger R.F. units. An additional £2,750,000 should cover the increase to 7.5 GeV with a further £750,000 for the building.

Stage III requires the installation of a further 180 R.F. units at a cost of £1,200,000.

The total cost to 15 GeV would therefore be about £6,000,000 to 7.5 GeV £4,800,000 and to 1.5 GeV £1,200,000.

Summing-up

The following are the main points in the philosophy behind the proposal.

1. At present we are not far behind in the electron linear accelerator field. If we start a project now we should be able to keep up with Stanford. Two years delay may make this impossible.
2. To make a good start we must use existing components, structures and klystrons already manufactured and tested. This rules out a change from 10 cms. wavelength.
3. A low power to length ratio should be used to keep the R.F. requirements to a minimum during the early stages of the project.
4. A maximum of 50-60 klystrons should be used until good reliability is obtained. This entails the development of a sealed-off version of the present 20 M.W. klystron a project which could be undertaken by industry and completed in 2-3 years
5. The cost of the project can only be brought down to a reasonable figure by simplifying and stream-lining the present designs. Because of the size of the project an entirely new approach to the method of manufacture of the accelerating structure should be made.
6. By considering the project in three stages a greater flexibility in design is achieved and any improvements in structures or R.F. sources reached during stage I can be incorporated in the later stages.
7. The time scale compares favourably with other high energy machines and has the advantage that operation at intermediate energies is possible at earlier dates.

Proton Possibilities

Since starting this paper Blewett at Brookhaven has studied the possibility of a 10 GeV proton linear accelerator. This machine would start acceleration using Alvarez-type structures on 200 Mc/s and then at 200 MeV go over to centimetric travelling wave structures. This latter part would be very similar to an electron accelerator and would be 3000' long. The pulse length would be about 10 microseconds and an average output current of 30 microamps should be achievable.

This machine has many more difficulties than it's electron counterpart but both depend fundamentally on the technological development of accelerating structures and R.F. sources to a stage where they can be made cheaply and reliably. In the proton machine there are also severe problems with focussing and phasing. Assuming that these could be solved then at the end of Stage I on the electron machine a decision could be made to change over to protons at Stage II. This would involve construction of the 200 MeV injector section and change of the accelerating structure in the 1000' run. The same building, power supplies klystrons, vacuum system etc. could be used.

Blewett's paper certainly emphasises the importance of continuing development of the linear accelerator to high energies in both the proton and electron machines.

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