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THE PROTON LINEAR ACCELERATOR AS A PION FACTORY

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The object of this paper is to present information on the proton linear acceleration (PLA) in such a manner that its value as a meson factory can be compared with the characteristics of the various circular accelerators discussed in other papers at this conference.

To do this I propose:-

(a) To discuss very briefly the advantages and disadvantages of the conventional PLA from the point of view of the conduct of experiments.

(b) To discuss the advantages and disadvantages of the conventional PLA from the point of view of the cost of construction and the reliability of operation.

(c) To report on the state of the research on the super-conducting PLA project (PLANET).

Advantages: From the point of view of the user

the advantages of the PLA are:-

(a) All the accelerated protons emerge as an external beam for use either directly or as a source to produce secondary beams.

(b) A consequence of (a) is that most experiments can be performed under low background conditions. If the maximum beam intensity is too high for a particular experiment, for example, it can be reduced at the injector 300 metres away from the experiment.

(c) The energy resolution is good, and the energy can be changed easily in discrete steps by switching off parts of the accelerator.

(d) Because all the beam emerges from the accelerator with good emittance characteristics it is possible to set up many experiments in different experimental halls transporting the beam to the experiment when required with quadrupole and bending magnets.

(e) Beam currents up to a few milliamperes are possible.

(f) A polarized proton beam of variable energy and good energy resolution can easily be produced. The 50 MeV proton linear accelerator at the Rutherford Laboratory has a polarized proton source which has been working for over two years now with very great reliability. It produces a 30% polarized beam of 5×10^7 protons per second. This will be improved in the near future, and in considering a new accelerator a polarization of 70% and an intensity of $5 \times 10^9 \times 10^9$

(g) In principle it is also possible to extend the machine to higher energies at a later stage.

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(h) There is no radioactivity problem in the accelerator.

The only disadvantage from the point of view of the user is the poor duty factor, and this is a serious restriction. However, the fine structure in the beam enables excellent time-of-flight techniques to be developed.

Reliability of Operation

Most of the advantages outlined above have been accepted for many years and it was for this reason that a decision to build a 600 MeV PLA with a 1% duty cycle was made in England in 1952. There were many factors which contributed to the decision in 1955 not to go ahead with this scheme. Some of the reasons are not relevant to this paper, but two which are particularly relevant were the estimated high cost of construction and the complexity of operation. In fact, as far as I know, there are only two high duty factor proton linear accelerators in operation in the world, a 68 MeV machine at the University of Minnesota and the vestigial remains of the Harwell 600 MeV machine, namely the 50 MeV PLA now in the Rutherford Laboratory, Chilton. This machine has a 1% duty factor and has been in use for research now for about three years. It operates on a 24-hour per day schedule and last month achieved our best reliability factor of 87% useful time. However, it has taken a great deal of effort to work up to this acceptable degree of reliability. A permanent engineering staff of 60 are required to operate and service the accelerator and to design and build the equipment for the 50 nuclear physicists who use the machine and the team of 30 who are concerned with accelerator research and RF valve development. We also draw on a considerable amount of effort in industry.

A 750 MeV accelerator would have more than ten times as many components and so one of the most important factors, in my view, to take into account in designing a high-energy PLA is that it should be as reliable as modern engineering can make it. It must also be easily serviced. However, experience of a small machine leads me to believe that a high-energy linear accelerator could be made to work reliably.

Cost of a Conventional 750 MeV PLA

A number of groups have recently been designing large linear accelerators, notably the Yale group and a report on their project is listed for discussion later in this session.

At the Rutherford Laboratory, Walkinshaw, Dickson, Carne, Batchelor and others have been collaborating with CERN in a design study for a 200 MeV injector for a possible 300 GeV proton synchrotron. This design study has involved a great deal of laboratory work on the testing of various kinds of accelerating structures and has enabled quite reliable estimates to be made of the cost of a 750 MeV PLA, see Table I.

Construction Time and Staff Required

This has not been estimated with any degree of reliability but the accelerator would have about 70 tanks and a great deal of electronic equipment and so must take about six years with a staff of 100.

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Table I

Cost of a 750 MeV Proton Linear Accelerator (5% duty factor)

	L million sterling
Injector + 200 MeV section	1.70
200 - 750 MeV section	3.08
Controls	0.70
Site development, buildings, etc.	1.20
Experimental areas + initial equipment	2.10
TOTAL	8.78

512. The cost of an accordance with a fock daty factor would be about 510.07m. However, such a machine would require 120 MW of electrical power for RF needs alone (assuming a valve efficiency of 50%) and the annual cost of the electrical power alone would amount to 52.55m in Britain.

Future Developments

There is little doubt that a high-intensity PLA could be made to work, but it is extremely ambitious to consider any accelerator with a duty factor greater than, say, 10%. With this in mind A.P. Banford and myself¹⁾ have made some calculations to determine the feasibility of constructing the PLA resonator out of some superconducting material. The use of super-conducting surfaces is particularly applicable to linear accelerator design because these machines only operate at a poor duty factor owing to the enormous amount of RF power that is required to operate them continuously at normal temperatures. It can be shown that at liquid helium temperatures RF losses in the resonator can be reduced by more than a factor of 10^4 . Even allowing for the power required in the proton beam the RF problem is then trivial and it is feasible to consider a machine working with a 100% duty factor. In fact, because of the very high Q factor of the resonating cavities it is essential to operate in a CW fashion. The high Q factor presents difficulties in operation, but it is possible that these could be overcome. There appears to be no fundamental reason to prevent such an accelerator working.

However, much remains to be done before these simple theoretical principles can be applied to a practical machine. Banford has been making some measurements during the past 18 months to study under what conditions of surface treatment good improvement factors can be achieved. To date the best results have been on small wire hairpins at low power level where improvement factors (compared with copper at room temperatures) of 9,000 have been obtained for electroplated lead and 12,000 for electropolished niobium wire. If these measured values could be achieved in a 750 MeV

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PLA it is calculated that a helium refrigerator capable of a 6 kW heat load at 4.2° K would be required. The additional cost of the helium refrigerator is offset by the greatly simplified RF system and so the total cost of the accelerator would be not greater than the $\pm 8.78m$ quoted above for the conventional accelerator with a 5% duty factor.

Concluding Remarks

The poor duty cycle of a conventional PLA is a serious drawback from the point of view of the user but apart from this it would have very great user appeal. It would be somewhat more expensive to build and to operate than a cyclotron, but taking into account the cost of the experimental programme which would be independent of the type of accelerator built, this extra machine cost should not influence the choice too strongly. Reliability of operation is, however, an important factor and although it should be possible to build a PLA which is as reliable as the cyclotrons now being considered it may be more difficult to achieve this ab initio. The use of a storage ring with a 750 MeV pulsed PLA may merit serious consideration.

As regards the super-conducting PLA I believe that it would be most unwise at this stage to consider it as a feasible proposition. However, in view of the very big advantages it is well worthwhile engaging in experimental work on a laboratory scale to study super-conducting resonators and the problems connected with the construction of a super-conducting PLA. Two years hence it should be known whether there is any substance in the proposal. Super-conductivity is a field of research that is developing very fast nowadays; it would be most unwise for us to dismiss this possibility.

In this paper a 750 MeV PLA has been considered to facilitate comparison with the cyclotrons being discussed. However, from the point of view of the physics it is very difficult to draw the line at this energy and should the sights be set at somewhat higher energies then the PLA merits very serious consideration, either as a straight forward proton accelerator or as a proton accelerator followed by another linear machine to accelerate the pions and muons to energies of a few GeV. Such a possibility was first proposed by Devons and his collaborators in 1959. The design of such a system of accelerators presents many problems but, in the light of the advances made since that date, such a scheme could merit further detailed investigation.

Reference

1. A.P. Banford and G.H. Stafford, Journal of Nuclear Energy Part (C), 3, 287 (1961).

DISCUSSION

RICHARDSON : I have never been able to understand the advantage of the storage ring and linac combination. Although you do, in fact, get an improved duty factor, you also have the problem of getting the beam out. This results in loss of availability of the - 332 -

beam. A more advantageous situation would be obtained if H ions are accelerated in the linac, injected into the storage ring, and then extracted by stripping. This, however, requires an expensive storage ring to avoid the electric stripping which would occur with strong magnetic fields.

STAFFORD : The possibility of using negative ions had not occurred to me; it is quite interesting. The idea behind the possible use of the storage ring is that one can either have short burst of particles for a particular experiment or one can feed particles into the storage ring and improve the duty factor. Designing a ring specifically for this purpose is probably somewhat simpler than designing a device which accelerates and provides for extraction as well.

TENG : In connection with reliability of linacs, I think the experience with the 50 MeV injector linac at Argonne may be interesting. After the construction of the linac was completed, it took about a month to produce a good vacuum and to tune up the RF coupling into the tank. It then took only about two days to obtain a beam of 2 mA, another two weeks to obtain 8 mA, and this without a buncher. Another month was needed to bring up the RF level in the buncher; then we were able to get the usual factor of 2.5 increase in the beam intensity. Since then we have had no trouble in getting an intensity of about 15 mA at a pulse length of 200 μ s. We have not tried to increase the repetition rate for high duty factor. The important point is that the linac operates very stably and seems to be a machine which is eager to work.

STAFFORD : This is also my impression. With modern techniques and good engineering there should be no difficulty in making these things work. Since the early linacs, the Minnesota one and ours, there have been enormous advances in modulator design and particularly in the availability of commercial tubes that can carry these large amounts of power. In the Rutherford laboratory, for instance, initially we had to design our own power supplies. Now we are stuck with tubes that we have to make ourselves; Minnesota has the same difficulty.

LIVINGSTON : What is the degree of difficulty in going from 1% or even lower efficiency (such as with the Argonne machine) to 5%.

STAFFORD : I don't think that there is any significant difficulty in connection with the reliability in going from a 1% machine to a 5% machine. I think that with the tubes the knowledge now available this is no problem. Essentially, this means a factor of five increase in beam-power dissipation. This requires improved cooling, but this is not a limitation at the moment.

LIVINGSTON : Could you do that on your present machine?

STAFFORD : No, we would have to change our modulators completely. The actual linac itself could carry perhaps a 5% duty factor from the point of view of the liner cooling. The only trouble that we have ever really had with this high duty-factor machine is with the modulator system, and sometimes the power supplies, but the linac is trouble free. Having used it, it really does turn out to be a very pleasant machine with very nice characteristics.

DOME : In connection with the improvement factor in the Q of super-conducting cavities, do you have any figures for super-cooled cavities made of niobium alloys, in particular Nb-Zr or Nb-Sn?

STAFFORD : Banford tried niobium-zirconium commercial wire and obtained rather poor improvement factors; it involves a lot of cookery at the moment. That reproducibility for Nb is very good but not for niobium-ziconium is something which requires a better knowledge of the physics of surfaces than we've got at present.

HUGHES: There are also two other linacs in operation, for heavy ions, at Berkeley and the Yale. They have about the same duty factors as your proton linac and, I believe, operate satisfactorily.

STAFFORD : I must admit I didn't think of them, I was thinking purely of the proton machines.

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SNELL : What is the reduction in power dissipated anticipated when super-conducting materials are employed?

STAFFORD : We get an improvement factor of 10^4 . A 750 MeV linac requires about 60 MW; this would reduce to 6 kW.