SIMULTANEOUS ACCELERATION OF TWO BEAMS IN A LINEAR ACCELERATOR

By C. H. Westcott

Chalk River Nuclear Laboratories, Atomic Energy of Canada Ltd.*

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The Canadian Project for an Intense Neutron Generator [1] required for maximum utility two separate beams of 1 GeV protons from a single linac, with currents roughly in the ratio 100 : 1. The system was continuous (*i.e.*, unpulsed, although of course the beam had a radio frequency time-variation) and it was desired that both beams be similarly continuous. A simple method of achieving this is described.

1. Introduction

Professor H. Niewodniczański and I cooperated in 1935 on an experiment on neutron thermalization, and I am pleased to contribute to the memorial issue of this journal a brief technical account of an suggestion for an improvement to a particle accelerator, especially as Professor Niewodniczański has also been concerned with particle accelerators. The idea now described arose in 1966 as part of the work towards the Canadian proposal for ING ("Intense Neutron Generator", unfortunately not founded). Most of the work reported was completed in 1967.

The main aim of the ING project [1] was to produce neutrons copiously by nuclear spallation from a 65 mA 1 Gev proton beam; working continuously such a beam should yield thermal fluxes near 10^{16} cm^{-2} sec^{-1}. Whereas most linear accelerators ("linacs") have a low duty cycle, the ING was to use a 100% duty cycle linac. In view of the cost of this device, it was also desired to produce simultaneously lower-intensity auxiliary beams, mainly for experimental work where the higher backgrounds and induced radioactivity expected from the full beam would have been troublesome.

2. Outline of the method

The main problem in diverting a part of the ING beam along an alternate beam-line arose because the operation was not pulsed but continuous. For a pulsed linac sufficient time for beam-switching usually exists between successive pulses, but in our case only the

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* Address: Chalk River Nuclear Laboratories, Atomic Energy of Canada Ltd., Chalk River, Ontario, Canada.

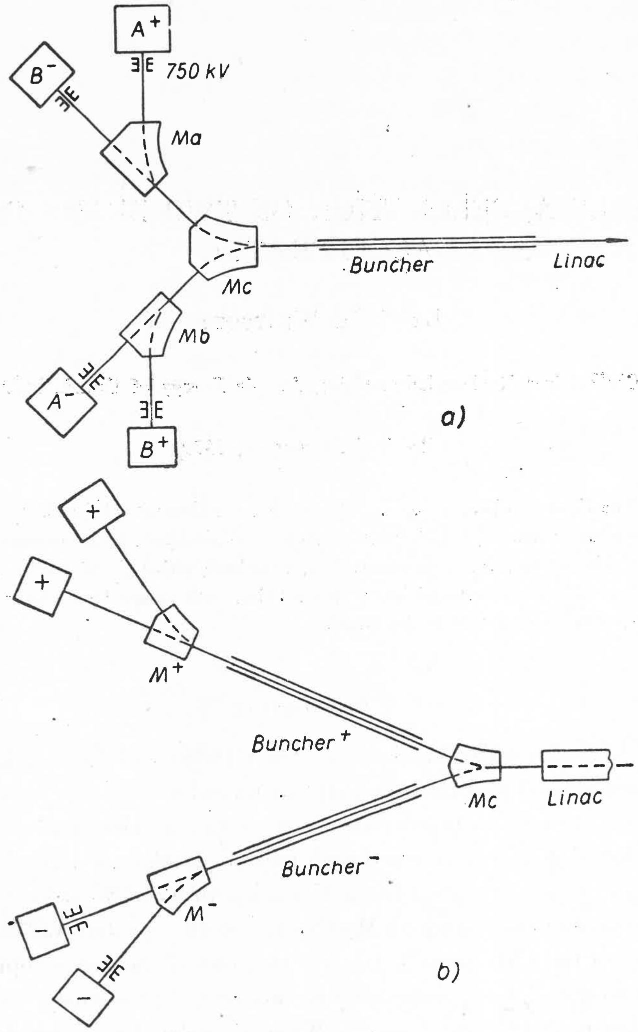

Fig. 1. Two alternative systems for injecting H+ and H− beams simultaneously into linac. *Mc* = beam combining magnet *Ma, Mb* (or *M*+, *M*−) enable us to choose between alternative ion sources needed so that maintenance can be carried out on one source during accelerator operation using the other. The Fig. 1(*a*) scheme is simpler if the buncher can work satisfactorily on both H+ and H− beams

inter-r. f. structure interval (of about 3.5 ns) was available. The ING concept consisted of a proton ion source and "buncher" with acceleration to 750 keV, then a short 268.3 MHz linac for acceleration to 100 MeV followed by an 805 MHz linac in which particles occur in every third r. f. cycle. The deflection of the resulting 1-GeV protons through an appreciable angle with a switching time of only ~ 3 ns is not feasible. However, a relatively simple alternative, which has been patented [2], exists for a linear accelerator, and it is understood that a similar scheme is to be used in the U. S. LAMPF installation [3].

The scheme uses a source of H^- ions as well as a proton ion source and allows both to be accelerated by the linac r. f., 180° out of phase with each other and both under phase-stable conditions. Figs 1(*a*) and 1(*b*) show alternative arrangements; in each the magnet *Mc* directs the H^+ and H^- beams onto the same path through the linacs. The simpler Fig. 1(a) scheme is allowable if ion densities are low enough (pre-bunching recombination being the main problem) and if the even harmonic requirement of the bunching system is low enough.

It should be noted that the two-frequency accelerator system can use both H^+ and H^- beams only if the ratio of the two frequencies is an odd integer[1] (to preserve a 180° phase difference), unless special devices are used between the two linac sections, as may be needed for LAMPF. After acceleration to 1 GeV, a bending magnet suffices to separate the two beams and a thin "stripping foil" will convert the H^- ions to protons without appreciable change of energy. Of course, it is not allowable to deflect the beam magnetically in the middle of the acceleration process, but small accidental misalignments may be dealt with by the normal quadrupole focussing systems (see below). Nor is there an analagous scheme for cyclotrons or other essentially curved-path devices.

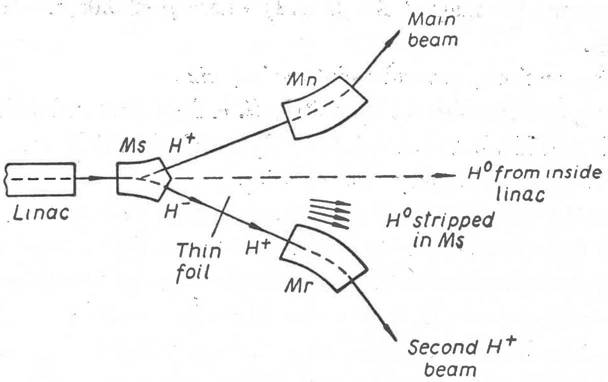

Fig. 2. Separation of beams after acceleration. *Ms* = separating magnet, *Mn* = main beam deflector, *Mr* = deflector for secondary beam (now also protons). Posible locations for unwanted beams (neutral ions) are also shown

3. *Technical problems*

It cannot be over-emphasized that for an accelerator like ING with a (mean) beam power of 65 MW, background effects and induced radioactivity, and therefore shielding, are of the utmost importance. For the lower-intensity H^- beam it was still necessary to achieve a quite low fractional loss of the beam within (as well as outside) the linac. The main sources of beam-loss which affect H^- more than H^+ ions (protons) are (*a*) "stripping" in collisions with gas molecules [4] and (*b*) electric stripping due to motion through a transverse magnetic field. Direct stripping by electric fields is improbable; accelerating fields in

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[1] Originally the ING project used 201.2 and 805 MHz, but later 268.3 MHz was substituted, to meet this condition.

ING average only some 11 kV/cm while fields of several MV/cm are needed to strip an H^- ion. But motion through a transverse field B induces an electric field of $\beta\gamma cB$ in the rest-frame of the ion (where, as usual, $\beta = v/c$ and $\gamma^2 = 1/(1-\beta^2)$) and these fields may be of the required magnitude.

The restriction which is therefore necessary on the field in the magnet *Ms*, Fig. 2 (the separating magnet), where for ING $\beta = 0.875$, is rather severe and limits the field which can be used to about 5 kilogauss. If a 10 kG field were used the transverse electric field would be close to 5 MV/cm, in which the mean life of H^- is only a few picoseconds (the mean life [5] varies exponentially, being perhaps milliseconds for 1.7 MV/cm and about 1 nanosec near 4 MV/cm; there is still some uncertainty, by a factor of up to 3, in these exact rates). On the other hand, for magnet *Mc* (Fig. 1) where $\beta < 0.05$, no serious limit on the magnetic field arises.

Within the linac sections, several points arise, *viz.*,

(a) The focussing quadrupoles act oppositely (*i. e.* focussing and defocussing planes are interchanged) for H^+ and H^-, but if each is suitably matched initially and the linac apertures are axially symmetrical, no difficulty should arise.

(b) Loss of beam by space charge repulsion and charge exchange with loss of focussing. The former is likely to be less severe for the H^- beam than for protons, since the H^- beam will always be the weaker (the inverse, H^- beam stronger than proton beam, is impossible due to ion source limitations but would in any case never be selected due to the H^- stripping causing beam loss). The latter may occur near the beginning of the linac; loss of H^- by charge exchange (recombination) with protons falling out of synchronism could be appreciable, but should not have serious consequences since the activation due to low-energy particles is relatively small. This loss can be minimized by suitable buncher design.

(c) H^- ion "stripping" in the quadrupole magnetic fields must be examined, although in most locations the resulting loss of beam is likely to be small. For the ING design, the strongest quadrupole (3.25 kG/cm) was at $\beta = 0.583$ — for β just below 0.583 the quadrupole strengths decrease rather slowly as β decreases, but at higher energies weaker focussing units suffice, and even at 1 GeV ($\beta = 0.875$) the electrical stripping force is considerably lower than for $\beta = 0.583$ since the quadrupoles there are weaker. If we assume a maximum beam radius of 2 cm, the electric stripping field at this radius for $\beta = 0.583$ is 1.58 MeV/cm, giving a mean life for H^- of $\gtrsim 0.1$ second. The quadrupoles extend over only $\sim 10\%$ of the total length of each section, so for say a length of 4 m of quadrupoles (10 units), which will be spread over about 40 m of the linac, the time each ion is within quadrupoles is about 23 nanosec, giving a stripping probability of $\sim 2.3 \times 10^{-7}$ In fact, within the last 10 quadrupoles before the "worst" location, β rises from ~ 0.55 to 0.583, γ from ~ 1.2 to 1.23 and the quadrupole gradient from ~ 3 kG/cm to 3.25 kG/cm. As a result the stripping probability will fall by a factor of at least 5 from its peak value, so that almost all the beam loss due to cross-field stripping is concentrated in these ten quadrupoles.

(d) loss of beam by collisions with residual gas depends on the pressure attained, and for most of the linac a pressure of $\sim 2 \times 10^{-7}$ Torr is desirable for a $\frac{1}{2}$ to 1 mA H^- beam. This should not be too difficult to attain, but near the ion source higher pressures are allowable, since any escaping protons or neutral H's here would have low enough energies to cause little trouble. It should also be noted that for intermittent H^- operation (say 8 hours per 24-hour day) either the pressure or the H^- current could be correspondingly larger, since it is the integrated activation which is likely to be limiting.

The activation tolerances for ING were quoted as losses allowable at various energies by Thorson [6]; for 200 MeV (the peak for cross-field stripping) 10 nA/m were allowed, and some 2 nA/m at 1 GeV, rising to 0.5 μA/m below 10 MeV. The allowable gas pressure quoted above is based on these figures; for the cross-field stripping a 1 mA H^- beam gives only about 0.3 nA in 20–40 metres at the worst location (we assume that we can "smooth" this loss over the ~4 metre length of a linac section, containing one quadrupole, since the lost particles travel essentially forward). This is well below the 10 nA/m quoted above, but a not very large (say 25%) increase in either beam-size or quadrupole gradient (*e. g.*, due to a design change) could well increase these beam spill rates by more than one order of magnitude, so that this tolerance is felt to be not greatly excessive.

4. *Utilization of the resulting beams*

Fig. 2 shows the scheme for separating the two beams after acceleration. If the magnet *Ms* has too high a field, H^0-ions from stripping in *Ms* would emerge in a fan-shaped region as shown; to avoid difficulties of this type at subsequent points the H^- beam is stripped to protons in a thin foil as soon as separate beam have been established. Heat production in this foil for a ~1 mA current is acceptable, and the additional beam spread introduced should be small.

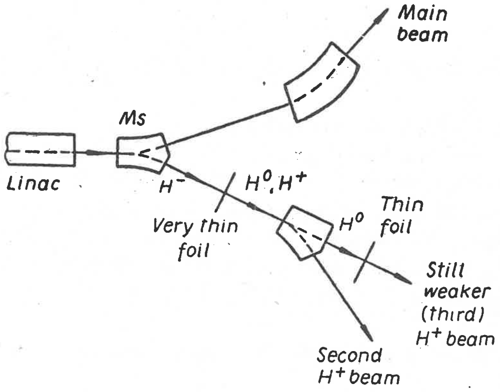

Fig. 3. Separation scheme giving three output beams. *Ms* and main beam as in Fig. 2; replacing *Mr* is a magnet separating the secondary beam into two, where the third beam, usually the weakest, arises from H^0's leaving the first stripping foil

Fig. 3 shows how three beams, instead of two, can easily be obtained. The stripping foil following magnet *Ms* is in this case only thick enough to change say, 90% of the H^- ions to protons; almost 10% will emerge as neutral H ions (the fraction remaining as H^- would be quite small for a suitable foil, depending on the material used, and generally could be neglected). A second bending magnet separates the protons from the neutrals, the latter being stripped to protons in a second foil. Each beam should have a manageable emittance in such a system but the distance travelled as H^0 should be minimised because quadrupole focussing would be impossible for this section of the beam transport system.

5. *Conclusion*

Other possible difficulties (*e. g.* the small mass difference between H^- ions and protons) appear to be trivial. Loading on the linac cavities of course corresponds to the total of the H^+ and H^- current, but the latter, being $\sim 1\%$ only, can be pulsed or modulated at the ion source if desired while the H^+ beam continues unaffected. This would allow further subdivision of the less-intense beam, by slow switching, if needed. The work on ING following this suggestion turned up no unforeseen problems. It is of course clear that only for linear acceleration does the idea appear feasible, but it is hoped that it can be of use in suitable cases.

The author wishes to acknowledge many helpful discussions with his colleagues of the ING study, particularly with those concerned with ion source and other problems of how the beam would enter the linac. Without their help, assurances that the idea is practical would not have been forthcoming.

REFERENCES

[1] Intense Neutron Generator, Atomic Energy of Canada Ltd. *Reports*, *AECL-2600* (1966) and *AECL-2750* (1967).
[2] *Canadian Patent 805, 240* foreign patents applied for.
[3] See, e.g., *Los Alamos Proposal for a High-Flux Meson Facility*, 1964; and *Science Journal*, **5A**, 39 (1968).
[4] S. K. Alison, *Rev. Mod. Phys.*, **30**, 1137 (1958); J. W. Verba *et al.*, *CERN report* 63–19 (1963); K. H. Berkner *et al.*, *Phys. Rev.*, **134A**, 1461 (1964); R. Smyth *et al.*, *Phys. Rev.*, **139A**, 15 (1965); and (lower energies) *Phys. Rev.*, **140A**, 1481 (1965); *Zh. Tekh. Fiz.*, **36**, 1239 (1966).
[5] G. M. Stinson *et al.*, *Nuclear Instrum. Methods*, **74**, 333 (1969); J. R. Hiskes (quoted by D. L. Judd, *Nuclear Instrum. Medhods*, **18–19**, 70 (1962)), T. A. Cahill *et al.*, *Nuclear Instrum. Methods*, **21**, 247 (1963).
[6] I. M. Thorson, quoted in *AECL-2750* (1967) see Ref. [1] above.