MAGNETICALLY SUPPRESSED ACCELERATOR TUBES[1]

F. A. Howe
Atomic Weapons Research Establishment
Aldermaston, Berkshire, England.

Summary

A method for effectively suppressing the electron loading in accelerator tubes is described, which utilises transverse magnetic fields. The electron trapping is achieved without affecting tube optics or producing undesirable ion beam deflections at the tube exit, even when the stack voltage gradient is disturbed.

Introduction

The electron loading phenomena present in conventional accelerator tubes, which becomes particularly troublesome as machine voltages increase, has been discussed in several papers[2,3]. Various methods or combination of methods are presently employed to surmount the problem, notably two types of inclined field tubes[2,3,4], apertured tubes[5,6], and back biased tubes[7]. It is probably fair comment to suggest that some problems, however, still exist in this field.

The magnetically suppressed tube described has been developed at AWRE over a period of years and uses transverse magnetic fields to deflect electrons onto the tube electrode structure.

The mechanism of electron trapping can best be understood by reference to the figures. Figs 1(a), 1(b) show the method by which permanent magnets, annular rings magnetised N,S. across the diameter, are housed in dished electrodes providing a simple and conventional tube structure.

Ion beam deflection and balancing

Fig 2(a)(b) shows a typical accelerator tube with an axial positive ion beam injected at the left.

In passing through the first magnetic field A, the ions acquire a transverse velocity the value of which may be derived as follows.

L = Length of field m
H = Magnetic field intensity Wb m^{-2}
v = Beam velocity $m.s^{-1}$
e = Particle charge C.
m = Particle Mass Kg.
R = Radius of curvature m.

Consider an increment of field length dL (fig 3) during the traversal of which, the beam velocity may be considered constant

$$HeV = \frac{m.V^2}{R} \text{ and } R = {}^{V}/_{H}\ \frac{e}{m}$$

$$\text{But } \sin\theta = \frac{dL}{R} = \frac{dL.H}{V}\ {}^{e}/_{m}$$

$$\text{Transverse velocity } V_T = V\sin\theta$$
$$= V\frac{dL}{V} H\ {}^{e}/_{m}$$

$$\text{and } V_T = HL\ {}^{e}/_{m} \qquad (1)$$

where HL = Integrated Field.
The integrated field is determined experimentally.

It is to be noted this transverse displacement velocity is independent of beam energy, decreases with increased mass and is maximum for hydrogen ions. It is also evident that the velocity derived at A may be completely cancelled at the Second trap B, if the HL value is identical to that of A, and the field reversed in direction. The beam leaving trap B will then be parallel to the tube axis but displaced from it by a small amount. The displacement may be deduced:-

E = Accelerating field V m^{-1}
V_o= Volts per section
V_T= Transverse velocity $HL^{e}/_{m})$ $m.s^{-1}$
a = Acceleration $m.s^{-2}$
t = Transit time s.
S = Beam displacement m.
d = Electrode spacing m.
N = Electrode number

Assuming beam velocity at tube entry as zero
Transit time of beam from tube entry to electrode N

$$t_N = \left(\frac{2.N.d}{a}\right)^{\frac{1}{2}}$$

$t_{N_1 \to N_2}$ (e.g. between magnet traps at N_1 N_2)

$$= \left(\frac{2.d}{a}\right)^{\frac{1}{2}} \left(N_2^{\frac{1}{2}} - N_1^{\frac{1}{2}}\right)$$

$$\text{But } a = E\frac{e}{m} = \frac{V_o}{d}\frac{e}{m}$$

$$\text{and } S_{N_1 \to N_2} = V_T\ t_{N_1 \to N_2}$$

$$= H\,L\ {}^{e}/_{m} \left(\frac{2\,d^2}{V_o\ {}^{e}/_{m}}\right)^{\frac{1}{2}} \left(N_2^{\frac{1}{2}} - N_1^{\frac{1}{2}}\right)$$

$$S_{N_1 \to N_2} = H\,L\,d\left(\frac{2\,\frac{e}{m}}{V_o}\right)^{\frac{1}{2}} \left(N_2^{\frac{1}{2}} - N_1^{\frac{1}{2}}\right) \qquad (2)$$

where $S_{N_1 \to N_2}$ is the beam displacement from the axis at trap N_2.

It would appear that in order to obtain a balance in the beam displacements, the factor $(N_2^{\frac{1}{2}} - N_1^{\frac{1}{2}})$ must equal the factor $(N_4^{\frac{1}{2}} - N_3^{\frac{1}{2}})$ and so on, and thus the trap spacings would necessarily increase. A complete tube however will contain several pairs of traps and it is therefore necessary only that the summation of displacements in one sense equal those in the opposite sense. In the case of fig 2 for example, the beam will leave on axis if:-

$$\left(N_B^{\frac{1}{2}} - N_A^{\frac{1}{2}}\right) + \left(N_F^{\frac{1}{2}} - N_E^{\frac{1}{2}}\right) = \left(N_D^{\frac{1}{2}} - N_C^{\frac{1}{2}}\right) + \left(H_H^{\frac{1}{2}} - N_G^{\frac{1}{2}}\right) \qquad (3)$$

and this is virtually satisfied by the arrangement shown.

Electron trapping

The Magnet spacings must moreover take into account their primary purpose which is the trapping of electrons, those originating between

H and G for example being deflected into the electrode structure between G and F. For a tube operating at 500KV/ft, a magnet spacing of 8 sections or about 300 KV between traps permits a maximum electron energy of around 600 keV. This design allows for an integrated field of $HL = 1.4 \times 10^{-3}$ Wb m^{-1}, and a magnet aperture of $3\frac{1}{2}$" diam giving a reasonable gas conductance in an $8\frac{3}{4}$" OD accelerator tube. Beam displacements between traps are maximum at the lower energies, that for protons at 3 KV per section or a total tube voltage of 200 KV being about 6 mm, reducing to $1\frac{1}{2}$ mm at 3 MV. In the case of negative ion injection, the electrons which enter with the beam are effectively trapped by this arrangement.

Ion Beam Stability

Disturbance of the tube voltage gradient due to beam loading, belt disturbance or other causes has no effect on the parallelism of the beam to the tube axis, but may cause very slight variations in beam displacement. In a typical case, one may assume an electrical short circuit of the tube section between two adjacent magnets. The beam displacement in such a case could be derived:- Assume normal acceleration to N_1, then a constant velocity to trap at N_2

$$V_{N_1} = \left(2 N_1 V_o \frac{e}{m}\right)^{\frac{1}{2}}$$

$$t_{N_1 \rightarrow N_2} = \frac{S}{V} = \frac{d\,(N_2 - N_1)}{(2.\,N_1 V_o \frac{e}{m})^{\frac{1}{2}}}$$

Beam displacement = $V_T\, t_{N_1 \rightarrow N_2}$

$$= H\,L\,d \left(\frac{2\frac{e}{m}}{V_o}\right)^{\frac{1}{2}} \left(\frac{N_2 - N_1}{2\,N_1^{\frac{1}{2}}}\right) \qquad (4)$$

Compared to equation (2) we obtain the ratio of disturbed condition beam displacement to Normal beam displacement.

$$\frac{N_2 - N_1}{2\,N_1^{\frac{1}{2}}} \; : \; N_2^{\frac{1}{2}} - N_1^{\frac{1}{2}}$$

and for the case $N_1 = 25$ $N_2 = 36$

the ratio is 1.1 - 1.0

The increase in displacement is thus 10% only, or in the case quoted above, a fraction of a mm. This is an indication of the degree of beam stability to be expected.

Experimental Tube performance

Experimental tubes have been used on the AWRE 5.5 MV and 3 MV accelerators and beam handling has been normal. On a recent trial of one month's duration on the 3 MV machine, analysed proton beams of 160 μamps on a 3 mm target were used at 2 MeV. In earlier voltage tests on the same machine, 3.6 MV was obtained with little conditioning, but an addition of 5% SF_6 to the normal 80% Nitrogen 20% CO_2 insulating gas was necessary to eliminate tank sparking. No beam wobble has been observed, and radiation levels have been greatly reduced.

A set of four traps following this design was fitted to the accelerator tube presently installed in the 10 MV Oxford Injector[8], to suppress electrons injected with the negative ion beam. A complete magnetically suppressed tube of OD 13" designed for both positive and negative operation is being constructed at AWRE for this machine and alsoa similar tube for the new 6 MV Harwell machine.

Conclusions

The advantages inherent to the design are:

(a) complete freedom from beam wobble due to machine instabilities and is therefore suitable for single or tandem stage machines,
(b) ability to handle multi charged heavy ions without complications,
(c) ability to accelerate high current beams,
(d) good gas conductance,
(e) simplicity of design,
(f) beam handling properties of the tube may be adequately assessed using low energy protons and without the application of the usual electric field gradient, e.g. as a drift tube; prior to installation in the accelerator.

The trapping system may also prove useful in for example negative ion injector systems where a quartet of traps inserted immediately prior to the accelerating tube entry would effectively prevent electron injection.

Acknowledgments

The author wishes to acknowledge the encouragement received from Prof. K. W. Allen, the assistance of Mr. Bell, Mr. Prosser and Mr. Eatwell in the construction and testing of the tubes and the assistance of Mr. A. Tyrell with magnet problems.

References

1. Patents pending in several countries.
2. The effects on pressure insulated electrostatic Accelerators of ionisation currents in the high pressure insulating gas. C.M. Turner, Brookhaven National Lab. Report 1955.
3. Properties of Inclined Field Tubes. K. H. Purser et al. Review of Scientific Instruments Vol.36 No.4 April 1965 and Nature September 29, 1962 Vol.195 p.1292-3.
4. A New Type of Accelerating Tube for Electrostatic Generators. W. D. Allen. Rutherford Lab. Report NIRL/R/21 1962.
5. Small Aperture Diaphragms in Ion Accelerator Tubes. L. Cranberg and J. B. Henshell. Journal of Applied Physics Vol.30 No.5 1959.
6. At AWRE, Harwell and Oxford. etc.
7. Experience with Back-Biased Accelerating Tubes. J. L. McKibben, Paper at International Symposium on Insulation of High Voltages in Vacuum October 1964.
8. Electrostatic Generator Group Final Report by W. D. Allen and R. H. V. M. Dawton. Rutherford Lab. Report RHEL/R 120. 1966.

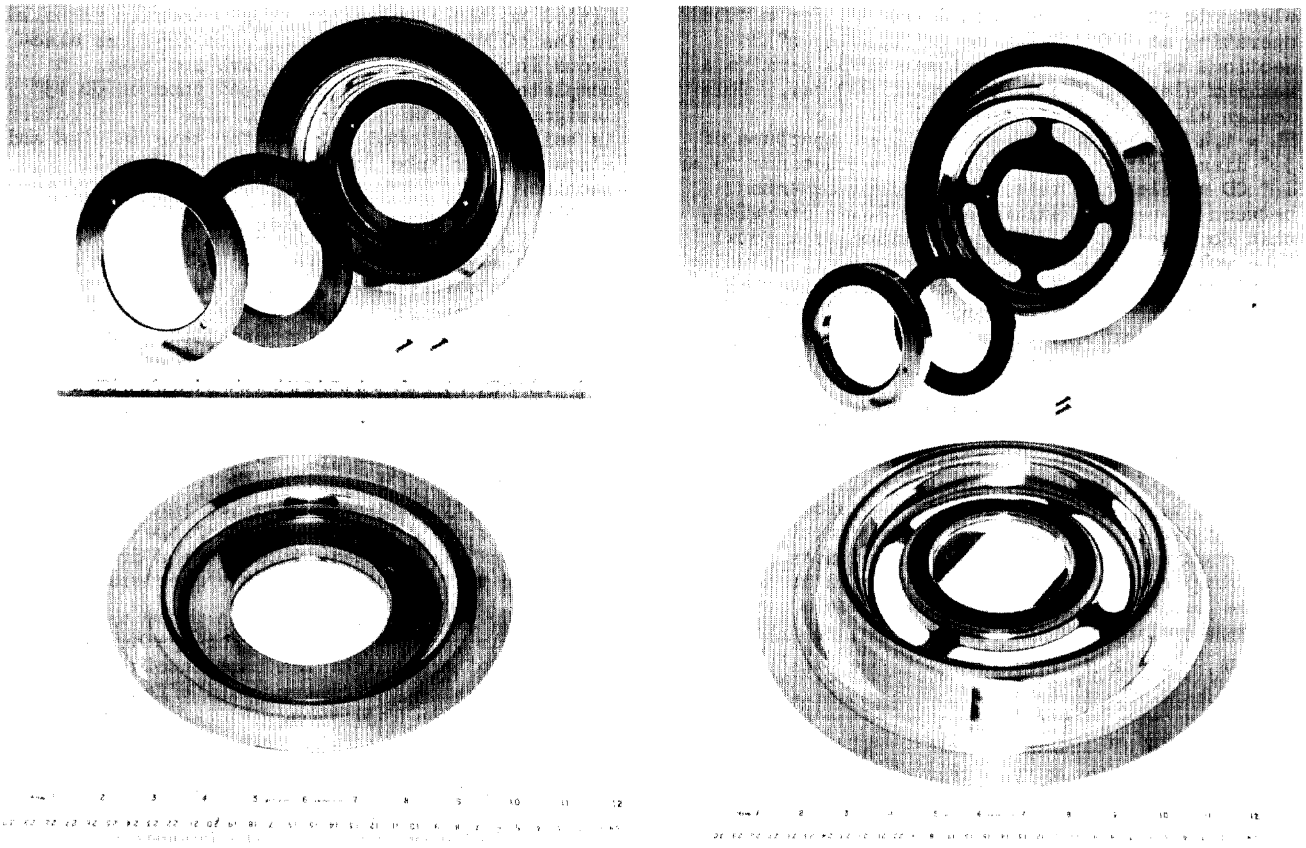

Fig. 1. Permanent Magnet Assembly.

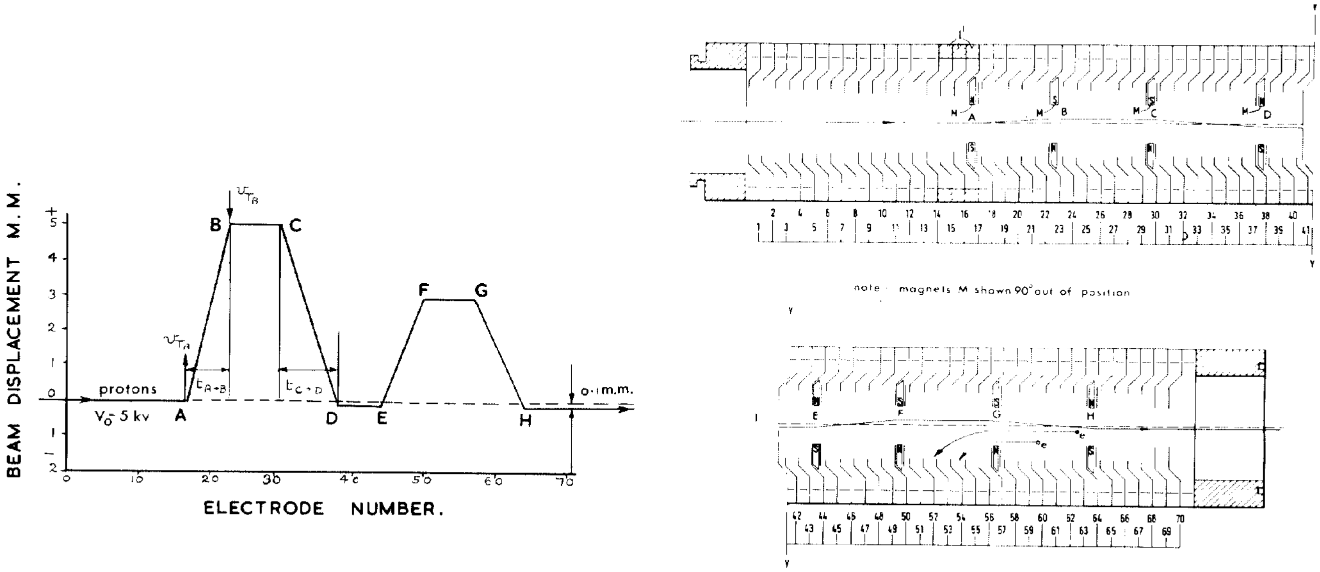

Fig. 2. Typical Accelerator Tube.

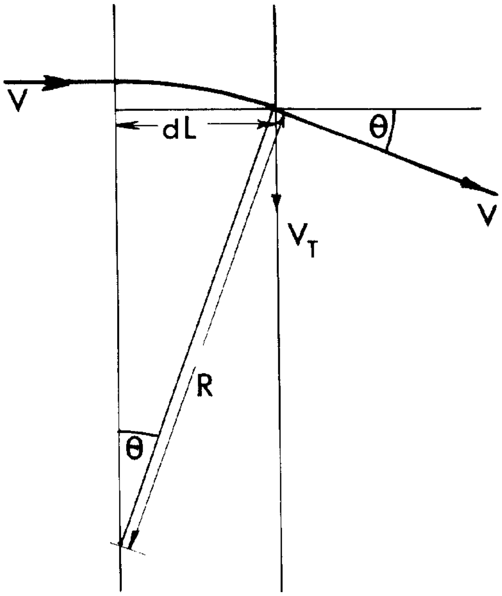

Fig. 3.