A HIGH CURRENT ELECTRON GUN SUITABLE FOR USE DOWN TO 1 NANOSECOND PULSE LENGTH

J. Willard
Vickers Limited
Radiation and Nuclear
Engineering Division

SUMMARY

A triode electron gun is described which has been developed to meet the increasing interest in short pulse high current operation. The gun is of variable perveance capable of injecting at least 15 amps under short pulse conditions (1 nanosecond) and 1.5 amps under long pulse conditions (5 microseconds) with a beam diameter of 1 cm.

Considerations of beam geometry have lead to the choice of a convergent flow Pierce-type gun incorporating an intercepting grid giving an amplification factor μo of 100 and a maximum beam perveance of 0.7μP for the high current condition. A conventional oxide cathode is used.

The cathode-grid structure, which is plug-in replaceable, forms part of a 50 ohm co-axial system mounted on the gun base from which a matched 50 ohm co-axial feeder is taken to the modulator.

Some experimental results for long and short pulse operation are given.

INTRODUCTION

The design of electron linear accelerators for research has become increasingly sophisticated during the last few years. In particular there has grown a demand for high current very short pulse operation. This technique uses pulses of duration much shorter than the filling time of the waveguide so that in a transient state the stored energy in the accelerator cavities is made to provide higher electron power than is instantaneously being supplied from the microwave power source. There is, therefore, a need for electron guns capable of injecting tens of amperes for pulse lengths of a few nanoseconds. The same gun must also be capable of injecting much smaller currents for pulse lengths of several microseconds for steady state operation of the linear accelerator.

The production of nanosecond pulses of beam currents of several amps or more poses several problems. Below one amp beam current it is possible to obtain reasonable results using deflector plates sweeping the beam across a slit. For instance pulse lengths of 3.5 nanoseconds for a current of the order of 1 ampere have been obtained with a deflector voltage of 8kV on the Glasgow and Toronto Linacs. At higher currents, and particularly where high magnetic focussing fields are necessary to prevent beam spread, the problems involved in getting the required rapid rate of change of high voltages across the plates becomes formidable. It is at these higher currents that a grid modulated gun becomes attractive and a considerable amount of work has been done recently on this type of injector.[1,2,3].

The gun described in this paper was designed to satisfy the beam requirements of two linear accelerators shortly to be installed, one at Ottawa for the National Research Council and the other at Paterson Laboratories, Christie Hospital, Manchester. An attempt has been made to produce a versatile variable perveance gun capable of fast pulse modulation while, at the same time, making gun maintenance as simple an operation as possible in order to keep accelerator down-time to a minimum.

As a corollary to the latter, the demountable structure allows rapid assessment of varying gun geometry to be made.

GUN DESIGN

The design parameters of the gun were determined by the beam requirements of the two linear accelerators, the most arduous of which are:-

	Output Beam Current	Pulse Length
Ottawa	5 A	1 ns
	350 mA	4 μs
Christie	10 A	10 ns
	750 mA	5 μs

The beam current is continuously variable between these limits and the pulse lengths variable in steps. 80 KeV was chosen as the injection voltage as a compromise between considerations and also is sufficiently high to permit injection into a v = c waveguide at L-band. Allowing for an accelerator efficiency of 65% and a gun efficiency of 75% a cathode loading of 20 amps giving an injected beam of 15 amps and perveance of 0.664×10^{-6} is required in order to meet the highest current condition.

Variable perveance electron beams can be produced in a variety of ways, the most common of which are -

1. variable beam stops

2. temperature limited emission from the cathode
3. grid controlled, space charge limited emission.

In view of the fast pulse modulation capabilities of a grid controlled gun it is logical to adopt the third system and combine both functions in a grid controlled gun. Considerations of current densities which are obtainable compatible with reasonable life expectancy from conventional cathodes dictate the use of a convergent flow gun. The design of electron guns of this type, commonly called Pierce guns, has been adequately described in the literature.[4,5] Such guns have been used successfully throughout the microwave valve and accelerator fields. A considerable amount of work has also been reported on gridded Pierce guns.[6,7] These design techniques have been used extensively in producing the present gun. The electrode shapes were determined using an electrolytic tank and the final configuration arrived at by adjusting the cathode and grid dimensions empirically and observing the beam shape on a fluorescent target.

The energy homogeneity specification of the Ottawa machine calls for a change in current (in the long pulse case) of less than 0.5% during the pulse. This is best achieved using D.C. for the cathode potential and pulsing the grid relative to the cathode. This system has the disadvantage that dark current, resulting from an incompletely cut-off gun, is a problem during the interpulse periods. For this reason, although cut-off amplification $\mu c = 100$ corresponding to 800V was chosen, a negative grid bias of 2kV is provided. The amplification factor $\mu o = 100$ was chosen as a compromise between a reasonable design of pulse modulator and the mechanical design of the grid.

Summary of Gun Parameters

Injection voltage	80 kV
current	0-15 A
Amplification factor μo	100
Cut-off Amplification factor μc	100
Area convergence	18°
Beam diameter at waist	1 cm
Brillouin field	382 gauss

Magnetic Focussing

In general, it is possible to design for optimum injection conditions at one value only of beam current. Variations in beam current will therefore require adjustment of the magnetic focussing field to compensate for beam aberrations. In an attempt to reduce this effect the magnetic field was designed for confined, or immersion, flow under maximum beam current conditions. It was then argued that at lower beam currents the electron trajectories would tend to follow the magnetic field lines in the accelerating region. The field linking the cathode was roughly determined by means of a Permendur plate which also serves to support the anode. This plate, which projects outside the vacuum envelope, is bolted to a large magnetic shunt plate attached to the gun focus coil. Fine control of the field shape is achieved by means of a pair of bucking coils situated round the gun itself. The main focussing over the injector region before entry into the accelerator proper is provided by a pair of coils capable of a uniform field of up to 1000 gauss. Steering coils mounted inside the first focus coil provide fine adjustment of beam alignment. Fig.1. shows the gun mounted on the Christie accelerator.

MECHANICAL DESIGN

Cathode

Early electron linear accelerators have generally utilised pure metal emitters such as tungsten spirals and tantalum cathodes heated by bombardment. However, the requirement for higher beam currents and the cleaner vacuum obtainable using ion pumps have made the semiconductor and dispenser cathodes increasingly attractive.

For a gun with a grid in close proximity to the cathode pure metal emitters are unsuitable because of the high temperatures involved. The choice was therefore made for a low temperature cathode of the conventional triple-oxide type. Although oxide cathodes are not as robust as the 'L', or impregnated tungsten cathode and do not permit of being let down to air when activated, they have the advantage of good pulse performance and are more readily fabricated on an experimental basis than the other types. In addition, there is much experience of their use in high power klystrons.and at higher voltages than considered here. For initial testing under pulsed cathode and grid conditions a sprayed coating was used but a nickel mush layer was found necessary to prevent undue damage from spark over during ageing. Cathode loading is 3.5 A/sq.cm. in the highest case, giving a cathode diameter slightly greater than 1".

The heater consists of a fine tungsten spiral mounted in an alumina block so shaped that there is a maximum temperature gradient of 20°C across the face of the cathode. A low current heater was chosen to ease contact problems in the demountable system. The cathode and grid subassemblies are shown in Fig.2.

Grid

Fabrication of a high transparency (85%) grid of 1 inch diameter and spherical form, and of sufficient rigidity to maintain its position relative to the cathode during operation proved difficult. Woven wire mesh and spark eroded sheet were tried and rejected in favour of photo-etching of sheet formed to a spherical shape. The finished grid took the form of a hexagonal mesh in order to help equalise the stress during the forming operation. The mesh dimensions are

0.08 in across flats and 0.007 in across the web, the material being molybdenum. After forming, the grid is spot-welded to a massive nickel pressing which acts as a rigid mount and heat sink. Cathode-grid spacing is 0.045 in and is maintained by ceramic pillars, metalised and brazed to Nilo K lugs which are machined to length after brazing.

The calculated temperature rise of the grid is about 350°C for the maximum duty ratio (0.0008) Although the gun has not yet been run at full duty ratio, tests of D.C. cut-off characteristics have not revealed any grid emission. However, should life tests show any deterioration the grid will be gold plated.

Co-axial System and Envelope

In order to achieve the low capacitance and inductance cathode and grid connections dictated by the requirement for fast pulse modulation, a co-axial system has been adopted, see Fig.3. The outer is connected to the grid and the inner to the cathode. One side of the heater is common to the cathode and the other connection is taken out through the hollow inner line. A suitable filter isolates the filament from the pulse voltage.

The impedance of the co-axial line is 50Ω at the base flange, the inner having an outside diameter of $\frac{7}{8}$" and the outer an inside diameter of 2". This connects directly via spring contacts to the air-spaced line, of the same dimensions, of the pulse generator. In the region of the cathode the line is tapered, preserving a uniform impedance, to accommodate the cathode diameter. A co-axial brazed metal-ceramic vacuum tight seal is situated between the inner and outer lines at the base flange. The concentric heater lead also emerges through a metal-ceramic leadthrough.

To facilitate changing the cathode attention has been given to plug-in replaceability. The cathode-grid assembly is rapidly detachable from the co-axial system by undoing six caphead screws round the circumference of the grid mount which forms part of the outer line. The assembly can then be unplugged, see Fig.4. The connection to the inner line is made by means of a helical tungsten spring located in a groove round the circumference of the line, and the heater connection by means of spring fingers backed by a tungsten spring. The cathode structure being rigidly mounted by ceramic pillars from the grid mount the inner line is allowed to expand and contract by the springs during heating and cooling cycles.

In order to allow rapid changes of gun geometry for experimental purposes and easy maintenance the gun has been made demountable wherever possible. Except for the ceramic components the envelope is constructed from stainless steel and the vacuum seals are made with indium wire.

The main insulator is a Sintox cylinder 7 in. long, 5 in. outside diameter and $\frac{1}{2}$ in. wall thickness. It is butt brazed at the ends to 0.020 in. Nilo K annular flanges which form the vacuum seal when argon-arc welded to the mating flanges. Backing the Nilo K flanges are $\frac{3}{8}$in. matching alloy flanges brazed on. These flanges are drilled and tapped and serve to carry the weight of the gun. Anti-corona shields are provided both externally and internally to protect the insulator.

CATHODE REPLACEMENT AND ACTIVATION

The electron gun, a short length of drift tube which may be used for a deflector chamber for dark current control, and a prebuncher form the injector system of the accelerator. A 1 in. diameter in-line, all metal vacuum valve serves to isolate the injector from the accelerator proper during gun maintenance and cathode activation. Pumping is provided by a 125 l/sec triode ion pump through a pumping port on the anode chamber of the gun. A valve on the pumping manifold allows the connection of a backing pump and also provides for the injector to be let down to dry nitrogen.

Spare cathode-grid assemblies may be stored in vacuum or a dry inert atmosphere ready for replacement. The cathode change, from letting the injector down to nitrogen to restarting the ion pump, can be readily accomplished in two hours.

The activation schedule follows the normal pattern for oxide cathodes and takes about four hours for a system which has not been down to air for an excessive period. The main limitation on the speed of activation appears to be the gas handling capability of the pump. After activation the gun is aged up to full 80 kV H.T. with the grid cut-off. Catastrophic flash-over is minimised by removing the 0.2μF ballast capacitor during this operation.

In general, the majority of the cathode-grid assembly components are recoverable, with the exception of the cathode itself. Experience has shown that the cathode, if let down to air or dry nitrogen when cold for brief periods only, can be reactivated to about 75% of its original activity.

GUN MODULATOR

A D.C. supply is provided from a conventional 10 kc/s R.F. E.H.T. unit and is stabilised to 0.1% to achieve the required pulse to pulse stability of injection voltage. The supply is connected to two charge storing capacitors in parallel. For long pulse work (5μsecs down to 0.2μsec) most of the energy for the emitted gun current is taken from a 0.2μF storage capacitor which due to stray inductance has a 50 nanosec rise time. For short pulse work, a single fast discharge storage capacitor of 1000pF value is mounted adjacent to the cathode/anode bushing and connected to provide a minimum of stray inductance. Space is available to provide at least another 2 such capacitors to achieve the very fastest rise time down to 1 nanosecond.

Incorporated with the D.C. supply unit is an isolating mains transformer to provide power to an isolated 80kV platform which supports a pulse generator, and gun heater and bias supplies. Remote control of gun heater, bias supply, pulse width and pulse amplitude is provided by potentiometer and/or rotary transformers whose movement is motorised through insulating drive shafts. The bias supply which is adjustable over the range of -2kV to +500V with respect to the cathode is connected between grid and the platform on which the pulse generator stands. Since the grid cathode co-axial system is terminated in 50 ohms and such a D.C. load is intolerable for the bias supply, a D.C. blocking capacitor of special design is incorporated in the outer cylinder of the co-axial system. The heater supply for the gun cathode is isolated from the pulsed co-axial system by a series of ferrite beads.

Three types of pulse generator have been considered for the gun modulator:-

1. Co-axially mounted U.H.F. plannar triode switching the pulser power supply into the co-axial system. A major difficulty exists as there is not a suitable triode available for the high currents required to be switched to achieve the fast rise times. Development is proceeding with the coupling of several triodes in parallel to achieve the required rating. Several stages of pulse amplification are required and each of these necessitates the use of similar U.H.F. plannar triodes. This results in a complex amplifier but the system has the capability of providing the whole of the required range of pulses and achieving the fastest rise and fall times.

2. A single deuterium thyratron discharging a capacitor across the termination load of the co-axial system. This is a development of an existing modulator and is capable of switching pulses down to widths below 10 nanoseconds with rise times limited only by the rate of rise of current tolerated by the thyratron. This system is only applicable for the short pulses.

3. A tail biting circuit using two deuterium thyratrons and discharging a P.F.N. across the termination load of the co-axial system. This utilises the same thyratron as Case 2. but switches each end of a pulse forming network. By varying the trigger times of the two switches, pulses of varying widths can be produced and fast rise times can be achieved into the termination of the co-axial system. Long pulses up to 10μsecs are possible and development is proceeding to investigate the shortest pulse possible from such a system.

EXPERIMENTAL RESULTS

Grid Control Characteristic

Experiments to determine the grid control characteristic were performed on a fully pulsed system, i.e. both cathode and grid pulsed at a few microseconds in order to avoid damage to the cathode should the gun fail to cut-off. Fig. 5. shows the results obtained for different cathode-grid spacing using the same grid aperture dimensions. It will be seen that a current of 15 amps was obtained at a grid potential of 800V.

The graph for 0.027 in. spacing clearly shows the effect of local cut-off. This could have been eliminated by using a grid of smaller mesh but at the cost of loss of rigidity for the same transparency. The results for 0.042 in. and 0.050 in. spacing show no sign of local cut-off and indicate that the design spacing of 0.045 in. is correct to give an amplification factor μo of 100.

The cut-off amplification factor μc, defined as the ratio of the cathode-anode voltage to the cathode-grid voltage for a current of 0.1% of the design current, is about 100 as measured under pulse conditions. However, under operating conditions as an accelerator the maximum dark current permitted is at least two orders down on this figure. D.C. tests have shown that with a negative grid bias of 2kV the current is a few microamps.

Short Pulse

Gun tests have commenced using modulator system 2 and short pulses of 8-10 ns. have been observed. Tests using system 1 are awaiting completion of the modulator development programme.

REFERENCES

1. F.W.K. Firk. Nuclear Instruments and Methods. 43 312-316 1966.
2. R.K. Houst. and N.J. Norris. I.E.E.E. Trans. NS-12 No.3. 830-835 1965.
3. W.J. Ramler, K. Johnson and T. Klippert. Argonne National Laboratory.
4. J.R. Pierce. Theory and Design of Electron Beams. D. Van Nostrend Company.
5. R.D. Frost, O.T. Purl and H.R. Johnson. Proc. I.R.E. 50 No.8. 1800-1807 1962.
6. H.E. Gallagher. I.R.E. Trans. ED-9 No.2. 234-241 1962.
7. D.W. Shipley. I.R.E. Trans. ED-7 No.4. 195-205 1960.

ACKNOWLEDGEMENT

The author wishes to thank the Directors of Vickers Ltd. for permission to publish this paper.

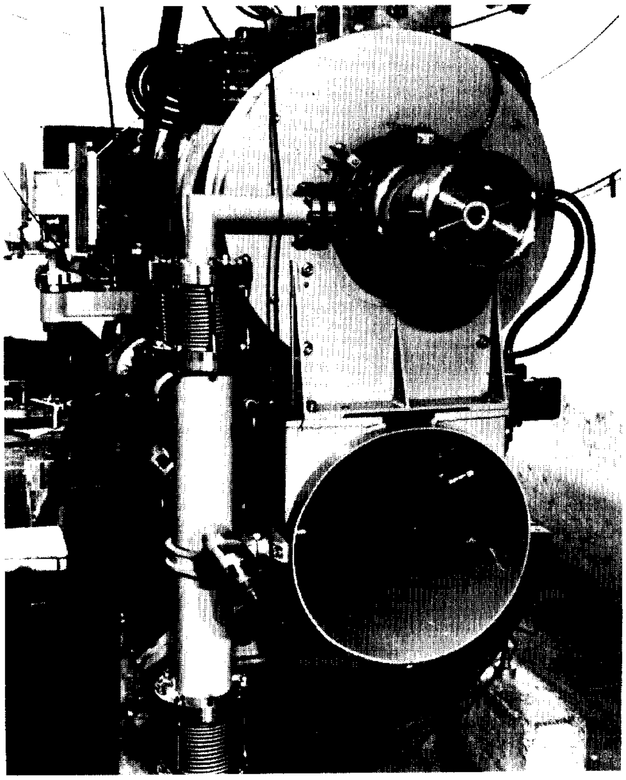

Fig. 1. Electron gun on Christie linac showing focussing coils.

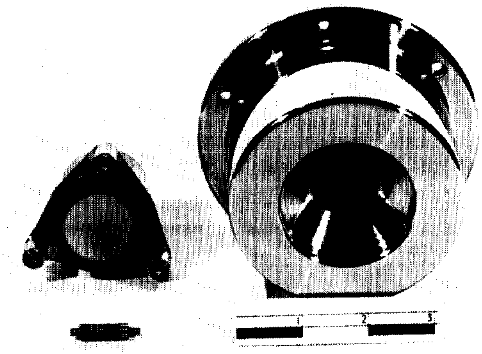

Fig. 2. Cathode and grid sub-assemblies.

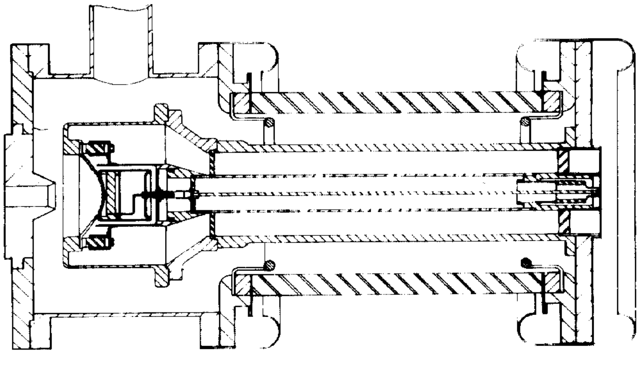

Fig. 3. 80kV Co-axial gun.

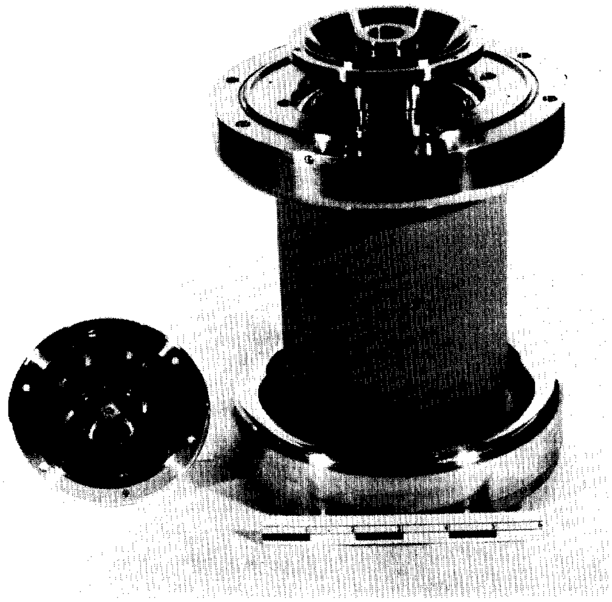

Fig. 4. Plug-in cathode-grid assembly.

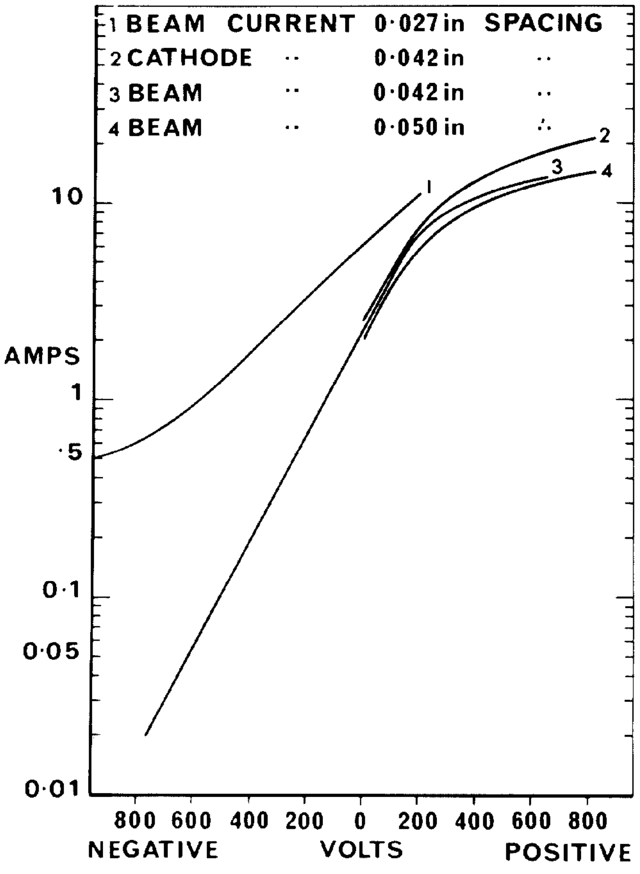

Fig. 5. Grid control characteristic.