High Power Switches for Ion Induction Linacs

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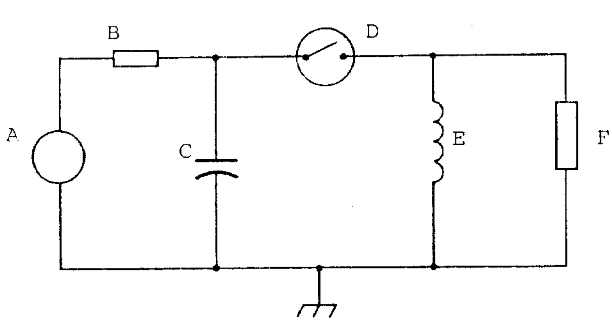
1. Introduction

The success of linear induction ion accelerators for accelerator inertial fusion (AIF) applications [1] depends largely on innovations in pulsed power technology. There are tight constraints on the accuracy of accelerating voltage waveforms to maintain a low momentum spread. Furthermore, the non-relativistic ion beams may be subject to a klystron-like interaction with the accelerating cavities [2,3], leading to enhanced momentum spread. In this paper, we describe a novel high power switch with a demonstrated ability to interrupt 300 A at 20 kV in less than 60 ns. The switch may allow the replacement of pulse modulators in linear induction accelerators with hard tube pulsers. A power system based on a hard tube pulser could solve the longitudinal instability problem while maintaining high energy transfer efficiency. The problem of longitudinal beam control in ion induction linacs is reviewed in Section 2. Section 3 describes the principles of the plasma flow switch. Experimental results are summarized in Section 4.

2. Longitudinal instabilities in pulseline-driven, ion induction linacs

Linear induction accelerator gaps are typically driven by a transmission line or pulse forming network. The characteristic impedance of the modulator is matched to the parallel combination of the beam and cavity damping resistors to provide a constant voltage over the beam pulse. We denote the damping resistor impedance as αR_o, where R_o is the beam impedance. Variations of beam current are decoupled from the cavity voltage when α is small. This limit is not useful for AIF since it implies low efficiency for energy transfer from the modulator to the beam. If α is high, variations in beam current can lead to an interaction of non-relativistic beams with the cavity circuit, resulting in growth of the beam momentum spread.



1. Hard tube pulser. A) HV power source, B) Isolation resistor, C) Capacitor bank, D) Opening-closing switch, E) Induction cavity leakage circuit, F) Beam load.

Computer PIC simulations of beam transport [2] (neglecting space charge effects and reactive components of the cavity circuit) lead to the conclusion that the momentum spread for stable beam transport is related to the damping resistor parameter by $\Delta p_z/p_z > \alpha/(\alpha+2)$. A typical requirement for momentum spread is $\Delta p_z/p_z < 10^{-3}$ [4]. This implies small α and an energy transfer efficiency of only 0.1 per cent. In early AIF induction linac conceptual designs, the beams had strong longitudinal space charge forces that would counteract bunching instabilities. Recently, there has been increased interest in multi-beam transport [5]. This approach reduces transverse space charge forces to aid in the preservation of low transverse emittance. Unfortunately, there is a corresponding decrease in longitudinal space charge forces, increasing the susceptibility to longitudinal instabilities. We have extended the model of Ref. 2 to include space charge force in the 1-D limit. Computer studies to determine requirements on pulsed power driving circuits for longitudinal stability are underway.

An effective solution to the problem of longitudinal dynamics is the use of a hard tube pulser instead of a pulse forming network. The hard tube pulser, illustrated in FIGURE 1, is a high capacitance bank connected directly to the gap. The current drawn from the bank in a pulse makes a negligible change in the stored charge. The gap voltage is relatively indepedent of the beam current; therefore, a damping resistor is unnecessary. The keystone of the circuit is the hard tube switch. It must be capable of both closing and opening the circuit rapidly. The switch must terminate current completely after the pulse; otherwise, the energy in the reservoir bank will discharge as leakage current through the inductive cavity. In relatively low power applications, the hard tube is usually a vacuum triode. Vacuum triodes have too high an impedance to be applied to ion induction linacs. The switch must have a conducting-state impedance less than 1 Ω in order to maintain the stability of a beam with low momentum spread.

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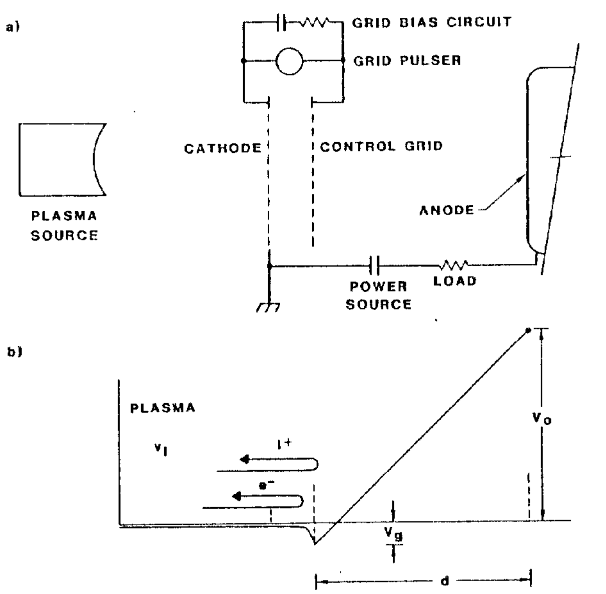
3. Plasma flow switch

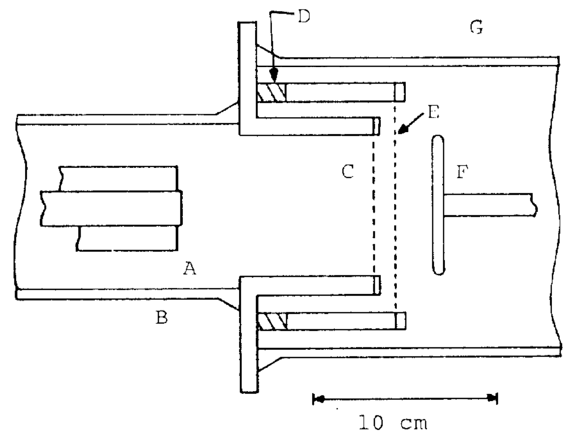
The switch that we developed utilizes electron conduction through a plasma filled gap. Therefore, in the conducting state, the voltage drop across the switch is small. Electron flow is controlled by a biased grid. In contrast to devices such as the thyratron and tacitron [6], there is no static gas fill. Plasma is generated external to and independent of the power gap. The plasma flow switch is illustrated in FIGURE 2(a). A controlled pulsed plasma source is activated a few microseconds before switching. In the off-state, the control grid is biased negative with respect to the cathode. As shown in FIGURE 2(b), plasma electrons cannot pass through the control grid. The ions that penetrate the grid cannot cross to the anode. Electron flow is initiated by clamping the grid potential to that of the cathode; subsequently, plasma enters the power gap and electrons are drawn to the anode. The switch reaches its low impedance state in the time it takes plasma to expand across the gap (~1 μs). Power flow is terminated by pulsing the grid negative, excluding electrons from the power gap. The switch returns to high impedance after plasma is cleared from the gap; because of the nature of plasma erosion, the opening time can be quite rapid (~30 ns). A complete theoretical treatment of the plasma flow switch is included in Ref. 7.



2. Plasma flow switch. a) Schematic view of electrodes. b) Particle flow and electrostatic potential in off-state.

4. Experimental results

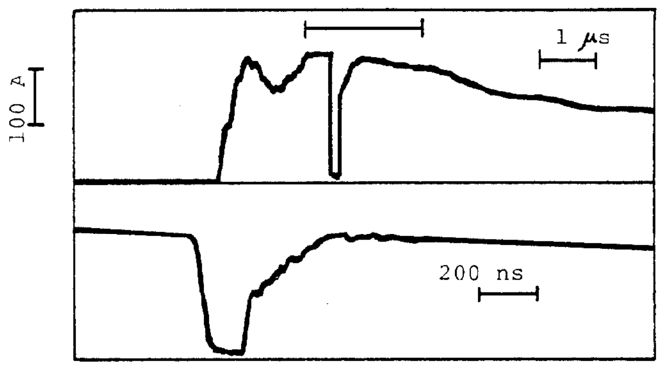
The experimental apparatus is illustrated in Fig. 3. Three surface spark sources (described in Ref. 9) were driven in parallel by a low inductance capacitor bank. They generated a 5 μs plasma pulse. The plasma flux could be adjusted by varying the distance of the sources from the switch. At a 10 cm spacing, measurements with a Langmuir probe and ion flux probe at the control grid showed that the plasma had a density of 3×10^{11} cm^{-3} and a directed ion velocity of 2×10^{6} cm/s. The available electron flux was ~10 A/cm^2. The shot-to-shot flux reproducibility was ~5 per cent. The grid voltage was normally clamped to the cathode potential through a 75 Ω resistor. After predetermined conduction time, electron flow was extinguished by a negative pulse on the grid, typically -400 V. The grid pulser had a risetime of 14 ns. The pulser could be configured to generate either a long pulse (~8 μs) or a 200 ns square pulse with a 20 ns falltime. The width of the gap between the control grid and collector could be varied; spacings from 1 cm to 3.5 cm were used. The anode had an area of 55 cm^2. The power circuit consisted of a 0.33 μF capacitor charged to +0-20 kV in series with a 50 Ω resistor.



3. Experimental apparatus. A) Three surface spark plasma sources, B) Plasma expansion chamber, C) Cathode grid, D) Ceramic standoffs, E) Control grid, F) Anode, G) Vacuum insulator.

A series of tests was carried with the 200 ns grid pulse. The intent was to observe features of both the opening and closing phases of the switch. An oscillograph showing current conduction through the switch at an open circuit voltage of 12.5 kV is reproduced in Fig. 4. The upper trace displays long term current variations, while the lower trace is an expansion near the switching time. The plasma reaches the switch 2.5 μs after initiation of the sparks. The time to reach full circuit current is determined by the risetime of the plasma flux and the time for plasmas to fill the power gap. The voltage on the switch drops almost to zero 1 μs after the arrival of the plasma; subsequently, the current is limited by the series resistor. When the grid is pulsed, the current drops from 220 A to 10 A in 55 ns while the voltage rises from +0 to 12 kV. The theoretical model of Ref. 7 predicts an opening time of 18 ns for an instantaneous grid pulse. The longer observed time is probably caused by the risetime of the grid pulser and grid loading immediately after switching. The residual current in the off-state represents ion conduction across the opening vacuum gap. The model of Ref. 7 predicts an erosion sheath width of 0.85 cm at 200 ns after switching; the space charge limited ion current at 12 kV for this gap width is 5 A, consistent with the measured current.

Conduction is resumed at the termination of the grid pulse. The current abruptly rises to 130 A and then approaches the circuit limited current after a time lapse of ~300 ns. The initial current rise is consistent with space charge limited bipolar electron flow from the grid across the 0.85 cm vacuum gap at 5.8 kV. The switch impedance approaches zero after a delay during which plasma expands into the vacuumn region of the switch. The predicted plasma drift time is 400 ns. The switch current has been successfully extinguished for a short pulse at open circuit voltages to 20 kV and currents to 300 A. This represents a power flow of 6 MW for 3 μs before switching. As predicted by theory, the behavior of the switch is almost unaffected by changes in the grid-collector gap width.



4. Switch current, short extinction pulse. Top: Long term current, 1 μs/div. Bottom: Expansion of region shown, 200 ns/div. (12.5 kV open circuit voltage, -400 V on grid).

With a long grid pulse, switch current could be completely terminated. In this case, the circuit acted as a hard tube pulser. Generation of a 3.8 μs, 250 A, 12.5 kV pulse across the 50 Ω load is illustrated in Fig. 5. In the expanded view, note the long term decay of ion current following switching. The decay time is consistent with the predicted plasma clearing time [7] of 0.5 μs. Also note that for the case shown the current is reinitiated after switching ultimately leading to discharge of the capacitor. This undesirable effect could result from the falling voltage of the grid pulser or electron emission by bombardment of the grid by energetic ions. Reinitiation of current does not occur when the open circuit voltage is reduced to 10 kV. We expect that the voltage range of the switch can be extended by 1) improving the grid pulse, 2) actively initiating current flow in the switch, and 3) terminating plasma flow soon after switch opening.

5. Conclusions

Experimental results on the plasma flow switch are encouraging. The small demonstration model already has the capability of controlling power levels of interest for linear induction accelerators. Extrapolation to higher current levels involves a straightforward increase in the size of the device. A 10 kA switch at the same current density requires a collector radius of 21 cm. The low jitter and active command of the plasma flow switch makes it possible to gang units in parallel. Operation of the switch is in unusually good agreement with theory; therefore, extrapolations can be made with confidence. We have not yet observed a failure of the switch to extinguish current. We are presently improving its long term holdoff ability at high voltage. The switch compares favorably with alternate technologies [10]. The pulselength and power flow figures quoted in this paper are comparable to tacitrons; the dV/dt achieved by the plasma flow switch is an order of magnitude higher.

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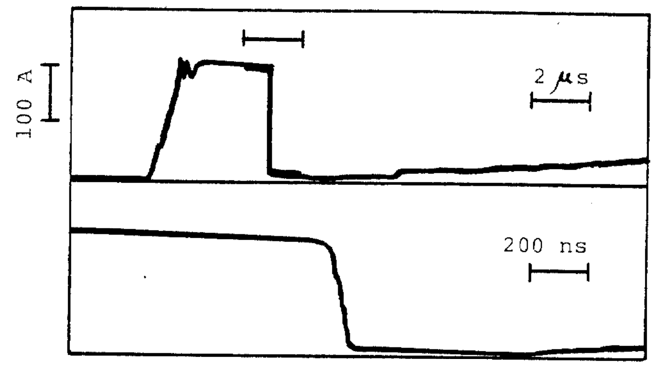

5. Switch current, long extinction pulse. Top: Long term current, 2 μs/div. Bottom: Expansion of region shown, 200 ns/div. (12.5 kV open circuit voltage, -400 V peak grid voltage).

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