FOCUSING MODERATE ENERGY LINACs WITH BACKGROUND ION PLASMA

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Introduction

We designed, constructed, and successfully tested an Ion Focused Linear Accelerator (IFLAC) which used a background of positive ions to focus the beam and stabilize it against various instabilities.[1] A 100 A electron beam was accelerated to approximately 120 kV over 75 cm with greater than 40% efficiency during a series of controlled experiments. The beam brightness exceeded 6×10^3 A/cm^2 Sr and emittance was less than 30π mR cm. Near the end of the work a 200 A beam was accelerated through the first 3 gaps with virtually 100% efficiency. These results demonstrate the value of ion focusing in reducing the cost and complication of electron induction accelerators.

Experimental Apparatus

The accelerator tube, shown schematically in Fig. 1, is the major accelerator component - it includes the individual accelerating modules, and the ion source. The plasma produced in the ion source drifted through a 5-10 cm region and through a 'grille cathode' into the accelerator. Electrons from the Gap 1 plasma source are accelerated and injected into the rest of the accelerator. In the final embodiment, no electron source other than the plasma produced by the flashover source was used.

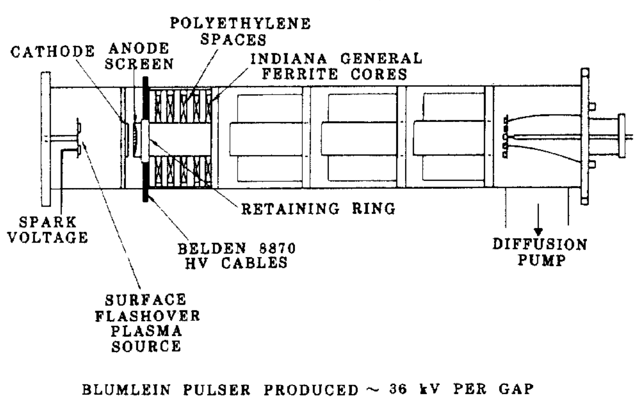

Figure 1. IFLAC has an ion source and 4 acceleration stages with 15 cm between gaps.

A screen anode constituted the output of Gap 1. All 4 modules were built the same way (with the exception of the grid), and they were placed inside 20 cm OD aluminum housings. The high voltage enters through the insulator/inner conductor assembly of Belden 8870 cable threaded through vacuum feedthroughs.

The most successful ion source configuration was the surface flashover system, however, the Lasertechnics piezo-electric puff valve gas plasma system provided a gas plume that was preionized and accelerated by a time varying radial magnetic field.[2] Use of the magnetic acceleration system was discontinued because there was not sufficient time to solve the problems of preionization non-uniformity. Observation of good (i.e., high fluence) plasma production on some pulses leads us to believe that this can be a viable plasma production technique, however.

In the surface flashover ion source, plasma formation is initiated when 15 kV pulse is applied across a carbonized polyethelene gap. A discharge occurs and current begins to flow through the system from the 6 μfd energy storage capacitor which provides most of the discharge energy.

The voltage pulse used to drive the accelerating gaps was produced by a Blumlein[3]-type pulse forming network constructed of Belden 8870 high voltage cables each with an impedance of 80 Ω, assembled in a very low inductance configuration. All transmission lines had electrical lengths of 12 ns. Voltages for the 4-line system are typically 36 kV/gap (rather than 50 kV) and ~ 35 ns due to Blumlein rise-time problems.

Experimental Observations and Discussion

In the first series of experiments, plasma generated by both the gas puff and the spark were injected through various cathodes in Gap 1. Cathodes consisted of felt electron-emitting material with different holes which allow plasma to flow into the gap from the source. Beam propagation efficiency downstream showed, in the absence of the plasma, beam current densities of approximately 2 A/cm^2 on average. When the plasma is turned on, the current density is increased by approximately a factor of 5. Sufficient plasma for complete charge neutralization was available for all positions at which current density was measured, yet the transport efficiency was not improved with the addition of plasma. The effective divergence angle for the beam over 15 cm is approximately 45° based on this data, with a transport efficiency of less than 10% over the first 15 cm of propagation. We believe that the cause of the large beam divergence is the predominance of edge emission in the cathode emission pattern.

Due to a high beam divergence observed, a concentric ring or 'grille cathode' was built to allow virtually unimpeded plasma flow into the diode. This cathode consisted of a 1.6 cm radius grille of thin copper annuli 2 mm thick in the axial direction spaced approximately 2 mm on the radius. The anode was made up of bronze screen with approximately 75% transmission. For most of the experiment the anode-cathode gap was approximately .2 cm, which results in a Child-Langmuir current of 3200 A at 36 kV. High transport efficiency was observed using this cathode. To understand the dynamics in this mode, the background plasma was diagnosed.

A series of planar Langmuir probe measurements and Faraday cup measurements were made to give some rudimentary information on the plasma properties. The most useful data was the plasma ion saturation current which was measured with a -90 V bias on the probe. Electron saturation currents were measured, but the data showed evidence of plasma perturbation due to the large currents which were drawn by the probe. The probe characteristic does indicate an electron temperature of 24 ± 4 eV.

The ion density profiles inferred from the saturation currents are displayed in Fig. 2 for a variety of times during the pulse. The gradient is highest early in the pulse, and drops as $1(Z+4)^2$ after approximately 25 μsec. The inverse square dependence

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of the density profile is consistent with the assumption of straight line ion motion.

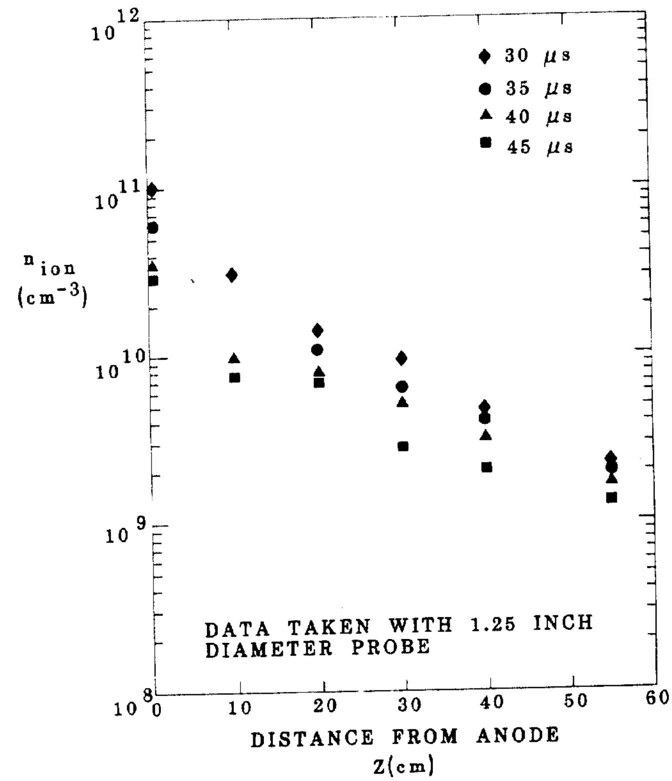

Figure 2. Ion density profile shows inverse square dependence consistent with straight line ion motion.

The gap voltage as a function of the time delay from flashover (plasma) initiation shows the gap is shorted approximately 2 μsec to 24 μsec. An intermediate value of approximately 20 kV was observed at our normal operating delay of 33 μsec. Based on observed waveforms, we conclude that the shorting results from a plasma-induced vacuum breakdown, possibly associated with neutrals from the gap. The gap shorting problem was the major limitation we encountered. When the injector gap was increased late in the experiment, improved results (200 A injected) were achieved. Thus, we conclude that gap shorting is a serious but solvable problem for ion focused accelerators.

The beam current transport through the accelerator was measured as a function of delay time from plasma flashover initiation and position in the accelerator. Figure 3 shows 120 A of beam current after 4 stages measured directly with a 1 3/4" Faraday cup and inductively with a Stoddart probe. Current transport for a delay time of 33 μsec and an anode-cathode (Gap 1) of 0.2 cm is shown in Fig. 4. Virtually 100% of the current is transported from Gap 1 to Gap 2, which is a significant contrast with the previous results where less than 10% of the injected current was transported to Gap 2. Figure 4 also shows that there is a 70% increase in beam current at Gap 2 and a small increase at the output of Gap 3. The beam current output of the injector was in reasonable agreement with predictions based on plasma flux measurements. This is not true of the current injected at Gap 2, where the predicted plasma flux is approximately 15 A, rather than the 50 A observed.

We suggest that the electron emitting sheath in Gap 2 penetrates to a position where the axial gap electric field is comparable to the sheath field of (T_e/λ_d) (T_e is the plasma electron temperature and λ_d is the Debye length) of approximately 700 V/cm. Estimating an E_z e-folding length as the tube radius/2.4 (root of J_0), we predict approximately 4 cm field penetration beyond the 15 kV/cm gap. Based on this reasoning there must exist an enhanced plasma current in the tube to supply electrons to the gap. This current could result from the two-stream instability, or from secondary effects on the chamber wall. Clearly, much further study of this problem is required.

Energy measurement of the beam were made by comparing beam penetration through foils of known thickness to the known range energy relations and absorption curves. The 3.1 cm diameter Faraday cup was covered with 1 to 5 layers, 5.1 mg/cm^2 thick aluminum, and current measurements were made as a function of delay time. The resulting range-energy curve is easily explained by a population of electrons in which 60% have 120 kV kinetic energy and 40% have energy less than 40 kV.

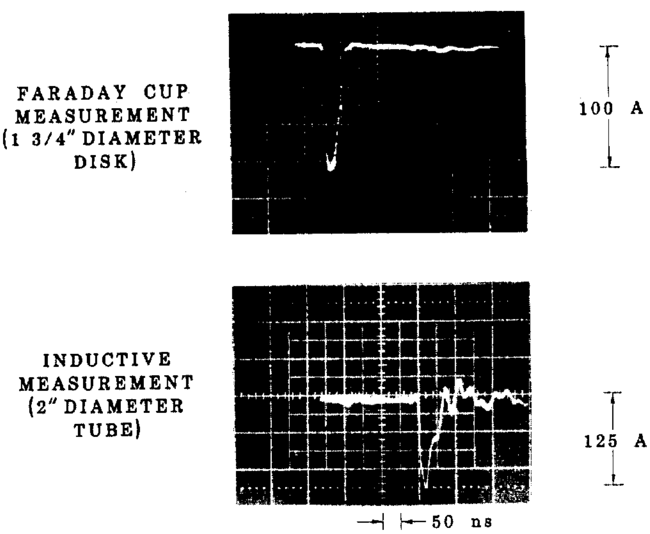

Figure 3. Current measurements after 4 stages (nominal 200 A injection).

The beam radial profile was measured at a position 25 cm beyond Gap 4 where the particles are no longer lost at the 2.5 cm wall. The data taken for a 33 μsec delay is shown in Fig. 5. The total current at this position (z = 70 cm) was measured to be 40-60 A, and the plasma density inferred was approximately 10^9 cm^{-3}. The radial profile data suggests that the beam is made up of a central, low emittance beam confined in its own self-magnetic field, plus a population of high emittance unconfined particles.

Two separate beam divergence measurements were made by placing a .6 cm diameter aperture at Z = 60 cm, and measuring the beam radius downstream. The first set of data taken with the triple Faraday cup showed the divergence was too low to measure with this technique. Then a scintillator was placed at Z = 85 cm (25 cm beyond the aperture) and the time-averaged beam profile was displayed on a photograph as shown in Fig. 6. Since this is a time integrated five-shot overlay, the actual spot diameter at any given time may be much less. Taking the apparent radius of .75 cm at Z = 25, and correcting for the initial radius $r_0 \sim 0.3$ cm, we have a divergence of 0.03.

The data suggest that the central low emittance portion of the beam originated in Gap 1, and the outer halo originates in Gaps 3 and 4. Electrons which originate in Gaps 2-4 receive a large inward impulse in the low velocity portion of their orbits near the effective cathode surface. Thus, they have high transverse velocities and are rapidly lost from the beam. Using the parameters I = 18 A, $\beta\gamma$ = 0.7, r = 2 cm, and r' (edge) = .03/.71 (corrected for RMS vs. edge) we have a normalized edge emittance of the central beam of $\epsilon_e \approx 55\ \pi$ mR cm. The RMS normalized emittance is 35 π mR cm. These numbers lead to normalized brightness values of $B_n = I/\epsilon_n^2 \approx 3\times10^3$ A/cm steradian.

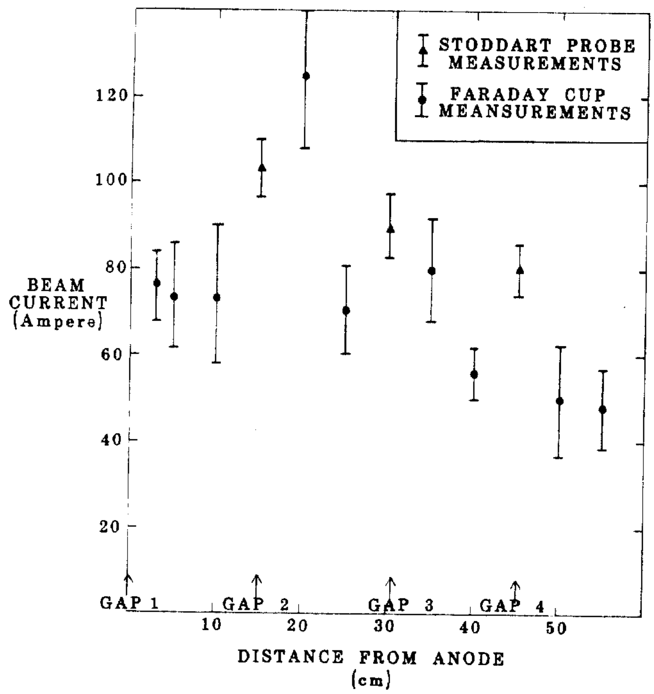

Figure 4. Current transport for 33 μsec delay time and 0.2 A-K shows 100% transport to Gap 2 and current enhancement from Gaps, 2, 3 and 4.

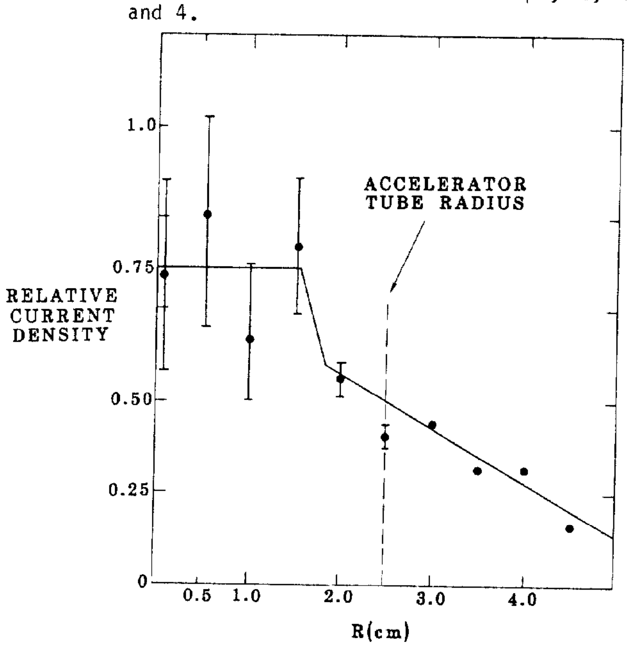

Figure 5. Beam radial profile 25 cm after Gap 4 suggests the beam has a central portion confined by self-magnetic fields and an outer high-emittance portion.

The high brightness 18 A central part of the beam, for example, is predicted to have an RMS divergence of approximately 0.04 from the formula, in reasonable agreement with the measured value of 0.03. Effects such as plasma currents in the center of the beam can reduce I and so, the divergence. Similarly, any reduction in ion density near the axis (for example reduction due to electron beam induced motion) will result in reduced equilibrium divergence. Note that the central high brightness beam observed could be transported with very low forces.

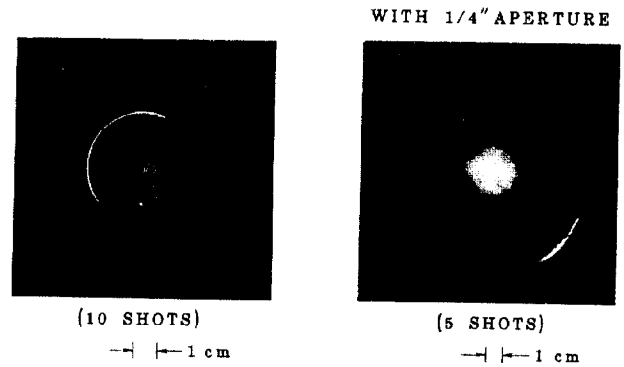

Figure 6. Beam profile with scintillator at end of accelerator shows central beam divergence of < 0.03 radians.

The last result obtained with the accelerator was an injection current of > 200 A with an output current of 100-200 A. Transport of 200 A to Gap 3 was routinely observed. Opening the anode-cathode gap to 3 mm allowed operation at approximately 23 μsec delay at a density of 3×10^{11} cm^{-3}. In this mode, microwave emission at approximately 4 GHz (plasma frequency corresponding to 2×10^{11} cm^{-3} which corresponds to Z = 0-5 cm) was observed. This microwave emission was thought to be associated with the two-stream instability. No brightness measurements were made in this mode, but they suggest that B > 10^4 is easily achievable.

Directions for Future Work

Many of the limitations found in our experiment - including gap shorting and over-neutralization - resulted from inadequate plasma control. Although the accelerated beam had high brightness, further improvements can be realized by tailoring the plasma profile. This could be accomplished by using a grid controlled plasma cathode or an electron beam gas ionization system as the plasma source.

Higher energy per gap would allow us to produce higher current beams for enhanced self-focusing in the channel, and would increase transport efficiency by reducing the particle deflections due to accelerating gap fields. The prospects for the construction of low cost, compact, induction accelerators by this technique is excellent.

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