# EXPERIMENTAL INVESTIGATION OF CERTAIN BEAM TRANSPORT ISSUES IN A PULSED TRANSMISSION LINE LINEAR ACCELERATOR

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## Summary

The successful development of a new generation of high current, high voltage, linear induction accelerators relies on the solution of a number of beam transport problems, including radial oscillations, diocotron instabilities, transverse beam break-up (BBU), etc. Most of the instabilities appear to onset either at the injector region or at the accelerating gaps. Radial oscillations were first observed in Radlac I, while transverse beam breakup was first observed on the SLAC accelerator, and more recently on the ETA accelerator.

A low emittance, high current, high voltage injector, precisely aligned with the guiding magnetic field axis and beam vacuum pipe axis is of prime importance for successful beam acceleration and transport. Similarly, an accelerating gap design which maintains radial force balance, and an accelerating cavity with low Q and very small transverse shunt impedance $Z_\perp$ should eliminate the most dangerous radial oscillations and beam break-up instabilities. The design and experimental studies of a new 4 MeV, 40 kA electron beam injector and accelerating gap will be presented. Test bench measurements of $Z_\perp$ and Q on a typical radial transmission line accelerating cavity prove that BBU is not of concern unless the number of accelerating gaps become excessively large.

## I. Introduction

In the last ten years, considerable work has been devoted to the production and acceleration of intense relativistic electron beams using linear induction accelerators.[1-4] Because of the extremely high currents involved, 10-100 kA, and the relatively large number of modules required, these accelerating structures are susceptible to a number of instabilities. Radial oscillations[4] and transverse beam break-up (BBU)[5] are the most serious.

The analysis and means of avoiding these instabilities were the objective of extensive analytical and numerical studies reported previously.[6,7] In this paper we report experimental work addressing the above instabilities. Section I describes the design and performance of a new 4 MeV, 40 kA foilless diode injector with low emittance and no radial oscillations. Section II involves the radial oscillation measurements on a new accelerating gap design with radial force balance. Finally in Section III, the test bench measurements of $Z_\perp$ and Q a of typical pulsed transmission line cavity are presented and its significance in exciting transverse beam break-up modes is discussed.

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## II. IBEX Foilless Diode Injector

A new high voltage isolated Blumlein accelerator (IBEX) was designed and constructed for these injector experiments.[8] The IBEX accelerator fitted with a foilless diode source has become one of the most reliable intense electron beam injectors.[9,10] It can provide a maximum pulse of 4 MV, 100 kA and 20 ns FWHM when matched with a diode impedance equal to its characteristic 40 ohm impedance. The design goals for these experiments were 20-40 kA at 4 MV.

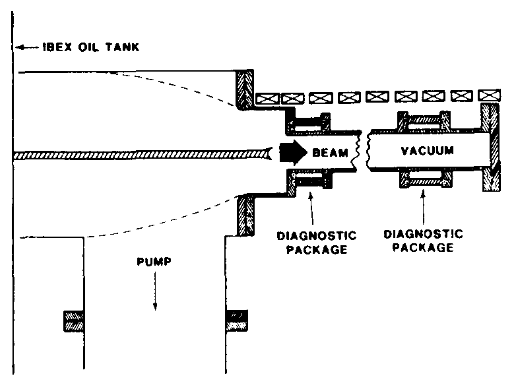


Fig. 1: Diagram of the IBEX experimental setup including the diode and the vacuum transport line.

Fig. 1 is a schematic diagram of the experimental set-up including the foilless diode and vacuum transport line. Typical voltage and current waveforms are shown in Fig. 2. The beam propagates a distance of 10 cyclotron wavelengths in vacuum along a uniform magnetic field.

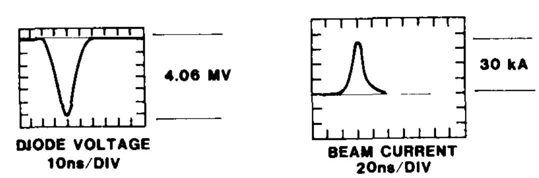


Fig. 2: Typical foilless diode voltage and current waveforms.

A systematic study of the diode performance and beam vacuum propagation was undertaken.[9] The free variables of the experiments were anode-cathode voltage, axial magnetic field, cathode shank radius and anode cathode spacing.

Fig. 3 shows the beam damage pattern on a set of brass witness plates for the radial oscillation measurements. The targets scanned an entire cyclotron wavelength distance and were positioned 1 cm apart for 7 consecutive shots. Fig. 4 shows the measured beam outer diameter ($2r_b$) at various distances from the cathode. The points lie on a straight line indicating no radial oscillations. The beam transmission to the end of the drift pipe was 100%.

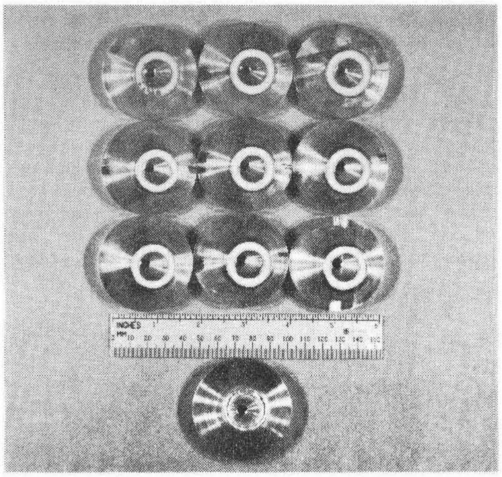

Fig. 3: Beam damage patterns in vacuum and at various distances from the cathode for radial oscillation measurements. The nine targets above the ruler were obtained with 7 kG guiding field. The lower one was obtained with 14 kG. Some fine structure is observed in the 14 kG target.

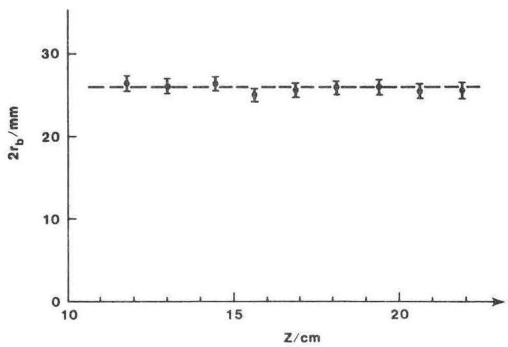


Fig. 4: Axial variation of the beam envelope. The distance z of each measurement point is from the cathode plane.

## III. Radial Oscillation Measurements of a Radial Force Balanced Accelerating Gap

The radial oscillations arise because of the lack of radial force balance in the gap region and can cause deterioration of beam quality and severe beam losses. Several methods of suppressing radial oscillations were proposed and theoretically studied,[7,11] including contouring the magnetic field in the gap region, and increasing the wall radius after each gap. These techniques are fairly easy to implement and require minor hardware modifications of the available Radlac I accelerating gap structure. The novelty of this experiment was the balance of the radial forces at the accelerating gap region.

Two of the Radlac I Pulse Forming Lines were connected in such a fashion as to provide twice the voltage of a single RPL. (Fig. 5) This configuration provided the accelerating voltage for the foilless diode injector (2-3 MV). The post accelerating gap used a single Radlac RPL structure.

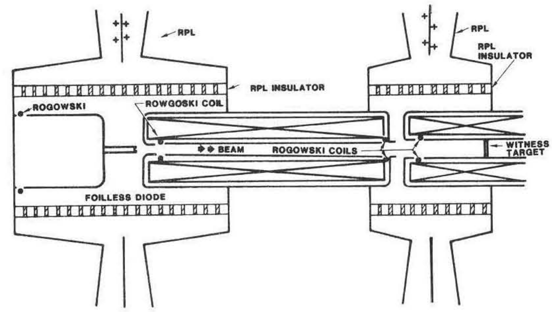


Fig. 5. Schematic diagram of the radial oscillation experimental indicating the key components.

The beam cross section was measured along its path upstream and downstream of the accelerating gap and in several locations. Brass witness plates were used for these measurements. The experiments were divided into two sets. In the first set, no accelerating voltage was applied to the post accelerating gap, while in the second set both injector and accelerating gap were activated. Because of a slight misalignment between vacuum pipe axis and the guiding magnetic field, the beam envelope was somewhat deformed to an elliptical shape rather than being circular.

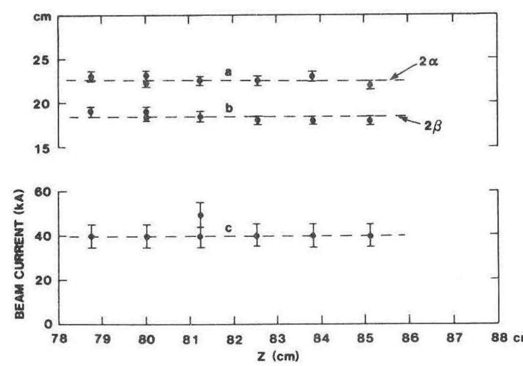


Fig. 6: Radial oscillation measurements with both the injector (2 MV) and accelerating gap (1 MV) activated. Trace a gives the major axis ($2\alpha$) of the beam ellipe, trace b gives the minor axis ($2\beta$) while trace c gives the beam current for every measurement.

Fig. 6 gives the major (trace a) and minor (trace b) axis of the beam ellipse. Trace c is the beam current for every envelope measurement. (Both the injector and the accelerating gap were energized.) Similar results were obtained with the first set of experiments. The error bars of $2\alpha$ and $2\beta$ are due to statistical fluctuations in the geometric measurements of the beam imprint on the witness plate. No radial oscillations were observed in either sets of experiments.

## IV. Measurements of the Resonant Frequencies $\omega$, Quality Factors $Q$ and Transverse Impedances $Z_\perp$ of Pulsed Transmission Line Cavities.

In an induction machine, the pulse forming line outputs are fed directly to the diode and accelerating gap via transmission lines. Hence, the accelerating cavities should in principle be free of any r.f. resonances with measurable quality factor Q. However, if there exist resonant modes of the accelerating cavities with electromagnetic field patterns such that a transverse magnetic field exists along the beam path, then the passage of the beam pulse can excite those modes. Interaction of the beam pulse with these fields can cause a transverse deflection of the beam. The resulting beam displacements add from cavity to cavity and eventually can lead to a large transverse oscillation and beam losses on the walls of the drift tubes. This instability is called beam break-up instability, and it was observed first at SLAC.[5] The magnitude of the beam displacement has been shown to be equal to a power series of the beam accelerator parameters such as pulse width $\omega t$, transverse impedance $Z_\perp$ and beam current, with the order of the series equal to the number of accelerating gaps.[5]

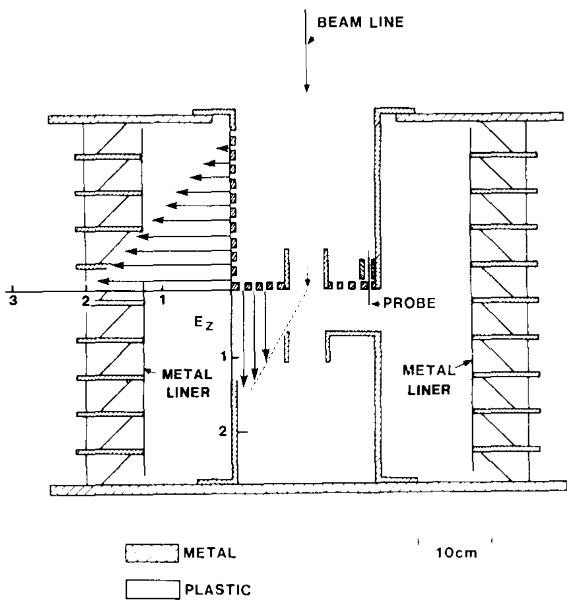


Fig. 7: Typical pulsed transmission line cavity. For the mode identification, the inner walls of the plastic grading rings are lined with copper tape to increase the Q of the cavity. The measuring ports, the probes as well as the $E_z$ field pattern of the cavity for one of the TM modes are also shown.

A typical cavity for a linear accelerator driven by pulsed transmission forming lines is shown in fig. 7. The outer cylindrical wall is composed of metallic and plastic grading rings and serves a double purpose. It acts as a high voltage standoff as well as an interface between the outer dielectric and the vacuum. The inner boundary is defined by the metallic wall of the field shapers. In the accelerator assembly, the cavity is surrounded by a liquid dielectric which can be transformer oil, water, or ethylene glycol. These complicated cavity boundaries present a formidable microwave problem for the theoretical and numerical prediction of the various resonant eigenmodes and the corresponding Q and $Z_\perp/Q$ values. Consequently, the direct approach of experimentally identifying the cavity modes and measuring the Q and $Z_\perp/Q$ values was undertaken.

The mode measurements were made by exciting the cavity with a 1.25 cm long probe. The probe was inserted through openings (fig. 7) inside the cavity and was r.f. driven with a sweep oscillator. A similar probe was used to detect the cavity signal which, after passing through a sensor crystal, was amplified and displayed on an oscilloscope as an amplitude versus frequency plot. For the mode identification only the $E_z$ was measured. The $E_z$ was mapped as a function of the radial (r) and axial (z) position inside the cavity. For the measurements of the $Z_\perp/Q$ the method of Hansen and Post[12] was applied.

To increase the amplitude of the transmitted signal, we lined the inside wall of the outer shell with a copper sheet. (The copper walls increase the Q of the cavity but do not affect appreciably the eigenmode frequencies). Fig. 7 gives the $E_z$ field pattern of the metal walled cavity for one of the TM modes obtained with the $E_z$ probe. Table I summarizes the results of those measurements. As expected, the Q and $Z_\perp/Q$ are relatively high. In the second stage of the experiment, the copper lining was removed, and the cavity was surrounded by water as outer dielectric. The plastic grading rings combined with the water made such a glossy environment that we were unable to identify any resonant mode. From the power output of our sweep oscillator and the sensitivity of our antenna, we believe that values of Q and $Z_\perp/Q$ of the order of 10 or less could have been observed.

## V. Conclusion

We have developed a very reliable 4 MeV, 40-100 kA electron beam injector. It produces a high quality annular or solid beam of low emittance with no radial oscillations. A new radial force balanced accelerating gap design has been successfully tested and proven to completely eliminate radial oscillations. Finally, an accelerating cavity composed of plastic and metal voltage grading rings immersed in deionized water constitutes such a low Q and $Z_\perp/Q$ resonator that BBU instabilities become insignificant. The injector, accelerating gap, and cavity presented here can be considered as very promising building blocks for a high current high voltage pulsed transmission line linear accelerator.

TABLE I

| F ($MH_Z$) | MODE TYPE | Q | $Z_\perp/Q$ (ohms) |
|---|---|---|---|
| 190 | TM010 | 450 | -- |
| 550 | TM110 | 660 | 50 |
| 620 | TM0 | 170 | -- |
| 650 | TM1 | 390 | 70 |
| 820 | TM1 | 100 | 40 |
| 1100 | TM2 | 290 | -- |
| 1150 | TM0 | 760 | -- |
| 1170 | TM0 | 460 | -- |
| 1250 | TM0 | 500 | -- |
| 1380 | TM1 | 1090 | 25 |
| continuum | | | |

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