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A full cusp diode geometry and fast puff valve system have been developed for the proton linac experiment. After passing through the first gap section, a transport efficiency of 99% has been achieved. Microwave input mode stability has been tested on a rectangular cross-section undulating guide accelerator cavity. Switching to a circular cross-section would appear to have certain advantages. Keywords

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22a. NAME OF RESPONSIBLE INDIVIDUAL
Robert J. BARKER

22b. TELEPHONE *(Include Area Code)*
(202) 767-5011

22c. OFFICE SYMBOL
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& SCHOOL OF ELECTRICAL ENGINEERING

CORNELL UNIVERSITY

ITHACA, NEW YORK 14853-5401

INTRODUCTION

This report outlines the research carried out at Cornell University under grant AFOSR–83–0364–C during the period from 30th Sept 1987 until 29th Sept 1988. Progress on three projects is reported, firstly the latest results from the proton linac experiment are outlined. Secondly, an update is given on the development of a repetition rate system. Thirdly progress towards a novel high field gradient electron accelerator using a pulse power driven high power microwave source is reported.

HARDWARE

Proton Linac Experiment

Following the successful development of a full cusp diode geometry and fast puff valve system our main experimental effort in the current contract period has been directed towards characterizing the first stage operation of the proton linac with this active source of beam neutralization. The beam profile and position is measured with carbon activation and thermal damage paper targets while the time evolution of the beam was studied using Faraday cup measurements. The information gained during this period has allowed us to consider designs for a new puff valve system that would allow operation of the second acceleration gap and more importantly help define the future possibilities for a prototype multistage ion accelerator.

Repetition Rate System

The development of a 1 Hz repetition rate electron diode system has continued with the construction and testing of the modified ETA switch chassis and pulse forming network. Phase one has been completed with the system producing a 230 kV, 90 nsec output pulse with a risetime of 30 ns into a dummy load. Output signals are shown in figure 1. This output is produced from a 20 kV charging voltage and shows that the input pulse transformer is working according to specifications.

We are now constructing a 2:1 output transformer. The 0.015 Volt-seconds of the ferrite cores should hold off 250 kV for 60 ns, to produce output pulses on the order of 500 kV. We anticipate low voltage operation of the two stage device before the end of the calender year and operation at high voltage in a 1 Hz repetition rate mode by spring 1989. This device will probably be used for the electron accelerator studies using the undulator configuration discussed below and in this years proposal.

Undulating Guide Electron Accelerator

A rectangular cross-section undulator has been constructed and couplers to mode convert from the TE_{10} mode in X-band guide inputs to the TM_{21} mode in the undulator guide system were developed. In order to characterize the undulator performance the pass bands for the TE_{10}, TM_{11} and TM_{21} modes have been measured. These results are described in a later section of this report.

In a related experimental program a high power travelling wave tube amplifier operating in the cylindrical TM_{01} mode has been developed. Following the successful operation of this amplifier we plan to use a source of this type to power the undulator guide electron accelerator.

Following these developments, and based on results obtained with the rectangular cross-section we are designing a circular cross-section undulator. This device will use the TM_{01} (rather than the TM_{21} of a rectangular guide) to accelerate appropriately phased electrons. Using this mode will allow direct coupling between the travelling wave tube amplifier and the undulating accelerator structure and avoid mode competition. The average accelerating field of the TM_{01} mode is expected be of order 6 MV/m for an amplifier output of 100 MW. Although this field is lower than could be realized using the TM_{02} mode the simplified coupling geometry will shorten the time required for a proof-of-principle experiment. We are also investigating a number of accelerated electron diagnostics that will be appropriate in the energy ranges expected from this experiment. If this experiment is successful we expect to test higher current lower frequency devices which should be suitable as compact drivers for FEL devices. The use of higher frequency and higher power devices will also be useful for ultra high gradient devices. Construction of the prototype test device is expected early in 1989.

EXPERIMENTAL RESULTS

Proton Linac Experiment

In our previous interim report the need for an active neutralization source to provide good beam transport in a full cusp diode geometry was established. Before constructing a gas puff system the optimum background conditions were determined by separating the transport region from the diode with a 3 μm Mylar foil. The background gas pressure was varied between 50 and 200 mTorr. with optimum profiles obtained at 100 mTorr Hydrogen.

Beam Transport with Static Gas Fill

Figure 2 shows a schematic diagram of the diode and transport section of the experiment. The beam profile is measured with two diagnostics. Thermal damage paper gives beam position at different axial positions and, when used in combination with an azimuthal slot shadow box, can give estimates for the beam divergence. Carbon activation techniques measure radial profiles and are also used to measure proton current transport efficiencies under different drift tube conditions.

The diode voltage and current are measured using standard voltage divider and Rogowski coil techniques. Typical output signals are shown in figure 3.

Figure 4 shows thermal damage patterns at 12 and 30 cm from the diode. The upper patterns show that for injection into background pressure $\approx 10^{-4}$ Torr the beam is in contact with the drift tube walls by the end of the transport section. In this case the beam was neutralized solely by electrons drawn from the drift tube walls and from the virtual anode. The beam divergence is measured using an azimuthally slotted shadow box. Results are shown in figure 5 , where the left pattern shows beam rotation and expansion for vacuum injection. The average beam radius is increasing with a divergence angle of $\Theta_d \approx 4°$.

For injection into 100 mTorr H_2 the bottom damage patterns in figure 4 show improved uniformity at 12 cm from the diode over that reported without an active source of neutralization. At 30 cm the beam has propagated through the drift tube without contacting the walls. The middle patterns show that the addition of the Mylar foil alone does not prevent the beam from diverging to the drift tube walls. Figure 5 shows the slot pattern with gas background and indicates a divergence in average beam radius of less than 0.8°, a factor of 5 better than that achieved earlier without the background gas fill. This represents the minimum angle measurable with this technique.

The transport efficiency is measured with carbon activation targets that are arranged to completely cover the drift tube cross section. Data is taken at 12 and 30 cm and normalized to counts obtained from two targets that remain in a fixed location at 12 cm from the diode. Results are shown in figure 6. The efficiency increases from 66% with no neutralization to 95% with a fill pressure of 100 mTorr H_2. The addition of the foil alone has no significant effect on the transport efficiency. This implies that the neutralization process is improved by presence of the neutral gas rather than any effects from the plasma created as the beam passes through the foil.

We are studying the various mechanisms that could provide neutralization in the full and half cusp geometries where an applied axial magnetic field is also present. The ionization of the background gas leads to the formation of ion pairs, which does not reduce the degree of charge imbalance. At the beam front electric fields may be large enough to allow background ions to escape from the beam channel. However as these fields are reduced by space charge neutralization there is insufficient time to allow further background ions to escape and further neutralization probably results from electrons being pulled along the field lines. In this sense the injection and neutralization process is similar to that found in our earlier experiments where the beam was injected through an electron cloud into the evacuated drift tube. The principal difference is that the source of the electrons is more copious and better controlled. In addition the ionization process continues as the beam travels through the background gas so that the electrons do not have to co-drift with the protons but only move sufficiently to allow charge neutralization. The understanding of the this process will improve the design of multiple gap systems which depend on neutralized beam transport between acceleration stages.

Beam Transport with Puff Valve System

Figure 7 shows damage patterns at 30 cm from the diode. By adjusting the delay on the puff valve trigger the position of the neutral gas front at the time of beam injection is controlled to give optimum beam profile at the end of the transport region. The damage patterns show that the beam remains detached from the drift tube wall throughout the transport region.

The radial beam profile is measured at 12 and 30 cm from the diode and the results are shown in figure 8. At 30 cm the profile is peaked near the outside radius of the emission region for vacuum injection. This is consistent with the thermal damage patterns described above, indicating that the beam diverges to the drift tube wall without a gas background in the transport region. In contrast the profiles for puff valve injection show that the beam profile is peaked within the anode emission region.

Figure 9 shows digitizer traces from Faraday cups located at 23 cm from the anode and at 4.7 cm radius, corresponding to the centre of the anode emission region. The development of a Faraday cup measuring ion current density [1] has been part of our ongoing effort to enhance time resolved diagnostics for high current proton beams. The ion Faraday cup shows a beam pulse of order 50 ns full-width-half-maximum and the net Faraday cup indicates good neutralization throughout the pulse. These results indicate that the background conditions achieved with the fast puff valve provide for well neutralized beam transport in the region between accelerating gaps.

The radial beam profiles have been compared with results from a single particle orbit code which gives a downstream radial position for particles emitted from different radii on the anode surface. The experimental results with puff valve operation are consistent with the single particle calculations. These show that the particles should be confined within the annulus corresponding to the anode surface. Our measurements show that the radial profile is indeed peaked in this region.

At the present time the single particle orbit calculations do not account for the broadening of the radial profile measured at 30cm from the anode. However this is probably due to the time variation of the energy spread inherent in the proton beam. We are planning to include this refinement in future versions of the single particle code.

The transport efficiency with the puff valve system is measured as described above and the results are included in figure 6. After passing through the inner cathode coil structure the beam transport efficiency is 99% (±25%).

Undulating Guide Electron Accelerator.

Coupling measurements performed on the rectangular cross-section undulator have shown that excitation of the TM_{21} mode is accompanied by unwanted lower modes, such as the TE_{01}. Some excitation of this mode appears to be unavoidable when coupling through the magnetic fields of the input TE_{10} and the TM_{21} undulator guide mode is employed. Although fairly straightforward the suppression of these lower order modes would significantly complicate the future fabrication of such devices.

The high power microwave source needed to drive the undulating accelerator is expected to be the output from an X-Band travelling wave tube amplifier currently under development at our lab. The amplifier uses a 850 kV, 1 kA, 100 ns electron beam and has been operated with a gain of 17 dB at 8.76 GHz. Output levels of order 10 MW have been measured and detailed characteristics of the amplifier performance have been recorded. Other amplifiers with gains between 13 and 29 dB have been fabricated and tested. A peak output power of 100 MW has been achieved at 10% efficiency.

As described above we have carried out a number of calculations and measurements on undulating structures for a phase slip accelerator. (This term is reserved for an accelerator in which the rf wave travels faster than the electrons being accelerated. In fact the electrons slip one cycle of the rf wave every period of the undulator; a criterion identical to that found in FEL's.)

There is evidence of mode conversion or at least multiple mode excitation in the rectangular undulator and we have elected to go to a cylindrical system for a proof of principle experiment. This accelerator will run in the TM_{01} mode and will couple directly to the high-power microwave source through a smooth transition. Phasing of the electrons to the wave will be accomplished using vacuum bellows. Note that the electrons will be prebunched from the rf amplifier driving the undulator. By operating in the TM_{01} mode the accelerator testing should not be complicated by multi-mode propagation, since only this and the TE_{11} mode are above cut-off. The excitation of the latter mode is not expected with the direct coupling method to be used between the amplifier and the undulating guide section. The following table shows the design parameters for the proof-of-principle experiment.

Guide Radius	1.43 cm
Undulator Period	11.3 cm
Undulator Modulation	80%
Wave Frequency	8.76 GHz
Cut-Off Frequency	8.04 GHz
Input Power	100 MW
Av. Accelerating Field	5.6 MV/m

We plan in these experiments to test the acceleration concept and to explore loading effects. The field gradient can be enhanced by use of higher power rf drives or by increasing the frequency and operating, with suitable mode suppressors, in the TM_{02} mode. Operation at higher beam currents can be achieved by working at lower frequencies. We note that use of the Mafia code by the Los Alamos and Stanford groups on this concept has shown a reduced wake field over scaled SLAC structures while maintaining a very good value for the accelerator elastance. Finally it should be pointed out that provisional patent approval for this concept has been granted, subject to some technical reporting requirements by the patent agent being fulfilled in a timely manner.

CONCLUSIONS

We have successfully developed a full cusp diode geometry and fast puff valve system for the proton linac experiment. This has enabled us to maintain an annular profile beam from the injector to the position of a second accelerating gap. After passing through the first gap section transport efficiency of 99% has been achieved. Thermal damage paper and carbon activation radial profiles show that the beam propagates without contacting the drift tube walls. Average beam radius divergence has been reduced from 4° for vacuum injection to less than 0.8° with a low pressure gas background. Faraday cup traces show that the full 50 ns beam width is maintained throughout the transport region.

Our results show that a high current proton beam can propagate through the system close to the drift tube wall where the effective width of the post acceleration gap is a minimum. Since the beam must pass through such gaps unneutralized it is essential to minimize their length thus reducing beam divergence caused by space charge effects. In addition post acceleration gaps will need inner coils to shape the gap magnetic field in a manner that will compensate for the remaining space charge divergence.

We are now studying designs for magnetic field geometries and puff valve mounting systems that will allow efficient operation of the second accelerating gap.

The undulating guide accelerator program has tested mode stability in such structures with measurement on a rectangular cross-section undulator. Coupling techniques from rectangular guide in the TE_{10} mode to the undulator were explored and satisfactory performance was achieved.

Our coupling measurements on the rectangular cross-section undulator have shown that there are potential advantages in switching to a circular cross-section. These include the availability of a high power driving source for the accelerator and the simplified coupling geometry involved. We are designing an undulator with parameters appropriate for a proof-of-principle experiment and expect to have initial results in the upcoming year.

[1] "Faraday Cup to Measure Ion Current in a Strong Magnetic Field", J. D. Ivers, I. S. Roth & J. A. Nation, *Rev. Sci. Instrum.* **57** (10), 2632, October 1986

PUBLICATIONS AND CONFERENCE PAPERS

The following is a list of the publications and conference presentations arising from the work carried out during the current contract period. A paper containing the recent results from the proton linac program is currently being prepared for publication.

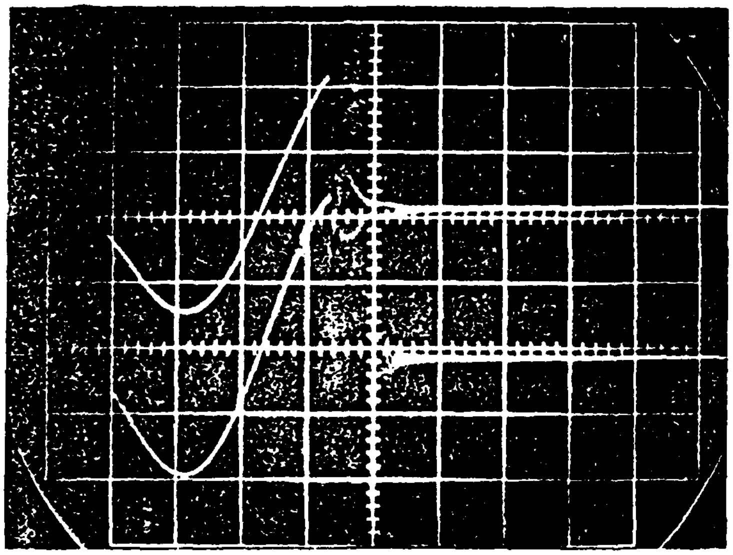
Presentations

"Application of Pulsed Power Technology to Ultra High Energy Electron Accelerators", Proceedings of the U. S. Particle Accelerator School, AIP Publications 1987.
"Confinement Systems for High Current, Proton Linear Induction Accelerators", *Bull. Am. Phys. Soc.* **32**, 1803, October 1987.
"Neutralization in High Current Proton Linacs", Proceedings of the 7th International Conference on High-Power particle Beams, Karlsruhe, F. R. Germany, July 4–8th, 1988

Seminar presentations

"Recent Developments in Proton Linear Induction Accelerators",
and
"Novel Methods of Particle Acceleration",
were given during the current contract period at the following institutions:

Institute of Laser Engineering, Osaka University, Japan.
Institute of Electrical Engineering , Bejing, People's Republic of China.
Atomic Energy Institute , Bejing, People's Republic of China.
Chengdu Institute of Radio Engineering, People's Republic of China.
Changsha Institute of Technology, People's Republic of China.



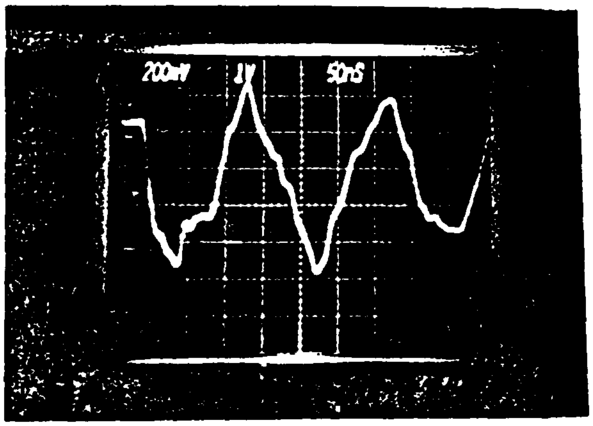


Figure 1. Scope traces from repetition rate system. Upper picture shows voltages on (a) the secondary side of the input transformer, 113 kV/div (upper trace) and (b) the blumlein, 89 kV/div. Time scale is 5 μs/div. Lower picture shows voltage at the resistive load output, 63 kV/div, 50 ns/div.

Schematic Diagram Showing Puff Valve Experiment

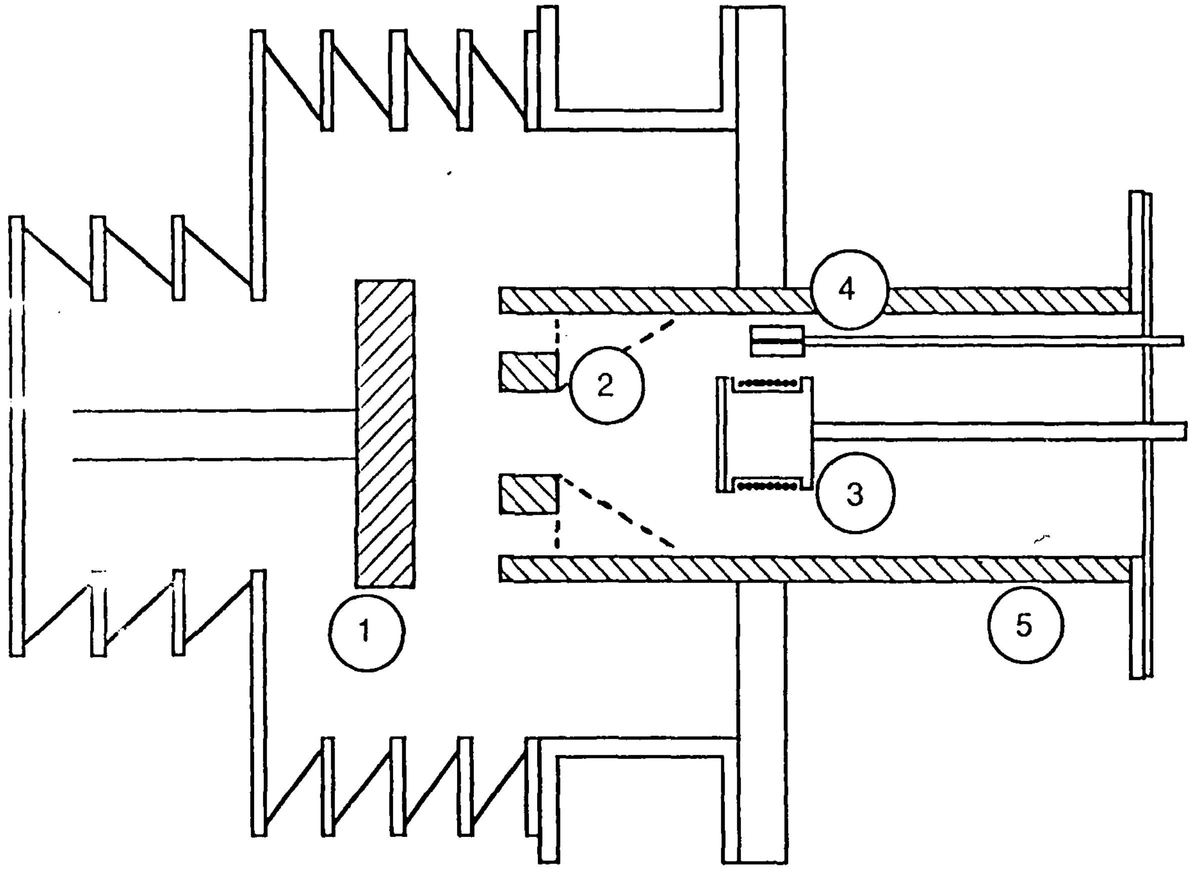


Figure 2. (1) Anode, (2) cathode field coils, (3) puff valve, (4) net and ion Faraday cups, (5) solenoidal field coils. Puff valve axial position is adjusted for optimum beam profile, and is completely removed for static gas fill operation.

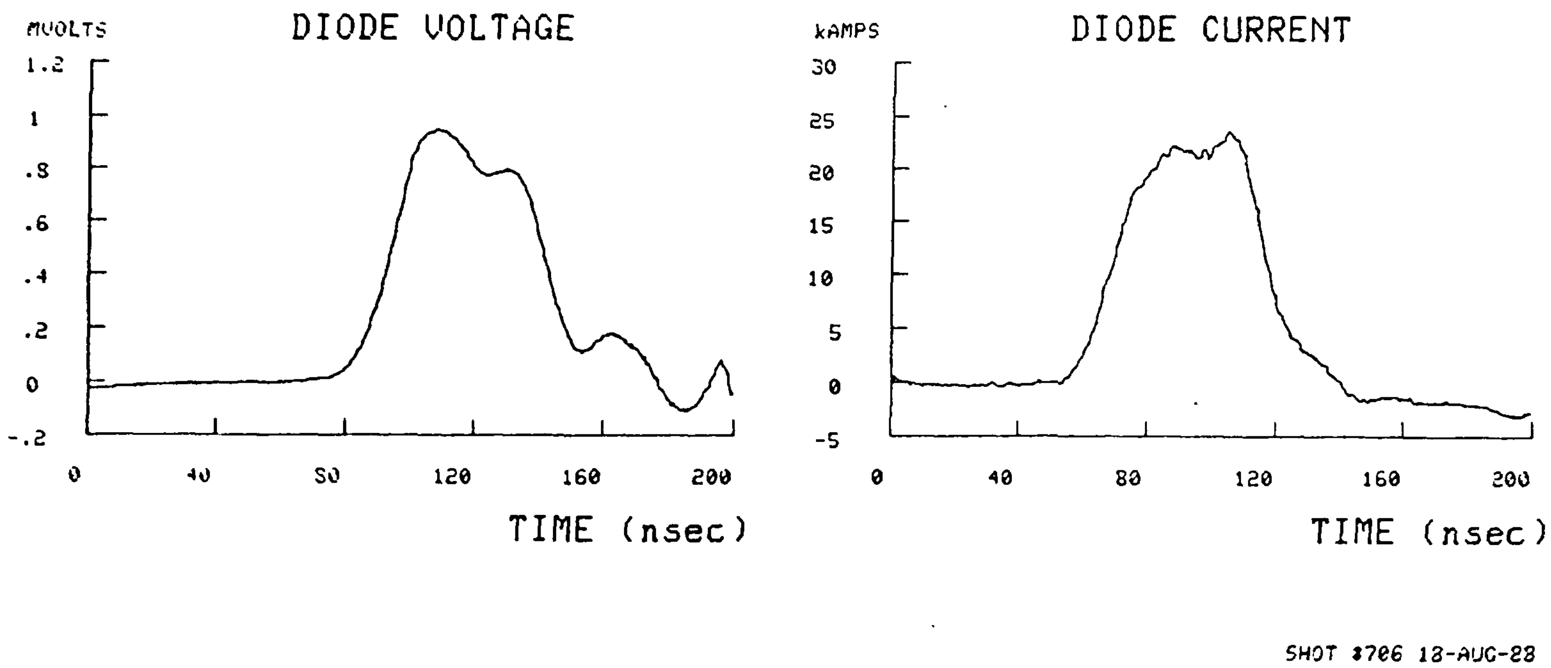


Figure 3. Digitizer output traces showing diode voltage and current.

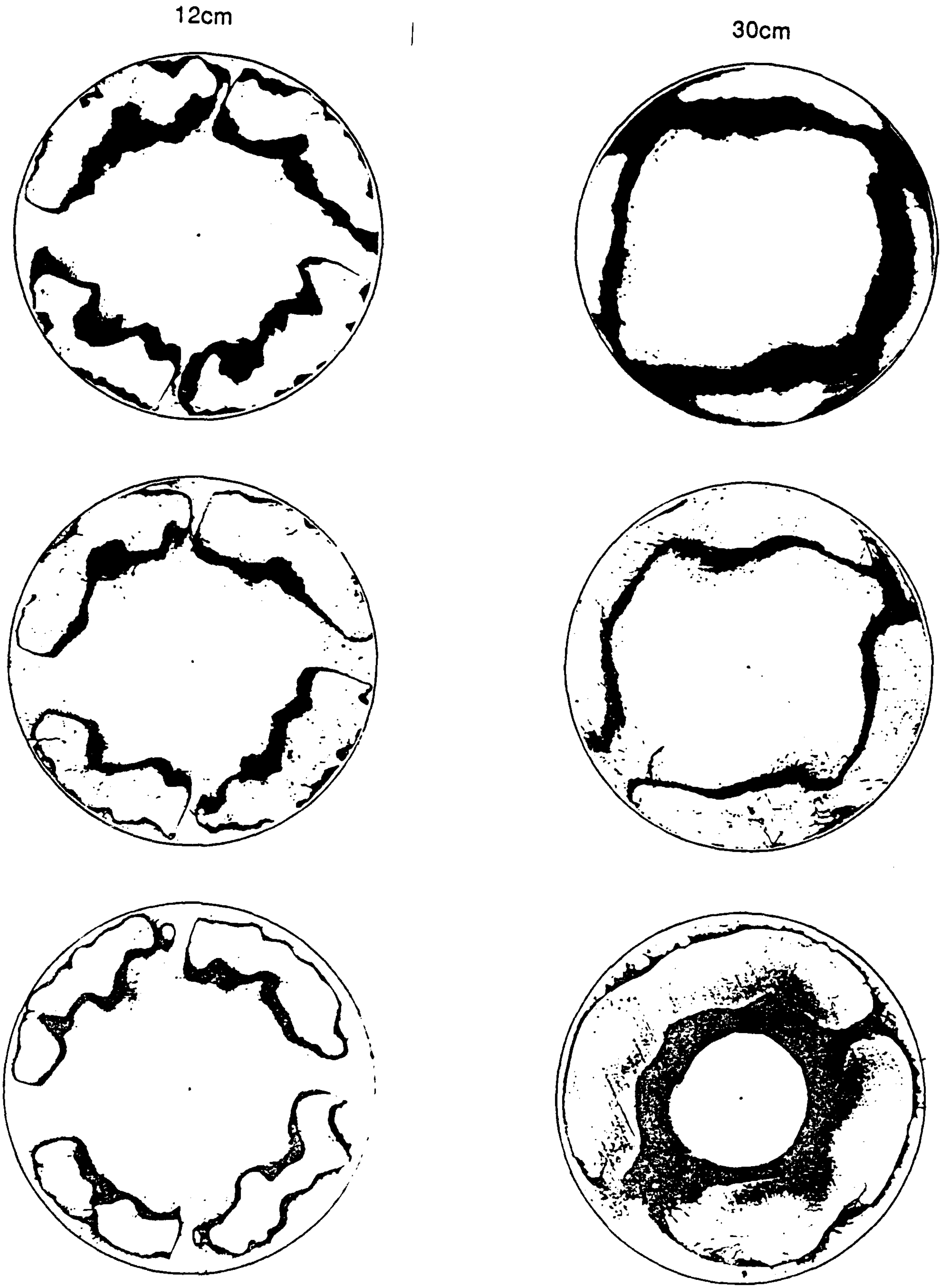


Figure 4. Thermal damage paper patterns showing full beam profile measured at 12 and 30 cm from the diode. Upper patterns are for injection into vacuum. Middle patterns are for injection through Mylar foil but with no background gas. Lower patterns are for injection into 100 mT static fill hydrogen.

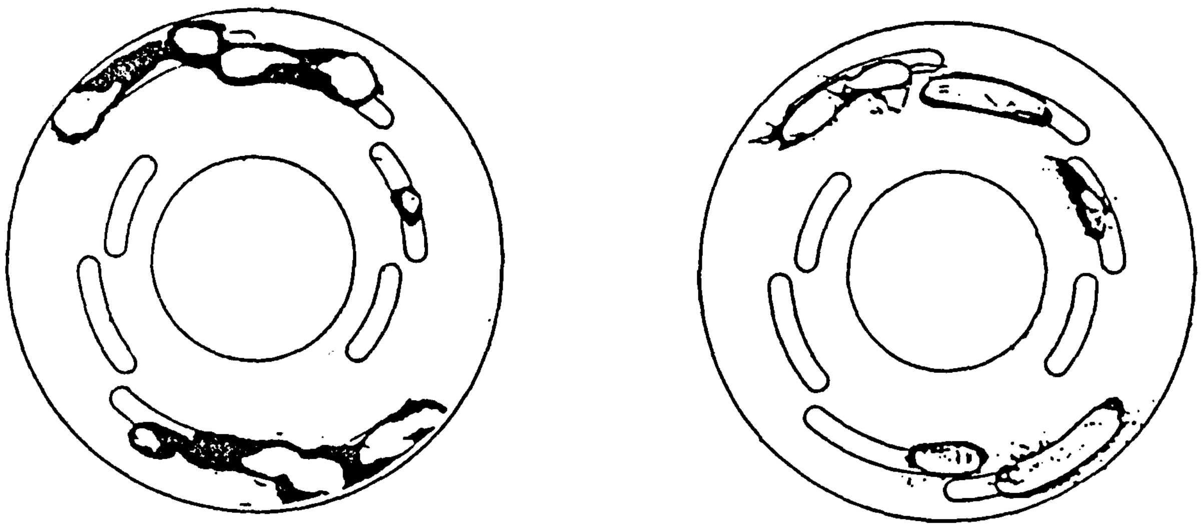


Figure 5. Thermal damage patterns with shadow box located 12cm from the diode. Left pattern is for injection into vacuum. Right pattern is for injection into 100 mTorr hydrogen.

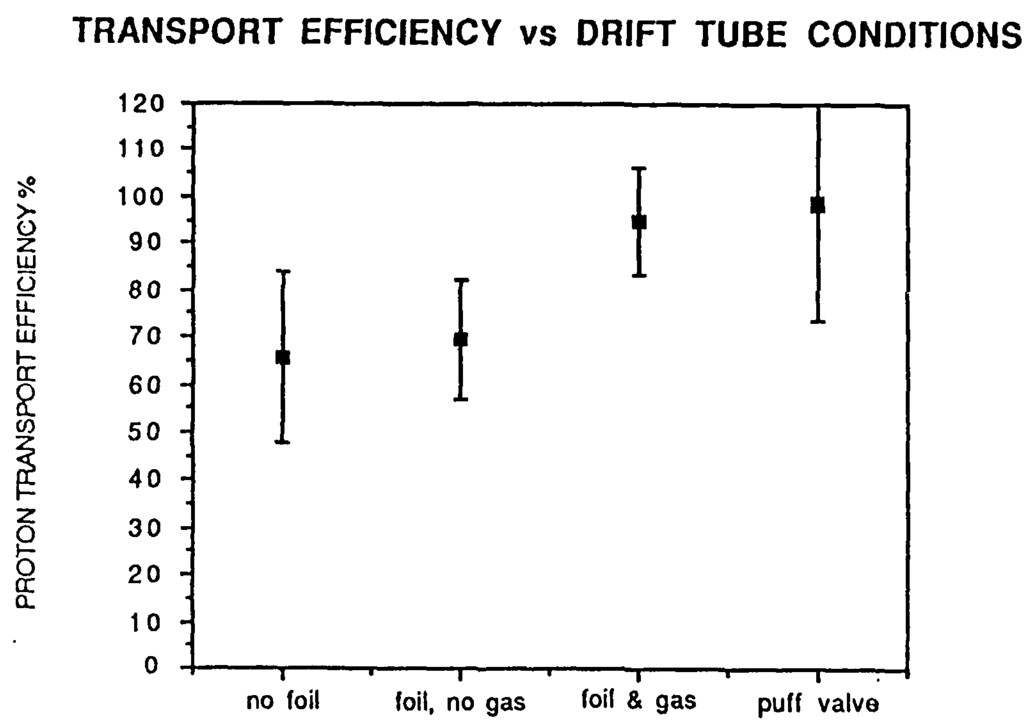


Figure 6. Current transport efficiency as a function of conditions in the drift region. For transport in static neutral gas the pressure was 100 mT.

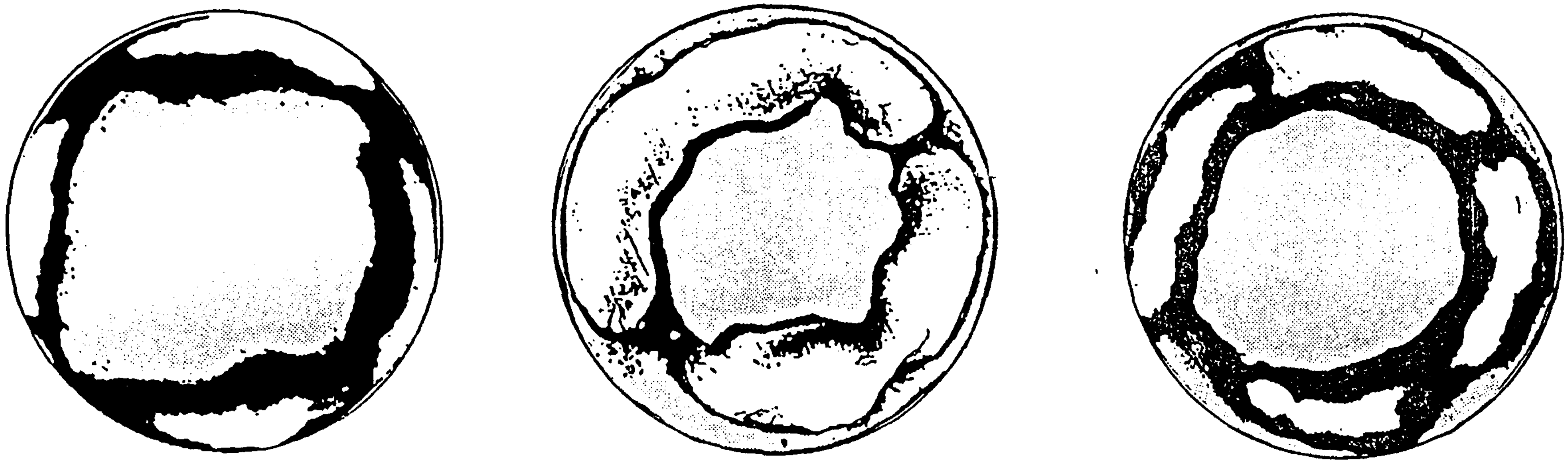
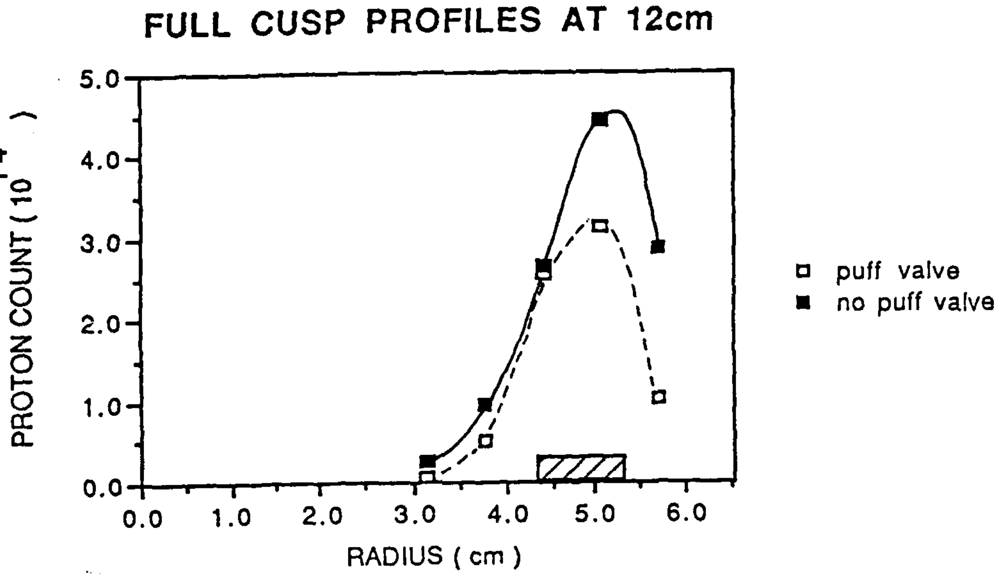


Figure 7. Thermal damage patterns showing full beam profile at 30cm from the diode. Left pattern is for injection into vacuum. Middle pattern is for injection into static fill 100 mTorr hydrogen. Right pattern is for injection into gas puff system. Position of intense beam is shown by the white areas outlined by less damaged black regions. Grey areas indicate undamaged paper.



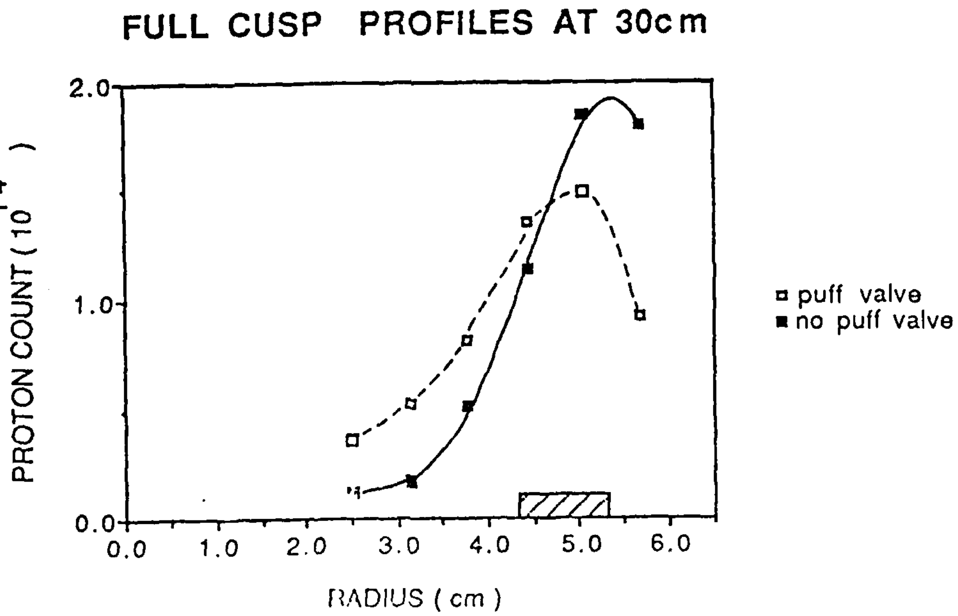


Figure 8. Radial proton count profiles for full cusp injection measured at 12 and 30 cm from the diode. Filled in squares are data from vacuum injection, outlined squares are for injection with puff valve. The shaded area between 4.3 and 5.3 cm indicates the radial position of the anode emission region.

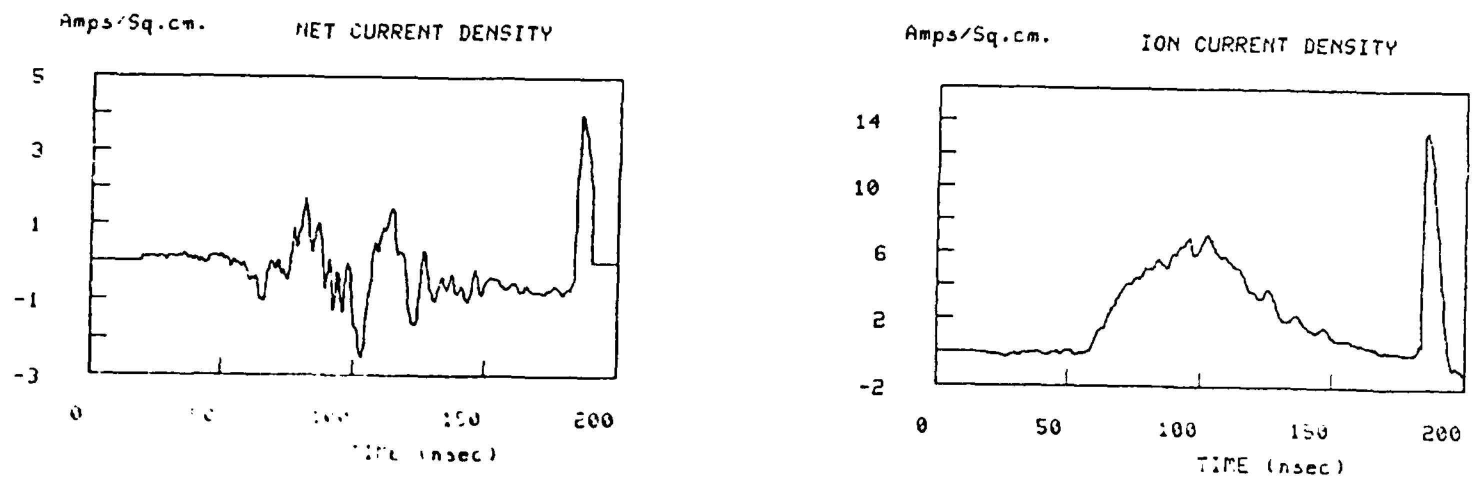


Figure 9. Digitizer traces from the Faraday cups located at a radius of 4.7 cm and 23 cm from the anode. The left trace shows the net current density and right shows the ion current density. The narrow positive spike at the end of both traces is a fiducial marker.