DESCRIPTION OF THE M1 MEQALAC AND OPERATING RESULTS*

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I. Introduction

MEQALAC stands for Multiple Electrostatic Quadrupole Array Linear Accelerator. The first model, M1, was designed, built, and tested in a three month period from July to October, 1979. Within a week of operation a Xenon output current of 85% of the calculated space-charge limit was obtained.

In the following sections we will describe the M1 components and operation. Some of the design choices were made to allow hand-fabrication with available tools (principally a table-top lathe and a table-top drill press), while others were influenced by the ion source development at hand. The major goal was to demonstrate the MEQALAC principle of accelerating multiple beams through arrays of strong focussing electrostatic quadrupoles. Xenon was used since it demonstrates the principles of a low beta linac as needed for the Heavy Ion Fusion program, without the complications of a heavy-metal ion source.

II. Evolution of the MEQALAC Idea

Our original plan for a heavy ion linac was a single bore Wideröe design operating at 2 MHz with a 500 kV Cockroft-Walton injector. (Figure 1.) It was realized early in the BNL program that magnetic focussing would be expensive due to the high momentum of heavy ions. Thus our initial design featured electrostatic quadrupoles.

Theoretical analysis of the space-charge limits ("Space-Charge Limits for Linear Accelerators"[1]) revealed no dependence of the current limit due to bore size. Moreover it was realized that electrostatic quadrupoles are amenable to small bore construction in matrix arrays, and that virtually no power is consumed for focussing. The injection energy is low enough to dispense with a Cockcroft-Walton entirely. These and other benefits of the MEQALAC concept are discussed in "MEQALAC; A New Approach to Low Beta Acceleration".[2]

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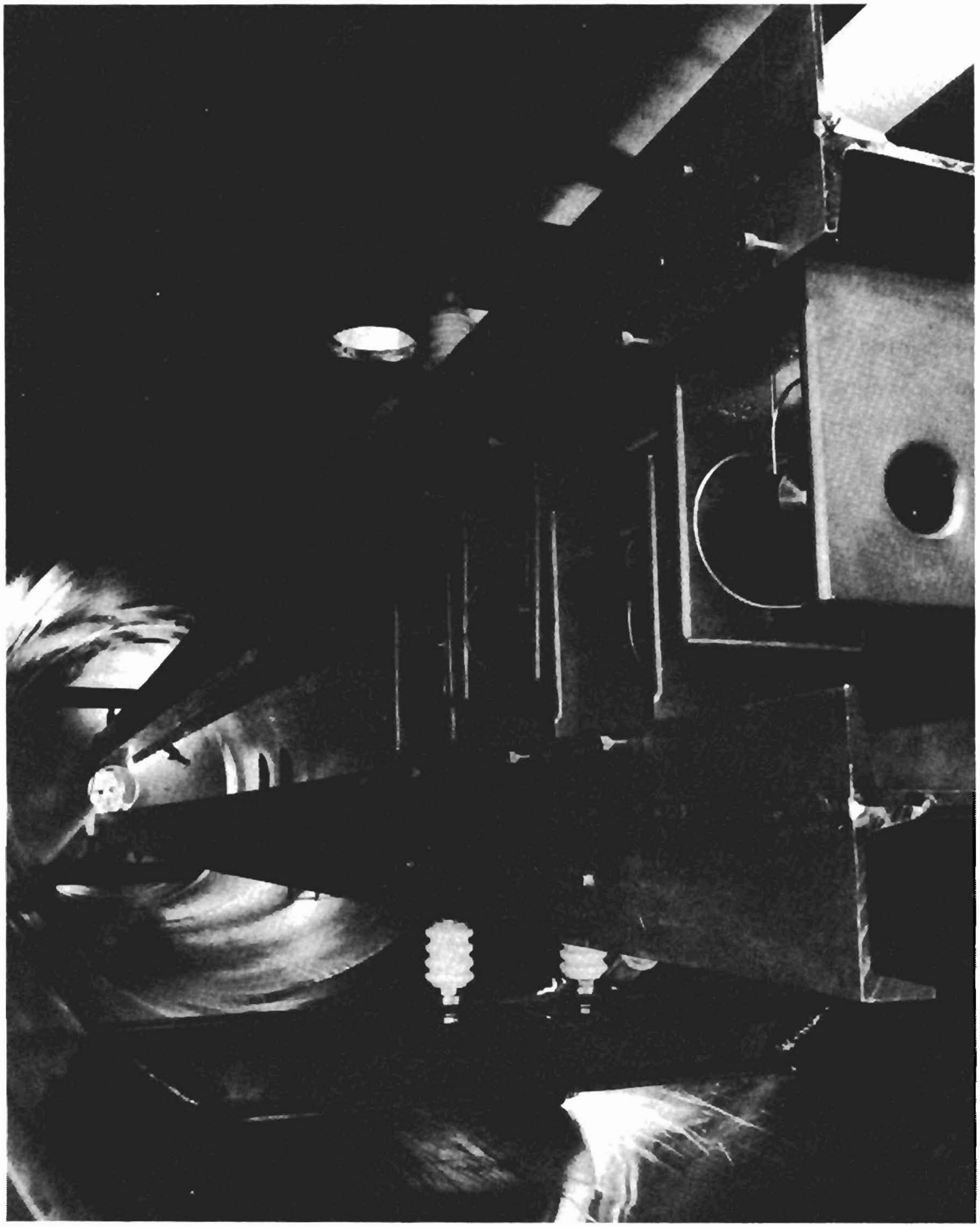


Figure 1. 2 MHz push-pull Wideroe showing four drift tubes with electrostatic quadrupoles.

III. M1 Components

a. M1 MEQALAC Assembly

Figure 2 shows the M1. Table I lists the major machine parameters. The discussion in this subsection is intended to give an overview of the machine before describing the components in detail.

TABLE I. M1 MEQALAC PARAMETERS

Ion Accelerated	Xe^{+1}
No. of Beams	9
Machine Type	Wideröe
Injection Energy	15.5-17.3 keV
Output Energy	71.5-73.3 keV
Input $\beta\lambda/2$	1.89 cm
Output $\beta\lambda/2$	3.95 cm
Rf Frequency	4 MHz
Peak Rf Voltage	5 kV
Accelerating Voltage	3.5 kV/gap
Stable Phase Angle	$\sim \sin^{-1}$ 3.5/5.0 45°
Nominal Quad Voltages	$\pm$ 2 kV
Repetition Rate	10 pps (arc supply ltd)
Pulse Length	500 usec (arc supply ltd)
Pre-Buncher	$\beta\lambda/2$, 4 MHz, 1-1.5 kV
Nominal Vacuum	10^{-5} torr
Gas Feed	Continuous
Calculated Avg. Current During Pulse - S.C.L.	3.3 mA
Measured Current	2.8 mA

The Wideröe assembly is suspended in the six inch Varian vacuum pipes shown. The ion source, operating at +15.5-17.3 kV dc, is shielded by the screen enclosure and isolated from the metal pipe by a 6 inch diameter x 6 inch long Pyrex vacuum pipe. The vacuum pump is a Welsh Turbo-Torr 1500 l/sec unit and it is mounted below the "cross" vacuum section. The upper port of the "cross"

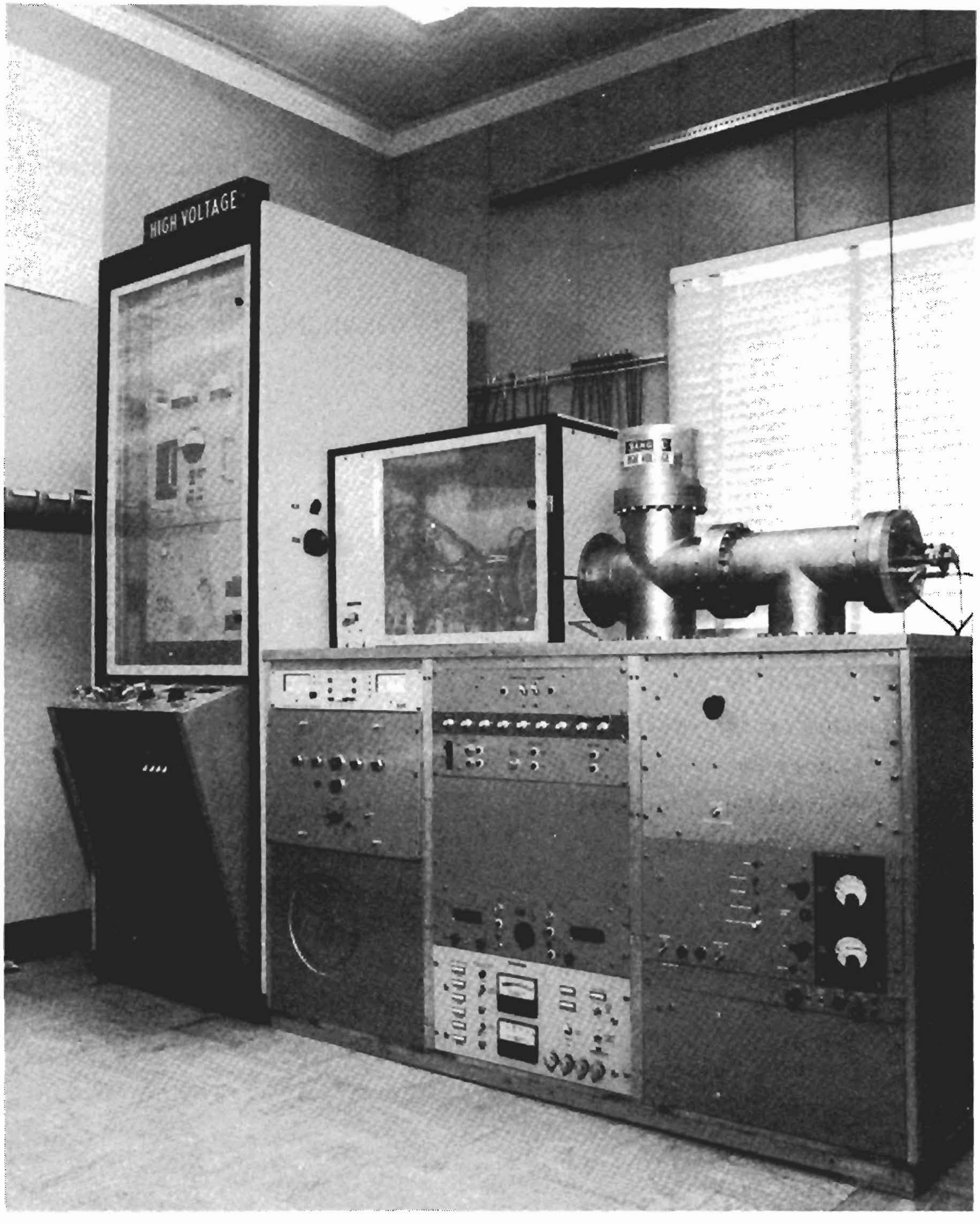


Figure 2. Assembled M1 MEQALAC.

is used for quadrupole high voltage feedthrus. The forepump sits behind the lower left panel with the circular ventilation screen.

The rf voltage is fed through the bottom of the "tee" section. The 4 MHz transmitter and tank circuit resonator are mounted in the far right rack. A Faraday cup is held on a rod inserted through a vacuum fitting on a Lucite end cover, and bias grid voltage and beam pickup connections are fed through the same cover.

The tall rack enclosure to the left is exclusive to the ion source power supplies, controls, and cooling system. The upper section contains the HV deck, which holds the arc and filament supplies for the source. The lower portion holds the HV supply, an isolation transformer for deck ac power, and a freon circulation pump and radiator. The tilted panel has the high voltage control knob and a small oscilloscope used to monitor arc current.

The accelerator has a pre-buncher "tube" or plate. The buncher tank circuit resonator is mounted beneath the ion source screen enclosure. The buncher rf is fed to the buncher tube through a Covar seal in the Pyrex pipe which isolates the ion source.

b. The Quadrupole - Drift Tube Configuration

Figure 3 shows the quadrupole array. The poles are made of 5/16 inch diameter aluminum, and arranged for nine beams with 5/16 bore diameter. It was estimated that a 1% ($\sim$.003 inch) tolerance was needed on the position of any pole tip. To accomplish this, the arrays were made on precision fixtures (see Figure 4). 1/8 inch precision-ground steel rods are pinned to the frame and pole tips in the fixtures, thus avoiding thermal expansion problems had they been soldered. The insulators at the corners were made of Rexolite.

Figure 4 shows the cover plates used to make a complete drift tube. The M1 has 8 drift tubes operating at rf potential, 7 drift tubes at ground potential, and 5 LEBT (Low Energy Beam Transport) quadrupole arrays, making 20 quad arrays in all. The LEBT and ground drift tubes are screwed to the steel alignment plate shown in the figure. This plate is hung from the top of the vacuum pipe. The rf drift tubes are suspended from 1/4" Rexolite rods which run through the side plates attached to the quad arrays as seen in Figure 3.

Rf connections are made to a copper bus bar which runs at the bottom of the vacuum pipe. Near the rf bus are two busses for the $\pm$ dc quad voltages for the rf quads. The feed lines for these are run through the resonator

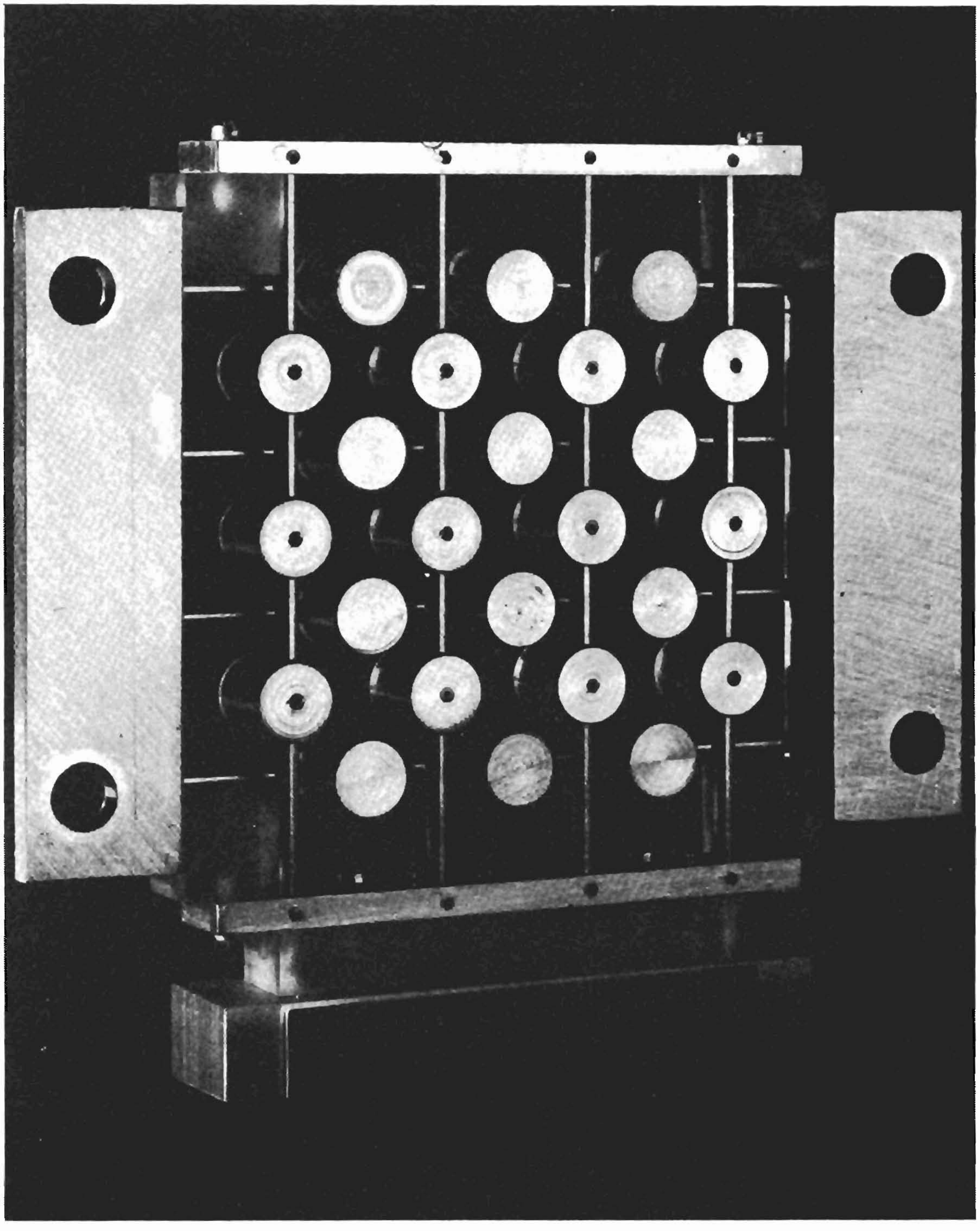


Figure 3. Nine beam quadrupole array.

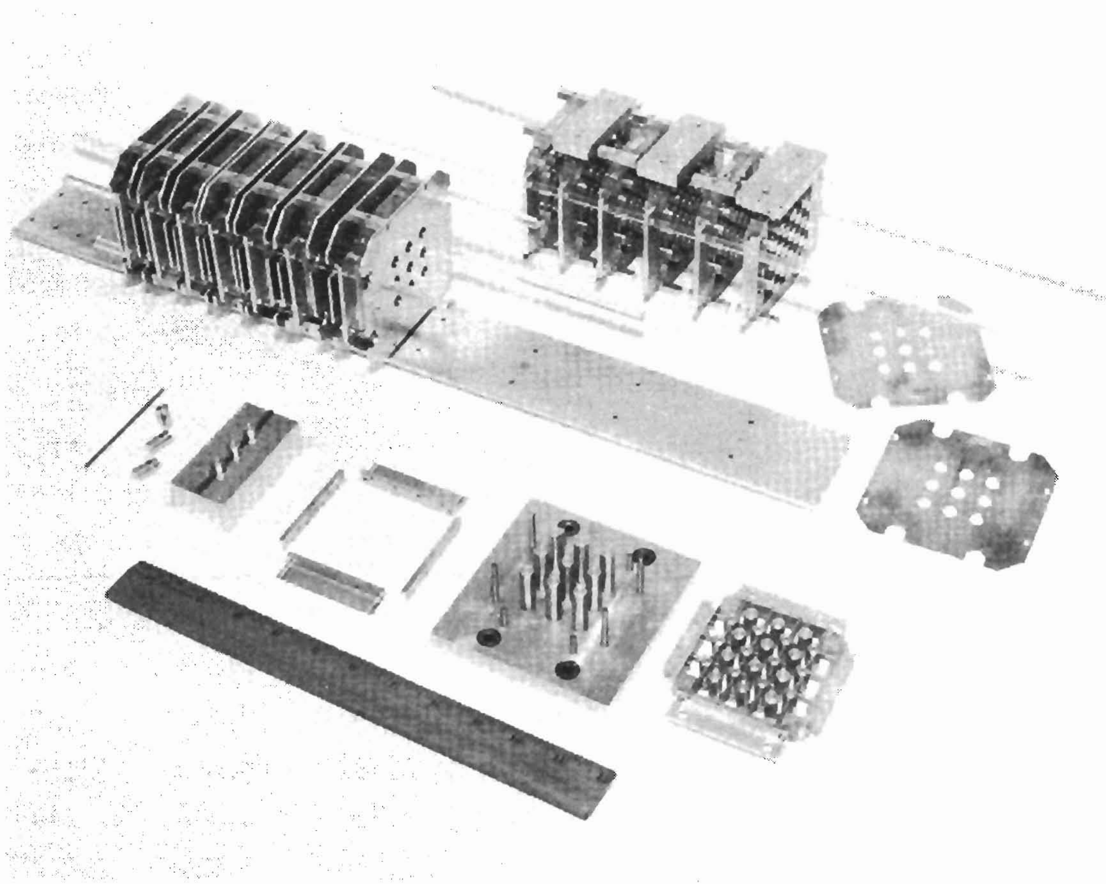


Figure 4. Quad arrays, drift tube cover plates, and precision fixtures.

coil. There are two busses above the Wideroe for the ± quad voltages for ground drift tubes. The complete assembly is shown in Figure 5.

The LEBT quads have separate busses and are run from a separate power supply. In operation, they run at a lower potential for two reasons: 1) the LEBT quads must compensate for any emittance mismatch between the ion source and the accelerating section and 2) a small rf defocussing effect in the accelerating section is expected.

The accelerating section has 16 accelerating gaps. The drift tube table (Table II) is calculated for 3.5 keV energy gain at each gap. The quadrupole lengths are proportional to the velocity of the particle. It follows that the same phase advance/cell is maintained by having the same voltage on all of the accelerator quadrupoles. Thus the M1 has a power supply which provides ± quad voltage for the accelerating section (with extra output connectors to feed the rf quads), and another which supplies ± voltage for the LEBT quadrupoles.

TABLE II. DRIFT TUBE TABLE

	DRIFT TUBE NO	ENERGY EV	TRANSIT TIME FACTOR	PARTICLE VELOCITY M/S	DRIFT TUBE LENGTH CM	DRIFT TUBE LENGTH IN	ELECTRODE LENGTH CM	ELECTRODE LENGTH IN
G	0	15500.		151262.	-	-	-	-
RF	1	19000.	0.913	166126.	1.702	0.670	0.990	0.390
G	2	22500.	0.926	181192.	1.890	0.744	1.080	0.425
RF	3	26000.	0.935	195054.	2.063	0.812	1.163	0.458
G	4	29500.	0.943	207968.	2.225	0.876	1.240	0.488
RF	5	33000.	0.949	220108.	2.376	0.936	1.312	0.517
G	6	36500.	0.953	231600.	2.520	0.992	1.381	0.544
RF	7	40000.	0.957	242539.	2.657	1.046	1.446	0.569
G	8	43500.	0.961	253000.	2.788	1.097	1.508	0.594
RF	9	47000.	0.964	263040.	2.913	1.147	1.568	0.617
G	10	50500.	0.966	272708.	3.034	1.194	1.626	0.640
RF	11	54000.	0.968	282041.	3.151	1.240	1.681	0.662
G	12	57500.	0.970	291073.	3.263	1.285	1.735	0.683
RF	13	61000.	0.972	299831.	3.373	1.328	1.787	0.704
G	14	64500.	0.973	308339.	3.479	1.370	1.838	0.724
RF	15	68000.	0.975	316617.	3.583	1.411	1.888	0.743
G		71500.		324683.				

Linac length = 41.017 + 16 x 0.375 = 47.017 cm

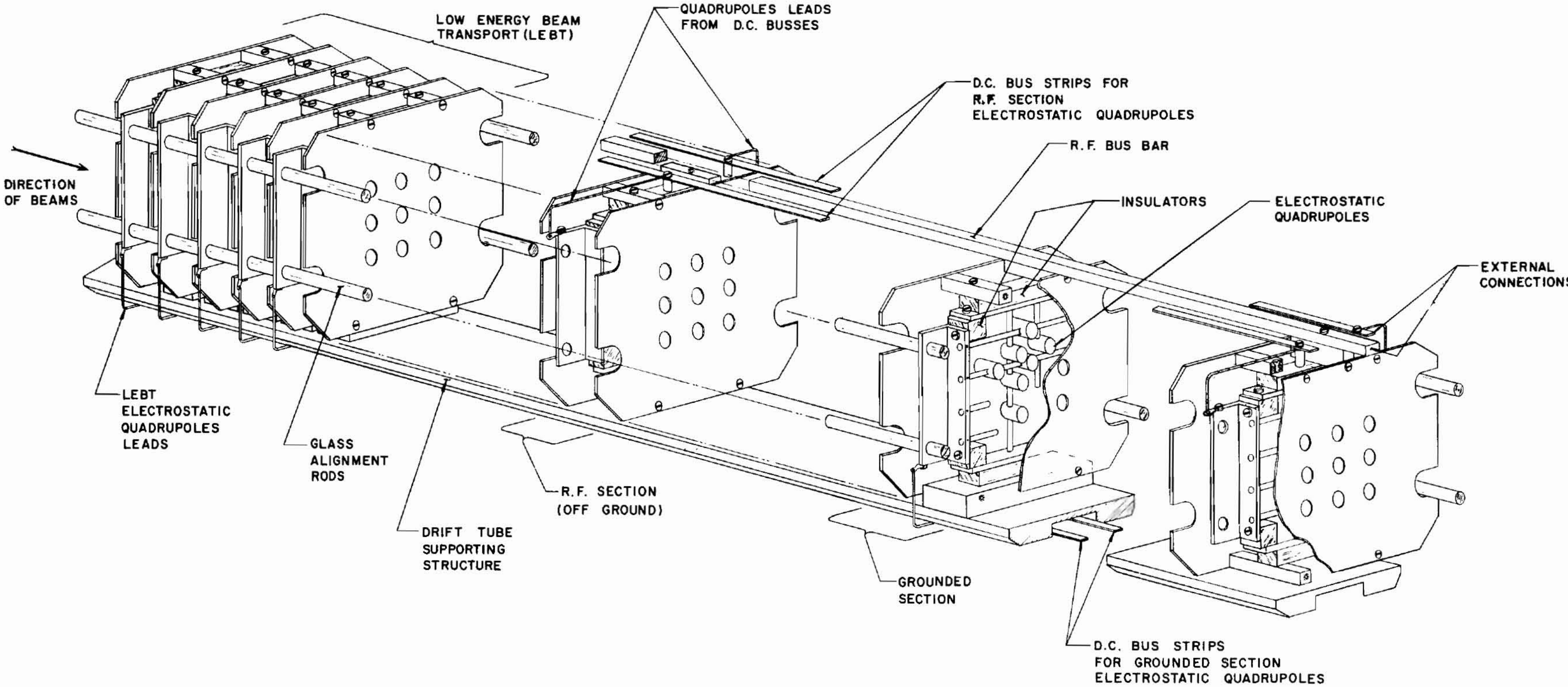


Figure 5. Schematic of M1 assembly showing bus bars. When mounted in the vacuum tank, the assembly hangs from the plate shown at the bottom.

c. <u>Ion Source, Match to LEBT, and Pre-Buncher</u>

The ion source is a version of the LBL-CTR ion sources (Figures 6 and 7). This type of source, with multiple distributed filaments in a chamber, produces a very quiet and uniform plasma. The electron efficiency is low, but when operated with xenon the filaments are long-lived even with cw filament operation for the modest current densities needed.

Figure 8 shows a spectrum indicating $\sim$70% Xe^{+1} purity.

Typical operating parameters are:

TABLE III. ION SOURCE PARAMETERS

Fil voltage	7.5 Vac
Fil current	150 amps ac
Arc current	25A
Arc voltage	50V
Ion current density	25 mA/cm^2

In operation, the filaments and gas run cw, and the arc voltage is pulsed. The current density is adjusted from 1-50 mA/cm^2 by varying the filament power.

Model studies were made with single channel transport systems (see Figure 9) for obtaining a good match between the source and the acceptance of the channel. The calculated acceptance area of the channel is 40 πcm-mrad (unnormalized), and the calculated space-charge limit is 3.3 mA of xenon. One must fill the acceptance of the channel uniformly in both emittance planes to approach the space-charge limit.

Previous emittance measurements with this source yielded 25 mA of Xe^{+1} into 10 πcm-mrad at 15.5 keV. Although these measurements were performed under space-charge neutral conditions after the extraction gap, it is clear that a considerable degree of emittance "spoiling" is necessary to fill the transport channel.

We have found one special solution to this highly non-linear problem experimentally. The slits shown in Figure 5 are cut in concave "dimples" of 1-1/4 inch radius in both the arc cover plate and grounded extraction plate.

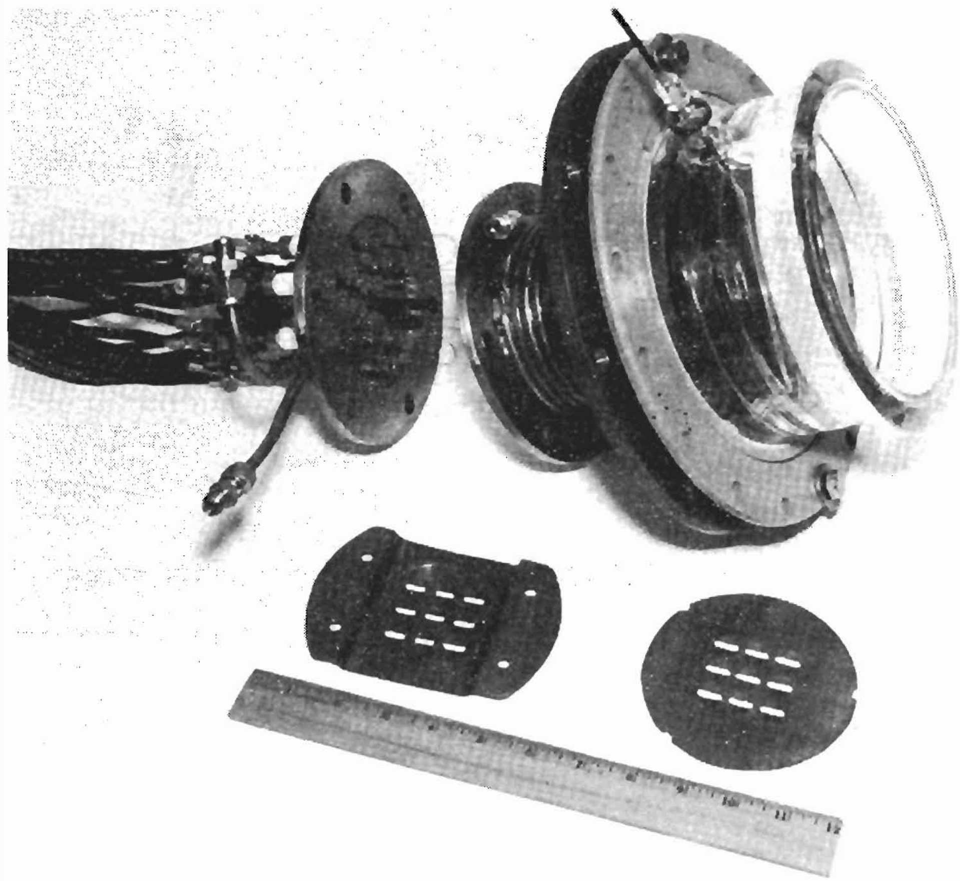


Figure 6. Ion source and Pyrex insulator.

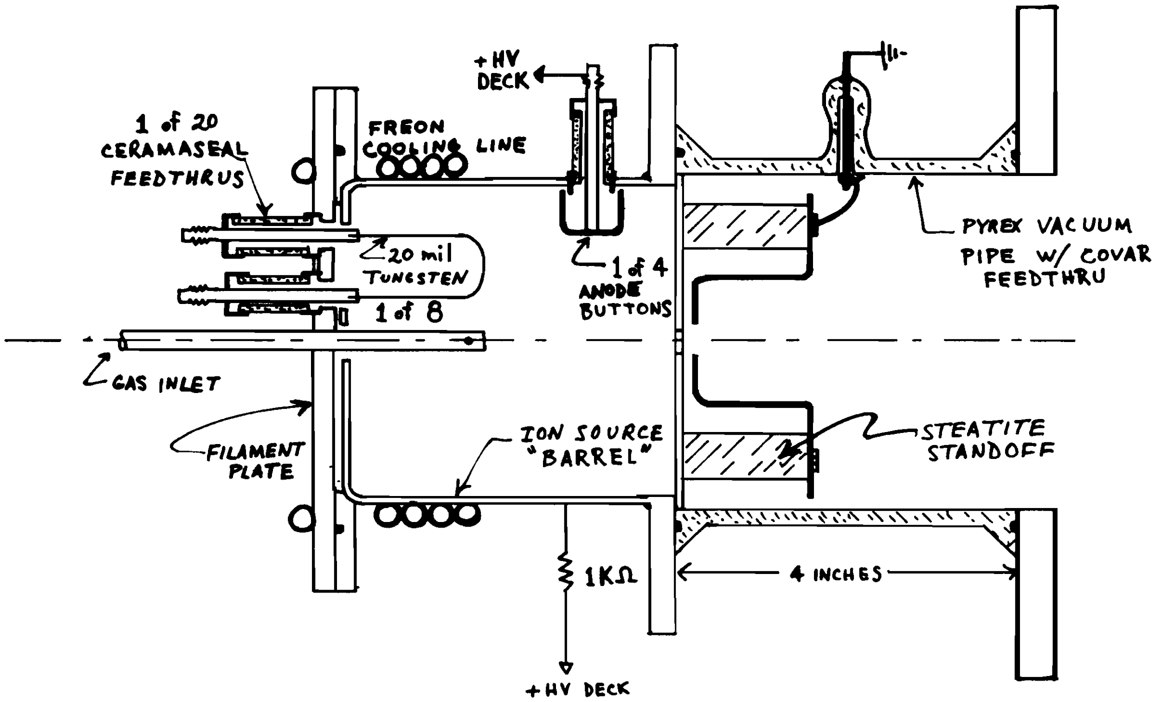


Figure 7. Schematic of ion source. The 4" dia. Pyrex pipe shown was replaced with a 6" dia. pipe.

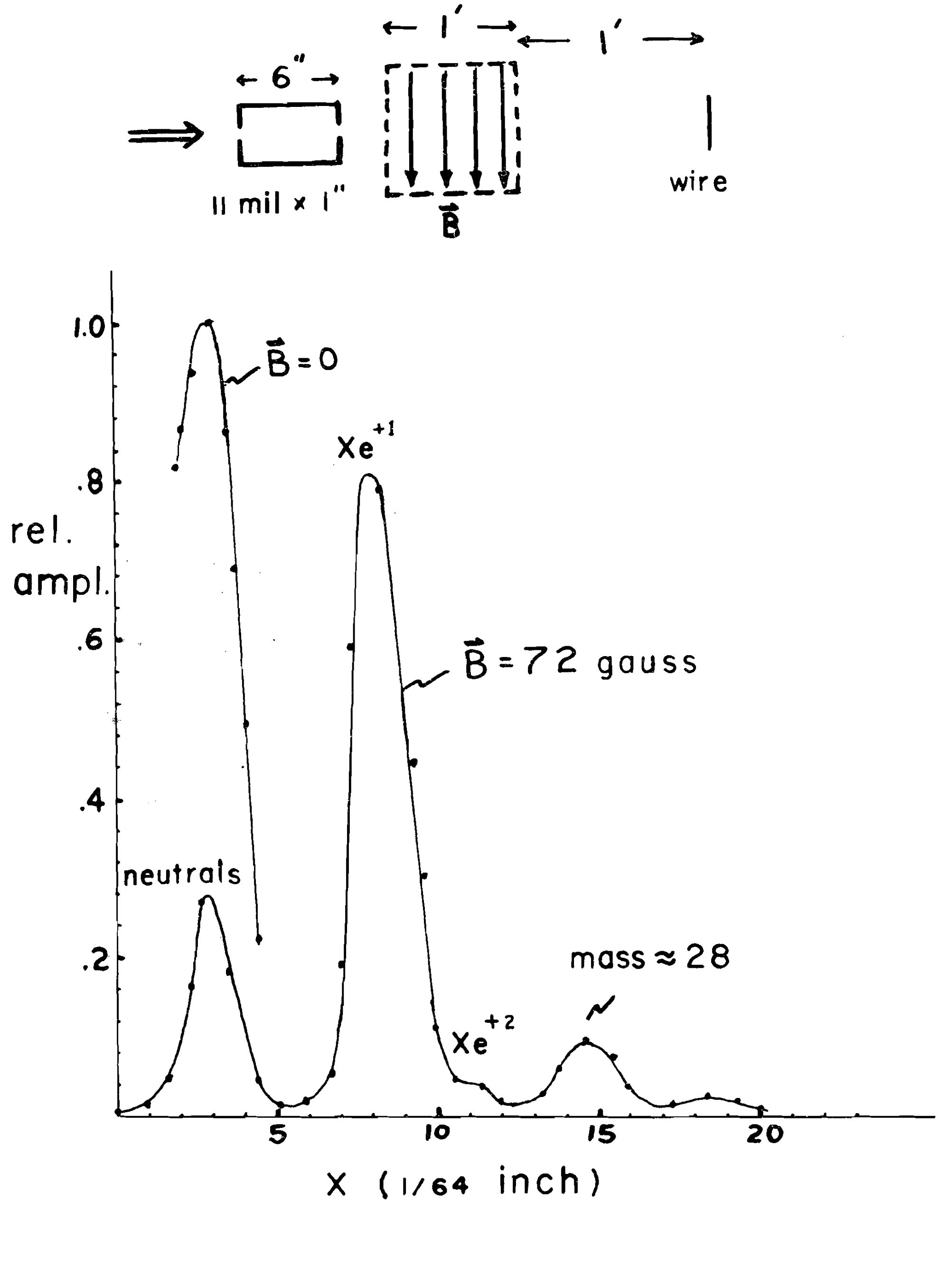


Figure 8. Spectrum of ion species from source showing $\sim 70\%$ Xe^+. The fact that the neutral peak is not deflected or badly distorted by the B field indicates that neutralization occurs only near the source.

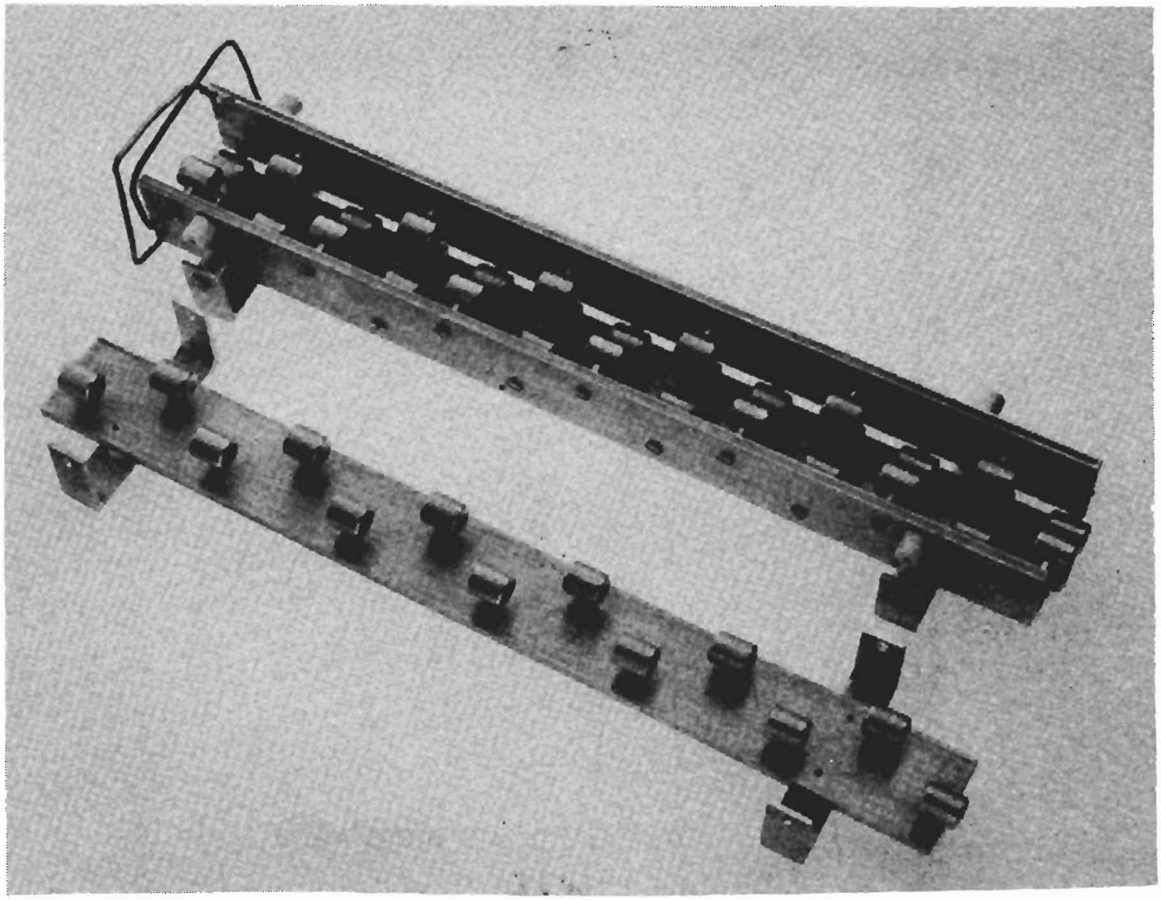


Figure 9. Transport channel for preliminary tests. This version has a 5/8" bore. Later versions were made with 5/16" bore for M1 modeling.

The area of the extraction hole is 0.35 cm^2, with an aspect ratio of 3:1. This gives us a converging beam in the dimension parallel to the slit, and a diverging beam in the direction perpendicular to the slit. We adjusted the quad channel position for maximum transported current, and obtained 2.4-2.6 mA of Xe^+ when the first quad end was 7/8 inch from the extractor plate. For the highest current levels, it was found that the arc voltage should be raised to 70-80 volts.

In this case, the total current emerging from the extractor is $\sim$8 mA, and we transport $\sim$2.5 mA. We assume that the acceptance of the channel is well filled, but this has not been measured todate.

With a 7/8" gap between the extractor plate and the first LEBT quad, we are able to insert a pre-buncher plate of 1/2 inch thick aluminum. This has nine 1/2 inch diameter holes and is suspended on the same Rexolite rods. The $\beta\lambda/2$ length between the centers of the buncher gaps is 0.75 inch.

The drift length from the buncher to the first rf gap is 4 inches (through five LEBT quad arrays). This drift length is sufficient to give a 45° phase shift with 1.5 kV buncher voltage.

The instantaneous bunch current has the same transverse space-charge limit as the dc transport limit. Therefore we have competing "bottlenecks" in the transport at each end of the LEBT. This was verified in operation of M1, by observing that the ion source could be run from 10-25 mA/cm^2 current density without changing the output current.

d. Rf System

The rf system consists of two major parts; an amplifier and a resonator.

The amplifier is a 4 MHz, 2 stage, 700 watt linear amplifier with broadband interstage coupling. The input rf amplitude range is 0 to 1 volt peak, for an output power level from 0 to maximum. The amplifier is single-ended throughout with the two output tubes driven in parallel. The input stage is operated in a class A mode with control grid modulation to compensate for beam loading. The interstage coupling is performed by a Tchebycheff filter so that tuning is unnecessary. The final stage tubes operate in a class AB_1 mode. This stage operates in a stable fashion with grid and screen parasitic suppressors but no neutralization. Figure 10 shows the rf amplifier with covers removed. In the foreground at the left is the

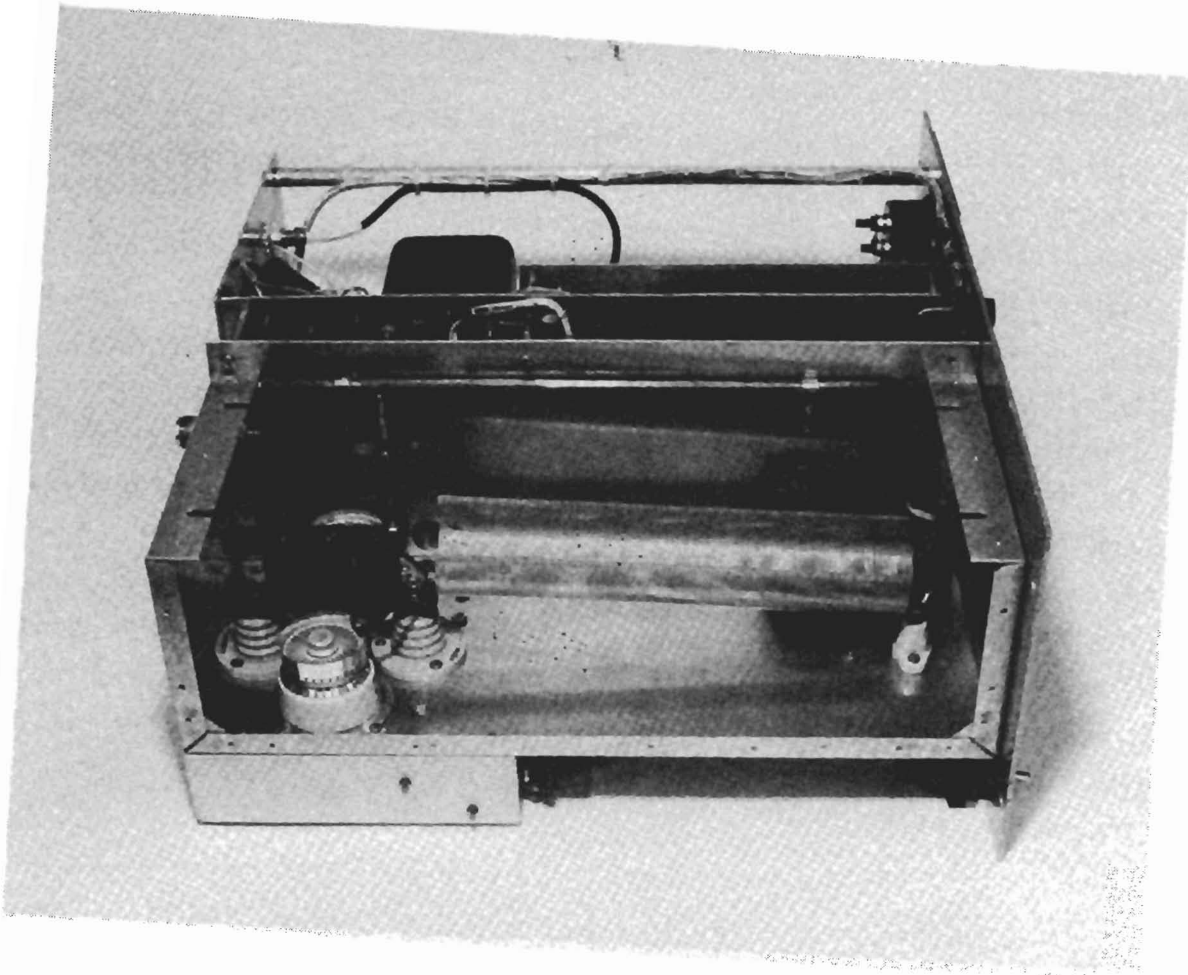


Figure 10. 4 MHz rf amplifier.

final stage showing the two 4CX350A tubes, plate choke and dc blocking capacitors. The rf plate connection is directed vertically and passes through a small duct (not shown) into the resonator compartment normally mounted above. The portions of the chassis in the background and those parts not visible in Figure 10 are the filament transformer, low voltage plate and bias power supplies, and first stage grid modulator PC board.

The resonator is a three turn coil of 3/4 inch copper tubing with a nine inch mean diameter. The amplifier plate connection is made at the first turn to give a step-up turns ratio of 1:3, thus providing 5 kV peak rf at the accelerating gaps. The unloaded Q of the resonator with the accelerating structure connected was measured at 680. The noload or tank and accelerating structure losses amount to 300 watts. The remainder of the output power is beam loading. Figure 11 shows the resonator assembly with the side panel removed. The plate tap is clearly visible, passing through the bottom panel from the first turn. The 3rd turn, or top of the coil has a flange to mate with a flanged bus from the accelerating structure just below a vacuum window. Two RG 58 coaxial cables for ± DC voltage for the rf quads can be seen entering the bottom coil mounting flange. They leave through the top mounting flange and thus have rf isolation. From the top of the resonator to ground is a 300 pF vacuum capacitor for final stage tuning. Below the tuning capacitor is a 1:1000 capacitive divider for monitoring the gap voltage.

The rf is switched at the oscillator and modulated at the first stage of the rf amplifier from timing pulses generated at a master timing panel.

The buncher is driven by a helical resonator and, in turn, driven by a commercially built wideband amplifier. The 4 MHz oscillator also provides the low level rf signal that drives the buncher amplifier. A separate rf amplitude control is provided, and a phase shifter is included so that the relative rf phase between the accelerating gaps and buncher may be tuned. Figure 12 is a block diagram of the complete rf system.

IV. M1 Operating Results

After running the M1 for several days, all systems were working together to produce the results shown in Figures 13-16, under the conditions of Table IV.

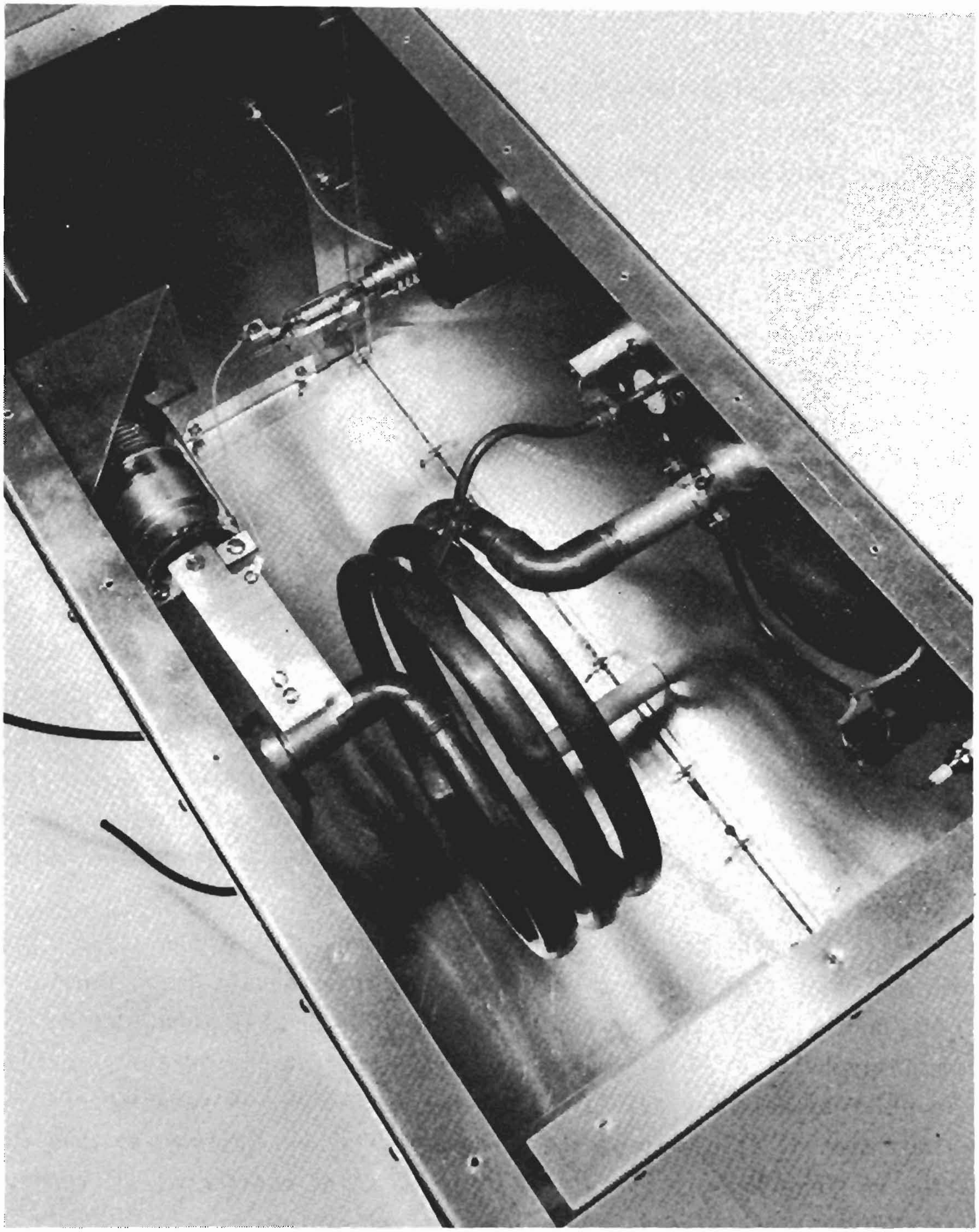
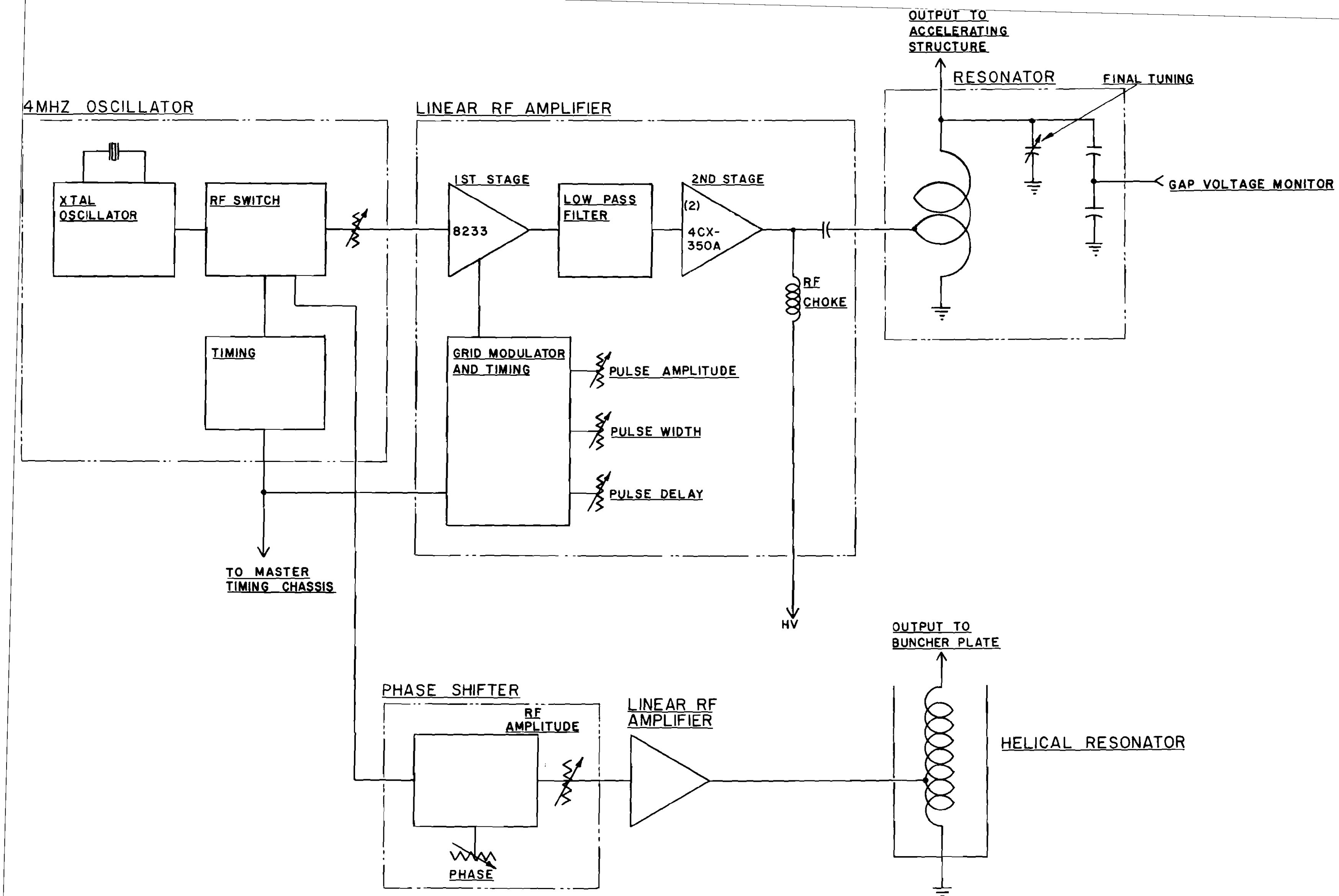


Figure 11. Rf resonator.



MEQALAC RF SYSTEM

Figure 12. Block diagram of rf system.

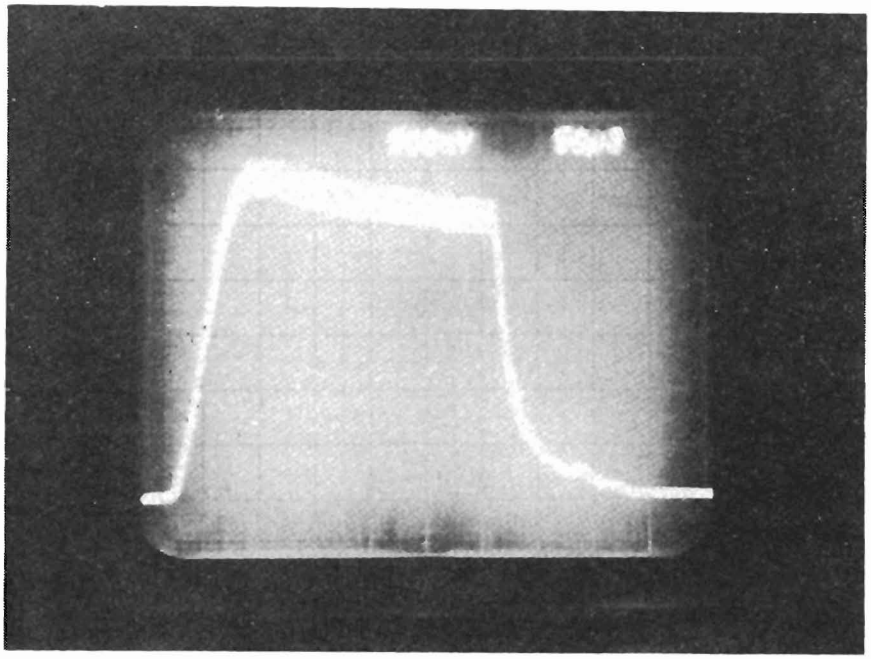


Figure 13. Full current (nine beams) at M1 output, 0.5 mA/div. vertical and 50 μsec/div. horizontal. Bunch structure is integrated.

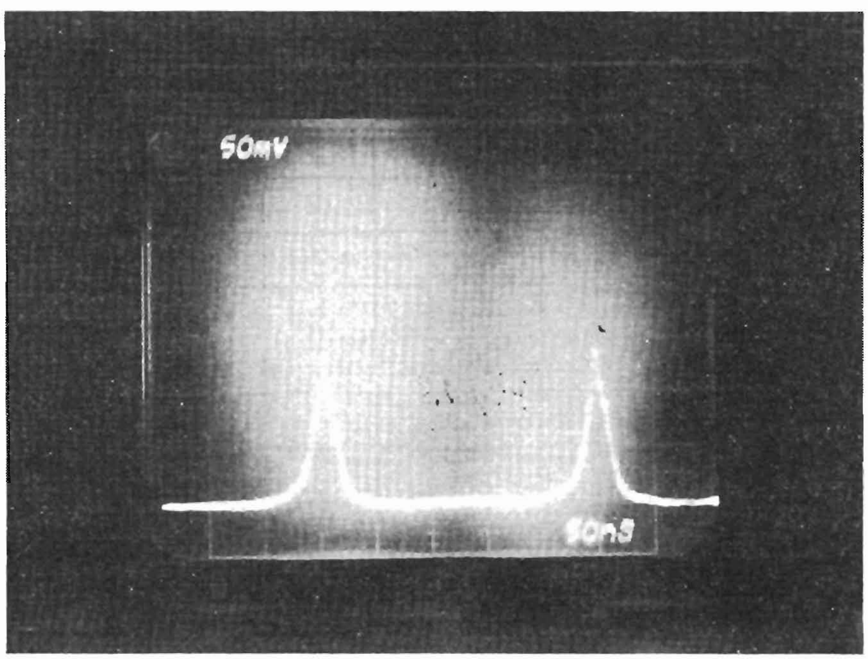


Figure 14. Single beamlet current showing 4 MHz bunches. 1 mA/div. vertical and 50 nsec/div. horizontal.

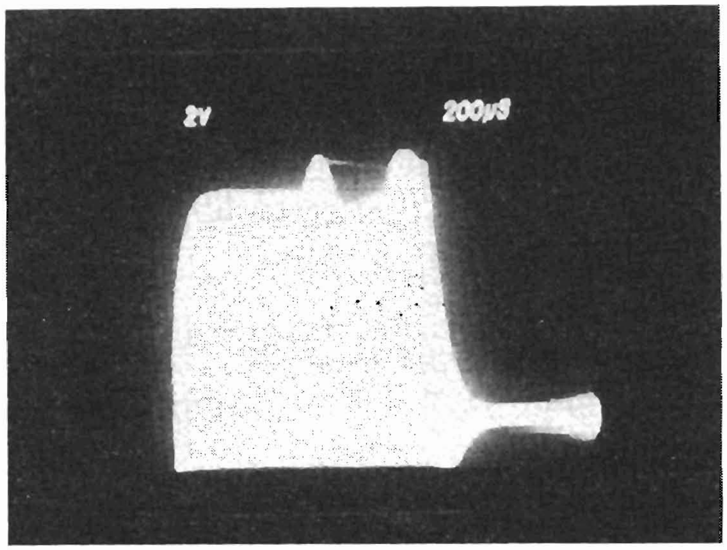
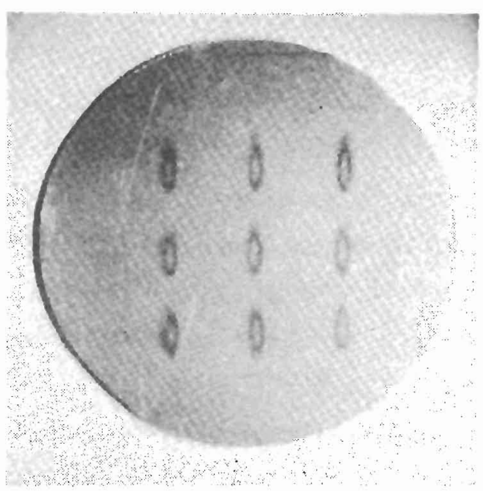


Figure 15. Rf envelope from voltage pickup on resonator. The rf amplitude is boosted ~50 μsec before beam-on time, and the subsequent dip is due to beam loading.



Nine Beam Witness Plate, 1" after end of MEQALAC.

Figure 16. Aluminum plate showing beam marks.

TABLE IV. OPERATING CONDITIONS

Source		MEQALAC	
Fil Current:	133A	LEBT Quads:	$\pm$1.8 kV
Arc Current:	29A	Linac Quads:	$\pm$2.25 kV
Source Voltage:	+17.3 kV	Rf Voltage:	4.7 kV
		Buncher Voltage:	1.5 kV

Vacuum: 2×10^{-5} torr

Figure 13 shows the output current of all nine beams collected in a single Faraday cup with a -300 V biased grid. The signal was terminated in 1 kΩ with an integrating capacitor. The peak current is 2.8 mA. There is about a 10% rf signal passing the integrator.

Figure 14 shows the bunch structure in a single beamlet. This signal was terminated with 50Ω. The instantaneous peak current is 2.8 mA. We obtain an experimental rf filling factor from these two results of 11 $\pm$ 1%. This is obtained by solving the relationship

(2.8 mA/beam) x (9 beams) x (fill factor) = 2.8 mA Total Avg Current

The error quoted is an estimate of several factors including different peak currents obtained for individual beamlets, which was probably due to the coarseness of the grid bias wires compared to the small beam sizes.

The theoretical estimate of this filling factor for an optimum MEQALAC is 13.3%.[3] This estimate assumes an equality between the longitudinal and transverse space-charge limits, and so the 11% result is a measure of the validity of that assumption for the M1. We suspect that we could improve the filling factor with the addition of a 2nd harmonic buncher.

The theoretical estimate of the space charge limit is 3.3 mA total average current. We obtained 2.8 mA, or 85% of that estimate.

Figure 15 shows the rf envelope and exhibits beam loading. At beam time a square wave pulse is added to the grid modulator. The additional rf amplitude needed to compensate for beam loading is seen to be $\sim$15%. This model is operating at greater than 30% beam loaded power.

The operation of the quadrupoles was straightforward and trouble-free. We measured 0.2 mA of current drain from the quad supplies during beam time. The optimum quad setting for a broad range of MEQALAC design is $V_Q = 0.115$ V_{input},[5] where V_{input} is the input accelerating voltage of the ion.

At V_{input} = 17.3 kV, V_Q is $\pm$ 2.0 kV. Our best results were obtained with $V_Q = \pm$ 2.25 kV. The theoretical estimate does not take into account the effect of rf defocussing.

An important consequence of the above quad voltage relationship is that the focussing channel can be arbitrarily close to the ion source extraction gap. That is to say, if the ion source operates without sparking at the extractor, then the channel shouldn't spark either. This is very favorable for future MEQALAC development since improvement calls for smaller beams and higher ion source current densities.

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3. Reference 1, p. 3.
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