IEEE Transactions on Nuclear Science, Vol. NS-28, No. 3, June 1981

MEQALAC DEVELOPMENT AT BROOKHAVEN*

G. Gammel, J. Brodowski, J. Keane, A. Maschke, E. Meier, R. Mobley and R. Sanders
Brookhaven National Laboratory
Upton, New York 11973

Summary

A novel method of transporting and accelerating high brightness ion beams, called MEQALAC[1], has been developed at Brookhaven. The concept and its motivation will be described first, with reference to other sources for detail, and then the performance of two operating MEQALAC's will be presented.

MEQALAC Concept

MEQALAC is an acronym for "multiple-beam electrostatic quadrupole array linear accelerator". Many beamlets propagate simultaneously in individual channels with electrostatic quadrupoles of alternating polarity lining each channel to keep the beams confined by strong focusing. The number of beamlets depends on the total current desired. One could conceivably have tens of thousands of beamlets in a square meter carrying a total of tens of amps. During acceleration (in a small Wideroe or Alvarez type structure), all beams share a common rf accelerating gap and drift tube at each step of acceleration.

This concept originally evolved as a solution to the need for transporting high brightness beams at the low beta end of a heavy ion accelerator for inertial confinement fusion. The argument went as follows.[2] For a given beam energy, it can be shown that the maximum current transportable in a quadrupole channel, the space charge limit i_{max}, is independent of channel size; but normalized transverse acceptance, ε_{NT}, decreases as channel size decreases. So brighter beams can be transported as channel size decreases. Thinking ahead to acceleration, this means small cell size, and therefore low initial β and/or high frequency. Of course, as β is decreased, so is i_{max}, but the final expression for $i_{max}/\varepsilon_{NT}^2$, or transverse brightness, varies inversely with β. For heavy ion fusion, the full six-dimensional brightness in the linac is of interest, and it varies as f^2/β_i^3. So, high frequency and low initial β, i.e., β_i, maximize 6-D brightness. Low beta and small bore size make electrostatic quads a natural choice for the focusing. Another condition for achieving maximum 6-D brightness, it should be mentioned, is that the average accelerating field should be about one-fifth of the electric field at the quad pole tips.

The analysis shows that the space charge limited current varies as the square of the ratio of channel radius to cell length, where cell length is twice the distance between adjacent quads.[3] For a Wideroe structure, then, cell length is $\beta c/f$, and it is $2\beta c/f$ for an Alvarez structure. This parameter should be maximized in MEQALAC design, or about 0.13. Above this, the quad length becomes too short. The quadrupole fields become distorted, and rf penetration into the drift space begins to be a problem. Therefore, once a bore radius, r_Q, is chosen, the optimum cell length is $r_Q/0.13$. Once an injection energy (β) is chosen, the frequency is fixed.

M1 MEQALAC

Preparatory to the first test of the MEQALAC concept, a 5/8" single bore channel was used to transport a 15 kV xenon beam. Using a circular extraction aperture, not enough beam was matched to the channel to fill it to its space charge limit of 2 mA. The match was improved with a slit-in-dimple extractor geometry. A shallow, spherical depression or "dimple" was stamped into the source cover and extractor plate, and a narrow slit was cut in each (length: width = 4:1). The emerging beam was convergent in the long direction of the slit, and divergent in the narrow direction. Only the angle of convergence could be controlled (by varying the radius of curvature of the dimple). A

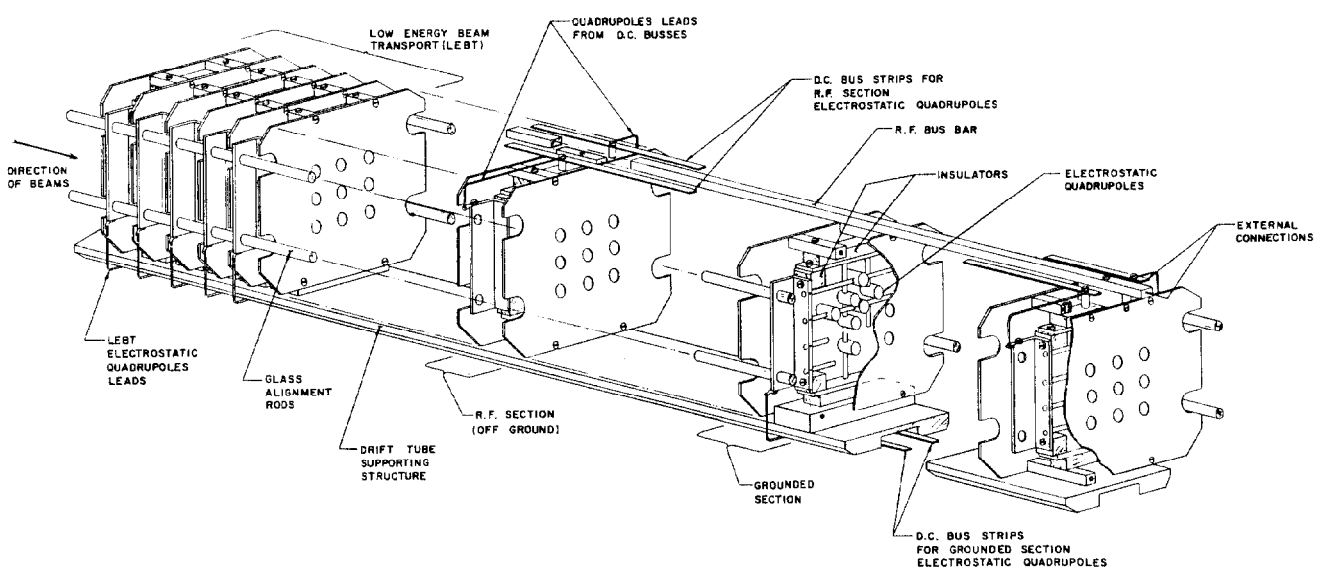

Figure 1. Sketch of M1 nine-beam xenon MEQALAC. Quads in LEBT are sandwiched between ground plates, and are pinned to a criss-crossing matrix of offset rods as shown in cutaway.

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matched beam must be just that: convergent in one plane and divergent in the other. With this extractor geometry, the space charge limit was reached.

The first test itself was to build a nine beam xenon MEQALAC. First, it was decided to halve the channel and source aperture dimensions, halve the extraction gap, and quadruple the arc current in the source. This was accomplished, and the space charge limited current through the new channel was again obtained with the scaled down slit-in-dimple geometry.

The MEQALAC sketched in Figure 1 (see also Figure 2) was then built, complete with ion source control rack, vacuum system, the rf system, in a three month period from July to September, 1979. The initial beam energy of 15 kV, final energy of 70 kV, and frequency of 4 MHz were chosen as a compatible match between a convenient source extraction voltage, a small but not too small bore size, and an available 700 W amplifier. Those choices pretty well determined the remaining machine parameters, which appear in a separate report.[4,5]

Within a week of operation, 90% of the calculated space charge limited current was obtained. The results are summarized in Figures 3 and 4. The project was undertaken with an eye toward transporting a beam of heavy ions with the level of brightness called for by heavy ion fusion. The normalized transverse brightness of each beamlet was 1.3×10^7 A/cm^2 rad^2. The 6-D brightness per beam was 3.3×10^{29} particles/cm^3-rad^3, which is at least ten times the uranium based Brookhaven requirement.[6]

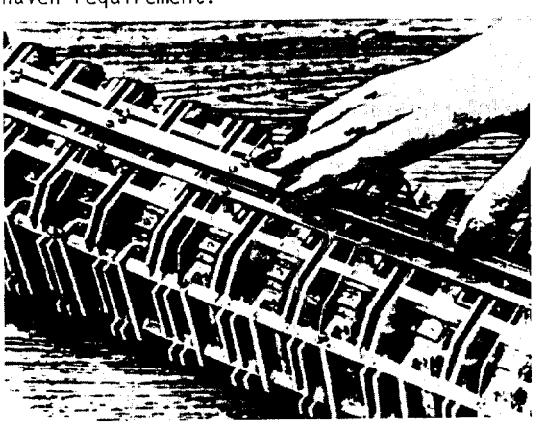


Figure 2. Photo of part of M1 acceleration section, showing quad arrays in the drift spaces. Also shows rf push/pull bus bar connecting to every other pair of plates, and their quad connection (connections to quads between ground plates are at bottom).

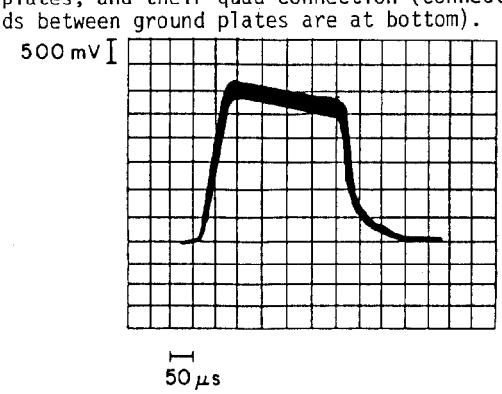


Figure 3. Average xenon current from all nine channels of the M1, collected by a Faraday cup terminated with 1 KΩ (1/2 mA per division).

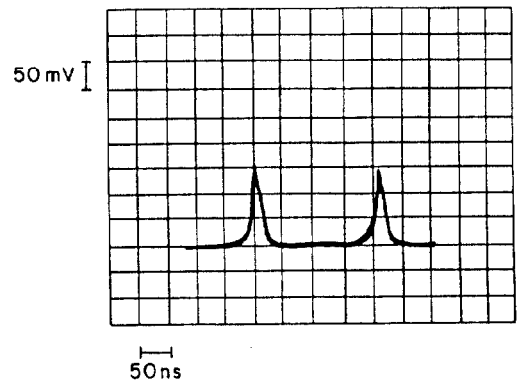


Figure 4. Instantaneous xenon current from a single channel of M1, collected by a Faraday cup terminated in 50Ω (1 mA per division).

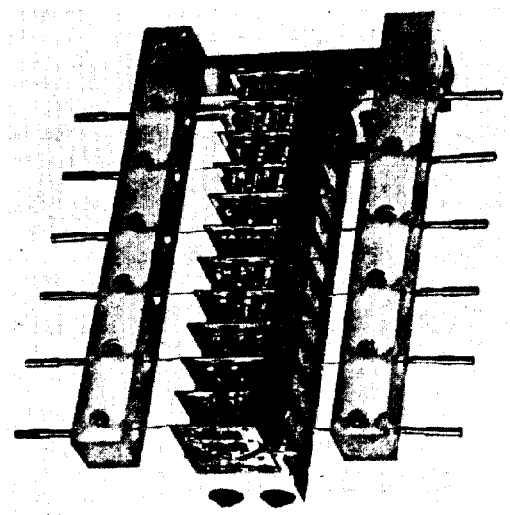
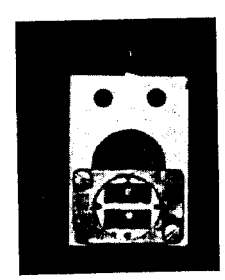


Figure 5. a. 40 kV LEBT design for M2 four-beam H^- MEQALAC. Square rod (60 mil x 60 mil) is spot-welded to 10 mil SS plate, and then spot-welded to each side of a larger 20 mil SS plate with 90° relative rotation. Each unit is chemically polished and then screwed to a boro-nitride insulator with 000-120 flat head screws. The units are then stacked up to form a 2 x 2 quadrupole array, and held together by two rods which also align the array.

b. One of the 2 x 2 quad units which fits in the drift space pockets of linac as described in ref.8, square rod is spot welded to a 15 mil SS plate. The pole tips are chemically polished, and the unit is screwed to one side of the boro-nitride insulator with 000-120 flat head screws. A similar unit is screwed to the other side with a 90° rotation to complete the quadrupole set. The two holes at the top are for the suspension and alignment rod.



M2 MEQALAC

In winter of 1979, work began on an application of the MEQALAC concept as a possible replacement for the BNL 750 kV Cockcroft-Walton. The bore size was reduced a further factor of 201/2, to make it 3 mm. This was partly a result of a decision to accelerate at the same frequency as the BNL 200 MeV linac, but it also provided

an opportunity to push MEQALAC development towards the high frequencies and smaller bore sizes where brighter beams are theoretically possible. It was decided to accelerate H^- using a high current density source. A BNL Mark III magnetron[7] capable of at least $1A/cm^2$ was chosen.

The first test, matching a 12 kV, 15 mA beam to a 3 mm channel, was done in February, 1980, in collaboration with the BNL H^- group. The beam emittance from a slit-in-dimple extractor was measured using the H^- group's computerized emittance measuring system. Comparing the result with the calculated channel acceptance, a maximum of 50% of the beam current could have been transported. In fact, 3.8 mA, or 25% was transported.

Work then began on the Cockcroft-Walton replacement, conceptually a four beam, 3 mm bore MEQALAC with 20 kV injection into a six cell DC transport section ("LEBT") followed by a two tank linac. After constructing the first tank and doing some tests with it, it became apparent that the cell length was too small to get reasonable quadrupole lengths in the available drift space in the tank, and a decision was made to increase the injection energy to 40 kV. The ratio of quad length to cell length then increased about 40%. Also, the quadrupole geometries in LEBT and linac were changed to increase their voltage holding capability (see Figure 5). A pair of voltage pulsers were built for the linac quads as well, since the quad voltage requirement was the most severe.

The higher source voltage necessitated a double gap extractor, namely a 2 mm gap followed by a 2-1/2 mm gap. The aperture was simplified from slits-in-dimples back to flat circular holes with successively increasing diameter.

Beam matching experiments with the new LEBT were resumed in fall, 1980. Some results of these experiments are presented in Figure 6. At 40 kV, 3.7 mA per channel was transported (15 mA total), with 15 mA per hole from the source.

Tests of the new first tank, which accelerates from 40 kV to about 120 kV, are presently underway. Like the earlier first tank, it is a resonant section of inter-digital waveguide (see description, ref. 8). The design of both tanks, as well as the design of the second tank, which accelerates from 120 kV to 750 kV, is discussed in a related paper in these proceedings.[8] Some parameters of LEBT and Tank 1 are listed in Table I.

Table I. M2 MEQALAC Parameters

LEBT	
Cell length, L	13.8 mm
Quad radius, r_Q	1.5 mm ±5%
No. of cells	6-1/2
r_Q/L	0.109
Quad length/L	0.4 for first 6 cells
	0. for last half cell
Tank 1 (Wideroe, 40 kV-120 kV)	
Quad radius	1.5 mm ±5%
Input $\beta\lambda/2$	7.5 mm
Output $\beta\lambda/2$	11.7 mm
Quad length/L	0.28
No. of accel. gaps	10
Frequency	4 MHz
Input power	5 kW

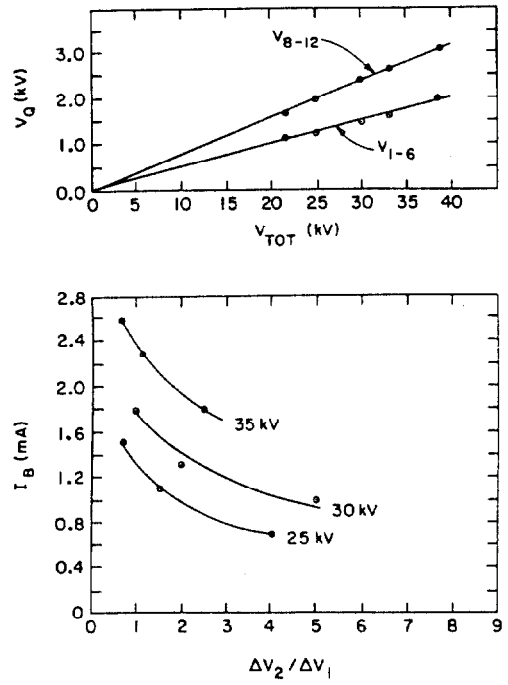


Figure 6. a. The LEBT of Fig. 5a. was divided into two parts. Maximum beam current out as a function of beam energy was obtained for the quad voltages shown. The voltage of the front half (V_{1-6}) was lower than that of the back half (V_{8-12}). Loss of beam current occurred in the front half only; none was lost in the rest of LEBT, indicating that the beam was well matched by then.

b. Beam current per channel out of LEBT as a function of (voltage across second extractor gap)/(voltage across first extractor gap), for three beam energies. The current directly out of the source behaved similarly, but transport through LEBT was more efficient for high ratios. The beam was more focussed at high ratios, which could be the reason for the improved efficiency.

References

1. U.S. patent pending.

2. For proof of statements in this paragraph, see A.W. Maschke, Space Charge Limits for Linear Accelerators, BNL 51022, May 1, 1979.

3. A.W. Maschke, Formulary for MEQALAC Design, BNL 51119, Nov. 27, 1979.

4. R. Adams, et. al., "Description of the M1 MEQALAC and Operating Results", BNL 27128, LBL 10301.

5. R.M. Mobley, et.al., "MEQALAC: A New Approach to Low Beta RF Acceleration", Sixth Conference on the Application of Accelerators in Research and Industry, Denton, Texas, Nov. 3-5, 1980. (BNL 28581).

6. A.W. Maschke, "Conceptual Design of a Heavy Ion Fusion Center", BNL 50817, March 1978.

7. K. Prelec, Proc. of the Symposium on the Production and Neutralization of Negative Hydrogen Ions and Beams, p. 111 (BNL 50727). See also Th. Sluyters and C. Lam, ibid., p. 211.

8. J. Keane, et. al., "MEQALAC RF Accelerating Structure", these proceedings.