Submitted to Sixth Conference on the Application of Accelerators in Research and Industry, North Texas State University--November 3, 4, 5, 1980.

BNL-28581

Conf-801111--60

MEQALAC: (Multiple Electrostatic Quadrupole Array Linac): A NEW APPROACH TO LOW-BETA RF ACCELERATION*

R.M. Mobley, J.J. Brodowski, G.M. Gammel, J.T. Keane, A.W. Maschke and R.T. Sanders

BROOKHAVEN NATIONAL LABORATORY
Upton, Long Island, New York 11973

BNL--28581

DE83 000714

Introduction

Beginning in 1977, the Department of Energy funded projects at several laboratories under the label Heavy Ion Fusion. The impetus was due to the realization that the energy of relativistic heavy ion beams in storage rings can be coupled to small thermonuclear pellets with power densities unavailable by any other means.[1,2,3,4]

Since the extant technology is largely that of proton accelerators, one obvious development needed for Heavy Ion Fusion is low beta (that is, low velocity, β = v/c) accelerators. Once one has accelerated a U^+ beam, for example, of sufficient intensity and brightness, to velocities of a medium energy proton beam, other aspects of the accelerator design are identical to high energy proton machine design.

The currents required from the low beta accelerator are ~100 milliamperes, wheras typical heavy ion machines for nuclear research are limited to several microamperes. The development of the MEQALAC at Brookhaven has overcome this limit.

MEQALAC is an acronym for a multiple-beam electrostatic-quadrupole array linear accelerator. The principle of operation is very simple. It makes use of the fact that electrostatic quadrupoles focus more effectively at low velocities than conventional magnetic quadrupoles. Moreover, the "pole-tip" field of an electrostatic quadrupole is limited by field emission of electrons, and is not a function of the size of the quadrupole. Conventional magnetic quadrupoles, on the other hand, require increasingly high current densities if one attempts to scale to smaller size.

In designing an rf drift-tube linear accelerator, it is necessary to make shorter and shorter drift tubes as the velocity of the particle decreases, assuming the frequency is kept fixed. However, as the drift tube gets shorter, the hole in it must also decrease or the drift tube would cease to act as a shield to keep the particles from being deaccelerated when the field reverses.

By using electrostatic quadrupoles, the bore sizes can be made orders of magnitude smaller than for magnetic quads. Furthermore, they require no power and can be produced for very little cost.

The beam intensity that can be accelerated in a single beam diminishes as the velocity is decreased. The total MEQALAC current, however, is the sum of a large number of independent low current electrostatically focused channels. It is feasible to construct electrostatic-quadrupole arrays that contain thousands of separate channels.

The same physical principles that make the MEQALAC attractive also apply to ion source design. For years, very high current ion sources have been made with arrays of very small apertures. The MEQALAC is ideally suited to take the beam directly from a multiple-aperture ion source and accelerate it with rf directly from the extraction voltage (10 to 50 kV, typically). In some cases it may be possible to actually run the extractors with rf and maintain the entire source body at ground potential.

The first model (the M1 MEQALAC) was a demonstration that multiple beamlets could be accelerated with common drift tubes and focused within individual channels without beam-beam interference. The second model (M2), presently under construction, is designed as a 750 keV H^- machine operating at 200 MHz as a prototype injector for proton linacs.

MEQALAC Theory

A.W. Maschke[5,6,7] has derived the principal MEQALAC equations in detail which is beyond the scope of this paper. We reproduce here a sketch of the derivation and the principal parameters and formulae.

A linac has a current limit due to the space-charge repulsion of particles in the ball (or small cylinder) of charge constituting a bunch.

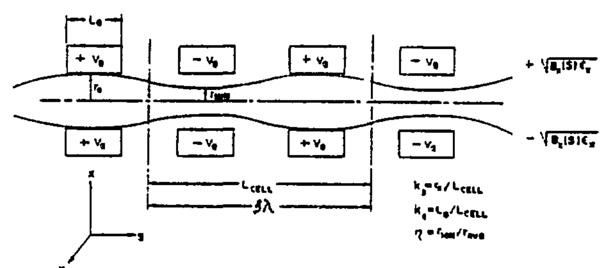

Figure 1. Schematic of beam envelope with emittance matched to quad channel acceptance. $\beta_x(s)$ is the betatron ellipse parameter. In a Wideröe structure, there is an rf accelerating gap between each quad set, with the gap distance $\beta\lambda/2$.

Consider a uniform sphere of N particles of charge ze in the channel illustrated by Fig. 1. An ion of atomic weight A (mass = Am_p) and charge ze experiences a linear force in the quadrupole of:

$$Am_p \ddot{X} = \pm ez E' X$$

in which m_p is the proton mass and E' is the electric field gradient in volts/m^2. The series of quadrupole "kicks" can be represented by an average linear restoring force $\overline{E}$'X, and moreover, the space charge force can be regarded as diminishing this force in a linear way:

$$Am_p \ddot{X} = -ez \overline{E'} (1-k) X$$

Clearly, k < 1, or the sphere is unstable. More elaborate theory and numerical simulation both indicate that charge can be added to the point where k ~ 0.5.

*Work performed under the auspices of the U.S. Department of Energy.

Equation (2) describes a simple harmonic oscillator with the solution:

$$X = X_0 \sin \omega t$$

$$\dot{X} = \omega X_0 \cos \omega t \qquad (3)$$

$$\omega = \sqrt{\frac{ez\,\bar{E}'\,(1-k)}{Am_p}}$$

The maximum values of X and $\dot{X}$ are directly related to the channel acceptance. The normalized transverse emittance ε_{NT} is defined by:

$$(\Delta X\,\Delta p_x) = \varepsilon_{NT}\,Am_pc = (XX')\,\beta\gamma\,Am_pc \qquad (4)$$

in which

$$X' = \frac{dx}{ds} = \frac{dx}{dt}\frac{dt}{ds} = \dot{X}/\beta c$$

One then obtains for $X = r_o$:

$$\varepsilon_{NT} = r_o^{3/2}\sqrt{\frac{ez\,\bar{E}_{max}(1-k)}{Am_pc^2}}\,\gamma \qquad (5)$$

where we substituted $\bar{E}_{max} = \bar{E}'\,r_o$.

With the two further steps: 1) writing Coulomb's law for the space charge field implicit in Eq. (2) and 2) calculating the instantaneous current peak as the sphere equator passes at velocity βc, one obtains:

$$i_{max_T} = \frac{k_3\pi\varepsilon_o c}{(1-k)^{1/3}}\left(\frac{m_pc^2}{e}\right)^{1/3}\left(\frac{A}{z}\right)^{1/3}\varepsilon_{NT}^{2/3}\,\bar{E}_{max}^{2/3}\,\beta\gamma \qquad (6)$$

where ε_o is the dielectric constant.

$\bar{E}_{max}$ is not simply the pole tip field, but is the maximum average field experienced by a particle undergoing strong focussing. Hence it is related to the parameters k_3, k_4 and η defined in Fig. 1, and also the optical parameter μ_o, the phase advance per cell, which must be $\leq\pi/2$ or particles at the edge of the bunch will be overfocussed. Analyzing this relationship, one finds the startling result:

$$i_{max_T} = 1.56\times10^7\left\{k\,\mu_o^2\,k_3^2\,\eta^{4/3}\right\}\frac{A}{z}(\beta\gamma)^3 \qquad (7)$$

That is, the maximum current does not depend on the bore radius. Inserting typical values for the parameters $k = 0.5$, $k_3 = 0.125$, $k_4 = 0.4$, $\mu_o = 1.5$, and $\eta = 0.707$ we get

$$i_{max_T} = 1.1\times10^5\,\frac{A}{z}(\beta\gamma)^3 \text{ Amperes} \qquad (8)$$

From the foregoing, one does not yet know how to design a MEQALAC. Clearly, the pole tip fields must increase to squeeze the same current through a small bore. Further, we have no guide for the optimum frequency and average accelerating field required to maintain longitudinal stability. We also need to show that the pole tip voltages are a small fraction of the particle energy or the focussing becomes very nonlinear. These relationships are derived in Ref. 5.

A similar procedure for the current limit due to longitudinal considerations gives

$$i_{max_L} = 4.73\times10^5\,k\beta^2\,\bar{E}/f \qquad (9)$$

where $\bar{E}$ is the average accelerating field and f is the frequency. Equating Eqs. (7) and (9) lead to the maximum brightness condition:

$$\rho_{6D} = \frac{\bar{i}/fez}{\varepsilon_{NL}\varepsilon_{NT}^2} \propto \frac{f^2}{\beta^3}\,\frac{A}{z} \qquad (10)$$

That is, a super-bright beam is obtained by starting with the lowest practical velocity and using the highest possible frequency. These requirements are only compatible with the smallest practical bore size.

We finish this overview of MEQALAC theory by stating the optimized results in terms of injection voltage V and quadrupole pole tip field $E_{Q_m} = 2\,V_Q/r_Q$ in mks units per beamlet:

$$i_{max} = 1.7\times10^{-8}\,\frac{V^{3/2}\,Z^{1/2}}{A^{1/2}}$$

$$\bar{I} = 0.133\,i_{max} \text{ (rf duty factor)}$$

$$\varepsilon_{NT} = 1\times10^{-6}\,\frac{V^{3/2}\,Z^{1/2}}{E_{Q_m}\,A^{1/2}} \qquad (11)$$

$$r_Q = 0.23\,V/E_{Q_m}, \quad V_Q = 0.115\,V\,.$$

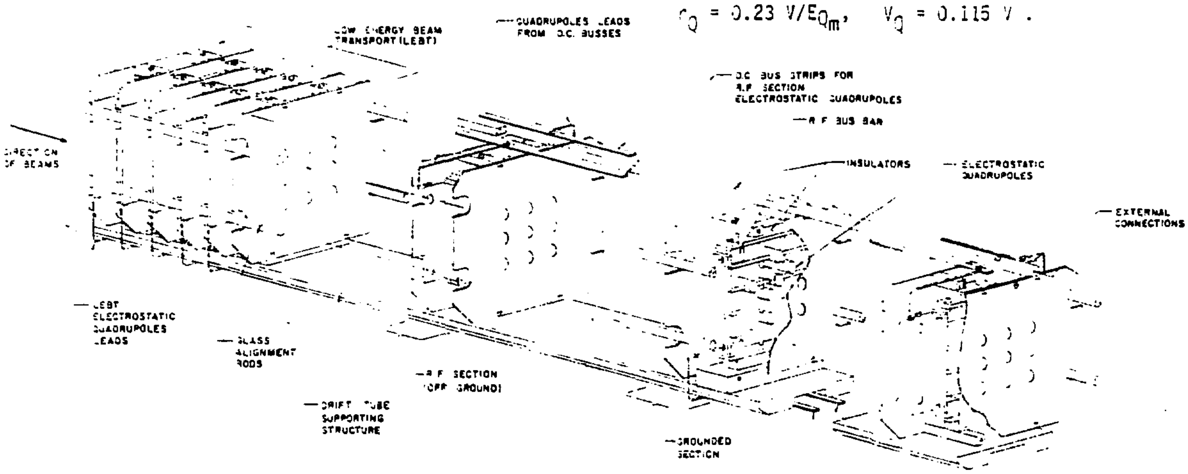

Figure 2. The M1 structure, showing quad arrays, low energy beam transport and rf sections. Metal parts are mostly Al, and insulators are Rexolite.

The M1 MEQALAC

The first MEQALAC was designed, built, and tested in three months in 1979. It accelerated nine beamlets of Xe^{+1} from 17 keV to 73 keV. The bore diameters were 5/16 inch. Figure 2 shows the linac structure, and Figure 3 shows the assembled machine.

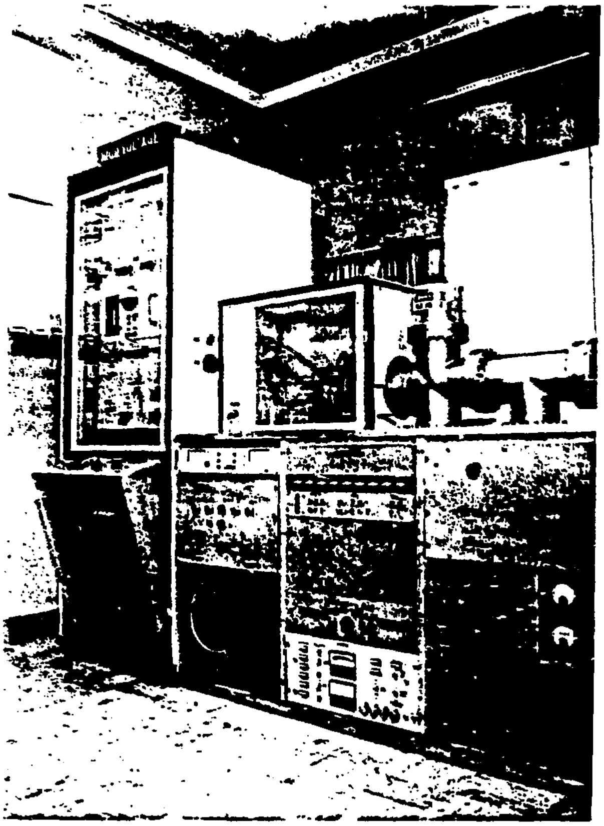

Figure 3. The assembled M1 MEQALAC. The Xenon ion source is located in the small screen enclosure, and associated power supplies are in the tall rack. The structure is mounted in six inch Varian vacuum pipe.

Table 1 lists other parameters. The overall length of 160 cm, measured from the extraction slits of the ion source, includes a buncher and drift length section before the first accelerating gap.

Table 1. M1 Parameters

Energy (keV)	17 in, 73 out	
$\beta\lambda/2$ (cm)	1.9 in, 3.9 out	
Accel. voltage	3.5 kV/gap, 4 MHz, 45° phase angle	
Buncher voltage	1.0-1.5 kV, 4 MHz, 2 gaps	
Quad voltages	±2.2 kV	
Current limit (theory)	3.3 mA	9 beams, avg. current for 500 μsec pulse.
Measured current	2.3 mA	

The output current was 2.8 mA, 85% of the calculated space-charge limit.

Rf power was provided by a 700 watt amplifier operating at 4 MHz. The resonator was essentially a tuned LC tank circuit, where the drift tube gap capacity provided the C, and the L was provided by a three turn coil of 9 inch diameter mounted outside the vacuum system.

A feedback system was provided to maintain the needed gap voltage under beam loading. Since the beam was pulsed (by pulsing the ion source arc current), the rf was pulsed and modulated to adjust to beam turn-on and turn-off conditions. The unloaded Q of the resonator was 680, and noload power was 300 watts. Since the beam power was ∼150 watts, the machine operated at 33% beam loading.

The M2 MEQALAC

The M2 is designed to accelerate 25 mA of H^- to 750 keV. This machine is a prototype injector for the BNL 200 MeV linac, which operates at 200 MHz. The high frequency implies smaller beamlets (3 mm bore diameters) and higher current density, the interesting direction for development of MEQALAC machines. The M2 has four beams in a 2x2 array featuring flat pole tip design and a much closer beam spacing than in the M1. The quadrupole arrays are illustrated in Figure 4.

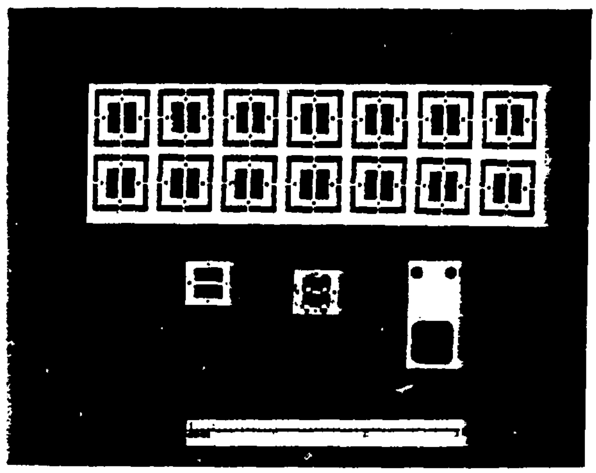

Figure 4. Parts for M2 quad assembly. Stainless steel pole tips are welded to photo-etched s.s. plates, and mounted on a boron nitride insulator. Alignment of the poles is then precise with respect to the skewer holes shown.

The various parts of the M2 are undergoing development at this writing. The source[9] is a magnetron using surface production of H^- from a cesiated molybdenum cathode. It provides 15 mA H^- from each of 4 holes of ∼2 mm diameter with 2 extractor gaps of 15 kV and 25 kV. The 40 kV beams then will be transported in 2x2 quad arrays of 13 mm L_{cell} length, to a $\beta\lambda/2$ buncher and drift section before capture in the first rf accelerator, which will accelerate the beams from 40 to 124 keV. A second rf section will accelerate from 124 keV to 750 keV.

The rf sections feature a unique resonator design[10] illustrated in Figure 5. The small bore sizes allow small rf gaps (1 mm and 5 mm) and large gap capacity, which in turn allows a large reduction in the resonator size for a given frequency, in analogy with ridged wave guide structures.

In our case, the resonators are ~5" wide, and the lengths of the 124 kV and 750 kV sections are about 6" and 19" respectively. The total length of the M2, including ion source, low energy transport and matching sections, will be about 1 meter.

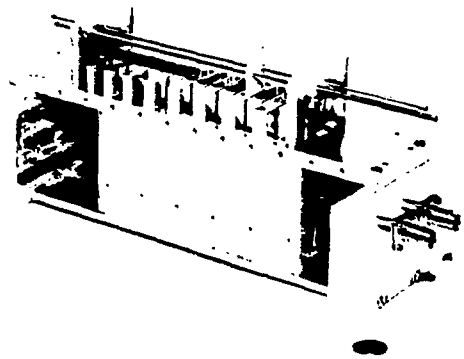

Figure 5. Rf resonator for 200 MHz. The side conductor is removed, showing the center post. The widths of the drift tubes increase as the length increases, to maintain constant capacity per unit length. The unloaded Q is ~ 1000.

Discussion

Current limits for linacs have been studied for years. Too often, the formulation of the space-charge problem is applied to a pre-existing accelerator design. The major conclusions here are that small bores, and low energy injection are desirable. This solves several issues listed in the abstract for this paper and points up areas needing development:

1. Precision fabrication of millimeter and sub-millimeter quad arrays, including micro-polishing and material selection.
2. Matching of high brightness ion sources to the high current densities attainable.
3. Design of rf systems for large current arrays.[11]

Acknowledgments

We thank the members of the Heavy Ion Fusion group, K. Riker, E. Meier, J. Bourch, and R. Glasmann for technical assistance and P. Knisely for help with the manuscript.

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