DESIGN, FABRICATION, AND TESTING OF THE BNL RADIO FREQUENCY QUADRUPOLE ACCELERATOR*

H. Brown, T. Clifford, S. Giordano, F. Khiari,#
R. McKenzie-Wilson, M. Puglisi,+ P. Warner

Brookhaven National Laboratory, Associated Universities, Inc.
Upton, New York  11973  U.S.A.

## Summary

The Brookhaven National Laboratory polarized H⁻ injection program[1] for the AGS utilizes a Radio Frequency Quadrupole Accelerator for acceleration between the polarized source and the Alvarez Linac.  Although operation has commenced with a few μ amperes of H⁻ beam, it is anticipated that future polarized H⁻ sources will have a considerably improved output.  The RFQ will operate at 201.25 MHz and will be capable of handling a beam current of 0.02 amperes with a duty cycle of 0.25%.  The resulting low average power has allowed novel solutions to the problems of vane alignment, rf current contacts, and removal of heat from the vanes.  The design philosophy, details of cavity fabrication, and vane machining will be discussed.  Results of low and high power rf testing will be presented together with the initial results of operations in the polarized H⁻ beam line.

## Introduction

Brookhaven National Laboratory utilizes a Radio Frequency Quadrupole Accelerator for acceleration between the polarized H⁻ ion source and the Alvarez Linac.  This RFQ is required to accelerate a maximum of 0.02 amperes from 20 kV to 760 kV, with a duty cycle of 0.25%.  The rf power required to drive the RFQ is provided by a subsystem of the existing linac rf equipment and operates at 201.25 MHz.  The low beam current results in a maximum of 150 watts of average power to be dissipated in the RFQ structure.  Testing of polarized H⁻ injection into the Alvarez Linac has been carried out intermittently over a three-month period.  A maximum beam current of 9 μA has been accelerated by the RFQ (limited by the ion source) with a 80% transparency.  A maximum transparency of 85% has been observed. Heating effects were observed during conditioning at very high average rf power levels.  At operating rf power levels no heating effects are observed.

## General Description

Table I lists the RFQ design parameters while Fig. 1 shows a typical cavity cross section.

### TABLE I
### RFQ DESIGN PARAMETERS

| | |
|---|---|
| Frequency | 201.25 MHz |
| Ion Species | H⁻ |
| Cavity Length | 148.27 cm |
| Cavity Diameter | 32.4 cm |
| No. of Cells (in vane) | 144 |
| Vane Length | 130.28 cm |
| Intervane Voltage | 63 kV |
| Peak Surface Field | 20.9 MV/m |
| Average Radius, $r_o$ | 0.4638 cm |
| Final Radius, $a_f$ | 0.299 cm |
| Final Modulation, m | 1.969 |
| Initial Synchronous Phase, $\phi_i$ | −90° |
| Final Synchronous Phase, $\phi_\phi$ | −30° |
| Estimated Peak RF Power | 60 kW (120 kW operating) |
| Nominal Current Limit | 56 mA |
| Nominal Acceptance | 2.7 πmm-mr (normalized) |
| Initial Energy | 20 keV |
| Final Energy | 760 keV |
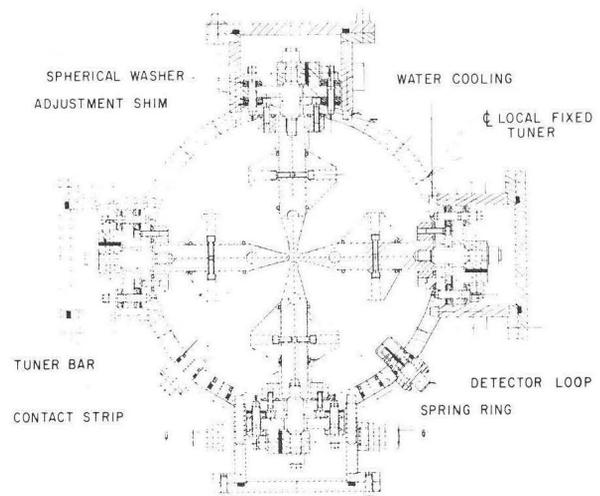
Fig. 1.  Typical cavity cross section.

All major features of the mechanical design have been adequately described elsewhere.[2]  The active profile on the vane tips was machined at BNL using information supplied by LASL and with modification to this information carried out at BNL.  It was originally intended that the vane active profile be machined using a ball ended milling cutter but final machining was carried out using a right-angle drive head and a 6" diameter cutter.  The outside diameter and profile radius of this cutter are used as input parameters for the N.C. milling machine.  The use of the right-angle drive head allows for a constant cutting speed over the complete profile cross section and resulted in a reduction of machining time.  The copper plate thickness on the vane was 0.1 mm and was held to a tolerance of ± 15% over the tip active profile.  Thickness of copper on the remaining surface of the vane was not controlled.
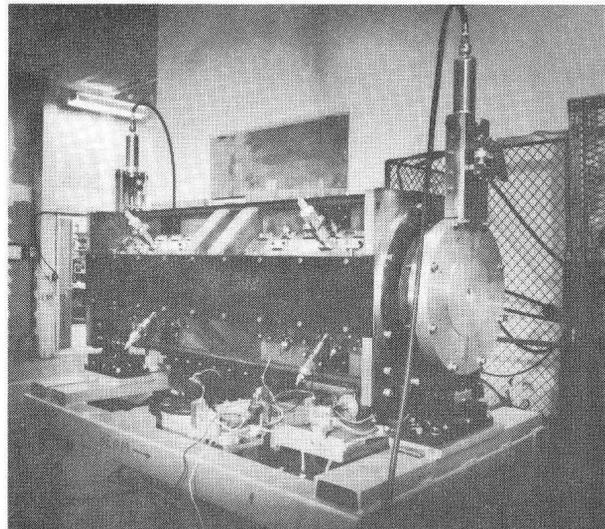


Fig. 2.  RFQ complete on transporter.

Installation of the vanes into the cavity was carried out using an installation fixture bolted to the end face of the cavity. It was found that optical alignment of the vanes was not possible and initial alignment was arranged by direct mechanical measurement with final alignment by reference to the rf tuning. The cavity end covers contain adjustable tuners adjacent to each vane. Fig. 2 shows the RFQ complete on its transporter just prior to installation in the beam line.

### RF Design and Low Power Testing

When considering the design of an RFQ structure, it is important that special attention be given to achieve a uniform field along the vanes, a uniform field in all four quadrants, and stability of the fields due to beam loading, temperature changes, etc. To gain these ends, a number of design concepts were incorporated in the BNL RFQ, which proved to be quite successful.

Before considering the actual structure, let us first look at the RF properties of the TE211 operating mode. Fig. 3 is a diagramatic representation of the RFQ structure, where $\ell_1$ and $\ell_2$ are the end cells and L is the region where the electric fields at the tips of the vanes must be kept uniform. Conceptually, we will consider these three regions independently. It should be noted that the center section, L, is not uniform since the vane tips vary (cell length, radius, and modulation index) along the length of the vane. This variation will be taken into account later on, but for our present discussion we will consider it uniform.
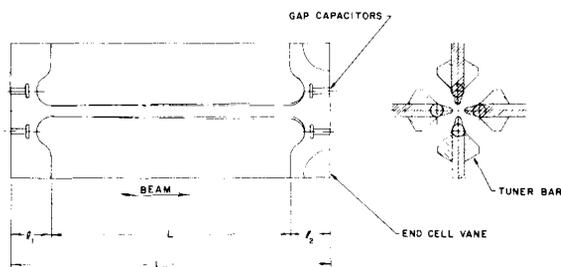


Fig. 3. Diagramatic representation of RFQ.

As with any uniform structure, the center section, L, can be characterized by an f vs $\beta g$ dispersion curve as shown in Fig. 4 ($\beta g = 2\pi/\lambda g$, where $\lambda g$ is the wavelength in the structure). For an infinitely long structure, or a finite structure of length, L, with a perfect open circuit (magnetic boundary) at each end,
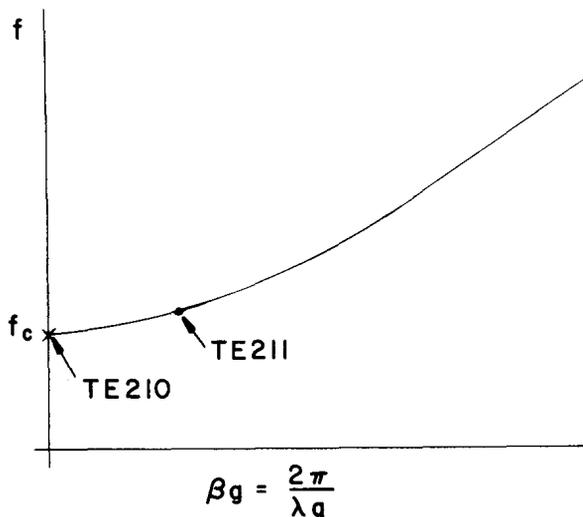


Fig. 4. Dispersion curve for uniform structure.

the cavity will be excited in the TE210 mode, which is the cutoff frequency (fc). The other TE21n modes, at considerably higher frequencies than fc (due to the fact that L is less than one wavelength of the free space wavelength of fc) will also exist depending on the end cell terminations (open or short circuited).

The cutoff frequency fc, can be found experimentally by replacing the end cells with cutoff pipes, which are simply an extension of the outside wall of the cavity. At fc the group velocity $v_g = 2\pi\frac{df}{d\beta g}$ is zero. To stabilize the longitudinal field distribution against mechanical errors, beam loading, temperature changes, etc., it is necessary to operate the RFQ above the cutoff frequency where $v_g > 0$. The end cells are used to establish the operating TE211 mode at a frequency of fo, as shown in Fig. 4. Operating above the cutoff frequency will result in a bowing upward of the longitudinal field distribution at the center of the cavity. But for this case, where the length of the cavity, L, is short, the effect is negligible. The operating frequency is 201.25 MHz, to match the frequency of the BNL 200 MeV linac, and the cutoff frequency is 199.00 MHz.

For the above discussion, it was assumed that the cross section, along the length L, was uniform and as previously noted this is not the case for the real structure. It was found that without compensation the field varied by 20% from end to end of the center section. To correct this variation the tuning bars were tapered. The tuning bars were, therefore, used to both tune the cavity to the proper frequency and to provide a first order correction of the longitudinal field distribution.

Before discussing the end cells, it should be pointed out that the length, L, represents the length along the vane tips where the fields must be uniform. The undercut on the vane ends do not extend into this region. This was done to insure that the transverse resonant frequency (two-dimensional, neglecting the effect of the $\beta$ and modulation index variation) was the same along the length, L. Other designs, where the undercut extends beyond this point, require that the end cells be tuned close to a resonance, which makes the tuning very critical and sensitive to changes.

With the tuning bars making a first order correction of the longitudinal fields, and by not having to compensate for the undercut on the ends of the vanes, the end cells need only provide a reactance to raise the frequency of the structure to the desired operating frequency. By adjusting the end cell lengths $\ell_1$ and $\ell_2$, and shaping the end cell vanes, it was a simple matter to tune the end cell gap capacitors to both set the desired operating frequency and equalize the fields in the four quadrants. The three parameters, $\ell_1$, $\ell_2$ and end cell vanes, were adjusted so that the physical gap of the end cell capacitors were greater than 0.5 cm, thereby reducing their sensitivity to changes of temperature, etc. It was possible to tune the operating frequency over a range of $\pm$ 0.2 MHz.

Fine tuning was done with the paddle tuners, six tuners in each quadrant. Actually, very little use was made of these tuners, and they are all set in their mid-range position. To compensate for small frequency shifts, motorized tuners are mounted into three quadrants while the fourth quadrant acts as a reference for the control circuit.

Final perturbation measurements were made at the vane tips in each quadrant and the results showed that the longitudinal electric field was uniform to within $\pm$ 3% in all four quadrants. The magnetic field at the wall had about a 20% tilt.

To drive the cavity, an eight-port manifold[3] was constructed as shown in Fig. 5. The impedance of the side arms is approximately 30 ohms. With the eight

output ports terminated in 50 Ohms, the manifold was tuned so that the 3" input port was matched to 50 Ohms. With the eight drive loops in the cavity all connected to the manifold, it was found that the fields in the cavity were considerably less sensitive to external perturbations. The drive loops were matched to the cavity and had a VSWR of 1.3:1. Although this is considered a good match, had the loops been made slightly larger in diameter, it would have been possible to get a 1:1 VSWR.
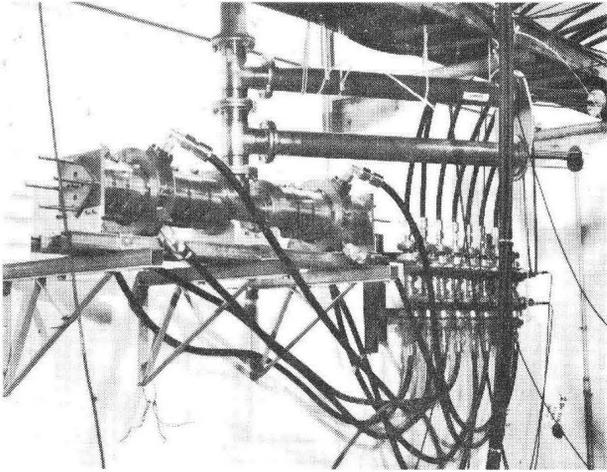


Fig. 5. 8-port manifold and directional couplers.

With operation at 201.25 MHz in the TE211 mode, a pair of degenerate TE111 modes were found at 199.70 and 198.21 MHz. The eight-port manifold in addition to tightly coupling together all four quadrants of the structure at the operating TE211 mode also suppresses the degenerate TE111 modes. When the eight loops are properly phased to excite the TE211 mode, they are in anti-phase with the TE111 modes. It was found that these degenerate modes were suppressed more than 25 db below the TE211 mode.

### RFQ Performance

The emittance of the 20 keV H⁻ source has been measured. With the solenoidal field in the charge exchange region set to operating values for good polarized H⁻ intensity, the measured values for horizontal and vertical emittances are comparable to those obtained by Hennies, et al.[4] for this type of source, namely

$$E_{xy} = 0.6 \ \pi \ (\text{mm-mrad, normalized})$$

Before installing the RFQ, the Twiss parameters $\alpha$, $\beta$, $\gamma$ were determined at the exit of the final Einzel lens and adjusted to those desired for proper matching to the RFQ.

With the RFQ in position, 0.5 µA of beam was transmitted and accelerated immediately. After some empirical adjustments of the 20 keV steering and lens units, the current through the RFQ reached 1.0 µA and the energy of 760 keV was confirmed by bending through the first 60° dipole. Subsequent refinements to the steering, focussing, and RFQ power level have brought the transmission up to a maximum of 85%, with 80% being the usual value. The maximum RFQ current has been about 9 µA, depending on source conditons.

There is an emittance device straight ahead from the RFQ. Preliminary results from it yield output emittances of

$$E_{x,y} = 0.8 \ \pi \ (\text{mm-mrad, normalized})$$

for 90% of the beam. There is a substantial amount of noise picked up by the emittance devices which has inhibited thorough investigation of the beam characteristics. The emittance dilution of 8/6 = 1.3 through the RFQ may still be a result of imperfect matching of the 20 keV beam to the RFQ and it could be partially due to the lack of a radial matching section at the RFQ exit (the nominal bunch width in rf phase is ± 20°, which leads to a certain amount of variation in radial motion for particles exiting at different phases).

Following the RFQ are two 60° dipoles. We suffer an as yet unexplained beam loss of about 40% in going through that region to the next Faraday cup. Further study time must be allotted to finding the reason for this loss. It should not be due to a large momentum spread, since a profile device between the two dipoles exhibits a well contained beam, and the dipole-dipole optics are designed to leave the beam dispersion free. The actual ($\Delta p/p$) for the RFQ beam has not yet been well determined.

Along the 5.8-meter path from RFQ to Linac, there are three rf cavities whose function is to preserve the bunch structure so that the 760 keV beam can be captured in the Linac accelerating buckets without loss. Empirical adjustment of the RFQ and cavity phase has been necessary so far since absolute phases with respect to the Linac are not yet available. With cavity amplitude tuning as well, the capture efficiency, measured between entrance and exit of the Linac, is at least 90%, within the present accuracy of the Faraday cup calibrations.

### Conclusions

The BNL RFQ accelerator has been in intermittent operation for three months and has performed satisfactorily. Testing is continuing to determine the operating characteristics and upper limits of this device as part of the polarized H⁻ beam line.

### Acknowledgments

### References

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