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TITLE: BEAR RFQ - Beam Experiment Aboard Rocket

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AUTHOR(S)	D. Schrage	F. A. Martinez	T. Butler
	L. M. Young	W. L. Clark	J. Rathke
	B. M. Campbell	W. S. Gibbs	R. Micich
	J. H. Billen	J. D. King	J. Rose
	J. Stovall	P. G. O'Shea	R. Richter
	G. Bolme	G. Rosato	

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Los Alamos National Laboratory
Los Alamos, New Mexico 87545

Los Alamos National Laboratory

BEAR RFQ - Beam Experiment Aboard Rocket*

**D. Schrage, L. Young, B. Campbell, J. H. Billen, J. Stovall, F. Martinez, W. Clark,
G. Bolme, S. Gibbs, D. King, P. O'Shea and T. Butler
MS-H817, Los Alamos National Laboratory, Los Alamos, NM 87545**

**J. Rathke, R. Micich and J. Rose
Grumman Space Systems, Bethpage, NY 11174**

**R. Richter and G. Rosato
GAR Electroformers, Danbury, CT 06810**

Los Alamos National Laboratory, Grumman, and GAR Electroformers have completed the design and fabrication of an electroformed RFQ for the BEAR (Beam Experiments Aboard a Rocket) project. The design of this 1-m-long, lightweight (<55 kg) accelerator incorporates four aluminum vane/cavity quadrants joined by an electroforming process. With the vane and cavity fabricated as a monolithic structure, there are no mechanical rf, vacuum, or structural joints. The completed BEAR RFQ has successfully passed flight qualification and beam transport tests in preparation for the flight, which is scheduled for March 1989.

1. Introduction

The BEAR [1] project is a test of a neutral particle beam (NPB) accelerator in space. It is a suborbital flight of a 1 MeV NPB accelerator and diagnostic payload aboard an ARIES booster. The flight is scheduled at the White Sands Missile Range in March of 1989. The BEAR accelerator consists of an H^+ ion injector [2], the RFQ accelerator, a high energy beam transport, and a gas neutralizer. The requirement is to produce a minimum of 10 mA of low emittance neutral beam at the output of the neutralizer, necessitating a beam current of ~20 mA of H^+ for the RFQ. The payload capacity of the ARIES booster placed severe weight constraints upon the accelerator module. These resulted in the selection of a resonant frequency of 425 MHz and a very low duty factor of 0.025% (50 μ s pulse at 5 Hz).

All components had to be designed to flight qualification criteria, including random vibration and shock loadings associated with the launch, separation, and flight [3,4]. Lastly, it was required that the BEAR RFQ utilize technology and

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materials that were extendible to higher duty factor (including CW) operation for follow-on programs. The final specifications and design parameters are given in Table 1. A second identical unit, the "Grumman RFQ," has been fabricated for use in the Grumman Accelerator Laboratory.

Table 1. BEAR RFQ design parameters

Particle	H ⁻
Resonant frequency	425. MHz
Injection energy	0.03 MeV
Energy at end of buncher	0.19 MeV
Final energy	1.00 MeV
Synchronous phase at end of buncher	-40°
Final synchronous phase	-34°
Transmission	87.4%
Final emittance	0.01 cm-mrad rms
Beam current	30 mA
Beam pulse width	50 ns
Beam pulse repetition rate	5 Hz
Beam power requirement	30. kW
Copper power requirement	70. kW
Total power requirement	100. kW
Duty factor	0.025%
Intervane voltage	0.044 Mv
Peak surface field	37.3 MV/m
Minimum aperture radius	1.20 mm
Final aperture radius	1.20 mm
Length	1.00 m (1.42 λ)
Outside diameter	0.18 m
Weight	55. kg

2. Design concept

After a conceptual design competition, a concept consisting of four 1-m-long copper-plated type 6061-T651 aluminum vane-cavity quadrants joined longitudinally by high strength electroformed copper joints was selected. A cross section of the RFQ is shown in fig. 1. This resulted in a monolithic assembly of high structural efficiency. The major features of this concept include the following:

- **Integral vacuum vessel:** The cavity walls form the vacuum vessel, thus minimizing both the weight and the number of vacuum seals.
- **No rf joints:** There are no longitudinal mechanical rf joints. This minimized concerns regarding degradation the cavity Q caused by corrosion of the rf seals and surfaces.
- **High structural efficiency:** The RFQ takes full advantage of the stiffness-to-weight ratio of aluminum. In addition, the vanes, being part of the monolithic structure, also carry load, corresponding to a 60% increase in bending stiffness and a 100% increase in axial stiffness relative to a more conventional design.
- **RF tuning stability:** The rf alignment is permanent. The RFQ vanes are not adjustable. Thus there is no stored energy to be released during launch and flight to misalign the vane tips.

3. Fabrication

The four vane/cavity quadrants of the BEAR RFQ were machined at the Grumman facility at Bethpage, New York. The vane tips were machined using a ball end mill tilted at an angle of 45° relative to the vane tips. This arrangement is shown in fig. 2 and is a variation of the method developed for the proof of principle RFQ [5]. The tilted cutter eliminates the "zero cutting speed" phenomenon at the apex of the tip as well, maintaining a consistent direction of cut on both sides of the vane tip. The method developed at Brookhaven [6] also accomplishes this but was unsuitable for the BEAR RFQ because of the small physical size associated with the 425 MHz frequency. It would have been desirable to have used a form cutter, but the beam dynamics design [7] specified a nonuniform transverse radius of curvature in order to minimize the length (weight) of the structure and the power supplied by the rf power systems.

The ball end mill is mounted in a collet in a directly driven spindle. The absence of gear meshes eliminates any tool bit chatter that might result from backlash. The vane tips were machined with a 12.7-mm-diam carbide cutter at 3600 rpm. The finished vane tips were within a tolerance of ± 0.025 mm; in fact, the majority of the area of tips was within ± 0.013 mm of true position. The surface finish was better than 32 micro-inches rms.

4. Electroforming

The electroplating and electroforming operations were carried out by GAR Electroformers in Danbury, Connecticut. Each vane/cavity quadrant was given a thin (0.01 mm) strike of CUFLEX [8]. CUFLEX is a high strength (TYPE II) electroform with electrical conductivity exceeding 98% IACS and yield strength exceeding 1.7×10^8 Pa. Following these operations, the vane tips were masked and the remaining surface was plated to a thickness of 0.08 mm from conformal electrodes. The plating provided a high conductivity layer on the internal rf surfaces as well as providing a coating to protect both the internal and the exterior surfaces from the caustic plating solutions. The purpose of the thin copper strike on the vane tips was to provide protection from the chemicals while at the same time not altering the vane tip geometry. It would have been possible to machine the vane tips so as to compensate for an arbitrary uniform plating thickness, which would have required development of high-accuracy conformal electrodes. Spark tests were carried out at LANL in a 45-cm-long cavity with 15-cm-long unmodulated vanes. These tests demonstrated that peak surface fields corresponding to 3.0 Kilpatrick with 60-ps pulses at 5 Hz could be achieved with both bare aluminum and copper-plated aluminum surfaces.

The vane/cavity quadrants were installed in a frame as shown in fig. 3 and adjusted as rigid bodies for mechanical alignment. A pair of tooling holes were located at both ends of each vane/cavity quadrant. The positions of these tooling holes relative to the vanes tips were known to a high degree of accuracy (0.008 mm). Dowel pins were inserted into the tooling holes, and their relative positions were measured. These measurements were input to software [9] developed at LANL that calculated shim sizes corresponding to displacements and rotations of the vane/cavity quadrants. This technique had been proved on the cold model RFQ. Tip to tip measurements made with feeler gauges indicated that the resulting alignment was within a tolerance of ± 0.03 mm. Following the mechanical alignment, the gaps

between the quadrants were filled with conductive mesh, and slug tuners were installed flush in all 20 ports. Under these conditions, the Grumman RFQ had a measured Q of 3800, 42% of the SUPERFISH value. Measurements of the rf field distribution were made by the "beadpull" method. The contribution of the residual dipole modes were less than 15% of the quadrupole field, well within the range of the slug tuners. On the basis of these measurements, it was decided to proceed with the electroforming of the longitudinal joints.

The joints were electroformed while the assembly was in a vertical orientation with the gaps between the quadrants backed by stainless steel members. The internal tooling was removed after sufficient thickness of copper had been deposited to provide a seal between the quadrants. Following the deposition of the first layer of electroform, which was 2.5 mm thick, a 7.5 mm thickness of multiple layers of lead tape was mechanically applied to the joint as a filler. This is shown in fig. 1. Use of the lead minimized the electroforming time. Lead was selected on the basis of its having a coefficient of thermal expansion approximately midway between copper and aluminum. The top layer of electroform was also 2.5 mm thick.

Near the end of the electroforming of the first (flight) unit, it was determined that the electroforming solution had attacked the copper strike on the vane tips. Removal of the strike was due to a poor seal of the joint backing in the joint areas that allowed a small amount of plating solution to enter the cavity during the initial phases of the electroforming of the first layer. Thus, the copper strike was removed by an acid dip. This was not necessary with the second (Grumman) unit. Final machining of both units was carried out at the Grumman facility

5. RF alignment

Final rf tuning was carried out in the RF Structures Laboratory of the Accelerator Physics and Special Projects Group (AT-1), Accelerator Technology Division at Los Alamos. The assembled BEAR RFQ is shown in fig. 4. The power is provided through a pair of drive loops installed in opposite quadrants at the midpoint of the RFQ. There are no vane coupling rings. Instead, stabilizers (similar to dipole suppressors [10]) are installed at both ends of each quadrant. These provide capacitive coupling to the end plates through slug tuners and shift the dipole to about 12 MHz from the quadrupole. Unlike the case of the cited reference, the BEAR RFQ stabilizers are mounted directly to the end plates, are on both ends of the RFQ, and the capacitive gap is to the radial slug tuner. These stabilizers also had the

effect of reducing the sensitivity to the drive loops being driven out of phase by 50%. With the two drive loops operated 120° out of phase, there is an increase in the dipole of only 2%. There are also slug tuners in the remaining ten ports, six of which also mount rf pickup loops. The rf fields were tuned by adjustment of the insertion depth of the 18 slug tuners. The resulting dipole fields are shown in fig. 5. The field tilts were reduced to less than 2%, and the contributions of the dipole modes were reduced to less than 2% of the quadrupole field. The bumps in dipole fields shown in fig. 5 are caused by the bead passing close to a tuner. These bumps do not represent bumps in the dipole field on-axis. The dipole fields are only measured accurately between the tuners (bumps) where the fields are flat.

The unloaded Q of the assembly is 6330, basically the anticipated 70% of the SUPERFISH value of 9000. The rf seal of the tuners is an annular choke joint of 0.5 mm width backed up by a copper-plated spring seal at the outside surface of the wall of the RFQ. This design was selected on the basis of its producing the highest cavity Q after some experimentation with various alternatives. The rf seals on the end plates are an aluminum wire mesh. Experimentation with various materials and seal configurations showed little effect, and the aluminum was chosen on the basis of its compatibility with the aluminum RFQ and end plates.

6. Structural/thermal testing

Prior to formal selection of the electroformed joint concept, a number of mechanical tests were carried out on the electroformed material and on electroformed copper/aluminum composites. In addition, witness electroforms were manufactured at all times during the electroforming process. Samples of these were tested per ASTM E-8, and in all cases, the yield strength exceeded 1.7×10^8 Pa. The strength of the adhesion to the aluminum had the same value. One criterion for the design was that stress levels in the RFQ not exceed the proportional limit during operation, both on the test stand and during flight, to assure that the structural analysis, which assumed a linear relationship between stress and strain, be valid. This effected a requirement that stresses under these conditions not exceed 5.6×10^7 Pa. All test specimens exceeded this value.

A one half length, full cross-section engineering model RFQ with unmodulated vane tips was constructed for the purpose of developing the electroforming technique and verifying the structural analysis performed by Grumman. Following fabrication, this unit was subjected to the full thermal load (a temperature increase

of 33°C) as well as to the full static loads and to the static equivalents of the flight dynamic loads. The latter involved applying a load of 900 newtons laterally at one end of the unit while the other end was cantilevered, which produced a moment load of 390 newton-meters at the fixed end. Pre- and post-test rf field distribution measurements (beadpulls) verified that there had been no change in the vane tip alignment.

The Flight Model RFQ was subjected to a random vibration shake test and to a shock test at levels corresponding to the ARIES specification [3,4]. Measurements of the rf field distribution were used as the pass/fail criteria.

7. Test stand operation

The RFQ was installed on the BEAR Test Stand and conditioned to 120% of the design power level in under 24 hours of operating time [11]. The outgassing rate was been measured at 1.0×10^{-9} torr-liter/cm²-s and a vacuum of 1.0×10^{-7} torr was achieved by pumping through the slots in high energy end plate. Since then the RFQ has been operated with both prototype and flight injectors. The results of beam transport tests are reported elsewhere in these proceedings [12].

8. Acknowledgment

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Figure Captions:

Fig. 1. BEAR RFQ cross section.

Fig. 2. BEAR RFQ vane tip machining.

Fig. 3. BEAR RFQ electroforming assembly.

Fig. 4. BEAR RFQ assembly.

Fig. 5. BEAR RFQ dipole fields.

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BEAR FLIGHT MODEL RFQ
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