A FLIGHT-QUALIFIED RFQ FOR THE BEAR PROJECT*

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Abstract

A 1-MeV, 30-mA, low-duty factor, 425-MHz RFQ has been designed and constructed for the BEAR (Beam Experiments Aboard a Rocket) Project by Los Alamos National Laboratory, Grumman Space Systems Division, and GAR Electroformers. The design of this 1-m-long, lightweight (<55-kg) accelerator is unique in that it was constructed of four copper-plated aluminum quadrants joined longitudinally by a room-temperature electro-forming process to produce a monolithic structure. There are no rf, vacuum, or mechanical joints in the vane/cavity region of the accelerator. As part of the design/fabrication process, spark-test, cold, and engineering model RFQs were constructed and tested. The completed flight unit has successfully passed static structural and thermal tests as well as dynamic structural (shake) tests according to the launch, separation, and flight specifications. In addition, the rf field distributions and beam-transport characteristics have been measured and found to satisfy the design requirements.

Introduction

The BEAR[1] project will be the earliest opportunity for testing a neutral particle beam (NPB) accelerator in space. An NPB accelerator is one of the directed energy technologies being developed under the Strategic Defense Initiative Organization (SDIO). The BEAR Project, which began in 1985, is a suborbital flight of a 1-MeV NPB accelerator and diagnostic payload to be launched on an ARIES booster. The flight is scheduled for March 1989 at the White Sands Missile Range. The 1200-kg payload will be launched to an apogee of 200 km, and the accelerator experiments will be carried out during a period of 400 s. The usual space-borne hardware requirements regarding minimal size and weight along with environmental conditions must be met by the equipment used in the BEAR flight.

Design Requirements

The BEAR accelerator payload consists of an H^- ion injector (small-angle source[2] and low-energy beam transport), the RFQ accelerator, a high-energy beam transport, and a gas neutralizer. The fundamental requirement is to produce a minimum of 10 mA of neutral beam at the output of the neutralizer. This effected a specification of a 30-mA beam current for the RFQ. Payload weight restrictions limited vacuum pumping capacity, prohibited cooling of the accelerator structure, and dictated minimum weight for the rf power system. These, as well as other considerations, led to the selection of a resonant frequency of 425 MHz along with a very low duty factor, 0.025%.

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The flight requirements dictated that all components and subassemblies pass environmental tests associated with operation under prelaunch ground support as well as under flight conditions.[3,4] Furthermore, even though the BEAR project involves a very low duty factor, it was required that the RFQ utilize technology and materials that were extendible to higher duty-factor (including CW) operation for future programs.

The beam dynamics design[5] was optimized to a short accelerator, 1 m long (1.42λ). The shorter length was achieved in part by using a varying transverse radius on the vane tips. Although this increased the complexity of the manufacture of the vane tips, it resulted in a 10% reduction in the length of the RFQ and a proportionate reduction in the copper power, along with similar reductions in the weight of both the RFQ and the rf power system. The final specifications and design parameters are given in Table I.

Table I. 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 MeV
Synchronous phase at end of buncher	-40°
Final synchronous phase	-34°
Transmission	87%
Final emittance	0.01-cm·mrad rms
Beam current	30 mA
Beam pulse width	50 μs
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 m (1.42λ)
Outside diameter	0.18 m
Weight	55 kg

Conceptual Design

The project began with a conceptual design competition. One of the two competing concepts was a conventional structure consisting of a set of vanes bolted into a core tank that was to be enclosed in a vacuum vessel. In one variation of this, the core tank also functioned as the vacuum vessel.[6] The alternative proposal was an unconventional, novel concept that consisted of four independent vanes with the cavity walls, supporting structure, and vacuum vessel fabricated as an electroformed, copper cavity wall. A variant of this concept involved joining four vane/cavity quadrants by electroforming a joint. These concepts are shown in Fig. 1.

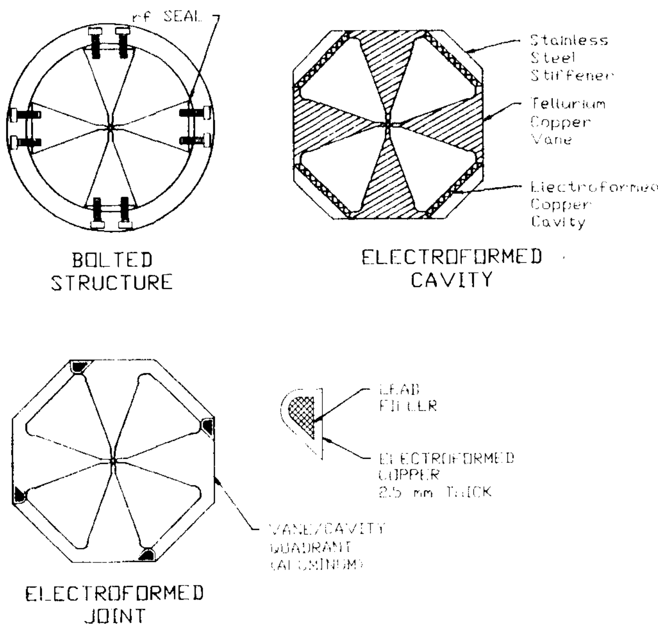

Fig. 1. BEAR RFQ options

Bolted Structure

The bolted structure is one of proven performance, dating back to the proof-of-principle (POP) RFQ.[7] The unit is simple to fabricate, and many of the fabrication tolerances can be relaxed because the vanes are adjustable. However, it is that adjustability that contributes to its major deficiencies. The vane adjustability basically necessitates mechanical rf joints. The possibility of using welded-in rf joints per the CERN 201-MHz RFQ[8] was deemed to be remote because of the small dimensions of the 425-MHz cavity. Experience with the POP had shown that a design with a significant amount of stored mechanical energy in adjustment mechanisms would likely not maintain vane-tip alignment over a period of months, particularly during any thermal cycling. For flight-qualified hardware, with shake tests, launch vibrations, plus launch and separation shock loads, the possibility of vane-tip misalignment was a major concern. This concept would also have many more vacuum joints than would the electroformed concepts. Lastly, given that the vanes should not carry structural loads, additional weight would be added to the tank structure.

Electroformed Cavity

The electroformed cavity has significant advantages over the bolted structure in that there are no longitudinal rf joints. The only rf and vacuum joints would be those associated with tuners and rf drive loops. Such an RFQ would be a monolithic copper structure with tellurium copper vanes and Type II (high-strength) copper cavity walls. Stainless steel flanges for the drive loops, rf pickup loops, and slug tuners would be joined to the cavity walls by electroformed copper. In addition, stainless steel stiffeners would be attached by electroformed copper. There were two identified disadvantages of this concept. The first was that the copper has a lower stiffness-to-weight ratio than aluminum and, therefore, for a structure subjected to equivalent dynamic loads, would weigh more. The second, now believed to have been an incorrect assumption, was that the lack of a capability for measurement of the rf field distribution before electroforming might result in a structure that could not be tuned. Experience with the BEAR RFQ has led to reconsideration of this assumption. Careful mechanical alignment of the vanes before electroforming does produce a structure that is tunable with slug tuners. This concept was considered a backup to the selected design, and a one-half length, full cross-section engineering model was fabricated.

Electroformed Joints

The concept that was selected and fabricated involved four copper-plated aluminum (Type 6061-T651) vane/cavity quadrants that were joined by electroforming. As in the case of the other electroformed concept, this one had no longitudinal rf or vacuum joints. Its main advantages were that measurement of the rf field distribution before electroforming was possible and the structure had the benefit of the stiffness-to-weight ratio of the aluminum. It was primarily on the basis of the provision to make pre-electroforming measurements of the rf field distribution that this concept was selected. A comparison of the concepts is summarized in Table II. The final design of the BEAR RFQ is shown in Fig. 2.

Table II. BEAR RFQ Concepts

Parameter	Bolted Structure	Electroformed Cavity	Electroformed Joints
Vacuum vessel	Separate or integral	Integral	Integral
Longitudinal rf joints	8	None	None
Vacuum joints	Yes	None	None
Mechanical joints	Yes	None	None
rf tuning stability	Poor	Excellent	Excellent
Premanufacturing rf tuning	No	No	Yes
Extension to CW	Poor	Good	Good

Spark Testing

A spark test cavity was constructed and tested with both bare aluminum as well as copper-plated (~0.01 mm thick) aluminum vane tips. The cavity walls were copper plated (~0.1 mm thick) in both cases. The 45-cm-long cavity was of rigid construction and the 15-cm-long vanes were not adjustable. The design relied upon the accuracy of manufacture for alignment of the vane tips. The cavity

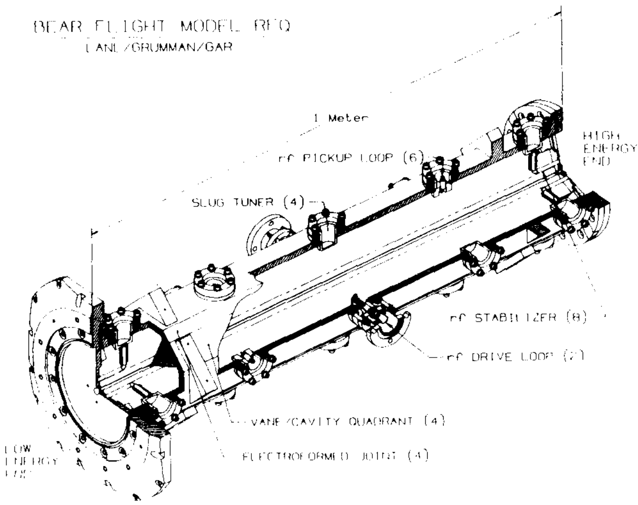

Fig. 2. BEAR flight model RFQ

was tested at Los Alamos, and in both configurations peak surface fields of 60 MV/m were achieved, corresponding to three times the Kilpatrick limit for 60-ms pulses at 5 Hz.

Cold Model RFQ Testing

A number of calculations using the code SUPERFISH were made to predict the frequency sensitivity and mechanical fabrication tolerances for the RFQ. A full-length, full cross-section, cold (low-power) model RFQ with unmodulated vane tips verified the SUPERFISH predictions of tuning sensitivity It was also used for experimental design of the end plates, for verifying the planned pre-electroforming alignment procedures, and for verifying the decision to use end stabilizers rather than vane coupling rings. These are similar in design to dipole suppressors[9] but are mounted directly to the end plates on both ends of the RFQ, and the capacitive gap is to the radial slug tuner.

The cold model RFQ consisted of four vane/cavity quadrants that were adjusted as rigid bodies on the basis of displacements and rotations determined by software[10] that was developed at Los Alamos for this purpose. The positions of tooling holes, whose locations relative to the vanes tips were known to a high degree of accuracy (0.008 mm), were used to determine the rigid body motions of the quadrants.

Engineering Model RFQ Testing

The one-half length, full cross-section engineering model RFQ with unmodulated vane tips was fabricated for the purpose of developing the electroforming technique and verifying the structural analysis performed by Grumman. This unit was fabricated jointly by Los Alamos and Grumman, with the electroforming being carried out by GAR. The alignment of the vane/cavity quadrants used software[10] that was developed as part of the cold model studies. The electroformed joint consisted of a 2.5-mm-thick layer of high-strength copper, a lead filler, and a 2.5-mm-thick layer of high-strength copper deposited over the lead. After completion of the electroforming, this unit was subjected to thermal testing as well as to the static equivalent of the flight dynamic loads. Comparison of pre- and post-test rf field distribution measurements (beadpulls) demonstrated that there had been no change in the vane tip alignment as a result of the thermal and structural loads.

Flight Model RFQ Fabrication

The vane/cavity quadrants were fabricated in the Grumman shops. The manufacture of RFQ vane tips had been a concern at Los Alamos since the POP unit. A technique that utilized a ball end mill was developed for the POP[11] and had been successful, but it had the fundamental deficiency of having zero cutting speed at the top of the vane tip, which resulted in a poor surface finish. A method developed at the Brookhaven National Laboratory[12] that utilizes a cylindrical tool bit overcomes this deficiency, but it was not suitable for the small size of the BEAR RFQ cavity. A variation of the POP method, which involved mounting the ball end mill at an angle relative to the axis of the vane, was developed for this project. This method resulted in an rms surface finish of better than 32 microinches on the entirety of the vane tip.

The experience gained in the electroforming of the engineering model RFQ allowed the flight model electroforming to be completed in 10 weeks. Throughout the electroforming process, witness tensile test and adhesion test coupons were electroformed and tested. In all cases both the strength of adhesion to the aluminum as well as the yield strength of the copper exceeded the design specifications. The original design called for the RFQ to be operated with a thin copper strike (~0.01 mm thick) on the vane tips with the cavity and the remainder of the vanes copper plated to a thickness of 0.08 mm. However, reaction with the plating solution caused the strike on the tips to peel in a few places; therefore, the strike was removed by an acid dip and the RFQ was operated with bare aluminum vane tips.

Testing of the Flight Model RFQ

After the completion of the electroforming by GAR, the RFQ was returned to the Grumman shops for final machining of the end flanges and penetrations for the tuners and rf drive loops. It was then delivered to Los Alamos for rf tuning. The assembled RFQ is shown in Fig. 2. Power is supplied to the cavity by two drive loops inserted into opposite cavities at midlength. Longitudinal rf field stabilization is achieved by eight end stabilizers mounted in the ports at the ends of the RFQ. These, along with ten slug tuners (six of which mount rf pickup loops) were used to tune the rf fields. After final adjustment of the tuners, the longitudinal field tilts were reduced to less than 2% and the dipole mode contributions were reduced to less than 2% of the quadrupole field strength.

The RFQ was installed on the BEAR test stand and rf conditioned to 120% of the design power level within 24 hours of operating time. The outgassing rate of the RFQ was 1.0×10^{-9} torr-liter/cm^2-s. The beam transport properties at 1 MeV were verified by testing with the prototype BEAR injector. The unit was then subjected to a random vibration shake test and to a shock test at levels corresponding to the ARIES specification.[3,4] Post-test rf field distribution measurements verified that there had been no change in the rf field distribution; i.e., vane-tip alignment had not changed as a result of operation on the test stand or because of the shake test. The measured performance parameters are given in Table III.

Present Status

At the present time the BEAR RFQ is installed on the BEAR test stand and is in use in the testing of the downstream components, such as the neutralizer and the flight beam diagnostics. In December of 1988 the entire rocket payload will be assembled and subjected to environmental and shock tests. The BEAR flight is scheduled for March 1989.

Table III. BEAR RFQ Performance Parameters

Parameter	Design Requirement	Achieved Value
Resonant frequency	425 ±0.5 MHz	425 ±0.5 MHz
rf fields	<5% dipole <5% tilt	<2% dipole <2% tilt
Cavity Q	6300	6330
Weight	55 kg	55 kg
Peak surface fields	37 MV/m 1.8 Kilpatrick	60 MV/m 3.0 Kilpatrick
Thermal loads	33° C temp rise	>33° C temp rise
Structural loads		
External pressure	117 000 Pa	Exceeded
Launch/separation	{ 5 g's lateral { 50 g's axial	Exceeded Tested
Random vibration	AFGL[a] ARIES spec	Tested
Material properties		
Copper yield str	≥ 1.47×10^8 Pa	≥ 1.69×10^8 Pa
Adhesion to Al	≥ 1.47×10^8 Pa	≥ 1.69×10^8 Pa
Outgassing rate torr-liter/cm^2-s	3.0×10^9	1.0×10^9

[a]Air Force Geophysics Laboratory.

Acknowledgment

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