THE BEAR ACCELERATOR*

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The Beam Experiments Aboard Rocket (BEAR) accelerator is the major component of an experiment designed to demonstrate the operation of an ion accelerator in space, and to characterize the exoatmospheric propagation of a neutral particle beam. It is the result of an extensive collaboration between Los Alamos National Laboratory and industrial partners, and is designed to produce a 10-mA (equivalent), 1-MeV neutral hydrogen beam in 50-µs pulses at 5 Hz. The accelerator consists of a 30-kV H^- injector, a 1-MeV radio frequency quadrupole, and two 425 MHz RF amplifiers, a gas-cell neutralizer, beam optics, vacuum system, diagnostics and controls. The design has been constrained by the need for a light-weight rugged system that would operate autonomously. The accelerator has undergone extensive environmental and operational testing in the laboratory in preparation for launch. The results of testing on the ground test stand are reported here.

INTRODUCTION

Neutral Particle Beams (NPB) are one of the directed energy technologies being developed for the Strategic Defense Initiative. The BEAR project[1] will be the first space test of the critical low-energy accelerator technology that is required to produce much higher energy NPBs. The technical issues addressed by the BEAR flight include the following:

a) Space operability of a particle accelerator
b) Spacecraft charging
c) Beam Propagation
d) Beam Avoidance
e) Spacecraft effluent/outgassing effects

There are three major sections on the spacecraft:

1) the Telemetry and Physics Section, which contains communications gear and a number of experimental packages to study spacecraft charging and the plasma environment around the payload;
2) the Accelerator Section, where the H^- beam is generated, accelerated and neutralized;
3) the Beam Diagnostics Section, which contains beam sensors, and visible and UV cameras for beam tracking.

This paper will deal almost exclusively with the Accelerator Section. Figure 1 shows the a cut-away view of the payload.

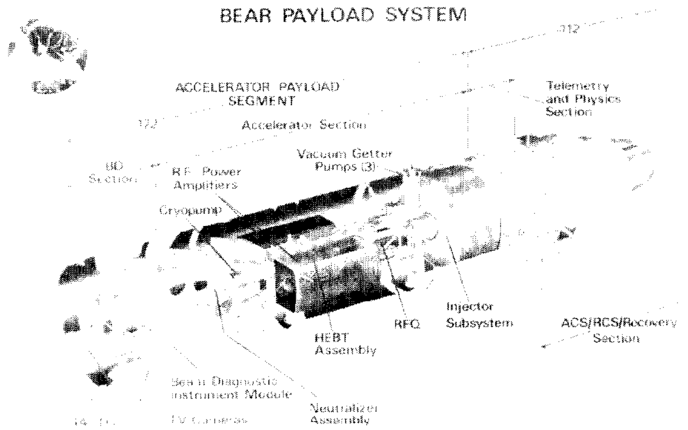

Figure 1. The BEAR payload as it will appear after booster separation.

ACCELERATOR

The main components of the BEAR accelerator are as follows: an H^- ion source with 30-kV extraction; a low-energy beam transport (LEBT) quadrupole system; a radio-frequency quadrupole (RFQ) and RF system which accelerates the beam to 1 MeV;[2,3] a high-energy beam transport (HEBT) system, which collimates the beam; and a gas neutralizer. A schematic diagram of the accelerator is shown in Figure 2. The general design parameters are given below:

OUTPUT BEAM PARAMETERS		
	Design	**Achieved**
Particle	**H°**	**H°**
Energy	**1 MeV**	**1 Mev**
Current	**10 mA**	**12 mA**
Pulse Length	**50 µs**	**50 µs**
Rep. Rate	**5 Hz**	**5 Hz**
Beam Diameter (rms)	**11 mm**	**10.0 mm**
Divergence (rms)	**1 mrad**	**0.9 mrad**
Brightness (rms)	**10^{12}**	**1.2×10^{12} A/(πm-rad)^2**

The accelerator conceptual and physics design were carried out by Los Alamos National Laboratory. The major industrial partners involved in the accelerator engineering design and fabrication are: McDonnell Douglas (injector, HEBT and vacuum system); Grumman (RFQ); and Westinghouse (RF amplifiers). The launch and flight environment required that all accelerator components be both rugged and light weight to a degree unnecessary for ground based-systems.[4,5] The payload capacity of the ARIES booster limited the accelerator weight to 1500 lbs. These constraints resulted in many novel approaches and techniques being developed to produce a working accelerator.

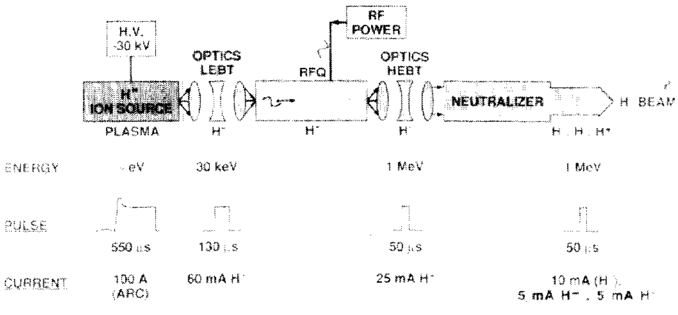

Figure 2. A schematic view of the accelerator.

The H^- ion source is a modified Penning-Dudnikov[6] source. Cesium is contained in a plenum inside the source in the form of $Cs_2Cr_2O_7$ mixed with Ti powder. The cesium is delivered to the plasma region by thermal decompositon on heating the anode. Both the anode and cathode are directly heated by internal heaters. The anode and cathode are a self aligning coaxial structure. The source housing is made of aluminum, the cathode is solid Molybdenum and the anode is stainless steel with a Molybdenum insert. Extraction of the H^- is at 30 kV across a single gap through a 4mm x 1mm slit.

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The LEBT, which focuses the H^- beam from the source to the RFQ, consists of a quadrupole triplet made of NdFeB permanent magnet blocks. The LEBT was designed to be a fixed focus system with no online adjustment of quadrupole strength or position. The match into the RFQ can be adjusted by varying the extraction voltage from the ion source, and by controlling the plasma neutralization in the LEBT region through the addition of xenon gas.[6] This has resulted in a less than ideal but stable and reliable match into the RFQ.

The vacuum system for the source/LEBT region consists of two specially modified SORB-AC™ getter pumps, which have an effective pumping speed of 600 l/s for hydrogen and zero for xenon. The only xenon pumping from the LEBT is 0.6 l/s through the RFQ orifice to a 2000 l/s helium cryo-condensation pump located between the HEBT and the neutralizer. This provides a means of allowing a high partial pressure of xenon and a low partial pressure of hydrogen between the source and the RFQ, which is desirable for optimum operation. The beam passes through the cryopump, which is a coaxial, hollow Dewar containing super-critical helium, with one of the vacuum walls being the condensation surface. The cryopump will pump all gases except H_2, He and Ne. Additional pumping is provided by a getter pump attached to the HEBT housing. Little electrical power is required by the vacuum system. For example, adequate pumping by the getter pumps requires less than 6 watts each to maintain a pumping temperature of 70°C.

The RFQ cavity, which weighs only 55 kg, is an electroformed aluminum-copper structure,[3] with no RF or mechanical joints. The cavity walls are copper plated on aluminum, with the vane tips being bare aluminum, and a minimum aperture diameter of 2.4 mm. The design intervane voltage is 44 kV (1.8 Kp). It is designed to accelerate 25 mA of H^- with a copper power requirement of 70 kW and 1 kW per mA of accelerated beam. The low duty factor of 0.025%, and frequency control of the RF amplifier, precluded the need for cooling.

RF power[7,8] is provided by two solid-state amplifiers, each capable of producing 60 kW pulses, 60-μs long, at 5 Hz with a frequency of 425 ± 0.5 MHz. The resonant frequency of the RFQ is automatically tracked to within 0.02 MHz. The BEAR accelerator is the first to be operated exclusively with solid-state amplifiers.

The HEBT is a quadrupole triplet similar to the LEBT. It collimates the diverging beam from the RFQ, and is designed to give a divergence of 1 mrad rms beam diameter of 11 mm rms.

The neutralizer is designed to be approximately 50% efficient. Xenon gas is the neutralizing agent which is injected into the beamline via a piezoelectric pulse valve. The efficiency of the neutralizer and the net current produced can be varied by adjusting the amount of gas injected. Typically the output beam is approximately 50% H°, and 25% each of H^- and H^+.

After passing through the neutralizer the beam exits the spacecraft through a gate valve. Beyond this is a shadow wire scanner that measures the beam profile and divergence.

PERFORMANCE

Testing of accelerator components on the ground test-stand (Figure 3) was completed in December 1988. Details of the RFQ tuning and performance have been published previously.[2,3]

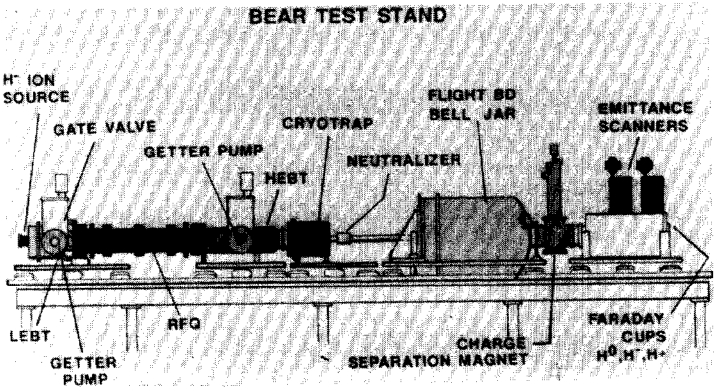

Figure 3. The BEAR ground test stand. A scale is provided by the RFQ which is 1 m long.

Typical prototype injector current is 55 mA (with Xe added), of which approximately 50% was matched into the RFQ. The injector has produced H^- currents in excess of 70 mA, but is not normally operated at this level. Because of the fixed nature of the LEBT optics, external steering magnets were added to the LEBT vacuum chamber to correct for accumulated misalignments and to steer the beam centroid by ~ 0.5 mm at the RFQ entrance. The small (2.4mm) aperture of the RFQ made this adjustment critical to the successful performance of the accelerator. The RFQ output current was ~ 16 mA without the compensation magnets and 24-27 mA with the magnets. It was found that the best transverse match of the beam into the RFQ occurred at an extraction voltage of 33-34 kV. The transmission of the RFQ is much more sensitive to the transverse rather than to the longitudinal match.

The RFQ output beam has an rms normalized transverse emittance of 0.014 πcm-mrad at a current of 25 mA.[9] The beam energy was measured to be 1 MeV, using a magnetic spectrometer.[3] A complete energy spectrum is shown in Figure 4. The transmission, energy spectrum and current agree well with PARMTEC simulation results.[10,11] At nominal RF field levels the intervane voltage was deduced to be 48 ± 3 kV (2 Kp) from the measured X-ray spectrum,[12] which is a little higher than the design value of 44 kV. This discrepancy explains why the energy spectrum is slightly broader than the design estimate.

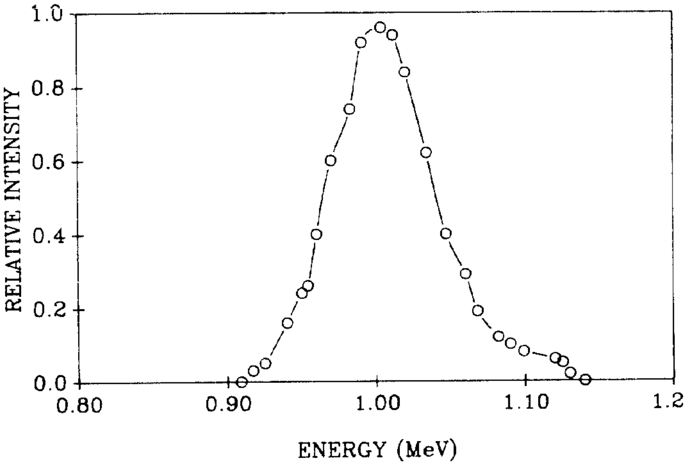

Figure 4. Measured energy spectrum of the H^- beam after exiting the RFQ.

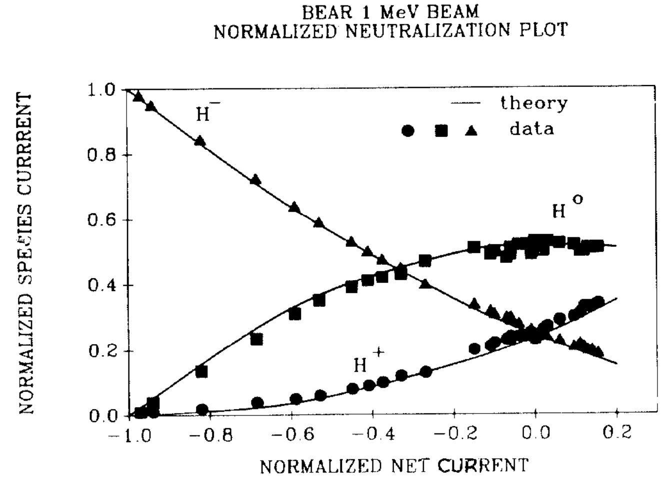

Figure 5. Comparison of the neutralizer performance with theory. Normalized currents are calculated by dividing the currents exiting the neutralizer by the total H^- current entering the neutralizer.

The HEBT output current was 25 mA with a beam diameter of 9 mm (rms), and a divergence of ± 0.85 mrad (rms).

A dipole separation magnet was placed beyond the neutralizer which directed the H^+, H°, H^- beams to three separate magnetically and electrostatically suppressed Faraday cups. The neutral current was measured by stripping the H° to H^+ with a 1.5μ Ni foil and then measuring the H^+ current. The neutralizer output performance is summarized in Figure 5. Agreement between theory and experiment was excellent. At optimum operation the accelerator produced a 12mA equivalent neutral-hydrogen beam, with near zero net current. The net current and species currents are varied by adjusting the quantity of Xe injected into the neutralizer. The normalized rms brightness of the neutral beam is 1.2×10^{12} A/(π m-rad).[2] This makes the BEAR accelerator beam the worlds brightest neutral beam at this current level. A phase space plot of the neutral beam is shown in Figure 6. The neutral beam diameter is 10 mm (rms), and the divergence is ± 0.95 mrad (rms). These measurements were made 2.5 m downstream of the neutralizer.

At the time of writing (March 1989) tests of the accelerator in the final flight configuration are beginning.

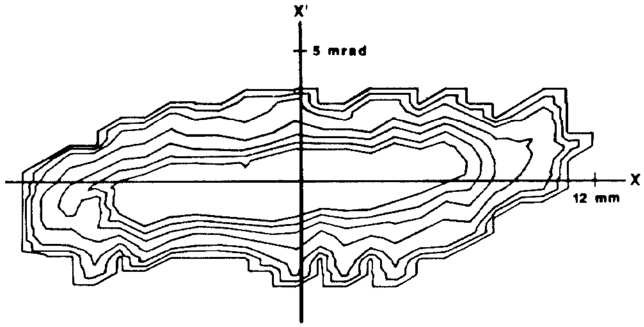

Figure 6. Phase space contour plot of the neutral beam. The contour levels are 0.01, 0.05, 0.1, 0.2, 0.3, 0.4, 0.5 of peak signal.

FLIGHT

The BEAR payload will be launched from White Sands Missile Range in New Mexico. The flight will be suborbital with an apogee of ≈ 200 km and a total flight time of approximately 500 s. (Figure 7). During flight the accelerator will be function autonomously. There will be a real-time down link which will give full information on the accelerator performance at the rate of 63 kbytes/pulse. There will be ≈ 1200 beam pulses during the flight.

At launch the ion source arc will be operating. The high-voltage extraction and RF power will be turned on after the payload has separated from the booster. A gate valve will open to allow the beam to exit the accelerator and pass through the Beam Diagnostics section to space. At apogee the free-space pressure will be approximately 10^{-7} torr. On board TV cameras will allow the beam to be tracked as it travels several kilometers from the spacecraft. The residual charged H^+ and H^- components will not be separated from the neutral beam, except ultimately by the earth's magnetic field. For most of the flight the net current exiting the spacecraft will be approximately zero. After the payload passes apogee the beam will be under-neutralized and later over-neutralized to produce net negative and positive currents, which will allow information on spacecraft charging to be gathered. The composition and divergence of the beam exiting the payload will be determined from TV camera, wire scanner and current toroid data.

Many of the techniques developed for BEAR will have applications for ground based accelerators where weight, size, and reliability are important. These will be detailed in future publications.

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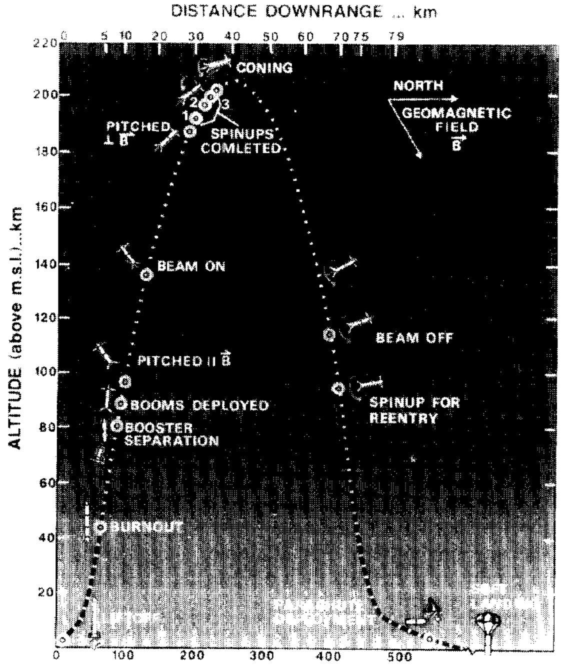

Figure 7. Mission Flight Profile

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