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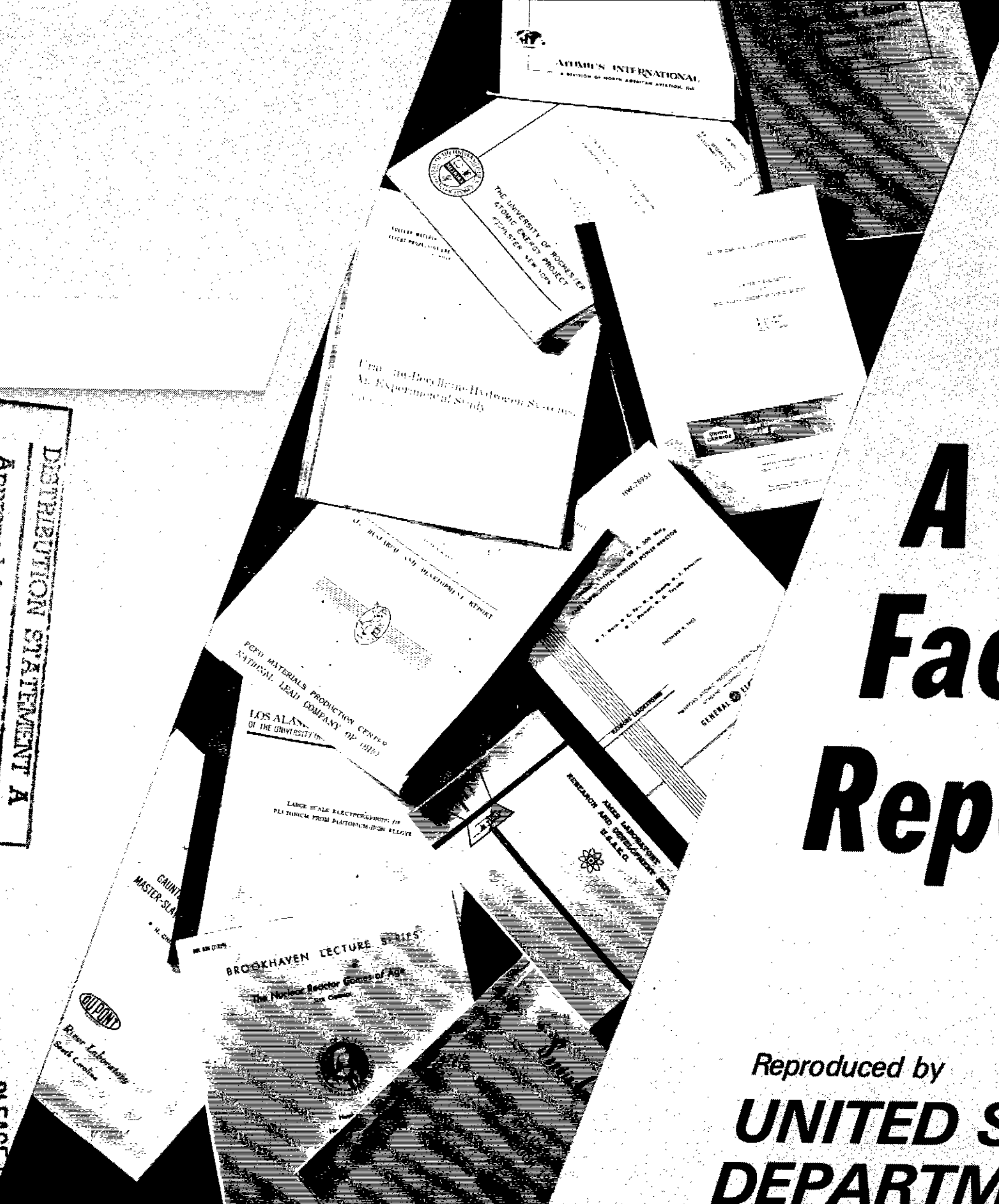

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A LINEAR ACCELERATOR IN SPACE - THE BEAM EXPERIMENT ABOARD ROCKET

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Abstract

On July 13, 1989 the BEAM experiment Aboard Rocket (BEAR) linear accelerator was successfully launched and operated in space. The flight demonstrated that a neutral hydrogen beam could be successfully propagated in an exoatmospheric environment. The accelerator, which was the result of an extensive collaboration between Los Alamos National Laboratory and industrial partners, was designed to produce a 10 mA (equivalent), 1 MeV neutral hydrogen beam in 50 µs pulses at 5 Hz. The major components were a 30 kev H^- injector a 1 MeV radio frequency quadrupole, two 425 Mhz RF amplifiers, a gas cell neutralizer, beam optics, vacuum system and controls. The design was strongly constrained by the need for a light-weight rugged system that would survive the rigors of launch and operate autonomously. Following the flight the accelerator was recovered and operated again on the laboratory.

Introduction

Neutral particle beam (NPB) technology is considered to be one of the most promising concepts under development for the United States Strategic Defense Initiative. The BEAR project was the first test in space of the critical low energy accelerator technology that will be built upon in future systems. The principal aims of the project were to successfully operate a particle accelerator in space and to study the propagation of a neutral hydrogen beam, and to examine the effects of spacecraft charging.

The three main sections of the spacecraft are (figure 1): a) the Telemetry and Physics section, containing communications equipment and a number of experimental packages to study spacecraft charging and the nearby plasma environment; b) the Accelerator section, where the H^- beam is generated accelerated and neutralized; c) the Beam Diagnostics section, which contains beam sensors, and cameras for beam tracking.

Accelerator

A conceptual view of the accelerator in shown in figure 2. The main components were 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 to accelerate the beam to 1 MeV, a high-energy beam transport (HEBT) system to collimate the beam; and a xenon gas cell neutralizer. The general design parameters are given in table 1.

The accelerator conceptual and physics design were carried out by Los Alamos National Laboratory. The major industrial partners involved in the accelerator engineering were: McDonnell Douglas (injector, HEBT and vacuum system); Grumman Aerospace (RFQ); and Westinghouse Electric (RF amplifiers).

The launch and flight environments required that all accelerator components be both rugged and light weight to a

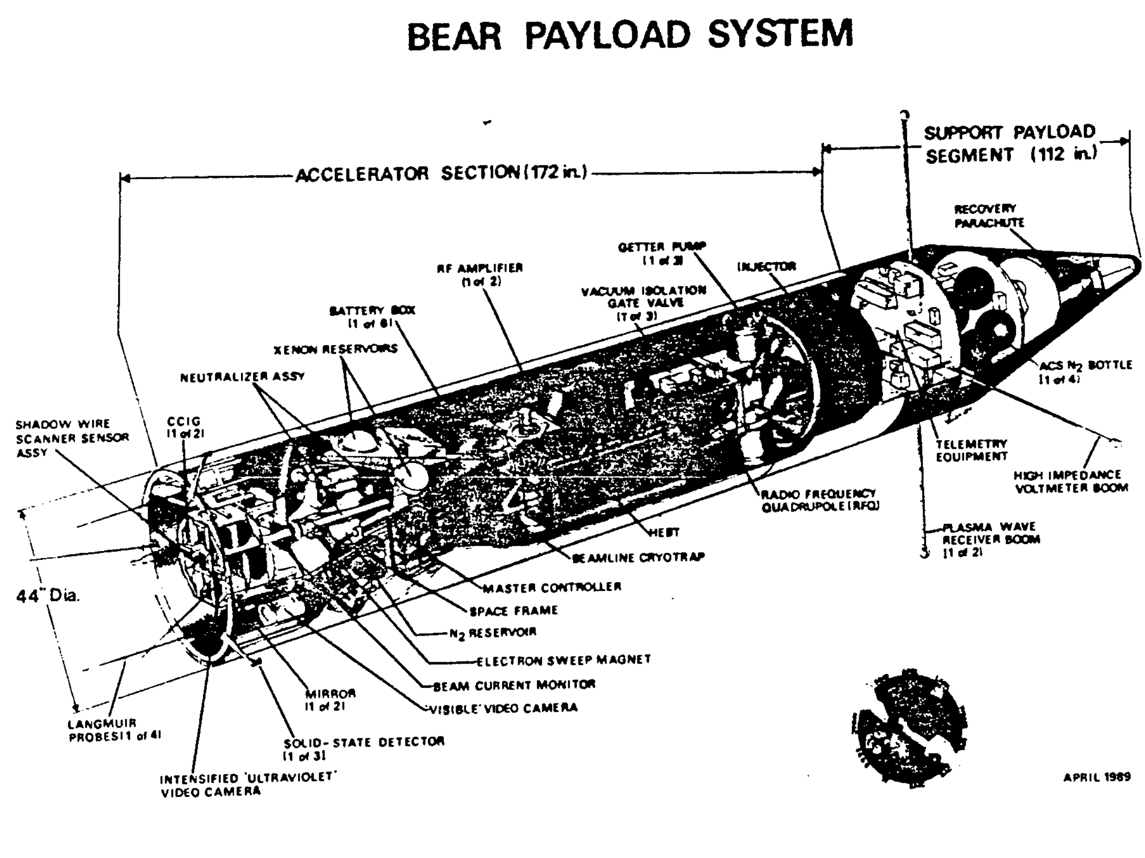

Fig. 1. The BEAR payload after booster separation.

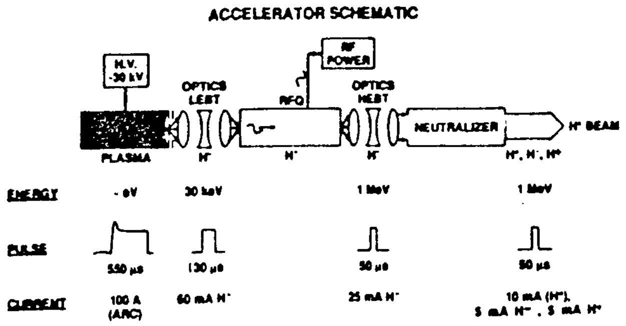

Fig. 2. A conceptual view of the accelerator.

Table 1. Bear Accelerator Performance.

	Design 1985	Test Stand** (10/88)	Payload (3/89)	PAD T-5 min	Flight
H^- Extraction Voltage (kV)	30	34	35	35	35
H^- Current from LEBT (mA)	40	60	55	54	40
Emittance at RFQ X (π cm-mrad)	0.007	0.007	-	-	-
(RMS) Y (π cm-mrad)	0.014	0.015	-	-	-
RMS Beam Diam into RFQ (mm)	1.5	2	-	-	-
Current out of RFQ (mA)	26	27	20	17	13
Rep Rate (Hz)	5	5	5	5	5
Beam Pulse from RFQ (µs)	50	50	50	50	50
Energy out of RFQ (MeV)	1	1	-	-	-
Emittance out of RFQ (π-cm-mrad)	0.011	0.012	-	-	-
Current out of HEBT (mA)	23	25	18	15	11
H^0 Particle Current (mA)	10	12*	7	-	5
Beam Divergence (mrad, rms)	±1	±1	±1	-	±1
Beam Diameter (mm, rms)	11	10	10	-	10
H^0 Beam Brightness (A/(π mrad)^2, rms)	3 x 10^{12}	1.2 x 10^{12}	0.7 x 10^{12}	-	0.5 x 10^{12}

–Not measured in flight configuration
*Without shadow wire
**Prototype injector

degree unnecessary for ground based systems. The payload capacity of the Aries booster limited the accelerator weight to 700 kg.

The H^- ion source is a modified Penning-Dudnikov source[1]. 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 decomposition on heating the anode and cathode. The anode and cathode are a self aligning coaxial structure. The source housing is made of aluminum, the cathode solid molybdenum, and the anode is stainless steel with a molybdenum insert. Hydrogen gas is pulsed into the plasma region by a piezoelectric valve at in 350 µs long pulses at 5 Hz. The average flow rate is 0.04 torr l/s. Extraction of the H^- at 30 kV across a single gap through a 4 x 1 mm^2 slit.

The LEBT, which focuses the H^- beam from the source to the RFQ, consists of a quadrupole triplet made of NdFeB permanent magnet blocks. This was designed to be a fixed focus system with no on-line adjustment of quadrupole strength or position. The match in to the RFQ is 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[1]. This has resulted in a less than ideal but stable and reliable match in to the RFQ.[2,3]

The vacuum system for the source/LEBT region consists of two specially modified SORB-AC^{tm}[4] 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, 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. All gases except H_2, He and Ne are pumped by the cryopump. The cryopump is assisted by a getter pump attached to the HEBT housing. Little electrical power is required by the vacuum system. For example, the getter pumps require less than 6 watts each to maintain a pumping temperature of 80°C.

The RFQ cavity, which weighs only 55 kg, is an electroformed aluminum-copper structure[5] with no RF or mechanical joints. The cavity walls are copper plated on aluminum, with the vane tips being bare aluminum. The minimum aperture diameter is 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%, along with frequency control of the RF amplifier, precluded the need for cooling.

The RF power[6, 7] 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, which eliminates the need for temperature stabilization. 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 beam from the RFQ, giving a divergence of 1 mrad rms and a 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 by a piezo-electric valve. The efficiency of the neutralizer and the net current produced can be varied by adjusting the amount of gas injected. For normal operation the one obtains approximately 50% H°, and 25% each of H^- and H^+.

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

Details of the performance of the accelerator during ground testing have been presented elsewhere,[8] and are summarized in table 1. The accelerator is shown in figure 3 in its flight configuration with the payload skins removed.

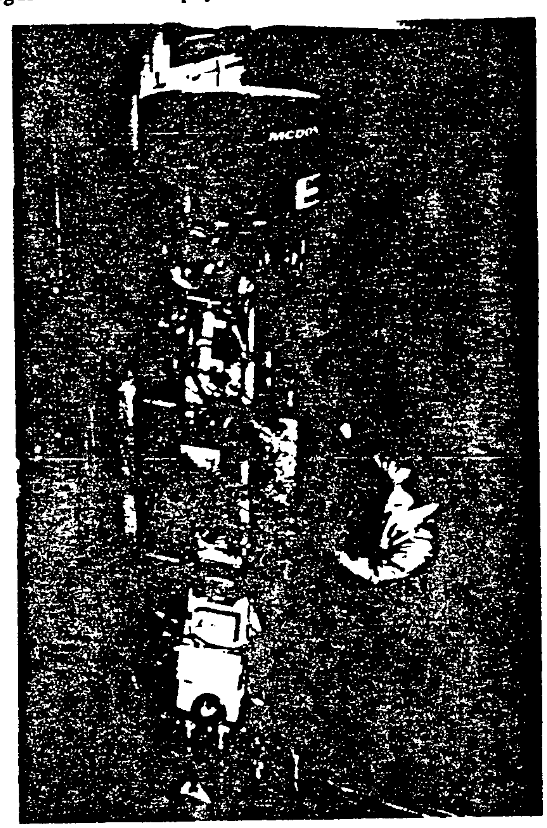

Fig. 3. The accelerator in its flight configuration. The injector is at the top of the picture.

Flight

The BEAR accelerator was launched into space on July 13, 1989. Details of the pre-programed accelerator and payload activities are given in table 2, and the nominal flight profile is shown in figure 4. The accelerator systems were maintained in a fully operational state until 155 seconds before launch. At this time the injector extraction high voltage and the RF power to the RFQ were switched off. The H^- ion source remained on through launch. By T+127 seconds all accelerator systems were operational. The beamline exit valve opened at T+128 s and the beam was injected into space. The neutralizer had been programed to produce a slightly net negative current of approximately 1 mA with individual species currents of $H^+ \approx 2$ mA, $H^O \approx 5$ mA and $H^- \approx 3$ mA. During the two periods when the neutralizer was switched off a net negative current of ~10 mA of H^- was emitted. Late in the flight excess xenon was injected into the beam producing a net positive beam current of + 1.4 mA. The three issues that were addressed by the BEAR flight were answered as follows:

Table 2. Bear Flight Timeline

Time (seconds)	Event
T = 0	Launch (Ion source on)
T + 85	Booster separation
T + 91	Extractor high voltage on
T + 105	RF system on Beam out of RFQ
T + 127	Neutralizer on
T + 128	Beamline exit gate valve open Beam injected into space (Net current -0.8 mA)
T + 260 - 270 and 322 - 332	Neutralizer off (Net current -10 mA)
T + 360 - 390	Overneutralize (Net current + 1.4 mA)
T + 390	Beamline gatevalve closed Accelerator off

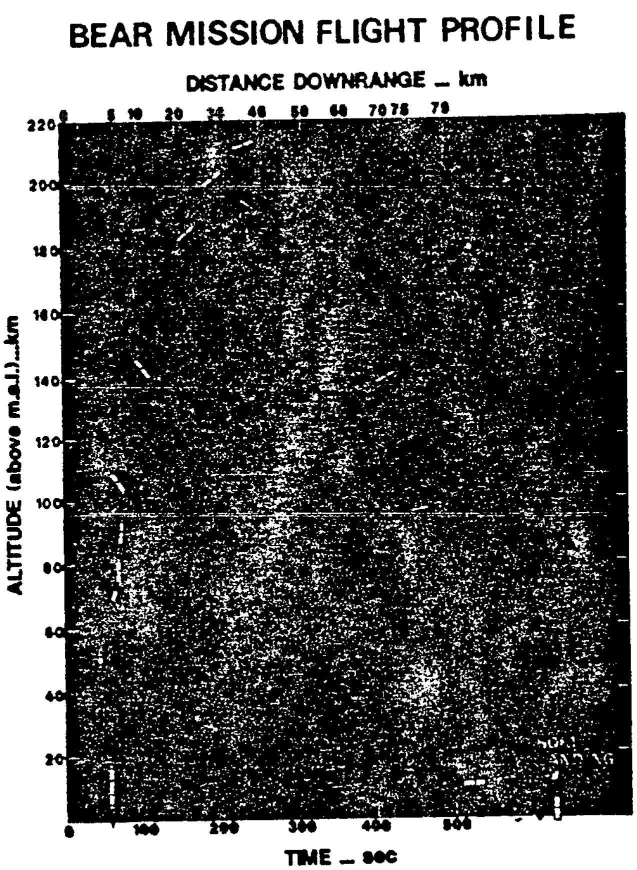

Fig. 4. Mission flight profile.

Accelerator performance: Figure 5 shows the beam divergence as the beam left the payload for various ground tests and for the flight. The divergence of 1.05 mrad during flight was comparable to the best results obtained on the ground.

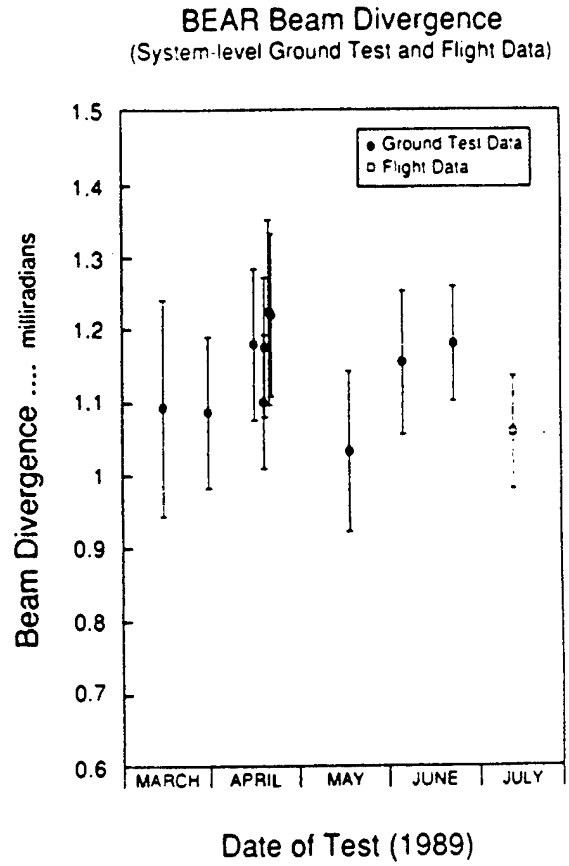

Fig. 5. Beam divergence history of the neutral beam.

NPB propagation: Figure 6 shows the beam propagating in space as seen by one of the onboard cameras. There was no evidence of any unexpected beam behavior such as

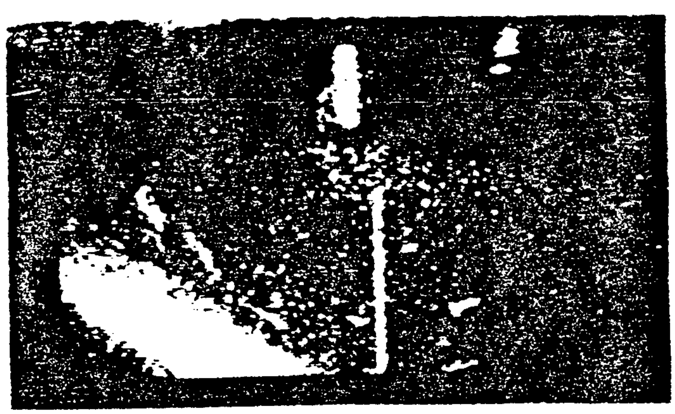

Fig. 6. Neutral beam (vertical line) propagating away from the spacecraft as viewed from an onboard wide-angle camera whose line of sight is almost parallel to the beam. The beam exits the accelerator at the bottom of the picture.