Space Plasma Physics Results from Spacelab 1

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The Spacelab 1 payload carried several instrument systems which together investigated a number of space plasma phenomena. These experiments used the Space Shuttle Orbiter as a platform for making controlled particle-beam, plasma and neutral gas inputs to the ionosphere and magnetosphere and for observing the outputs produced. Spacelab 1 space-plasma investigations included the Space Experiments with Particle Accelerators (SEPAC), Phenomena Induced by Charged Particle Beams (PICPAB), Atmospheric Emissions Photometric Imaging (AEPI), and the Low Energy Electron Spectrometer and Magnetometer. Among the major phenomena investigated both singly and jointly by these experiments are vehicle charging and neutralization, beam-plasma and wave-particle interactions, anomalous ionization phenomena produced by neutral-gas and plasma injections and several phenomena induced by modulated particle beam injections.

Introduction

THE Spacelab 1 payload was launced aboard the STS-9 Space Shuttle on November 28, 1983, into an orbit with a 57 deg inclination at an altitude of 240 km. Due to resource consumption that was lower than expected, the mission was extended by one day, with landing on December 8. A multidisciplinary international mission, Spacelab 1 accommodated some 74 experiments, obtaining significant new scientific results in such diverse fields as biology, astronomy, and materials science. One of the important fields of study for Spacelab 1 was space plasma physics, a well-developed discipline of space science which has advanced primarily through passive measurements from free-flying spacecraft, beginning with the first earth-orbiting satellites.

Over the past decade, a comprehensive plan was developed for utilizing the large resource capabilities of the Space Shuttle Orbiter in a program of active experimentation in near-earth space plasma research. The term active experimentation applies to the use of artificial inputs to the space plasma environment, which act as tracers of naturally occurring phenomena, or as stimulants of phenomena which otherwise would not occur at a particular time and place. This latter approach is closely akin to scientific experiments conducted in a traditional laboratory setting. It promises to be of great value in separating cause and effect in phenomena that tend to occur together naturally at low altitudes and in producing analogs of plasma phenomena that occur naturally but in remote parts of the magnetosphere, solar system, or universe. This promise began to be realized with Spacelab 1.

Among the many Spacelab 1 instrument systems, the following were developed specifically for space plasma investigations: Space Experiments with Particle Accelerators (SEPAC)[1]; Phenomena Induced by Charged Particle Beams (PICPAB)[2]; Atmospheric Emissions Photometric Imaging (AEPI)[3]; and the Low Energy Electron Spectrometer and Magnetometer (1ES019).[4] These systems were used both singly and in carefully planned, coordinated investigations of space plasmas. Several classes of plasma phenomena were investigated on Spacelab 1, including vehicle charging and neutralization, beam-plasma and wave-particle interactions, anomalous ionization, and beam-modulation effects. In the following sections, each of these classes of investigations is reviewed, followed by a summary of planned future Spacelab experiments in this discipline.

Presented as Paper 85-0150 at the AIAA 23rd Aerospace Sciences Meeting, Reno, NV, Jan. 14-17,1985; submitted April 29,1985; revision received Aug. 7,1985.

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Vehicle Charging and Neutralization

As a practical matter, the processes leading to the buildup of electric potential on the Orbiter, and its neutralization, have to be understood and controlled if the ultimate capabilities of charged-particle beam injection experiments are to be realized. Thus, one of the primary goals of the SEPAC experiment was to investigate these processes while increasing electron beam energy and current in steps. Beam current will ultimately be limited by the conductive collecting area for the return current of ambient electrons and the density of the ambient electrons. Most of the Orbiter surface is covered with insulating heat-resistant tiles, and the pallet-mounted instruments are generally covered by thermal insulation, leaving only about 60 m^2 of conductive area at the three main engine nozzles. Although it was impractical to increase the conductive area significantly on Spacelab 1, SEPAC did make provisions for increasing temporarily the ambient electron density at the time of electron beam ejections.

A summary of SEPAC hardware systems, along with brief capability statements, appears in Table 1. The potential of the Orbiter (at the DGP) relative to the surrounding plasma could be sensed by the plasma probes (floating probe and Langmuir probe) and by the energetic electron analyzer. In addition, the MTV provided qualitative data on charging effects as the returning electrons, accelerated by the vehicle potential, produced illumination of the shuttle bay as they collided with mechanical surfaces and with the ambient neutral gas. By pulsing the MPD at EBA firings, an additional source of neutralizing electrons could be briefly added to the ambient plasma. Similarly, firing the EBA through the neutral gas cloud ejected from the NGP produced secondary electrons that could return to the Orbiter and assist in charge neutralization.

SEPAC performed EBA firings in four different experiment sequences (functional objectives or FO's), all performed in darkness but at different Orbiter orientations, and one of which included MPD firings. It was found that charging was minimized significantly when the conductive engine nozzles were directed near the vehicle ram direction.[5] A saturation effect was observed in the charging measurements, as illustrated in Fig. 1. That is, at low power levels the charging potential was roughly proportional to beam current, while at currents above 100 mA charging to approximately the beam voltage was commonly observed. In Fig. 1, measurements below 10 V were made with the Langmuir probe, while measurements above 1000 V were derived from the energetic electron analyzer data. The vertical bars between 10 and 100 V are data from the floating probe, which had higher uncertainty levels because of plasma sheath effects.[1]

As shown in Fig. 2, strong illumination of the Spacelab 1 pallet was also observed by the SEPAC MTV as beam power

Table 1 **SEPAC hardware system**

Electron Beam Accelerator (EBA)	≤7.5 keV, ≤ 1.6A, pulse duration 10 ms-5 s.
Magneto-Plasma-Dynamic Arcjet (MPD)	Argon plasma, 2 kJ in 1-ms pulse.
Neutral Gas Plume (NGP)	N_2 gas, 10^{23} molecules in 100-ms pulse.
Monitor Television Camera (MTV)	Low-light-level TV.
Diagnostic Package (DGP)	Plasma wave detectors, photometer, plasma probes, energetic electron detector, pressure gauge.
Control and Display (CD)	Interface unit, dedicated experiment processor, and control panel.

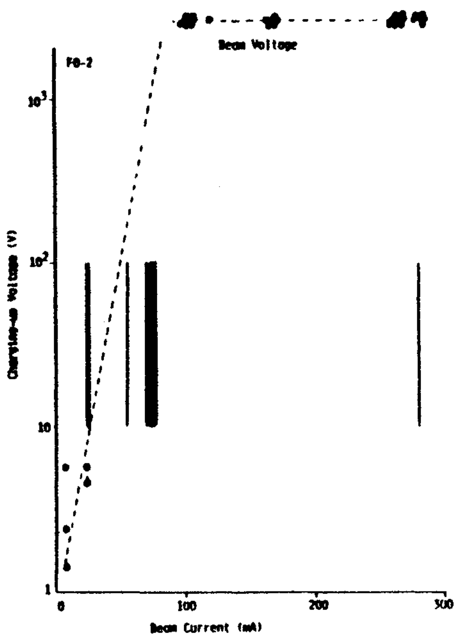

Fig. 1 Shuttle charging potential vs electron beam current.

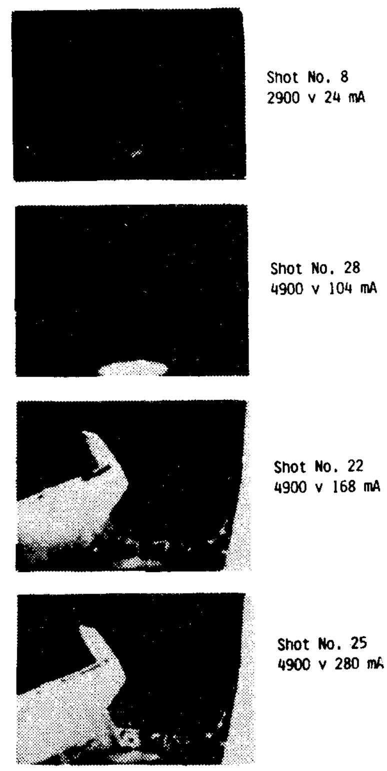

Fig. 2 Illumination of pallet instruments during electron beam ejection.

and charging effects increased. At a low beam current of 24 mA, the top panel of Fig. 2 shows that the only illumination present was from the heated EBA cathode. However, as beam power increased above 100 mA, strong illumination occurred. Comparison of Figs. 1 and 2, along with pre-launch beam-firing tests in which similar illumination occurred, leads to the conclusion that the pallet illumination was also caused by Shuttle charging as the positive potential assumed by the Orbiter accelerated ambient electrons onto the pallet surfaces. Electron impact with the surrounding neutral gas may also have contributed to the illumination.

As mentioned above, an attempt was made to neutralize the vehicle charging potential by injecting an MPD plasma plume simultaneously with the EBA electron beam.[6] This approach proved to be very successful for temporary neutralization. In a typical case, the MPD firing would quickly reduce the charging potential to zero and maintain complete neutralization for 6 to 20 ms, after which a return to the original charging level would occur within another 6 to 100 ms. The time for which neutralization was maintained varied inversely with beam current in agreement with pre-launch chamber tests, as shown in Fig. 3. This effect is expected from the limited quantity of plasma in the MPD plume. However, the time for recovery to the pre-MPD-pulse charging level shows no clear dependence on beam current, instead being roughly proportional to the charging potential, as determined from the floating-probe data (see Fig. 4). A simple model of the MPD plasma-plume expansion has shown that the recovery times shown in Fig. 4 are comparable to the time required for the MPD plasma to expand to near the background plasma density. These rather long times also indicate that the MPD is effective in maintaining vehicle neutralization even when the ejected plasma plume has drifted several hundred meters away from the Orbiter.[6]

The PICPAB experiment[2] also made investigations of vehicle charging using pulsed and modulated electron beams with currents from 10 mA to 100 mA at a beam energy of 8 keV. In a joint PICPAB/SEPAC experiment, the neutralization effects of the SEPAC NGP were investigated for 10 mA PICPAB electron beams. Contrary to expectations, the neutral gas cloud was not effective in neutralizing the rather low (10 V) charging potentials produced by the 10 mA beam. It has been suggested[6] that an ionization cascade effect, which results when the charging potential exceeds the neutral-gas ionization potential, must be initiated before effective neutralization can be attained. Pre-launch laboratory tests, in which neutralization did occur for higher charging potentials, are in agreement with this suggestion.

Beam-Plasma and Wave-Particle Interactions

In the Spacelab 1 space-plasma data there are many indications that significant beam-plasma and wave-particle interactions were triggered by the SEPAC and PICPAB beam ejections. For example, the rapid onset of pallet illumination for SEPAC beam currents above 100 mA was accompanied by a transition of the collimated electron beam to a plasma discharge, as seen in enhanced MTV images. Other such indications include the observation of a return flux of electrons with a broad energy spectrum extending up to four times the primary beam energy, along with electrostatic and electromagnetic wave emissions at harmonics of the electron

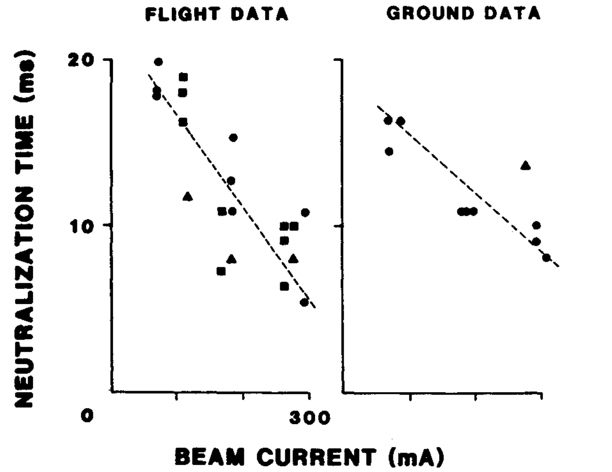

Fig. 3 Dependence of the duration of vehicle charge neutralization by the MPD on EBA beam current for Spacelab 1 and for pre-launch tests. Circles are for beam voltages of 3 kV, triangles for 4 kV, and squares for 5 kV.

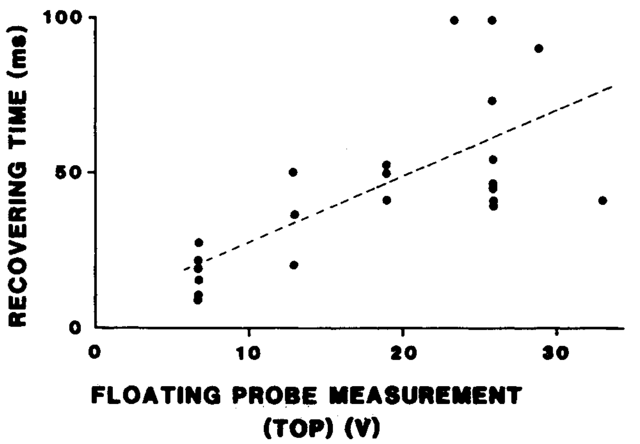

Fig. 4 Dependence of vehicle charge recovery time on the floating-probe voltage, showing more effective neutralization for higher charging potentials.

gyrofrequency and at the plasma and upper hybrid frequencies.[1,2,4,7]

In attempting to identify the modes of interaction between the Spacelab 1 electron beams and the plasma surrounding the Shuttle Orbiter, attention has first been directed toward the well-known beam-plasma discharge (BPD), which has been observed many times in the laboratory and possibly in rocket-borne electron beam experiments. In fact, the SEPAC beam perveance ($IV^{3/2}$) near the pallet-illumination threshold point was about 3×10^{-7}, or about a factor of 20 higher than the critical beam perveance for BPD ignition that was derived empirically for several sounding-rocket beam experiments.[8] However, the Spacelab 1 data are still somewhat ambiguous with respect to BPD ignition because of the accompanying intense charging effects, which themselves are expected to result in ionization-cascade effects as ambient electrons are accelerated toward the pallet.

Measurements of the energy and angular distributions of the return electron flux were obtained by a unique electron spectrometer,[4] which could electronically sweep through nearly all pitch angles and azimuths in the upper hemisphere of the Orbiter while stepping over a wide energy range from 100 to 12,400 eV. Since Spacelab 1 did not carry any deployable instruments, particle measurements could only be made in the backscatter zone of the artificial electron beams.[4] Nevertheless, several distinct signatures of electron acceleration and trapping near the Orbiter could be observed. An example of this type of data is shown in Fig. 5. The three middle traces in Fig. 5 are plots of detector count rates for three different azimuths about the magnetic field direction and for equal magnetic pitch angles. The pitch angles and energies of the detected electrons are plotted vs time in the top and bottom traces, respectively, with the logarithmic energy scale also noted along the bottom horizontal axis. The format in Fig. 5 alternates between longer periods of energy stepping at constant pitch angle and shorter periods of pitch-angle stepping at constant energy. Comparing the energy spectra measured at 80 and 0 deg, it is clear that at 80 deg pitch angle, significant electron fluxes extend up to the maximum sampled energy of 12,500 eV, while at 0 deg the count rate drops to near zero at approximately the beam energy of 4.9 keV. Other features of the electron spectra at 0 and 80 deg are qualitatively equal except for the large peak near 300 eV at 80 deg pitch angle. Of

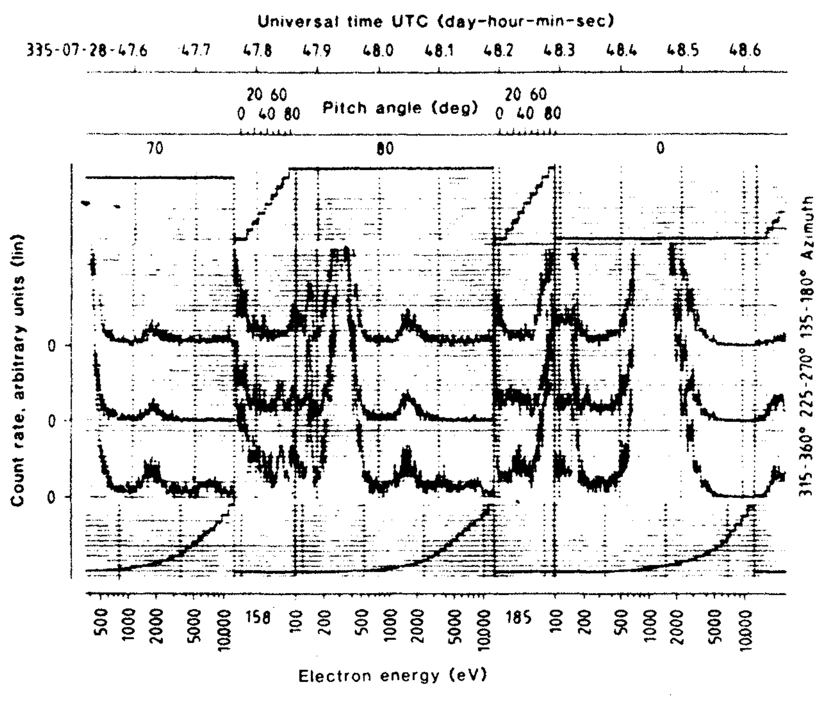

Fig. 5 Quick-look data from the Low Energy Electron Spectrometer[4] during a 5-s SEPAC electron beam emission at 4.9 keV and 300 mA beginning at 335:07:28: 45.220 UT. The five traces, beginning at the top, are electron pitch angle, electron count rate at three different azimuths about the magnetic-field direction, and electron energy.[4]

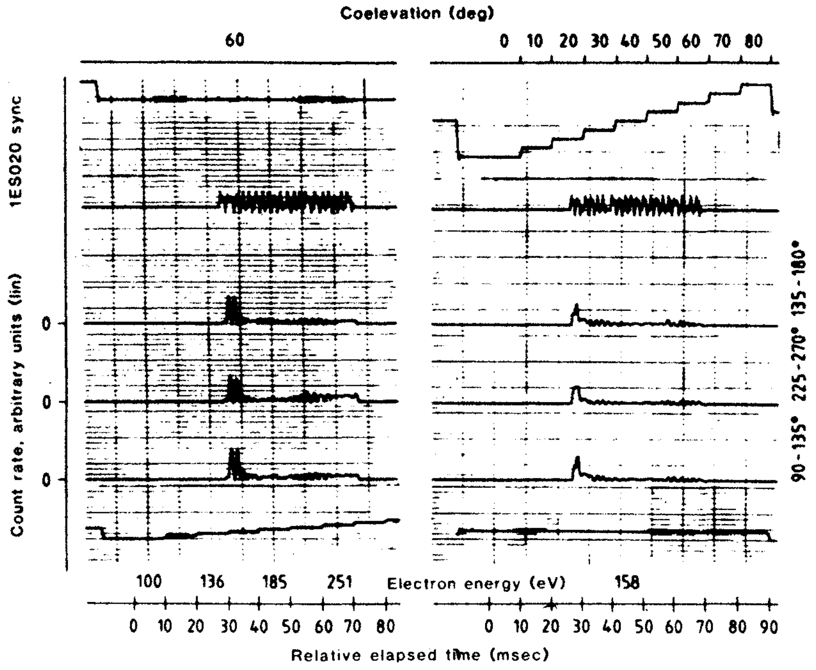

Fig. 6 Response of the Low Energy Electron Spectrometer to the 500-Hz modulation of the PICPAB 8-keV electron beam. The top trace is the coelevation of the measured electrons relative to the pallet normal, while the azimuths of the three electron channels are listed at the right. The second trace is the PICPAB synchronization signal, which was sent directly to the electron spectrometer showing the beam modulation. The next three traces are the count rates of three of the electron azimuthal channels.[4]

particular interest for beam-plasma interactions is the existence of the broad electron spectrum extending to energies well in excess of the beam energy but only at large pitch angles. Wilhelm et al.[4] have pointed out that electrons with large pitch angles are more easily trapped in the vicinity of the Orbiter by electrostatic fields or wave electric fields, while those with small pitch angles may escape along field lines.

Evidence for resonant interactions between electrons and plasma waves generated by the electron beams is provided by the PICPAB wave receiver, which was deployed through the scientific airlock of the Spacelab module. This instrument detected strong wave emissions at multiples of the electron gyrofrequency as well as a general increase in background wave noise at frequencies up to at least 10 MHz in the electric component.[2]

Recently analyzed data from AEPI have shown yet another type of evidence for beam-plasma interactions.[12] At SEPAC EBA currents above 100 mA, when the collimated electron beam was replaced by a general glow and the pallet was strongly illuminated, a flickering effect was noted in the AEPI TV images. Such oscillations, produced by a DC beam, provide strong evidence of an instability that couples the directed energy of the electron beam into collective oscillations of the local plasma.

Anomalous Ionization Pheonomena

The SEPAC NGP and MPD both produced anomalous ionization effects when they were fired nearly into the Orbiter ram direction, a configuration which maximized their velocities relative to the ambient ionospheric plasma and neutral gas. In the case of the NGP, the anomalous ionization is thought to have been produced by a shock wave in front of the Orbiter,[9] while the MPD phenomenon has been attributed to Alfven's critical velocity process.[10]

In four different nighttime operations, the SEPAC NGP was emitted in different Orbiter configurations with respect to the ram direction, the magnetic field direction, and the local nadir. As expected, the neutral gas pressure increased from about 1×10^{-6} T to 2-3 $\times$ 10^{-6} T during the 100-ms NGP pulse of 10^{23} N_2 molecules. Unexpected, though, was the increase of Langmuir-probe current by factors of 20 to 60 times the ambient level for certain configurations. These ionization-density enhancements were accompanied in some cases by VLF waves and a broad spectrum of energetic electrons extending up to 4 keV. The ionization effects produced by the NGP are anomalous because the relative velocity between the gas molecules and the ambient cold electrons is less than 8.5 km/s (Orbiter velocity plus ejection velocity), corresponding to electron energies of 10^{-4} eV. Therefore, ionization by electron impact would require a mechanism for accelerating the ambient electrons.[9] One plausible explanation seems to be the heating of ambient electrons by a shock wave ahead of the Orbiter.[9] The correlation with the ram direction also suggests a possible relationship between the anomalous ionization and the Shuttle glow, which has been observed from Orbiter surfaces facing the ram direction.[11]

In the case of MPD argon plasma ejections, similar plasma enhancements and VLF wave effects were observed. However, one feature of the MPD phenomena suggests a possible link with the critical-velocity ionization process.[10] In addition to an association with ejection into the ram direction as with the NGP, a threshold velocity of 7 to 8 km/s perpendicular to the magnetic field was also indicated, this same threshold being observed for strong aftereffects in both ionization levels and VLF emissions lasting up to 200 ms.

Modulated Electron Beam Effects

Both Spacelab 1 electron accelerators had the capability of emitting beams with AC modulated outputs. The objective of these operations was to investigate the coupling of wave energy from the beam to the ionosphere and to test the feasibility of using electron beams as long spaceborne VLF antennas. One very striking result in this area was obtained by the Low Energy Electron Spectrometer in response to 500-Hz modulations of the 8-keV PICPAB electron gun. In each case, a very close temporal correspondence was observed between beam current oscillations and periodic fluctuations in the return electron flux, as illustrated in Fig. 6.[4] This close temporal relationship is a strong indication that the electron flux reactions to electron beam emissions are produced with delay times of a millisecond or less in the immediate neighborhood of the Spacelab accelerators.[4]

Beghin et al.[2] have investigated the effectiveness of the PICPAB electron beam in triggering wave emissions in a modulated mode and in a pulsed mode. Examples of electric and magnetic wave spectra produced in the two modes is shown in Fig. 7. The pulsed mode is shown on the left side (a), with the modulated mode at the right (b). In each case a timing diagram, showing the pulse shape of the beam and the frequency of the receiver, is shown at the top. The next five traces

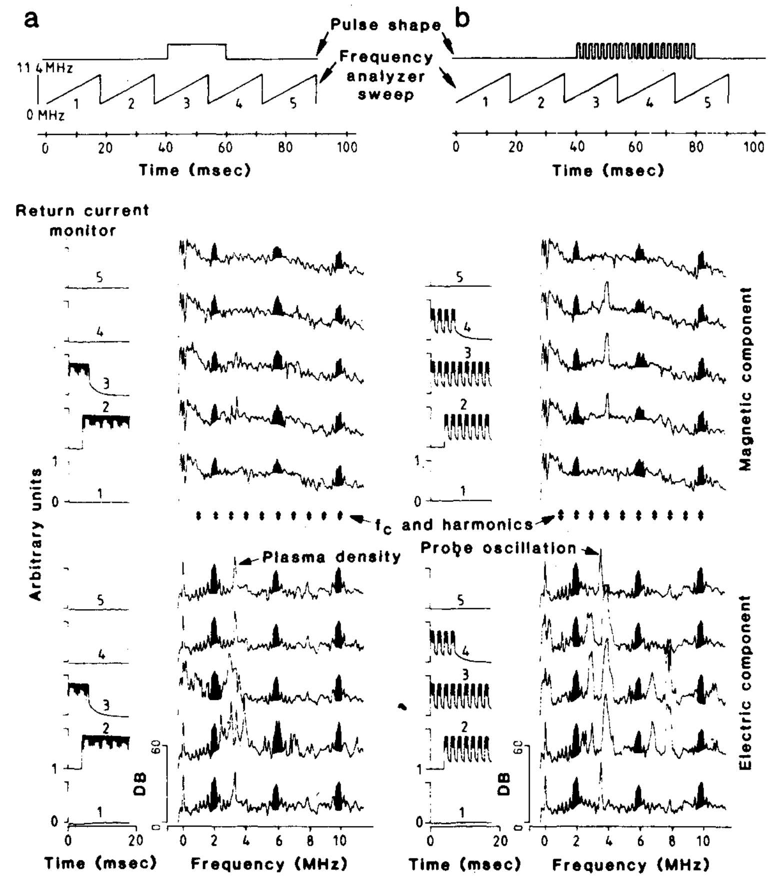

Fig. 7 Frequency spectra recorded before, during, and after a PICPAB electron accelerator pulse (100 mA, 8 keV) in the pulse mode (a) and the modulated mode (b). Five consecutive spectra are displayed for the electric and magnetic wave components.

plot the magnetic wave component vs frequency with plots of the return current at the left of each trace reproducing the beam pulse shape. Time runs progressively from the bottom trace (1) to the top trace (5). Similar plots of the electric wave components are shown in the bottom half of the figure. The black-shaded peaks in the wave spectra are interference lines, while background whistler-mode emissions were observed continuously below the electron cyclotron frequency (f_c). When the beam was fired, strong emissions appeared at harmonics of f_c, particularly in the electric component and particularly in the modulated mode (Fig. 7b) in this example.

Future Spacelab Experiments

A reflight of SEPAC and AEPI is now planned for the EOM 1/2 mission in 1986. This mission will allow the completion of several Spacelab 1 FO's that were not accomplished due to unfavorable orbital lighting conditions and to a malfunction of the EBA that occurred during the Spacelab 1 mission. An upgrade of the EBA beam modulation capability is planned for EOM 1/2. On the Spacelab 2 mission in 1985 the STS-3 VCAP electron accelerator[13] and Plasma Diagnostics Package (PDP)[14] will be reflown, but in this case the PDP will be released to provide a remote diagnostic capability within and near the electron beam itself.

A comprehensive Spacelab space-plasma research program is planned for a series of Space Plasma Lab missions beginning in 1989. An upgraded SEPAC, along with the Waves in Space Plasmas (WISP) wave injection facility, recoverable PDP, AEPI, and the Magnetospheric Multiprobes (MMP) are among the instrument systems being considered for these missions.

Acknowledgments

This research was supported by NASA Contract NAS8-32488.

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