Electron Flux Intensity Distributions Observed in Response to Particle Beam Emissions

Abstract. *Modifications of the suprathermal electron population were observed by an electron spectrometer on Spacelab 1 during electron beam injections. The instrument covered its energy range (100 to 12,500 electron volts) and field of view ($\approx 2\pi$) with high energy, angle, and time resolution. The measurements demonstrate the presence of strong beam-plasma interactions during high-current modes of accelerator operations. Spacecraft charging could be studied as well as processes that accelerated electrons to more than four times the injection energy.*

The scientific goals of the low-energy electron spectrometer and the magnetometer (*1*) were diversified. They included studying the natural magnetic field and the energetic electron flux distribution at high latitudes during auroral precipitation events, probing the magnetospheric electric field configuration with the help of artificially injected low-intensity electron beams, and investigating the plasma disturbance during powerful beam emissions. Although all these aspects are closely related, we will limit the discussion to the last aspect in this report (*2*).

Studies of plasma disturbances created by charged particle beams are of interest in quite different areas. (i) There is a long-standing question concerning the charging effects of space vehicles and the neutralization mechanisms. (ii) Of equal importance are the stability criteria of the emitted beam and its interaction with the plasma and the neutral atmosphere. (iii) Finally, the similarities and differences between space and laboratory effects should provide a clue to understanding the physical processes operating in beam-plasma interactions.

A comprehensive summary of these aspects has been given by Winckler (*3*). Laboratory studies of beam-plasma interactions have, after initial investigations in the early 1960's (*4*), been intensified with a view to understanding some of the ionospheric beam-plasma experiments (*5*). The stability of the electron beam is also of interest for any probing experiment that relies on using electrons as geomagnetic field tracers (*6*) and for electric field studies (*7*). Many processes that occur in natural aurorae and in other geophysical or astrophysical environments seem to involve energy transfer to charged particles in wave-particle interactions. Theoretical concepts devised to explain these effects may profit from observations of artificial electron beams in a collisionless, unbounded plasma. In the laboratory, strong acceleration of electrons was observed in a mirror configuration (*4*) and energy diffusion up to 30 percent above the beam energy was detected in beam-plasma discharges (*8*). Energetic electrons with up to four times the beam energy have been observed in space by a sounding rocket experiment (*9*). Concurrent with the energy gain of a small portion of the distribution, electron energy spreading to values below the beam energy for the bulk of the population appears to be a characteristic pattern of any strong beam-plasma interaction (*10–14*).

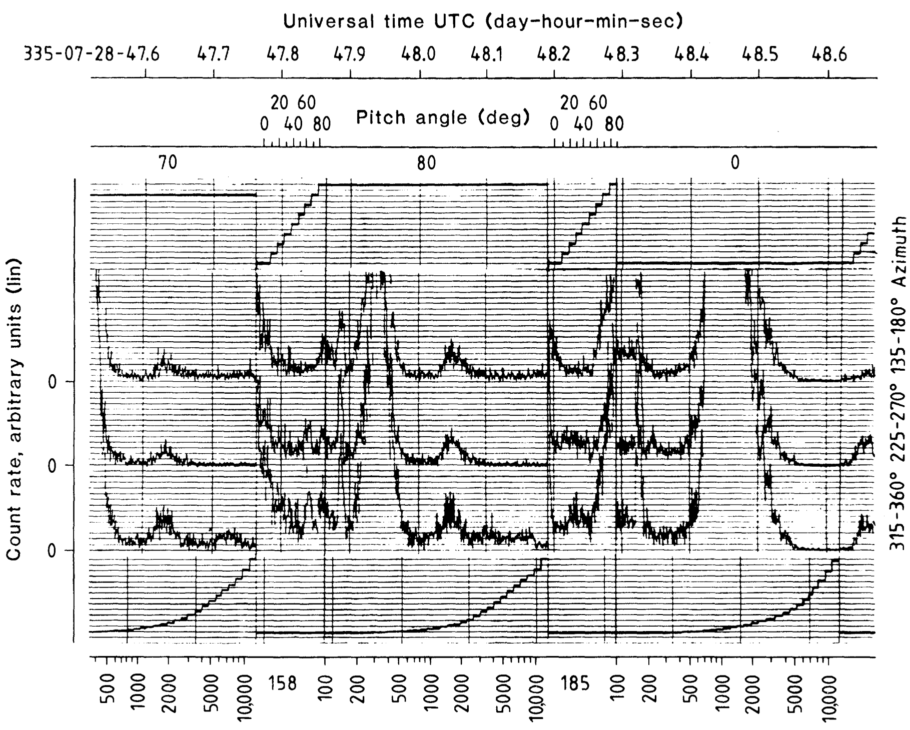

Fig. 1. Quick-look data of the electron spectrometer showing the count rate of three of eight azimuthal channels (central traces) as a function of time (upper scale). The switch status of the instrument is given by the upper trace for the coelevation angle and the lower trace for the energy. Angle and energy values are also converted to abscissa scales at the top and bottom, respectively. Complete energy sweeps from 100 to 12,500 eV are shown for pitch angles of 0° and 80°. A beam energy of 4900 eV was effective during this 1-second interval of data. Note that during constant-angle intervals energy sweeps were performed alternatively with coelevation (pitch angle) sweeps at constant energies. Similar observations at lower beam energies (3 and 4 keV) allowed the deduction that electron heating up to four times the injection energy regularly occurred at large pitch angles. Note that obstruction by other pallet elements may affect the measurements of this instrument at high pitch angles. The differences observed in azimuthal channels as far as the high-energy electron population is concerned could thus be introduced artificially and must be studied further. The count rates at high pitch angles and energies were above the instrumental background, as can be seen from a comparison with those at 0° pitch angle.

Instrumentation. The electron spectrometer was optimized to observe electron flux distributions in the energy range 100 to 12,500 eV in a wide solid angle of nearly 2π with sufficient angular resolution to detect pitch angle and azimuth anisotropies. The basic element is a 75° electrostatic deflection device for energy selection followed by continuous-channel electron multipliers (CEM's) as electron detectors. The deflection system consists of two concentric half-spheres with a mean radius of 10 cm and a cutout around the pole axis for housing eight CEM's and appropriate collimators. The analyzer voltage can be stepped in 64 levels in both linear and logarithmic fashion. Collimators in front of the aperture of the energy deflection device provide the possibility of reducing the geometric factor by applying an electrostatic cross-field. In addition to energy selection, angular resolution is a major requirement for studying artificial electron distributions (*15*). This is achieved by a toroidal structure consisting of a high-transparency net as the outer electrode and a set of concentric rings as inner electrodes. A high voltage proportional to that at the energy analyzer is applied to the angular deflection device in such a way that rings can be switched on and off sequentially starting from the equatorial aperture. In this manner, coelevation angles between 0° and 80° with respect to the instrument axis can be selected in steps of 10°. At the same time, the eight channels will accept electrons from different 45° azimuthal sectors. The center of the toroid is occupied by ^3H radioactive sources. By using maximum deflection, the view cones can be directed toward these sources for calibration and any external radiation will be shut off. In line with the fast reaction time of the instrument, a basic sampling time of 1 msec in 12-bit registers was implemented as well as energy and angle step times of 10 msec (*16–18*).

Observations of the Spacelab 1 flight. Investigations related to the long-duration electron beam emissions of experiment 1NS002 (*19*) were hampered by the fact that only a few successful operations of the beam could be achieved. Nevertheless, interesting findings were obtained (Fig. 1). The measurements were made during a 5-second pulse of the 1NS002 electron accelerator operating at a voltage of 4.9 kV and a beam current of approximately 300 mA. The pulse commenced at 335:07:28:45.220 GMT and the first portion of the data presented was recorded 2.3 seconds later. Interpretation of the measurements is greatly facilitated by the fact that the z-axis of the spacecraft and thus the central axis of the instrument were nearly parallel to the undisturbed magnetic field of the earth during this event. Consequently, the coelevation angles should approximately coincide with the magnetic pitch angles of the electrons observed. The following features are obvious from this example and were confirmed on other occasions during this flight. (i) No electron flux could be observed above the primary beam energy at small pitch angles, whereas a broad flux intensity maximum extended from approximately 700 eV to the beam energy (*20*). (ii) At high pitch angles, however, significant electron flux could be observed up to the highest energy step of the instrument, and a small count rate maximum was apparent near 1500 eV accompanied by a low-energy intensity maximum at about 300 eV. (iii) No indication of the primary beam spectrum could be detected at any pitch angle. (iv) At very low energies, the flux distribution was very variable, as can be seen by the two pitch angle scans at 158 and 185 eV.

Not demonstrated in Fig. 1 is the observation that during the first part of the pulse, when a plasma emission was operative, the intense maximum at low pitch angles was not present in the keV region but was shifted to lower energies. Also, strong effects could occasionally be observed as much as 1 second after the cessation of an accelerator pulse (*21*).

A strong indication that most of the electron flux reactions to electron beam emissions occur with very short delay times in the immediate surroundings of the accelerators is provided by Fig. 2, which shows a pronounced 500-Hz modulation effect in phase with a corresponding modulation of the primary beam of experiment 1ES020 (*22*). Whether the enhanced flux levels near the beginning of the activity periods are of any significance could not be decided on the basis of the quick-look data, although they seem to be a consistent feature in this mode of operation. Observations of pulses in experiment 1ES020 supported the findings reported for beams in experiment that consistent energy diffusion toward lower energies took place and that energies higher than the injection energy of 10 keV could be observed at large coelevation angles (*23*).

At low coelevation angles and very low energies the measurements indicate a long lifetime of the return flux, up to several hundred milliseconds.

Interpretation. The measurements support earlier observations that high-current electron beams strongly interact with the plasma environment and that Coulomb scattering does not play a major role in generating the return flux. The broad energy spectrum of that flux in a wide angular range seems to indicate that the interaction is very efficient in generating energy and pitch angle diffusion. As most of the effects occur promptly, the growth times of the instabilities appear to be small compared to the sampling time of 1 msec. It should, however, be noted that the intense flux directed toward the instrument at about 1 keV was substantially suppressed and shifted to lower energies during the operation of the plasma jet. These findings are clearly consistent with charging of the spacecraft up to rather high potentials, as

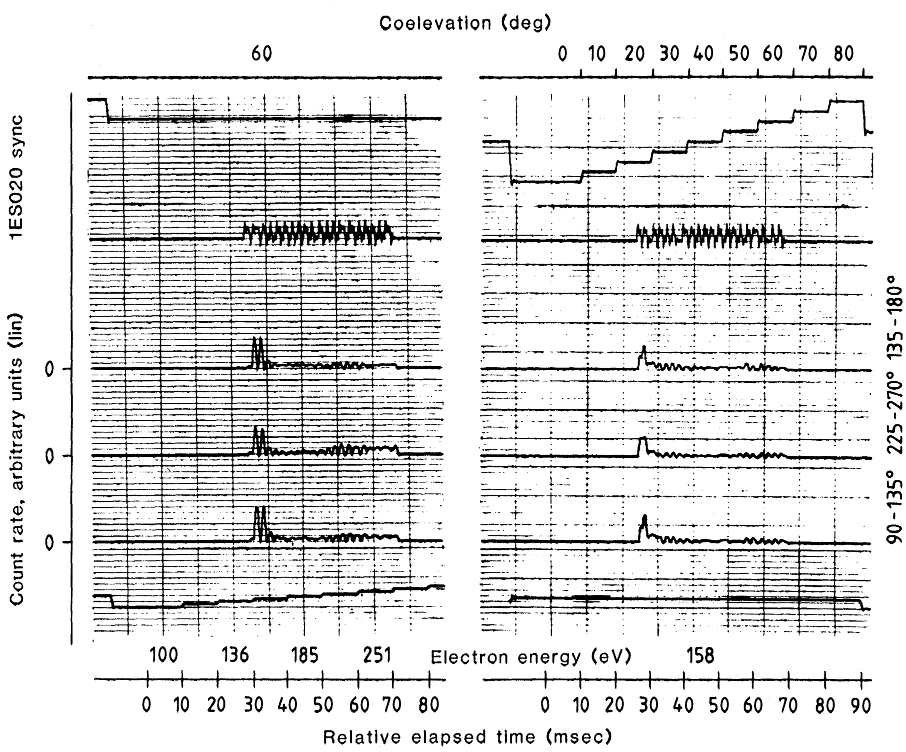

Fig. 2. Response of the electron spectrometer to the 500-Hz modulation pulse at 8 keV electron energy of the accelerator in experiment 1ES020. The format is the same as in Fig. 1 with higher time resolution. The close temporal relation can be seen from a comparison of the synchronization signal that was sent directly from the accelerator to the spectrometer and the count rate channels. The time resolution with 1-msec sampling intervals is marginally capable of resolving the event. Azimuths of the channels are given on the right-hand side.

expected on the basis of sounding rocket observations (*24*).

In addition to the energy diffusion toward lower energies, the demonstration of the existence of acceleration processes is of particular interest. It implies that the beam-plasma interaction is capable of heating electrons to more than four times the primary beam energy. The observation that the energetic component was present only at high pitch angles is of great importance, as these electrons could be confined much more easily (for instance, by electric fields parallel to the magnetic field) than those with substantial longitudinal energies.

KLAUS WILHELM
WOLFGANG STÜDEMANN
Max-Planck-Institut für Aeronomie, D-3411 Katlenburg-Lindau, Federal Republic of Germany
WILLIBALD RIEDLER
Space Research Institute, Austrian Academy of Sciences, A-8010 Graz

References and Notes

1. A three-axes magnetometer with a time resolution of 1 second was included in the instrument package (experiment 1ES019B). The sensors were mounted close to the spectrometer (1ES019A). During flight, deviations of the magnetic field vector of up to 30° as compared to the nominal model magnetic field were observed, probably due to line and stray currents on the space shuttle and Spacelab. In the absence of final data, no further analysis can be performed at present; analytic models are being worked on.
2. One of the reasons for this restriction is the fact that no flight data other than quick-look information were available for the preparation of this report. As this field of study is relatively new, it is felt that even without having all the supporting information available some conclusions of general interest can be drawn. It must be realized, of course, that important aspects could be overlooked before a detailed analysis of the flight data has been performed.
3. J. R. Winckler, *Rev. Geophys. Space Phys.* **18**, 659 (1980).
4. W. D. Getty and L. D. Smullen, *J. Appl. Phys.* **34**, 3421 (1963).
5. W. Bernstein *et al.*, *Geophys. Res. Lett.* **5**, 127 (1978).
6. J. R. Winckler, in *Artificial Particle Beams in Space Plasma Studies*, B. Grandal, Ed. (Plenum, New York, 1982), pp. 3–33.
7. K. Wilhelm, W. Bernstein, B. A. Whalen, *Geophys. Res. Lett.* **7**, 117 (1980).
8. R. J. Jost, H. R. Anderson, J. O. McGarity, *ibid.*, p. 509.
9. K. Wilhelm, C. Becker, R. Schmidt, Report W84-014, Bundesministerium für Forschung und Technologie, Bonn (1984).
10. B. N. Maehlum, B. Grandal, T. A. Jacobsen, J. Trøim, *Planet. Space Sci.* **28**, 279 (1980).
11. K. I. Gringauz *et al.*, *Ann. Geophys.* **36**, 371 (1980).
12. W. Bernstein, P. J. Kellogg, S. J. Monson, R. H. Holzworth, B. A. Whalen, in *Artificial Particle Beams in Space Plasma Studies*, B. Grandal, Ed. (Plenum, New York, 1982), pp. 35–64.
13. K. Wilhelm, W. Bernstein, P. J. Kellogg, B. A. Whalen, in *Active Experiments in Space*, (ESA-SP 195, European Space Agency, Paris, 1983), pp. 113–120.
14. All space observations available up to now have been made in the backscatter region of the injected beam. Although the measurements presented here fall in the same category, it is hoped that the space shuttle and Spacelab will in the near future provide the facilities required to study the primary beam on a regular basis.
15. As fast reaction times are required, mechanical systems were excluded during the design phase. Instead, a novel electrostatic angular deflection system was devised.
16. The high data collecting capability led to a data rate of more than 200 kbit/sec on a dedicated telemetry channel. A more detailed description of the instrument is given by K. Wilhelm, in *Proceedings of the 21st Convegno Internazionale Scientifico Sallo Spazio* (Rome, 1981), pp. 185–194.
17. The instrument nominally performed more than 100 operational sequences during the Spacelab 1 flight from switch-on 10 hours after launch on 28 November 1983, to shutdown on mission day 9. Since the instrument was encapsulated in a tank with movable cover for protection during take-off, hottest phases, and landing, several cover activations were required during the flight.
18. Other instrumentation required for the intended investigations includes charged-particle accelerators (experiments 1NS002 and 1ES020) and plasma release systems (1NS002). They are treated in this issue in reports by T. Obayashi *et al.* (*19*) and C. Beghin *et al.* (*22*).
19. T. Obayashi *et al.*, *Science* **225**, 195 (1984).
20. The recorder saturated during the event. However, this does not imply overflow of the count registers.
21. From the fact that these count rate increases did not depend on the switch status of the instrument in both angle and energy and, moreover, did not occur in all azimuthal channels, we conclude that they are related to an as yet unexplained instrumental behavior.
22. C. Beghin *et al.*, *Science* **225**, 188 (1984).
23. Lacking detailed attitude and magnetic field information for the time being, a general conversion from coelevation to pitch angle could not be performed.
24. G. G. Managadze *et al.*, in *Active Experiments in Space* (ESA-SP 195, European Space Agency, Paris, 1983), pp. 161–169.
25. We thank C. Becker, H. Eichel, W. Engelhardt, J. Fein, E. Frank, W. Grill, E. Krahn, W. Neumann, E. Ofner, W. Ramsauer, H. P. Schmidt, R. Schmidt, R. J. Schmidt, K. Schwingenschuh, K. Sommer, and N. Valavanoglou for dedicated work on the technical implementation of the instruments. The project was financially supported by the German Bundesministerium für Forschung und Technologie through grant 01 QV 197-ZA WF-WRK 275/4 and by the Austrian Bundesministerium für Wissenschaft und Forschung as well as the Austrian Academy of Sciences. The assistance of the European Space Agency and National Aeronautics and Space Administration personnel during the development, integration, and mission phases and the cooperation within the Space Plasma Physics Discipline Group of the Spacelab 1 Investigators Working Group as well as the support by the flight crew are greatly appreciated.

27 March 1984; accepted 1 May 1984

Phenomena Induced by Charged Particle Beams

Abstract. *The effects of electron beam emissions from Spacelab were recorded with onboard diagnostic instruments. The variation of the Spacelab-shuttle potential with respect to the ambient plasma near the scientific air lock was investigated. Data on the waves and instabilities triggered by the electron beams are discussed. Within the electron gyrofrequency and electron plasma frequency range, strong signals were detected by both electric and magnetic antennas during the beam emissions. The frequencies of the emitted waves were compared to the characteristic plasma frequencies to enable mode identification.*

One of the active experiments on Spacelab 1 was designed to investigate phenomena induced by charged particle beams (PICPAB) emitted from the space shuttle. The primary scientific objectives of the PICPAB experiment are related to spacecraft charging, neutralization processes, and beam-plasma interactions. In addition, the experiment was designed to study the transition range between low- and high-power electron beams. Laboratory experiments and experiments in which particle beams were injected into space from rockets had shown that different interaction regimes exist. An initially linear regime extended into intricate nonlinear regimes involving complex mechanisms such as the beam-plasma discharge (*1*). The PICPAB experiment was also designed to begin studies on high-energy ion beams in the ionosphere.

Instrumentation. The PICPAB instrumentation consisted of three packages (*2, 3*). The active package, located on the pallet, contained the electron and ion accelerators and diagnostic instruments (particle analyzers and a plasma potential probe). The passive package, deployed outside the scientific air lock by the crew, contained high-frequency (HF) electric (0.1 to 90.9 MHz) and magnetic (0.1 to 11.4 MHz) antennas, a double-sphere electric probe (d-c to 500 Hz), a plasma frequency probe, and an electron temperature probe (ETP). The rack unit, located in the module, was composed of a sweep frequency analyzer connected to the HF antennas and a control unit devoted to mode control, data collection, and main interfacing with the active and passive units and with the general onboard Command and Data Management System. The telemetry rate of the experiment was 1 Mbit/sec. Two basic modes were used and are referred to as "floating" and "nonfloating." In the floating mode the active package was electrically insulated from the Spacelab structure; the package could "float" with respect to the Spacelab potential (limited to ±200 V by design). In the nonfloating mode the active package was electrically grounded to the Spacelab structure, and the net current flowing between the package and the structure was measured. Using one of these two modes, a 5-minute sequence was divided into several modules including low (10 mA) or high (100 mA) beam currents with an electron energy of 8 keV, a pure ion beam (2 mA, 6 keV), two beams of electrons (10 mA) and ions (2 mA), and a neutralized ion beam (ions at 2 mA and electrons at 0 to 4 mA, 100 to 200 eV) (*4*). The PICPAB accelerators were operated