Extrapolation of Space-Simulation Beam-Plasma Investigations to Shuttle-Borne Applications

E. P. Szuszczewicz*
E. O. Hulburt Center for Space Research, Naval Research Laboratory, Washington, D.C.

Laboratory simulations of space-plasma phenomena provide an important link in establishing broader perspectives of various plasma processes, in helping to understand spatially or temporally limited rocket and satellite observations, and in planning future space-borne experiments. One such area has been the artificial injection of energetic electron beams in space, which has transitioned from an early and somewhat confused set of rocket data, through a relatively intensive program of laboratory-based space simulations, to an ambitious program which exploits the Shuttle as a readily accessible laboratory in space. While accumulated information points to a considerably improved understanding of beam-plasma parameters, which define single-particle behavior on the one hand and collective beam-plasma properties on the other, the extrapolation of these results to Shuttle-borne applications is met with a number of constraints. Focusing on the transition from single-particle behavior to the collective nonlinear interactions in the beam-plasma discharge, this paper provides a comparative analysis on aspects involving Shuttle-unique environmental effects. Emphasis is placed on Shuttle potentials and associated sheaths, ambient plasma and neutral density effects, including relative spacecraft motion, pulsed vs dc gun operation, and beam-plasma discharge criteria in general. The laboratory-based space-plasma simulations are found to provide valuable guidelines for intelligent planning of Shuttle-based beam-plasma investigations and promote a productive era of plasma experiments in space.

Nomenclature

B	= magnetic field
c	= velocity of light
e	= electron charge
I_c	= critical beam current for beam-plasma discharge ignition
k	= Boltzmann constant
L	= beam-plasma system length
m_e	= electron mass
N_b	= energetic electron beam density
N_e	= ambient plasma density
N_n	= ambient neutral density
P	= neutral gas pressure
R_p	= probe (or Shuttle) radius
R_s	= sheath radius
S	= dimensionless sheath size
T_e	= electron temperature
V_b	= energetic electron beam accelerating potential
θ	= beam injection angle
λ_D	= Debye length = $(kT_e/4\pi N_e e^2)^{1/2}$
ϕ_p	= probe (or Shuttle) potential
$\omega_c^e/2\pi$	= electron cyclotron frequency = $eB/2\pi m_e^c$
$\omega_D/2\pi$	= electron drift frequency = $kT_e(\mathrm{d}N_e/\mathrm{d}x)/eB\lambda N_e$
$\omega_p^e/2\pi$	= electron plasma frequency = $(N_e e^2/\pi m_e)^{1/2}$

Introduction

THE artificial injection of energetic particle beams in space represents one of the most exciting areas for controlled experiments in the Earth's ionosphere and magnetosphere.[1,2] Under the influence of a large number of controlling parameters[3] (e.g., N_b, N_e, V_b, B, N_n, and θ), a monoenergetic electron beam can follow well-defined single-particle trajectories or it can undergo collective beam-plasma effects that destroy the simple single-particle description and render the beam-plasma system unstable to a multitude of plasma modes.[4] If the beam behaves as a single-particle model would predict, there are a number of valuable space-borne applications, including the mapping of geomagnetic field lines; detection of geomagnetic conjugates; the study of beam spreading, atmospheric excitation, and ionization processes; and the measurement of magnetic field aligned potentials. On the other hand, there is great interest in studying the collective beam-plasma processes that destroy the "classical" single-particle behavior. This interest focuses on basic beam-plasma interaction processes and their relationships to a variety of space-plasma phenomena, including 1) nonlinear ionization, 2) wave-particle interactions, 3) plasma turbulence and anomalous diffusion in high latitudinal ionospheric domains, 4) the generation of electrostatic and electromagnetic waves, and 5) anomalous spacecraft charging/discharging mechanisms in energetic particle environments.

In recent years, one of the subjects in space-related beam-plasma interactions to receive considerable attention has been the collective plasma process called the beam-plasma discharge (BPD): A phenomenon related to each of the issues listed above as items 1-5. Fundamentally a high-frequency discharge triggered by nonlinear interactions between the beam and ambient plasma electrons, the BPD was first studied in the 1963 laboratory work of Getty and Smullin.[5] It began to gain the attention of the space science community when the initial series of space-borne beam experiments in 1970 yielded results that were at substantial variance with expectations.[6-8] Further rocket experiments[9-12] and rather intensive laboratory simulations,[13-20] supported by theoretical analyses,[18,21,22] provided many clues to the previously ill-understood space-borne results. Today, a fair amount is known about the BPD characteristics and the nonlinear processes that drive the basic high-frequency beam-plasma interactions. It is generally agreed that the BPD is a complex beam-plasma state that is triggered at a critical beam current with a parametric dependence[3] on the beam energy, the superimposed magnetic field, the ambient neutral density, and the system length. This critical current level yields 1) a marked increase in ion-pair production (factors up to 20 times greater than that which would result from single-particle collisional ionization processes); 2) a greatly enhanced 3914 Å emission; 3) a broadening of the beam-plasma cross section (a

Received Sept. 7, 1982.

*Head, Ionospheric Diagnostics Section.

factor of 10 is typical) and an associated modification of the primary beam velocity distribution; 4) the creation of a large suprathermal electron population extending over the 5-100-eV range; 5) the generation of intense high-frequency emissions to frequencies above the electron plasma frequency ω_p^e; and 6) the development of large-amplitude (up to an order of magnitude) low-frequency ($\lesssim 150$ Hz) ion acoustic and/or drift-wave modes.

Since many of these results are steady-state BPD signatures and have found plausible theoretical descriptions, it is fair to say that the steady-state space-simulated BPD is approaching a reasonable level of accepted scientific understanding. However, the extrapolation of this understanding to space-borne applications is accompanied by a number of conditions which have not been adequately simulated or extensively studied. These conditions include the existence of a uniform and quiescent prebeam plasma, the existence of a moving beam-plasma reference frame (as would be the case for a Shuttle-borne accelerator), an unbounded beam length, manifestations of plasma density turbulence, temporal beam-plasma behavior, and possible spacecraft perturbations involving plasma sheaths and gaseous effluents.

These items come as no surprise to workers in the field, and, indeed, several of the issues have had limited treatment.[23,24] The existence of a uniform and quiescent prebeam plasma is an important consideration, since progressive applications of beams in space will initially concentrate on stable and homogeneous regions of the ionosphere. In contrast, the pre-BPD plasma in the large-chamber space simulations (and undoubtedly in the original gas discharge work) is far from quiescent. Indeed, the study of charged-particle-beam interactions with turbulent plasmas is a subject in its own right. In some cases, the presence of plasma inhomogeneities (or turbulence) can attenuate an instability process, while in other cases the same inhomogeneities may lead to new instabilities.

It is clear that each of the issues require substantial consideration before extrapolations can be made from the space-simulation results to Shuttle-borne applications. With this perspective, subsequent sections will describe planned Shuttle experiments, measurement requirements, and potential impact of Shuttle-unique environmental constraints.

Shuttle-Borne Applications

As noted above, the extrapolation of laboratory space-simulation results to Shuttle-borne applications is met with a number of qualifications. These qualifications can be put into perspective with reference to Fig. 1, which schematically displays various beam-plasma interaction domains in Shuttle-borne applications. (See Refs. 25-27 for more detailed discussions of beam-injection considerations on the Shuttle.) The NASA/Spacelab Program plans a number of Shuttle-borne beam-plasma investigations, incorporating the Japanese Space Experiments with Particle Accelerators[25] (SEPAC). SEPAC subsystems include an electron beam accelerator which can deliver currents and beam energies up to 1.5 A and 7.5 keV in a pulse-controlled mode. Pulse widths are variable from 10 ms to 1 s at repetition rates ranging from 0.1 to 60 s^{-1}. [NASA also plans a number of studies employing a faster, but lower power, electron gun (1 keV, 100 mA) which is part of an experimental effort called Vehicle Charging and Potential (VCAP).[28] The first VCAP tests were conducted on STS-3.] When an electron beam is injected into the ionosphere, interaction processes can be cataloged into four space-time regions,[26,27] labeled I-IV in Fig. 1. The study of these four regions is the subject of a NASA-supported program, Theoretical and Experimental Study of Beam-Plasma-Physics (TEBPP).[26,27]

In region I, the beam is expected to spread as a result of various effects, which include its own space charge repulsion, neutralization by ambient and beam-created plasma, and beam divergence. In addition, region I is considered to include the effects of spacecraft charging and potentially large plasma sheaths which will alter the beam energy by an amount equal to the potential drop across the sheath.

Region II-A defines the region in which the beam has reached an equilibrium condition (from a geometrical perspective), and begins strong beam-plasma interaction processes that spread the beam energy distribution function, develop strong ac electric fields, and result in various forms of plasma turbulence. If BPD is to occur in planned Shuttle experiments, it is expected to occur in this domain.

The beam, with its modified energy distribution function, then moves into the kinetic regime (region II-B), where the ac electric fields are expected to be considerably less than in region II-A.

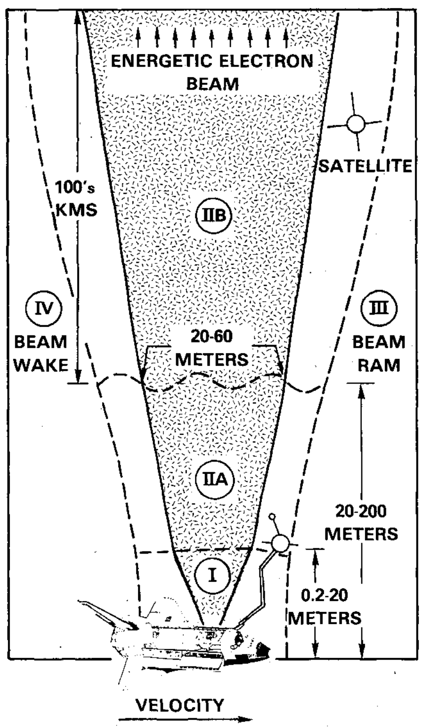

Fig. 1 Schematic representation of beam-plasma interaction domains in Shuttle-borne applications.[26,27]

Table 1 Sheath sizes

	Reasonable limits of probe theory			Substantial extrapolations of model		Plasma conditions	
$e\phi/kT_e$	1	10	10^2	10^3	10^4	N_e, cm^{-3}	T_e, K
$S=(R_s-R_p)/\lambda_D$	2.5	7.9	25	79	250	...	...
(R_s-R_p), m	0.21	0.67	2.1	6.7	21	10^3	1500
(R_s-R_p), m	0.007	0.021	0.07	0.21	0.70	10^6	1500
ϕ_p, V	0.13	1.3	13	130	1300	...	1500

Region III is ahead of the beam, where precursor effects are likely to be detected; and region IV is in the beam wake, where the ionosphere returns to its original unperturbed state.

It is planned that these regions will be probed by complementary instrument packages: one mounted on the end of the Shuttle's 15-m Remote Manipulator System (RMS), and one on a maneuverable subsatellite. The degree to which beam-plasma processes can be properly diagnosed in Shuttle-borne applications and the degree to which laboratory-based simulations can be applied to mission planning will now be addressed in a number of select areas.

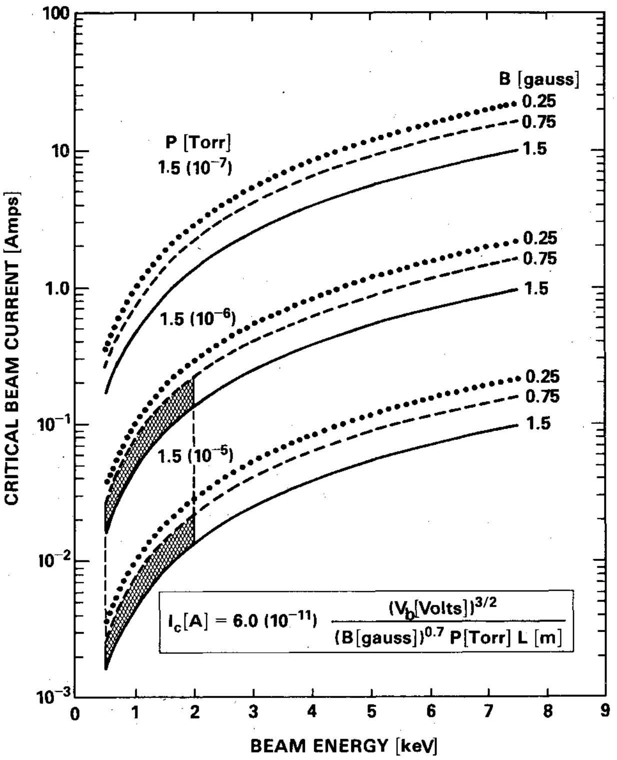

Fig. 2 Critical electron beam current I_c at which the beam-plasma discharge is ignited. The analytic representation is an empirical fit to the original laboratory results of Bernstein et al.[14] for parallel injection. The connected crosshatched region represents the parametric domain over which the original experiments were conducted. For comparative purposes note that the Shuttle-borne SEPAC accelerator has I(max), V_b(max) = 1.5 A, 7.5 keV.

Plasma Sheaths

It is an established fact that the operation of energetic particle accelerators on space vehicles can have significant effects on the vehicle potential and the attendant plasma sheath. Because of plasma current conservation laws, it is possible in tenuous plasma environments for the spacecraft to charge to positive potentials equal in magnitude to the beam energy. These potentials are expected to result in anomalously large plasma sheaths.

Extrapolation of existing probe theory can establish an estimate of possible sheath sizes. Consider[29]

$$S=\frac{R_s-R_p}{\lambda_D}=\left[2.50-1.54\exp\left(\frac{-0.32R_p}{\lambda_D}\right)\right]\left(\frac{e\phi_p}{kT_e}\right)^{1/2} \qquad (1)$$

where S is the dimensionless sheath thickness for a positively charged cylindrical body of radius R_p immersed in a fully-Maxwellian, magnetically-free plasma at rest; λ_D is the electron Debye length; and $e\phi_p/kT_e$ is the body (vehicle) potential normalized to the ambient electron temperature. Taking the thick- and thin-sheath limits, we find

$$\lim_{R_p/\lambda_D\to 0}(S)=(e\phi_p/kT_e)^{1/2} \qquad (2a)$$

and

$$\lim_{R_p/\lambda_D\to\infty}(S)=2.5(e\phi_p/kT_e)^{1/2} \qquad (2b)$$

respectively. Since R_p (the Shuttle radius in our case) will tend to be large compared with λ_D, Eq. (2b) more appropriately represents the experimental configuration. Substituting $e\phi_p/kT_e=1$, 10, 10^2, 10^3, and 10^4 yields the results summarized in Table 1.

The sheath sizes listed in Table 1 suggest that for operation near peak ionospheric densities ($N_e\sim10^6$ cm^{-3}), Shuttle sheaths should not be much of a problem, even if the spacecraft charges to 1300 V. At low ambient densities ($N_e\sim10^3$ cm^{-3}), sheath sizes can become comparable to RMS dimensions (6.7-m sheath at 130 V, 21-m sheath at 1300 V). Under these conditions, it is unlikely that any instrumented package mounted at the end of the RMS will penetrate regions of the Shuttle-near-space unperturbed by sheath potentials.

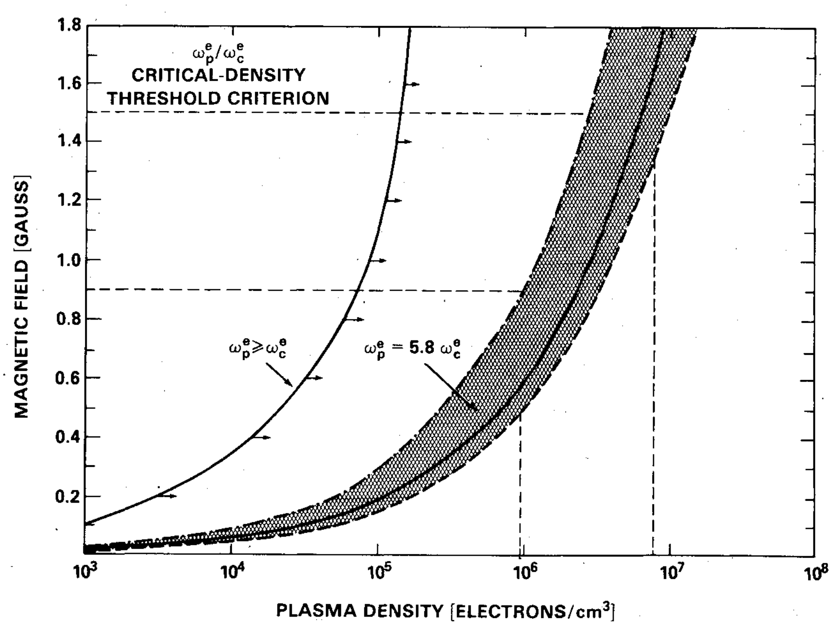

Fig. 3 Density-dependent ignition criterion for BPD ignition. $\omega_p^e/\omega_c^e=5.4$ was the average value determined experimentally. The dotted lines identify range of experimental parameters, while the crosshatched region represents spread in the results. The condition $\omega_p^e\geq\omega_c^e$ stems from earlier investigations.[5,14]

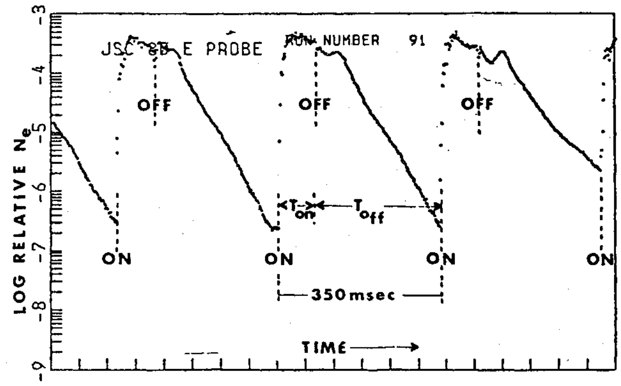

Fig. 4 Time-dependent plasma response during three consecutive pulsed-gun periods. $N_e^{max} = 1.3 \pm 0.5 \times 10^7$ **cm^{-3}.**

It should be pointed out that Eq. (1) cannot be applied rigorously to the full domain of possible sheath sizes and Shuttle potentials. Attendant limitations are identified with the assumptions in the physical model employed in the derivation. Ramming currents, magnetic field effects, secondary electron sputtering, surface conductivities, detailed Shuttle geometry, and ionization sources within the sheath have all been neglected. Because of the complexity of the problem and inherent assumptions that are necessitated (even if all effects are included), it is unlikely that a more complicated model will yield improved confidence in final predictions.

Ignition of the BPD

The possibility of BPD ignition in Shuttle applications can be viewed from a number of perspectives. We focus here on ignition criteria established in space-simulation laboratory experiments. These criteria are summarized in Figs. 2 and 3, and associated Eqs. (3) and (4), respectively:

$$I_c(A) = 6.0 \times 10^{-11} \frac{(V_b[\mathrm{V}])^{3/2}}{(B[\mathrm{G}])^{0.7} P[\mathrm{Torr}] L[\mathrm{m}]} \tag{3}$$

$$\overline{\omega_p^e} = 5.4 \omega_c^e \tag{4}$$

With regard to Fig. 2, we emphasize considerations regarding pressure. In the case of the other parameters note that $0.2 \lesssim B$ (G) $\lesssim 0.6$ for nominal Shuttle orbits and that the system length L is not expected to be a controlling term. L dependence in Eq. (3) is interpreted in two ways: 1) ion loss rates to the ends of the chamber, and 2) resonance feedback for finite system size resulting in an absolute instability under space-simulation conditions. In the unbounded Shuttle application, the instability is expected to be convective and therefore carries no L dependence. In addition, there are considered to be no unit volume loss rates along the unbounded system axis, and if BPD were ignited for a 20-m length in laboratory simulation, it is expected to be ignited in space[30] (all other parameters being the same).

Typically, Shuttle altitudes will be confined to domains between 200 and 400 km, where diurnal and solar-cycle variations allow $9 \times 10^{-8} \lesssim P$ (Torr) $\lesssim 3 \times 10^{-7}$ at the lowest altitude limit and $3 \times 10^{-9} \lesssim P$ (Torr) $\lesssim 2 \times 10^{-8}$ at the upper altitude region. Reference to Fig. 2 suggests that BPD ignition at 400 km ($\langle P \rangle \sim 1 \times 10^{-8}$) is a virtual impossibility with the SEPAC accelerator [I(max), V_b(max) = 1.5 A, 7.5 keV]. At the very lowest altitude ($\langle P \rangle \sim 2 \times 10^{-7}$), BPD ignition appears possible only for maximum SEPAC current (1.5 A) at energies less than 1.5 keV. However, SEPAC gun perveance appears to preclude BPD operation in this domain.

The results of Fig. 2 also suggest that the VCAP electron gun at 0.1 A, 1.0 keV is marginally capable of triggering BPD in the low-altitude regime. Local increases in pressure (e.g., factors of only 2-5) due to Shuttle outgassing will greatly increase VCAP BPD-ignition probabilities.

It is important to note that this discussion of pressure limitations on BPD ignition is greatly simplified in that it has not included the motion of the beam across the geomagnetic field. This motion can represent a loss mechanism as the beam moves away from field lines where it has already created ionization. Considerations of this phenomenon suggest that even at 200-km altitudes the SEPAC accelerator will not be able to trigger BPD if the only neutrals available for ionization are from the natural environment. However, the SEPAC experiment includes a nitrogen source for creation of a neutral gas plume (NGP). The NGP has been designed to provide neutral densities in the range 10^{12}-10^{13} cm^{-3}, corresponding to pressures of the order 10^{-5} Torr. Except for the NGP nozzle velocity, this plume will move along with the Shuttle and make the SEPAC ignition of BPD a virtual certainty.

Existence of a Prebeam Plasma

While the critical current relationship [Eq. (3)] established the controlling system parameters for BPD ignition in the laboratory simulations, a more fundamental form of the ignition criterion involved a plasma density dependence. Early thoughts[5,14] suggested that $\omega_p^e \geq \omega_c^e$ satisfied ignition threshold criteria, while a recent systematic direct measurements effort[18] yielded $\overline{\omega_p^e} = 5.4\omega_c^e$ as the plasma density dependent form of BPD threshold conditions (see Fig. 3).

The majority of these BPD experiments were conducted without a pre-existing plasma; that is, the beam interacted with the plasma that it created in collisions with ambient neutrals. In ionospheric applications, there will be a naturally occurring plasma environment with a density which varies with magnetic latitude, altitude, and local solar zenith angle, as well as solar and geomagnetic activity. For most considerations the ambient plasma densities at Shuttle altitudes will vary from a maximum value near 2×10^6 cm^{-3} to a minimum $\sim 10^4$ cm^{-3}. The upper limit is a harder number than the lower, since orbital passes below the F region peak and through the midlatitude trough could push the lower limit to $\sim 10^3$ cm^{-3}. Recalling that $0.2 \lesssim B$ (G) $\lesssim 0.6$ at Shuttle altitudes, Fig. 3 suggests that the density dependent threshold criterion[18] $\omega_p^e \geq \omega_c^e$ can be readily satisfied in Shuttle beam-plasma applications. The question to be answered, however, is whether or not the ω_p^e/ω_c^e criterion applies to the situation in which there exists a prebeam plasma. Theoretical models suggest it does, but the exact value is dependent upon gun geometry and beam expansion processes. In any event, it is expected that the condition $\omega_p^e/\omega_c^e \geq 1$ will apply, but an exact value ($\omega_p^e/\omega_c^e = 5.4$?) remains to be determined.

Pulsed Gun Operation

The operation of the gun with pulse widths as short as 10 ms is expected to lead to varying results. This is illustrated in Fig. 4, where the temporal behavior of relative plasma density is presented for three consecutive electron gun pulses under laboratory conditions. The gun's current and voltage were set for BPD conditions at 34 mA and 1.9 keV, respectively, and the pulse operation cycle was at 80 ms ON and 270 ms OFF for a total 350-ms period. The results in the figure can be characterized as follows:

1) A rapid increase in plasma density as the gun turns on (about 3 orders of magnitude increase in approximately 5 ms).

2) A "flat" quasi-steady-state BPD condition during the pulse-ON time.

3) An exponential decay in plasma density once the gun pulse is terminated.

Two points will be made relative to the results in Fig. 4:

1) The BPD onset time is a function of gun current (previously treated in Ref. 18), energy, and ON/OFF cycle time. If the pulse width had been less than 5 ms for the conditions in Fig. 4, BPD would not have been achieved.

2) The onset time dependence on ON/OFF cycle time represents a dependence on the local plasma density when the gun is retriggered. For shorter OFF times (and correspondingly higher local prebeam plasma densities), the onset time is reduced. This means that BPD onset time in a prebeam plasma environment is shorter than cases in which the beam itself generates the plasma. Thus the presence of ionospheric plasma may help alleviate possible problems of plasma loss as the beam moves across the geomagnetic field.

Comments and Conclusions

The conditions detailed in the preceding paragraphs by no means exhaust the various issues to be considered in extrapolating the current understanding of beam-plasma interactions to Shuttle-borne applications (see, e.g., Ref. 23). It cannot be emphasized too strongly that such extrapolations must be recognized for what they are: indicators of possible effects and guidelines for experiment planning. Even within the areas treated, the approach has been somewhat cursory, with a focus on primary impact rather than comprehensive treatment.

Limitations notwithstanding, it is expected that accumulated rocket-borne and laboratory information along with intelligent instrument design and experiment planning will lead to successful energetic electron beam experiments on the Shuttle that reap the benefits of single-particle behavior, as well as those which explore the multitude of nonlinear interactive processes in beam-plasma systems.

Acknowledgments

It is with great pleasure that the contributions and discussions of the entire TEBPP Science Team be acknowledged. Valuable inputs have been provided by H. Anderson, W. Bernstein, K. Papadopoulos, H. Leinbach, P. Kellogg, J. C. Holmes, D. N. Walker, T. Hallinan, J. R. Jost, L. Linson, R. Holtzworth, and P. Rodriguez.

References

[1] Winkler, J. R., "The Application of Artificial Electron Beams to Magnetospheric Research," *Reviews of Geophysics and Space Physics*, Vol. 18, Aug. 1980, pp. 659-682.

[2] Grandal, B., ed., *Artificial Particle Beams Utilized in Space Plasma Physics*, Plenum Publishing Co., New York, 1982.

[3] Szuszczewicz, E. P., "Laboratory Simulations of Controlled Energetic Electron-Beam-Plasma Interactions in Space," *AIAA Journal*, Vol. 21, Oct. 1983, pp. 1374-1381.

[4] Linson, L. M. and Papadopoulos, K., "Review of the Status of Theory and Experiment for Injection of Energetic Beams in Space," Science Applications Inc., La Jolla, Calif., Report No. LAPS 69 SAI-023-80-459-LJ, 1980.

[5] Getty, W. D. and Smullin, L. D., "Beam Plasma Discharge: Buildup of Oscillations," *Journal of Applied Physics*, Vol. 34, Dec. 1963, pp. 3421-3429.

[6] Hess, W. N. et al., "Artificial Aurora Experiment: Experiment and Principal Results," *Journal of Geophysical Research*, Vol. 76, Aug. 1971, pp. 6067-6081.

[7] Hendrickson, R. A., McEntire, R. W., and Winkler, J. R., "Electron Echo Experiment: A New Magnetospheric Probe," *Nature*, Vol. 230, April 1971, pp. 564-566.

[8] Cartwright, D. G. and Kellogg, P. J., "Observations of Radiation from an Electron Beam Artificially Injected into the Ionosphere," *Journal of Geophysical Research*, Vol. 79, April 1974, pp. 1439-1457.

[9] Cambou, F. et al., "The Zarnitza Rocket Experiment on Electron Injection," *Space Research*, Vol. XV, 1975, edited by M. J. Rycroft, Akademie-Verlag, Berlin p. 491.

[10] Cambou, F. et al., "ARAKS—Controlled or Puzzling Experiment?" *Nature*, Vol. 271, Feb. 1978, pp. 723-726.

[11] O'Neil, R. R., Bien, F., Burt, D., Sandock, J. A., and Stair, A. T. Jr., "Summarized Results of the Artificial Auroral Experiment, Precede," *Journal of Geophysical Research*, Vol. 83, July 1978, pp. 3273-3280.

[12] Galeev, A. A., Mishin, E. V., Sagdeev, E. V., Shapiro, R. Z., and Shevchenko, I. V., "Discharge in the Region Around a Rocket Following Injection of Electron Beams into the Ionosphere," *Soviet Physics Doklady*, Vol. 21, 1976, p. 641 (English translation).

[13] Bernstein, W. et al., "Electron Beam Experiments: The Beam Plasma Discharge at Low Pressures and Magnetic Field Strengths," *Geophysical Research Letters*, Vol. 5, Feb. 1978, pp. 127-130.

[14] Bernstein, W., Leinbach, H., Kellogg, P. J., Monson, S. J., and Hallinan, T., "Further Laboratory Measurements of the Beam-Plasma-Discharge," *Journal of Geophysical Research*, Vol. 84, Dec. 1979, pp. 7271-7278.

[15] Smullin, L. D., "A Review of the Beam-Plasma Discharge," in *Relation Between Laboratory and Space Plasmas*, edited by Hiroshi Kikuchi, D. Reidel Publishing Co., Dordrecht, 1981, pp. 45-66.

[16] Anderson, H. R., Jost, R. J., and Gordenk, J., "Electron Energy Distribution Produced by Beam-Plasma-Discharge," *Artificial Particle Beams (Utilized) in Space Plasma Physics*, edited by B. Grandal, Plenum Publishing Co., New York, 1982, pp. 351-359.

[17] Jost, R. J., Anderson, H. R., and Bernstein, W., "Radial Dependence of the HF Wave Field-Strength in the BPD Column," *Artificial Particle Beams (Utilized) in Space Plasma Physics*, edited by B. Grandal, Plenum Publishing Co., New York, 1982, pp. 431-437.

[18] Szuszczewicz, E. P., Papadopoulos, K., Bernstein, W., Lin, C. S., and Walker, D. N., "Threshold Criteria for a Space-Simulation Beam-Plasma-Discharge," *Journal of Geophysical Research*, Vol. 87, March 1982, pp. 1565-1573.

[19] Szuszczewicz, E. P., Walker, D. N., and Leinbach, H., "Plasma Diffusion in a Space Simulation Beam-Plasma Discharge," *Geophysical Research Letters*, Vol. 6, March 1979, pp. 201-204.

[20] Kellogg, P. J. et al., "Laboratory Simulation of Injection of Particle Beams in the Ionosphere," *Artificial Particle Beams in Space Plasma Physics*, edited by B. Grandal, Plenum Publishing Co., New York, 1982, pp. 289-329.

[21] Rowland, H. L., Change, C. L., and Papadopoulos, K., "Scaling of the Beam-Plasma-Discharge," *Journal of Geophysical Research*, Vol. 86, Oct. 1981, pp. 9215-9218.

[22] Papadopoulos, K., "Theory of Beam-Plasma Discharge," *Artificial Particle Beams (Utilized) in Space Plasma Physics*, edited by B. Grandal, Plenum Publishing Co., New York, 1982, pp. 505-524.

[23] Linson, L. M. and Papadopoulos, K., "Theoretical Support of the Spacelab Instrument/Experiment Definition of a Theoretical and Experimental Study of Beam-Plasma Physics (TEBPP)," Science Applications Inc., La Jolla, Calif., Report No. LAPS 76/SAI-023-081-316-LJ, Sept. 1981.

[24] Szuszczewicz, E. P. and Lin, C. S., "Time-Dependent Plasma Behavior Triggered by a Pulsed Electron Gun Under Conditions of Beam-Plasma-Discharge," *Artificial Particle Beams in Space Plasma Physics*, edited by B. Grandal, Plenum Publishing Co., New York, 1982, pp. 361-370.

[25] Obayashi, T., "Space Experiments with Particle Accelerators: SEPAC Program for the First Spacelab Mission," in *Relation Between Laboratory and Space Plasmas*, edited by Hiroshi Kikuchi, D. Reidel Publishing Co., Dordrecht, 1981, pp. 299-326.

[26] Anderson, H. R. et al., "Theoretical and Experimental Study of Beam-Plasma-Physics Using Shuttle/Spacelab for the Experiments," Dept. of Space Physics and Astronomy, Rice Univ., Houston, Tex., NASA Proposal, Nov. 1978.

[27] Anderson, H. R. and Bernstein, W., "Theoretical and Experimental Beam-Plasma-Physics (TEBPP): Summary of Definition Study for Requirements Review," Science Applications Inc., Bellevue, Wash., Sept. 1981.

[28] Banks, P. M., Raitt, W. J., and Denig, W. F., "Studies of Beam-Plasma Interactions in a Space Simulation Chamber Using Prototype Space-Shuttle Instruments," *Artificial Particle Beams in Space Plasma Physics*, edited by B. Grandal, Plenum Publishing Co., New York, 1982, pp. 393-404.

[29] Szuszczewicz, E. P. and Takacs, P. Z., "Magnetosheath Effects on Cylindrical Langmuir Probes," *Physics of Fluids*, Vol. 22, Dec. 1979, pp. 2424-2429.

[30] Linson, L. and Papadopoulos, K., Private communication, Science Applications Inc., La Jolla, Calif., 1981.