Nonlinear Plasma Effects of Electron Beams Injected in the Ionosphere: Observations and Theory

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Active experiments in space: Past, present, and future
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OUTLINE

- Unexpected (nonlinear) effects in ARAKS, Zarnitsa-2, Echo, Polar-5, … rocket experiments with electron beams
  - Artificial Aurora and near-rocket glow
  - Artificial radio emission
  - Suprathermal electrons
  - Elevated electron temperature
  - Beam scattering and prompt electron echo (PEE)

- Beam-Plasma discharge theory
  - Threshold (beam energy, current, pitch angle, and neutral density)
  - Saturation: Beam-trapping and Strong Langmuir Turbulence
  - Optical and radio emissions from the BPD region
  - Artificial auroral rays and natural (Enhanced) aurora

- Summary
  - Based on E. Mishin et al. (1989), Interaction of electron fluxes with the ionospheric plasma, Hydrometeoizdat, Leningrad (in Russian).
ARAKS, ECHO-7, Electron 2, Polar 5

- On-site UHF radio receivers

Winckler, 1989

Electron 2 mother-daughter experiment

10-100 mA
2-10 ms pulses

Plasma source 5A

similar to Polar 5 [Grandal et al., 1980]

“mother” - “daughter(s)” experiments
Zarnitsa-2 (Aurora-2)
Dokukin et al., 1981

- Electron beam pulses
- 9.3 keV 270 mA on the upleg 109 to 136 km
- 7 keV 450 mA 136 to 154 km (apogee) and to 82 km

5 A 1.5 km s⁻¹
Collisional (single-particle) interaction in the E/F-region ionosphere

Beam (primary) electrons excite & ionize neutral particles via collisions (Beam-Atmosphere Interaction)

Luminosity altitude-profile calculated for $\varepsilon_b = 7.2$ keV by Monte Carlo method. The dashed line shows MSIS neutral density.

- Peak altitude and thickness are explicitly determined by the electron beam energy $\varepsilon_b$

Beam ($\text{primary}$) electrons excite & ionize neutral particles via collisions

$\text{(Beam-Atmosphere Interaction)}$

Energy dissipation rate
(Bethe's formula)

$$\frac{d\varepsilon_b}{dz} \approx -\varepsilon_b/l_b \propto N(z)$$

$\Phi(\varepsilon) \propto \varepsilon^{-3.5}$

$\sim 6 -- 300 \text{ eV}$

Flux of suprathermal (secondary) electrons

defines brightness and colors of auroral glow, e.g.,

the red-to-blue ratio

$L_b [\text{km}] \approx 5 \frac{N[120 \text{km}]}{N} \sqrt{\varepsilon_b [\text{keV}]}$

$Q_\lambda = N \int \sigma_\lambda(\varepsilon)\Phi(\varepsilon, \vartheta) d\Omega d\varepsilon$

Excitation/ionization rate
Optical emissions

Zarnitsa-2
Low-light TV Observations

Near rocket glow
ellipse 300-500 x 50 m
radar and optical data

ECHO-7
The Echo 7 beam near 150 km altitude

ACCELERATOR

AA rays
Near-rocket glow vs. altitude

Greatly exceeds Monte Carlo (single-particle) values near the rocket.
Near-rocket glow

Shape & dimensions are similar to Zarnitsa-2

- Greatly exceeds Monte Carlo (single-particle) values near the rocket
Beam Plasma Discharge

The HF ($\omega_n \gg \nu_e$) breakdown criterion or Townsend condition:

$$\tau_{\text{loss}} > \tau_{\text{heating}} (\varepsilon \sim \varepsilon_{\text{ion}}) + \tau_{\text{ionization}}$$

**electron lifetime**

**elastic collisions**

**heated electrons**

**collisional heating** $\varepsilon_{\text{ion}} \sim \nu_e(\varepsilon) \frac{e^2 E_0^2}{3m\omega_0^2}$

The ionosphere is a weakly ionized plasma $\omega_{p0} > \omega_{ce}$

In BPD, the waves are excited by the beam.

First, beam-plasma instability (BPI) must develop:

Let's $n_b^*$ is the threshold beam density for BPI.

At $n_b > n_b^*$, BPD is self-sustained if:

- **heated bulk** $n_e \nu_{ion}(T_e)$
- **accelerated** $n_{tail} \nu_{ion}^{tail} > n_b \nu_{ion}(\varepsilon_b)$

**Ionization cross-section in $7.5 \times 10^{-17} \text{ cm}^2$**

$\gamma_b(n_b, n_0) > \frac{\nu_e}{2} \propto N_n$
Beam Plasma Discharge near a rocket

**BPI is much faster than the macroscopic processes**

\[
\tau_{BPI} \ll \tau_{\text{ionization}}, \tau_{\text{heating}}, \tau_{\text{loss}}
\]

- Steady state \( W = \left\langle \frac{|E|^2}{8\pi} \right\rangle = \alpha_b n_b \varepsilon_b \)
- \( \alpha_b \) depends on the BPI nonlinear saturation

Let’s neglect ionization by the accelerated tail electrons

- **Townsend condition**
  
  \[
  \tau_{\text{heating}} \sim \frac{(3 - 5) n_e \varepsilon_{ion}}{n_e \varepsilon_{ion} \alpha_b n_b \varepsilon_b} \lesssim \tau_{\text{loss}} = \frac{\text{BPD radius}}{\rho_{\perp}}, \frac{V_{R\perp}}{\text{rocket speed}} \perp B_0
  \]

- The BPD maximum density

\[
\frac{n_e}{n_b} \sim \frac{\nu_e(\varepsilon_{ion})}{3 - 5 \varepsilon_{ion} V_{R\perp} \rho_{\perp}} \propto \frac{I_b N_n}{V_{R\perp}}
\]
Zarnitsa-2: UHF radio emission

Dokukin et al., 1981

power flux (1-2) $10^{-20}$ W/m²Hz
power 30-100 W
1% - 3% beam power
Beam Plasma Interaction

Beam structure

- The beam is not "locked" by the spatial charge (virtual cathode) at the beam currents

\[ I_b \ll I_c = \frac{v_b \varepsilon_b}{e} = 30 \left(\frac{\varepsilon_b [\text{keV}]}{10}\right)^{3/2} [\text{A}] \]

- If \( n_b^{(0)} \gg n_0 \), the beam expands due to electrostatic repulsion until \( n_b(z_*) \leq n_0 \) at \( z > z_* \sim \frac{v_b}{\omega_{p0}} \)

- The beam radius and effective pitch-angle at \( z_* \)

\[ \rho_\perp(z_*) = \left(\frac{I_b}{I_c}\right)^{1/2} \frac{v_b}{\omega_{p0}} \]

\[ \theta_c = \frac{\omega_{ce} \left(\frac{I_b}{I_c}\right)^{1/2}}{\omega_{p0}} \ll 1 \]

- For injections at \( \theta_0 \gg \theta_c \), the electrostatic repulsion ends at

\[ z^{**} \sim \frac{v_b}{\omega_{p0}} \cdot \theta_c \]

resulting in a hollow cylinder

\[ \rho_{ce} - \Delta \rho \leq \rho \leq \rho_{ce} = \frac{v_b}{\omega_{ce}} \sin \theta_0 \]
Beam Distribution Function

- Bump-in-tail in \parallel direction and beam of "oscillators" in \perp direction (el. ring)
- Instabilities of a radially bounded beam at small and large injection pitch-angles

\[ f_b(v, \rho) = n_b(\rho) \begin{cases} 0 & \text{at } \rho > \rho_\perp \\ f_\parallel(\frac{v_z - u_b}{\Delta u}) f_\perp(\frac{v_\perp - v_{b\perp}}{\Delta v_\perp}) & \text{at } \rho \leq \rho_\perp \end{cases} \]

- BPD diameter \( R_{BPD} \) is the wave excitation region \( \perp B_0 \)

- Narrow beam, \( \rho_\perp \ll \frac{u_b}{\omega p_0} \) at \( \theta_0 \leq \theta_c \)

\[ R_{BPD} \sim \left( \frac{I_e}{I_b} \right)^{1/4} \frac{u_b}{\omega_{ce}} \gg \rho_{ce} \]

- Linear theory: Alekhin, Karpman, Ryutov, Sagdeev, 1972
- Lab. experiments: Jost et al., 1982; Bernstein et al., 1983
Modulation by the rocket spin

The variation of the radioemission spectrum due to the rocket spin

dependence of the 75-50 MHz delay on the injecton pitch-angle

Radioemission during one rocket's revolution

Mishin and Ruzhin, 1980
BPD initial stage

Bump-in-tail instability at $\Delta u/u_b < (n_b/n_e)^{1/3}$

$J_1(\xi_j) = 0$

$\gamma_h \sim \left(\frac{n_b}{n_e}\right)^{1/3} \left(1 + \left(\frac{\xi_j}{k_0 \rho_\perp}\right)^2\right)^{-1/3}$

$\gamma_h \sim \omega_p 0 \left(\frac{n_b \omega_p 0}{n_0 \omega_c e}\right)^{1/2}$

Saturation due to trapping of the beam electrons

$W_0 = \frac{|E_0|^2}{8\pi} \sim n_b \varepsilon_b \cos^2 \theta_0 \left(\frac{\gamma_h^0}{\omega_p 0}\right)^{1/2}$

$l_\parallel \sim l_h^0 \sim 4\pi \frac{u_b}{\gamma_h^0} \ll \frac{u_b}{\nu_b}$

$W_0 \gg n_0 T_e^0 \rightarrow \text{Aperiodic instability saturated by trapping of the bulk electrons}$

$T_e \rightarrow W_0/n_0$

[DeGroot and Katz, 1973]
BPD development

- Quasi-oscillatory process: Rise → Saturation → Heating → Suppression (due to conversion) → Rise, etc.
- At each step, the beam propagates through the "suppression" zone farther from the rocket

- \( T_e^{\text{heat}} > \varepsilon_{\text{ion}} \) at
  \[
  I_b > I_\ast = \left( \frac{\omega_p 0}{2 \omega_\infty} \right)^{3/2} \left( \frac{\varepsilon_b}{10} \right)^{3/4} \sin^{3/2} \theta_0
  \]

- Townsend condition
  \[
  \nu_{\text{ion}}(T_e^{\text{heat}}) > \tau_{\text{loss}}^{-1} = \frac{V_{R\perp}}{R_{BPD}}
  \]

- \( N_n > N_{\text{thr}} = 3 \cdot 10^{10} \left( \frac{10}{\varepsilon_b} \right)^{1/2} \frac{\varepsilon_{\text{ion}}}{T_e^{\text{heat}}} B_0 [G] V_{R\perp} [\text{km/s}] \)
ARAKS: Signal from a ground receiver at 50 MHz

Delay of the 50-MHz signal relative to the injection pulse

Power flux: $(1-2) \times 10^{-20} \text{ W/m}^2\text{Hz}$

Power: 30-100 W

1% - 3% beam power

Consistent with the BPD ionization rate

Mishin and Ruzhin, 1980
Altitude and neutral density range over which BPD is expected [Linson, 1982]

The electron temperature near the ARAKS rocket from the RPA data

Greatly-elevated electron temperature

\[ n_e > n_\ast = n_b \frac{\varepsilon_b}{\varepsilon_{i\text{on}}} \sim 10^3 n_b \]
Strong Langmuir Turbulence

Waves are trapped inside density cavities,
Collapsing cavities transfer the wave energy toward short scales,
In saturation, the wave energy is

\[
n_b^{(th)} \approx 10^{-6} \left(1 + \frac{2\nu_e \varepsilon_b}{3\omega_p T_e}\right) n_e
\]

\[
W_{SLT} \approx \sqrt{\frac{3m \gamma_b}{M \omega_p}} n_e T_e \ll W_\infty
\]

Ionization by accelerated electrons

Short-scale waves are absorbed by plasma electrons, leading to non-Maxwellian suprathermals

\[
F_a(\varepsilon ||) \approx \frac{2p_a - 1}{\nu_{min}} n_a \left(\frac{\varepsilon_{min}}{\varepsilon ||}\right)^{p_a}
\]

(p_a \approx 0.8-1)

The electron distribution function and the simulated Langmuir spectrum [Sotnikov et al., 1992]
Suprathermal Electrons

- Flat suprathermal spectra
- Many more suprathermal electrons than collisional values
Artificial Aurora Rays

Mishin et al., 1981
As the collapse rate is smaller than $\Gamma_b$, the beam can excite waves but the trapped waves are damped faster than collapsing. As nonlinear transfer is reduced, the Langmuir wave energy grows until collapse will be possible.

The limiting collision frequency is given by:

$$\nu_* = \omega_p \left( \frac{m \Gamma_b}{M \omega_p} \right)^{1/2}$$

Wave energy density is:

$$\frac{W_L}{n_e T_e} \approx \frac{3M}{m} \left( \frac{\nu_e}{\omega_p} \right)^2$$

Ionization by accelerated electrons is:

$$q_{ion}^{(t)} \approx 10 \nu_e(T_e) n_b \frac{T_e}{\varepsilon_{ion}} \left( \frac{\varepsilon_b}{\Delta \varepsilon_{||}} \right)^2$$

Volokitin and Mishin, 1979
Plasma Turbulence Layer

Schematic of altitude-profiles

Collisional interaction

Collisionless SLT

EISCAT UHF ISR

55 events

\( T_e \)

\( n_e \)

Schlezier et al., GRL 1997

Mishin and Telegin, 1989

Mishin and Telegin, 1989
Enhanced Aurora

Double-peaked auroral rays

Dzyubenko et al., 1980

sharp upper boundary

Hallinan et al., 1995
Beam-Plasma Instability

Natural Auroras

Beam of field-aligned electrons over the II class arc [Arnoldy et al., 1974]

Inverse Landau damping

\[ \Gamma_b \sim \omega_p \frac{n_b}{n_e} \left( \frac{\varepsilon_b}{\Delta\varepsilon_\parallel} \right)^2 - \nu_e(T_e) \]

Bump-in-tail

Bump-in-tail

Bryant et al., 1978

Observed spectrum

Primary spectrum + reflected albedo

Primary spectrum

N = 0.635 cm\(^{-3}\)

E\(_e\) = 10.2 keV

\(\frac{1}{\varepsilon} \)

Electron intensity cm\(^{-2}\) s\(^{-1}\) ster\(^{-1}\) keV\(^{-1}\)

\(\theta_0 \leq 10^\circ\)
Beam scattering near the rocket

- Greatly exceeds collisional scattering near the rocket
- Prompt Electron Echo (PEE) [Hendrikson et al., 1975; Winckler et al., 1975; Maehlmn et al., 1980; Wilhelm et al., 1985] with time delays < 100 ms during upward beam injections
Prompt Electron Echo SLT model

\[ \frac{\partial \langle f \rangle}{\partial t} + \mu v \frac{\partial \langle f \rangle}{\partial s} - \frac{1 - \mu^2}{v} \frac{v^2}{2B} \frac{\partial B}{\partial s} \frac{\partial \langle f \rangle}{\partial \mu} = \langle S \rangle \]

\[ \langle f \rangle = \frac{1}{2\pi} \int_0^{2\pi} f(\phi)d\phi \]

\( \mu = \cos \theta \), \( s \) is the coordinate along the geomagnetic field:

\[ \langle S \rangle_{ep} = \nu_{eff} \frac{\partial}{\partial \mu} \left[ (1 - \mu^2) \frac{\partial f}{\partial \mu} \right] \]

\[ \nu_{eff} = \omega_p \left( \frac{W_L}{n_e T_e k_L r_D} \right) \left( \frac{T_e}{E_b} \right)^{3/2} \approx \omega_p \left( \frac{n_b}{n_e} \right)^{1/2} \left( \frac{u}{\Delta u} \right) \left( \frac{T_e}{E_b} \right)^{3/2} \]

\[ k_L \gg k_0 = \frac{\omega_p}{v_0} \]

\[ \Phi^+(E) = \int_0^1 \mu \psi(E, \mu)d\mu \]

Mishin et al, 1989
PEE calculations

Albedo at the source altitude (160 km) for upward injection

\[ \frac{\Phi^+}{\Phi^-} \]

Mishin et al., GA 1993
Khazanov et al., GRL 1993

\[ \nu_{\text{eff}} = 10^3 \text{ s}^{-1} \]

\[ \nu_{\text{eff}} = 10^4 \text{ s}^{-1} \]

\[ E_b = 10 \text{ keV} \]

Pitch-angle distribution 20 km above upward injection

\[ \Phi^+(E) = \int_{0}^{1} \mu \psi(E, \mu) d\mu \]
Strong LT in auroral plasma

\[
 n_b^{(th)} \approx 10^{-6} \left( 1 + \frac{2\nu_e \varepsilon_b}{3\omega_p T_e} \right) n_e
\]

**Flat accelerated electron spectrum**

\[
 F_a(\varepsilon_{||}) \approx \frac{2p_a - 1}{\nu_{\text{min}}} n_a \left( \frac{\varepsilon_{\text{min}}}{\varepsilon_{||}} \right)^{p_a}
\]

\( p_a \approx 0.8-1 \)

**Joining condition**

\[
 F_a(\varepsilon_{\text{min}}) = F_0(\varepsilon_{\text{min}})
\]

**Acceleration of secondary electrons**

\[
 \varepsilon_{\text{min}} \approx 30 (W_L/n_s T_e)^{-2/5} \text{[eV]}
\]

\( n_s \) is the density of secondary electrons

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Mishin & Telegin, 1989

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DISTRIBUTION STATEMENT A – Unclassified, Unlimited Distribution
SUMMARY

- Limited survey of nonlinear beam-plasma interactions during active experiments with electron beam injections in the ionosphere is given.
- Artificial aurora and near-rocket glow, artificial radio emission, accelerated and albedo electrons, rocket potential and electron temperature near a rocket, and telemetry damping.
- Theory of beam-plasma discharge
- Enhanced aurora
Collisionless Beam Plasma Interaction

Inverse Landau damping

\[ \Gamma_b \sim \omega_p \frac{\pi n_b}{n_e} \left( \frac{\varepsilon_b}{\Delta \varepsilon} \right)^2 \quad - \nu_e(T_e) \]

Langmuir waves gain energy at the expense of the beam

\[ n_b \frac{d}{dt} \langle \varepsilon \rangle_b \simeq - \frac{d}{dt} \sum_k W_k \simeq -\Gamma_b W_r \]

Relaxation length

\[ l_r \simeq \frac{\Delta \nu \infty}{\gamma_b} \frac{n_b \varepsilon_b}{W_r} \]

QL-saturated wave energy (no wave-wave coupling)

\[ W_\infty \simeq 0.1 n_b \varepsilon_b \frac{\varepsilon_b}{T_e} \gg n_e T_e \]