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ELECTRON FLUXES SYNCHROTRON RADIATION IN THE EARTH MIDDLE LATITUDE IONOSPHERE

A.V. Agapitov, S.I. Musatenko (*Taras Shevchenko Kiev National University, Ukraine)*

Abstract. Middle latitude radiofluxes in VHF and UHF ranges with drift frequencies are considered. They were interpreted as monoenergetic near relativistic electron beams penetrating from the magnetosphere to the ionosphere layer *E*. Radiation in high harmonics (11th, 12th, and 13th) was detected. Numerical simulation of the electron beam dynamics in the Earth's magnetosphere has been performed, with analyzing the modeling spectra of different energy electron beams. The parameters of the beams are obtained.

Introduction

Middle latitude and auroral ionosphere radionoise has been registered in VHF and UHF ranges for a few decades [1, 2, 3, 4]. Their relation to solar and geomagnetic activity was established, the morphological and spectral classification of events was obtained. But, in fact, only average characteristics are clarified. There are many problems in the study of separate events and measurements with high temporal and spectral resolution. The purpose of the present research is to study the parameters of middle latitude radio bursts with drifting frequency, based on Troizk - Pushchino complex experiment [5]. We also perform modeling of penetration and movement of charged particle beams in the ionosphere as well as the simulation of electron beam dynamic spectra, based on cyclotron (synchrotron) mechanism of radiation and compare the results of modeling to observations.

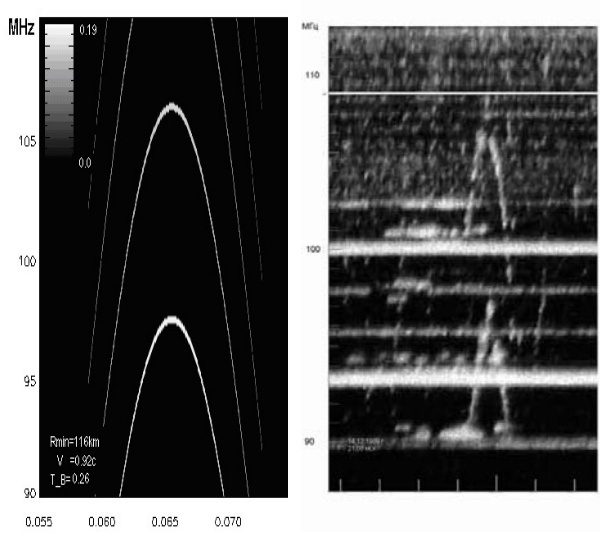

Fig. 1. Dynamic radiation spectra derived from the simulation (a) and experimental dynamic radiation spectra (b) of electron beam reflection in the ionosphere. Frequency ranges of the 11th and 12th harmonics are shown.

Observation of high-energy electron beam radiation

The observed dynamic spectra of bursts with drifting frequency (called sweepers by the authors of [6, 7]) are given in Fig. 1a. We interpret them as charged particle beams, propagating and reflecting in the ionosphere. A distinctive radiation frequency drift corresponds to magnetic field change along particle trajectory such that $B/\sin^2\alpha = const$. Only several events are found which are close to ideal; then we can follow the entry of a beam into the ionosphere, reflection and steaming-out. As a rule, only a part of the beam trajectory is detected. It depends on the parameters of the radiotelescope polar pattern [8].

With the time resolution of 0.02 s, these effects should be shown, especially when scanning in frequency. In fact, we have registered 10 - 13 harmonics. The events were successfully observed during quiet Sun and low geomagnetic disturbance (K_p index was about 2-3). The frequency spread can be explained by the beam parameter spread.

Thus the conditions for modeling radiation of harmonics synchrotron, the radiation of a relativistic electron beam can be the following:

- Typical frequency drift;

- Reflections of beams at ionosphere altitudes;
- High intensity of beams and low particle temperature in a beam.

Numerical simulation of electron beam radiation in the Earth' magnetic field (in the dipolar approximation)

The Earth's magnetic field in the inner magnetosphere is approximately dipolar. For a stationary magnetic field it is possible to use magnetic potential *U* such that $\vec{B} = -\nabla U$. The potential of magnetic dipole field is determined by the expression $U = -M \sin\theta / r^2$, where *M* is the dipole magnetic moment (for geomagnetic dipole ***M****=8.02E25* Gs/м^3), ***r*** the geocentric distance in meters, θ the magnetic latitude. The modulus of the intensity of the magnetic field in this case is $\left|\vec{B}\right| = \frac{M}{r^3}\left(1 + 3\sin^2\theta\right)^{1/2}$. The equation of a dipole magnetic field line is $R = L\cos^2\theta$, where *L* is the McIlwain parameter or geocentric distance measured in the Earth's radii from the center of the Earth to the point where the magnetic field line crosses the geomagnetic equatorial plane. The magnetic field along a field line varies from 0.05 to 0.5 Gs.

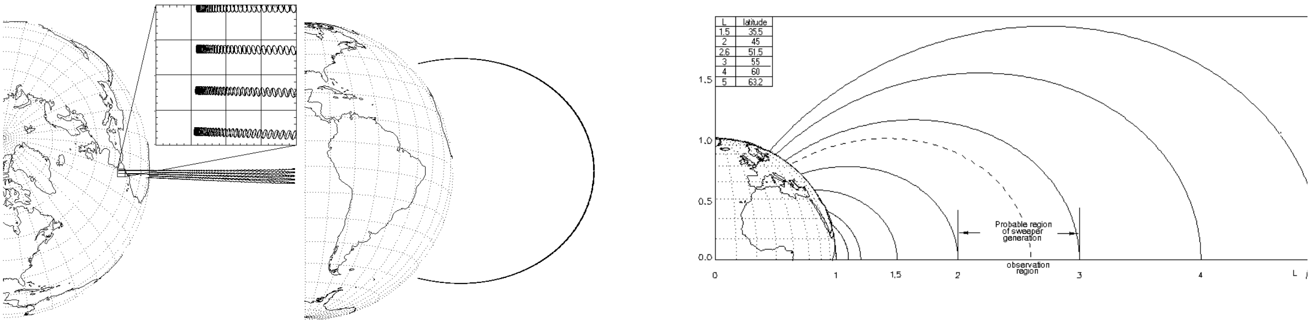

Fig. 2 (a) Movement of charged particles in the dipole magnetic field. The reflection point is shown on a large scale; **(b)** The region of possible generation of monoenergetic electron beams. The field line that refers to the measurements is shown by the dotted line (L=2.6).

However, in a slowly variable magnetic field (the spatial and temporal scales of variations are much greater than the radius and period of the Larmor rotation) it is possible to use the adiabatic invariants $I_i = \frac{1}{2\pi}\oint p_i dq_i$. The transverse invariant is $I = \frac{1}{2\pi}\oint\left(m\vec{v} + \frac{e}{c}\vec{A}\right)d\vec{l}$, where enters the generalized momentum of a particle in the magnetic field with the vector potential $\vec{A}$. The integration is performed along the trajectory of Larmor rotation. In integrating the first term, one can take into account that v is constant. The integration of the second term can be performed with using the Stoks formula $I = mv_\perp\rho + \frac{e}{2\pi c}\iint rot\vec{A}d\vec{s}$, where the integration region is the circle of Larmor rotation. If the magnetic field along the Larmor circle can be considered as stationary, after substitution $\rho = v_\perp / \omega_B$, one can obtain $I = \frac{3cm}{e}\frac{E_\perp}{B} = const$. This coincides with the magnetic moment of a charged particle in the magnetic field.

The pitch-angle (the angle between the beam velocity vector and magnetic field) varies along a magnetic field line according to the law $\sin^2\alpha = \frac{B}{B_0}\sin^2\alpha_0$, where B_0 and α_0 are the magnetic field amplitude and equatorial pitch-angle, respectively. Thus the magnitude of the critical pitch-angle can be found from the expression $\theta = \arccos\left(1/L\right)^{1/2}$. The charged particles reach the Earth's surface at exceeding critical pitch-angle.

Table 1

Electron beam velocity, in velocity of light units	Bounds oscillation period, in seconds	Minimal Larmor radius, in meters	Azimuth drift during one oscillation, in meters
0.3	0.820	12.5	440
0.5	0.48	20.0	710
0.9	0.26	104.0	3400

The momentum equation for a charged particle in the magnetic field is $\frac{d\vec{p}}{dt} = \frac{e}{c}\left[\vec{v} \times \vec{B}\right]$. It was numerically solved with using the Runge-Kutta technique, dependent on gyrofrequency time step. At the motion in the magnetic field, the modulus of particle velocity does not change. It was used to estimate the calculation accuracy in the simulation. The period of relativistic electron oscillations between the mirror points on L=2.6 is 0.24 s. The oscillation period of the electrons with smaller velocities is equal to $\tau = 0.24 \cdot c/v$. The results of the modeling, which has been performed for L=1.7 agree with those given in [3]. The particles radiate at gyrofrequency f_{Be} and its harmonics $f_m = m\, f_{\mathrm{Be}}$. The radiation intensity rapidly decreases from harmonics to harmonics with ratio $\left(c/v_{\perp}\right)^2$. The parameters of beam motion with various group velocities are given in Table 1. According to the experimental dynamic spectra, the first harmonics should radiate at the frequency of about 8 MHz. It exceeds approximately 6.5 times the maximal frequency obtained without relativistic effects.

Taking into consideration the relativistic Doppler effect, we obtained the group velocity of the beam. It is equal to 0.92 c for the event in Fig.1a [10]. The same velocity is obtained from the analysis of integrated intensity of radiation for various harmonics.

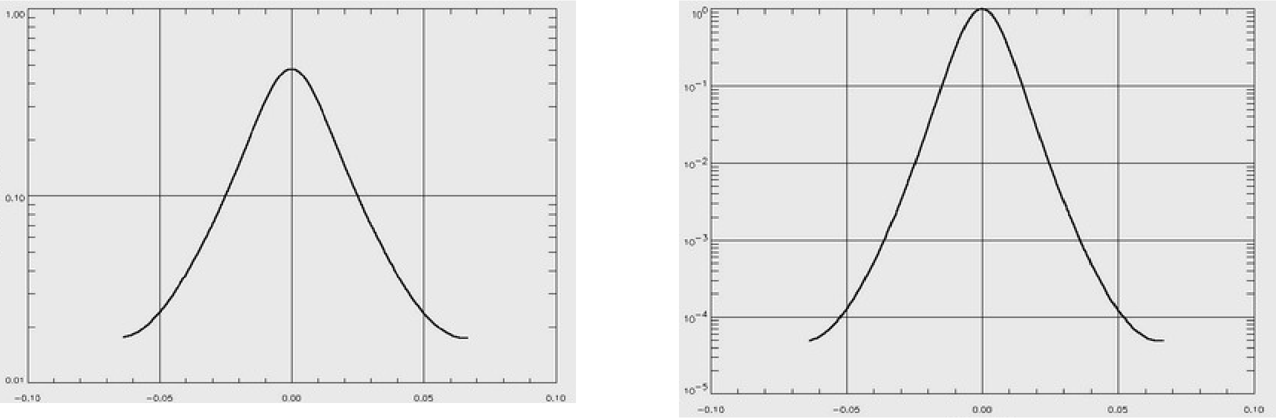

Fig. 3 (a) Dependence of the Earth's magnetic field (in gauss) on time (in seconds). The magnetic field along the trajectory of a particle varies from 0.05 to 0.5 Gs; (b) Dependence of the integrated radiation intensity (in relative units) on time (in seconds). The moment of particle reflection in the ionosphere corresponds to zero time.

The dynamic spectrum of monoenergetic electron beam radiation (the group velocity is 0.92*c*) at the reflection in the ionospheric *E* layer is given. The dynamic temperature of the particles in a beam is lower than 230 *K*, which is confirmed by the absence of harmonics overlapping in the dynamic spectrum. The temperature of the particles obtained from numerical simulation is about 40-80 *K*. The radiation intensity depends on the magnetic field (Fig. 3b) and transverse to the magnetic field velocity component.

Conclusions

In the present study, relativistic electron beam radiation in the E-layer of the Earth's ionosphere is studied. The numerical simulation that we have performed suggests the following results:

1. We propose an approach that enables to find the ionospheric radionoise generated by monoenergetic electron beams. The beam parameters, such as drift velocity, frequency, temperature, equatorial pitch-angle, speed, height of reflection, are determined.
2. A technique for numerical simulation of electron beam penetration to the Earth's ionosphere is developed.
3. It is shown that there is a frequency drift that refers to magnetic field increasing along particle trajectory. The heights of beam reflection correspond to the ionospheric E-layer for the frequencies about 100 MHz.
4. The observed dynamics of the beam is found to be in a qualitative agreement with the results of modeling: the changes in the intensity of radiation depend on the position along the trajectory.
5. A local increase of radiation at the beam reflection point, obtained in modeling, is in a good agreement with that obtained in experiment. In the bottom part of the beam trajectory, other radiation mechanisms are involved (for example, braking).

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