GENERATION OF FIELD-ALIGNED CURRENTS IN SPACE PLASMAS BY ION BUNCHING

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Abstract

Magnetic field aligned currents can be driven in space plasmas by phase bunching of heavy minority ions. Phase bunching can very generally be produced by disturbances which are faster than the ion gyro time, or spatial parameter changes over regions smaller than the ion gyro radius. A model for phase bunching was developed for the CRIT II ionospheric injection experiment, and verified by the measured field and particle data. One particularly interesting finding was that, for strong injections, the driven current system can spontaneously develop a fine structure through a feedback mechanism. This result is applied to a magnetospheric auroral current generator proposed by Rothwell *et al*. Their generator, which is based on a phase bunching mechanism, is found to be in the correct parameter range for fine structuring to occur; we therefore propose that phase bunching with feedback can have relevance for auroral arc structuring.

1. Introduction

Two requirements for phase bunching are that there is a minority population of heavy ions in the plasma, and that there is some discontinuity which is abrupt enough to give finite Larmor radius effects for these minority ions. A very simple example is shown to the right in Fig. 1. The heavy minority ions are here, within a small region, given outwards velocities at a time $t = 0$. Half a gyro period later they have all moved half a gyro orbit and are spread out over a larger volume, and after a full gyro period they gather again within the original small region. The process is obviously repetitive with the gyro frequency.

This periodic motion of the minority ions across the magnetic field represents a periodic time variation in the positive space charge density. If the region has a limited extent $L_{//}$ along the magnetic field, then space charge neutrality can be maintained by field aligned electron currents $\mathbf{i}_{//}$. In order to draw these currents from the ambient plasma some electric field **E** is necessary. As we will see below, these are related to the currents $\mathbf{i}_{//}$ by the Alfvén conductivity, $\Sigma_A = 1/(\mu_0 V_A)$.

For weak injections, this electric field only has a minor influence on the orbits of the ions that are phase bunching. For stronger injections, a feedback will occur (Fig. 1, left panel) and the ion orbits will be influenced by the **E** field. The process is then no longer repetitive on the ion gyro period. Brenning *et al.* [1] studied this situation in a simplified geometry and found that there is a parameter K which can be taken as a measure of the strength of the injection,

$$K = (\Delta n \, e \, \mu_0 \, V_A \, L_{//})/(4B), \qquad (1)$$

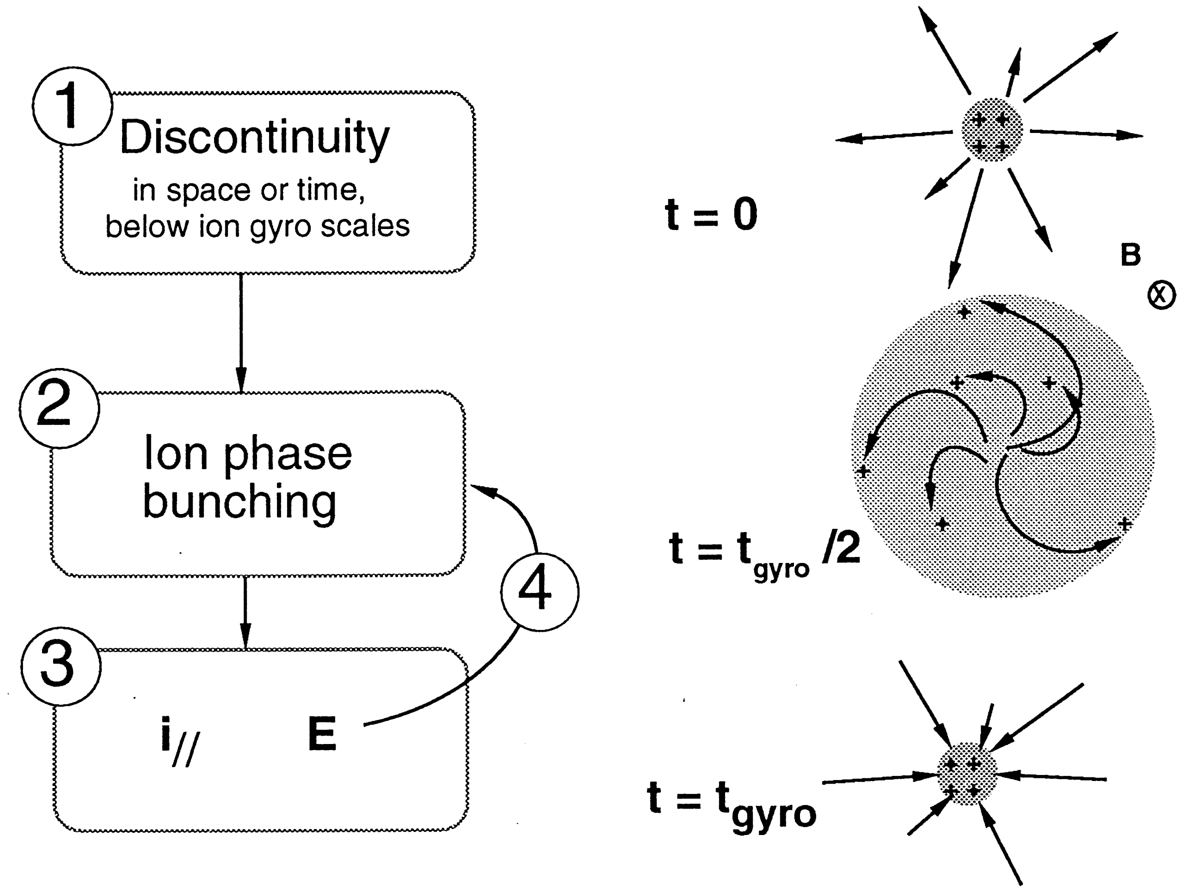

Fig. 1. Left: overview of the phase bunching process. Right: a simple example of phase bunching.

where Δn is the density modulations due to phase bunching and $L_{//}$ is the extent of the phase bunch structures along the magnetic field. Situations with K values below, say, 0.1 can be regarded as weak while for larger K values the feedback of the **E** field on the ion motion becomes increasingly important.

2. Ionospheric injection experiments

Many experiments have been made with neutral clouds which have been injected across the magnetic field in the ionosphere. If there is an ionization mechanism operating, such a cloud acts as a moving source of ions, created at each location at the time when the neutral cloud sweeps by. This process can be regarded as a smooth succession of single injections such as shown to the right in Fig. 1. For weak injections the ions would perform simple gyro motions. There would then, at each location, be an ion density enhancement at even multiples of the gyro time. Due to the motion of the neutral cloud, these density oscillations are phase shifted between the locations. The result is that a sequence of waves of density enhancements is created, moving across **B** with the velocity of the original source, *i.e.*, the injected neutral cloud. Such density waves were seen optically in the G-2 barium release from the CRRES satellite, and explained in terms of ion bunching by Bernhardt *et al.* [2]. This experiment gave a clear demonstration of an essential feature of ion bunching: that the velocity of the phase

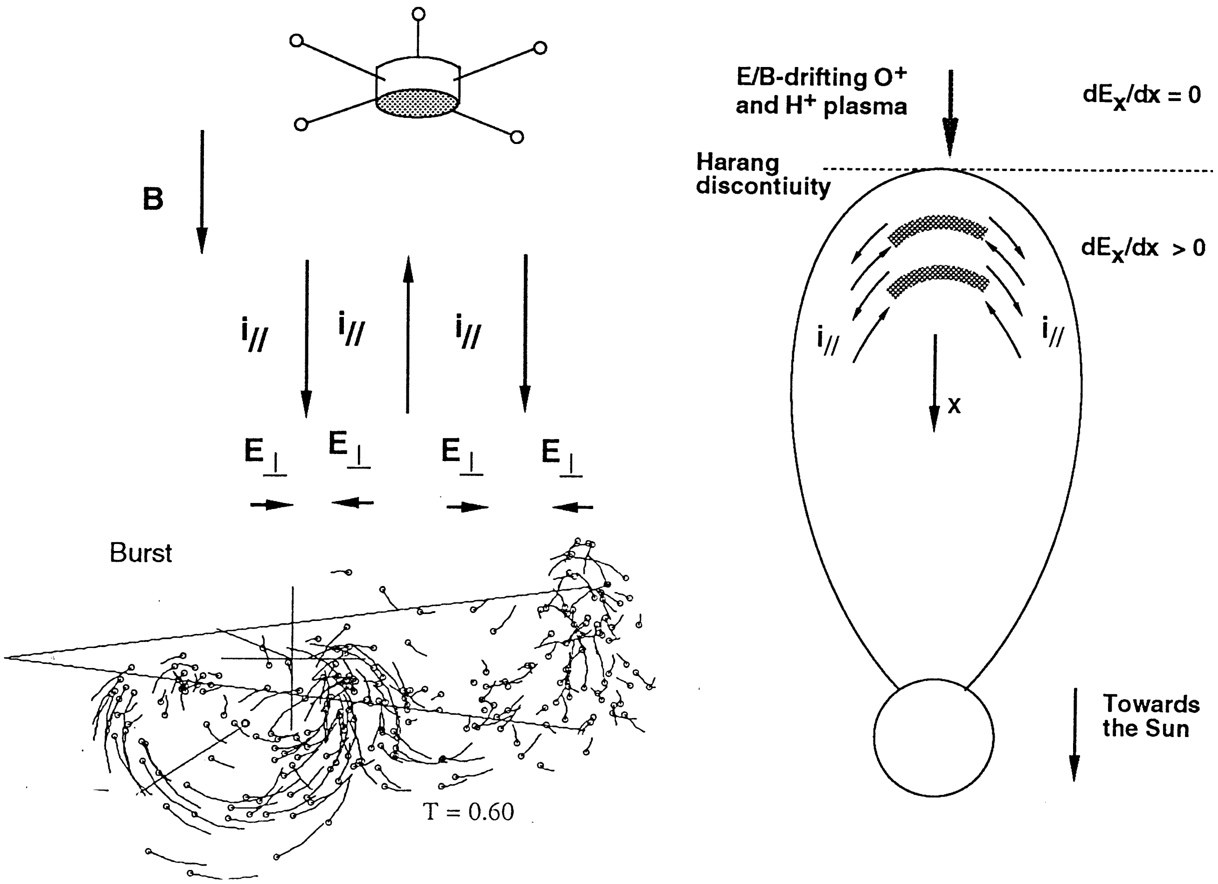

Fig. 2. The CRIT II ionospheric injection experiment. Right: the auroral current generator of [5].

bunch structures is given by the motion of the original disturbance, and is decoupled from the motion of the plasma. This is important in the present context, because the relative motion across **B** between the plasma and the phase bunch structures is the basic reason why they draw field-aligned currents. In the CRIT II ionospheric injection experiment local measurements were made, and it was possible to make - and test - a quantitative model of the ion bunching process. A neutral barium cloud was injected across the magnetic field by a shaped charge explosion. Barium ions were created along the injection path, and formed ion bunch structures as shown at the bottom left of Fig. 2 [1]. There were complete vector measurements of the magnetic and the electric fields, both inside the injection path and, by a sub payload, two km above it along the same magnetic field line. In addition to this, both electron and ion spectra were measured at various pitch angles.

The analysis of the data and the model calculations can be found in [3] and [4]. The most important findings for our discussion here were the following:

• **E** and **B** field measurements at the sub payload fully supported the interpretation that the field aligned currents were carried by shear Alfvén waves [3]. In particular, the expected relationship $\Delta E/\Delta B = V_A$ was verified, which determines the relation between field aligned currents $\mathbf{i}_{//}$ and the perpendicular electric fields in Fig. 2. This relation is essential for correct modelling of the ion bunching process.

• A particle simulation model [4], based on this relation, could as a beginning value problem (i.e., based only on the neutral gas injection parameters an the ionization rate) reproduce both the electric and the magnetic fields and also the very complicated ion spectra of the injected ions. This we take as verification that the model is physically correct.

• Computer experiments with this model showed how the ion motion is influenced by the strengh of the injection, quantified by means of the K value of Eq. 1. A range of K values between 0.02 and 0.23 was investigated (the higher value corresponded to the actual CRIT II situation). For the higher K values in this range, an experimentally observed dramatic fine structuring of the ion bunches was reproduced, with a sharply narrowed ion density enhancement at the leading edge. The simulation model also showed the appearence of electric field modulations at twice and four times the original gyro frequency.

3. Phase bunching and auroral arc structure

The panel to the right in Fig. 2 shows a mechanism proposed by Rothwell *et al.* [5] to act as a current generator in the auroral circuit. In contrast to the transient ionospheric injection experiments described above, this model can produce ion bunches in a steady state situation. Hydrogen plasma with a minority population of oxygen ions drifts from the magnetotail towards the Earth, through a region corresponding to the poleward region of the Harang discontinuity, mapped to the magnetosphere. A change in the gradient of the earthward E field component occurs at the dashed line in Fig. 2. Ensembles of O^+ ions are traced through this region by [5], and found to produce ion bunch structures as schematically shown in Fig. 2.

These structures are closely equivalent to those in the CRIT II experiment shown to the left in Fig. 2. An observer following the magnetospheric E/B - drift through the O^+ density striations would correspond to an observer fixed in the ionospheric rest frame who sees the periodic bunching of the barium ions. The auroral current system proposed by [5] corresponds to the current system which was measured and successfully modelled in CRIT II.

An order-of-magnitude estimate shows that the K value of Eq. (1) probably is around unity for the auroral current generator of Rothwell *et al*. Based on the result from the CRIT II ionospheric experiment, we therefore propose that phase bunching with feedback should be an important process in the auroral current generator of [5], and that it might be one of the mechanisms behind auroral arc fine structuring.

References

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