N O T I C E

THIS DOCUMENT HAS BEEN REPRODUCED FROM
MICROFICHE. ALTHOUGH IT IS RECOGNIZED THAT
CERTAIN PORTIONS ARE ILLEGIBLE, IT IS BEING RELEASED
IN THE INTEREST OF MAKING AVAILABLE AS MUCH
INFORMATION AS POSSIBLE

010430

99503

RECEIVED BY.
ESA - IRS
DATE: 1 4 MAR. 1991
DCAF NO. 0 1 0 4 3 0
PROCESSED BY
☐ NASA STI FACILITY
☐ ESA - IRS ☐ AIAA

VETENSKAP
OCH
KONST

Document for
Entry into ESIS

DTA
FID
MFA   RPA

Department of Plasma Physics

The Royal Institute of Technology
S-100 44 Stockholm SWEDEN

THE COLLECTIVE GYRATION OF A HEAVY ION CLOUD IN A MAGNETIZED PLASMA

N. Brenning, C. Swenson, M. C. Kelley,
J. Providakes and R. Torbert

September 1990

Department of Plasma Physics
The Royal Institute of Technology
S-100 44 Stockholm, Sweden

THE COLLECTIVE GYRATION OF A HEAVY ION CLOUD IN A MAGNETIZED PLASMA

Brenning[1], N., Swenson[2], C., Kelley[2], M. C., Providakes[3], J and Torbert[4], R.

1: Royal Inst. of Technology, S-100 44 Stockholm, Sweden;

2: Cornell University, Ithaca, NY 14835 USA;

3: MITRE Corp., Burlington Road, Bedford, MA 01730-2028 USA;

4: Space Science Center - IEOS, Univ. of New Hampshire, Durham, NH 08324 USA.

Abstract

In both the ionospheric barium injection experiments CRIT I and CRIT II, a long-duration oscillation was seen with a frequency close to the gyro frequency of barium and a time duration of about one second. A model for the phenomenon which was proposed for the CRIT I experiment is here compared to the results from CRIT II which made a much more complete set of measurements. The model follows the motion of a low-β ion cloud through a larger ambient plasma. The internal field of the model is close to antiparallel to the injection direction v_i but slightly tilted towards the self-polarization direction $E_P = -v_i \times B$. As the ions move across the magnetic field, the space charge is continuously neutralized by magnetic-field aligned electron currents from the ambient ionosphere, drawn by the divergence in the perpendicular electric field. These currents give a perturbation of the magnetic field related to the electric field perturbation by $\Delta E/\Delta B \approx V_A$. The model predictions agree quite well with the observed vector directions, field strengths, and decay times of the electric and magnetic fields in CRIT II. The possibility to extend the model to the active region, where the ions are produced in this type of self-ionizing injection experiments, is discussed.

1. Introduction

In the ionospheric injection experiments CRIT I from 1987 and CRIT II from 1989, which were designed to study the Critical Ionization Velocity (CIV) mechanism by means of fast jets of neutral barium in the ionosphere, a long-duration oscillation with close to the barium ion gyro frequency was observed. In the following we will call these the barium oscillation. These barium oscillations had a time duration of 2 - 4 full cycles with decreasing amplitude and followed after the passage of the fastest and densest part of the jet, where most of the ionization and also most of the higher-frequency wave activity was observed. The CRIT I data from 1987 was sufficiently detailed to permit the formulation of the barium swarm model for the phenomenon (Brenning *et al.*, 1990a), which will be briefly described below. However the data set from CRIT I was limited; it did not for example contain reliable magnetic field measurements, density measurements, or ion flux measurements. For this reason the observational support for the model had to be patched together using measurements made by the CRIT I payloads, optical observations from ground, and observations from the earlier Porcupine experiment. There was also a competing model (Providakes *et al.*, 1990) which explained the barium oscillations in CRIT I as a kinetic Alfvén wave.

The CRIT II rocket which was launched from Wallops Island on May 4, 1989, produced a much more complete data set, and the barium swarm model using this data actually becomes over-determined to a high degree. The purpose of the present paper is twofold: first we will apply the barium swarm model to the observations of the long-duration barium oscillation in CRIT II and show that it agrees very well with the observations. This will give us some confidence that we physically understand the electric, current, and magnetic field patterns around a cloud of heavy ions which moves in a non-turbulent and orderly fashion through the ionosphere. The second step is to investigate to what degree we can apply this understanding also to the quasi-dc electric and magnetic fields observed in the fast part of the barium jet, which is the period of most interest in these experiments. We will call this the active region; it was in CRIT II characterized by rapid ionization, strong magnetic-field aligned electric fields, and strong wave activity, all of which makes it difficult to construct a theory. The barium swarm model will give us the expected quasi-dc electric and magnetic field in the absence of these complications, which is a useful basis for further development.

2. Description of CRIT I and CRIT II

The geometries for the CRIT I and the CRIT II experiment were very similar. Both experiments consisted of two separate shaped-charge releases of barium in fast streams with 14 degrees full opening angle and peak velocity 13 km/s, made at about 400 km altitude. The geometry for the CRIT II experiment is shown in Fig. 1, which also defines the magnetic coordinate system to be used later in the text (from Swenson et al., 1990a). The injections were at 57 degrees angle to the magnetic field and were aimed directly at the main payload which made plasma density measurements with high time resolution, vector measurements of the electric and magnetic fields, and measurements of the ion and electron particle fluxes in the range 1 - 1000 eV/q. The ion spectra were taken in ten different look directions (Torbert et al., 1990). A sub payload was positioned a few km above from the main payload close to the same magnetic field line, and measured a similar but somewhat smaller data set.

The purpose of the CRIT experiments was to examine the CIV hypothesis by Alfvén (1954), which states that an anomalously efficient ionization process should be expected when the perpendicular velocity component of the neutral barium atoms is high enough to make ionization energetically possible. For this reason the releases were made in shadow to exclude photoionization. Due to the angle between the injection direction and the magnetic field, the ions continued upwards along the field, past the sub payload and into the sunlight, where an inventory of the ion production was made by ground-based optical observations (Stenbaek-Nielsen et al., 1990).

Apart from minor geometrical differences (and a much smaller data set from CRIT I), there was as far as we know only one significant difference between the experimental conditions of CRIT I and CRIT II: both the neutral oxygen and the plasma density were higher in CRIT II than in CRIT I, the plasma density with as much as a factor 10-20. Probably as a result of this density difference, CRIT II ignited in a much more efficient fashion, and produced a region of high ionization extending 40-50 km from the injection point. The electric field measurements of the payloads showed both a similarity and a difference: the long-duration barium oscillations were similar in CRIT I and CRIT II, with electric field amplitudes in the range 10-60 mV/m and a time duration of 1-3 cycles. The electric field inside the stream in the active region on the other hand was much different: in CRIT I there were quasi-dc electric fields with 800 mV/m amplitude in burst 1 and 200 mV/m in burst 2, which have been described by Kelley et al. (1990) and are discussed by Brenning et al. (1990b). The term quasi-dc here refers to an electric field which varied on the comparatively slow time scale of the neutral barium stream, as opposed to the waves in the active region which had higher frequencies. In spite of the much stronger ionization, the corresponding quasi-dc fields

in CRIT II were a factor 5-20 weaker (Swenson et al., 1990a,b).

3. The Barium Swarm Model

The physical idea behind the barium swarm model of Brenning et al. (1990a) is that the barium ions will have some phase and density correlation when they leave the barium stream and therefore collectively spiral up the field lines in a swarm as illustrated in Fig. 2. The barium oscillations are seen when this swarm repeatedly (on the ion gyro frequency) crosses the field line of the payloads. A good phase correlation of the ions can be expected if the time duration τ_{active} of the active region (where the ions are produced) is short compared to the ion gyro time $1/\Omega_{gi}$. In burst 1 of CRIT II this is the case, $\tau_{active}\Omega_{gi} = 1.2$. A second reason for good phase correlation is if the width W of the barium stream is small compared to the barium gyro radius r_{gi}. This quantity depends on the ion velocity; if the ions keep the neutral velocity after ionization, then $W/r_{gi} = 1.2$ in burst 1. In burst 2 $\tau_{active}\Omega_{gi} = 2.4$ and $W/r_{gi} = 3$, and the phase correlation should be less good.

Due to their large gyro radius, typically a few hundred meters, these phase-correlated ions constitute a cross-field ion current which is closed by magnetic-field aligned currents $i_{//}$ from the ambient ionosphere. In the barium swarm model this current $i_{//}$ is drawn by an electric field pattern which is maintained by the ion motion across **B** and which launches Alfvén waves in both directions along the magnetic field. The motion and the electric and current pattern around such a cloud of heavy ions is studied under the simplifying assumptions that the cross section of the cloud across **B** is a circular cylinder, and that the ions are all perfectly in phase. The model is shown in Fig. 3. In reality the barium swarm must have a more complicated cross section across the magnetic field, and also some velocity and phase spread, but for a physical understanding of the process such a simple model is useful. The main result of Brenning et al. (1990a) is that the cloud motion is characterized by the K parameter (in MKS units)

$$K = \frac{\Delta n\, e\, \mu_0\, V_A\, L_{//}}{4\, B}$$

(1)

where Δn is the density in the barium swarm, V_A is the Alfvén velocity in the ambient ionosphere, and $L_{//}$ is the extent of the ion cloud along **B**. Fig. 4 illustrates cloud motion for dense, intermediate and thin clouds, where the separation between these types is based on the K value. For a dense cloud $K >> 1$, and the ions continue "skidding" in the original direction of motion a distance about $L_{skid} = Kr_{gi}$, where r_{gi} is the barium ion gyro radius. The ambient plasma in the flux tube through the cloud is dragged with the motion, and the internal field in the cloud is close to the well-known self-polarization field of a dense cloud, $E_p = -V_i \times B$. For a cloud of intermediate

density $K = 1$ and the ion motion is rapidly stopped, on a time scale $\tau_{stop} = 1/\Omega_i$, where Ω_i is the barium ion gyro (angular) frequency. For a thin cloud $K \ll 1$ and we have the collective spiral motion of the ions illustrated in Fig. 4c. This case is closest to the CRIT II barium oscillations.

The electric field inside the flux tube which goes through the cloud is given by an expression which is valid for all values of K,

$$\mathbf{E}_i = - \mathbf{V}_{i,perp} \frac{K\,B}{1 + K^2} - \mathbf{V}_{i,perp} \times \mathbf{B} \frac{K^2}{1 + K^2} \; , \tag{2}$$

where $\mathbf{V}_{i,\,perp.}$ is the ion's velocity component across the magnetic field. The velocity component along the magnetic field does not influence $\mathbf{E}_i$. For a thin cloud as we will discuss for CRIT II the internal field has a strength

$$|E_i| = V_{i,perp.}\, B \frac{K}{(1 + K^2)^{1/2}} \; . \tag{3}$$

and is directed close to antiparallel (at and angle $\alpha = \arctan(K)$) to the $\mathbf{V}_{i,perp}$ direction. The cloud continually looses energy to the Alfvén waves launched along $\mathbf{B}$ and therefore the electric field decays with a decay time constant which is longer for a thinner cloud,

$$\tau_{Decay} = \frac{1}{K\,\Omega_{gi}} \; . \tag{4}$$

Finally the magnetic and electric fields outside the cloud obey the relation:

$$\frac{\delta \mathbf{E} \times \delta \mathbf{B}}{|\delta B|^2} = \pm V_A \frac{\mathbf{B}}{B} \; . \tag{5}$$

i.e., $\delta \mathbf{B}$ is perpendicular both to $\mathbf{B}$ and to $\delta \mathbf{E}$, and the relative amplitude of the perturbations is $\delta E/\delta B = V_A$. The sign in Eq. 5 depends on whether the observation is made above or below the cloud because the Poynting vector in an Alfvén wave is directed along the energy flux, which here is away from the cloud.

4. Application of Barium Swarm to CRIT II

Our aim here is to use the barium swarm model to explain the barium oscillations using only the initial conditions. The only required inputs into the model are the geometry of the experiment (Fig. 1) and the density increases in the two burst (Fig. 5) which combined with Eq. 1 determine the K values. Because K is the most important single parameter here we will discuss in some detail how it is obtained for the two bursts. The magnetic field strength was 4.3×10^{-5} T, and the ambient

Alfvén velocity was about 300 km/s. We are going to evaluate the data at the time of the first return pulse and therefore we should ideally have values of $L_{//}$ and Δn at that time. However, K contains only the product $\Delta n_e L_{//}$. This quantity is independent of the expansion of the cloud along the magnetic field, and we can instead choose the time of the active region when $\Delta n_e L_{//}$ is easier to estimate. At this time the ions had not yet moved out along **B** from the neutral barium stream and $L_{//}$ is given by the width of the stream in the direction along **B**, $L_{//}$ = 500 m in burst 1 and $L_{//}$ =1200 m in burst 2. For Δn we use the density measurements shown in Fig. 5. An ambiguity arises because the density decreases after the passage of the active region, with density minima at times 0.2 seconds in burst 1 and 0.5 seconds in burst 2. According to Swenson *et al.* (1990a,b) the reason is that the ambient oxygen ions in the active region are pushed out from the beam and replaced by barium ions. The density minimum is then formed when the barium ions, which have velocities much above the ambient ion acoustic velocity. leave the region faster than the ambient ions can return. If the oxygen ions were initially pushed out slower than the rise time to the density maxima in Fig. 5 then we should calculate the density increase Δn from the level prior to the burst, but if it was faster we should calculate Δn from the minimum density after the burst. The alternatives are shown in Fig. 5. We keep this question open and use both values, which gives the following limits on K:

<u>Burst 1</u>: $0.07 < K < 0.18$
<u>Burst 2</u>: $0.05 < K < 0.08$

Clearly, both bursts corresponded to the "thin cloud" version of the barium swarm model. Apart from K, we need $V_{i,perp}$ for the calculation of E_i. We use the perpendicular component of the neutral stream velocity, at the time when the main payload was in the centre of the active region. This neutral velocity is obtained from the time of flight from the explosion point, and also agrees with the ion energy observed by the ion detector 3CD which looked towards the explosion (Torbert *et al.*, 1990).

These K values together with the injection velocity vector $V_{i, perp}$, put into the barium swarm model, completely determine the δE and δB vectors in amplitude, vector direction, frequency of oscillation, and decay time. However a complete comparison between these theoretical fields and the observed fields is complicated: Eq. 2 gives E_i only inside the magnetic flux tube which passes through the interior of the barium swarm, and the swarm performs a collective gyration and sweeps past the payloads only once per revolution. Between these times the payloads would see the fringing fields outside the swarm, which are shown to the right in Fig. 3. Although these fields also are determined by the model (Brenning *et al.*, 1990) they are more complicated to extract.

Also, the payloads had a non-negligible net velocity with respect to the ambient ionosphere which introduces an effect related to Doppler shifts. We therefore have made only one evaluation of δE and δB, at the time when the payload was inside the first return of the barium swarm and Eq.s 2 and 3 can be directly applied.

We start with burst one. The bottom panel in Fig. 6 shows the output from the 5AB ion detector on the main payload which measured ions with velocities close to perpendicular to B. There were at least three returns of the barium swarm at close to integer multiples of the barium gyro time 0.2 s. (Unfortunately this black-and-white reproduction does not show this as clearly as the colour original). Because these ions returned "on the beat" counted from the time of the active region, we call them on-beat ions. There are also crescent-shaped structures between the on-beat ions in Fig. 6 which we will return to below. The small time spread in the on-beat ions indicates very good phase correlation, probably due to the small values $\tau_{active}\Omega_{gi} = 1.3$ and $W/r_{gi} = 1.2$ as discussed above. The on-beat ions in Fig. 6 are spread out in energy over at least 40-50 eV; the peak energy is about 100 eV which was a typical neutral energy in the active region. Everything indicates that the on-beat ions were produced and spread downwards in energy in the active region, and then performed a collective gyration as in the barium swarm model. The upper six panels if Fig. 6 show that there were both magnetic and electric perturbations in correlation with the on-beat ions. We have evaluated these fields at the first on-beat, which is marked by a vertical line. A point should be made here, however: if the ions had retained their magnetic-field-aligned velocity component they would have moved along B completely away from the main payload during the first gyro period. Already their presence at the main payload therefore indicates that the ions produced in the active region have been scattered in parallel velocity. However an unknown expansion of the cloud in the direction along the magnetic field does not limit the applicability of Eq.s 2-3 for the electric field, since it would not change the product $\Delta n_e L_{//}$.

A comparison between the observations in burst 1 and the expectations from the barium swarm model is shown in Table I. The observed frequency is taken from the time spacing between the on-beat pulses on the ion detector. There is a small downshift in frequency from the expected barium gyro frequency 4.8 Hz to 4.6 Hz. This is probably a Doppler shift effect due to the motion of the payload with respect to the ionospheric rest frame. The electric field strength in the second row of Table I is the root of the sum of the squares of the observed electric field components. The values, 54 mV/m at the main payload and 60 mV/m at the sub payload, lie within the expected theoretical range 30-80 mV/m. The magnetic field perturbation is evaluated in the same way and gives $\delta E/\delta B = 280$ km/s at the main payload and $\delta E/\delta B = 290$ km/s at the sub payload. This is in fair agreement with the ambient Alfvén velocity $V_A = 320$ km/s. The δE vector direction for $K <<$

I should, according to Eq. 2, be close to the direction - $v_{i,perp.}$, which in our coordinate system means the -x direction. This is the case at our chosen time of evaluation as can be seen in panels 4-6 of Fig. 6. The magnetic vector should then, according to Eq. 5, be perpendicular both to δE and B, i.e., lie in the y direction. This is also the case as can be seen in panels 1-3 of the same figure. Finally, the cross product $\delta E \times \delta B$ should be directed along the energy flux, away from the centre of the barium swarm. When the swarm has moved up along the field lines as indicated in Fig. 2, $\delta E \times \delta B$ should point down along the magnetic field towards the payload, in the -z direction. This is also the case.

The decay time constant in Table I was obtained from the decay in the magnetic field perturbations; the measurements from the sub payload are shown in the top three panels of Fig. 7. The barium oscillations are here made observable by rotating the measurement into a coordinate system with one axis approximately parallel to the Earth's magnetic field. Imperfections in the rotation show up as large scale trends with periods of 0.5 seconds or more (Swenson et al., 1990a). We have estimated the time constant by fitting an exponential to the amplitude of the barium oscillations, and obtained $\tau_{Decay} = 0.24$ s. In view of the fast decay of the oscillations such a fit must necessarily be rather crude, but still it lies in the expected range 0.19 to 0.47 seconds.

The results from burst 2 are summarized in Table II. They were obtained in the same way as in burst 1, except that the period here was deduced from the electric and magnetic fluctuations which in this burst gave better accuracy than the particle detectors. Again, the frequency of oscillation, the $\delta E/\delta B$ ratio and the decay time agree quite well between theory and observations. The only disagreement is the amplitude of the oscillations, which in burst 2 was a factor 3 below the theoretical. This low amplitude probably was due to the poorer phase correlation in burst 2, which can be seen in the ion detector shown in Fig 8 as a large time spread in the returning barium swarm. The poor phase correlation in burst 2 was probably due to the larger values of $\tau_{active}\Omega_{gi} = 2.4$ and $W/r_{gi} = 3$.

Apart from the absolute values of the quantities shown in Tables I and II there is also the trend of change between the two bursts. In burst 1 the injected ion density was a factor 3-5 higher than in burst 2. In agreement with the model, both the frequency of oscillation and the ratio $\delta E/\delta B$ were independent of this change. On the other hand there are very clear trends in the expected direction, both in the amplitude and in the decay time, which can be seen directly in Fig. 7. In agreement with Eqs 3 and 4 the amplitude was higher in burst 1, while the oscillations had longer time duration in burst 2.

Although the barium swarm model agrees very well with several features of the barium oscillations, it is still highly idealized. In reality there is neither a perfect correlation in velocity nor a simple cylindrical geometry. The ion detector signal on the bottom of Fig. 6 gives a more realistic idea of the velocity distribution in burst 1. Between the narrow on-beat pulses there are several crescent-shaped structures that we will call "off-beat" although they are spread out considerably in time (a pure off-beat would come precisely between the on-beats). A tentative explanation to the off-beat ions is shown in Fig. 9, which shows the consequences if the ions were scattered both backwards and forwards in the active region. One half gyro period after the ionization, the ions which were scattered backwards would arrive from the direction of the burst with some upper energy limit given by the gyroradius and the width of the beam. This would be the off-beat ions; the reason for the spread in arrival time in Fig. 6 could be that they are not purely scattered backwards but have some spread in angle. Half a gyro period later the on-beat ions would arrive without any constraint in energy. The pattern would then repeat periodically.

It is interesting to speculate how the existence of two such populations of ions, scattered mainly in opposite directions, would change the barium swarm model. One should certainly expect some magnetic and electric perturbations both the on-beats and on the off-beats, but it is not certain that it would be a simple superposition of the fields from the two individual barium swarms. Fig. 10 shows the total magnetic field perturbation δB in burst 1, which gives a clearer resolution of the oscillations than the individual vector components shown in the earlier figures. Both the on-beat and the off-beat magnetic perturbations can be resolved as indicated by arrows in Fig. 10. There is even the "barium swarm type" of anti-correlation between the amplitude and the decay time: the on-beat pulses which start out with higher amplitude decay faster than the off-beat pulses, analogous to the difference between burst 1 and burst 2 shown in Fig. 7.

5. The Active Region

One reason for this study of the barium oscillations is that it can shed some light on the interaction during the active phase, which is the time of most interest in these CIV injection experiments. The electric field fluctuations in the active region cover a broad spectrum from quasi-dc up frequencies above ten kHz. The term quasi-dc here is used for fluctuations on time scales comparable to the time variation of the density and the velocity in the neutral barium stream, which is typically 0.1 s. It is usually assumed that the quasi-dc and the higher frequencies have different roles in the CIV process (e.g. Haerendel, 1982; Brenning et al., 1990b). The higher frequencies are probably associated with microinstabilities which tap the directed energy of the ion beam and transfer some fraction of the energy to the electrons. In the process the ions become scattered in energy and the

electrons become energetic enough to ionize more barium. This aspect of the CRIT II experiment is treated in the companion papers by Torbert et al. (1990) who discuss the ion scattering and electron heating, and by Swenson et al. (1990a,b) who discuss the high frequency fluctuations in the fields. We will here discuss the quasi-dc fields. Probably these fields are associated with a current system which exchanges momentum between the ionized beam and the surrounding ionospheric plasma. This process is as fundamental for the ionospheric CIV experiments as the microinstabilities because energy can only be released if momentum is exchanged between these two plasmas.

Three different models have been proposed for the quasi-dc electric fields: the mass loading model, the barium swarm model and the current limitation model. The main differences between the models are (1) if the rate of ionization is zero or not, (2) if the new ions are picked up immediately or not, (3) if the charge separation in the direction along the beam is included or not, and (4) if the magnetic-field-aligned electric field is zero or not. As a consequence of these different assumptions they differ both in the direction and in the strength of the expected electric field. Apart from these three models there are also computer simulations by Machida et al., (1988) and Goertz et al. (1990) which also produce quasi-dc electric fields. We will not discuss them here because the electric fields seen in these simulations are difficult to compare quantitatively to a real ionospheric experiment.

In the mass loading model (Haerendel, 1982; Torbert, 1987) the rate of ionization is included but not the absolute value of the density increase, or the charge separation along the beam. The new ions are immediately picked up by the plasma in such a fashion that they get a common perpendicular velocity with the ionospheric plasma inside a magnetic flux tube which extends out to the Alfvén wave fronts. The magnetic-field-aligned electric fields are zero. Momentum conservation within the flux tube gives an electric field which is perpendicular to the injection direction and proportional to the rate of ionization,

$$E_P = - v_{Ba} \times B \frac{\lambda_m}{1 + \lambda_m} \ , \tag{6}$$

where the mass loading factor is

$$\lambda_m = \frac{dn_{Ba}}{dt} \cdot \frac{m_{Ba} L}{4 \rho_m V_A} \ , \tag{7}$$

and ρ_m is the mass density of the ambient plasma.

The mass loading model can be applied to CRIT II using the rate of density increase in Fig. 5. This gives an electric field (in the coordinate system defined in Fig. 1) E_y = -50 mV/m in burst 1 and E_y = - 40 mV/m in burst 2. In the mass loading model, $E_x = 0$.

In the barium swarm model of this paper the ionization rate is zero, while the absolute density increase is included as well as the charge separation in the direction of the beam. The ions are not assumed to be picked up immediately as in the mass loading model but lose their velocity relative to the ambient plasma on the slower time scale given by Eq. 4. The electric field which is given by Eq. 2 has components directed both against the beam and across it, but not along the magnetic field.

We would expect the barium swarm model to apply rather well in CRIT II because the quasi-dc fields in the active region have an amplitude which seems to smoothly decrease into the barium oscillations (see e.g. Fig. 7). If the barium swarm model holds, the amplitude decays exponentially. We can therefore extrapolate the barium oscillations back into the active region and use both the observed electric field strength and the observed decay time. This gives the amplitude of the electric field $|E_{i,active}|$ at the time t_{active}

$$|E_{i,active}| = |E(t)| \exp\frac{t - t_{active}}{\tau_{Decay}} . \tag{8}$$

where $|E(t)|$ is the amplitude of the barium oscillations at time t. In burst 1, Eq. 8 using the main payload data gives $|E_{i,active}|$ = 120 mV/m, and the sub payload data gives $|E_{i,active}|$ = 130 mV/m. We take an average of 125 mV/m and use Eq. 3 to calculate the corresponding value of K, which turns out to be 0.29. The angle α between $\mathbf{E}_i$ and - $\mathbf{V}_{i,perp}$ from Eq. 2 becomes $\alpha = \arctan(K)$ = 16 degrees. In the active region new-born ions should dominate and we can assume that the vector $\mathbf{V}_{i,perp}$ points in the x direction. This gives the following electric field components: E_x= - 125 $\cos(16^0)$ = - 120 mV/m, and E_y = - 125 $\sin(16^0)$ = - 34 mV/m. A similar calculation in burst 2 gives E_x = - 14 mV/m and E_y = 0 mV/m.

In the current limitation model finally (Brenning et al., 1990b), the rate of ionization is included but the momentum exchange along the magnetic field is limited by magnetic-field-aligned electric fields. As a consequence the ion current across the magnetic field cannot be closed by field-aligned currents and the perpendicular electric field increases until it stops the charge separation. This give an electric field which is antiparallel to the flow direction and proportional to the ionization rate:

$$E = -v_{Ba} \frac{m_{Ba}}{n_e e} \frac{dn_{Ba^+}}{dt} . \tag{9}$$

In CRIT I the plasma density was not measured, and Eq. 9 was actually used to estimate the ionization rate from the very strong quasi-dc electric fields observed in that experiment. In CRIT II we can insert the measured ionization rates from Fig. 5 in Eq. 9. This gives the electric fields $E_x =$ -620 mV/m in burst 1 and $E_x = $ -170 mV/m in burst 2. In the current limitation model, $E_y = 0$.

Fig. 11 shows the electric field vectors in burst 1 according to the three models above, together with the observed electric field in the active region. The values used for the observed field are marked with dashed lines in panels 4 and 5 of Fig. 6. It is immediately obvious from Fig. 11 that the current limitation model does not apply. The probable reason is that the ionosphere here was able to supply the magnetic-field-aligned current required to short-circuit the field of Eq. 9. The situation could have been much different in CRIT I where the ambient plasma density was a factor 10-20 lower. The mass loading model gives the perpendicular (E_y) electric fields which agrees best with the observed, while the barium swarm model gives an E_y field with the correct sign but half the observed strength, and an E_x field component which agrees quite well with the observed.

We can not make a similar comparison for burst 2 because the vector direction of the electric field in that burst is not yet evaluated. However, it is clear that also in this burst the electric field according to the current limitation model is much higher that the observed.

6. Discussion

Concerning the barium oscillations we feel confident that we understand the basic plasma physics: on short time scales (compared to the gyro time) the barium ions move as individual particles through the ambient plasma with gyro radii of several hundred meters. The ambient ionosphere does not follow in this motion but only feels a minor ripple in the form of weak Alfvén waves emitted in both directions along **B**. However these Alfvén waves are essential to the process: they deliver just the right amount of magnetic-field-aligned current to maintain space charge neutrality which otherwise would be threatened by the barium ion motion across **B**. The electric field in the Alfvén waves also determines the rate of energy loss of the ions on a longer time scale, and thus the decay time of the barium oscillations. Although the barium swarm model uses the idealized geometry of a circular cylinder with uniform density, it seems likely that the approach can be

be generalized to more complicated phenomena.

Concerning the quasi-dc fields in the active region the conclusions are not yet so clear. From one point of view, the mass loading and the barium swarm models represent two extreme assumptions concerning the influence of microinstabilities on the ion motion. Such instabilities act as a frictional coupling between the beam of newly produced barium ions and the local plasma. If this "instability friction" is very efficient the ions can be stopped quickly, as assumed in the mass loading model, and part of their directed kinetic energy can be transferred to the electrons. This is precisely the energy transfer process in most theories for CIV. A very rapid stopping of the ions would also reduce the charge separation in the direction of the beam and give a low E_x field component, again as in the mass loading model. If the "instability friction" is weak on the other hand, the ions would move through the ambient plasma as in the barium swarm model. If this is the case no energy is available for electron heating because it all goes to the Alfvén waves. The quasi-dc fields would be a passive response to a given amount of ionization, without the feedback of energy to the ionization process which lies in the heart of the CIV mechanism.

Although both models are very simplified, one should thus expect the mass loading model to apply better when CIV interaction is efficient, and the barium swarm model to apply better when ions are produced in the absence of CIV. The observations in CRIT II actually support both models to some extent. The perpendicular (E_y) field could, within the uncertainties of the models and the observations, agree with either model. The E_x field was in good agreement with the barium swarm model but disagreement to the mass loading model where $E_x = 0$. On the other hand there were several indications of efficient CIV interaction, which should support the mass loading model: there was both rapid electron heating (Torbert *et al.*, 1990) and lots of electron impact ionization (Stenbaek-Nielsen *et al.*, 1990; Swenson *et al.*, 1990a,b). Also, the observed ion energy loss in the active region (Torbert *et al.*, 1990) was much faster than the decay time 0.2 - 0.7 seconds according to the barium swarm model.

It seems most likely that the real situation lies somewhere between the barium swarm and the mass loading models, and that an improved understanding of the quasi-dc fields would give valuable insight into this type of injection experiments. We believe this can be obtained if the physical assumptions behind the barium swarm model are generalized to include both a variable ionization rate and a more realistic geometry. We plan to develop a two-dimensional computer model along this line. The difference between the real field and the the field in such an extended barium swarm model should be directly related to processes which tap the ion beam energy and transfer the energy to the electrons.

Acknowledgements

References

Alfvén, H., 1954: On the Origin of the Solar System, Oxford University Press, New York.

Brenning, N., Kelley, M., Providakes, J., Stenbaek-Nielsen, H. C. and Swenson, C. 1990a: *Barium Swarm: an Ionospheric AC Generator in CRIT I*. Accepted for publication in J. Geophys. Res.

Brenning, N., Fälthammar, C.-G., Haerendel, G., Kelley, M., Marklund, M., Pfaff, R., Providakes, J., Stenbaek-Nielsen, H. C. Swenson, C. Torbert, R., and Wescott, E. M., 1990b: *Interpretation of the Electric Fields Measured in an Ionospheric Critical Ionization Velocity Experiment*. Accepted for publication in J. Geophys. Res.

Goertz, C. K., Machida, S., and Lu, G., 1990: *On the Theory of CIV*, Adv. Space Res. Vol 10, No 7, pp (7)33-(7)45.

Haerendel, G., 1982: *Alfvén's Critical Velocity Effect Tested in Space*, Z. Naturforsch. **37a**, 782.

Kelley, M. C., Swenson, C., Brenning, N., Baker, K., and Pfaff, R. 1990: *Electric and Magnetic Field Measurements inside a High Velocity Beam Undergoing Ionization*. Manuscript in preparation.

Machida, S., Goertz, C. K., and Lu, G., 1988: *Simulation Study of the Critical Ionization Velocity Phenomenon*, J. Geomagn. Geoelectr., **40**, 1205-1219.

Providakes, J., Kelley, M. C., Pfaff, R., Brenning, N., Torbert, R., Swenson, C., and Swartz, W. E., 1990: *In Situ and Radar Observations of Ion Cyclotron Waves Associated with Two Barium Shaped Charge Releases*. Submitted to J. Geophys. Res.

Stenbaek-Nielsen, H.-C., Wescott, E., Haerendel, G. and Valenzuela, A, 1990: *Optical Observations on the CRIT II Critical Ionization Velocity Experiment*, EOS, Trans. AGU, 70.

Swenson, C., Kelley, M. C., Brenning, N., Torbert, R. B., Primdahl, F., and Baker, K. D., 1990a: *CRIT II Electric, Magnetic, and Density Measurements in an Ionizing Neutral Jet*, to be published in Advances in Space Research.

Swenson, C., Kelley, M. C., Primdahl, F., and Baker, K. D., 1990b: *CRIT II Electric, Magnetic, and Density Observations in an Ionizing Neutral Stream*. Accepted for publication in Geophys. Res. Lett.

Torbert, R. B., 1987: *Critical Velocity Experiments in Space,* unpublished manuscript.

Torbert, R. B., Kletzing, C. A., Liou, K. and Rau, D., 1990: *Prompt Ionization in the CRIT II Barium Releases,* Advances in Space Research (this issue).

THEORETICAL	OBSERVED
$\dfrac{\omega}{2\pi} = \dfrac{\Omega_{Ba^+}}{2\pi} = 4.8 \text{ Hz}$	Ion detector: 4.6 Hz
$|E_i| = V_{i,perp.} \dfrac{B\,K}{(1+K^2)^{1/2}} = 30 - 80 \text{ mV/m}$	Main Payload: 54 mV/m Sub Payload: 60 mV/m
$\dfrac{\delta E_{perp.}}{\delta B_{perp.}} = \pm\, V_A = 320 \text{ km/s}$	Main Payload: 280 km/s Sub Payload: 290 km/s
$\tau_{Decay} = \dfrac{1}{K\Omega_{Ba^+}} = 0.19 - 0.47 \text{ s.}$	δB, sub payload: 0.24 s

Table I. Comparison between the Barium Swarm model
and the observations in burst 1.

THEORETICAL	OBSERVED
$\dfrac{\omega}{2\pi} = \dfrac{\Omega_{Ba^+}}{2\pi} = 4.8 \text{ Hz}$	Field fluctutations: 4.6 - 5.0 Hz
$|E_i| = V_{i,perp.} \dfrac{B\,K}{(1+K^2)^{1/2}} = 25 - 35 \text{ mV/m}$	Main Payload: 10 mV/m
$\dfrac{\delta E_{perp.}}{\delta B_{perp.}} = \pm\, V_A = 310 \text{ km/s}$	Main Payload: 230 km/s
$\tau_{Decay} = \dfrac{1}{K\Omega_{Ba^+}} = 0.4 - 0.6 \text{ s.}$	δB, main payload: 0.7 s

Table II. Comparison between the Barium Swarm model
and the observations in burst 2.
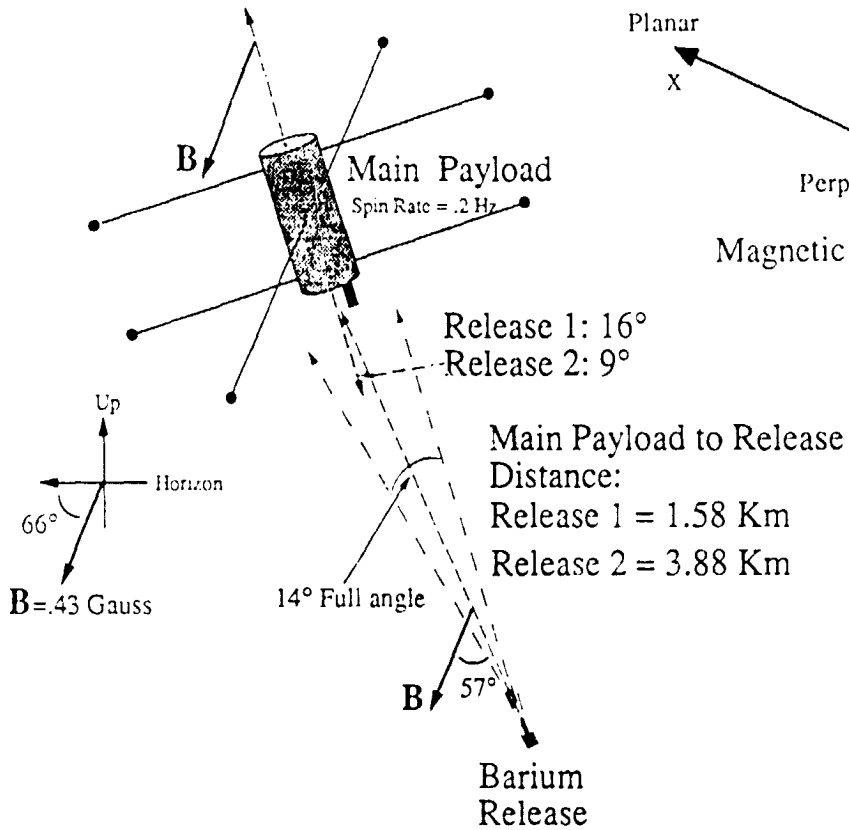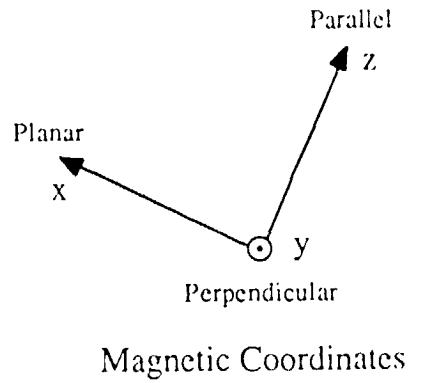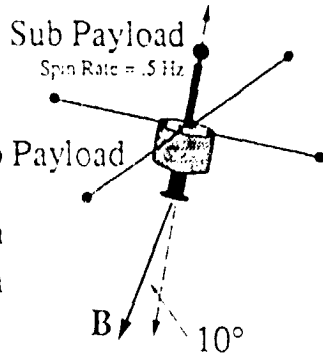
Fig. 1. The geometry for the CRIT II release, and the definition of the magnetic coordinate system (from Swenson *et al.*, 1990a)
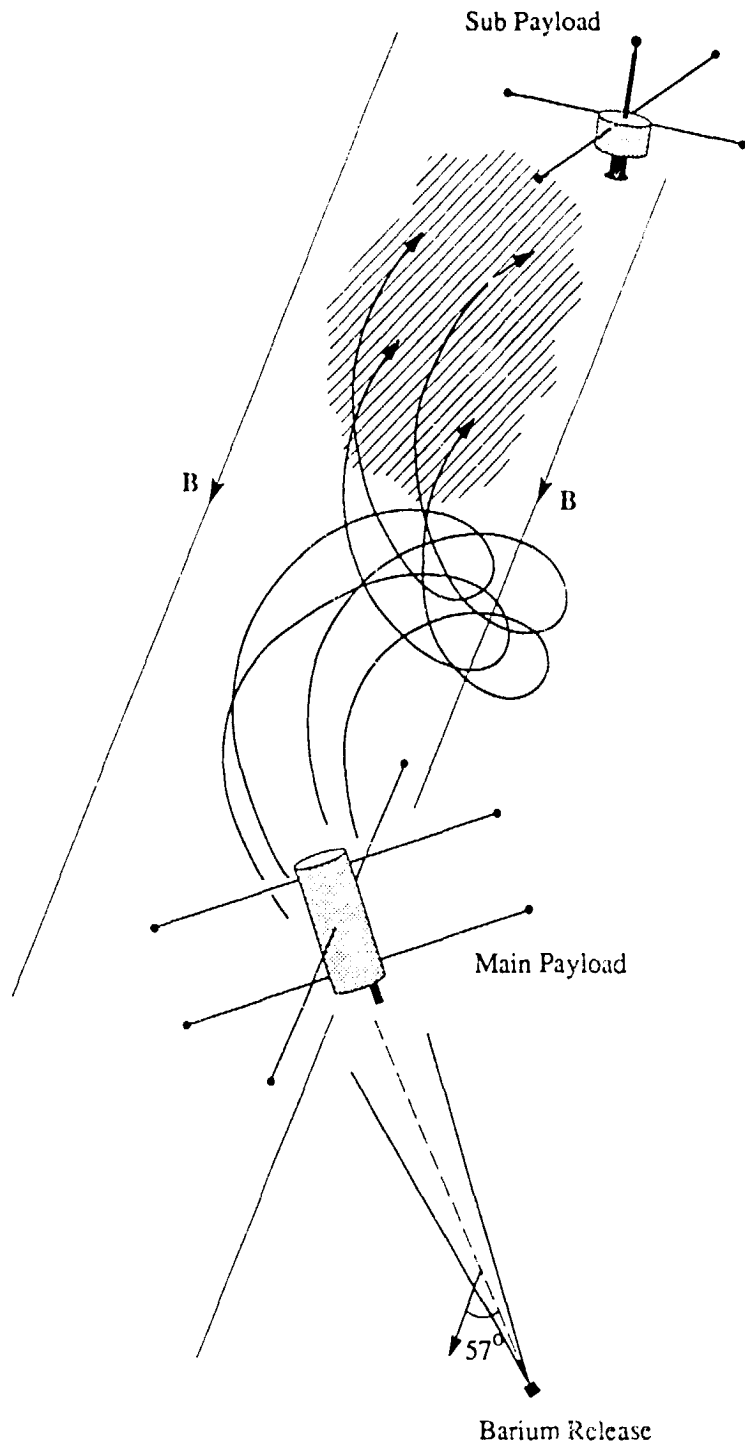
Fig. 2. A sketch of the barium swarm motion along the magnetic field.
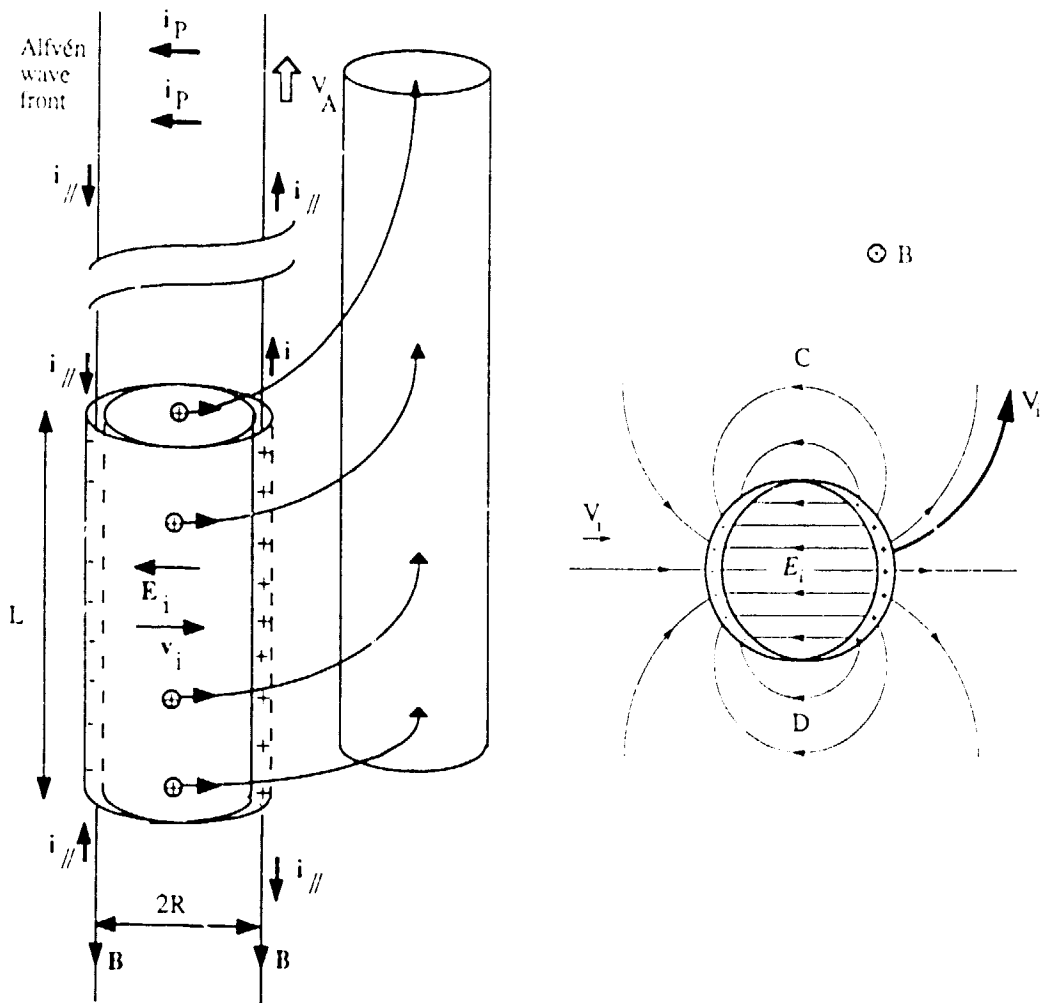
Fig. 3. The barium swarm model (from Brenning *et al.*, 1990a).

Dense cloud, $K = 4$
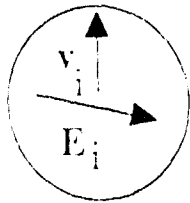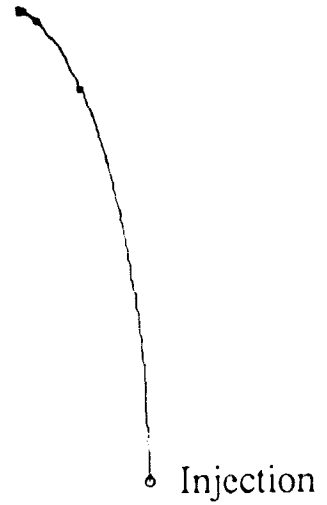
Intermediate cloud, $K = 1$
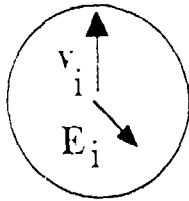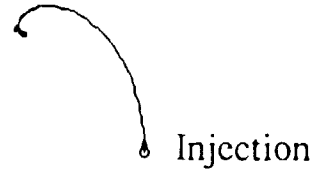
Thin cloud, $K = 0.1$

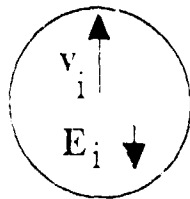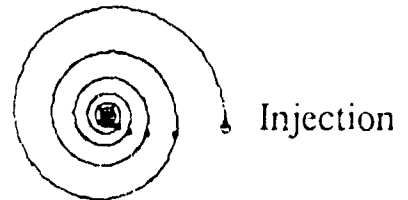Fig. 4. The motion of three barium ion clouds of different density which are injected with a perpendicular velocity of 5 km/s across a magnetic field of 4×10^{-5} Tesla. The time separation between the black dots on the trajectories is one gyro period.
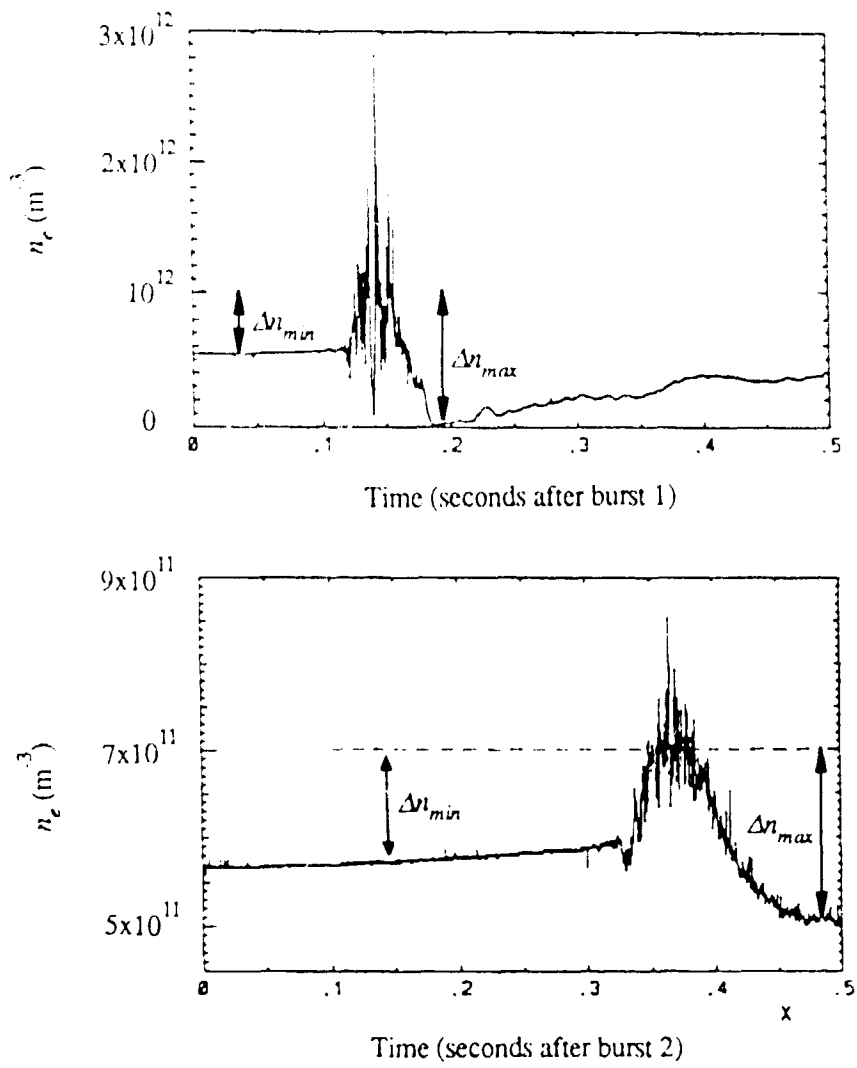
Fig. 5. Density measurements in CRIT II. The upper curve shows burst 1 and the lower burst 2.
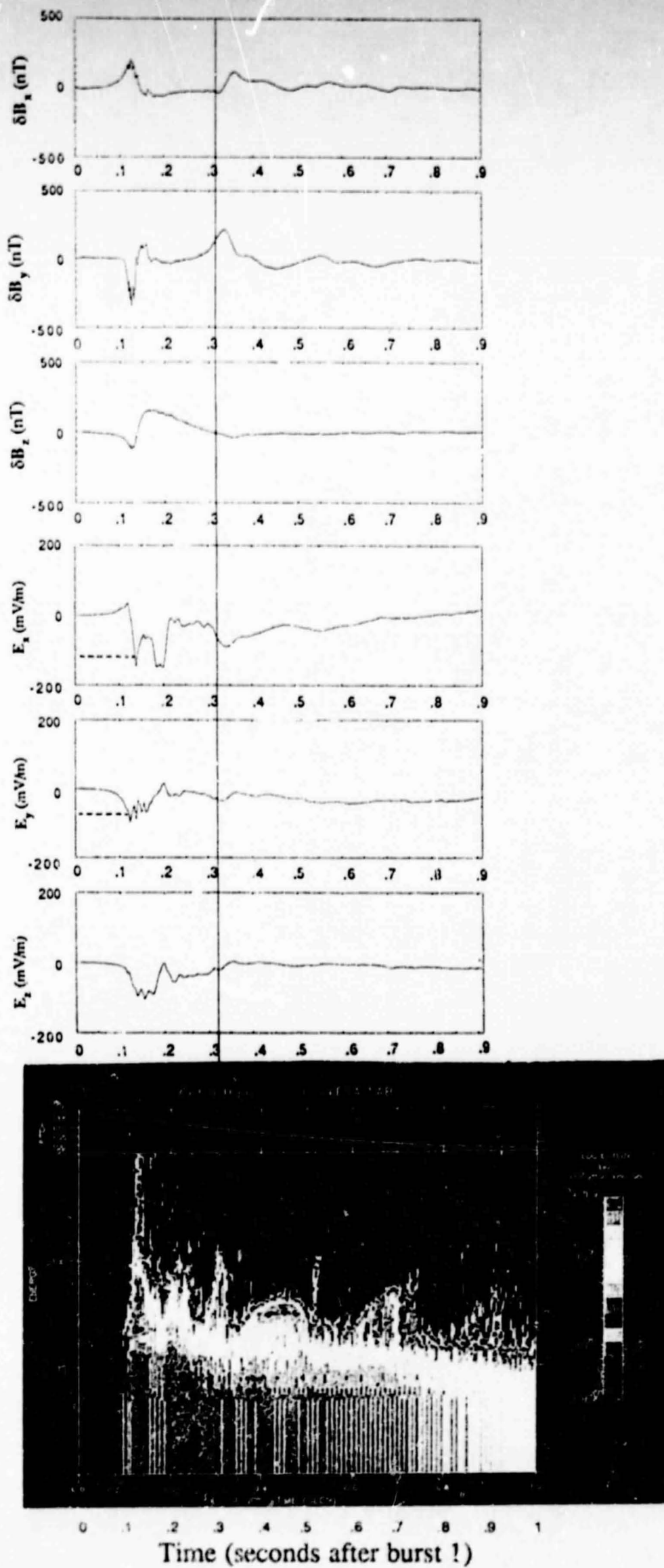
Fig. 6. Electric and magnetic field measurements from the main payload in burst 1, and the output from ion detector 5 AB on the main payload. The coordinate system is defined in Fig. 1. The vertical line marks the time at which the comparison to the barium swarm model is made.
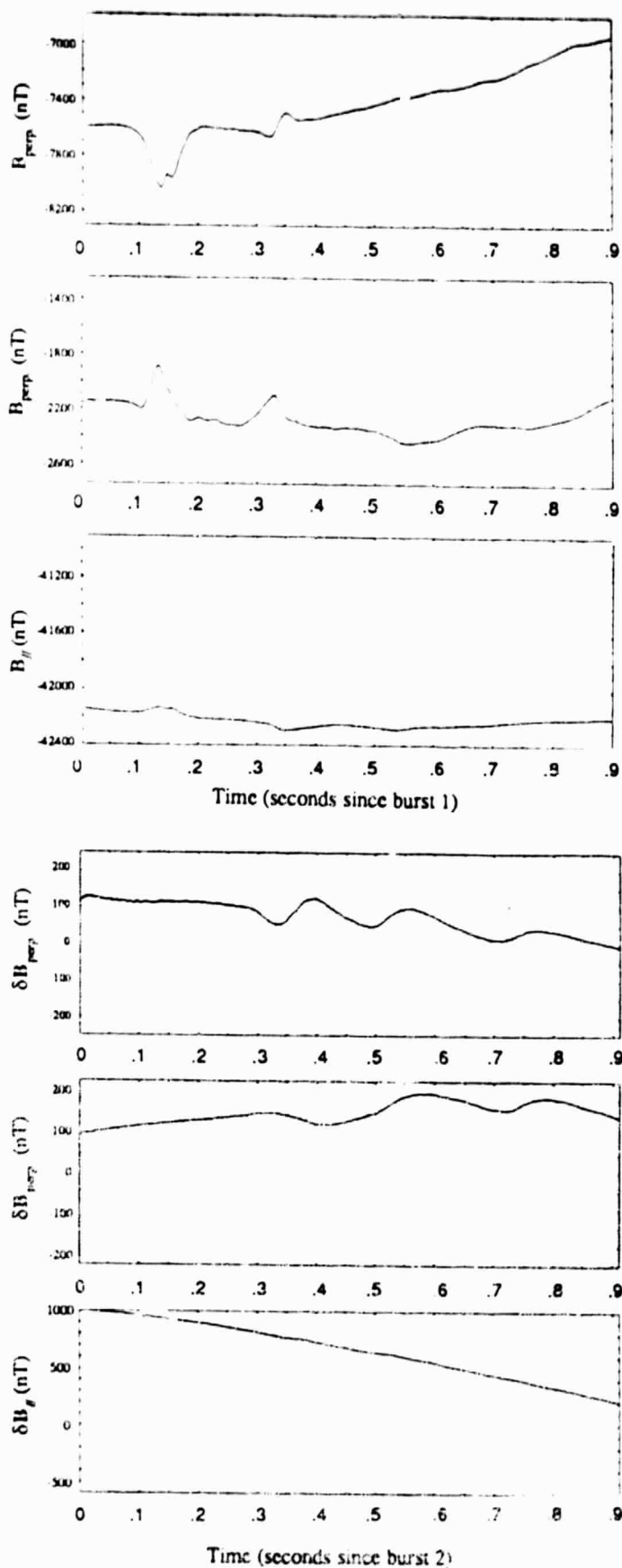
Fig. 7. The magnetic field fluctuations. The upper three panels show measurements from the sub payload in burst 1, and the lower three panels show measurements from the main payload in burst 2. For reference, the barium ion gyro period is 0.21 seconds.
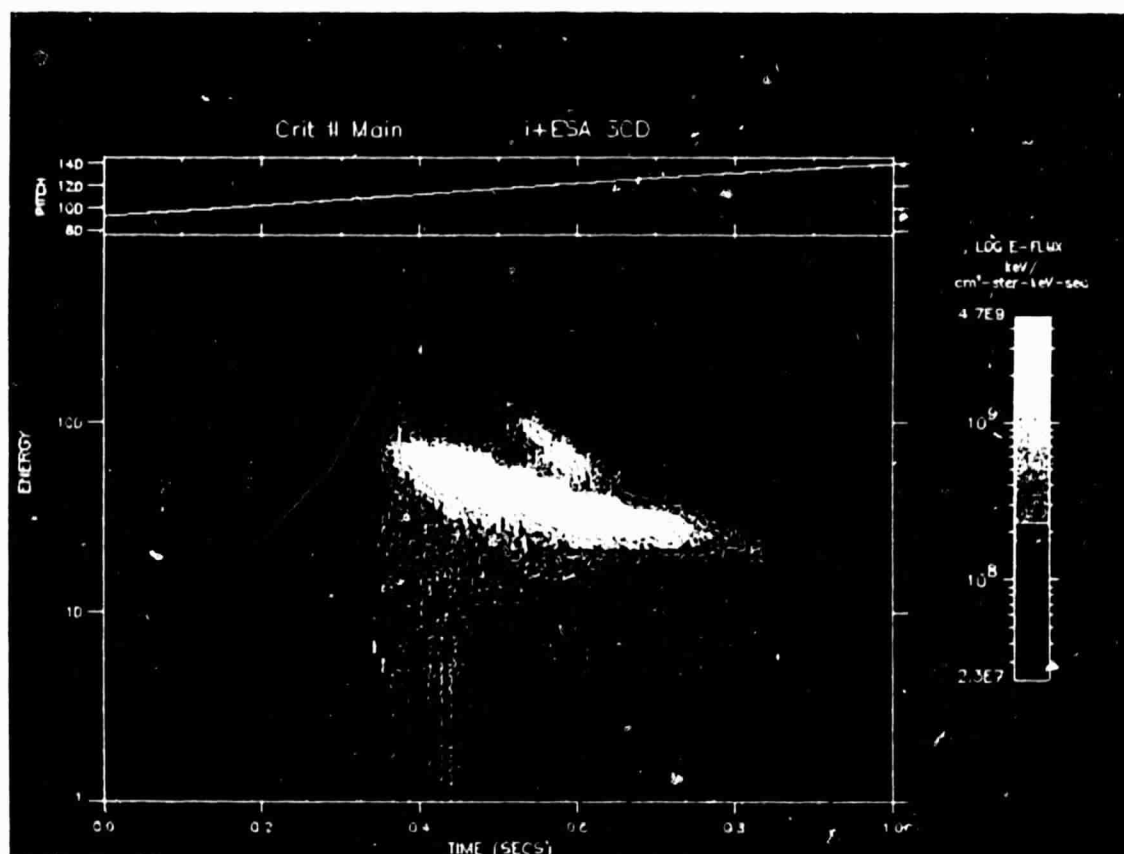
Fig. 8 The output from ion detector 3 CD on the main payload in burst 2. Only one return of the swarm can be seen, at 0.59 seconds, because the detector was tilted away from the plane perpendicular to the magnetic field.
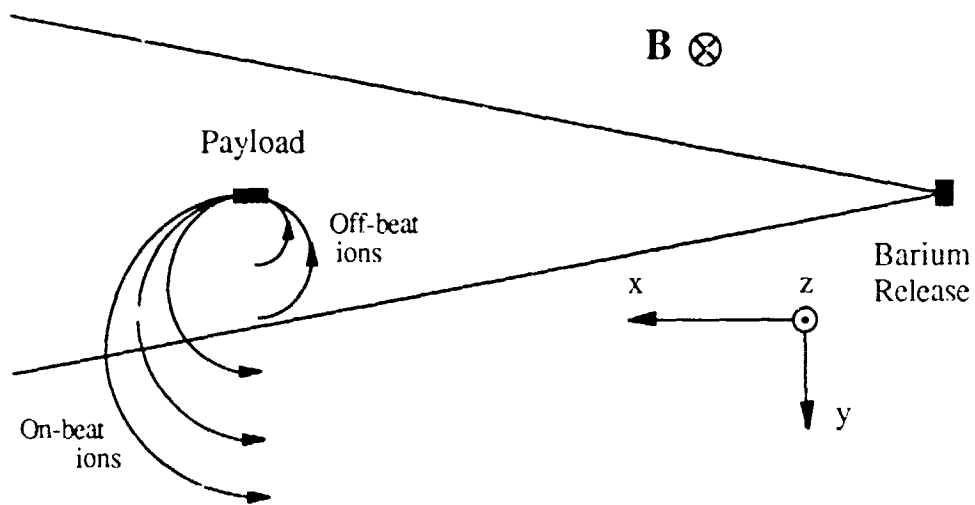
Fig. 9. Ion trajectories during the first half gyro period after the ionization, for ions that are scattered mainly in the two directions parallel and antiparallel to the beam direction.
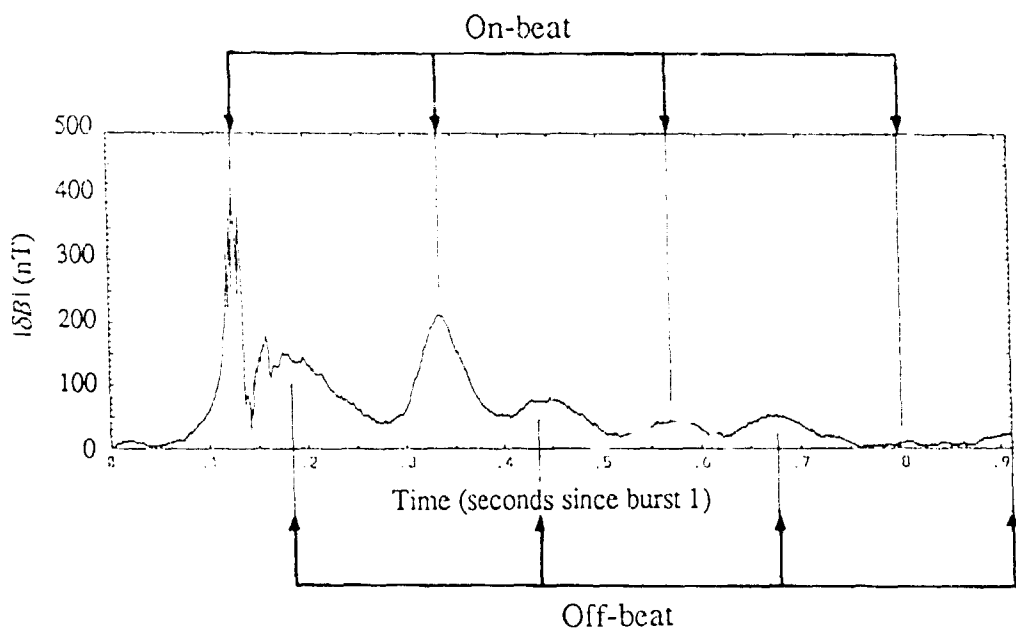
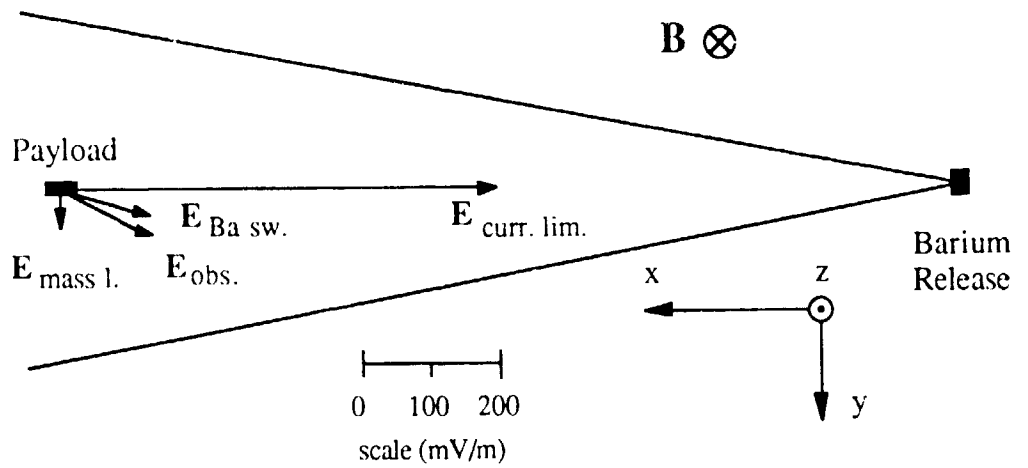Fig. 10. The total magnetic perturbation δB in burst one.

Fig. 11 The observed perpendicular electric field vector E_{obs} in the active region of burst 1, together with the values according to the current limitation model, the mass loading model and the barium swarm model.

The Royal Institute of Technology, Deptartment of Plasma Physics
S-100 44 Stockholm, Sweden

THE COLLECTIVE GYRATION OF A HEAVY ION CLOUD IN A MAGNETIZED PLASMA

N. Brenning, C. Swenson, M. C. Kelley, J. Providakes and R. Torbert
September 1990, 28 pages incl. ill., in English.

In both the ionospheric barium injection experiments CRIT I and CRIT II, a long-duration oscillation was seen with a frequency close to the gyro frequency of barium and a time duration of about one second. A model for the phenomenon which was proposed for the CRIT I experiment is here compared to the results from CRIT II which made a much more complete set of measurements. The model follows the motion of a low-β ion cloud through a larger ambient plasma. The internal field of the model is close to antiparallel to the injection direction $\mathbf{v}_i$ but slightly tilted towards the self-polarization direction $\mathbf{E}_P = -\mathbf{v}_i \times \mathbf{B}$. As the ions move across the magnetic field, the space charge is continuously neutralized by magnetic-field aligned electron currents from the ambient ionosphere, drawn by the divergence in the perpendicular electric field. These currents give a perturbation of the magnetic field related to the electric field perturbation by $\Delta E/\Delta B \approx V_A$. The model predictions agree quite well with the observed vector directions, field strengths, and decay times of the electric and magnetic fields in CRIT II. The possibility to extend the model to the active region, where the ions are produced in this type of self-ionizing injection experiments, is discussed.