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ABSTRACT :

A method of measuring both the perpendicular and parallel D.C. electric field in the vicinity of a spacecraft using artificially injected charged particles is presented. This method uses a rendezvous between the spacecraft and injected particles after a number of complete gyrations around the magnetic field plus one partial gyration, to measure the field and potential structure at short distances (up to few kilometers or tenth of kilometers) from the spacecraft. The solutions of the rendezvous problem are derived in the general case, and in realistic cases related to possible potential structure due for example to anomalous resistivity and electrostatic shocks. The characteristics of the measurements are evaluated, in particular the echo delay time of the particles (and hence the time resolution) and the sensitivity (i.e. the minimum electric field, the extent and the magnitude of the potential measurable). Among other, the minimum parallel electric field ( $\sim$ 1 mV/m) and the minimum time resolution ( $\sim$ 20 ms) are found to the very suitable to describe potential structures associated with anomalous resistivity and electrostatic shocks. Finally the requirements for guns and detectors are evaluated i.e. their orientations, the beam intensity and the detectors time resolution and sensitivity.

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RESUME :

On présente une méthode de mesure des composantes perpendiculaire et parallèle du champ électrique continu au voisinage d'un engin spatial, utilisant des particules chargées injectées artificiellement. La méthode utilise le rendez-vous entre un engin spatial et des particules injectées effectuant un nombre entier de rotations autour du champ magnétique plus une rotation partielle, pour mesurer le champ et la structure du potentiel à de faibles distances (jusqu'à quelques kilomètres ou des dizaines de kilomètres) de l'engin spatial. Les solutions du problème de rendez-vous sont obtenues dans le cas général puis dans des cas pratiques associés à des structures du potentiel possibles dues par exemple à la résistivité anormale ou à des chocs électrostatiques. Les caractéristiques de la mesure sont évaluées et en particulier le temps d'aller et retour des particules (par conséquent la résolution temporelle) et la sensibilité (c'est-à-dire le champ électrique minimum, l'étendue et la valeur du potentiel, mesurables). La valeur minimum de la composante parallèle du champ électrique ($\sim$ 1 mV/m) et la résolution temporelle minimum ( $\sim$20 ms) entre autres sont parfaitement bien adaptées pour décrire les structures du potentiel associées avec les phénomènes de résistivité anormale et de chocs électrostatiques. Finalement les caractéristiques nécessaires des canons et des détecteurs sont évaluées, c'est-à-dire leur orientation, l'intensité des faisceaux, la résolution temporelle et la sensibilité des détecteurs.

## 1 - INTRODUCTION

In recent years, much effort has been devoted to the measurement of the magnetic field aligned DC electric fields proposed to explain results from early experiments (HULTQVIST et al., 1971 ; FAHLESON, 1972 ; MOZER and BRUSTON, 1967 ; REME and BOSQUED, 1971). Such results indicating the presence of potential drops as large as a few KV in the auroral zone during disturbed periods have been followed by others identical results obtained from either direct measurements using double probes (MOZER, 1976 ; MOZER et al., 1977) or indirect methods using barium ions as tracers (HAERENDEL et al., 1976 ; WESCOTT et al., 1976), anisotropic distributions of natural precipitations of protons and electrons (EVANS, 1975) or "inverted V" precipitations (BURCH et al., 1976).

At the same time, several theoretical explanations have been proposed, for example anomalous resistivity (KINDEL and KENNEL, 1971), double layers (BLOCK and FALTHAMMAR, 1976) or electrostatic shocks (SWIFT, 1975) supported by large drift velocity driven instabilities.

As yet, there is no general agreement on these theories, nor on the existence of such electric fields. Nevertheless, it appears that there are two possible shapes of the potential variation along the magnetic field lines. The first is a small magnetic field aligned parallel electric field of large extent, which could be explained by anomalous resistivity. The second is a small layer of a few tens of meters or kilometers which could be explained by double layers or electrostatic shocks associated with large electric fields (of a few hundreds of mV/m). Remote sensing experiments using charged particles have been proposed by several groups as a method which could definitely solve the problem. The basic principle of the experiments is to inject charged particles from a spacecraft along the magnetic field lines, and to detect the echoes obtained if the beam has been reflected by the potential drop along the magnetic field line. The measurement of the echo delay time as a function of the injection parameters leads to the knowledge of the potential as a function of the distance from the injector. Such experiments are able to describe in detail the potential drop along the field line and so give an understanding of the phenomena that lead to the existence of parallel electric fields, or conversely to disprove their existence. Nevertheless, such experiments have not yet been performed due to the difficulty of obtaining a rendez vous between the echoes and the spacecraft when one attempts to trace the field lines over distances of a few thousands of kilometers (WILHELM, 1977). Indirect detections of the echoes are also possible using the interaction of the particles with the atmosphere or a gas release by detecting the emitted light. In this case, the injected intensity has to be large to obtain echoes well above the natural background. However, too large an intensity could involve more complicated interactions with the medium than the single particle motion. But if we limit our ambition to describe the electric potential over a few kilometers, the rendez vous problem can be easily solved. Indeed the echo delay time can be short enough in order that the spacecraft does not move over distances larger than the gyroradius of the particles and so obtain the rendez vous on the same spacecraft which carries the particle source.

As we can see above, much effort is needed to find feasible methods to measure the parallel electric field by a remote sensing technique at large or small distance. The aim of this paper is to contribute to that effort, studying the capabilities of the remote sensing experiment over small distances to describe some realistic structure of the electric potential or at least, if that measurement is not possible,to measure the local total electric field. This study will be performed assuming that only the electric and magnetic fields of natural origin act on the trajectories of the particles. Other parameters can influence those trajectories as for example the potential difference between the spacecraft and the surrounding medium, the interaction between the beams of charged particles and the plasma or the collision of the charged particles with the neutral atmosphere. It is not the aim of this paper to discuss these effects , but it is clear that theoretical calculations including these and/or experiments will be necessary to prove definitely the feasibility of the method. The two first effects are largely dependent on the required intensities of the beams which will be computed in this paper. The importance of the last effect decreases while the altitude of the measurements increases.

## 2 - MEASUREMENTS REQUIRED TO GIVE THE ELECTRIC POTENTIAL ALONG THE FIELD LINE

### 2.1. The echo delay time as a function of injection parameters

Let $E_o$ be the initial energy of the particles injected at the origin and $\gamma$ their pitch-angle. The echo delay time $t$ for the particle to go to the reflection point and back is :

$$t = 2\int_{o}^{s_F} \frac{ds}{V_{//}} \quad \text{where} \quad V_{//}^2 = \frac{2}{m}(E_o + \mu B(s) - q\ \Phi'\ (s)) \qquad (1)$$

where

| | | |
|---|---|---|
| $V_{//}$ | : | the parallel velocity of the particle |
| $s$ | : | the path length along the magnetic field |
| $s_F$ | : | the reflection point |
| $q$ , $m$ | : | the charge and mass of the particle |
| $B(s)$ | : | the magnetic field as a function of $s$ |
| $\Phi'(s)$ | : | the electrostatic potential as a function of $s$ |
| $\mu = \dfrac{E_o \sin^2 \gamma}{B}$ | : | the magnetic moment of the particle which is an invariant of motion |
| $B_o$ | : | the magnetic field at the injection point |

The inversion problem which leads to the knowledge of $\Phi'$ as a function of $s$ knowing $t$ as a function of injection parameters has been solved by WILHELM (1977). In our particular case of short distance measurements the function :

$$q\,\Phi(s) = q\,\Phi'(s) + \mu B(s)$$

is generally monotically increasing between the injection and the reflection points because the parallel electric field is present close to the spacecraft. This leads to an important simplification of the inversion problem. Furthermore, to simplify the discussion we will consider the magnetic force :

$$\mu \frac{dB}{ds} = \frac{W_\perp}{B} \frac{dB}{ds}$$

where

$W_\perp$ : the perpendicular energy at the injection as an equival ent electrostatic force associated with a almost constant electric field directed upward for ions and downward for electrons. Its magnitude depends on the perpendicular energy $W_\perp$ of the particles and on the altitude of the measurements. It is for example $E_{//} = 0.4$ mV/m if $W_\perp$ is 1 Kev at 1000 km and $E_{//} = 2.4$ mv/m if $W_\perp$ is 10 kev at 6000 km.

The echo delay time is thus :

$$t(W_{//}) = (2\,m)^{\frac{1}{2}} \int_o^{s_F} \frac{ds}{(W_{//} - q\,\Phi(s))^{\frac{1}{2}}} \qquad (2)$$

where $W_{//}$ is the parallel energy of the particles

Figure 1 shows t divided by the square root of the mass M of the particles (in a.m.u.) versus $W_{//}$ in the particular case where the parallel electric field $E_{//}$ is constant and equal to 20 mV/m or 200 mV/m .
Following WILHELM (1977) the relation (2) is :

$$t(W_{//}) = (2\ m)^{\frac{1}{2}} \int_{0}^{W_{//}/q} \frac{g'(\Phi)\ d(\Phi)}{(W_{//}-q\Phi)^{\frac{1}{2}}}$$

where $s = g(\Phi)$

and therefore : $ds = g'(\Phi)\ d\Phi$

This is the so called Abel's integral which can be solved (KAWVAL, 1971) to give :

$$g'(\Phi) = \frac{1}{(2\pi^2\ m)^{\frac{1}{2}}} \frac{d}{d\Phi} \int_{0}^{q\Phi} \frac{t(W_{//})\ dW_{//}}{(q\Phi - W_{//})^{\frac{1}{2}}}$$

and

$$s = \frac{1}{(2\pi^2\ m)^{\frac{1}{2}}} \int_{0}^{q\Phi} \frac{t(W_{//})}{(q\Phi - W_{//})^{\frac{1}{2}}}\ dW_{//}$$

The knowledge of t as a function of $W_{//}$ gives in consequence the value of $\Phi$ as a function of s whatever this function is,if the following conditions are fulfilled :

1) the electric field is present close to the spacecraft
2) t versus $W_{//}$ is continuously differentiable.

## 2.2. The echo delay time for both electrons and protons injected upward and downward

Depending on the injection and parallel electric field directions only electrons or ions will be able to be reflected by the potential drop. The use of both electrons and ions injected upward and downward are therefore desirable to describe the potential above and below the spacecraft. Using relation (1) the echo delay time t is proportional to the square root of the mass of the particles, so that it is advantageous to use the lighest possible ions i.e. the protons to improve the time resolution of the measurements.

## 3 - SOLUTIONS OF THE RENDEZ-VOUS PROBLEM IN THE GENERAL CASE

### 3.1. Description of the rendezvous

In this section we will assume that the electric field variations are small 1) spatially over one gyroradius of the particles which will be typically 10 m for electrons and 500 m for protons. 2) temporally as seen from the spacecraft compared with the echo delay time.

Moreover we will neglect the drift of the particles perpendicularly to the magnetic field due to gradient or curvature of the field. Indeed, the magnitude of such a drift is always smaller than 50 m/s for the energies and altitudes considered in this paper. This value is small in comparison with the velocity of the spacecraft and/or the drift due to the perpendicular electric fields prevailing in disturbed periods.

The motion of the injected particles as well as the spacecraft can be split into their two components : perpendicular and along B.

Let $\underline{V_{sp}}$ be the velocity of the spacecraft with respect to the plasma in the plane P. $\underline{V_p}$ is the component of the particle velocity in that plane at injection, $\alpha$ is the angle between the two vectors. We can see from figure 2 that we can obtain a rendezvous between the projected trajectories of the spacecraft and particles if $\alpha$ and $\underline{V_p}$ are chosen correctly. Notice that this is completly different to other methods proposed such as in the GEOS experiment (MELZNER et al., 1978) where a single complete gyration of the particle is required. In our case, a rendezvous is obtained after a number of completegyrationsplus one partial gyration.

Furthermore, if the pitch angle $\gamma$ of the particle at the injection is chosen so that the echo delay time is the same as the time of rendezvous in the plane P, a complete rendezvous is possible. In this case, the pitch angle of the returning particles is $\gamma' = \pi - \gamma$ .

### 3.2. Rendez-vous equations - Number of solutions

#### 3.2.1. Rendezvous in the plane P

From figure 2 it is easy to show that the rendezvous condition in the plane P can be fulfilled if the particle and the spacecraft reach the point R at the same time i.e. if

$$t = \frac{2r_b\,(\alpha + n\pi)}{V_p} = \frac{2r_b \sin\alpha}{V_{sp}} \qquad (3)$$

where $r_b$ is the gyroradius of the particles.

That leads to :

$$\frac{V_p}{V_{sp}} = \frac{\alpha + n\pi}{\sin\alpha} \qquad (4)$$

where $n$ is the number of gyrations around the magnetic field (on figure 2, $n = 2$), $\alpha$ is between 0 and $\pi$. Let $\underline{V_{o\perp}}$ be the velocity of the particles in the spacecraft frame of reference and $\beta$ the angle between $\underline{V_{sp}}$ and $\underline{V_{o\perp}}$ (see figure 3). We can write :

$$V_p \sin\alpha = V_{o\perp} \sin\beta \qquad (5)$$

and

$$V_p \cos\alpha = V_{sp} + V_{o\perp} \cos\beta \qquad (6)$$

(5) and (6) lead to

$$\mathrm{tg}\ \alpha = \frac{V_{o\perp} \sin\beta}{V_{sp} + V_{o\perp}\cos\beta} \qquad (7)$$

(4) and (5) to

$$\alpha + n\pi = \frac{V_{o\perp} \sin\beta}{V_{sp}} \qquad (8)$$

Using (6)

$$\alpha = \mathrm{Arctg}\left(\frac{V_{o\perp} \sin\beta}{V_{sp} + V_{o\perp}\cos\beta}\right) \quad (\alpha \text{ is between 0 and } \pi)$$

Replacing the value of $\alpha$ in relation (8) we obtain :

$$\frac{V_{o\perp} \sin\beta}{V_{sp}} = \mathrm{Arctg}\left(\frac{V_{o\perp} \sin\beta}{V_{sp} + V_{o\perp}\cos\beta}\right) + n\pi \qquad (9)$$

We can note that $\sin\beta$ is essentially positive and in consequence $\beta$ can only vary between 0 and $\pi$

Let $k = \dfrac{V_{o\perp}}{V_{sp}}$ and $u = \cos\beta$

the equation (9) becomes

$$k\ (1-u^2)^{\frac{1}{2}} = \mathrm{Arctg}\left(\frac{k\ (1-u^2)^{\frac{1}{2}}}{1 + ku}\right) + n\pi$$

If k is known, the solutions u of this equation are obtained at the intersection of the two curves

$$y = (1-u^2)^{\frac{1}{2}} \quad \text{and} \quad z = \frac{1}{k} \text{Arctg}\left(\frac{k\,(1-u^2)^{\frac{1}{2}}}{1+ku}\right) + \frac{n\pi}{k}$$

Figure 4 shows these two curves for $k = 10$. In this case n cannot be larger than 2. We notice that there are 2 solutions for each n (if $n \geq 1$) and only one solution if n is 0.

Figure 5 is an illustration of the rendezvous in the plane perpendicular to B. It represents the computed trajectories of the particles as seen from the plasma frame of reference and from the spacecraft leading to 3 of the solutions shown on figure 4. Using figure 4 we can see that if k is increasing . z decreases for a given value of u while y is constant. Consequently the possible values of n increase as well as the number of solutions. That means in particular that if $E_o$ is the same for electrons and protons, n is larger for electrons than for protons because k is larger. For example if $V_{sp}$ is 7 km/s and if $E_o$ is 1 Kev n is 40 for protons and 1600 for electrons.

We can note that, using (3) and (5) the times of rendezvous corresponding to n gyrations can be written

$$t_{n,i} = \frac{2\,k \sin \beta_{n,i}}{\omega} \tag{10}$$

where $\omega$ is the gyrofrequency

$\beta_{n,i}$ is one of the two solutions corresponding to n gyrations $(i=1,2)$

### 3.2.2. Complete rendezvous

(10) can be written as

$$\underset{(i=1,2)}{t_{n,i}} = \frac{2\,V_o \sin\gamma \, \sin\beta_{n,i}}{\omega}$$

where $V_o$ is the injection velocity of the particles.

Figure 6 shows the variation of $t_{n,i}$ for some values of n as a function of $\gamma$ (solid lines) or $W_{//}$ ($W_{//} = E_o \sin^2\gamma$) for a given $E_o$ (in this case $E_o$ is 1 Kev). The echo delay time is also shown in this figure (dotted line) as a function of $W_{//}$ for some values of the parallel component of the electric field.

A complete rendezvous can be obtained if the echo delay time can be made equal to $t_{n,i}$ for a given value of $W_{//}$ (or $\gamma$).

Notice from figures 6 and 7 that if $E_o$ is given (1 Kev in both figures) the solutions corresponding to electrons and protons are obtained for the same range of parallel energy $W_{//}$. Nevertheless, the number of solutions is larger (as $1/\sqrt{m}$) and the echo delay time is shorter (as $\sqrt{m}$) for electrons than for protons.

### 3.2.3. Conclusion

In conclusion to this section, we can say that, if we are able to measure the echo delay time t and $W_{//}$ for each solution of the rendezvous problem we can build the curve t versus $W_{//}$ and consequently derive the value of the potential along the magnetic field as a function of s as seen in section 2.

All these solutions could be obtained by injecting particles at a given energy , in a suitable range of pitch angle and in the azimuth range 0 to $\pi$ from the $\underline{V_{sp}}$ direction. But, that direction is unknown because it is a function of the perpendicular electric field. So let $\eta$ be the angle between $V_{o\perp}$ and the spacecraft orbital velocity $\underline{V_{se}}$ (the direction of which is known), if $\varepsilon$ is the angle between $\underline{V_{se}}$ and $\underline{V_{sp}}$ and $\eta'$ the angle between $\underline{V_{o\perp}}$ and $\underline{V_{se}}$ at the rendezvous , we can derive easily, using fig. 3, that :

$$\eta = \beta + \varepsilon \quad , \quad \eta' = -\beta + \varepsilon \quad \text{and thus} \quad \eta' = -\eta + \varepsilon \qquad (11)$$

Because $\varepsilon$ can vary between O and $2\pi$ , $\eta$ and $\eta'$ can vary also between O and $2\pi$ . It is therefore necessary to inject the particles in all azimuth around B and to detect them also in all these azimuths.

Finally, we can notice that the measurement of $\eta$, $\eta'$ and t for given an energy $E_o$ and pitch angle $\gamma$ at the injection leads to a measure of the velocity vector $\underline{V_{sp}}$ , that is to a measure of the perpendicular component of the electric field. Indeed $\eta$ and $\eta'$ give $\varepsilon$ after relation (11) , that is the direction of $\underline{V_{sp}}$. $\beta$ is also obtained from (11) , then the knowledge of $t_{n,i}$ gives k using relation (10) and therefore the magnitude of $\underline{V_{sp}}$ .
We have seen that the particles must be injected in a suitable range of pitch angle It is the aim of the next chapter to calculate that range in realistic cases.

## 4 - EXAMPLES OF POSSIBLE MEASUREMENTS OF DC ELECTRIC POTENTIAL STRUCTURES

### 4.1. Measurement of structures associated with small parallel electric fields at low altitude (300 - 1500 km)

As mentioned in the introduction, there are two possible electric potential structures. The first, due to anomalous resistivity, leads to a small parallel electric fields of large extent. Theoretical calculations lead to electric field strengths lower than 3 mV/m at about 1000 km, decreasing with altitude (SHAWHAN et al., 1978). On the other hand, experimental measurements (MOZER, 1976) lead to larger electric fields up to 10–20 mV/m below 500 km. In this altitude range (300–1500 km) the measurements can be performed by satellites travelling at about 7 km/s or by high altitude sounding rockets the velocity of which in the plane perpendicular to B is much smaller ($\sim$ 1 km/s). Figure 8 shows an example of curve t versus $W_{//}$ which could be obtained at 1000 km by injecting 1 Kev electrons and assuming a perpendicular electric field of 50 mV/m oriented at 45° to the spacecraft velocity. The parallel electric field is assumed to be uniform and ranges between 1 and 20 mV/m. The accuracy of the measurement is mainly a function of the accuracy of measurement of the pitch-angle (this angle can be measured at the injection or at the detection because the return particles have a pitch-angle $\gamma' = \pi - \gamma$ ).

We can see that the accuracy needed is certainly too high to measure such electric fields using satellites. Indeed, it is almost impossible to separate particles with 90° pitch angles corresponding to no parallel electric field (if we neglect the magnetic force) from those with pitch angles ranging between 90° and 87°.

On the other hand using sounding rockets, the accuracy could be sufficient to measure electric potential structure associated with parallel electric fields above 5 to 10 mV/m.

We can see also that using 1 Kev particles we can describe the potential structure up to 200 V if $E_{//}$ is 20 mV/m i.e. up to 10 Km from the spacecraft. If $E_{//}$ is decreasing up to 5 mV/m that distance decreases to 1 Km (20 V). By using 10 Kev particles we could describe the potential up to 2 kV in the first case and up to 200 V in the second case. The equivalent electric field (due to the convergence of the field lines) is now 4 mV/m and therefore has to be included in the calculations.

As we have seen above the proposed method is not sufficiently accurate to describe potential structures associated with small parallel electric field ($\leqslant$ 5 mV/m using rockets and $\leqslant$ 20 mV/m using satellites). Nevertheless, if we assume that the parallel component of the electric field is not varying over the distance covered by the particles along the field lines (i.e. few km) we will show that the measurement of this component (which we will call the "local parallel component") is possible using electrons alone.

## 4.2. Measurement of the local parallel component using electrons

In order to understand easily the method let us neglect the non uniformity of B as a first approximation. If there is no parallel electric field the electrons injected outside of the plane P perpendicular to B are lost and those injected perpendicularly will meet the essentially unmoved spacecraft during the first gyration, so the echo will be received before one gyroperiod. On the other hand, if a parallel electric field exists the particles injected outside of P can rendezvous after many gyroperiods as described in the previous sections, if they drift far enough along B to avoid the satellite after one gyroperiod. Therefore, we can conclude that if long echoes (echoes for which the echo delay time is many gyroperiods) exist, it is the signature of a parallel electric field.

Now, let us include the effect of the convergence of the magnetic field which is equivalent to the effect of a small parallel component of the electric field (hence forth called equivalent electric field to distinguish it from the real electric field). We are going to show as a first step, that if the energy of the electrons is small, the previous conclusions are yet valid. Indeed, let us assume no real parallel electric field in the case of fig. 8 for rocket measurements (the equivalent electric field in this case is 0.4 mV/m directed downward). It is possible to show that electrons with pitch angles varying between 90° and 89°4 at the injection could lead to long echoes (see fig. 8). But, the calculation of the maximum drift along B shows that it is no more that 14 cm after one gyroperiod. Thus, for a spacecraft size of typically $\sim$ 1 m the particles will return to the spacecraft after one gyration as previously. For smaller pitch angle, it is possible to show that the existence of long echoes is possible if the real parallel electric field is larger than $\sim$ 1 mV/m directed downward or larger than 1.8 mV/m directed upward (in this case the maximum echo delay time is 5.6 ms). The existence of long echoes is therefore the signature of a parallel electric field larger than 1 to 1.8 mV/m. In a second step, we are going to show but in fact more information can be obtained on the value of the real parallel electric field if we change the energy of the injected electrons.

Indeed, let us increase the energy $E_o$ of these electrons. We have seen that the equivalent electric field is increased. If $E_o$ is increased to 4 Kev for example , that field becomes 1.6 mV/m. Moreover, it is easy to show that the available pitch angle range to obtain a rendezvous is independent of $E_o$ , therefore, from fig. 8 we can see that if equivalent $E_{//}$ is now 1.6 mV/m the available pitch angle range is 90° to 87°65. The maximum drift of the particles after one gyroperiod in these conditions is now 1.25 m. So, even in the case of no real parallel electric field long echoes are possible. Per contra, we have to note that if the real parallel electric field is close to 1.6 mV/m and directed upward (i.e. in the opposite direction to the equivalent electric field) the particles will hit the spacecraft after one gyration, so long echoes are impossible. In the particular case considered here, the range of real parallel electric field for which these long echoes are impossible is 0.8 mV/m to 2.4 mV/m. Figure 9 shows the range of parallel electric field for which the long echoes are received (solid lines) or not (dotted lines) if $E_o$ is 1 Kev and 4 Kev. If we assume that $E_{//}$ is upwards (as found in many experiments), it is shown that :

1 - $E_{//}$ is between 0 and 0.8 mV/m if long echoes are received for 4 Kev electrons but not for 1 Kev.

2 - $E_{//}$ is between 0.8 and 1.8 mV/m if no long echoes are detected.

3 - $E_{//}$ is between 1.8 and 2.4 mV/m if long echoes are received for 1 Kev electron but not for 4 Kev electrons.

4 - $E_{//}$ is larger than 2.4 mV/m if long echoes are received for both energy.

If $E_{//}$ is assumed to be upward or downward, it can have an uncertainty because it may be also smaller than 1 mV/m downward in the first case and larger than 1 mV/m in the fourth case. In the two other cases, there are no uncertainties. It is obvious that the measured range of possible values of $E_{//}$ can yet be reduced if the number of energies considered increases.

These results are obtained assuming that the time of rendezvous is maximum. Using (10') that means that $\beta$ must be close to 90°. For those requirements to be fulfilled, it is necessary to inject the particles in different directions because the perpendicular electric field component is not known. That can be realised using 8 guns, the axis of which being in the plane perpendicular to B at 45° to each other. So, in all the cases there is one gun for which $|\beta - 90°|$ is smaller than 22°5 that is close enough to 90° in order that t be larger than $\sim 0.9\, t_{max}$.

The natural $\pm$ 3 or 4° divergence of the beam is then theoretically enough to inject particles to the right pitch angles. The detectors must be able to receive the particles in all the possible directions of the plane perpendicular to B, and in a small range of pitch angle around 90°. The time resolution of these detectors must be small compared with the time of rendezvous . It can be typically 100 µs. The time resolution of the measurement depends on the echo delay time and on the number of energies considered if a new energy is injected only when the echoes corresponding to the previous injection has been or would have to be received. In the case considered, the echo delay time is typically 10 ms. The time resolution is therefore 50 ms if we use 5 energies.

Finally, it is interesting to estimate the influence on the trajectories of the elastic collisions between the electrons and the neutral atmosphere which change the pitch angle of the electrons. Assuming the total elastic collision cross section to be typically $5.10^{-16}$ $cm^2$ (BANKS and KOCKARTS, 1973), the distance covered by electrons between the injection and the rendezvous to be 100 km and the number of atoms to be between $10^6$ and $10^7$ per $cm^3$ at 800 km and between $10^7$ to $10^8$ per $cm^3$ at 500 km depending on the local time and on the solar activity (CIRA, 1965), it is easy to show that this influence is small at 800 km because the number of electrons which collide with an atom over the distance covered is only 0.5 % to 5 %. But, it can be important at lower altitude, indeed this number increases to 5 % to 50 % at 500 km. These collisions will have therefore to be included into the calculations if the measurements are performed at too low altitude.

### 4.3. Measurements of potential structures associated with large electric fields

The second kind of possible structures are the so called double layers (BLOCK and FALTHAMMAR, 1976 ; SHAWHAN et al. 1978, GOERTZ and JOYCE, 1975) or electrostatic shocks (SWIFT, 1976) which lead to large total electric fields up the few hundreds of mV/m in small region of a few kilometers. These layers are expected to be oblique (SWIFT, 1976) and in consequence could extend over large altitude range.

Several measurements could be explained by the existence of such structures, that is "inverted V" precipitations (BURCH et al., 1976) dipole probe measurements (MOZER et al., 1977) or barium ion jets acceleration (HAERENDEL et al., 1976 ; WESCOTT et al., 1976). These measurements have been performed between 2000 and 8000 km and show potential drops ranging between a few tens of volts and a few kilovolts. Figure 10 shows the possible structure of the equipotentials (SWIFT et al., 1976) which could explained both the "inverted V" precipitation and dipole probe measurements. The inclination of the equipotentials is arbitrary. But, because the dimensions perpendicular to the magnetic field are of a few kilometers or hundred of kilometers as a maximum and on the other hand can be of a few thousand of kilometers along B , that means that the angle between B and the equipotential is often low . Therefore, the parallel component of the electric field can be assumed lower than the perpendicular one. The total field can be very large up to 500 mV/m.

Figure 11 shows an example of curve t versus $W_{//}$ that can be obtained injecting 7 KeV protons at 3000 km assuming a perpendicular electric field of 200 mV/m oriented at 45° to the satellite velocity. The parallel electric field is assumed to be uniform and to range between 20 mV/m and 100 mV/m. The accuracy of the measurement of the pitch angl es could be enough to describe the potential structures associated with parallel electric field of this magnitude and it is clear the larger the parallel electric field the better is the accuracy of the measurements. We can see that using 7 KeV particles we can describe electric potential up to 2 kV if $E_{//}$ = 100 mV/m but just up 100 V if $E_{//}$ = 20 mV/m. The total potential attainable can be increases theoretically by increasing the energy of the particles but we will see in the next chapter that especially for ions we are limited by the intensity needed.

Figure 12 shows the same curves assuming a perpendicular field of 500 mV/m. We can see that the accuracy of the measurement of potential structure associated with the same parallel electric field decreases when the magnitude of the perpendicular one increases. We can conclude roughly that the measurement is possible if $E_{//}/E_{\perp}$ is larger than about 10 %. If $E_{//}$ is lower we can just measure the local component by the method described before. As we have seen above, the measurement of the perpendicular electric field component is also possible and is very interesting in the case of electrostatic shocks because the time resolution is very good : 4 ms using electrons. Moreover the accuracy of the measurement is increased if the corresponding drift velocity is larger than the spacecraft velocity which is the case in the electrostatic shocks.

The accuracy of the measurement of the perpendicular component using our method is the best if $\beta$ is close to 90°. As previously shown this can be realised in all the cases using 8 guns with their axis at 45° to each other in the plane perpendicular to B.

To measure at the same time the perpendicular component of the electric field and the local parallel component (assuming that this one is small) the detectors must have the same characteristics as those already defined but, moreover they must be able to measure the azimuth of the returning particles.

The knowledge of the azimuth at injection is also necessary ; that can be possible if we code the injected pulses. Using as before 5 energies the time resolution of the measurement can be very short (about 20 ms in the case of fig. 12).

If now $E_{//}$ is large we must use both electrons and protons and the detectors must be able in addition to measure the pitch angle of the returning particles. The injection must be moreover swept over the total range of pitch angle needed. In this case at each injection from the guns over the total pitch angle range it is possible to receive the echoes of 4 of these guns (because as seen before echoes are possible only for $\beta$ between 0 and $\pi$). That means that we know 4 points on the curve $t$ versus $W_{//}$. It seems reasonable therefore to inject the particles with two different energies which give now 8 points on the curve. The time resolution of that measurement depends on the complexity of the detectors that is if these are able to measure instantaneously or not the pitch angles. If it is not the case, assuming that the typical value of the total pitch angle range is 60° to 120° and that the pitch angle range resolution must be $\pm 2°$ , the time resolution is 250 ms using electrons and 10 s using protons. That resolution is sufficient in the case of electrons, but certainly not in the case of protons. More complex detectors are therefore needed in that latter case.

## 5 - CALCULATION OF THE RETURNING FLUXES AS A FUNCTION OF THE INJECTED INTENSITY

The feasibility of the method is partly dependent on the intensity of beams needed for the returning fluxes be detectable. The calculation of these fluxes is therefore necessary.

Let Oxyz be a spacecraft frame of reference where Oy is along $\underline{V}_{sp}$ and Ox along $\underline{B}$ (fig. 5). Let assume that the particles are injected at time $t = 0$ from O. At time $t$ the coordinates of the particles are given if we assume a constant parallel electric field for simplicity, by

$$x = -\frac{q E_{//} t^2}{2 m} + V_o \cos \gamma t$$

$$y = -\frac{A}{\omega} \cos(\omega t + \rho) - V_{sp} t + \frac{b}{\omega}$$

$$z = \frac{A}{\omega} \sin(\omega t + \rho) - \frac{a}{\omega}$$

where $\omega = \dfrac{qB}{m}$

$$a = V_o \sin\gamma \cos\beta + V_{sp}$$

$$b = V_o \sin\gamma \quad \sin\beta$$

$$A = (a^2 + b^2)^{\frac{1}{2}}$$

$$tg\,\phi = \frac{a}{b} \qquad - \frac{\pi}{2} < \phi < \frac{\pi}{2}$$

These particles cross the plane $z = 0$ (figure 5) each gyroperiod.

After $n$ completegyrationsthey cross that plane at the point $M(x_1, y_1)$ and at the the time $t'$ such as :

$$x_1 = - \frac{q E_{//} t'^2}{2m} + V_o \cos\gamma \; t'$$

$$y_1 = \frac{2b}{\omega} + 2\phi \frac{V_{sp}}{\omega} - (2n+1) \pi \frac{V_{sp}}{\omega}$$

Let assume now that the injection angles $\gamma$ and $\beta$ change from $\gamma$ to $\gamma + d\gamma$ and from $\beta$ to $\beta + d\beta$ then $\underline{r} = \underline{OM}$ move to $\underline{r} + \underline{dr}$ where

$$\underline{dr} = \underline{dr\gamma} + \underline{dr\beta}$$

$\underline{dr\gamma}$ and $\underline{dr\beta}$ are the vectors corresponding to a change of $\gamma$ and $\beta$ respectively.

So, let $J\,d\Omega$ be the number of particles injected per second into the solid angle $d\Omega = \sin\gamma \; d\gamma \, d\beta$ . These particles will cross the $z = 0$ plane after $n$ gyrations at the point $M$ through the elementary surface $dS(t')$ given by :

$$dS(t') = | \underline{dr\gamma} \times \underline{dr\beta} |$$

If $N(t')$ is the number of particles per second and per $cm^2$, received at $M$ we can write :

$$N(t') \; dS(t') = J d\Omega$$

At the rendezvous point, this relation is :

$$N(t_{n,i}) \; dS(t_{n,i}) = J d\Omega \qquad (12)$$

where $t_{n,i}$ is the time of rendezvous

The components of $\underline{dr\gamma}$ and $\underline{dr\beta}$ can be easily found to be

$$\begin{aligned} dx\gamma &= -V_o \sin\gamma \, d\gamma t_{n,i} \quad \text{and} \quad dy\gamma = \frac{2}{\omega}\left(\frac{db}{d\gamma}\, d\gamma + V_{sp} \frac{d\phi}{d\gamma}\right) d\gamma \\ dx\beta &= 0 \qquad\qquad\qquad\quad \text{and} \quad dy\beta = \frac{2}{\omega}\left(\frac{db}{d\beta}\, d\beta + V_{sp} \frac{d\phi}{d\beta}\, d\beta\right) \end{aligned} \qquad (13)$$

where $\frac{db}{d\gamma} = -V_o \cos\gamma \sin\beta$ and $\frac{db}{d\beta} = V_o \sin\gamma \cos\beta$

$\frac{d\phi}{d\beta}$ can be found to be $\frac{d\phi}{d\beta} = -1$

Using (13) :

$$dS(t_{n,i}) = |dx\gamma \;\; dy\beta|$$

Therefore

$$dS(t_{n,i}) = \frac{2 V_o t_{n,i}}{\omega} |V_o \sin\gamma \cos\beta - V_{sp}| \, d\Omega$$

Using (10) and (12) we can write the value of N at the rendezvous point as :

$$N = \frac{J \omega^2}{4 V_o K \sin\beta |V_o \sin\gamma \cos\beta - V_{sp}|}$$

Let N' be the number of particles crossing the unit surface perpendicular to the direction of the particles at the rendezvous point, per second. The minimum value of N' as a function of $\gamma$ and $\beta$ is easily found to be :

$$N'_{min}(cm^{-2} \times s^{-1}) = \frac{7.26\,10^{-11} \times J(ster.^{-1}.s^{-1}) \times B^2(gauss) \times V_{sp}(Km.s^{-1})}{E_o^{3/2}(Kev) \times M^{\frac{1}{2}}(a.m.u)}$$

So $N'_{min}$ decreases if $E_o$ is increasing or if B is decreasing i.e. if the altitude is increasing.

As seen before the time resolution of the detectors must be chosen to be small with respect to the delay time which is typically ~ 150 ms using protons and ~ 4 ms using electrons, so it seems reasonable to chose a time resolution of 5 ms for protons and 100 μs for electrons.

To be detectable the returning fluxes must fulfilled two conditions :

(1) The count rate corresponding to the time resolution must be large enough to be statistically detected.

(2) The fluxes must be larger or at least of the same order than the natural ones.

Table 1 gives the minimum count rate in the cases of fig. 8 (rocket), fig. 11 and fig. 12 , assuming a typical aperture $\Delta S$ of the detectors $\Delta S = 0.05\ cm^2$ , a beam intensity of 1 mA and a beam divergence of $\pm 3°$ for electron beams and $\pm 7°5$ for proton beams. The count rates are those measured by detectors of an infinitely small field of view which could receive returning particles after $n$ gyrations. But in the case of electrons the returning angles of the particles after a number of gyrations close to $n$ are also close to those of these particles. Moreover, the echo delay times are also very similar (one solution each $\sim 1\ \mu s$). Thus, finite field of view detectors will measure many solutions in the time resolution interval and so the count rate is often larger, depending on the acceptance angle of the detectors. The real count rates can be typically evaluated to be 10 times larger. That is not the case for protons.

On the other hand the count rate due to natural background will depend on the field of view of the detectors and on their energy resolution. Because in the case of artificially injected particles the energy is very well defined it is our interest to limit the energy resolution to a small value. So, assuming an energy resolution of $\Delta E$ = 100 eV, a field of view $\Delta\Omega = 2.10^{-2}$ ster. and maximum fluxes of $10^7$ proton/cm$^2$.s.ster.Kev and $10^9$ electrons/cm$^2$.s.ster.Kev. we can compute a natural background of 5 protons per 5 ms and 10 electrons per 100 $\mu$s. We can therefore conclude that the typical values of the beam intensities must be 100 $\mu$A to 1 mA for proton and 10 $\mu$A to 100 $\mu$A for electrons.

We can note that these intensities are certainly too small to lead to large potential difference between the spacecraft and the surrounding medium due to the non-neutralization of the spacecraft. Therefore only the potential difference of the sheath will act on the trajectories of the particles in addition to the natural electric and magnetic fields. Because this potential is sufficiently small compared with the particles energy and also because the main part of the trajectories is located far away from the spacecraft (up to 1 to 10 km along the magnetic field lines) it is certainly reasonable to neglect the perturbations from the spacecraft

## 6 - CONCLUSION

The solution of the rendez vous problem for charged particles injected and received by the same spacecraft after they have performed a large number of gyrations around the magnetic field has been found in the general case. If the spacecraft travels through regions where DC electric field exist it has been shown that the perpendicular component can be deduced from the delay time of the rendezvous and the returning particle directions in the plane perpendicular to B. It has also been shown that the measurements of the electric potential along the magnetic field line can theoretically be obtained from the curve giving the echo delay time as a function of the pitch angle of the injected and returning particles. This curve can be deduced from the measurement of a large number of solutions of the rendezvous problem. Nevertheless, considering realistic structures of the electric potential it has been shown that the latter measurement is just possible in some cases and in particular in the so called electrostatic shocks structure if the parallel component of the electric field is large enough relative to the perpendicular one (larger than about 10 %). If this condition is not fulfilled only the local parallel component can be deduced. In this case the proposed method is nevertheless of great interest to measure either the possible DC parallel electric field due to the anomalous resistivity because the sensitivity is low ( $\sim$1 mv/m) or both the parallel and perpendicular components in electrostatic shocks when the equipotentials are almost aligned with the magnetic field, because the time resolution is very good (of the order of 20 ms i.e. about 130 m of spatial resolution at 3000 km).

The required particle detectors must be capable of detecting the returning particles in all the azimuth directions in the plane perpendicular to B but only in a small range of pitch angles around 90° if we want to measure the local parallel component of the DC electric field. They must be capable of measuring the azimuth of the particles if we want to measure in addition the perpendicular component of that field. In these two cases we can use only the electrons. The beam intensities needed are typically 10 to 100 μA. On the other hand if the equipotentials of the electrostatic shocks are less aligned with the magnetic field lines, that is if the parallel component is not too small relative to the perpendicular one, both electrons and protons must be used in order to measure the electric potential as a function of the distance from the spacecraft, above and below that spacecraft. In that case the time resolution is increased to about 250 ms and the detectors become more complex because they must be able also to measure the pitch-angle of the returning particles. It has been shown also that for both the complexity of the detectors and the beam intensities needed the use of electrons is much easier than the protons.

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## - FIGURE CAPTIONS -

Fig. 1 : Echo time divided by square root of the particle mass in a.m.u. as a function of parallel energy $W_{//}$ , assuming a uniform parallel electric field equal to 20 mv/m or 200 mv/m.

Fig. 2 : Rendezvous between the spacecraft and the particle projected trajectories in the plane perpendicular to B as seen from the plasma frame of reference.

Fig. 3 : Definition of axes OY and OZ and the angles $\epsilon$, $\beta$ , $\eta$ and $\eta'$
$\underline{V_{sp}}$ and $\underline{V_{se}}$ are the spacecraft velocities relative to the plasma and to the earth.
$\underline{V_{o\perp}}$ and $\underline{V_p}$ are the particles velocities relative to the spacecraft and to the plasma.

Fig. 4 : Intersection of $y = (1 - u^2)^{\frac{1}{2}}$ (solid line) and $z = \frac{1}{k}$ arctg $\left(\frac{k\ (1 - u^2)^{\frac{1}{2}}}{1 + ku}\right) + n\pi$ (dotted lines) which leads to 5 solutions for $\beta$ (3 of which are shown in Fig. 5) in the case $k(= V_{o\perp}/V_{sp}) = 10$.

Fig. 5 : Selected trajectories in the plasma frame of reference and the spacecraft frame of reference for k = 10, in the plane perpendicular to B.

Fig. 6 : Example of solutions of the complete problem of rendezvous in the case of protons. These solutions are obtained at the intersection of the curves t versus $W_{//}$ (dotted lines) where t is the echo delay time,and $t_{n,i}$ versus $W_{//}$ (i = 1,2) (solid lines) where $t_{n,i}$ are the times of rendez-vous in the plane P corresponding to n gyrations around B. The parallel electric field is assumed to be $E_{//}$ = 20,25 or 100 mV/m , $V_o$ is 440 km/s (i.e. $E_o$ = 1 Kev), the gyroperiod is 7 ms and $V_{sp}$ is 5 km/s. The solutions are shown for n = 5, 10, 12, 15, 20, 25, 27.

Fig. 7 : As fig. 6 for electrons in the same conditions ($E_o$ = 1 Kev).

Fig. 8 : Solutions of the rendez vous problem showing t versus the pitch-angle $\gamma$ (or $W_{//}$) for 1 keV electrons injected from a spacecraft or rocket at 1000 Km, assuming a perpendicular electric field of 50 mv/m oriented at $\theta = 45°$ to the spacecraft velocity relative to the Earth. The parallel electric field is assumed to be uniform, and ranges from 1 to 20 mv/m. There are two solutions per gyroperiod (0.71 µs) aligned along the curve. All these solutions are therefore indistinguishable from each other.

Fig. 9 : Ranges of parallel electric field for which long echoes are received (solid lines) or not (dotted lines) if $E_o$ is 1 Kev and 4 Kev. The numbers are referred to in the text.

Fig. 10 : Possible structures of the equipotentials after SWIFT et al. (1976).

Fig. 11 : Solutions of the rendezvous problem showing t versus $\gamma$ (or $W_{//}$) for 7 keV protons injected from a spacecraft at 3000 km, assuming a perpendicular electric field of 200 mv/m at $\theta = 45°$. The parallel electric field is assumed to be uniform and ranges between 20 and 100 mv/m. There are two solutions per gyroperiod (3.25 ms) aligned along the curve.

Fig. 12 : The same as fig. 11 for a perpendicular electric field of 500 mv/m.

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- TABLE 1 -

| | Protons (counts/5ms) | electrons (counts/100 µs) |
|---|---|---|
| case of fig. 8 (rocket) | 535 | 2814 |
| fig. 11 | 32 | 168 |
| fig. 12 | 98 | 513 |

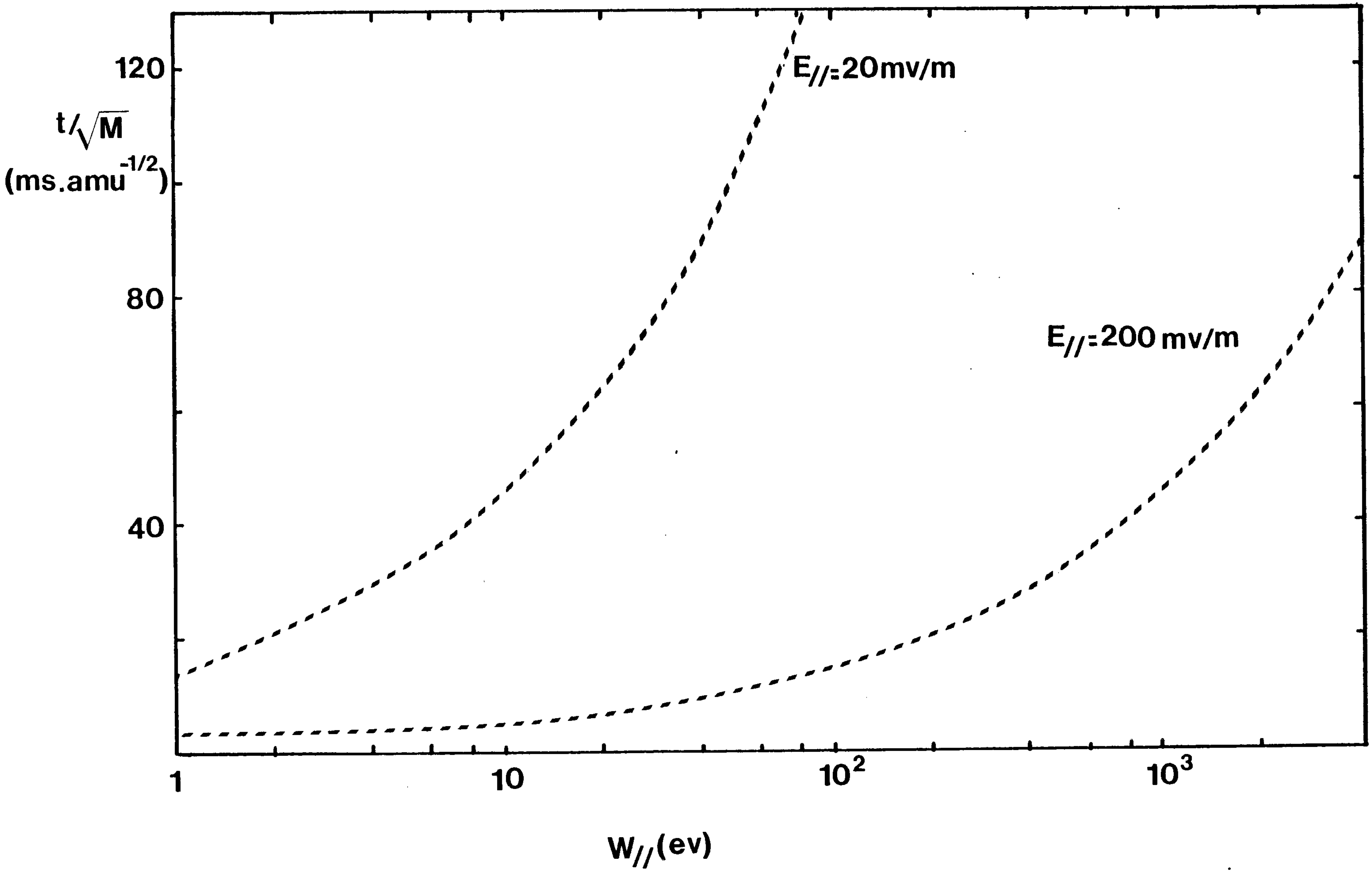



fig. 1

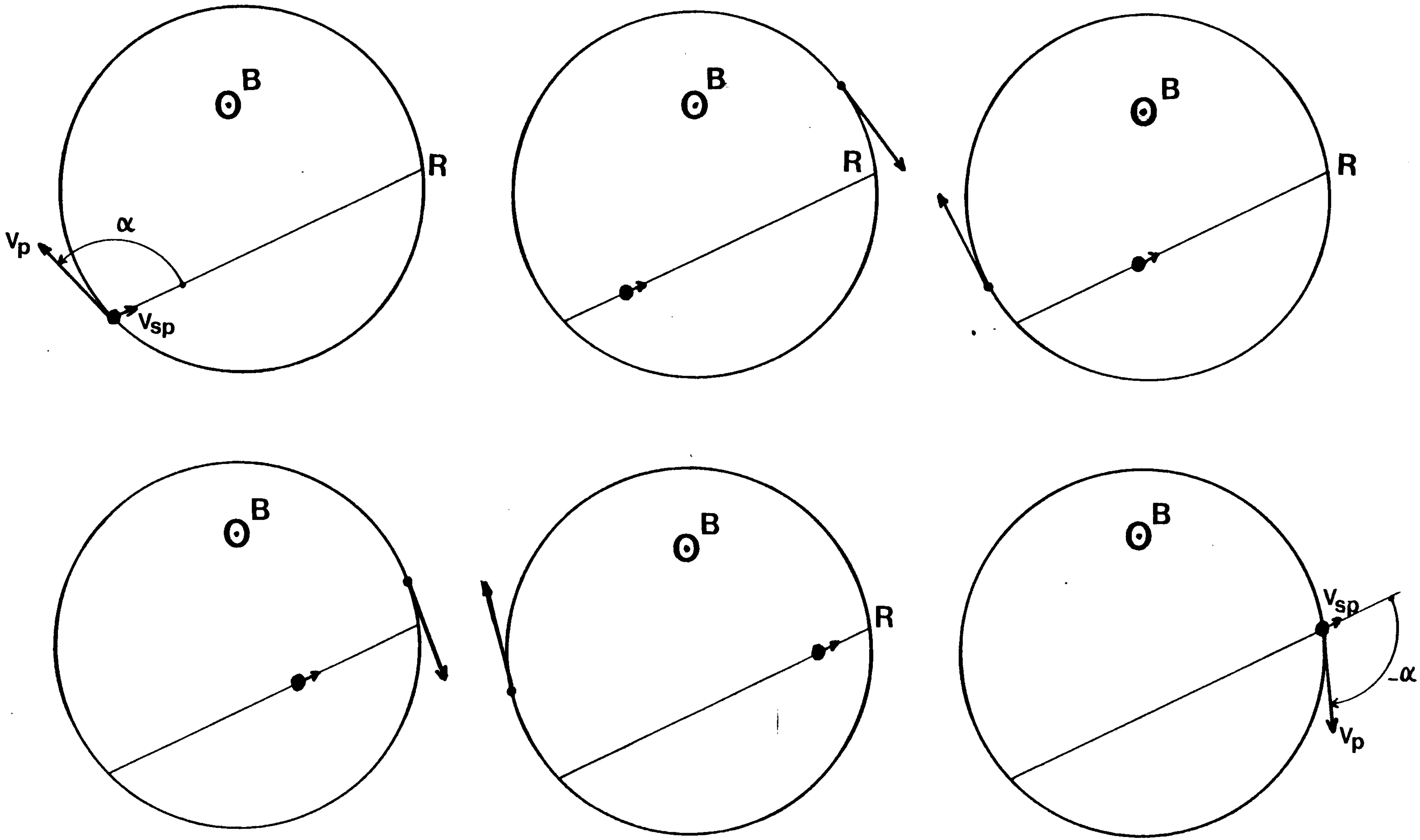
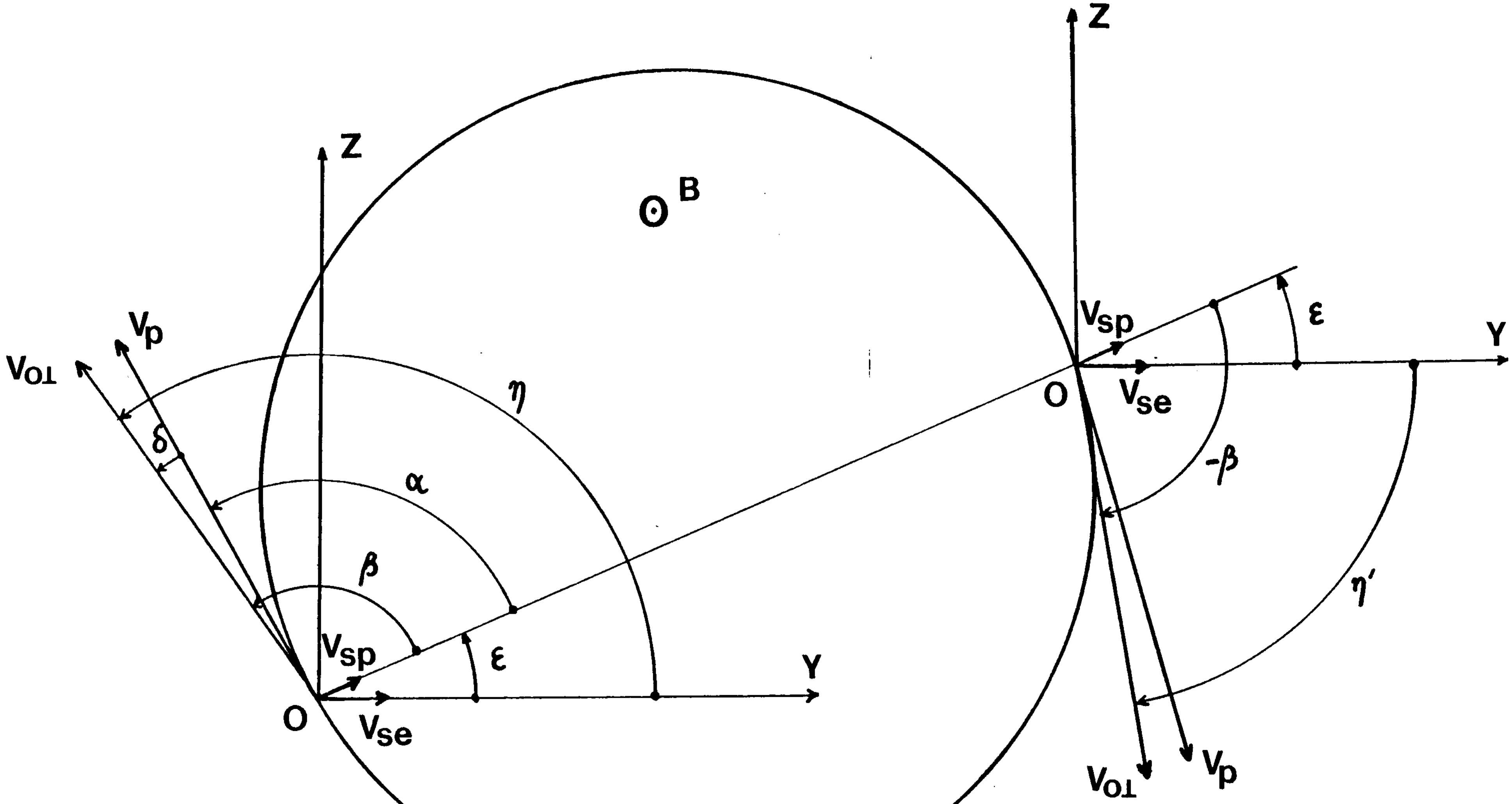



fig.2




$\eta = \beta + \varepsilon$

$\eta' = -\beta + \varepsilon$

$\eta' = -\eta + 2\varepsilon$

fig.3

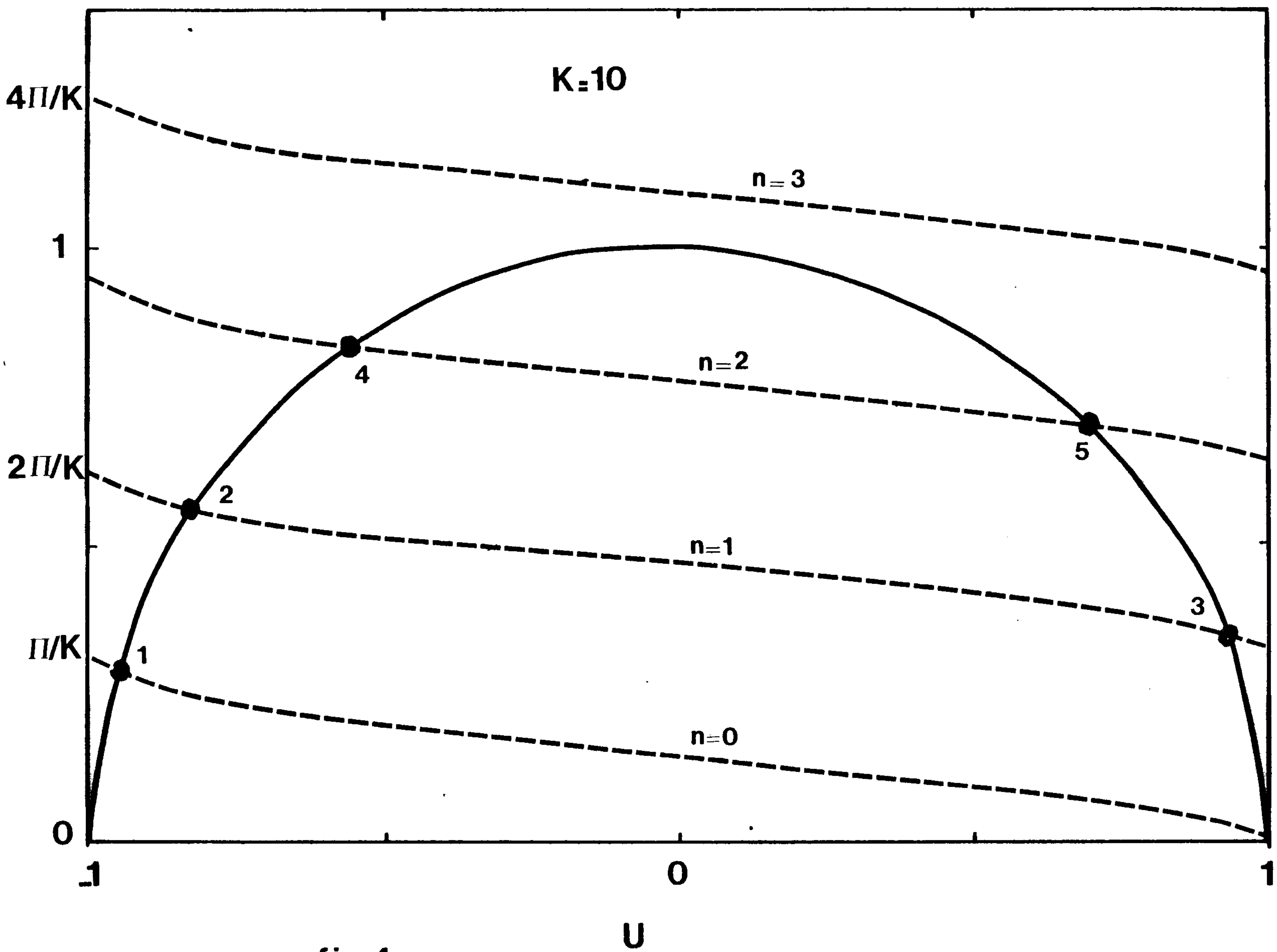



fig.4

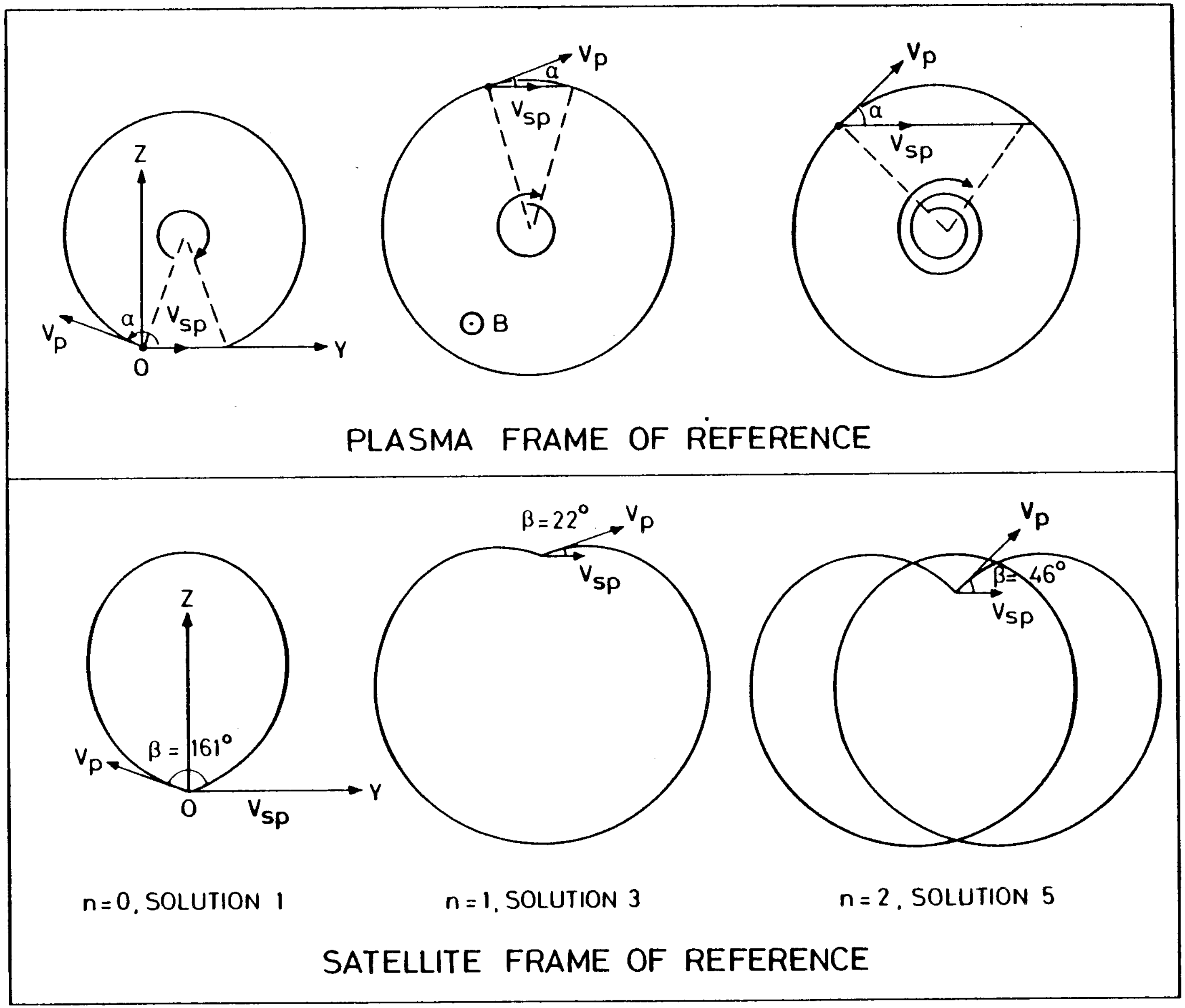

Z
$V_p$
α
$V_{sp}$
O
Y
$V_p$
α
$V_{sp}$
B
$V_p$
α
$V_{sp}$
PLASMA FRAME OF REFERENCE
Z
$V_p$
β = 161°
O
$V_{sp}$
Y
β = 22°
$V_p$
$V_{sp}$
$V_p$
β = 46°
$V_{sp}$
n = 0, SOLUTION 1
n = 1, SOLUTION 3
n = 2, SOLUTION 5
SATELLITE FRAME OF REFERENCE

fig.5

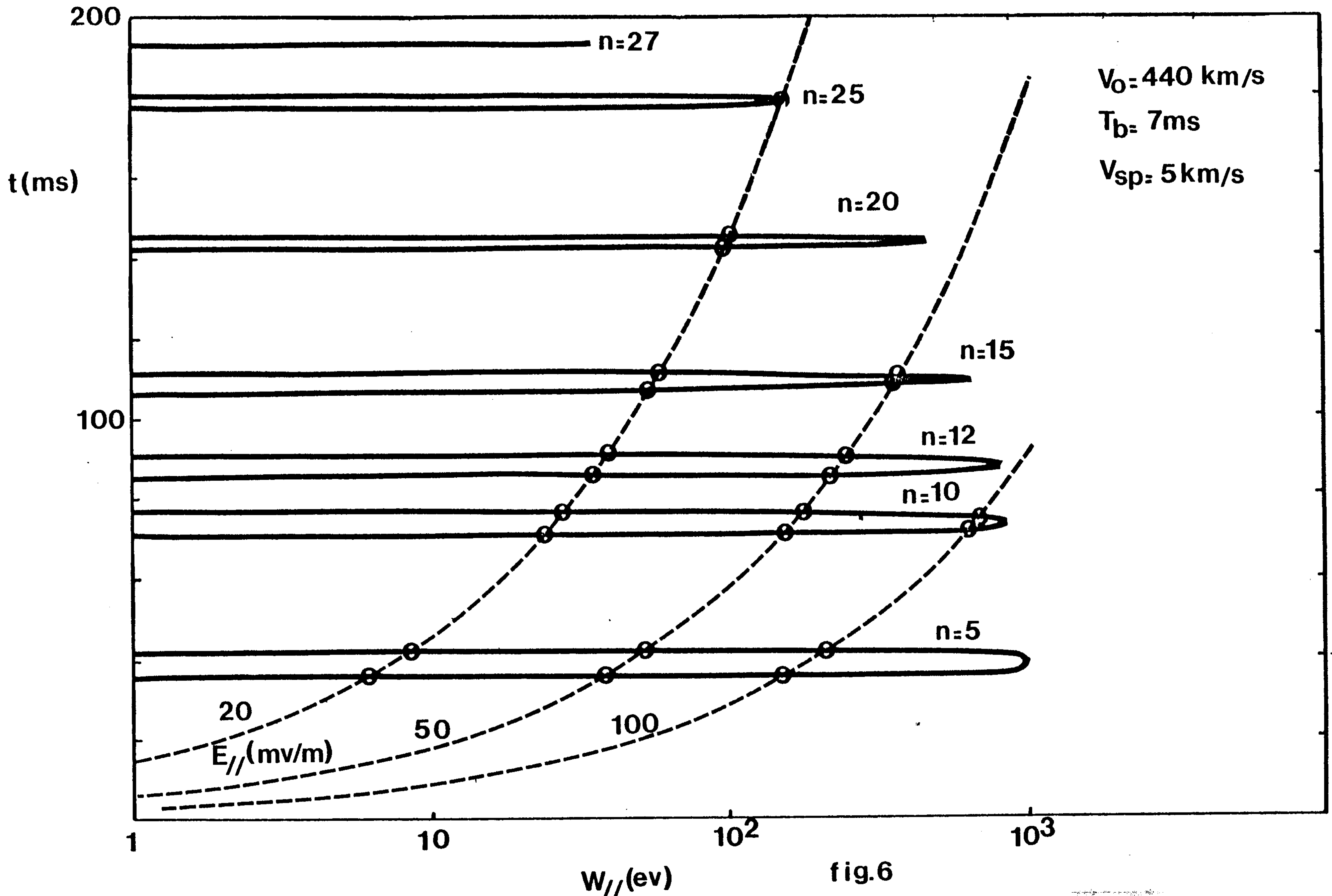

200
100
t(ms)
n:27
n:25
n:20
n:15
n:12
n:10
n:5
$V_o$: 440 km/s
$T_b$: 7ms
$V_{sp}$: 5km/s
20
50
100
$E_{//}$(mv/m)
1
10
$10^2$
$10^3$
$W_{//}$(ev)

fig.6

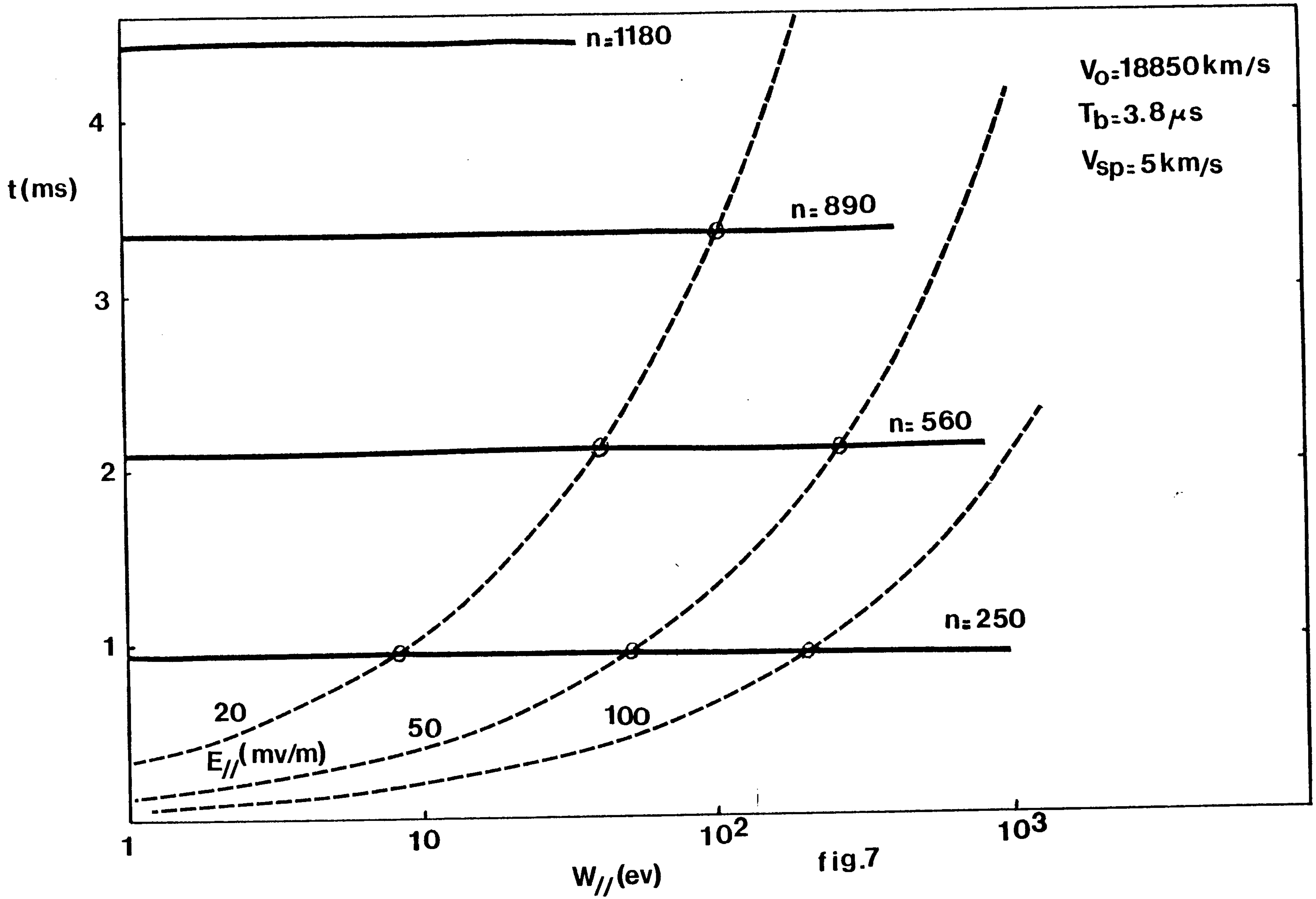

n=1180
n=890
n=560
n=250
$V_0$=18850km/s
$T_b$=3.8μs
$V_{sp}$=5km/s
t(ms)
4
3
2
1
20
50
100
$E_{//}$(mv/m)
1
10
$10^2$
$10^3$
$W_{//}$(ev)

fig.7

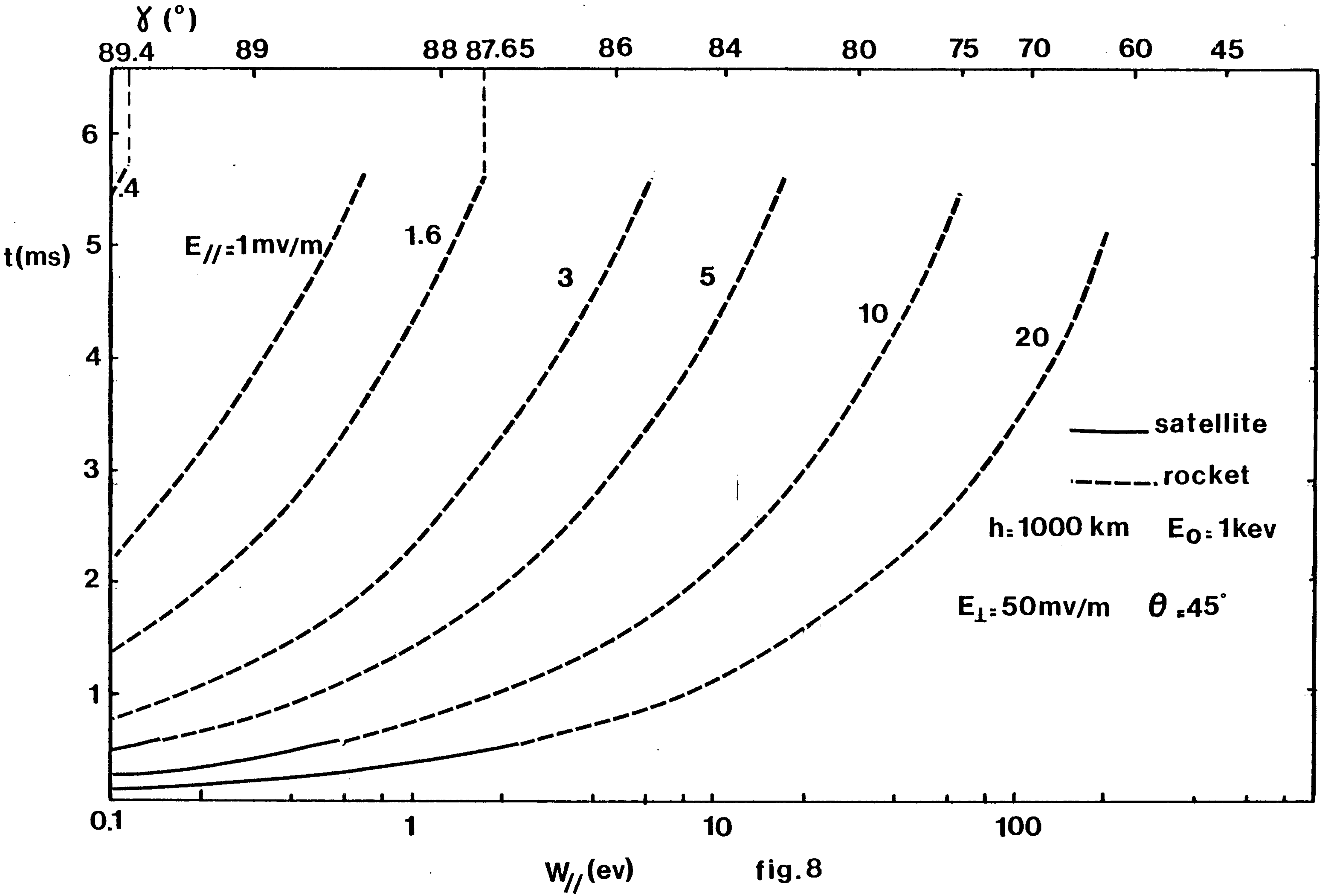

γ (°)
89.4
89
88
87.65
86
84
80
75
70
60
45
t(ms)
6
5
4
3
2
1
.4
E//=1mv/m
1.6
3
5
10
20
satellite
rocket
h=1000 km
E0=1kev
E⊥=50mv/m
θ=45°
0.1
1
10
100
W//(ev)

fig. 8

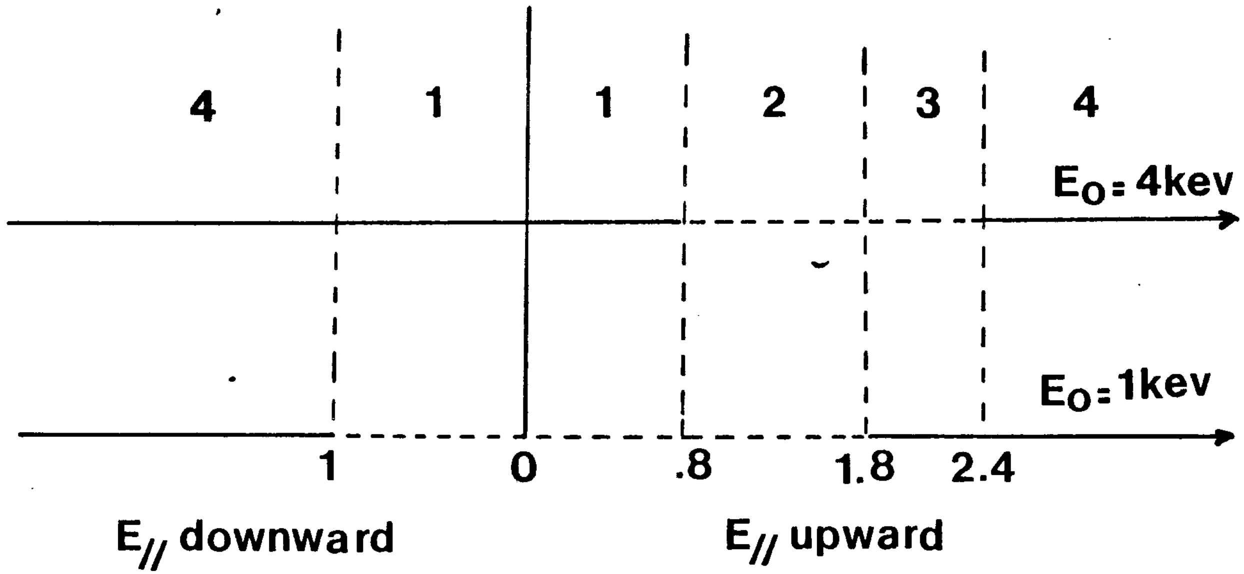



fig.9

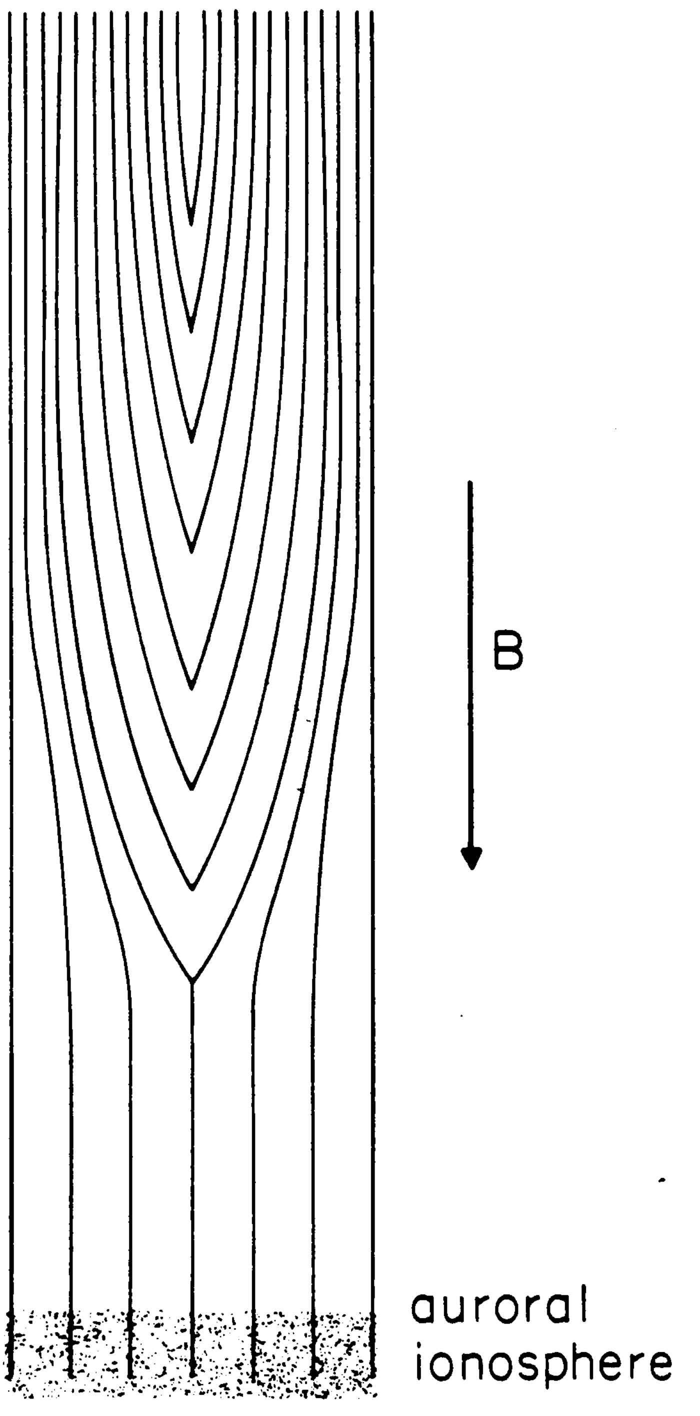



fig.10

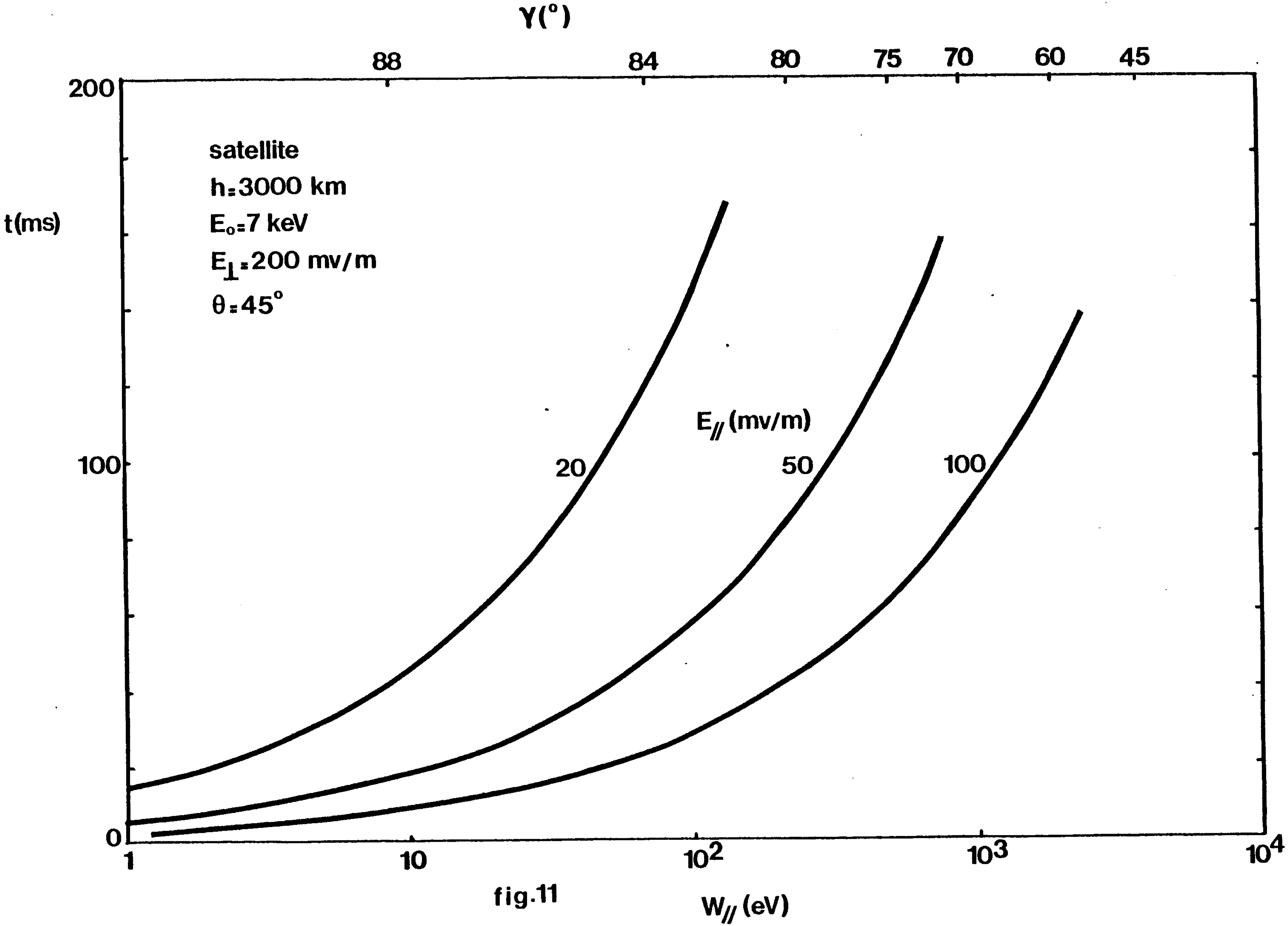

γ(°)
88
84
80
75
70
60
45
200
t(ms)
100
0
satellite
h=3000 km
E₀=7 keV
E⊥=200 mv/m
θ=45°
E// (mv/m)
20
50
100
1
10
10²
10³
10⁴
W// (eV)

fig.11

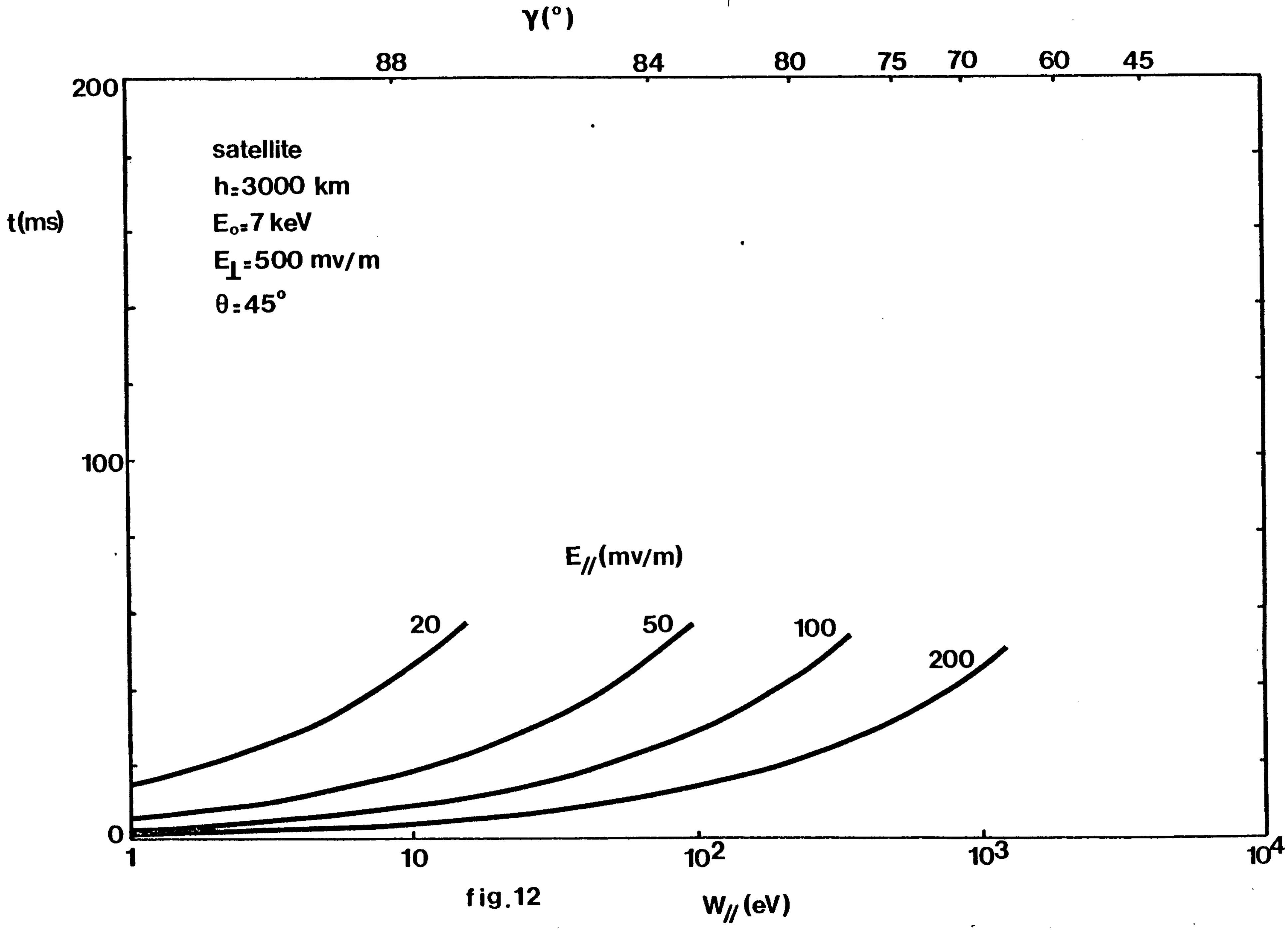

γ(°)
88
84
80
75
70
60
45
200
100
0
t(ms)
satellite
h=3000 km
E₀=7 keV
E⊥=500 mv/m
θ=45°
E//(mv/m)
20
50
100
200
1
10
10²
10³
10⁴
W//(eV)

fig.12

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