REVERSE DEFLECTION AND CONTRACTION
OF A PLASMA BEAM MOVING ALONG
CURVED MAGNETIC FIELD LINES
by
L. Lindberg and L. Kristoferson

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Royal Inst. of Technology
Division of Plasma Physics
100 44 Stockholm 70
Abstract. A plasma beam which originally moves in a longitudinal magnetic field and enters a region of curved magnetic field is investigated experimentally. It is found that the beam contracts perpendicular to the vxB-direction and the whole beam becomes deflected in the direction opposite to that in which the magnetic field is curved. The deflection is caused by propagation backwards of the transverse electric field which is induced when the beam enters the region with curved field.
Introduction

Plasma motion in curved or transverse magnetic fields is treated in a number of papers, e.g. Schmidt (1960), Eubank and Wilkerson (1961, 1963), Baker and Hammel (1962, 1965), Demidenko et al. (1966, 1969), Colomès and Veron (1969). The aim of the experimental work has mainly been to study injection into magnetic bottles and separation of impurities. The aim of the present experiment is to produce a stream of collisionless plasma in a magnetic field making an angle of $45^\circ$ with the direction of flow and study interactions with various obstacles. Such a stream has similarities with the solar wind.

Depending on density, velocity, and conductivity we might expect the plasma to behave in a number of different ways. Single particles moving from a region of longitudinal field into a curved field will in the first approximation follow the field lines, fig. 1 a. If instead a thin plasma is injected, drift motions give rise to charge separation and an electric field is set up. The plasma becomes self-polarized and can proceed straight on as indicated by fig. 1 b. A necessary condition for this should, according to Schmidt (1960), be $nm/eB^2 >> 1$, which means the Alfvén velocity $<< c$.

If the plasma makes electric contact along the field lines with a conducting wall or with a region of plasma having high cross-conductivity (e.g. a plasma gun), or with a region of plasma polarized in the opposite direction, depolarization currents are set up, which reduce or short-circuit the induced field, and the plasma again follows the curved field, fig. 1 c. This case is very clearly demonstrated by the experiments of Baker and Hammel (1962, 1965) and Colomès and Veron (1969). If the conductivity is high and if also the kinetic energy density exceeds the magnetic energy density, i.e. $nmv^2/2\mu_0/B^2 > 1$, which means $nm/\varepsilon_0 B^2 > c^2/v^2$, the plasma might be able to change the shape of the magnetic field and proceed straight on, "stretching the field lines" or, if initially unmagnetized, "pushing the magnetic field aside", fig. 1 d. Its behaviour is then more like that of a conducting liquid or solid body. This behaviour
is discussed for an unmagnetized plasma by Schlüter (see Gold 1958) and by Tuck (1959).

The criteria mentioned above define densities $n_1$ and $n_2$ resp., which have approximately the ratio $n_2/n_1 = c^2/v^2$. The discussion consequently covers a very wide range of densities.

In our experiments we observe an induced transverse electric field in the region of curved field. This electric field is of the right order to allow the plasma to proceed straight on by ExB-drift as in the case b). However, this electric field is also propagated backwards along the beam into the region of longitudinal magnetic field where it gives rise to an ExB-drift of the whole beam upwards, as in fig. 1 e. A detailed study of the plasma motion in the region of curved field also reveals features characteristic of the cases c) and d).

There are several situations in cosmic physics where the reverse deflection could possibly become of importance. Mass motions in solar flares is one example, and plasma motion along the curved dipole field of a central body is another example. Several other similar situations could be suggested.
Experiment

An electrodeless gun (conical theta pinch) is used to inject plasma into a longitudinal magnetic guide field, fig. 2. This field decreases along the path of the plasma so that the plasma beam expands, increasing its diameter by a factor of about three. The properties of the gun are described by Lindberg (1969). In the present experiment a transverse magnetic field is added in the "interaction space", so that the resulting field is curved as indicated by the dashed lines in fig. 2.

The applied magnetic field in the interaction space can be varied between 0.01 and 0.02 Vsm⁻². The plasma density is $10^{18}-10^{19}$ m⁻³, and its velocity $2-4 \times 10^5$ ms⁻¹. The translation energies of the ions are 300-1000 eV, while the ion thermal energies are negligible. For the electrons, the thermal energy is of the order 5-10 eV, which is much more than their translational energy. The plasma is collisionless, and the Alfvén Mach number between 1 and 2. The plasma is studied by various methods; the beam cross section is made visible by letting the plasma collide with a grid of thin glass rods, electric and magnetic probes are used to map density, electric field and magnetic field changes. Particle flux and energies are studied by means of a Faraday cup and an ion energy analyzer.

If we observe the plasma beam cross-section when it enters the interaction region we find that the plasma first moves straight on and contracts to a flat slab essentially perpendicular to the $v \times B$-direction. A few microseconds later this slab is displaced vertically in the direction opposite to that in which the field is curved (e.g. upwards when the field is curved downwards as in fig. 2). The contraction takes place only in the region of curved magnetic field, while the vertical displacement essentially takes place in the region of purely longitudinal
magnetic field prior to the bend. At later time the beam moves further upwards and lands to its main part on the upper wall of the expansion space.

The behaviour of the plasma is roughly understood on basis of drift theory. The plasma becomes polarized and proceeds through the region with transverse magnetic field by $E \times B$-drift. However, the electric field is almost curl-free, which means that besides the induced polarization field, $E_\perp$, there are also $E_y$- and $E_z$-components. These components give rise to drifts responsible for the contraction of the plasma (Baker, 0000, Demidenko et al., 1969). The vertical drift of the plasma takes place in the region of longitudinal field and begins when the induced $E_x$-field spreads backwards in the plasma beam. This field is propagated by means of energetic electrons which are accelerated by the potential differences set up by the induced electric field in the interaction space. Electrons are streaming backwards in the beam on one side, while on the other side of the plasma beam electrons are streaming towards the interaction space. The induced potential difference across the beam is 100-200 V. Measurements with a Faraday cup located upstream at the side of the beam $(x<0)$ indicate a backflow of energetic electrons (20-40 eV) when the applied transverse field component $B_y$ is negative, but no such backflow when $B_y$ is zero or positive.

It is of fundamental importance that initially electric field components parallel to the magnetic field are set up. These fields accelerate the electrons which propagate the electric field backwards and they also constitute the driving e.m.f. for the depolarization currents. These currents in turn tend to make $E_\perp$ approach zero.
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Different types of behaviour of a plasma initially moving parallel to a magnetic field when entering a region of curved field.

a. Single particles follow in first approximation magnetic field lines even if they are curved.

b. A thin plasma beam becomes self-polarized and proceeds straight on by $E \times B$-drift.

c. The polarization field is short-circuited by depolarization currents and the beam has to follow the curved field.

d. A plasma beam with high conductivity and kinetic energy moves straight on, "stretching and pushing the magnetic field lines aside".

e. Our experiment shows that in a polarized beam the polarization field is propagated backwards and causes a deflection by $E \times B$-drift in the direction opposite to that in which the magnetic field is curved.
Section of apparatus.

The applied magnetic field is shown by dashed lines. When this field is curved downwards, the plasma beam is deflected upwards and contracts (perpendicular to the plane of the figure) to a flat slab.