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A test of the frozen in the magnetic field theorem

R. Lundin, M. Yamauchi, J.-A. Sauvaud, A. Balogh
Swedish Institute of Space Physics, Kiruna, Sweden (rickard.lundin@irf.se)

The notion Frozen-in Magnetic Field originates from Hannes Alfvén, the result of a work on electromagnetic-hydrodynamic waves published in 1942. After that the notion frozen-in magnetic field, or ideal MHD, has become widely used in space plasma physics - misused according to the inventor himself. The controversy on the applicability of ideal MHD started in the late 1950:ies and has continued ever since. The applicability of ideal MHD is particularly interesting in regions where solar wind plasma may cross the magnetopause and access the magnetosphere. It is generally assumed that macroscopic system can be described by ideal MHD provided the violations of ideal MHD are sufficiently small-sized near magnetic x-points (magnetic reconnection). On the other hand, localized departure from ideal MHD also enables other processes to take place such that plasma may cross the separatrix and access neighbouring magnetic flux tubes. It is therefore important to be able to quantify from direct measurements ideal MHD, a task that has turned out to be a major challenge. An obvious test is to compare the perpendicular electric field with the plasma drift, i.e. to test if E = - vxB. Yet another is to rule out the existence of parallel (to B) electric fields. These two tests have been subject to extensive research for decades. However, the ultimate test of the "frozen-inn" condition based on measurement data is yet to be identified. We combine Cluster CIS- and FGM- data, estimating the change of magnetic flux (dB/dt) and the rotation of plasma -vxB (rot(vxB)), the terms in the "frozen-in equation". Our test suggest that ideal MHD applies in a macroscopic sense in major parts of the outer magnetosphere, for instance in the external cusp and in the high-latitude magnetosheath. However, we also find significant departures from ideal MHD, as expected on smaller scales, but also on larger scales near the cusp and in the magnetosphere-boundary layer. We discuss the importance of these findings.