Constraining electric fields from electrostatic deflector plates: A brief report and case study from the Fast Plasma Investigation for the Magnetospheric Multiscale Mission

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Abstract A common feature of top hat space plasma analyzers are electrostatic “deflector plates” mounted externally to the aperture which steer the incoming particles and permit the sensor to rapidly scan the sky without moving. However, the electric fields generated by these plates can penetrate the mesh or grid on the outside of the sensor, potentially violating spacecraft electromagnetic cleanliness requirements. In this brief report we discuss how this issue was addressed for the Dual Electron Spectrometer for the Magnetospheric Multiscale Mission using a double-grid system and the simple modeling technique employed to assure the safe containment of the stray fields from its deflector plates.

1. Introduction

It is necessary for space plasma instrumentation to see as much of the sky as practicable in order to measure the 3-D velocity distribution function of the local plasma. Whilst a top electrostatic analyzer [Carlson et al., 1982] accepts plasma from up to 360° azimuthally, the field of view is limited to a few degrees of elevation (dependent on the amount of collimation). On spinning spacecraft such as the European Space Agency (ESA) Cluster [Johnstone et al., 1993] or the NASA THEMIS [McFadden et al., 2008], the sensor can be mounted with the instrument symmetry axis perpendicular to the spin axis, so that the instrument scans the entire sky (4π) with each revolution of the spacecraft. However, this technique limits the temporal resolution of the investigation to the spacecraft spin rate and cannot be employed on a three-axis stabilized vessel (such as the NASA STEREO, MAVEN, and the ESA Solar Orbiter). Thus, a common solution to this problem is the employment of “deflector plate” electrodes mounted externally to the analyzer head [see, e.g., Young et al., 2007; Lin et al., 1995; Barabash et al., 2006, 2007; Nilsson et al., 2007; Carlson et al., 2001; Luhmann, 2005]. When a voltage is applied, the electrostatic field generated steers charged particles into the electrostatic energy analyzer, permitting the instrument to rapidly scan the sky. At least one grounded grid must be placed over the outside of the instrument (e.g., the Solar Orbiter Electron Analyzer [Collinson, 2010]) and often two (e.g., FAST [Carlson et al., 2001]; MAVEN Solar Wind Electron Analyzer [Halekas et al., 2015]) or more (e.g., MAVEN SupraThermal and Thermal Ion Composition [McFadden et al., 2015]) depending on the design of the instrument or measurement requirements. The grid concentrates the total electric potential drop, enhancing the “leverage” of the plates (compared to if the electric field were allowed to simply leak into space) and containing the electric fields within the sensor.

The Magnetospheric Multiscale (MMS) Mission was launched in 2015 to investigate the phenomenon of magnetic reconnection, and in particular, to probe the electron diffusion region. Due to the small size (~10s of km) of this region, the Fast Plasma Investigation (FPI) [Pollock et al., 2016] on board each identical spacecraft had to be designed to deliver full-sky (4π), high-resolution (11°) electron plasma velocity distributions once every 30 ms. This unprecedented measurement cadence is far greater than the ~20 s spin period of each spacecraft, necessitating the use of deflector plates on both the Dual Ion Spectrometer (DIS) and Dual Electron Spectrometer (DES) [Collinson et al., 2012]. In addition to an array of particle instruments, each MMS spacecraft carries numerous sensors dedicated to the measurement of magnetic and electric fields [Torbert et al., 2014]. The sensitive nature of these instruments necessitated
a (spacecraft-wide) electromagnetic cleanliness requirement on FPI that it not generate steady state or alternating electric fields greater than 1 V at the surface of the spacecraft.

Another key driver of electric field containment is the close proximity of the DIS and DES spectrometers on the spacecraft (see Figure 1). This is a fundamental challenge for FPI because DIS and DES need to able to operate independently at different cadences (150 ms and 30 ms, respectively) and not cross-contaminate each other. We can imagine a common scenario when DES is looking for 10 eV electrons, whilst DIS is applying maximum voltages to its deflector plates to search for 30 keV ions. Should any electric fields leak out of the DIS deflector plates, they could potentially interfere with the trajectories of the 10 eV electrons. Although the converse scenario (DES contaminating DIS) is also possible, DES is particularly vulnerable to contamination from DIS, since DIS uses higher voltages on its deflector plates ($V_{\text{max}}(\text{DIS}) \sim 5700$ V) than DES ($V_{\text{max}}(\text{DES}) \sim 4000$ V) [Pollock et al., 2016]. Assuming comparable designs, a higher voltage on a deflector plate will lead to higher electrostatic fringing through any grid, and greater contamination.

Figure 2 shows a simple 3-D simulation to qualitatively illustrate how DIS could potentially cross-contaminate DES. It incorporates accurate models of the DIS and DES sensor heads [Collinson et al., 2012; Pollock et al., 2016], with the exception that the outer grid of the DIS has been replaced with a solid electrode onto which a voltage can be applied to approximate the electric fields penetrating through the outer grids. The DIS and DES units are simulated to their proper scales, but their relative positions are approximate, and none of their housing is included. Thus, whilst this simulation cannot replicate the exact topography of the electric fields penetrating through the grids of DIS, it serves adequately to qualitatively illustrate the problem and estimate its magnitude.

Two cases are shown. Figure 2a shows the case for the electric fields penetration being equivalent to a 1 V surface potential on the grids. In this case, 10 eV electrons (green) entering DES are not deflected from their trajectories, enter the electrostatic analyzer, and are detected. Figure 2b shows the exact same case, but this time with an 80 V equivalent surface potential applied to the outer grid of DIS. Curved red lines of electric field equipotential are seen curving out from the sensor, and this time the 10 eV beam is deflected by this electric
field and does not enter the aperture. Thus, in the case of an +80 V equivalent surface potential, the electric fields leaking through the grid are interfering with the low-energy electrons being measured by DES.

During the design of FPI, it was discovered that one grid alone was insufficient to completely contain the electric field generated when the maximum voltage (5000 V) was applied to the deflector plates (see 3-D simulation, Figure 3a). In this brief report, we describe the simple technique used to rapidly estimate the effective equivalent surface potential of the Dual Electron Spectrometer, and how it was used to design the two-grid solution whereby this field was successfully contained within the instrument. This double-grid approach to guard against electrostatic leakage was implemented on both DES and DIS. This issue was briefly discussed by Pollock et al. [2016] (the FPI instrument paper), and here we provide a more in-depth discussion of the approach and a quantitative analysis of its efficacy.

**Figure 2.** 2-D slices through two 3-D simulations demonstrating cross-contamination between the DIS and DES sensors in approximate relative positions: (A) +1 V surface equivalent potential on the outer grid of DIS with minimal deflection of 10 eV electrons; (B) +80 V equivalent potential on the outer grid of the DIS.

1.) +1 V effective surface potential at DIS outer grid
2.) Electrons not deflected
3.) 10 eV electrons detected

1.) +80 V effective surface potential at DIS outer grid
2.) Electrons deflected
3.) No 10 eV electrons detected
2. A Simplified Technique for Rapidly Estimating Equivalent Surface Potentials

Full 3-D models of plasma analyzers require a significant amount of memory, and thus processing time, to calculate electric fields. Whilst the verification of any instrument with accurate 3-D models is a vital part of any development process [see, e.g., Sablik et al., 1988; Woodliffe, 1991; Collinson et al., 2009; Collinson, 2010; Collinson and Kataria, 2010], this level of fidelity is unnecessary for a first-order estimate of the equivalent surface potential electric field penetration, or for the rapid prototyping of possible solutions. Thus, our approach was to approximate the deflector plate and grid with a far simpler model, and then use a full 3-D simulation for final validation of our solution.

Figure 3. 2-D slices through full 3-D simulations of the Dual Electron Spectrometer showing lines of equipotential emanating from one of the electrostatic deflector plates and penetrating: (A) DES with a single grid; (B) DES with two grids, safely containing the electric fields with an equivalent surface potential <1 V.
Figure 4. Simplified grid simulations for determining effective surface potentials showing equipotential lines for 2, 5, 10, 20, and 30 V: (a) single grid simulation with aperture opening \(A\) equal to the aperture of the FPI-DES; (B) a solid electrode is substituted for the grid, showing that the penetrating field equipotentials can be replicated by a surface voltage of 80 V.

In this simplified geometry, the aperture of the instrument is approximated to a flat 2-D plane of size \(a\), equal to that of the actual aperture. The deflector plate is approximated as a flat electrode mounted behind the grid at its minimum distance \(d\). Figure 4a shows a slice through a such a simplified 3-D simulation (in our case, using a commercial, off the shelf package called SIMION), showing equipotential lines between 2 V and 30 V. As with the full 3-D simulation, these potential drops between these equipotential lines show significant electric field penetration through the grid when 5000 V is applied to the deflector. Although this simple model does not perfectly reproduce the results of the full 3-D simulation (Figure 3a), it is a far simpler model to build, and the information that we glean from it is exactly the same: a single grid cannot adequately contain the electric fields generated by the deflector plate. A second simulation is then performed, wherein the grid is replaced with a single flat electrode (Figure 4b). The voltage on this electrode is then adjusted until the lines of electric equipotential approximately match that of the earlier simplified grid simulation (Figure 4a). Thus, we estimate that the fringe-fields penetrating from the grid are approximately equivalent to a surface potential of \(\sim 80\) V. Again, whilst this is a highly simplified approach, it permits us to rapidly determine that this design fails to meet (by roughly 2 orders of magnitude) our electromagnetic cleanliness requirements. Although full analytical solutions of field penetration are possible [Read et al., 1998], we do not require such precision when simply determining whether or not a grid design acceptably meets requirements.

3. Containing Fringe Fields From Deflector Plates With a Double Grid

One possible solution would be to simply make the outer grid finer (i.e., with a tighter spacing between wires). However, using the above technique, it was rapidly determined that to get an effective surface potential \(<1\) V, such a grid would have to be between 300 and 600 lines per inch, would have a relatively low transparency \((<36\%)\), be challenging to manufacture and mechanically support, and would also be fragile and highly susceptible to breakage during launch. Thus, this solution was quickly deemed impractical and abandoned.

Using the above simulation technique, it was determined that the most effective way to contain such fringe fields on the FPI-DES and FPI-DIS sensors was through a double grid: the first (inner) grid reduces the problem to the equivalent of an \(\sim 80\) V surface potential and the second (identical outer) grid reduces electromagnetic contamination to below acceptable levels. Each grid is 90\% transparent, and thus, the addition of a second
such grid reduces the total transparency of the aperture resulting from the two grids to 81%. Figure 5 shows four simulations of a simplified FPI-DES deflector plate and grid, with the separation between the grids systematically increased between 2.5 mm and 5 mm. This later case represents the final configuration selected for the FPI-DES. The outer dual grids for FPI-DES are a square mesh, and every DES grid is identical. The effect of the transparency of the grids on the geometric factor (sensitivity) of the instrument was included in the laboratory pre-launch calibration [Pollock et al., 2016].

A full 3-D model of the FPI-DES was then built (see Figure 3b) and it was confirmed that this two-grid system successfully contained the 1 V equipotential line when the maximum voltage (5000 V) was applied to the deflector plates. Although even better containment (and thus more margin for electromagnetic cleanliness) would have been achieved with a few more millimeters of separation, \( s = 5 \) mm already expanded the FPI instrument to the outer limits of its defined volume envelope, and since any further expansion would have eaten into engineering margins, it was deemed that the electromagnetic containment provided by \( s = 5 \) mm was sufficient. Given the excellent agreement between earlier simulations with idealized grids (i.e., 100% transparency with no fringe fielding) and laboratory calibration [Collinson et al., 2012; Pollock et al., 2016], the effect on the trajectories of the electrons resulting from the second grid is negligible.

4. In-Flight Test of Electric Field Containment

In order to test whether the second outer grid is successfully containing the electric fields from the deflector plates, we compared 4π electron sky maps of a known and stable electron population, to verify that there is no distortion in the incoming direction of low-energy electrons (as one would expect were electric fields leaking from DIS, see Figure 2). Solar wind electrons are separated into three populations [Pilipp et al., 1987]:

Figure 5. Containing fringe fields with a double-grid system. Note the 1 V equipotential is contained within a second grid as the distance between the grids is increased.
the Core, Halo, and Strahl. Whilst the Core and Halo are semi-isotropic Maxwell-Boltzman distributions, the Strahl is a narrow electron velocity distribution, aligned with the interplanetary magnetic field [Schwenn and Marsh, 1991]. The Strahl is therefore an ideal electron population for such a test whether the second grid on DIS is doing its job and successfully containing the electric fields from the deflector plates.

Figure 6 shows an example of 30 ms burst-mode observation of solar wind electrons taken by the four FPI Dual Electron Spectrometer units aboard MMS observatory № 1. The data is presented as a series of 16 skymaps, each skymap being at a single given energy step, from 12 eV up to 484 eV. Within each skymap, the x-axis shows the elevation (from the 16 anodes of each DES spectrometer head [Pollock et al., 2016]), and the y-axis shows the azimuthal angle. In each skymap, the data is normalized to a single relative intensity of flux. The magnetic field direction is plotted in each skymap with the “circled dot” and the anti-field-aligned direction denoted by “circled cross”. The Strahl is visible as a (red) field-aligned distribution that persists from the lowest energy bins (where most of the skymap is dominated by the relatively isotropic Core and Halo) up though the 379 eV energy bin. Also visible is an anti-field-aligned population (blue), which are strahl electrons being reflected from Earth’s bow shock. As one would expect, the direction of these populations remains aligned (and anti-aligned) with the direction of the interplanetary magnetic field down through the lowest energies measured by FPI-DES. We observe no evidence of any distortion in the arrival direction of the lower energy portion of these skymaps, and thus we confirm that the dual grids are successfully containing the electric fields from the deflector plates.

5. Summary

In this brief report, we demonstrated how a model of the aperture of a plasma analyzer could be simplified in order to rapidly determine whether or not the electric fields penetrating through its outer grids met electromagnetic cleanliness requirements. Using the same technique, we determined that the best solution was the deployment of a second identical grid outside of the first, such that the equivalent surface potential is stepped down in two stages, whilst having minimum impact (9%) on total particle throughput. The final configuration was verified using a high-fidelity full 3-D simulation, and accepted by the MMS instrument critical design review as meeting MMS electromagnetic containment requirements.

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