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Microchannel plate lifetime experiment for the DIS and DES instruments on the Magnetospheric Multiscale Mission

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ABSTRACT

The stability of microchannel plate (MCP) gain with time impacts the success of long-term space plasma missions that use such detectors. Gain stability is of particular importance for the Fast Plasma Investigation (FPI) suite on NASA's Magnetospheric Multiscale (MMS) mission, which operates 64 independent MCP assemblies. Due to this massive number of sensors, there was not sufficient time to fully precondition all flight detectors prior to MMS launch. Therefore, an understanding of the change of MCP gain with time is vital to ensure quality FPI performance. We have conducted lifetime experiments with flight-grade FPI-like MCP assemblies for both ion and electron detectors. These experiments demonstrate that MCP gain stabilizes after$\approx 1.0\ C/cm^2$ has been extracted from the plates. Based on these results, the FPI MCPs could potentially operate for 20+ years on-orbit.

1. Introduction

Continuous Channel Electron Multiplier (CEM) detectors have been used for particle and photon detection since the 1960s (e.g. (Goodrich and Wiley, 1962; Adams and Manley, 1966)). A CEM is a hollow tube made from a material with a high secondary electron-electron emission coefficient. Any single incident particle impacting the wall of the tube with sufficient energy emits secondary electrons. The CEM is biased with a $\sim$ kV potential, such that an electric field accelerates secondary electrons towards the end of the tube. As these electrons travel down the CEM, they gain energy before re-impacting the tube wall. This process repeats many times over the length of the CEM, producing a cascade of electrons over a few nanoseconds. One particle or photon can produce $\sim 10^6 - 10^7$ electrons that can be detected as a current pulse with appropriately configured electronics.

A Microchannel Plate (MCP) is formed by fusing many very small diameter ($\sim 10\mu m$) glass CEMs (i.e., microchannels) together in long bundles and then slicing the bundles transverse to their longitudinal axes into thin ($\sim$ 0.5 mm) wafers. In a typical MCP there are several hundred thousand channels per square centimeter. The first MCP detector was fabricated in the early 1960s at the Bendix Research Laboratory (Wiley and Hendee, 1962). MCPs were originally intended as amplifiers for image intensification devices (Wiza, 1979), but their use has since been expanded to a diverse set of disciplines. MCPs can detect both photons and particles that have sufficient energy to liberate an electron upon entering a channel. MCPs need to operate at pressures of $\approx 10^{-6}$ Torr (Paschen, 1889) or lower, which makes them suitable detectors for the space environment.

A property of MCPs is that their gain, defined as the typical number of electrons exiting for a single incident particle, changes as a function of the total charge extracted per unit area. Early in the lifetime of an MCP, the gain will start high and rapidly drop with extracted charge. This behavior is hypothesized to be due to water vapor and other impurities becoming ionized, generating a large but artificial initial gain (Siegmund and Csorba, 1989). Eventually, as more charge is extracted, the MCP gain flattens out and should remain stable. This plateau is where MCPs are most stably operated as particle detectors. Late in the life of an MCP, the gain reduces to the point that the MCP ceases to serve as an effective

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detector. Therefore, before flight, MCPs are typically preconditioned or 'burned-in' at high fluence until $\approx 1.0\,C/cm^2$ is extracted (Siegmund et al., 1986, 1991; Siegmund and Csorba, 1989). This process could take as much as a month or more depending on the MCP channel aspect ratio (i.e., the ratio of the length of a channel to its diameter).

NASA's Magnetospheric Multiscale (MMS) mission (Burch et al., 2016) was launched on 12 March 2015. The objective of MMS is to explore the Earth's magnetosphere for evidence of a phenomenon called magnetic reconnection. To do this, MMS employs four identical spacecraft in a tetrahedron formation with instruments that measure thermal plasma, electromagnetic fields, and high energy particles. One suite of instruments is the Fast Plasma Investigation (FPI) (Pollock et al., 2016). The 'Fast' in FPI's name indicates that FPI is required to rapidly measure the three-dimensional structure of space plasmas. This requirement was based on the need to resolve very small structures that convect past the spacecraft at high speed. FPI measures a full 4π steradian phase space distribution over 32 energies every 30 (150) ms for electrons (ions) (Pollock et al., 2016). To achieve this performance, four dual ion and four dual electron spectrometers were placed on each spacecraft, resulting in 64 independent MCP detector stacks across the MMS constellation.

For an estimate of the time required for fully preconditioning FPI, consider just the Dual Electron Spectrometers (DES). There are 16 DES instruments on MMS, each with two sensor heads and 8 flight spare MCP stacks. The time to burn-in one MCP stack to $\approx 1.0\,C/cm^2$ was roughly one month and the facility designed to burn-in the flight MCPs could accommodate two stacks. Therefore, 20 months of continuous operations would have been required, which was not feasible given the MMS development schedule. FPI's unique approach to preconditioning was to extract only $\approx 0.1 C/cm^2$ in the laboratory and then closely to monitor and adjust the gain of each MCP stack on-orbit (Pollock et al., 2016; Gershman et al., 2016).

The goal of the experiment described in this paper was to subject flight spare MCPs to high ultraviolet flux for an extended duration, thereby simulating the in-flight lifetime of FPI detectors. Pulse Height Distributions (PHDs) were recorded at regular intervals using a low-intensity beta source. This data yielded both MCP count rate and gain as a function of time. These results inform the FPI team to effectively manage MCP high voltage operations.

In the following sections we will discuss the DES/DIS MCPs in more detail and provide a brief description of the FPI in-flight calibration process. In section four, we will describe the hardware used for the experiment, and in section five we will detail the test methodology. Finally we will conclude with a summary of the results and their impact on the MMS data.

2. DIS and DES MCPs

The MCPs used in this study were flight spares from the development of the FPI suite of instruments on MMS. FPI consists of 16 Dual Electron Spectrometers (DES) and 16 Dual Ion Spectrometers (DIS), each with two matched sets (two heads per unit) of MCPs in a 'Chevron' stack configuration.

Table 1 summarizes the major properties of the DES/DIS MCPs. The DES MCPs had a simple 'D' shape, while DIS had a more complex annular shape (see Fig. 1). The DES and DIS MCPs had pore diameters of 25 μm and 12.5μm, respectively, and bias angles of 8°. The DES MCPs were tested, burned-in, and installed at NASA Goddard by the FPI team. The DIS MCPs were prepared by PHOTONIS France by a proprietary unpublished method. The charge extracted from these stacks before flight was unknown.

3. FPI MCP operating voltage

As will be shown, the gain of the FPI MCPs constantly changes until sufficient charge is extracted. Therefore, to maximize data quality, it is critical to vigilantly monitor the gain trend and determine when the MCP voltages need adjustment. In addition, knowledge of the expected gain drift is important to ensure that operational decisions appropriately consider hardware limitations. For example, FPI power supplies have a finite voltage headroom (DIS: 3000 V, DES: 3600 V) and the electron MCPs have a recommended high voltage limit of 2400 V from Photonis USA. Photonis France S.A.S. did not provide a recommended high voltage limit for the ion MCPs.

It is desirable to have constant gain with well-balanced crosstalk and signal loss. Crosstalk here is defined as the combined effects of electron cloud spreading below the MCP, MCP to anode coupling, and anode to anode capacitive coupling. Signal loss refers to the portion of a PHD that is outside a variable discriminator threshold. A common procedure in the lab for finding an appropriate operating voltage for an MCP stack is to record count rates in the presence of a constant signal source while incrementally increasing the high voltage until the count rate ceases to increase. However, this procedure does not reveal anything about the crosstalk. Instead, the FPI sensors are programmed to perform daily in-flight sweeps of their discriminator threshold.

As the discriminator threshold is increased, the measured counts represent an integral of all the pulse heights above the threshold. Crosstalk dominates the measured count rates at lower pulse heights, and cannot be fully excluded from the integration without eliminating some portion of the real signal. The threshold sweep is fit with multiple gamma distributions. This fit accomplishes two things: (1) it provides an estimate of the contribution of crosstalk and signal loss at the sensor's operating threshold, and (2) provides the MCP gain as a function of time can be recorded for trending (Pollock et al., 2016; Gershman et al., 2016). This gain is regularly compared with the lifetime experiments described in this paper.

Knowledge of how the MCP will evolve long term and its overall expected lifetime are critical to deciding MCP voltage settings. Adjustments of these settings regularly, and in a timely manner, are essential to maintain FPI MCP performance for the duration of the MMS mission. The purpose of these lifetime experiments is to enable such estimates.

4. Hardware

The vacuum chamber used for the lifetime experiment had a minimal volume of $\approx 760\ cm^3$ to allow for very low pressures (i.e., 10^{-8} Torr). The main vacuum pump was a Leybold Turbovac 151C turbomolecular pump that operated continuously. A Lesker G100F hot-filament ionization gauge was employed to monitor the pressure. The High Voltage Power Supply (HVPS) was a Bertan 225, which had a maximum output voltage of 5 kV and a maximum current of 5 mA. To process pulses out of the anode, the signal was first passed through an Ortec 572A amplifier and then the pulse height distribution was measured using an Ortec ASPEC-927 Multi-Channel Analyzer (MCA) configured to sample with 2048 channels. Chamber cleanliness was monitored with a Stanford Research Systems RGA200 Residual Gas Analyzer.

The circuit for measuring the PHD using the MCA was calibrated using a pulse generator over a wide range of input voltages across a 1 pF capacitor, linking the MCA channel number to a known charge. The uncertainty of the gain was defined by the circuit calibration, which was less than 10%. Once calibrated, the full range of a single PHD was $2.20x10^9$ electrons/pulse with an increment of $1.06x10^6$ electrons per

Table 1
DES/DIS microchannel plate properties.

	Manufacturer	Aspect Ratio	Strip Current (μA)	Radius (mm)	Effective Area (cm^2)
DES	PHOTONIS USA	L/ D = 60	55–150	OUT:44	30.4
DIS	PHOTONIS France S.A.S.	L/ D = 80	30–100	OUT:56 IN:44	19.53