RESPONSE OF THE MMS SPACECRAFT TO BEING ACTIVELY CONTROLLED

Klaus Torkar[1], Owen Roberts[1], Rumi Nakamura[1],
Alexander C. Barrie[2], Yuri V. Khotyaintsev[3]

1) Space Research Institute, Austrian Academy of Sciences, Graz, Austria
2)) NASA Goddard Space Flight Center, Greenbelt MD, 20771, USA
3) Swedish Institute of Space Physics, Uppsala, Sweden

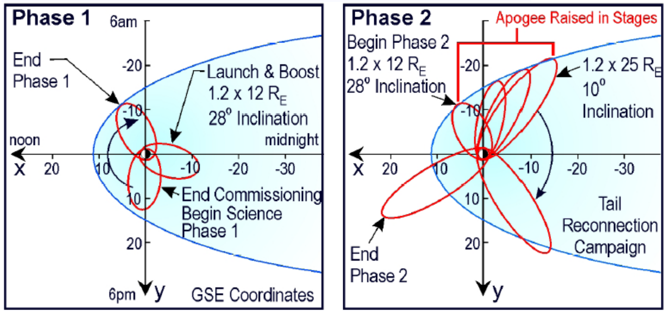
28th SPINE, June 9, 2021

ÖAW IWF

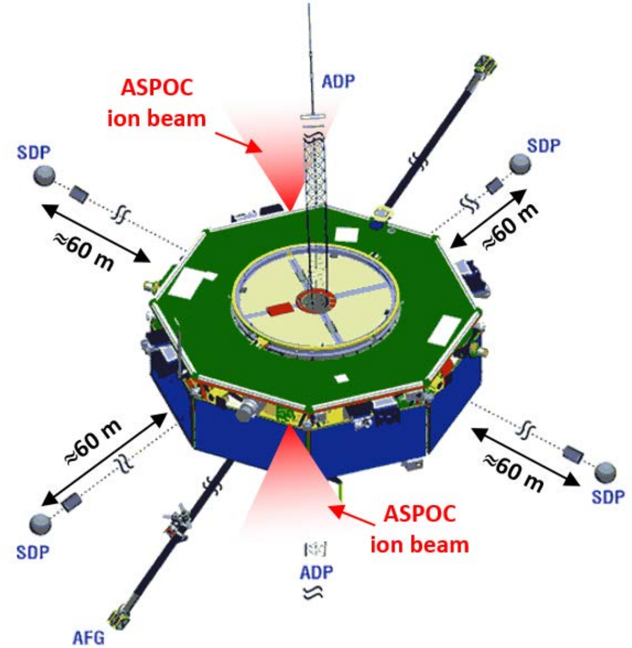
MMS MISSION

4-spacecraft NASA Magnetospheric Multiscale (MMS) mission launched in March 2015

Near-equatorial, eccentric orbits with apogees starting at 12 Earth Radii going to 25 R_E



Spacecraft dimensions	≈3.2 m Ø (octagon), ≈1.3 m height surface area ≈34 m² total, ≈5.9 m² projected (including all booms)
Active instrument	Active Spacecraft POtential Control (ASPOC), two units per spacecraft
Emitters	Liquid metal source, capillary type
Probes	Spin plane double probes (SDP) 2 pairs on 60 m wire booms, axial double probes (ADP) on ≈15 m booms
Plasma instrument	Fast Plasma Instrument (FPI), <30 keV, electron (DES) and ion (DIS) sensors



[after Torbert et al., JGR, 2016]

ÖAW IWF

ASPOC EMITTERS

- Liquid Metal Ion Sources with Indium
- 4 emitters per instrument,
  one active at a time
- Unfocused beam (±20° to 30° FWHM)
- Energy (typical) 5.5 to 7 keV
- Current nominally 10 µA, for tests ≤80 µA

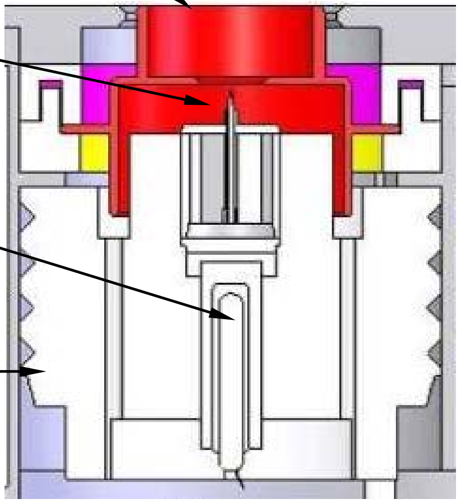
Indium LMIS
Sharpened Tantalum Capillary

Extractor Electrode / FOV Limiter

Emitter

Heater

Thermal
Isolation

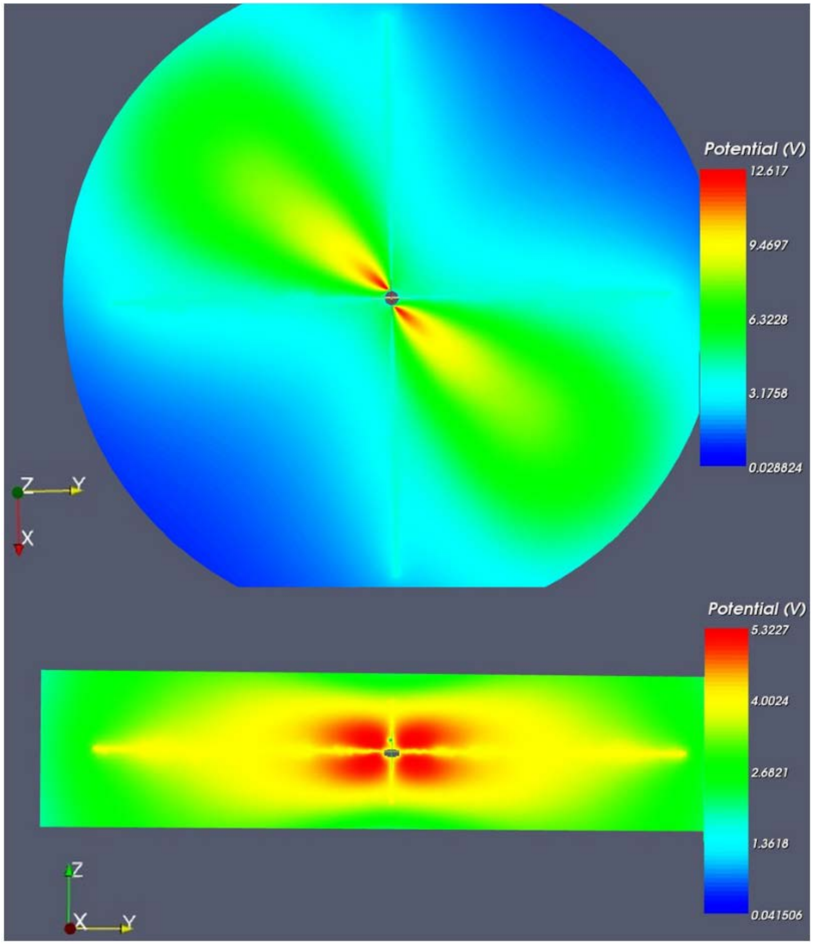


Instrument

ÖAW IWF

INTRODUCTION-ASPOC

- The Active Spacecraft Potential Control instrument regulates the potential of the four Magnetospheric Multiscale (MMS) spacecraft with the goal V_{sc}<4V to allow more accurate measurements of the plasma environment.
- Spacecraft illuminated by the Sun charge positively with respect to plasma.
- Relevant currents are the electron thermal current (electrons collected by the spacecraft), photoelectrons emitted by the spacecraft, the ion current emitted by ASPOC, secondary electron emission (when ambient electrons are hot).
- The spacecraft potential can be calibrated to give a measurement of the electron density.
- We also investigate the charging timescales of the spacecraft.



PIC Simulation of MMS with ASPOC on (F. Cipriani, private comm., 2010)

CALIBRATION TO OBTAIN ELECTRON DENSITY

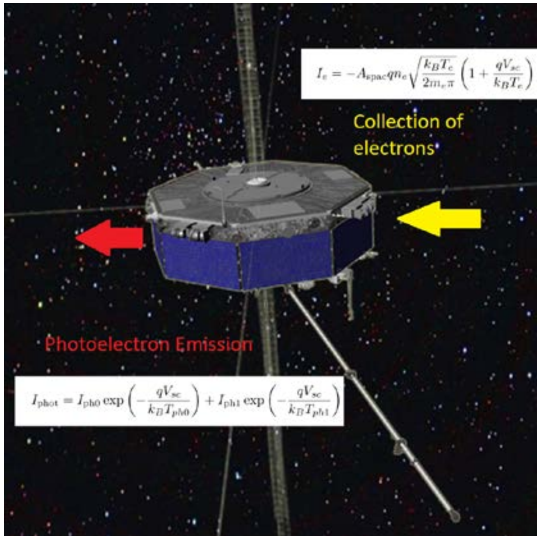
$$I_e = -A_{\text{spac}} q n_e \sqrt{\frac{k_B T_e}{2 m_e \pi}} \left(1 + \frac{q V_{sc}}{k_B T_e}\right)$$

Get from lower resolution FPI data

$$I_{\text{phot}} = I_{\text{ph0}} \exp\left(-\frac{q V_{sc}}{k_B T_{ph0}}\right) + I_{\text{ph1}} \exp\left(-\frac{q V_{sc}}{k_B T_{ph1}}\right)$$

Fit $I_e + I_{ASPOC}$ to V_{sc} to get photoelectron parameters

- When ASPOC is off currents are predominantly due to the electron thermal current and the photoelectron current.
- They can be assumed to be equal and having opposite signs $I_e = I_{ph}$ allowing the density to be derived. If ASPOC is on, we can still obtain the density but there is an additional current from ASPOC.

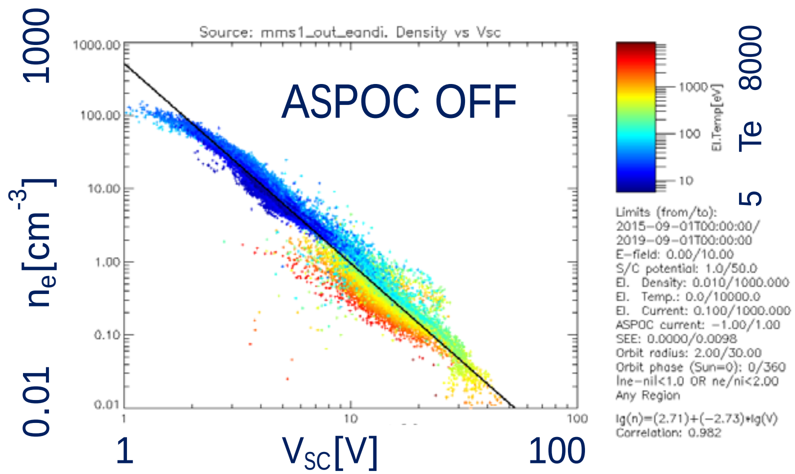


$$n_{SC} = \frac{1}{eA} \left(\frac{2\pi m_e}{k_B T_e}\right)^{1/2} \left(1 + \frac{e V_{SC}}{k_B T_e}\right)^{-1} \left[I_{ph0} \exp\left(\frac{-e V_{SC}}{k_B T_{ph} 0}\right) + I_{ph1} \exp\left(\frac{-e V_{SC}}{k_B T_{ph1}}\right) - I_{ASPOC} \right]$$

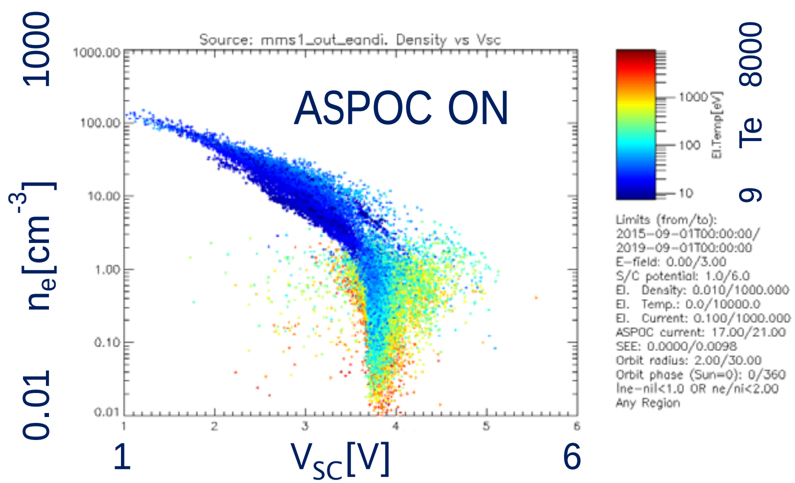
ÖAW IWF

4-YEAR SUMMARY OF ELECTRON DENSITY AND SPACECRAFT POTENTIAL

- Density depends on electron temperature, T_e as expected from theory
- ASPOC OFF: A power law fits reasonably well as a proxy to two or more Maxwellian functions as expected from theory, except at very low potentials (<2 V) or at low density<0.04 cm^{-3} where counts statistics of the sensors become poor

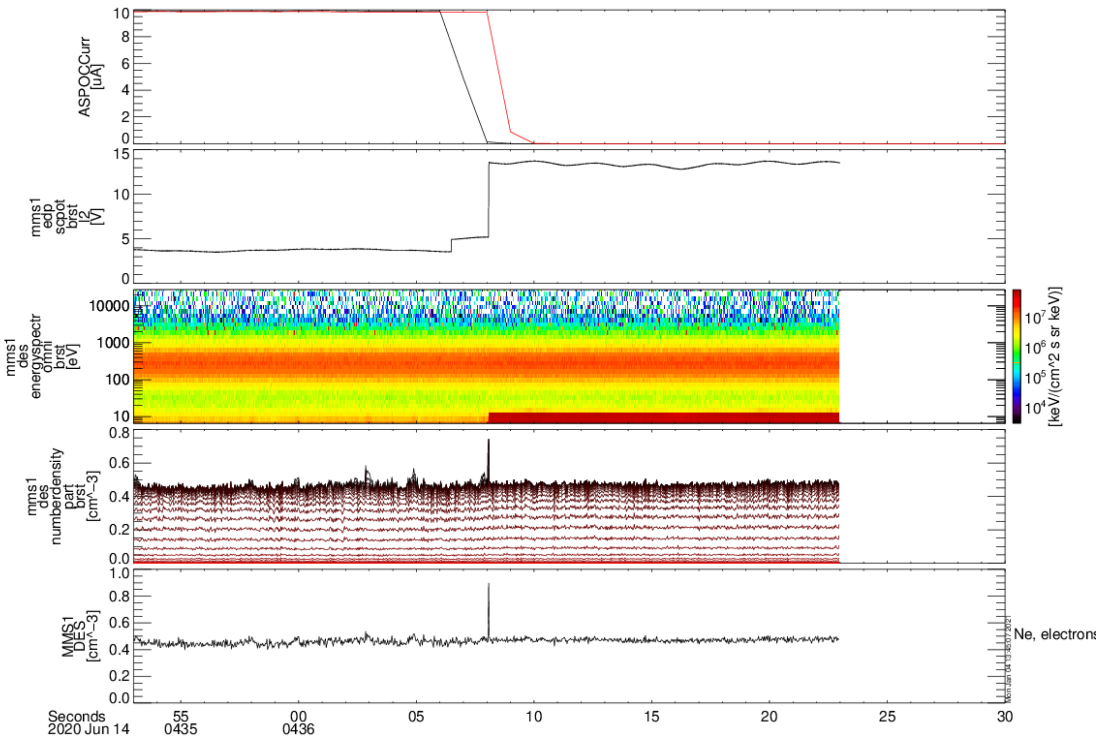


- ASPOC ON (2 x 10 µA): Increased scatter at lower density (<3 cm^{-3}) likely due to other influences on the potential (e.g., electric field, secondary emission, wakes)



OVERVIEW OF AN ASPOC SWITCH-OFF

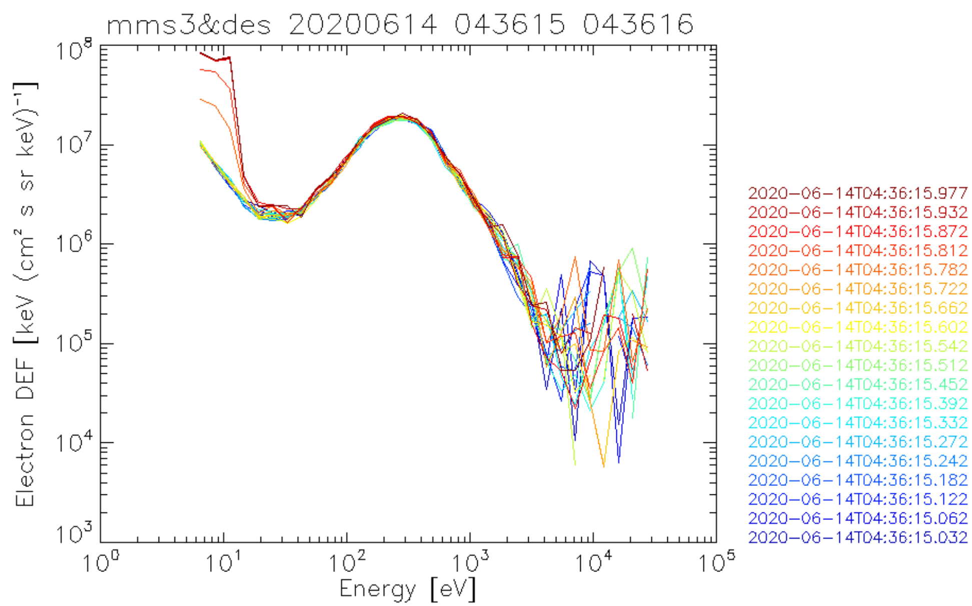
- MMS1 data on 2020-06-14, Burst Mode telemetry interval in a quiet region where ASPOC switches off
- Low plasma density n ~ 0.6 cm^{-3}
- ASPOC current data have a time resolution of 1 second and do not resolve detail
- Time resolution of electrons (Fast Plasma Investigation): ~0.03 s and spacecraft potential V_{sc} (Spin-Plane Double Probes): ~0.0001 s
- ASPOC1 switches off first followed by ASPOC2 giving a two step profile to the spacecraft potential
- Ion beams stop within microseconds due to the physics of LMIS emitters
- At the second switch-off time there is a spike in the density data derived from the electron spectra
- Derivation requires subtraction of photoelectrons, which might be erroneous if the potential varies very quickly

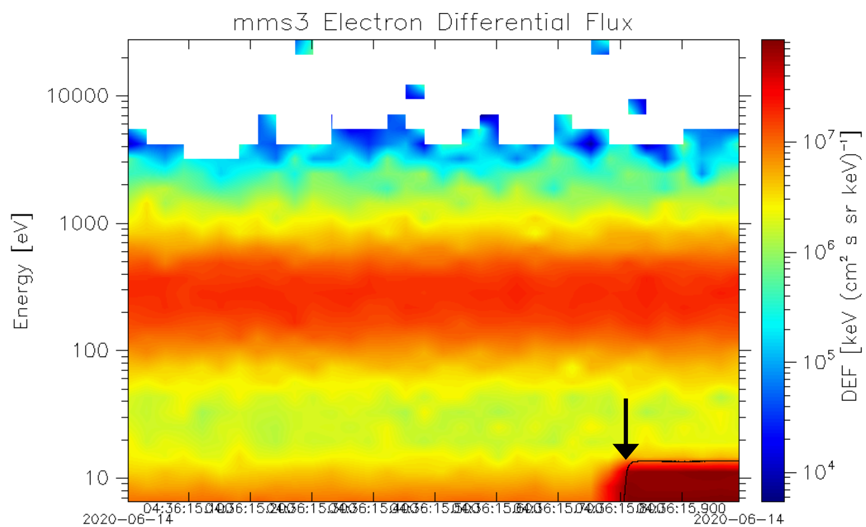


ÖAW IWF

MMS3, DETAILED ELECTRON DATA

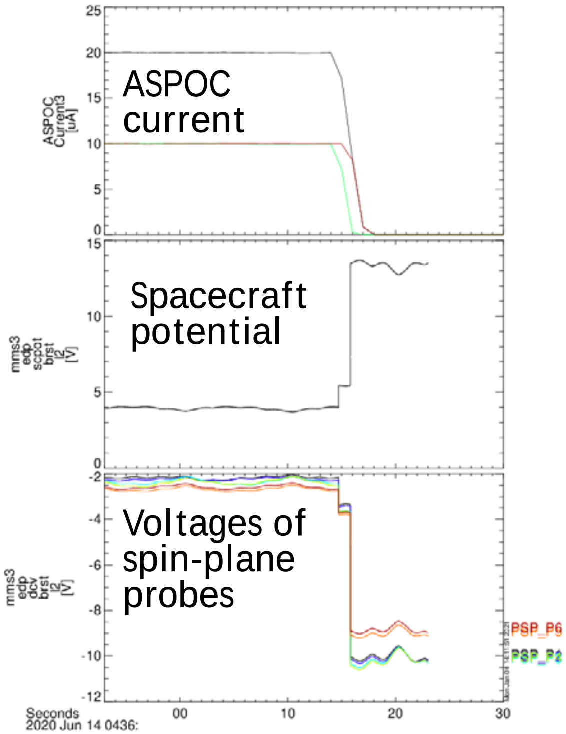
- On MMS3, several electron energy distributions were measured during the relaxation of the potential
- Color scale goes with time from blue to red
- Data interval covers 1 second
- Lower energy part of spectra shows that photoelectrons are gradually returning with increase of potential
- Finally the photoelectrons fully return and produce a small peak in the distribution at ~12 eV
- Black line in spectrogram indicates the spacecraft potential
- Sharp increase of potential together with flux of photoelectrons makes it difficult for algorithms to calculate the density during the transition



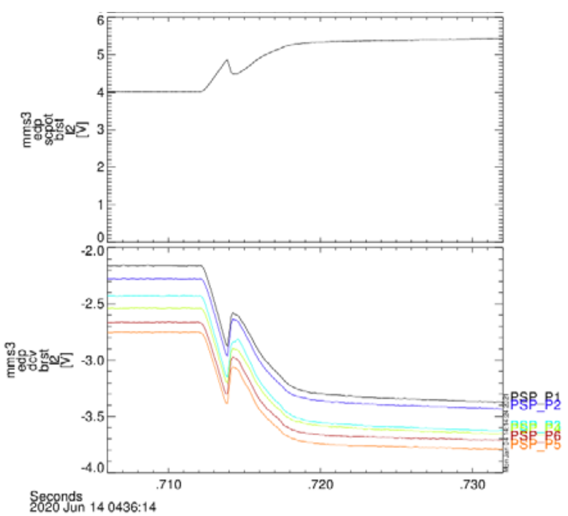


A CLOSER LOOK AT MMS3 POTENTIAL

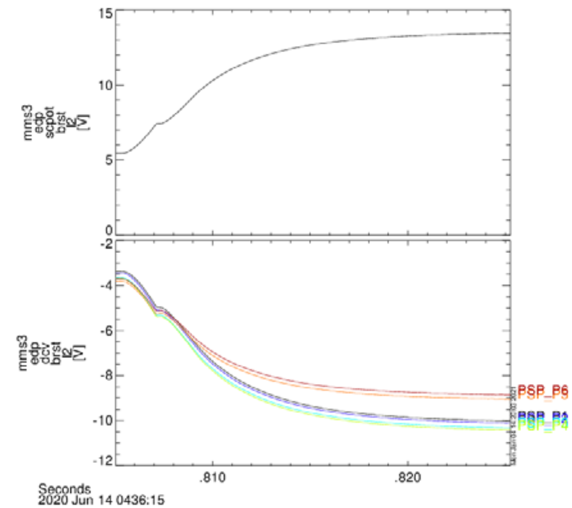
Overview



First Step



Second Step

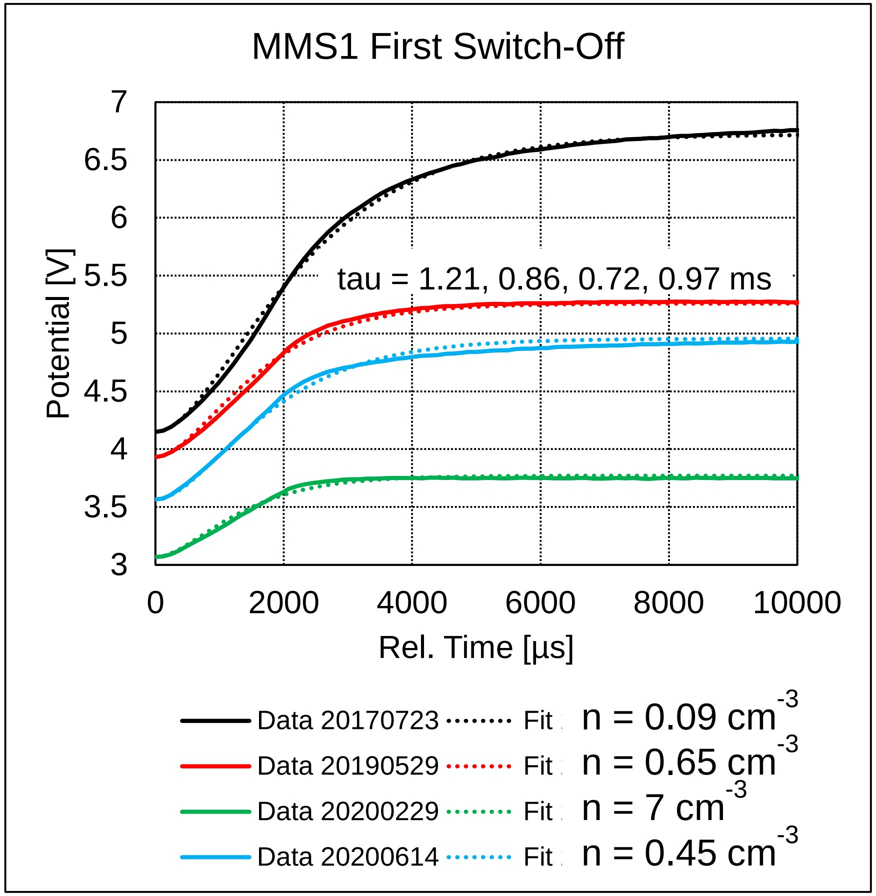


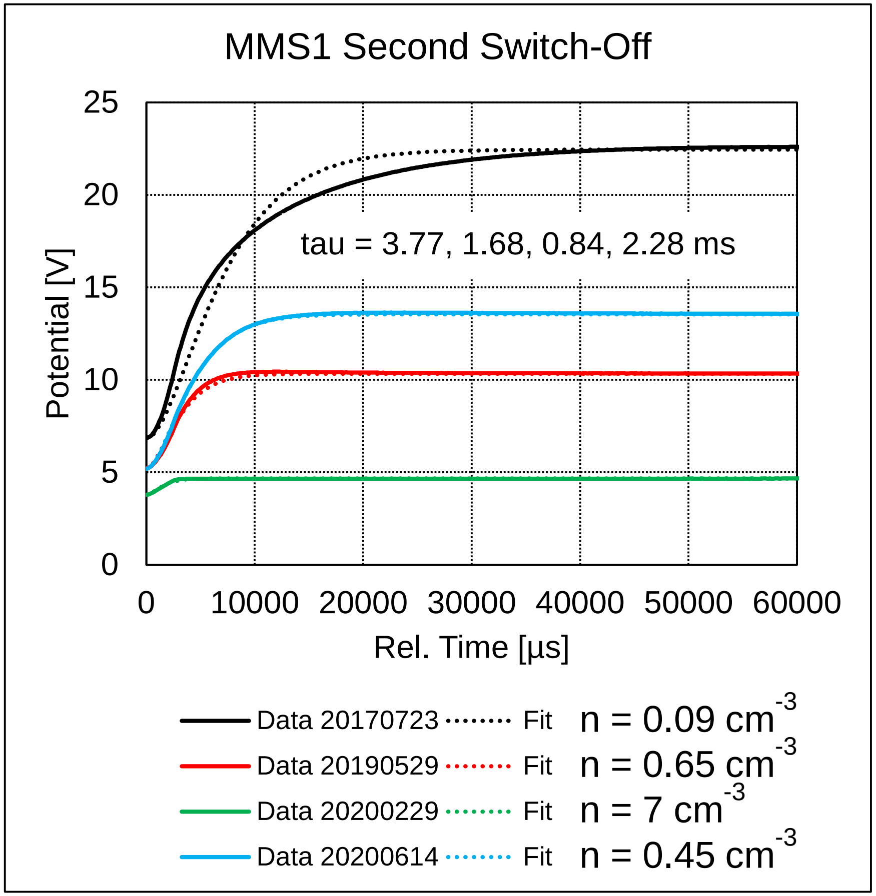
- Bump in the potential seen in all 4 probes of MMS3 for both steps
- Bumps are occasionally present also on MMS2. No bumps are seen on MMS1 and MMS4
- Bumps occur ~2 ms after high voltage switch-off
- Likely reason is a brief re-ignition of the ion beam
- The root cause of the re-ignition is under investigation

ÖAW IWF

RELAXATION OF THE POTENTIAL

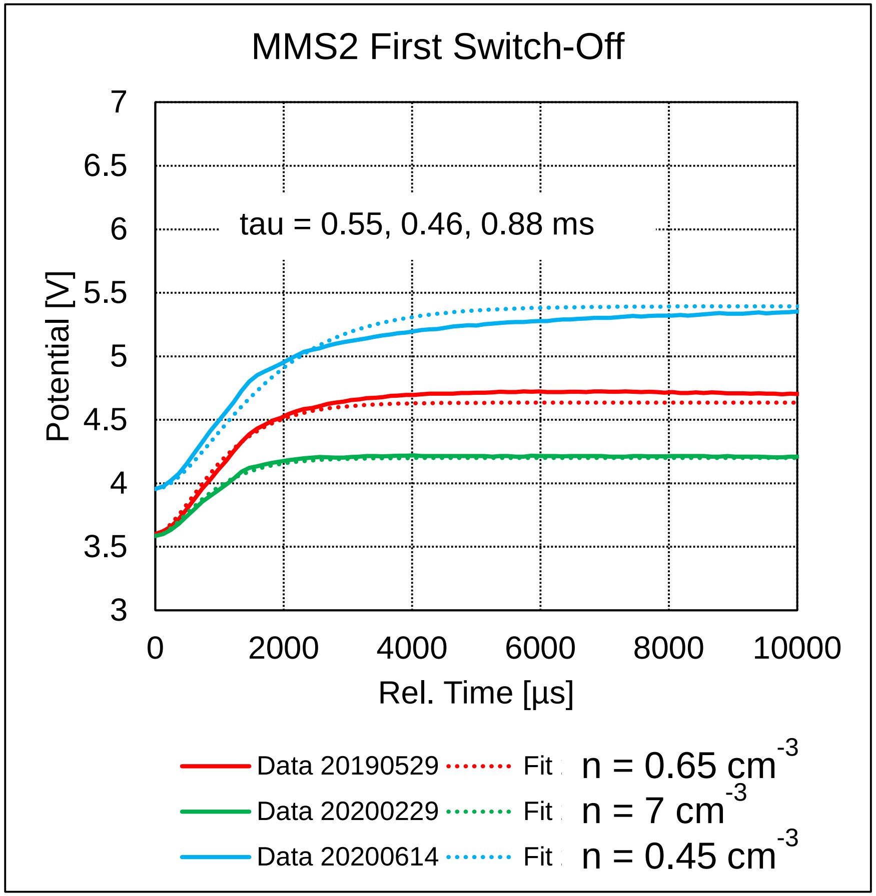
- Four events with switch-offs in various plasma densities have been selected
- Potentials with ASPOC OFF range between 3.2 V and 23 V, densities from 0.09 to 7 cm^{-3}
- Relaxation time constants are calculated assuming a perfectly damped system

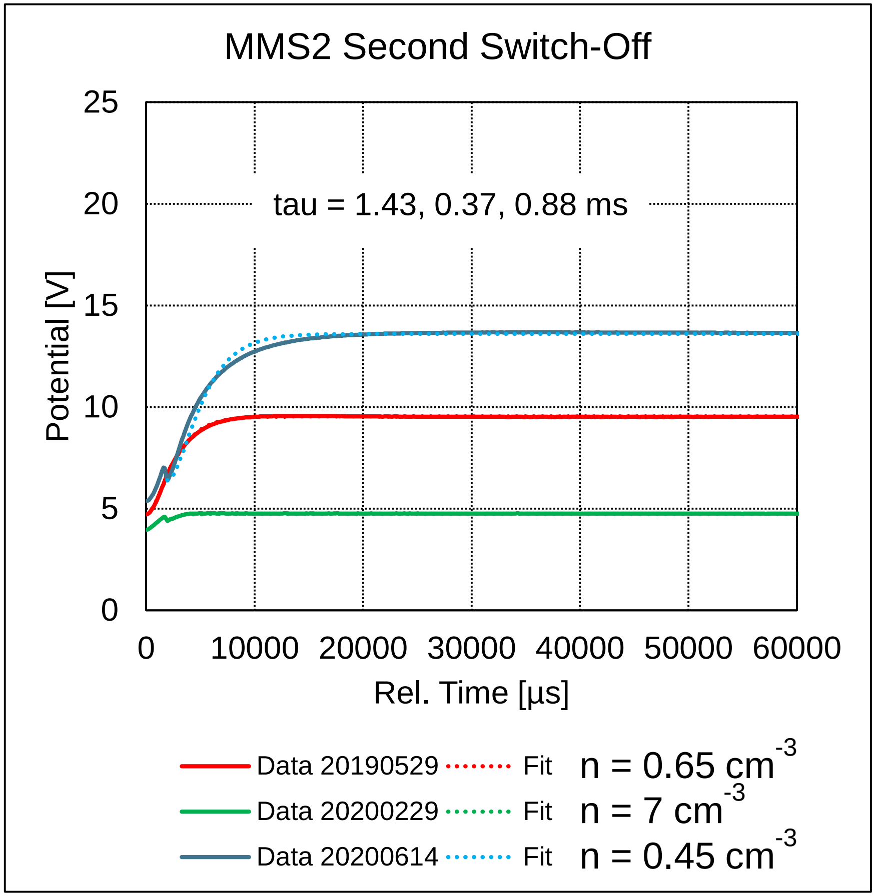




RELAXATION OF THE POTENTIAL

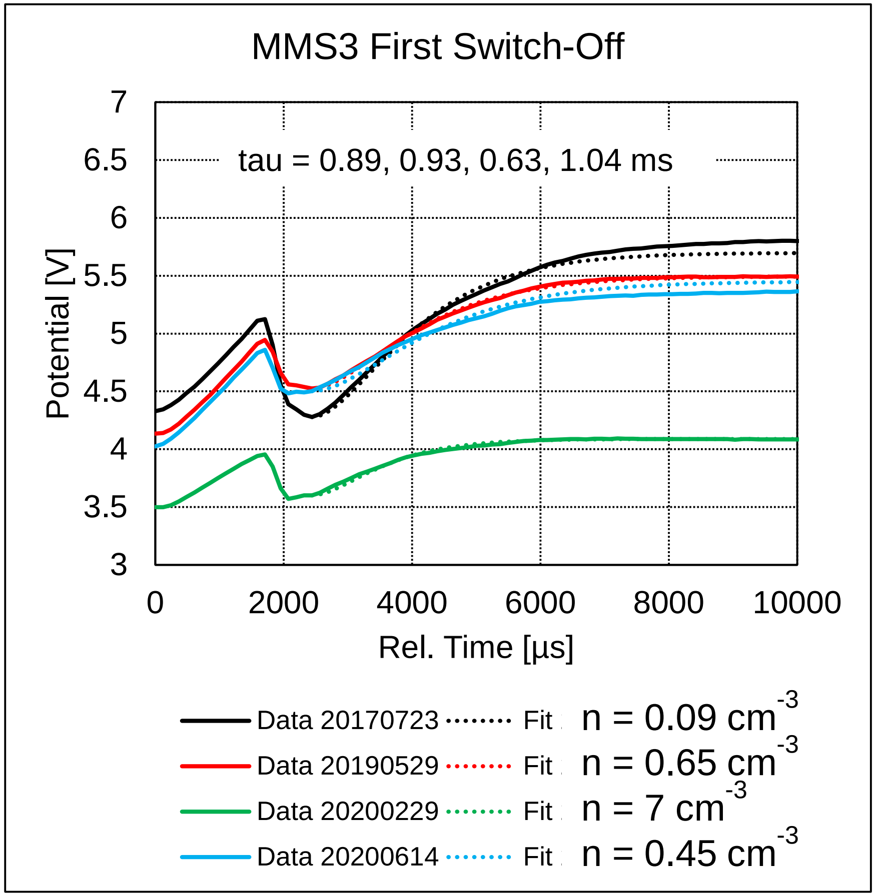
- Four events with switch-offs in various plasma densities have been selected
- Potentials with ASPOC OFF range between 3.2 V and 23 V
- Relaxation time constants are calculated assuming a perfectly damped system

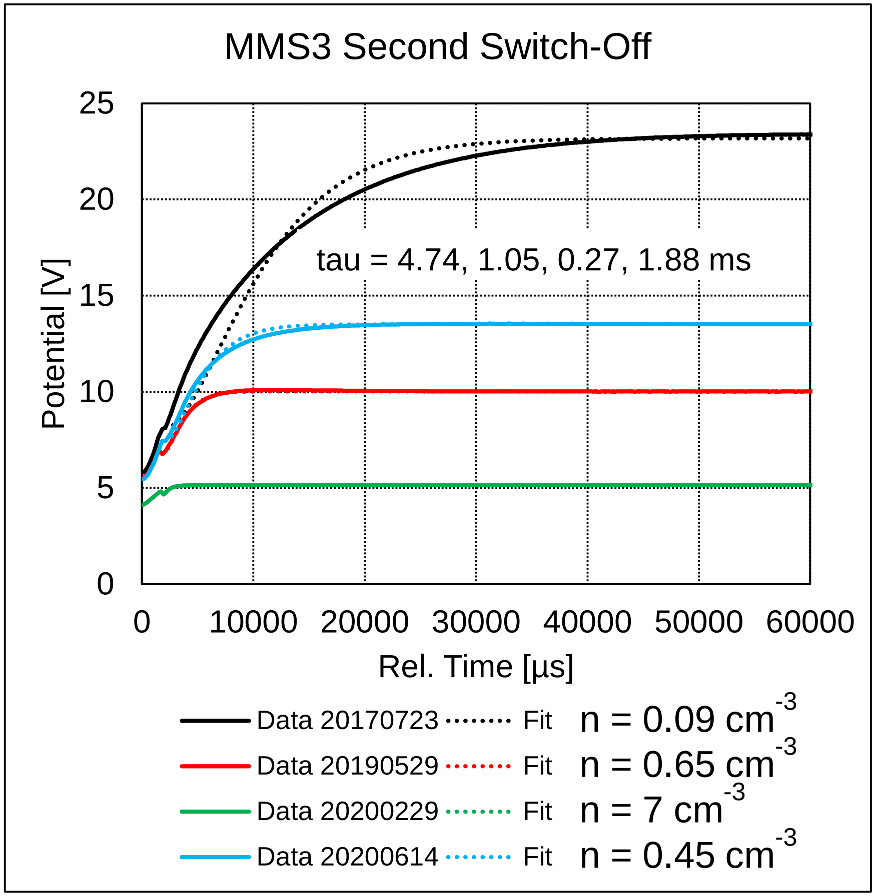




RELAXATION OF THE POTENTIAL

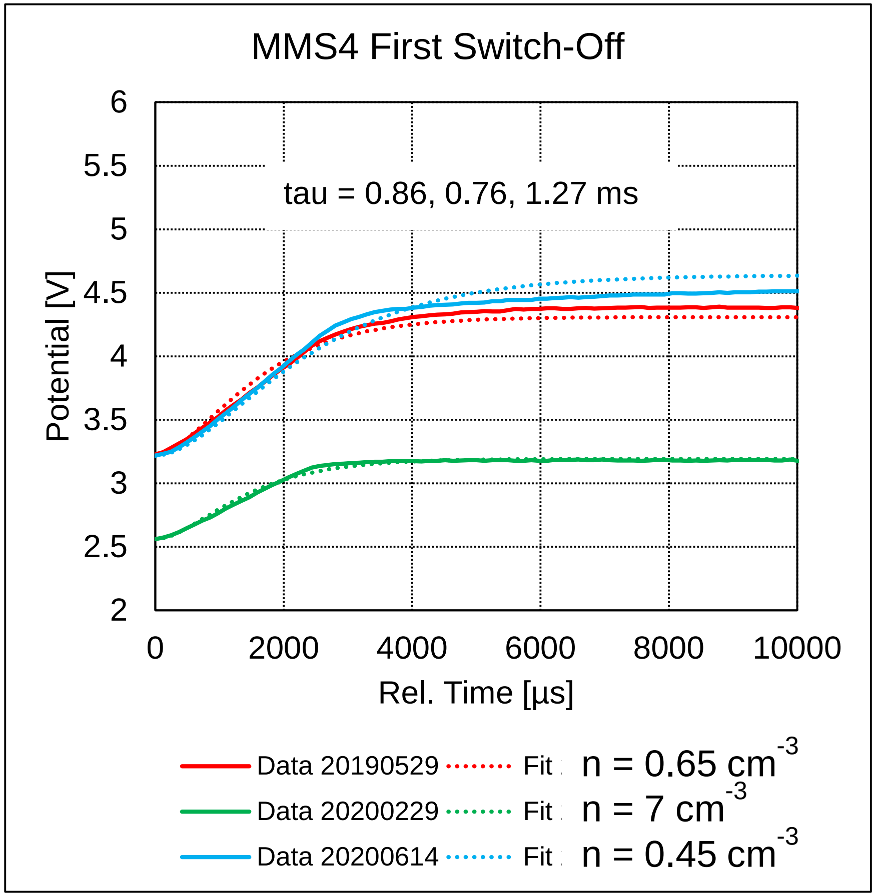
- Four events with switch-offs in various plasma densities have been selected
- Potentials with ASPOC OFF range between 3.2 V and 23 V
- Relaxation time constants are calculated assuming a perfectly damped system

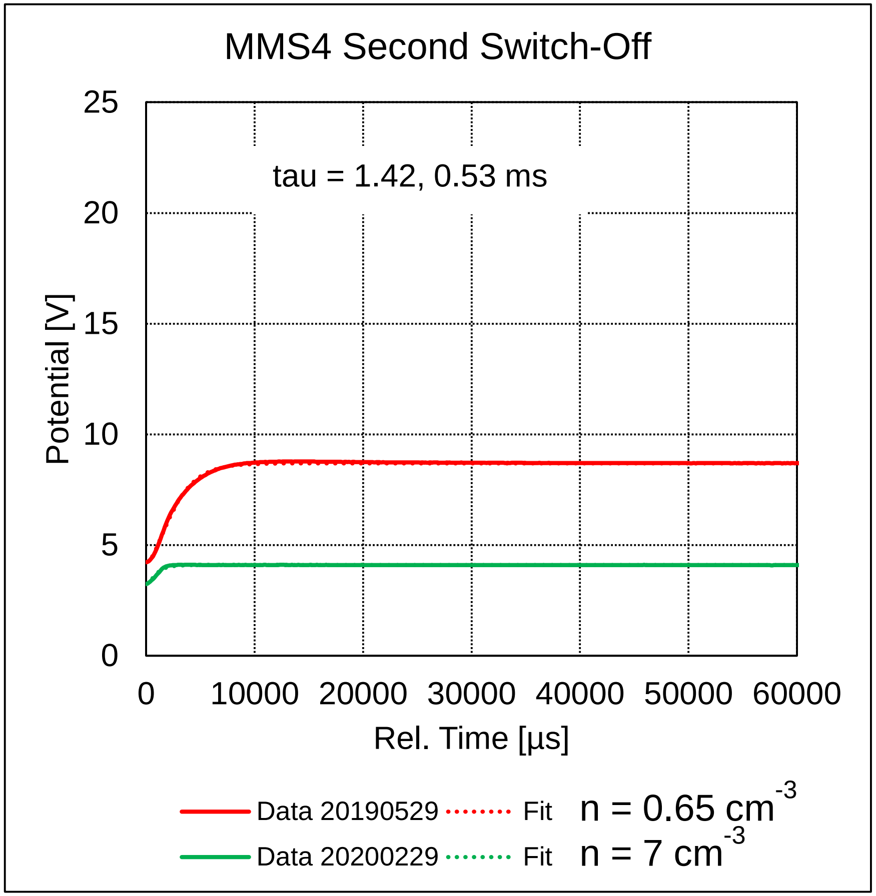




RELAXATION OF THE POTENTIAL

- Four events with switch-offs in various plasma densities have been selected
- Potentials with ASPOC OFF range between 3.2 V and 23 V
- Relaxation time constants are calculated assuming a perfectly damped system

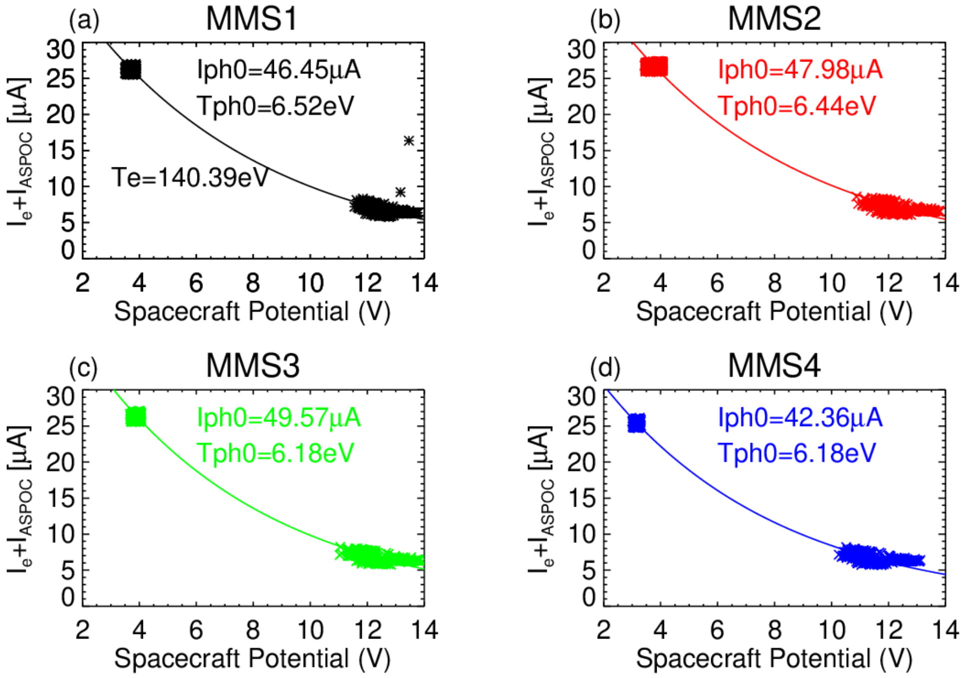




ÖAW IWF

PHOTOCURVES 1h FAST SURVEY MODE

- Photocurves (current of escaping photoelectrons = sum of currents from plasma electrons and ASPOC as a function of spacecraft potential) can be used to obtain plasma density in absence of particle data
- Currents are of interest for relaxation time constants as these are a function of spacecraft capacitance and impedance
- Photocurves were derived from 1 h of data around the event on 2020-06-14 (n~0.45 cm^{-3})
- Parameters of all 4 spacecraft are very similar
- Results should be valid for all four events as the variation of solar flux and ageing of materials are negligible



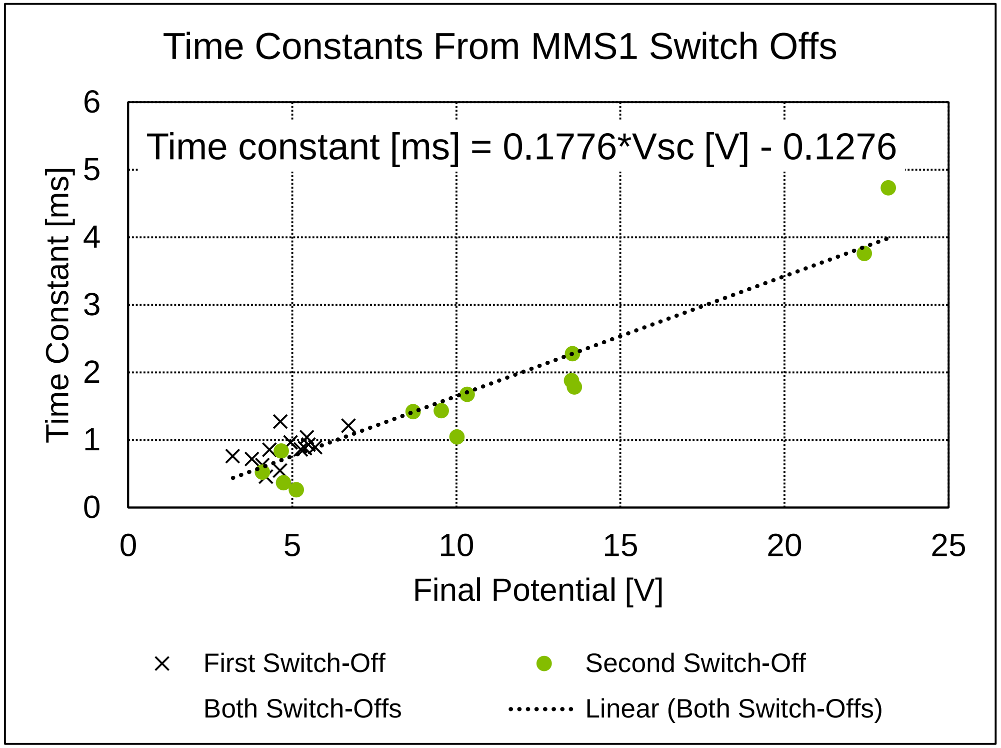
ÖAW IWF

TIME CONSTANTS AND POTENTIAL

- Both the time constants and photocurves are similar for all four spacecraft
- MMS1 is taken as example, as its emitters do not produce bumps at switch-off
- There is a clear linear relation between time constant and potential at ASPOC OFF
- Potential at ASPOC OFF depends on plasma density through the photocurve
- The calculated trend converts to a best fit capacitance C of ~ 5.7 nF
- Calculated C is high compared to a typical free space capacitance of 100 to 200 pF for a 3-m sized spacecraft
- Literature of dust impact effects on spacecraft potential shows time constants between 0.1 and 1 ms (Vaverka et al., JGR, 2017)
- Estimate following Meyer-Vernet (1985) for 2020-06-14, n_e=0.45cm^{-3}, T_e=180eV, A=34m^2, T_{ph}=6.5eV, V_{sc}=13.5V, tau=2ms

$$\tau = \frac{CT_{ph}}{eAn_e}\sqrt{2\pi m_e/eT_e}$$

obtains a value of C = 4.2 nF which is similar to the best fit with MMS data



SUMMARY

- Burst Mode data on the MMS spacecraft allow high time resolution measurements of the relaxation of the spacecraft potential and the reaction of the plasma when the ASPOC emitters are switched off.
- Due to the fast variation of the potential when ASPOC is switched off, photoelectron removal from the particle data needs careful consideration. It may be better to use partial moments, integrating higher energies only.
- Charging curve has a two-step morphology due to the non-simultaneous switch off by the two ASPOCs.
- Occasional bumps in the relaxation curve are most likely instrumental, due to brief re-ignition of the ion source in the shutdown process.
- When deriving the photocurve one must be careful to avoid errors which occur due to interpolating the ASPOC current data.
- Charging curves of MMS1-4 of 4 events with $0.1<n_e<7$ cm^{-3} have been fitted
- Time constants are well correlated with potential and therefore electron density, and allow to derive an effective spacecraft capacitance
- Capacitance is on the high side but of same order as from dust impact studies