In-situ measurements of space plasmas, including examples from space missions

Επί τόπου μετρήσεις διαστημικού πλάσματος, με παραδείγματα από διαστημικές αποστολές

Γιάννης Σ. ΔΑΝΔΟΥΡΑΣ

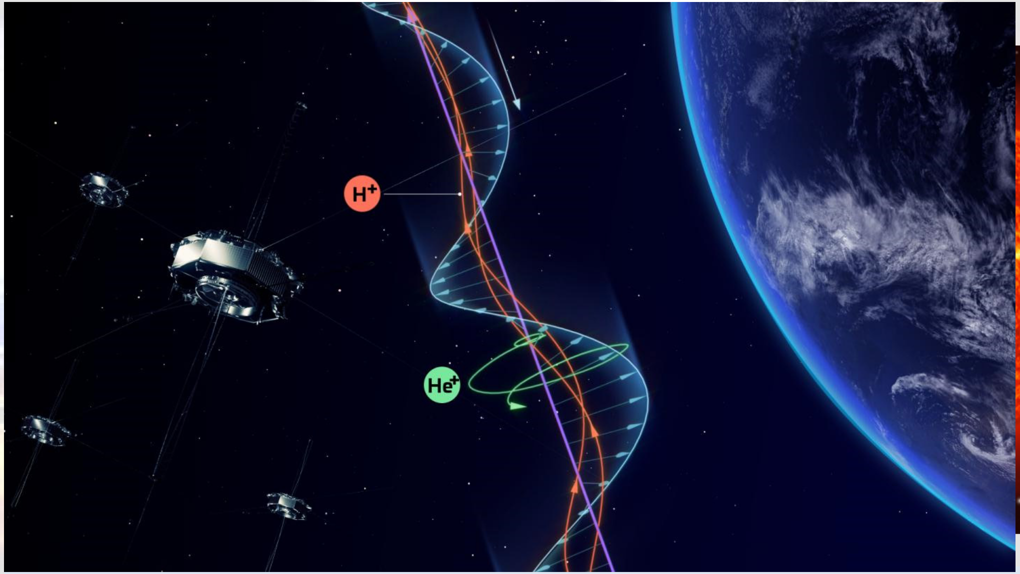
Institut de Recherche en Astrophysique et Planétologie
Université de Toulouse / CNRS / CNES, Toulouse, France

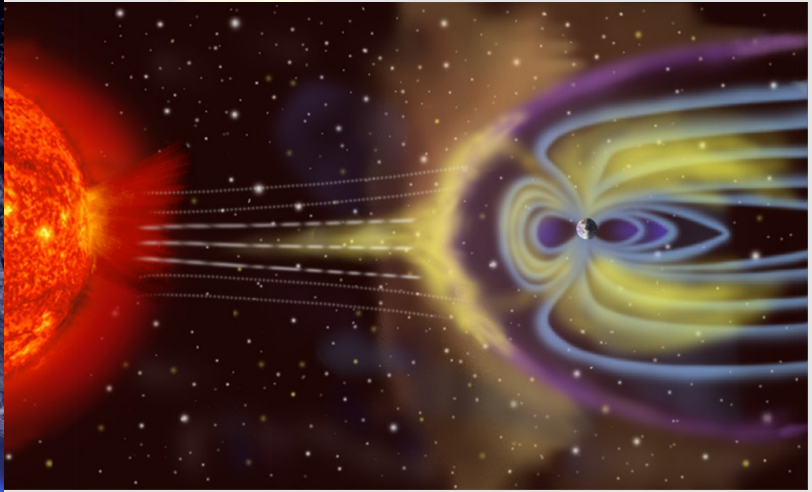
Εθνικό και Καποδιστριακό Πανεπιστήμιο Αθηνών - Τμήμα Αεροδιαστημικής Επιστήμης και Τεχνολογίας
7 Δεκεμβρίου 2023

Outline

- **What space plasma parameters do we need to measure**
- **How do we measure them**
  - particles
  - electric and magnetic fields
- **Measurement examples**
- **Example of a space plasma physics instrument package conceptual design**

Space plasma parameters we need to measure





Plasma: ions (various species) + electrons + electric field + magnetic field + neutral particles

Particles: 3D velocities + local density, i.e. **particle distribution functions**

Fields: magnetic field vector ***B***, electric field vector ***E***

Particle distribution functions

In kinetic theory in physics, a particle's **distribution function** is a function of seven variables:

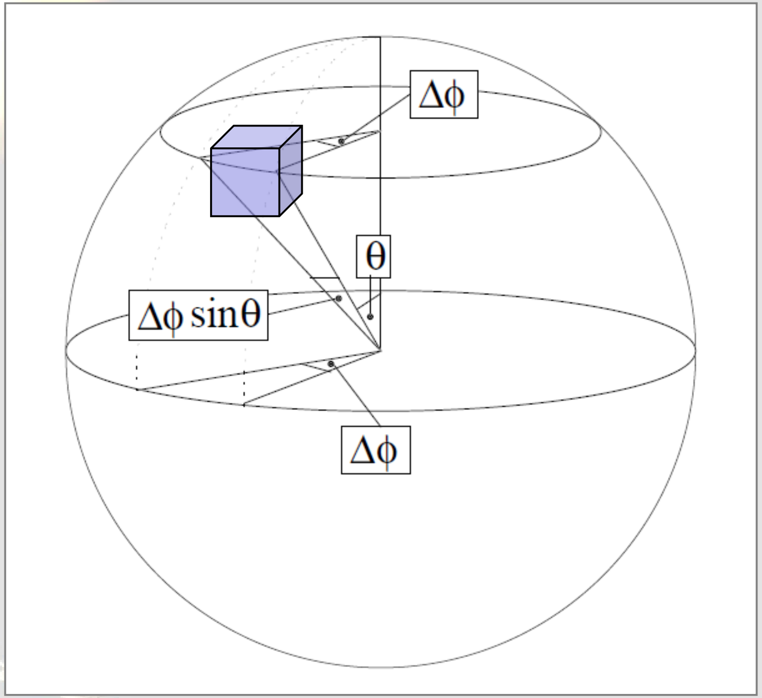
$f\,(x, y, z, t; v_x, v_y, v_z)$, which gives the number of particles per unit volume in phase space

Distribution function:

Number of particles per unit volume having approximately the velocity
$\boldsymbol{v} = (v_x, v_y, v_z)$ near the position $\boldsymbol{r} = (x, y, z)$ at time t

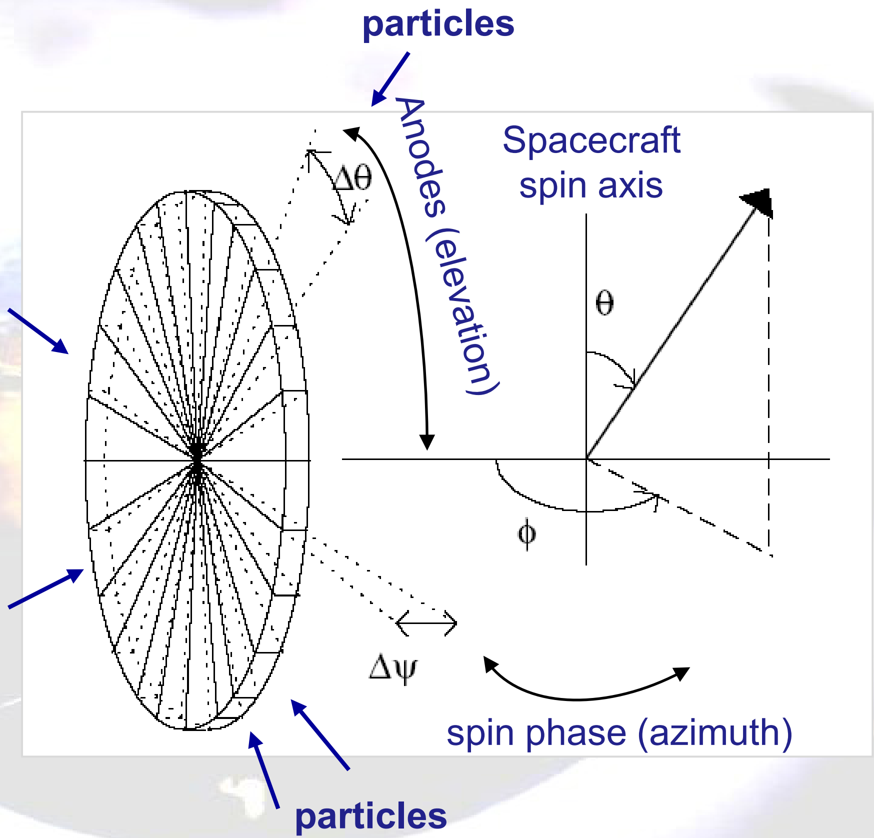
From a distribution function we can then calculate **other plasma parameters**
(**density**, **bulk velocity**, **pressure**, **temperature**, …)
as moments of the distribution function

(see later)



Measurement of particle distribution functions

Spinning spacecraft case



Arrival direction

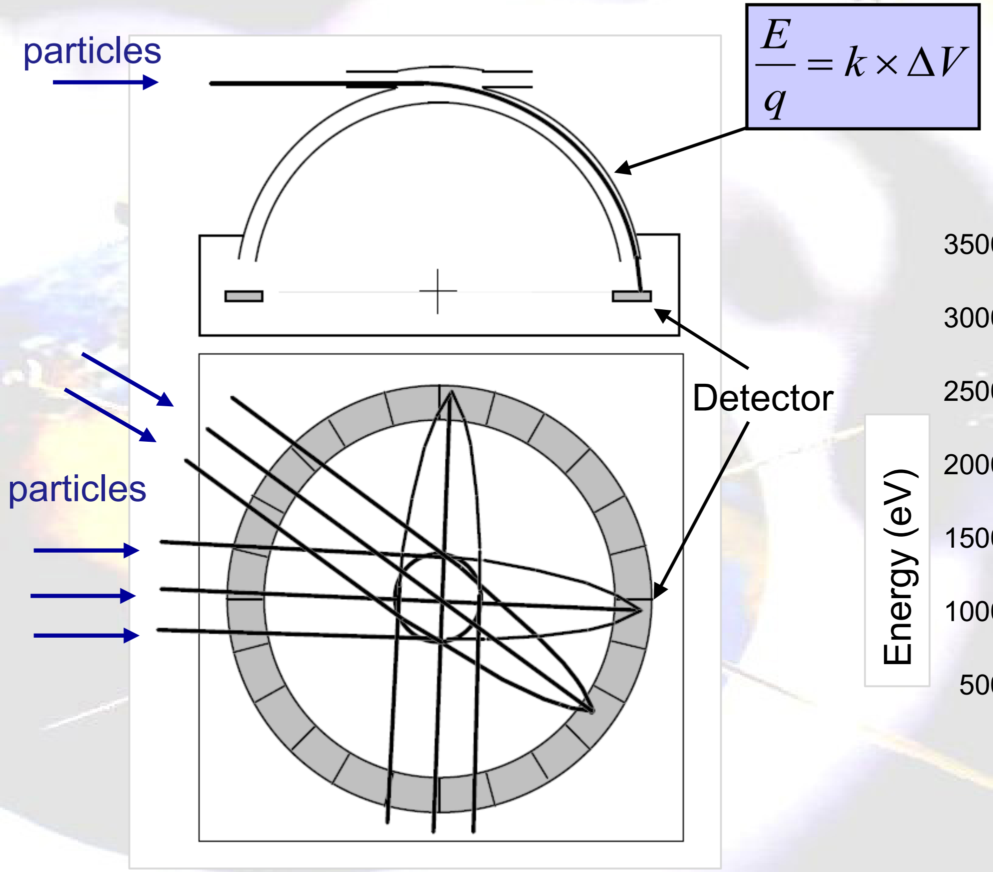
Position on the detector (detection anode):

particle elevation θ

Spacecraft spin phase:

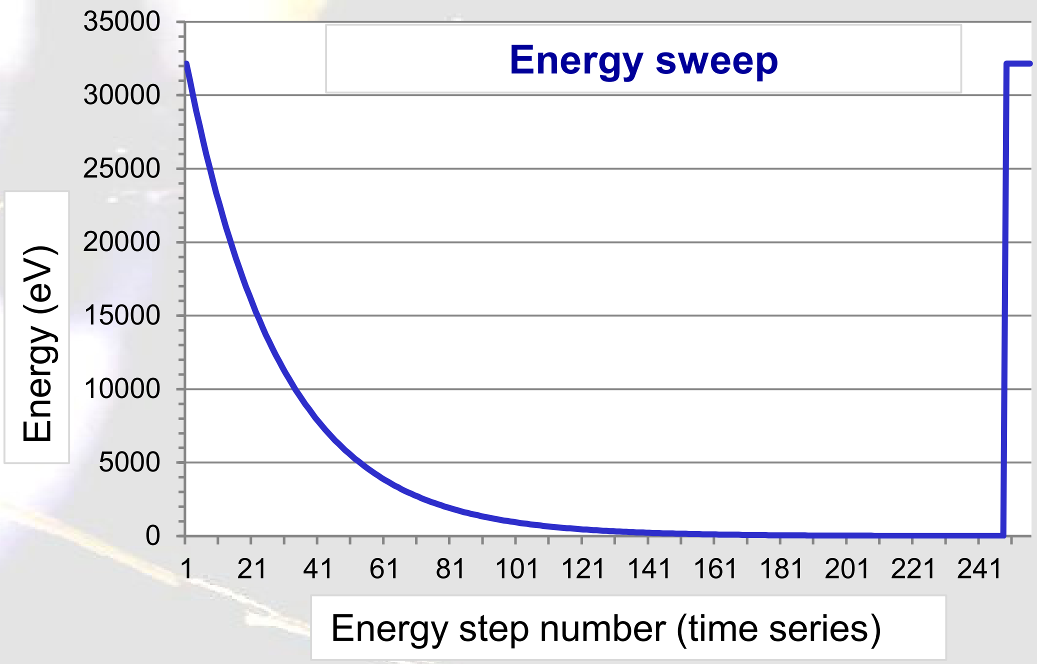
particle azimuth φ

Measurement of particle distribution functions



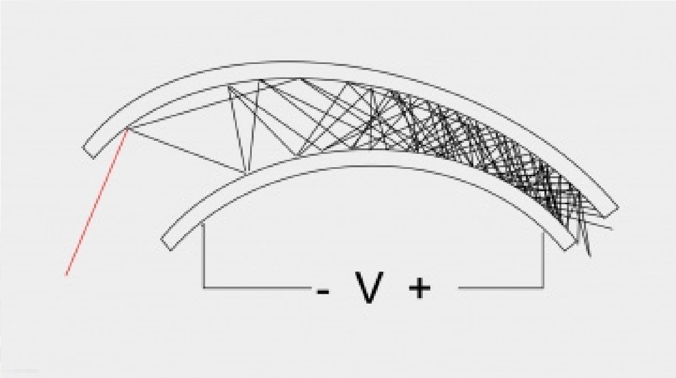
Energy selection: Electrostatic analyser

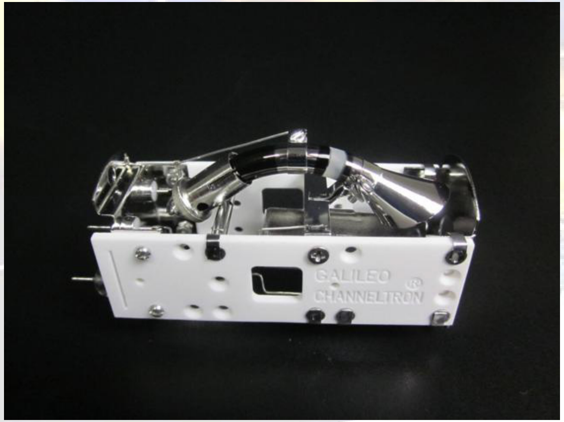
(top-hat hemispherical electrostatic analyser example)



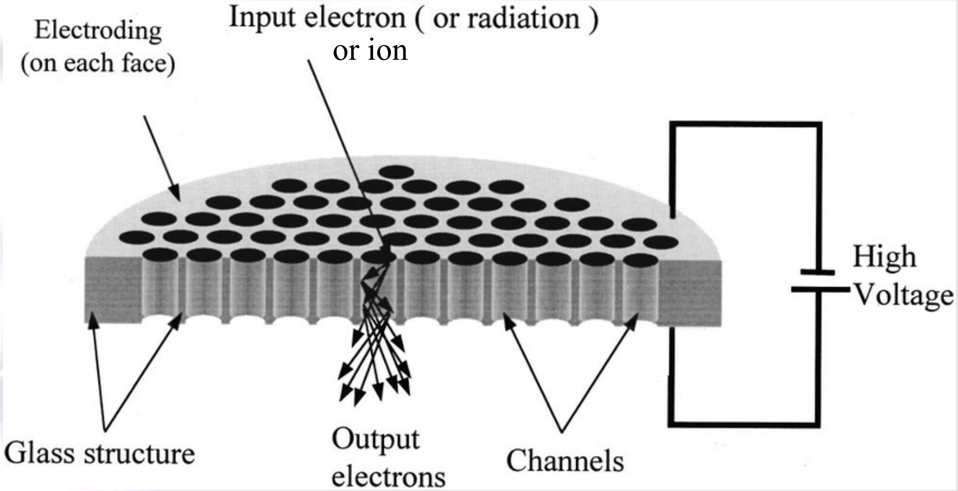
The particle detectors

Channeltron

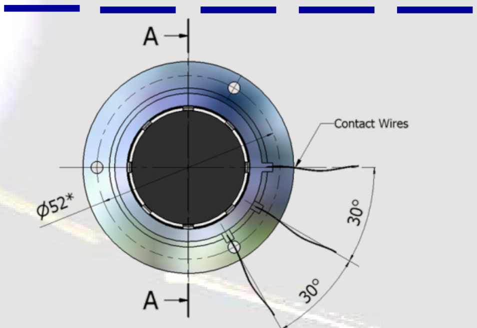




Micro-Channel Plate (MCP)

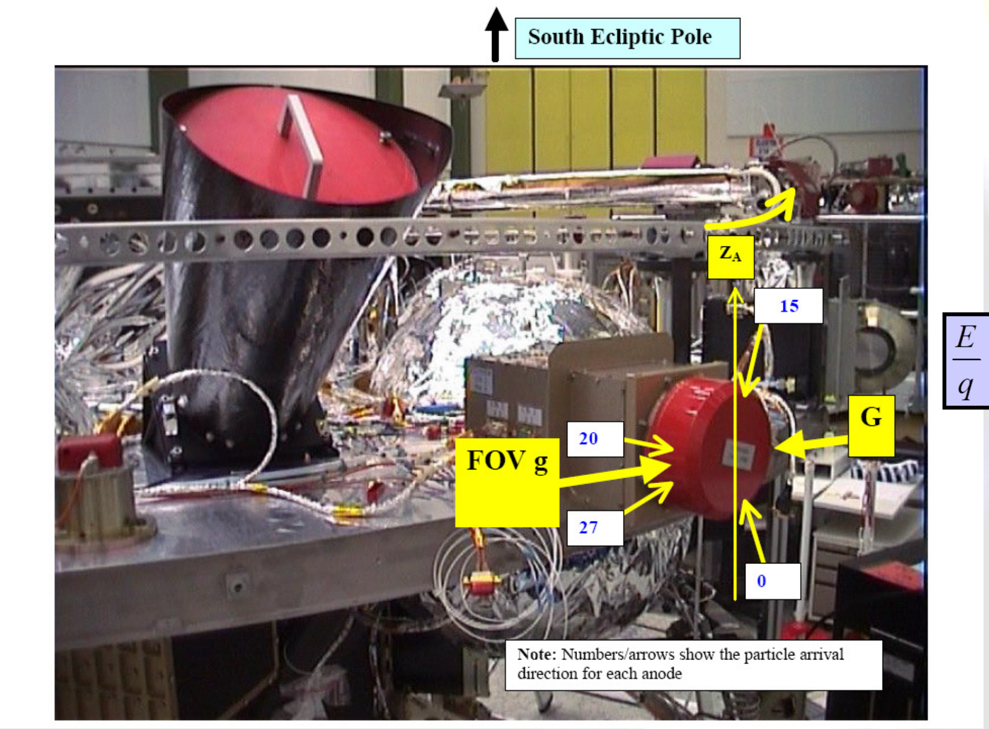


Anode: electron collection & output signal

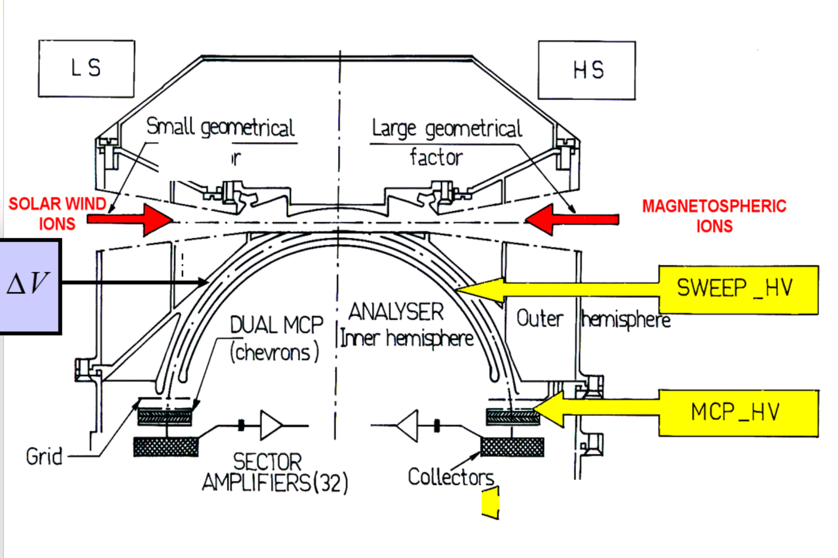


Example: HIA (Hot Ion Analyser) instrument onboard Cluster

(CIS experiment)



$$\frac{E}{q} = k \times \Delta V$$



3D ion distributions (E, ϕ, θ, t)

with high angular resolution: 5.625° × 5.625 °

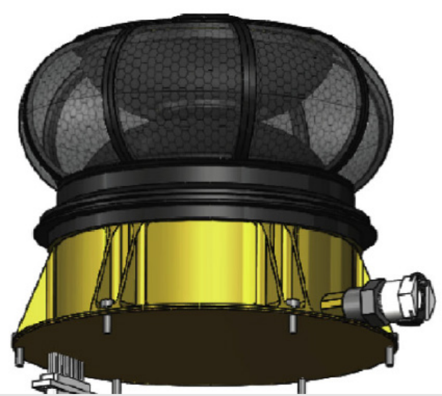
5 eV/q – 32 keV/q energy range

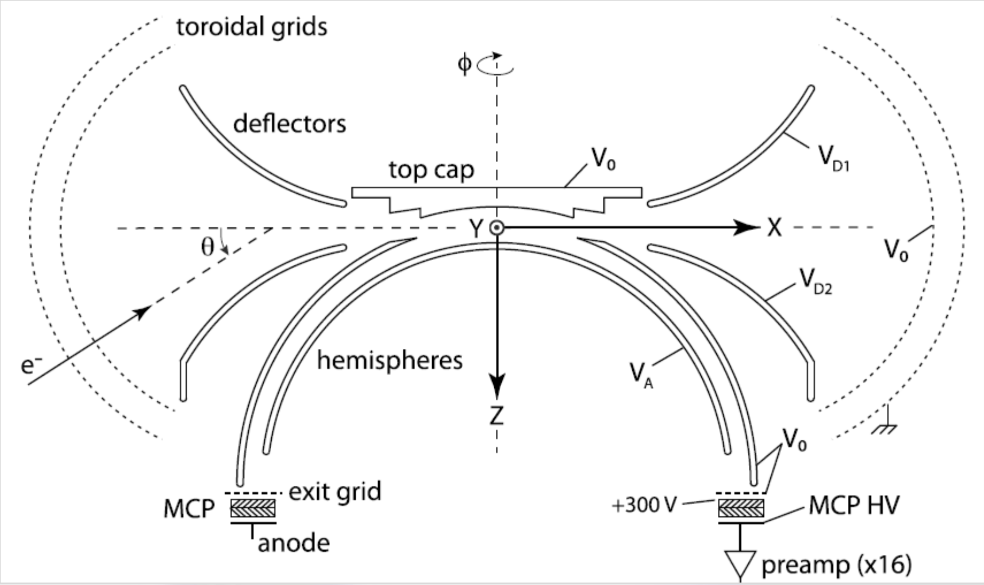
Rème et al., *Annal. Geophys., 2001*

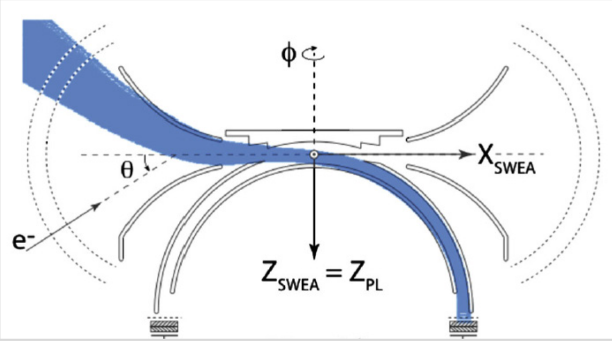
Measurement of particle distribution functions

3-axis stabilised spacecraft case

- Addition of an electrostatic deflection system, in the instrument entrance
- Example: Solar Wind Electron Analyzer (SWEA) onboard MAVEN
- SWEA electrostatic deflection system:
  ±60° coverage in elevation, ~3 eV – 4.6 keV energy range



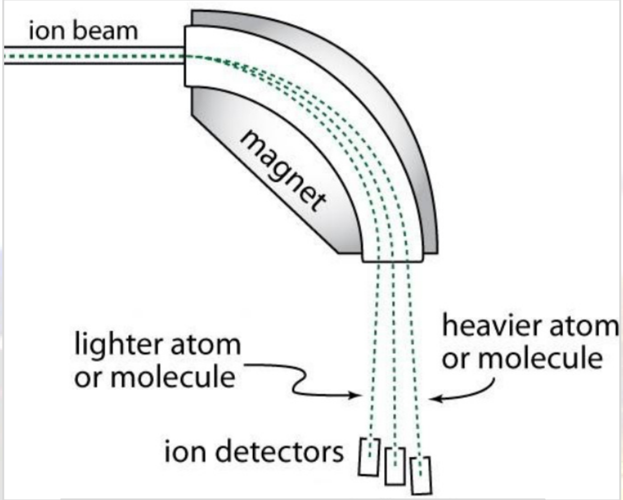




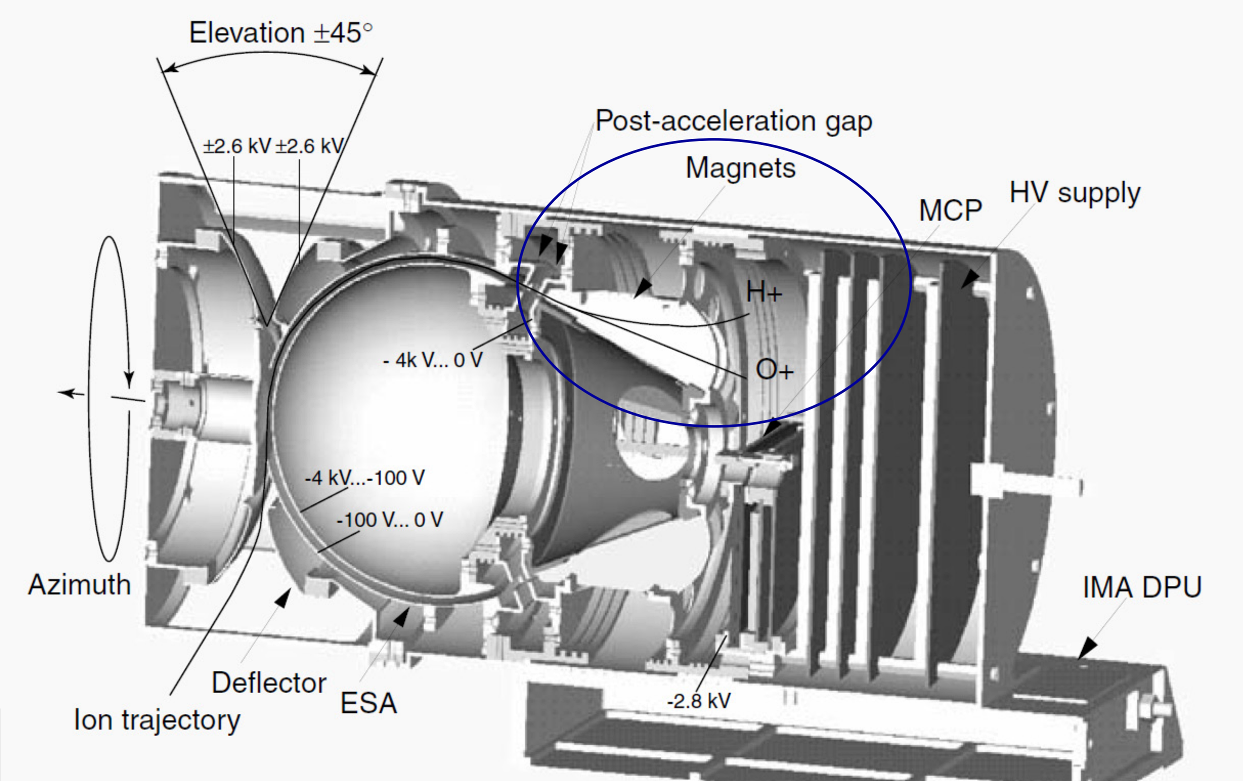
Mitchell et al., *Space Sci. Rev., 2016*

Ion Mass Spectrometry

Magnetic ion mass spectrometer



Principle of operation



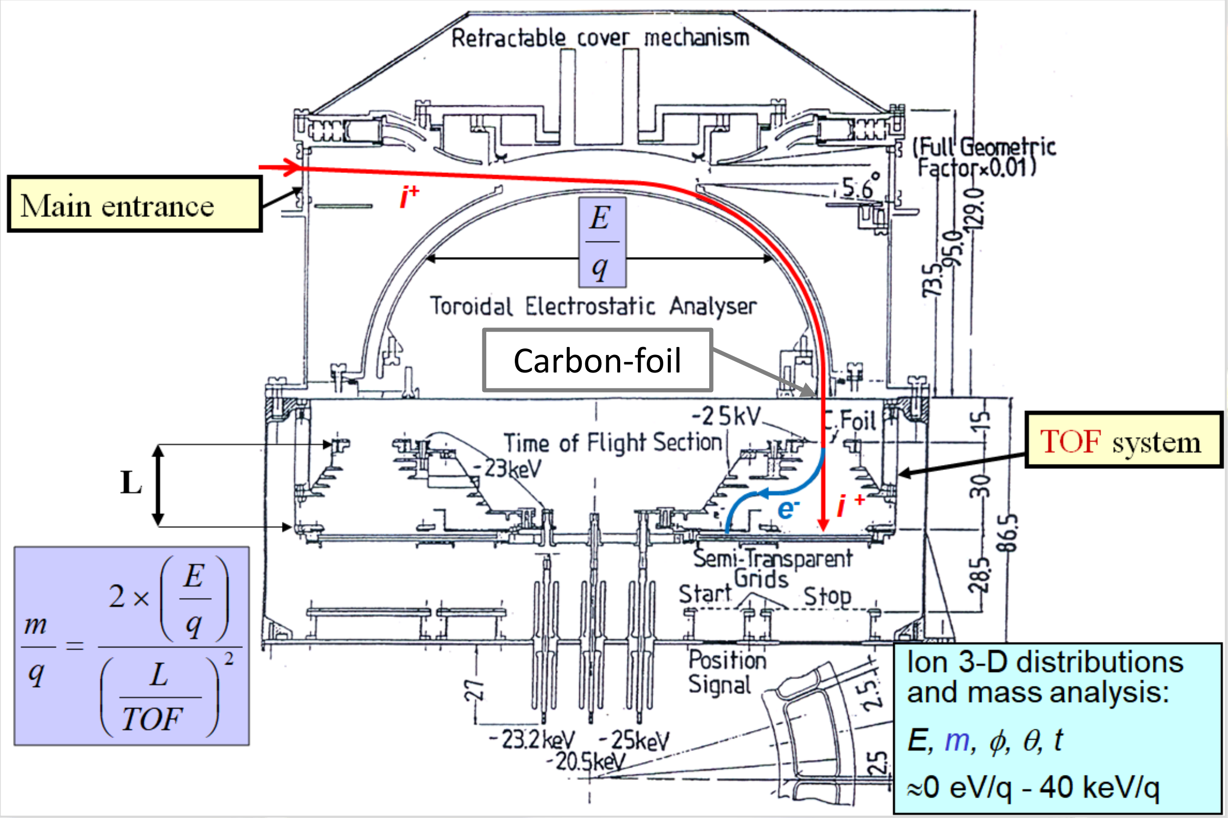
0.01 - 40 keV/q

IMA onboard Mars Express

Barabash et al., *Space Sci. Rev., 2006*

Ion Mass Spectrometry

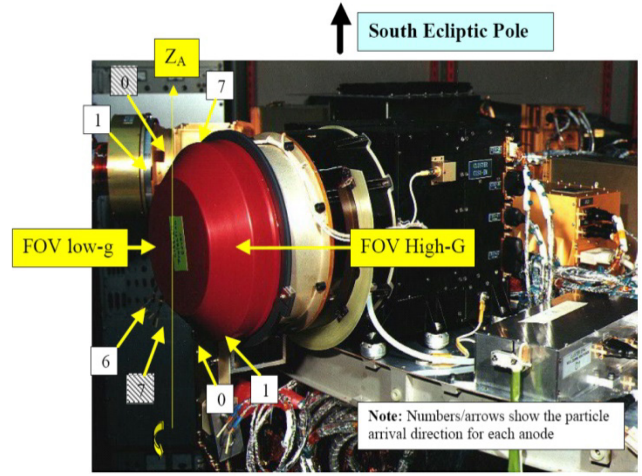
Time-of-Flight (TOF) ion mass spectrometer

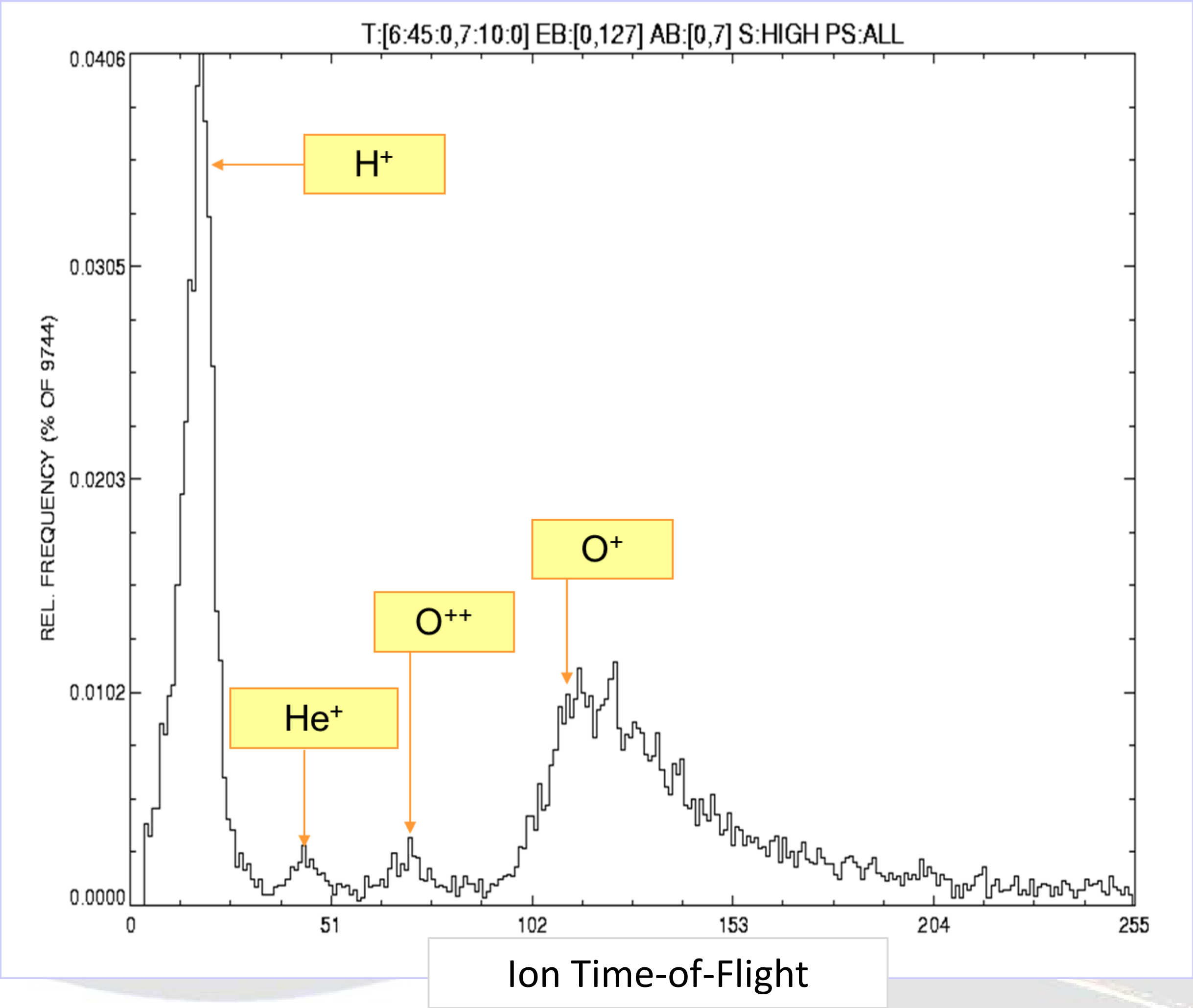


CODIF
(Ion Composition & Distribution Function Analyser)
instrument onboard Cluster

(CIS experiment)

Rème et al., *Annal. Geophys., 2001*

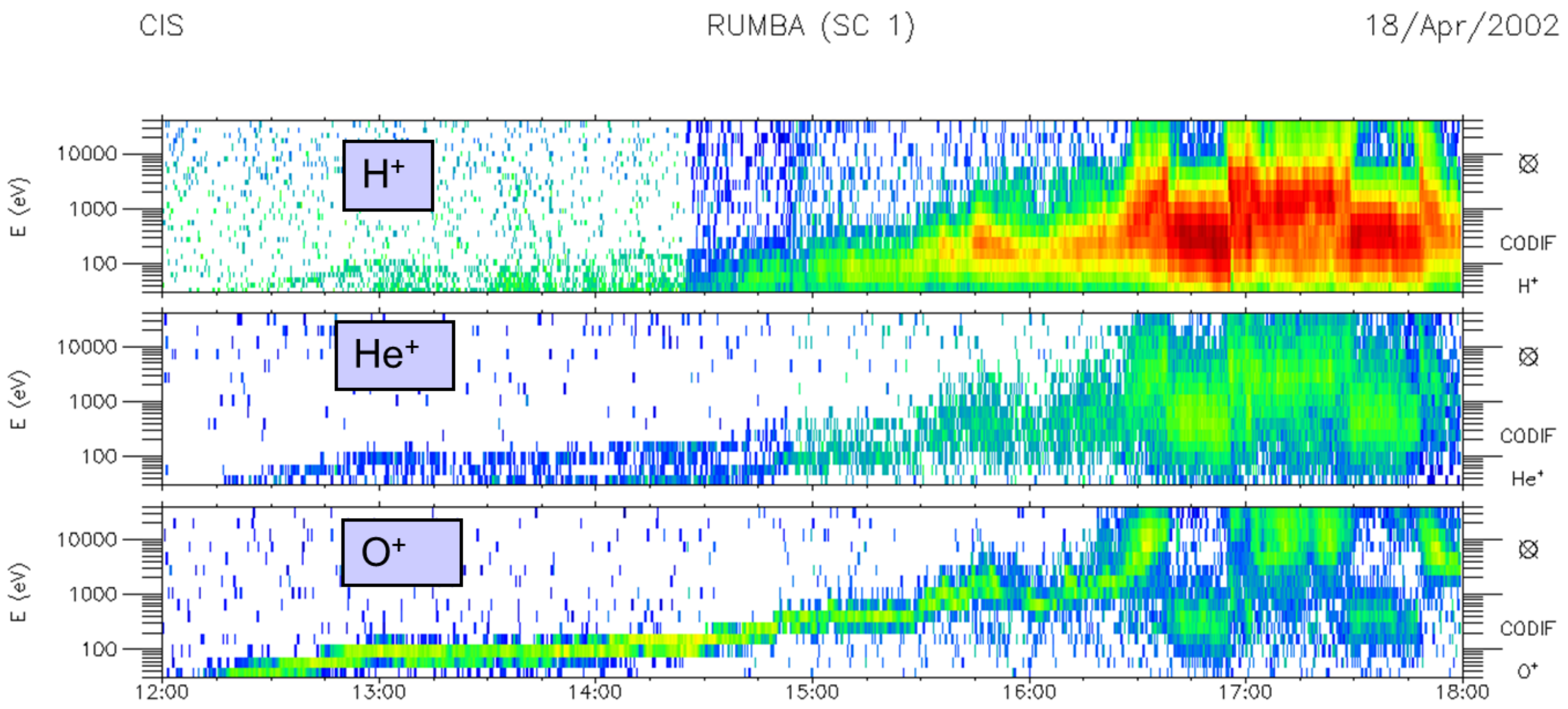


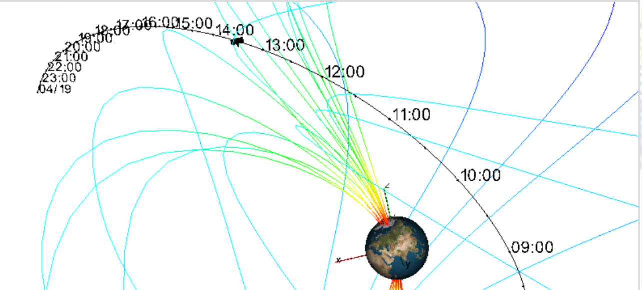


Example of
TOF ion mass spectrum
acquired by CODIF:

Upwelling ions beam over the
magnetospheric polar cap

CODIF: m / Δm ~ 5 – 7





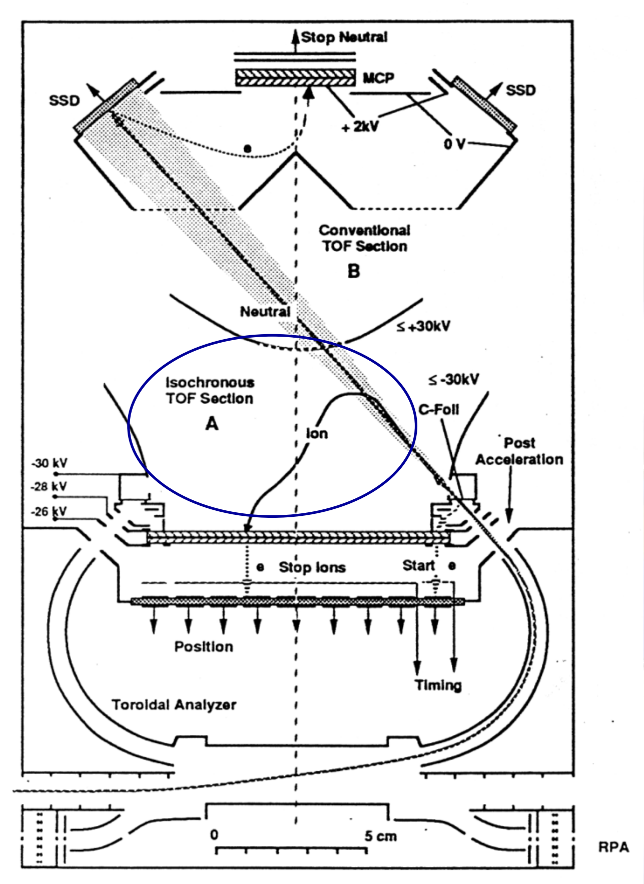
Example of energy – time spectrogram, for three ion species, acquired by CODIF:

Upwelling ions beam over the magnetospheric polar cap

Dandouras, *J. Geophys. Res., 2021*

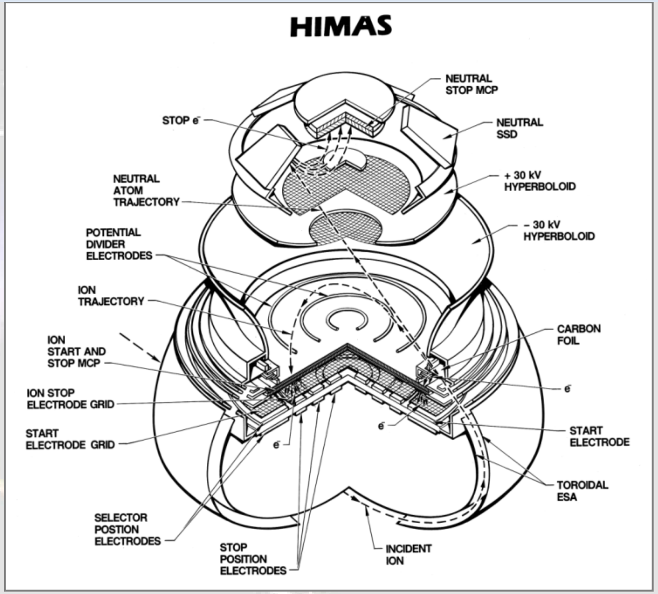
Ion Mass Spectrometry

Isochronous Time-of-Flight (TOF) ion mass spectrometer

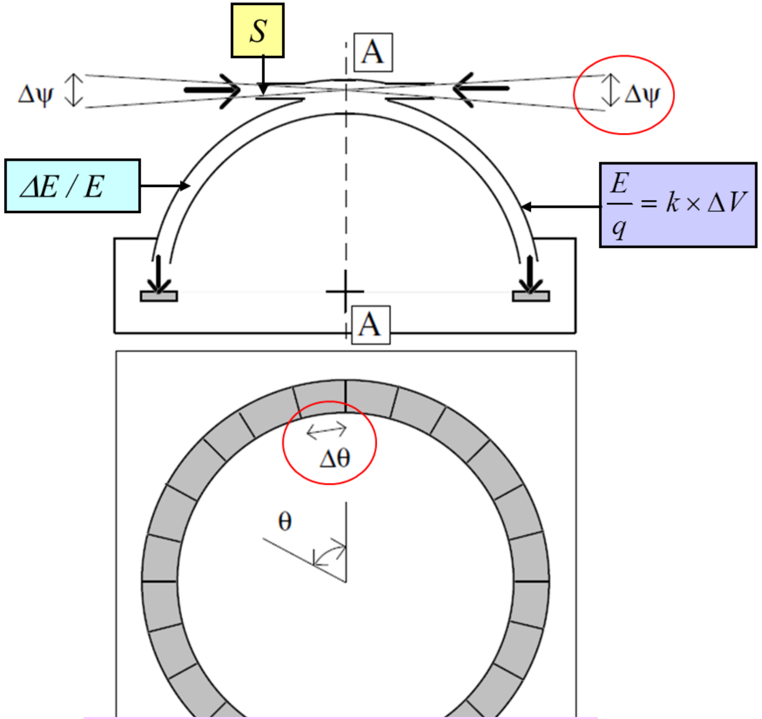


ion →

If the E-field in the TOF section increases as a linear function of *z*,
the time-of-flight of the ion is:
half-period of an harmonic oscillation,
i.e. proportional to $\sqrt{(m/q)}$
=> independent of the energy



Geometric characteristics and detection efficiency of an electrostatic analyser instrument



In some missions:
instrument with **variable G**

Geometric factor :

G : $cm^2\ sr$

Detection efficiency:

$\varepsilon\ (\theta, E, m, t)$

Energy resolution: $\Delta E / E$

Mass resolution: $\Delta m / m$

Angular resolution: $\Delta\theta$

Time resolution: Δt

These parameters are used to convert **particle count rates** in **phase space density**

Each instrument design is a compromise between antagonistic requirements:

- Sensitivity in low fluxes: *requires high G*
- No saturation in high fluxes: *requires low G*
- Energy and mass resolution: *they result in low G*
- Time resolution: *requires high G*
- Instrument mass, power, produced telemetry rate

Moments of the Distribution Function

Density

Ion density *n* is the zero-order moment of the 3D ion distribution function, given by:

$n = \iiint fdist(v)\, d^3v$, v : ion velocity

Taking into account the finite angular and velocity resolution of the instrument, this becomes:

$$n = \sum_i \frac{\Delta v_i}{g_v \cdot v_i^4} \sum_j v_i \cdot \Delta\phi_j \sum_k \cos\theta_k \cdot v_i \cdot \Delta\theta_k \frac{C_{cor}}{\Delta t}$$

Corrected for detection efficiency number of particle counts

Velocity geometric factor for the given angular bin

As all moments of the distribution function, the density supplied by a particle instrument is in reality the partial density, in the energy domain covered by the instrument.

Moments of the Distribution Function

Velocity

Ion bulk velocity vector $\underline{V}$ is the first order moment of the 3D ion distribution function, given by:

$$\underline{V} = \frac{1}{n} \iiint \underline{v}\, fdist(v)\, d^3v$$

or in practice:

$$V_x = \frac{1}{n} \frac{\Delta\phi \cdot \Delta\theta}{g_v} \cdot \sum_i \frac{\Delta v_i}{v_i} \sum_j \cos\phi_j \sum_k \cos^2\theta_k \cdot \frac{C_{cor}}{\Delta t}$$

$$V_y = \frac{1}{n} \frac{\Delta\phi \cdot \Delta\theta}{g_v} \cdot \sum_i \frac{\Delta v_i}{v_i} \sum_j \sin\phi_j \sum_k \cos^2\theta_k \cdot \frac{C_{cor}}{\Delta t}$$

$$V_z = \frac{1}{n} \frac{\Delta\phi \cdot \Delta\theta}{g_v} \cdot \sum_i \frac{\Delta v_i}{v_i} \sum_j \sum_k \sin\theta_k \cdot \cos\theta_k \cdot \frac{C_{cor}}{\Delta t}$$

Paschmann et al., “Moments of Plasma Velocity Distributions”, in *Analysis Methods for Multi-Spacecraft Data., ISSI, 2000*

Pressure

Ion pressure tensor ***P*** is the second order moment of the 3D ion distribution function, given (in the plasma centre of mass reference frame) by :

$$\boldsymbol{P} = m \iiint (\underline{v}-\underline{V}) \cdot (\underline{v}-\underline{V})\, fdist(v)\, d^3v$$

or

$$\boldsymbol{P} = m\, [\boldsymbol{M} - n\, \underline{V}\cdot\underline{V}]$$

where ***M*** is the tensor in the measurement reference frame:

$$\boldsymbol{M} = \iiint \underline{v}\cdot\underline{v}\, fdist(v)\, d^3v$$

In practice:

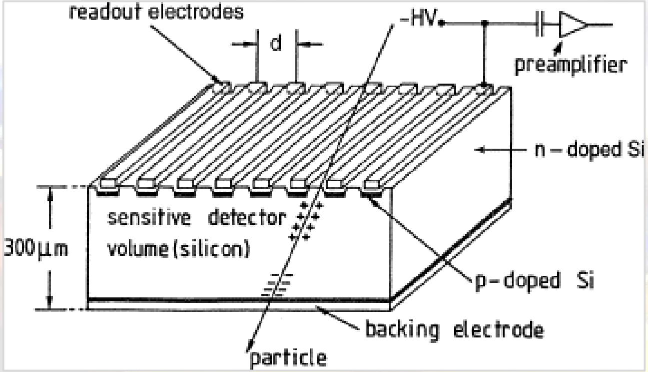
$$M_{xx} = \frac{\Delta\phi \cdot \Delta\theta}{g_v} \cdot \sum_i \Delta v_i \sum_j \cos^2\phi_j \sum_k \cos^3\theta_k \cdot \frac{C_{cor}}{\Delta t}$$

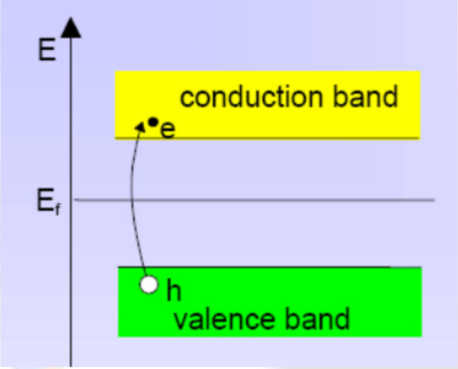
$$M_{yy} = \frac{\Delta\phi \cdot \Delta\theta}{g_v} \cdot \sum_i \Delta v_i \sum_j \sin^2\phi_j \sum_k \cos^3\theta_k \cdot \frac{C_{cor}}{\Delta t}$$

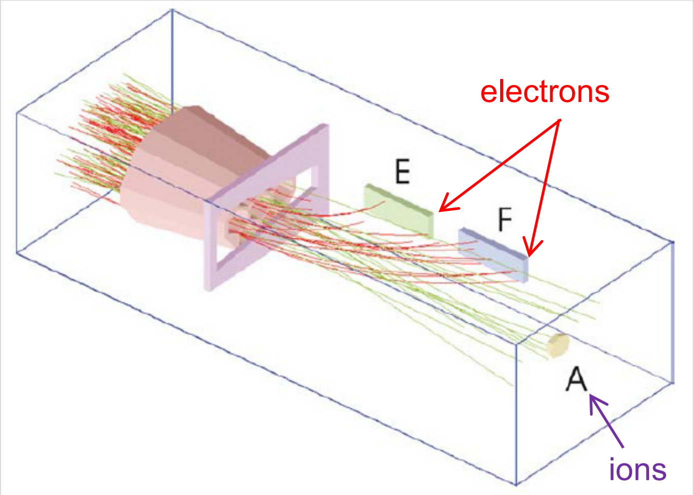
…

High-Energy particle detection instruments

- Above ~50 – 100 keV, particle energy is too high to use an electrostatic analyser
- **Solid State Detectors (SSD)** used to measure the energy deposited by the particle in the detector **(pulse height analysis)**







- Use a magnetic field to separate electrons from ions

High-Energy particle detection instruments

- Separate **heavy ions** from **light ions**:
  Use a **multiple SSD stack** and compare the energies deposited in each of the SSDs

Bethe Formula for Stopping Power

$$-\frac{dE}{dx} = \frac{4\pi k_0^2 z^2 e^4 n}{mc^2 \beta^2} \left[\ln \frac{2mc^2\beta^2}{I(1-\beta^2)} - \beta^2 \right].$$

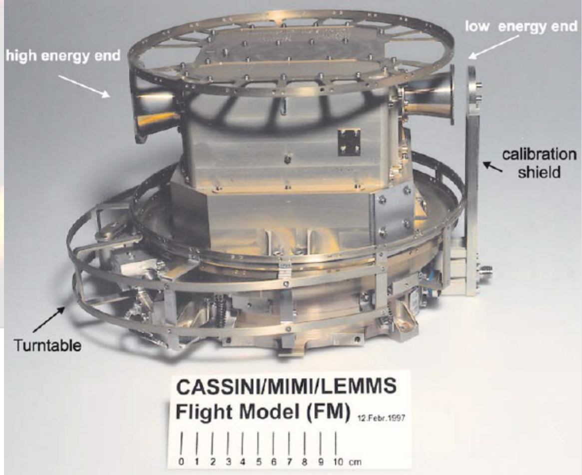
$k_o = 8.99 \times 10^9\ \mathrm{N\ m^2\ C^{-2}}$, (the Boltzman constant)
z = atomic number of the heavy particle,
e = magnitude of the electron charge,
n = number of electrons per unit volume in the medium,
m = electron rest mass,
c = speed of light in vacuum,
$\beta = V/c$ = speed of the particle relative to c,
I = mean excitation energy of the medium.

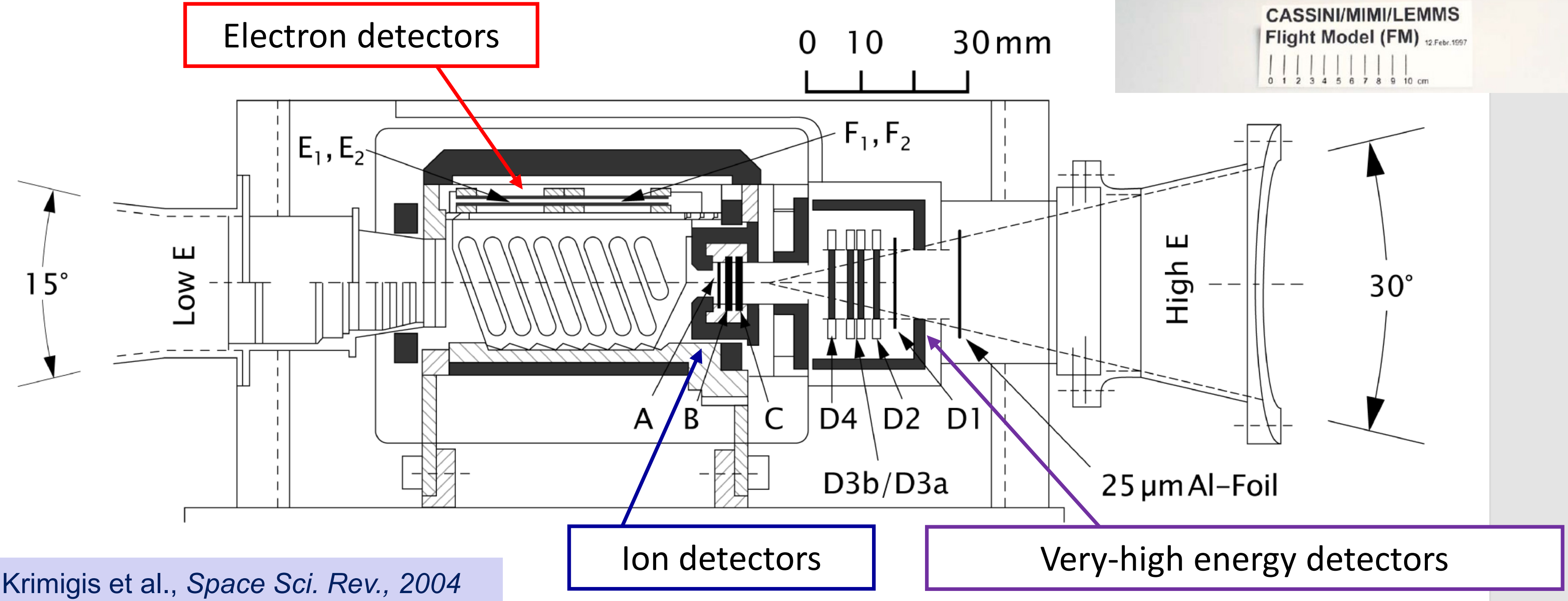
The **heavier** the energetic particle
the **shorter** its travelling distance
in the solid, before loosing its kinetic energy
and getting to a stop
(for a given initial energy)

High-Energy particle detection

The LEMMS instrument onboard Cassini

30 keV - 160 MeV ions
15 keV - 5 MeV electrons

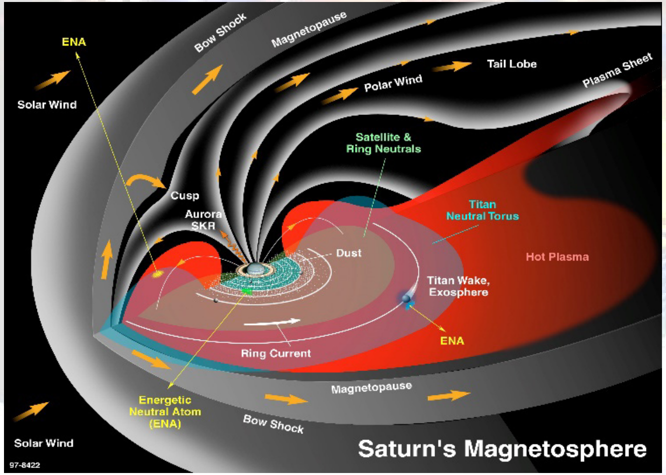


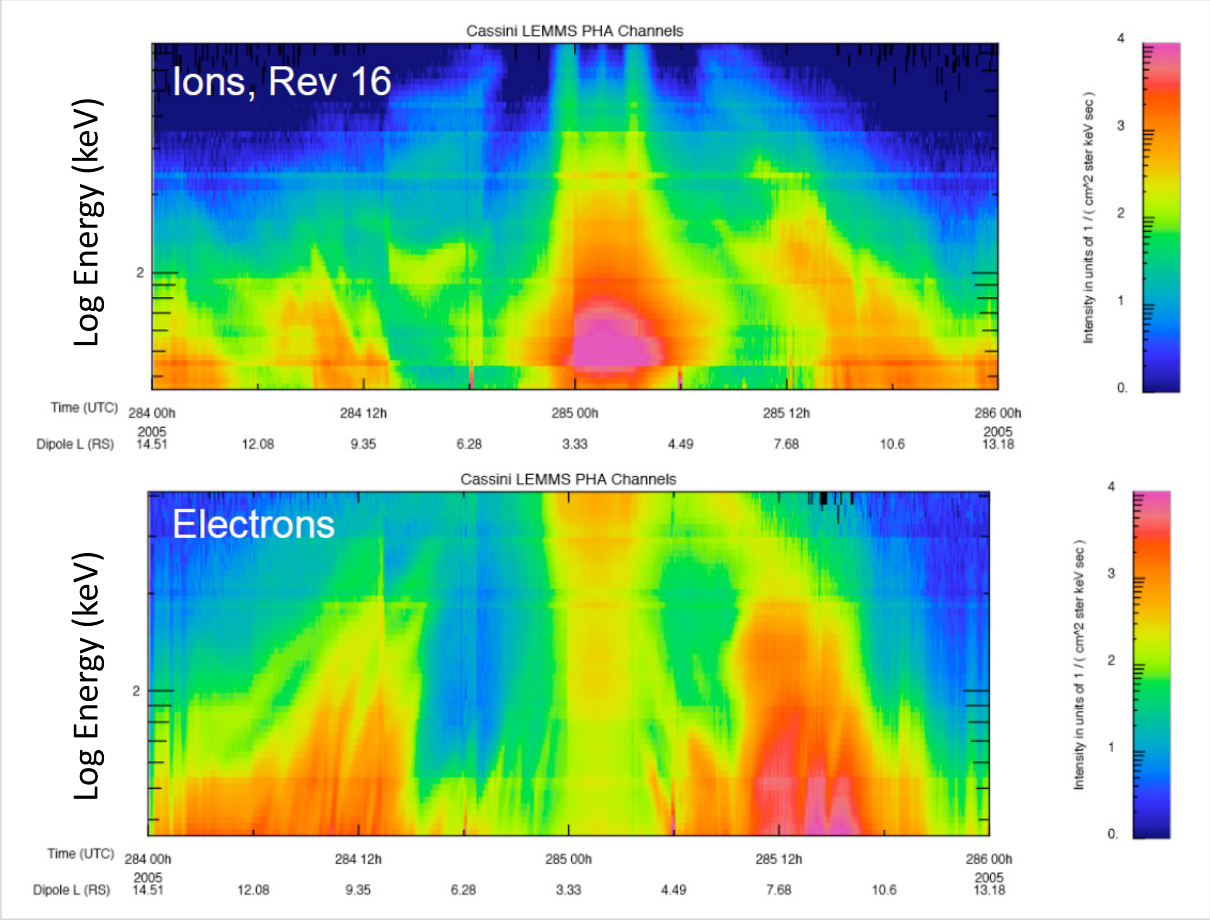


Krimigis et al., *Space Sci. Rev., 2004*

High-Energy particle detection instrument

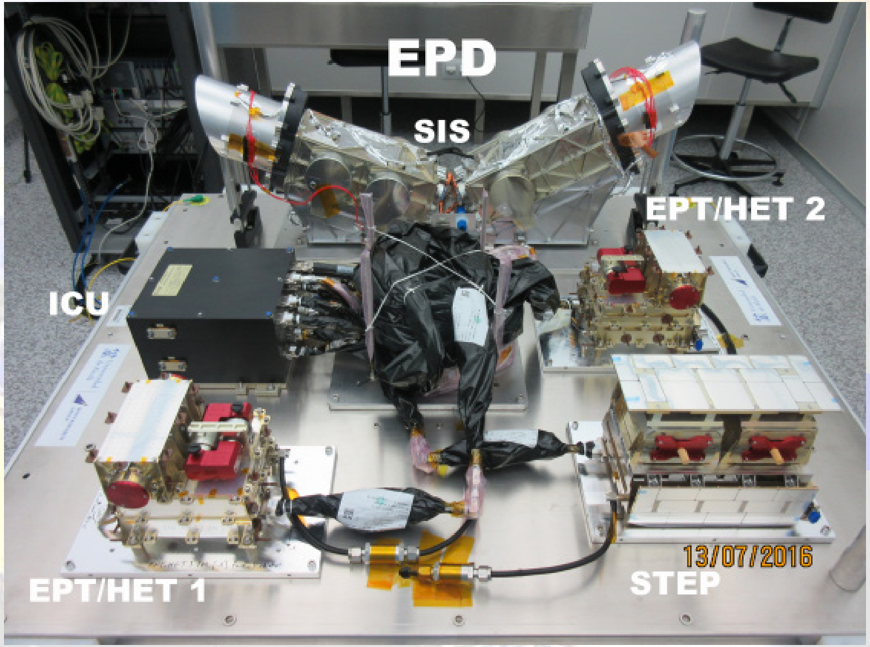
Example of Cassini - LEMMS instrument data from Saturn's Inner Magnetosphere





High-Energy particle detection

The EPD instrument onboard Solar Orbiter



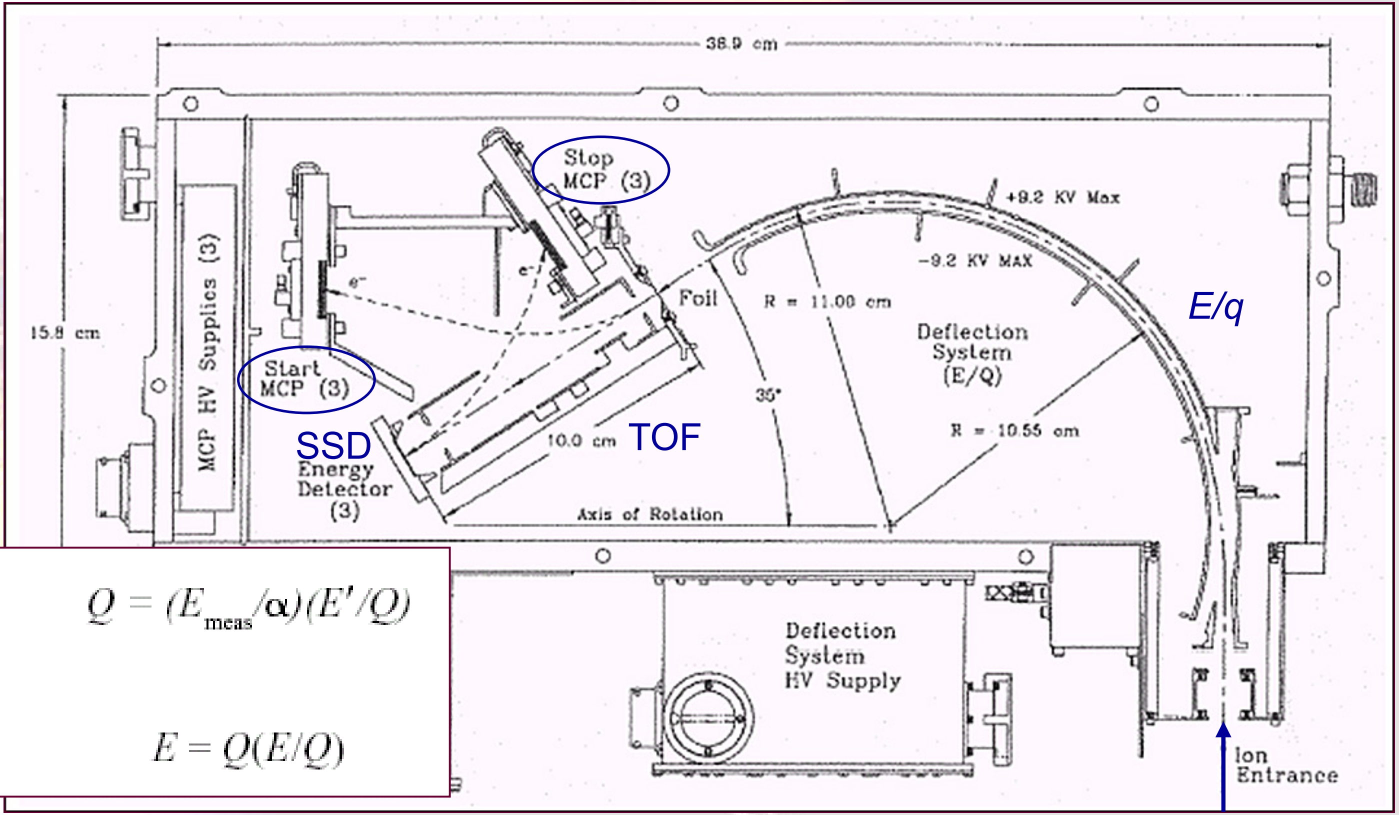
Rodríguez-Pacheco et al., *Astronomy &Astrophysics, 2020*

On a space mission, **energy ranges of low-energy particle instruments and high-energy particle instruments should be complementary** (with some overlap, for continuity and instrument cross-calibrations)

Medium – High Energy ion mass spectrometry
The CHEMS instrument on Cassini: combining *E/q*, TOF and SSDs

10 – 220 keV/q
1 – 80 amu

Krimigis et al.,
Space Sci. Rev., 2004



$$M/Q = 2(\tau/d)^2(E'/Q) \qquad Q = (E_{meas}/\alpha)(E'/Q)$$

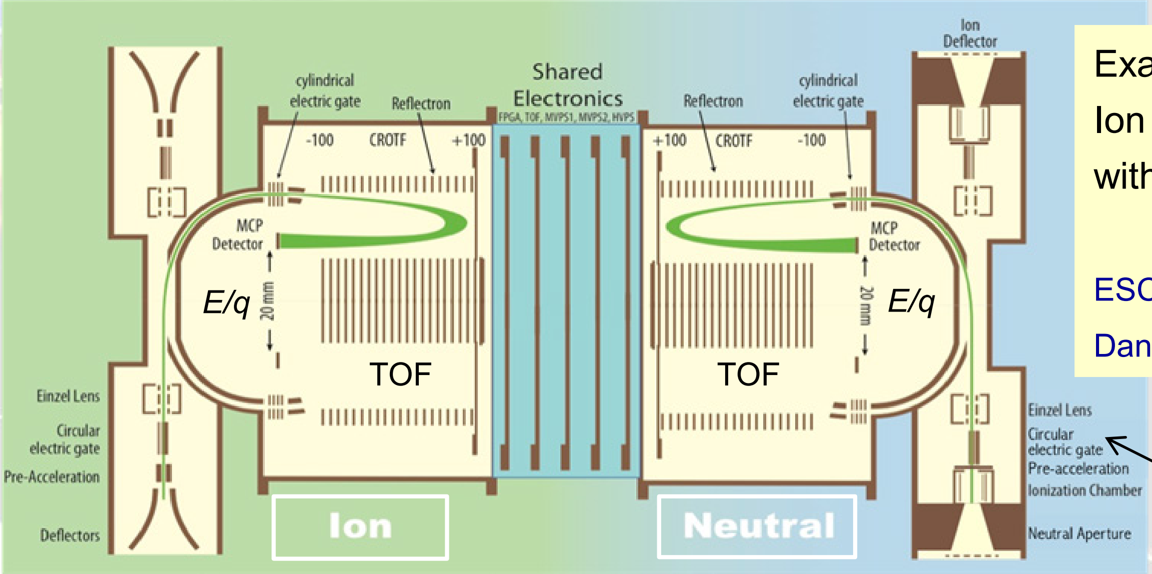
$$M = 2(\tau/d)^2(E_{meas}/\alpha) \qquad E = Q(E/Q)$$

Neutral particle measurements in space plasmas:

Neutral Mass spectrometers

Operating principle:

- ❑ First use an electric field to **deviate away all charged particles**, and admit only neutrals
- ❑ Use an electron beam to **ionise the neutrals**
- ❑ Then proceed as for ion mass spectrometry

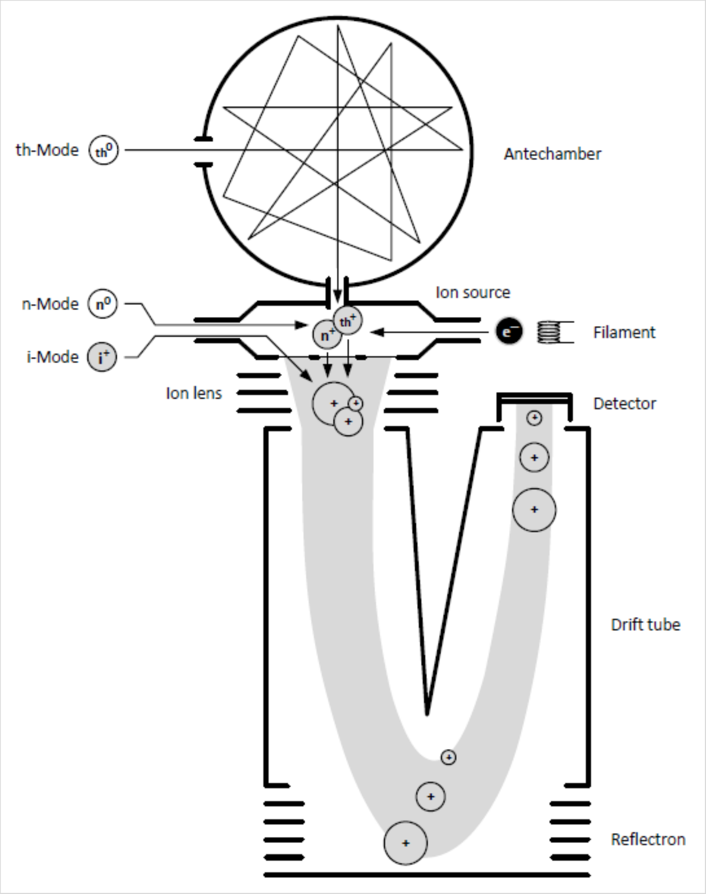


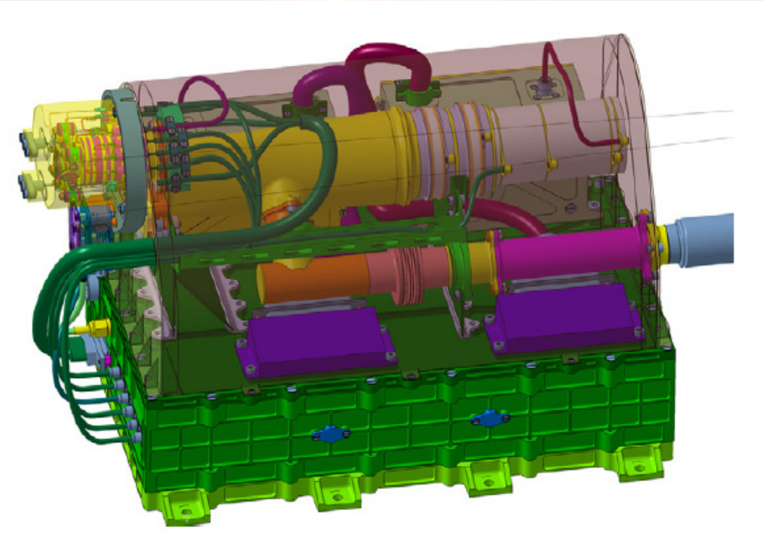
Example of combined
Ion Mass and Neutral Mass Spectrometer,
with separate detector heads

ESCAPE mission proposal to ESA,
Dandouras et al., 2016

Electron gun
to ionise the neutrals

Neutral particle measurements in space plasmas:
Neutral Mass spectrometers





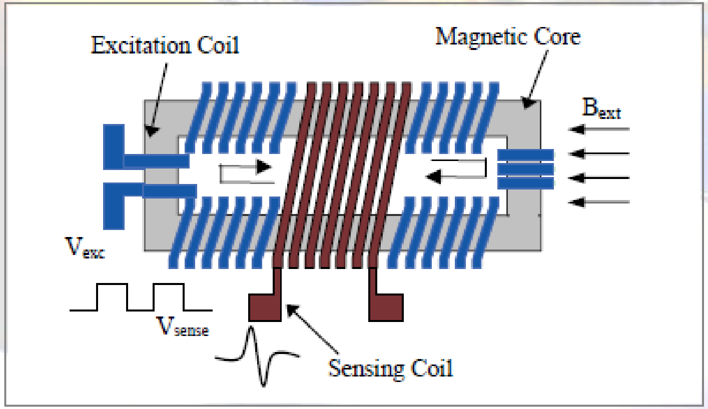
NGMS for the lunar exosphere
Wurz et al.,
Planet Space Sci., 2012

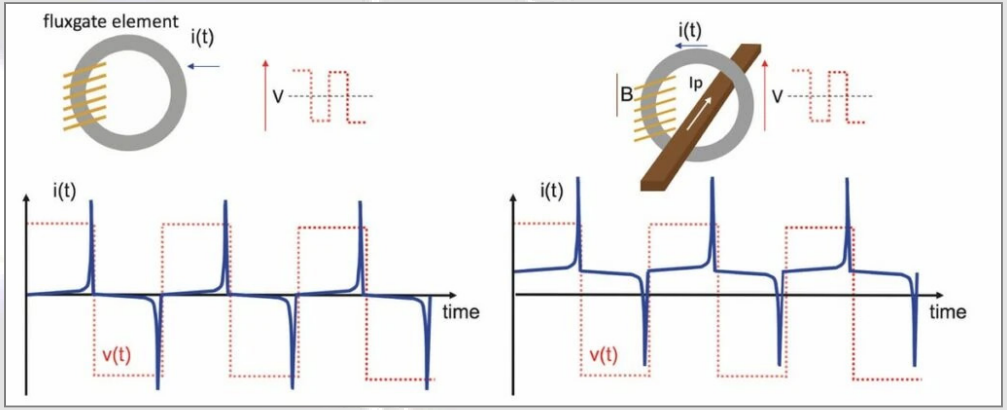
NIM onboard JUICE
Meyer et al.,
Geosci. Instrum. Method. Data Syst., 2017

Magnetic Field Measurements

The **Fluxgate Magnetometer** (DC and low-frequency magnetic fields):

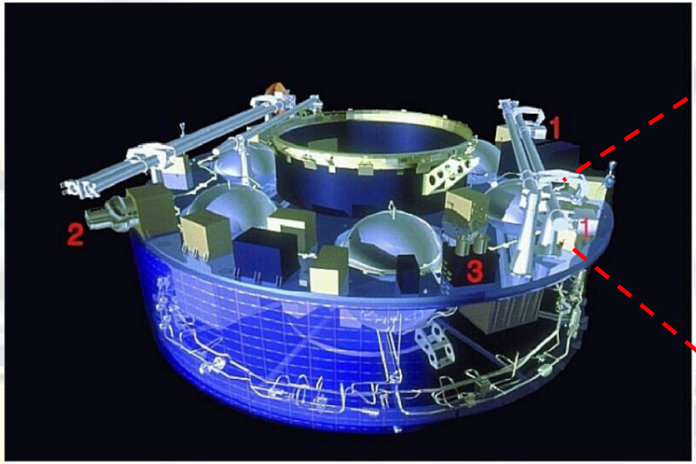
- ❑ 3 measuring units (mutually perpendicular), one for each component of ***B***
- ❑ Each unit:
  - A small magnetically susceptible core wrapped by **two coils**.
  - An **alternating electric current is passed through one coil**, driving the core through an alternating cycle of **magnetic saturation**.
  - **In the presence of an ambient magnetic field**, it is more easily saturated when in alignment with that field and less easily saturated when in opposition to the field.

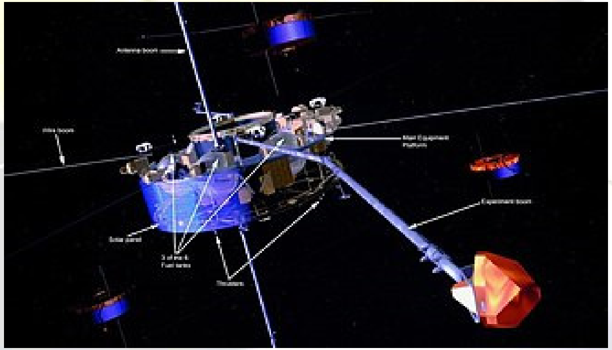




Magnetic Field Measurements

The FGM (Fluxgate magnetometer) experiment onboard Cluster





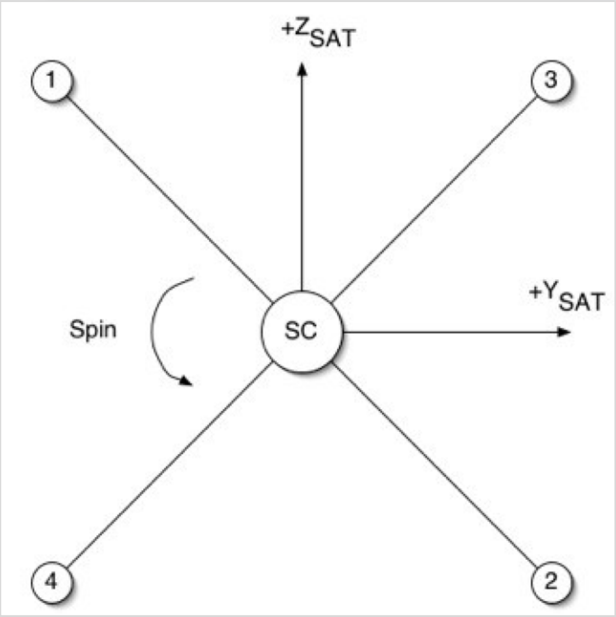
Balogh et al.,
Annales Geophysicae., 2001

Electric Field Measurements

Electric field vector ***E*** : the **gradient of the electric potential *V***

$E_x = -\mathrm{d}V / \mathrm{d}x \qquad E_y = -\mathrm{d}V / \mathrm{d}y \qquad E_z = -\mathrm{d}V / \mathrm{d}z$

$\Rightarrow$ Measuring electric fields implies measuring differences in the (floating) potential in space



Example of the probes configuration for measuring the electric potential in the spin plane of the Cluster spacecraft:

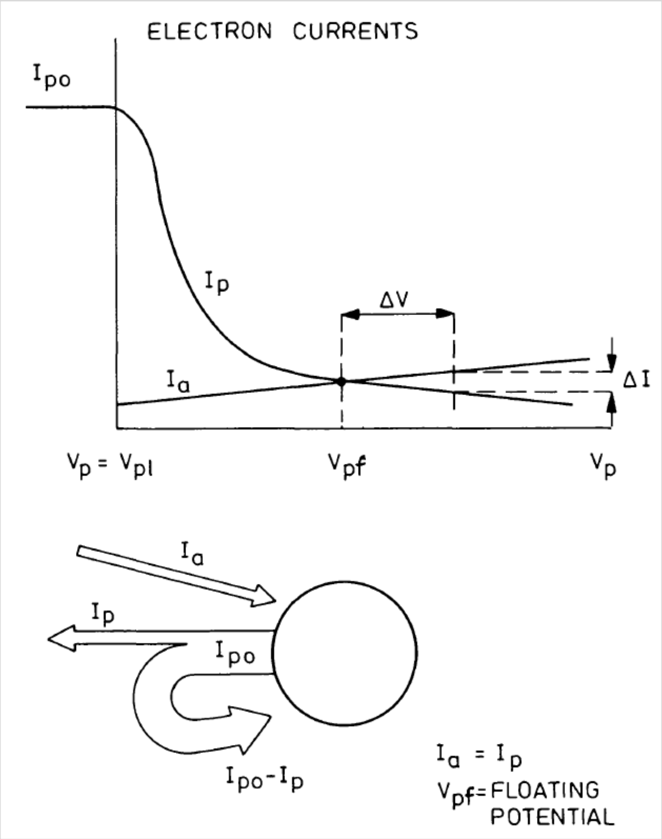
EFW experiment:

4 probes, each at the tip of a 44 meter long wire boom

Gustafsson et al., *Annales Geophysicae., 2001*

Electric Field Measurements:

Floating potential



Probe floating potential V_{pf}:

Determined by the balance of the electron currents to and from the probe

I_p : escaping photoelectrons

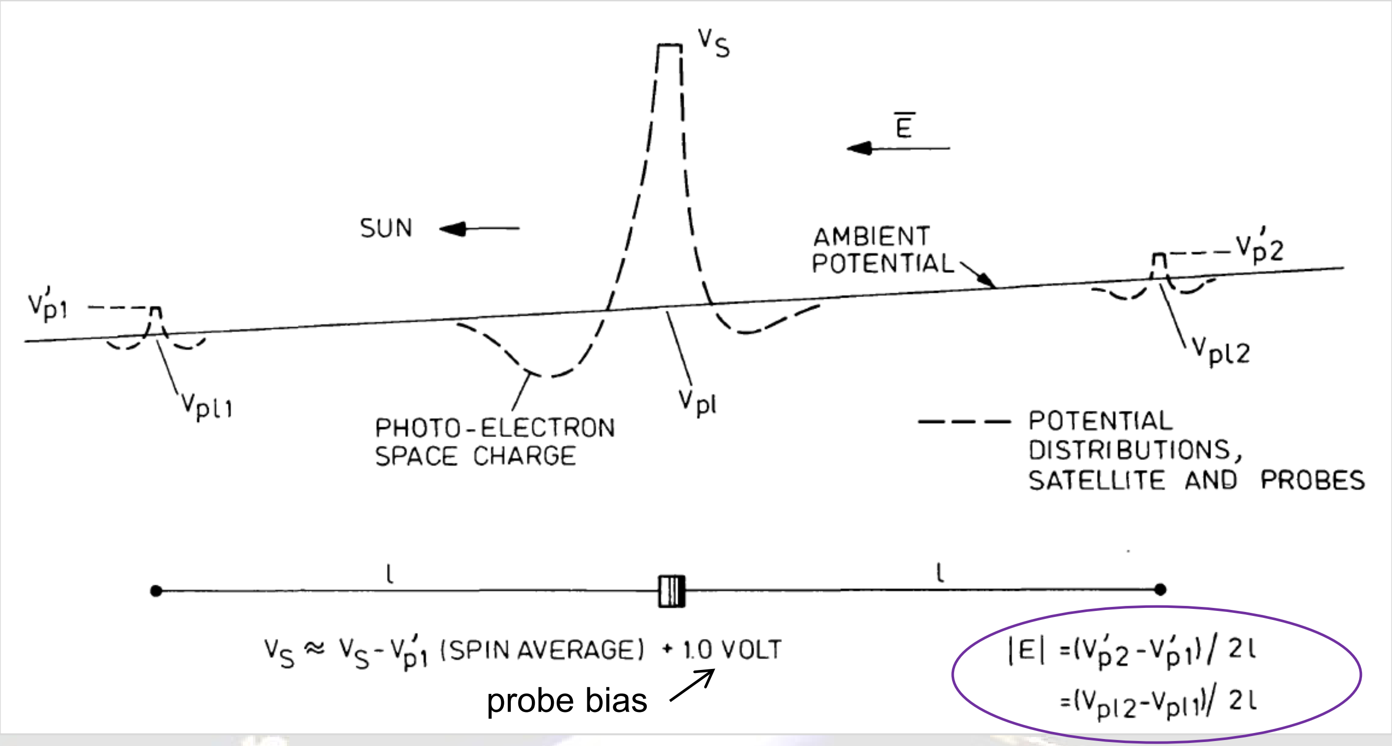
I_{p0} : total photoelectron emission

I_a: ambient electrons to the probe

Pedersen et al.,
Space Sci. Rev., 1984

Electric Field Measurements:

Potential distribution near the satellite and the probes



V_s : satellite floating potential

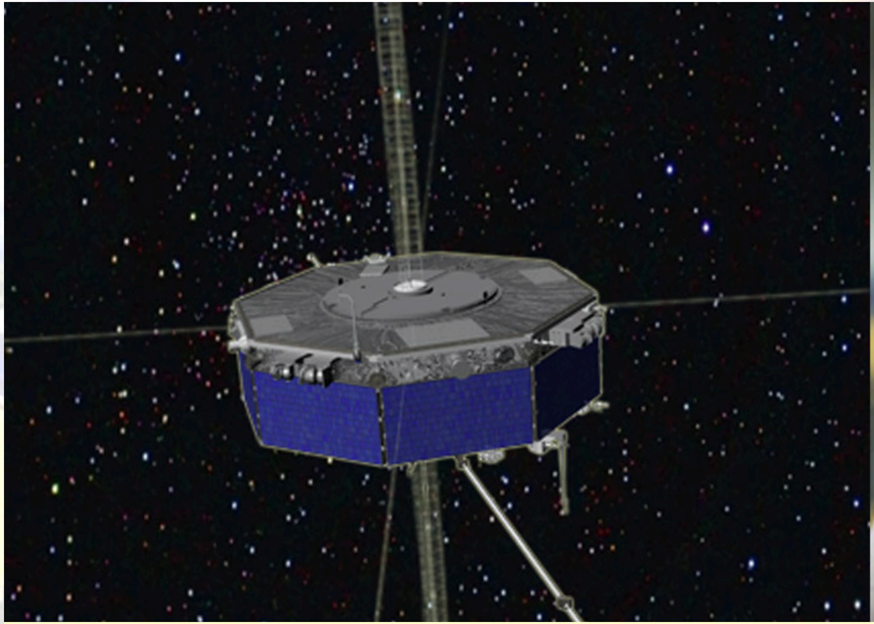
V_{pl} : plasma potential

V_{p1}' : probe 1 floating potential

V_{p2}' : probe 2 floating potential

Electric Field Measurements:

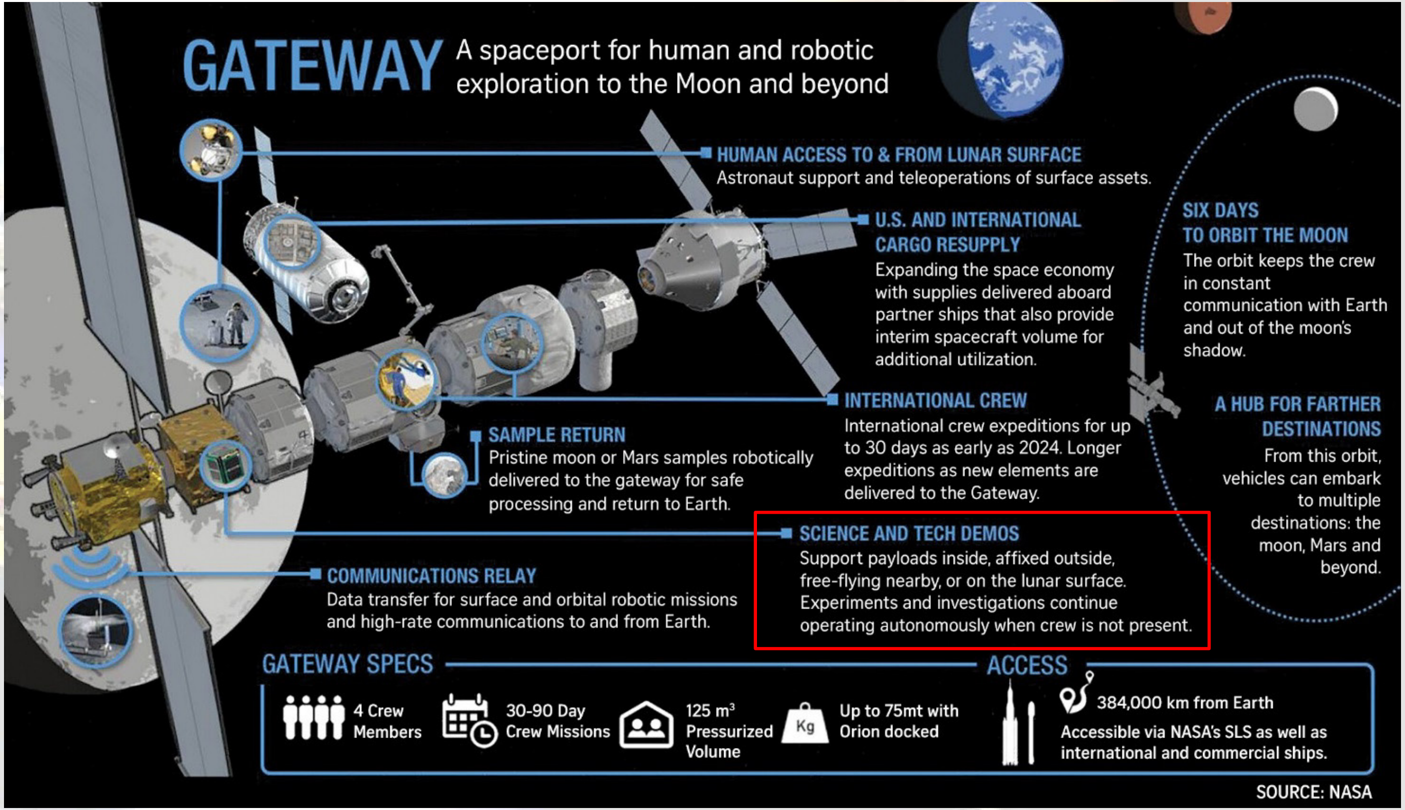
SDP + ADP experiment onboard MMS



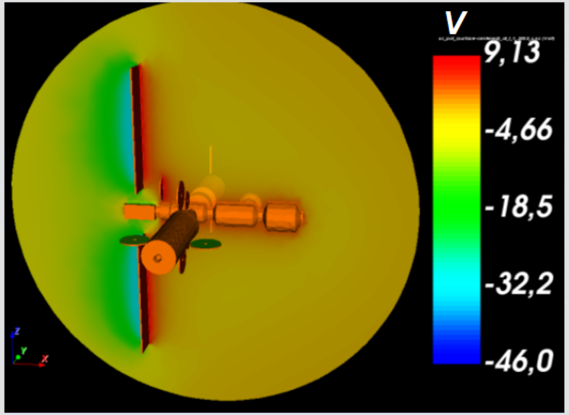
Four wire probes in the spin plane + 2 boom probes along the spin axis

Lindqvist et al., *Space Sci. Rev., 2016*

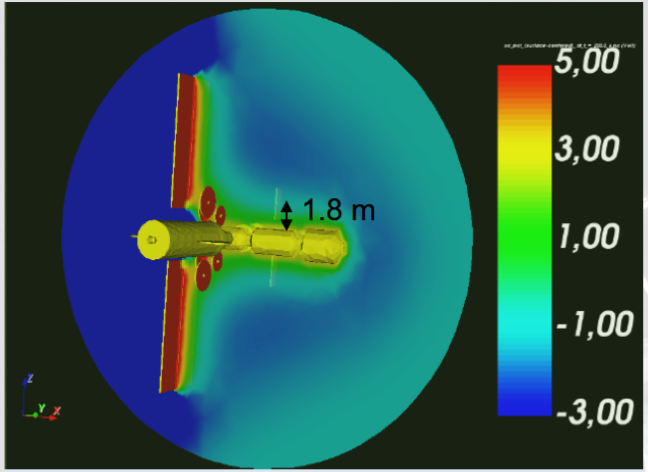
Example of a space plasma physics instrument package conceptual design: onboard the *Lunar Gateway*



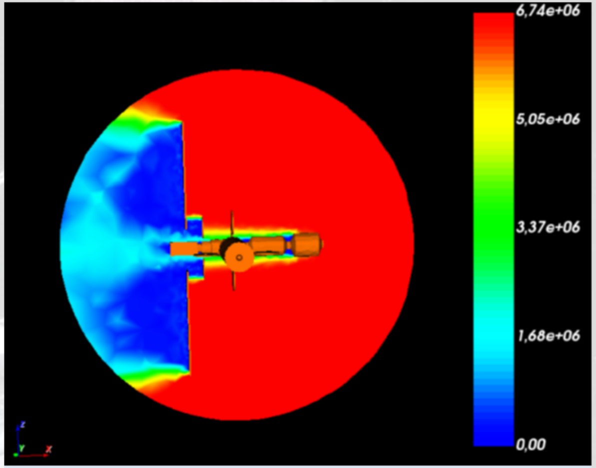
Simulation of the Gateway – plasma environment interaction



Electrostatic potential simulation
in the solar wind



Electrostatic potential simulation
in the solar wind:
scale saturated at +5 / -3 V



Ambient proton density (m^{-3})
in the solar wind

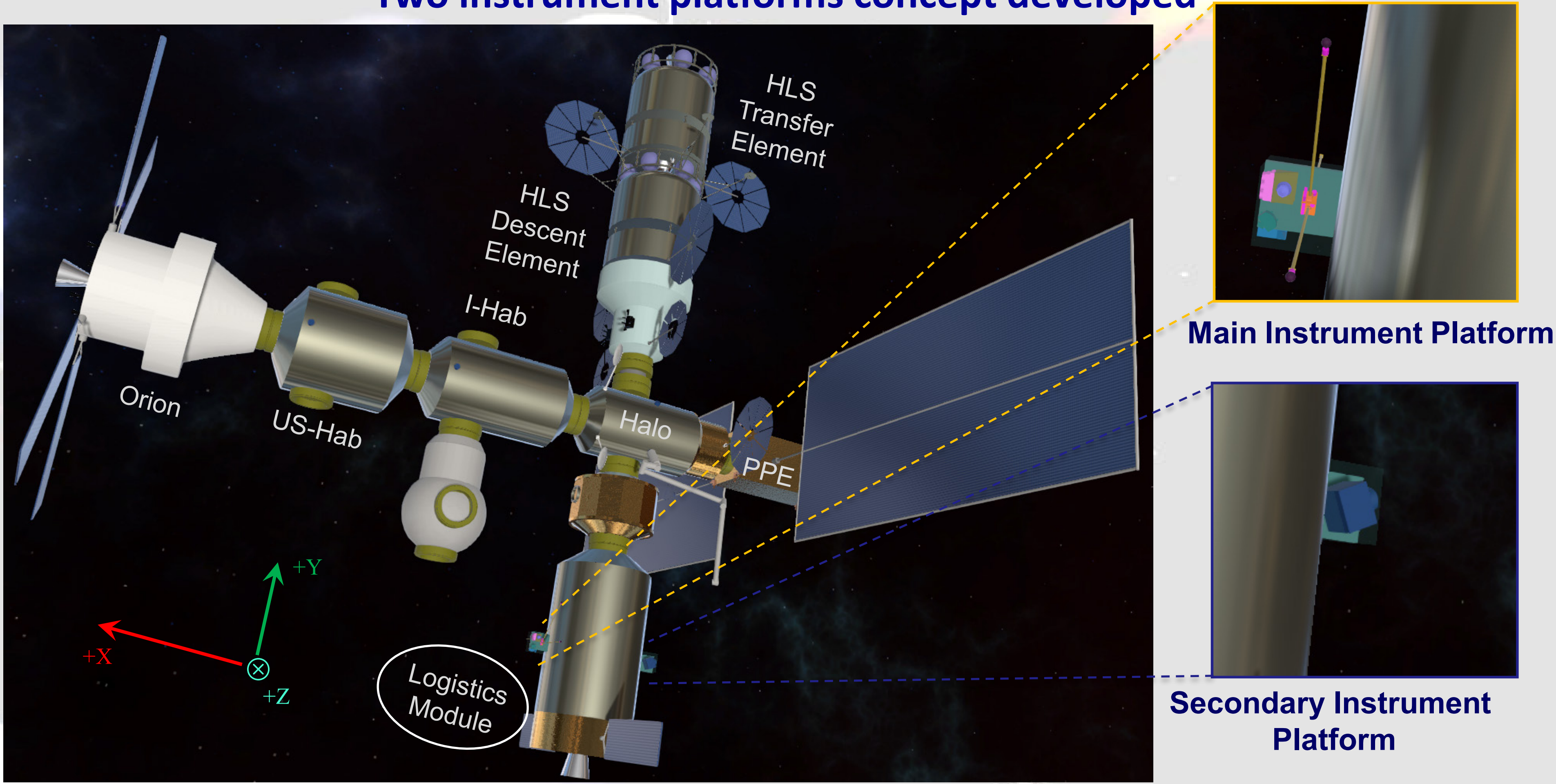
Artenum – ONERA SPIS simulations

Dandouras et al., Front. Astron. Space Sci., 2023

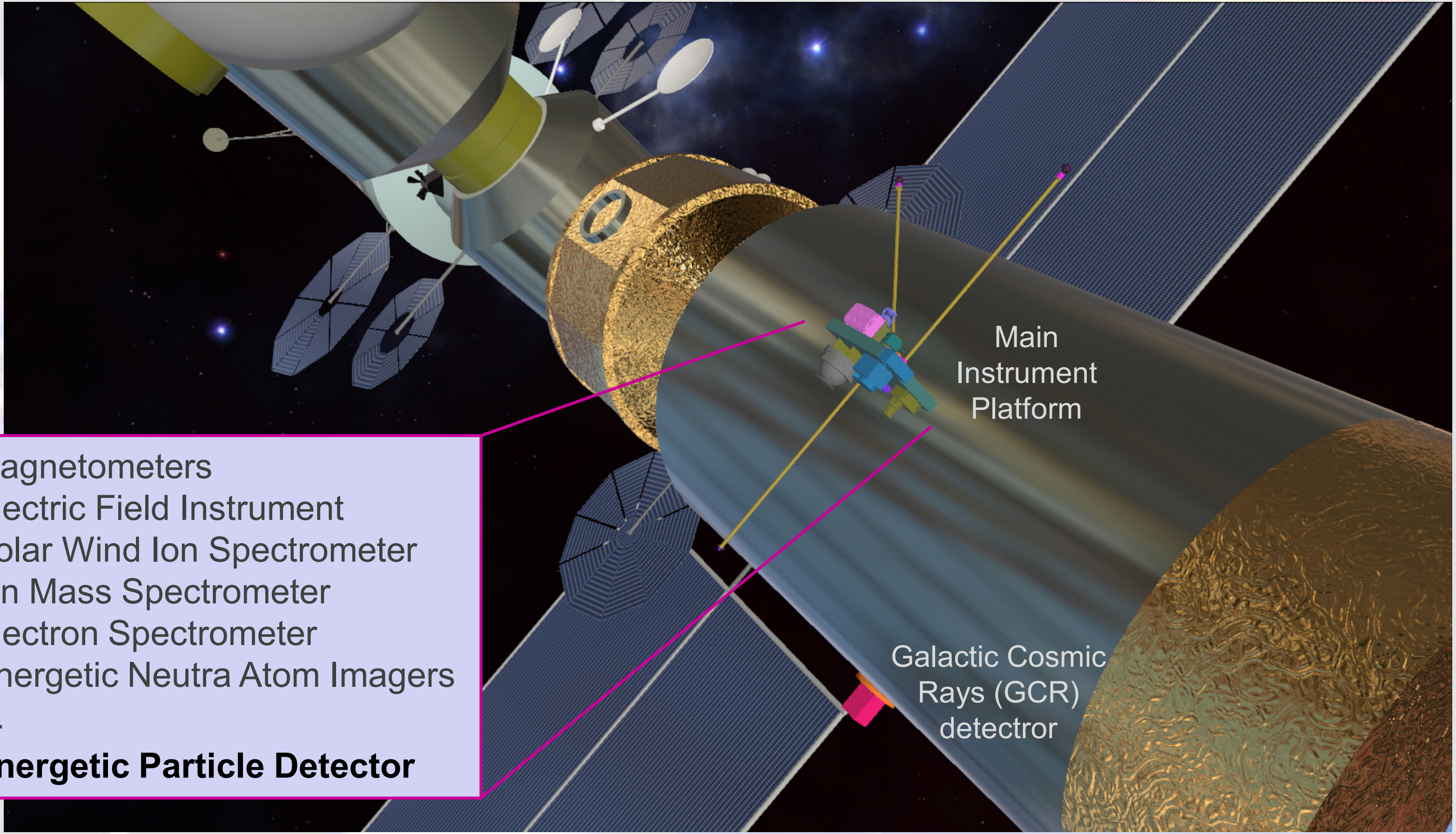
Identification of the most favourable positions for the plasma instruments

Remaining positions can then be used for energetic particle & magnetospheric imaging instruments

Space plasma physics instrumentation conceptual design: Two instrument platforms concept developed



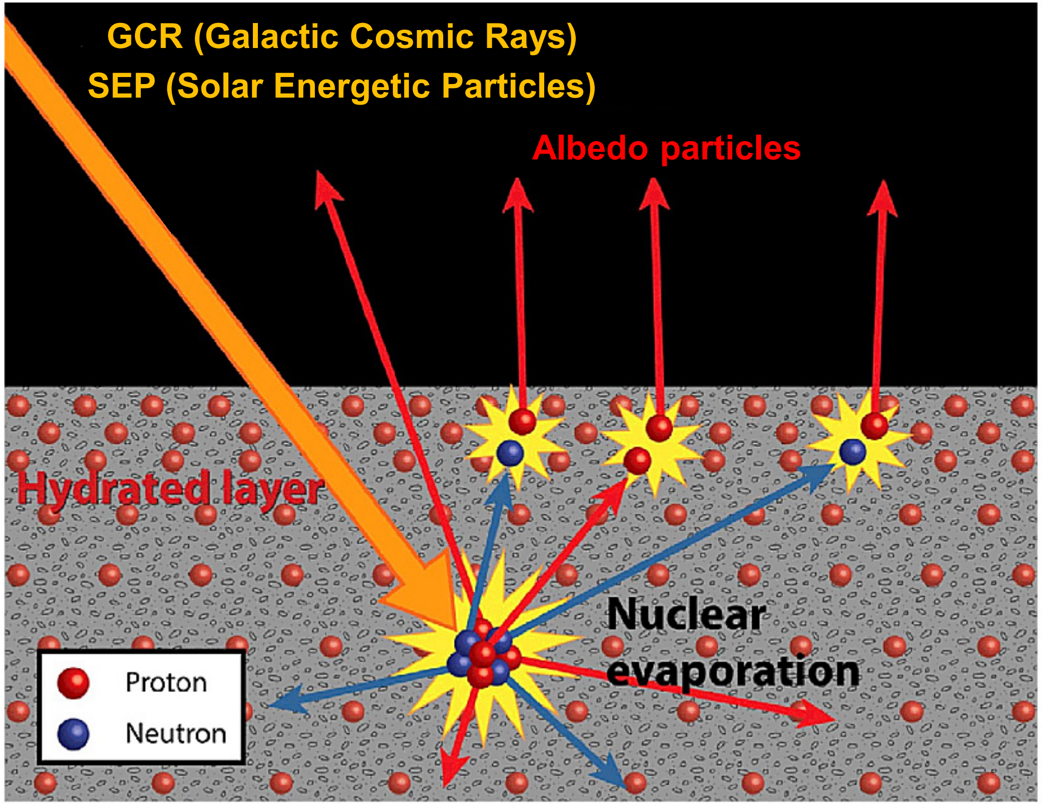
Main Instrument Platform on the Logistics Module +X side



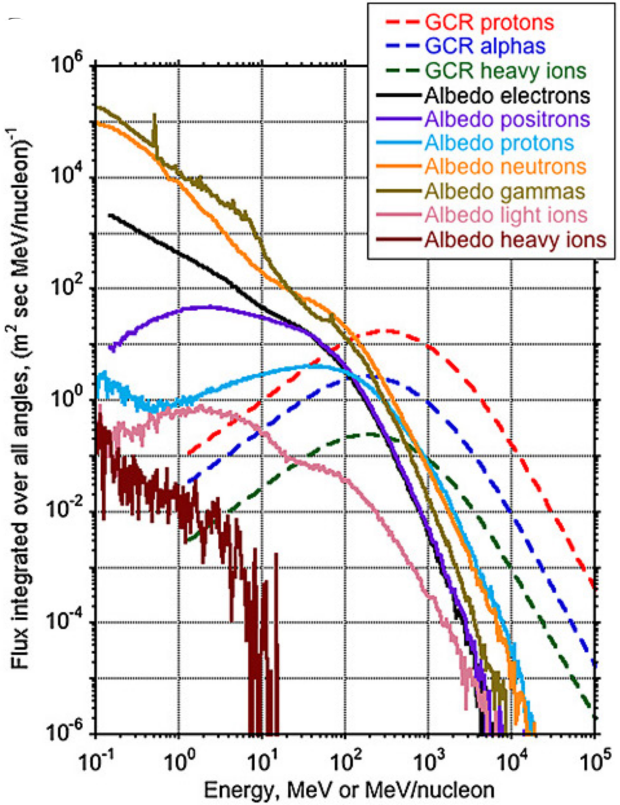
- Magnetometers
- Electric Field Instrument
- Solar Wind Ion Spectrometer
- Ion Mass Spectrometer
- Electron Spectrometer
- Energetic Neutra Atom Imagers
- …
- **Energetic Particle Detector**

Dandouras et al., *Front. Astron. Space Sci., 2023*

Effect of the lunar regolith on the production of SEP and GCR albedo particles

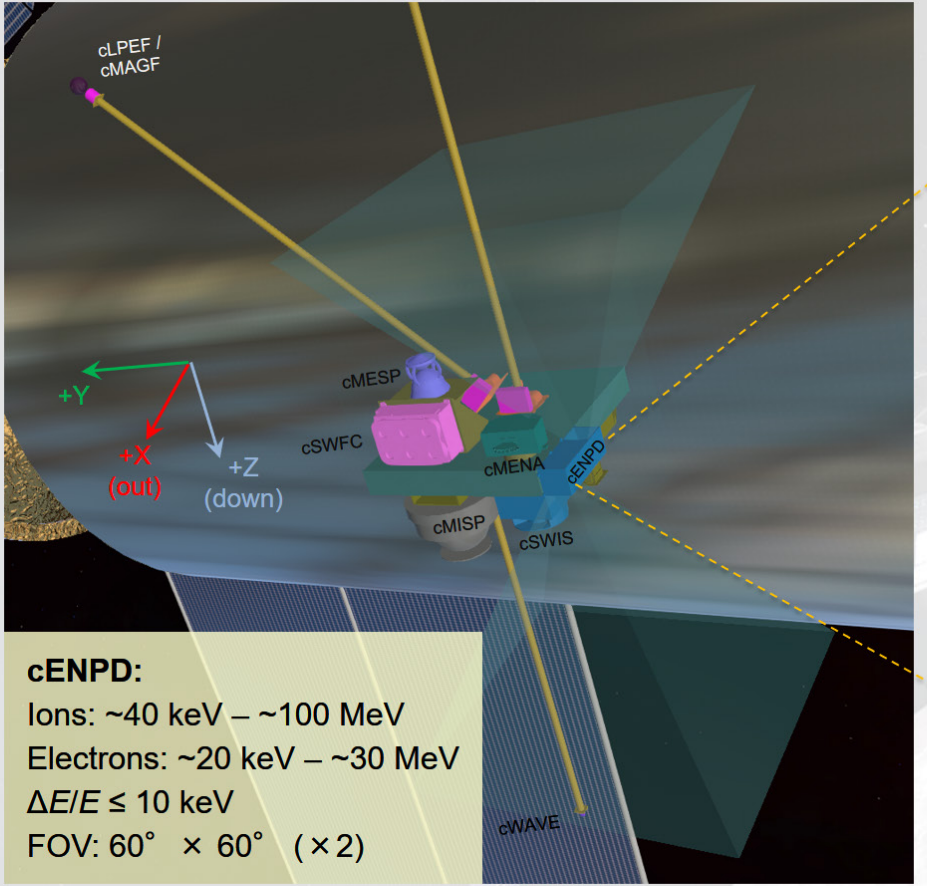


Schwadron et al., *Icarus, 2016*



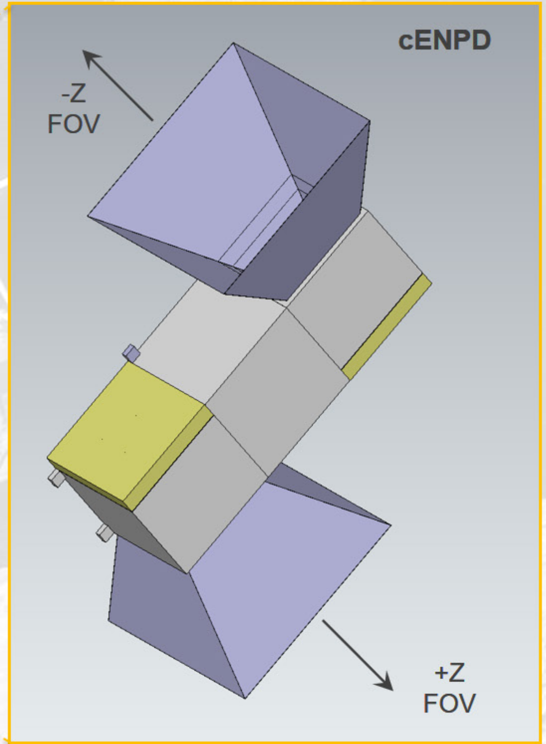
Looper et al., *Space Weath., 2013,*

Space plasma physics instrumentation conceptual design:
Main Instrument Platform: + X / - Y edges



cENPD:
Ions: ~40 keV – ~100 MeV
Electrons: ~20 keV – ~30 MeV
$\Delta E/E \leq 10$ keV
FOV: 60° × 60° (×2)

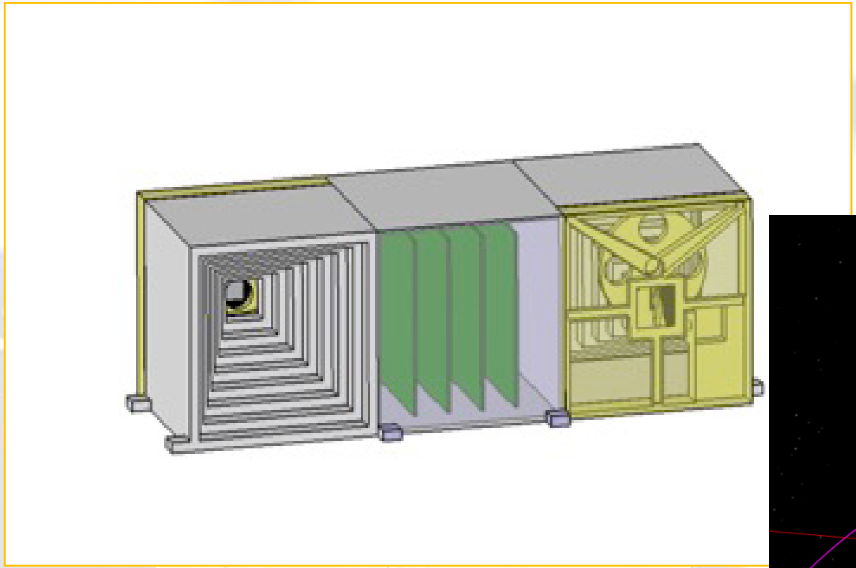
Energetic Particle Detector

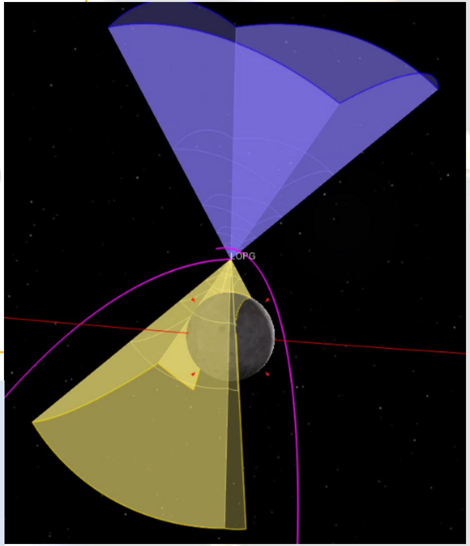


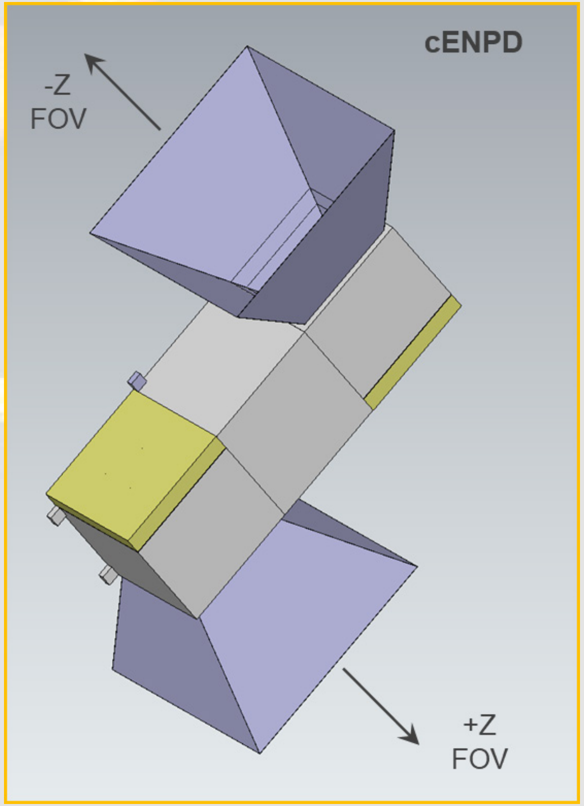
cENPD
(mounted on the -Y edge of the platform)

High-Energy particle detection

The ENPD instrument conceptual design for the Lunar Gateway





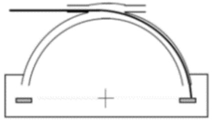


- Pristine energetic particles flux (purple FOV)
- Moon albedo energetic particles flux (yellow FOV)

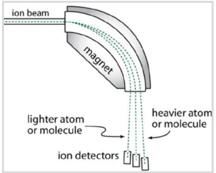
Dandouras et al., *Front. Astron. Space Sci., 2023*

Synopsis

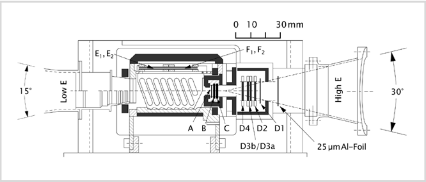
- **What space plasma parameters do we need to measure:** particles and fields
- **How do we measure particle distribution functions**
  - Low – medium energy: electrostatic analysers ---->



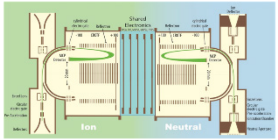
  - Ion mass spectrometers -->



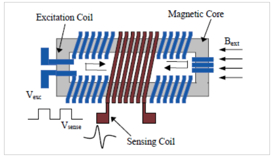
  - Medium – high energy: solid state detectors -->



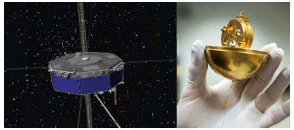
  - Neutral mass spectrometers -->



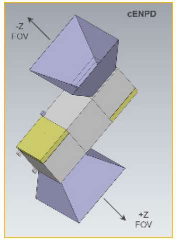
- **Magnetometers** --->



- **Electric field probes** ---->



- **Example of a space plasma physics instrument package conceptual design:** onboard the Lunar Gateway ---------------------->



Ευχαριστώ !