Mass spectrometry for VLEO and DISCOVERER

Dhiren Kataria
d.kataria@ucl.ac.uk

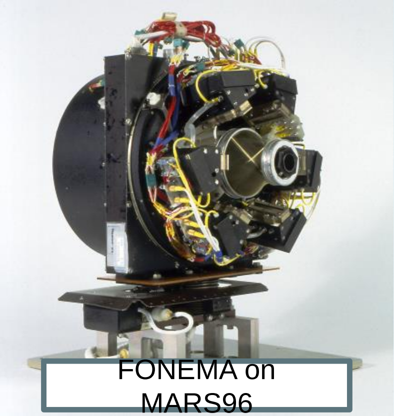
Mullard Space Science Laboratory
Dept. of Space and Climate Physics

Research at MSSL

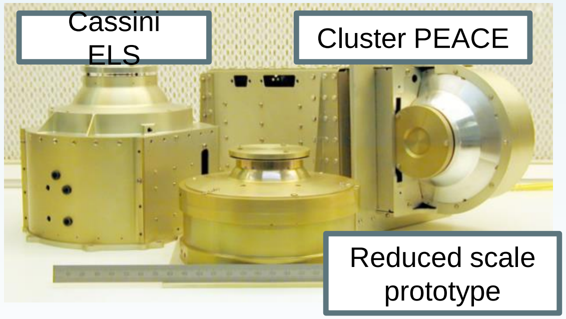
- **Department of Space and Climate Physics, University College London**
- **Research groups supported by specialist engineers conduct our scientific research:**
  - Astrophysics
  - Climate Physics
  - Magnetospheric Physics
  - Planetary Science
  - Solar and Stellar Physics
  - Theory
  - In-situ Detection Systems
  - Photon Detection Systems
  - Imaging
  - Cryogenic Physics

In-situ Plasma Instrumentation

- Strong plasma instrumentation heritage
  - Planetary environments: Cassini, Mars and Venus Express (built by SWRI), Mars 96 (launcher failed), AMPTE-UKS
  - Magnetospheric missions: Cluster, Double Star, Polar, CRRES, STRV, QB50
  - Cometary studies: Giotto
  - Technology Demonstration: TechDemoSat
- Top-hats, with enhanced capabilities
  - Solar Orbiter, SMILE (built by NSSC, China)
- Highly miniaturised particle sensors
  - DISCOVERER, CIRCE



FONEMA on MARS96



Cassini ELS

Cluster PEACE

Reduced scale prototype

Improved Plasma Analyser with miniaturised prototype

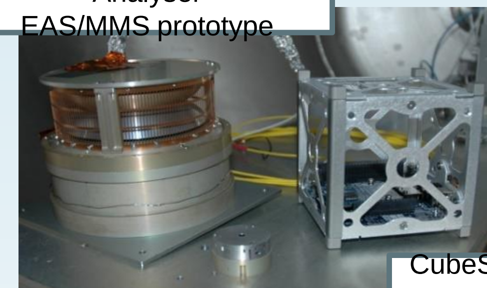
Solar Orbiter EAS

Mars Express in the calibration chamber

Instrument Miniaturisation

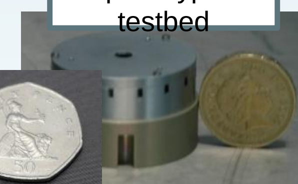
- Driven by CubeSat and Space Weather
  - Horses for courses
- Generic technology development
  - Charged Particle Optics
  - Electronics miniaturisation – HV, readout, digital
  - Detection systems – combined e-ion
- Alternative geometries to top-hats
  - Cylindrical, Bessel box
- Technology demonstration
  - UK TechDemoSat, QB50 precursor

Improved Plasma Analyser EAS/MMS prototype

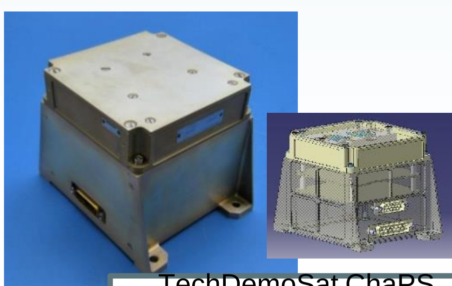


CubeSat

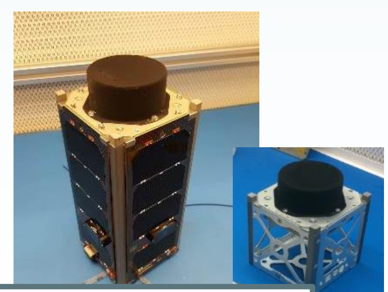
EJSM prototype testbed



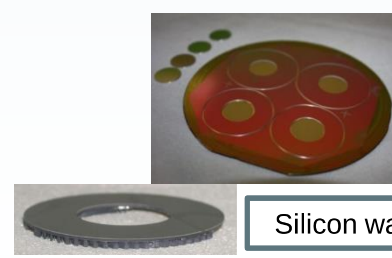
High temporal resolution proof-of-concept analyser



TechDemoSat ChaPS instrument and CAD model



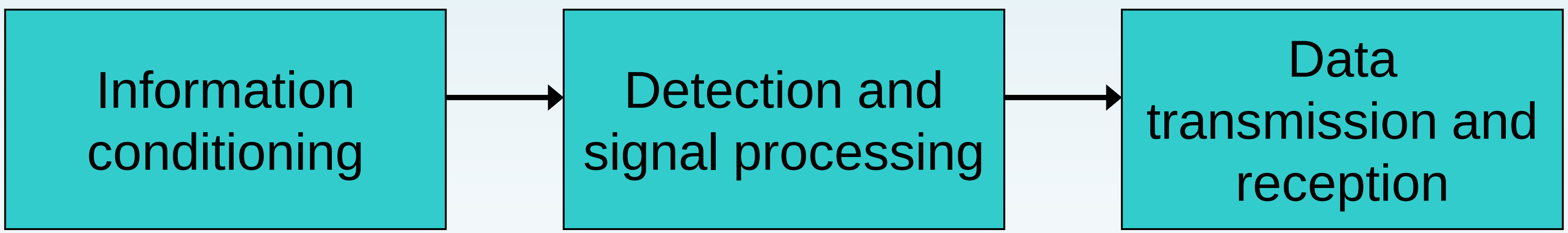
Ion and Neutral Mass Spectrometer for QB50



Silicon wafer analyser

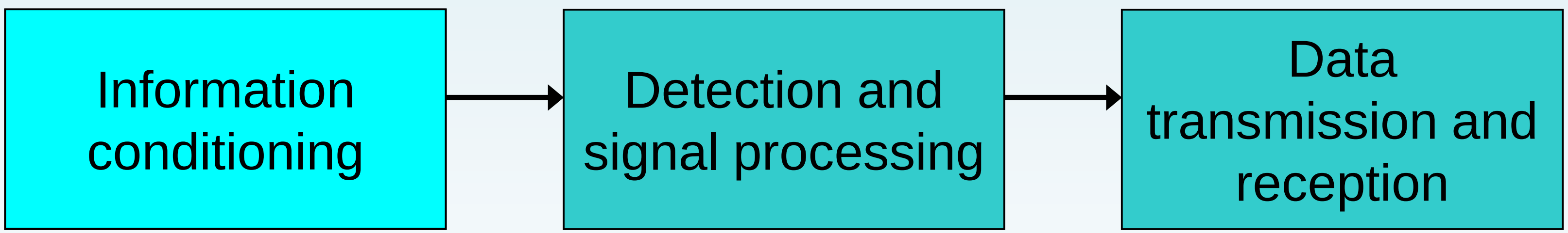
Overview

- Typical elements of a space instrument



Overview

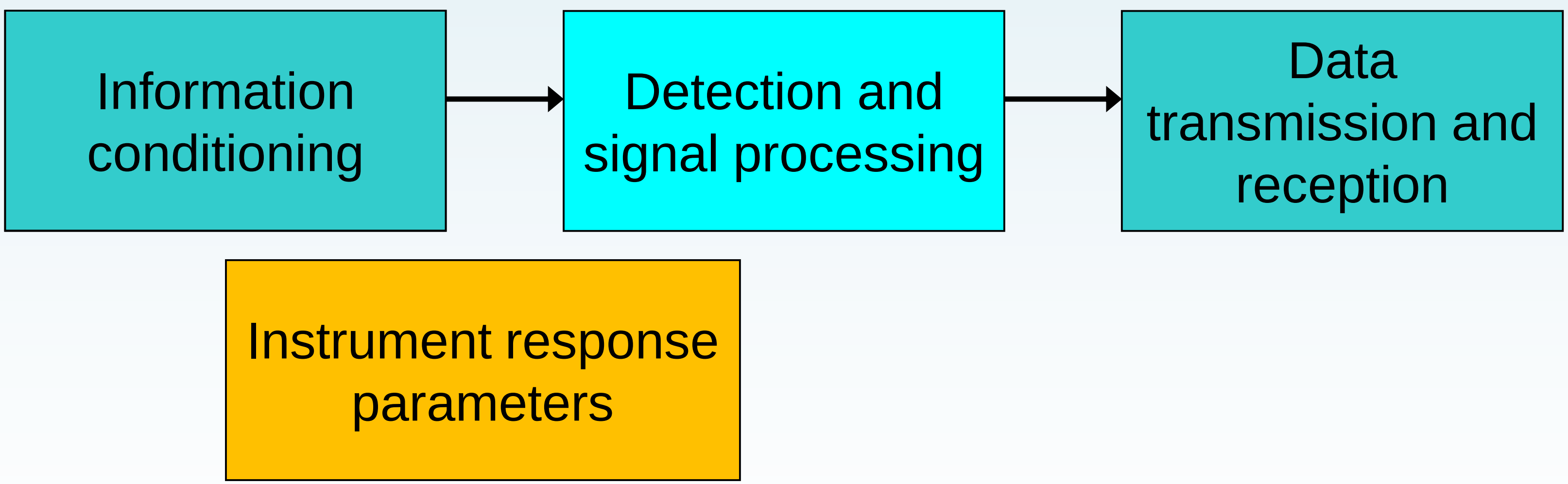
- Typical elements of a space instrument



- Information conditioning: Collectors (telescopes), filters, analysers, apertures or collimators
- Combinations of above

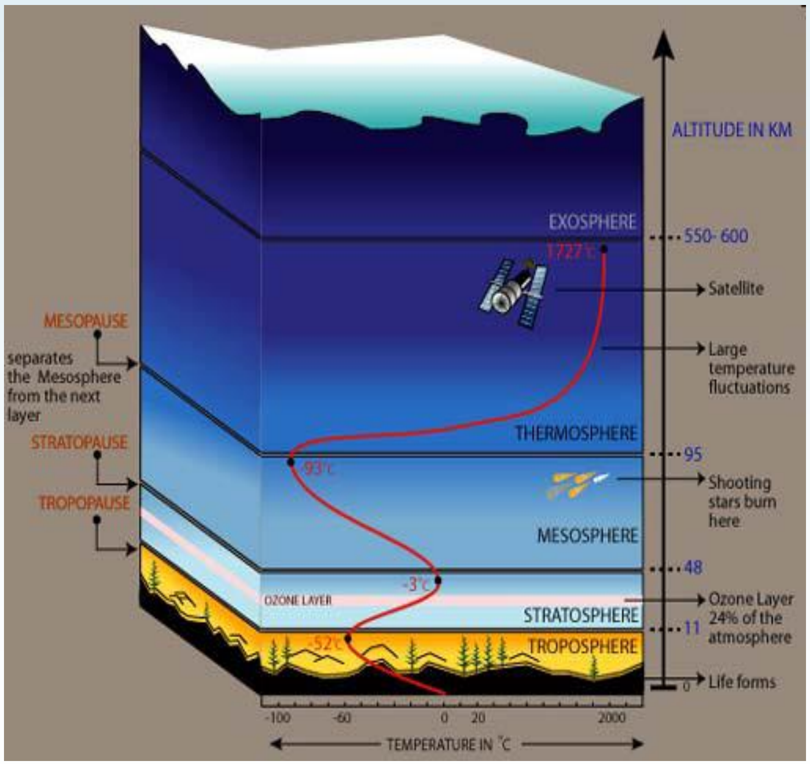
Overview

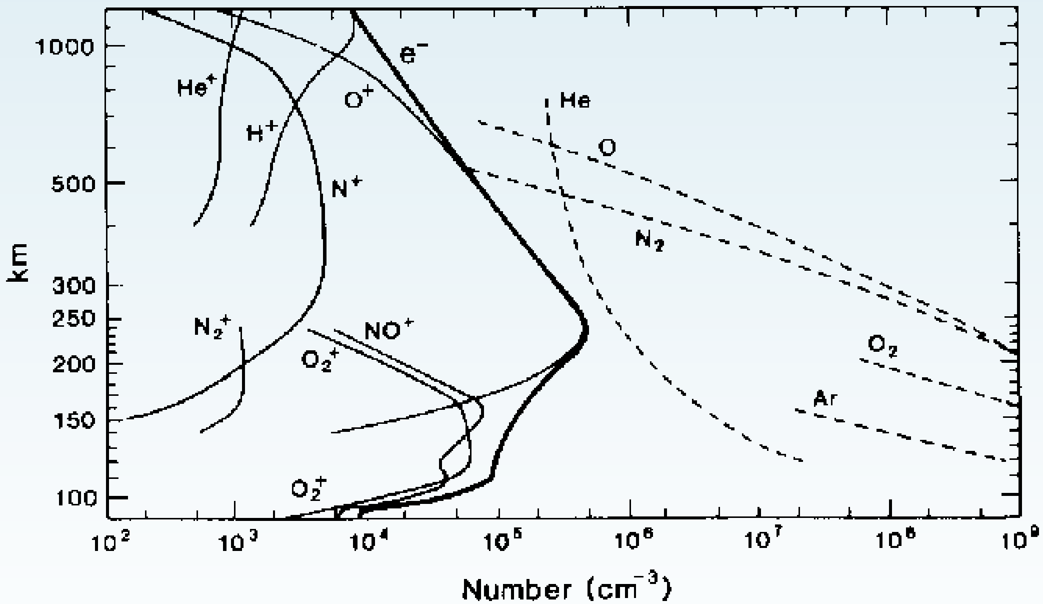
- Typical elements of a space instrument



Requirements Definition

Plasma Environments –Ionosphere/Exosphere





http://www.nar.ucar.edu/2010/lar/hao/upper-atmosphere-and-ionosphere-community-models.html

http://www.physics.usyd.edu.au/~cairns/teaching/lecture16/node2.html

Requirements definition

- Science, Engineering drivers
- Orbit
  - Measurable quantities
    - e.g. range of flux, particle types
  - Environment
    - In-situ environment - Radiation, thermal
    - Launch environment - vibration,
- Measurement aims
  - Science focus
  - Monitoring vs science
  - Discovery vs further scientific investigiations

Measureable parameters – How?

- At any instant, instrument samples fraction of total parameter space. Key parameters sampled
  - Area
  - Angular range
  - Time variability
- Measurement requirements drive total parameter space to be covered.
  - E.g., solar wind ions vs solar wind electrons

In-situ Plasma Measurements

- Design an In-situ Instrument
  - Requirement Definition, Geometries and Fields
- In-situ Measurement Techniques
  - What and How with Examples
- Instrument Sub-systems: Brief Introduction
  - Plasma Detectors, Electronics
- Instrument Acceptance Parameters
  - Extracting the answers

In-situ instrumentation - How

- $E = 1/2*mv^2$

- Determine two quantities from amongst the three above

  Electric field force – $q\vec{E}$
  Magnetic field force – $q\, v\times\vec{B}$

  Requirements driven by mission science. Not all quantities are required to be measured

- Analysers:
  - Electrostatic
  - Magnetic
  - Combinations

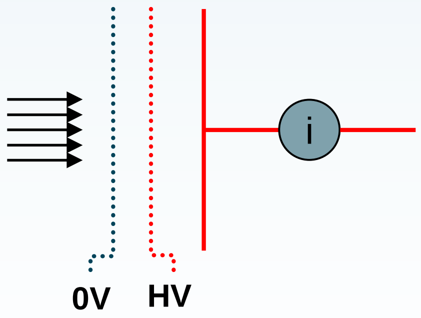
Electrostatic Analysers

Two main types

- Integrating
- Differential

Electrostatic Analysers

- Integrating
  - RPA
    - Retarding potential analyser
      - Gridded Faraday cup
      - Langmuir probes

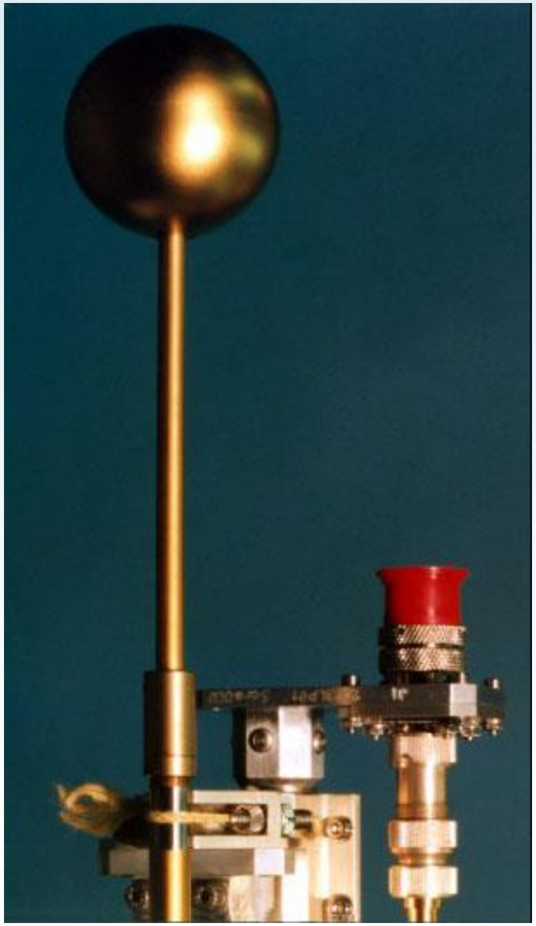


- Energy cut-off proportional to applied voltage
- Sweeping voltage samples full energy distribution
- Various geometries
  - Planar, cylindrical, spherical, segmented

- Relatively simple instruments
- Needs high voltages
- Limited detail
- Affected by spacecraft effects

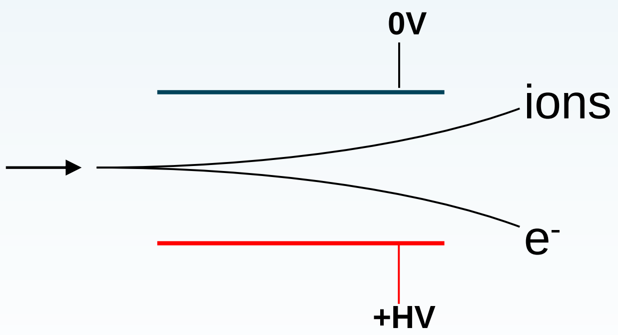
Example

- Rosetta langmuir probe



Electrostatic Analysers

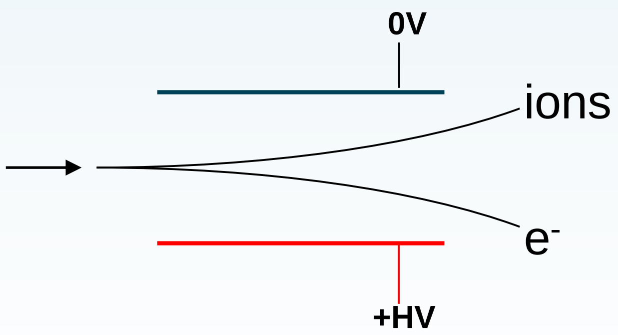
- Integrating
  - RPA
- Differential
  - Planar



- Field perpendicular to particle velocity v
  - Motion in x
  - Motion in y

Electrostatic Analysers

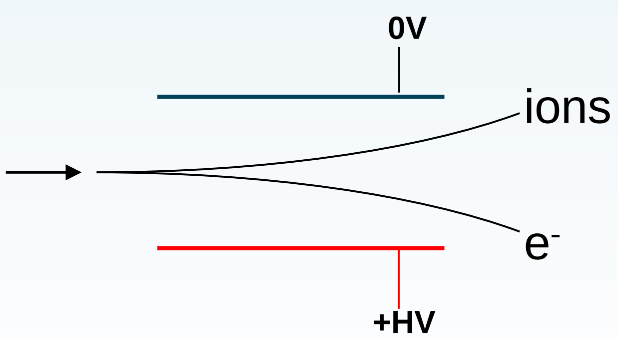
- Integrating
  - RPA
- Differential
  - Planar



- Field perpendicular to particle velocity v
  - Motion in x
  - Motion in y
- $y=(1/4)*(q/E)*(V/d)*x^2$
- $y \alpha x^2$
  - Parabolic path
- $y \alpha 1/(E/q)$
  - Provides energy dispersion
- Position sensitive detector

Electrostatic Analysers

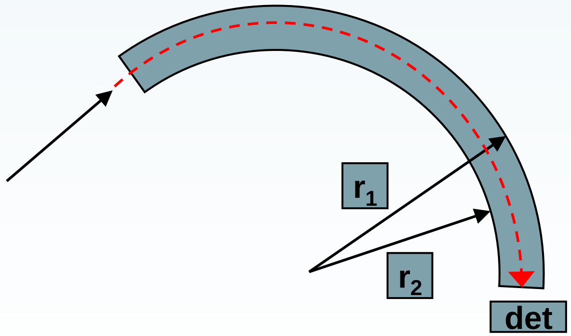
- Integrating
  - RPA
- Differential
  - Planar



- Low voltage requirement
- Simultaneous electron and ion detection possible
- Dispersion is non-linear
- Used on FONEMA along with magnetic field dispersion

Electrostatic Analysers

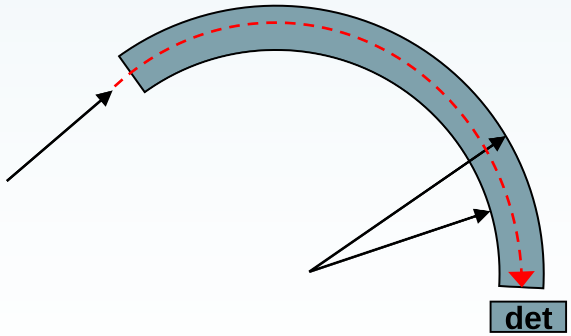
- Integrating
  - RPA
- Differential
  - Planar
  - Spherical



- Radial field perpendicular to particle motion

Electrostatic Analysers

- Integrating
  - RPA
- Differential
  - Planar
  - Spherical



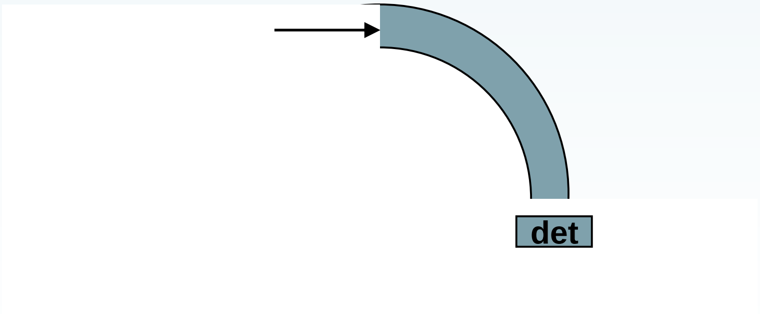
- Radial field perpendicular to particle motion
- Centripetal force mv^2/r
- $E/q = \Delta V^* r_0/2\Delta r$
  - $r_0 = (r_1+r_2)/2$
  - $\Delta r = r_2-r_1$
- $E/q = k^*\Delta V$
- Sweep V to obtain energy distribution
- $r_0/2\Delta r$ - k-factor

Electrostatic Analysers

- Integrating
  - RPA
- Differential
  - Planar
  - Spherical

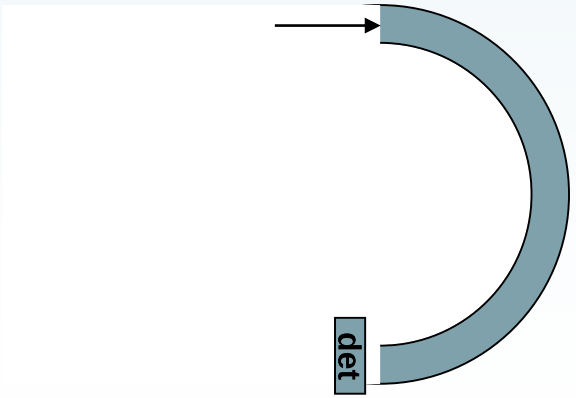
Various geometries

- Quadrispheric



Electrostatic Analysers

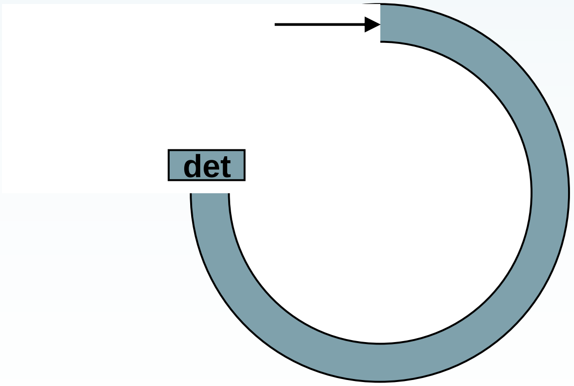
- Integrating
  - RPA
- Differential
  - Planar
  - Spherical
- Quadrispheric
- Hemispheric



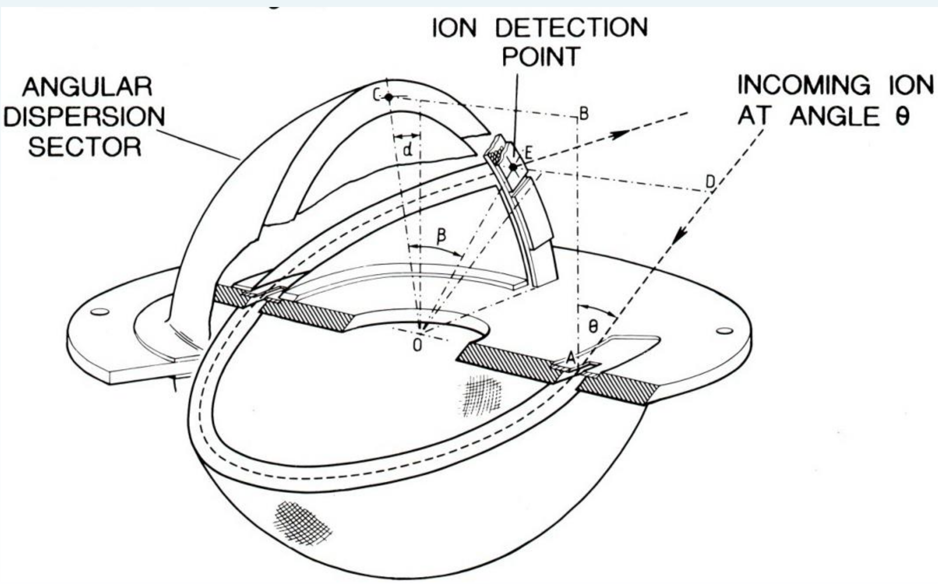
Electrostatic Analysers

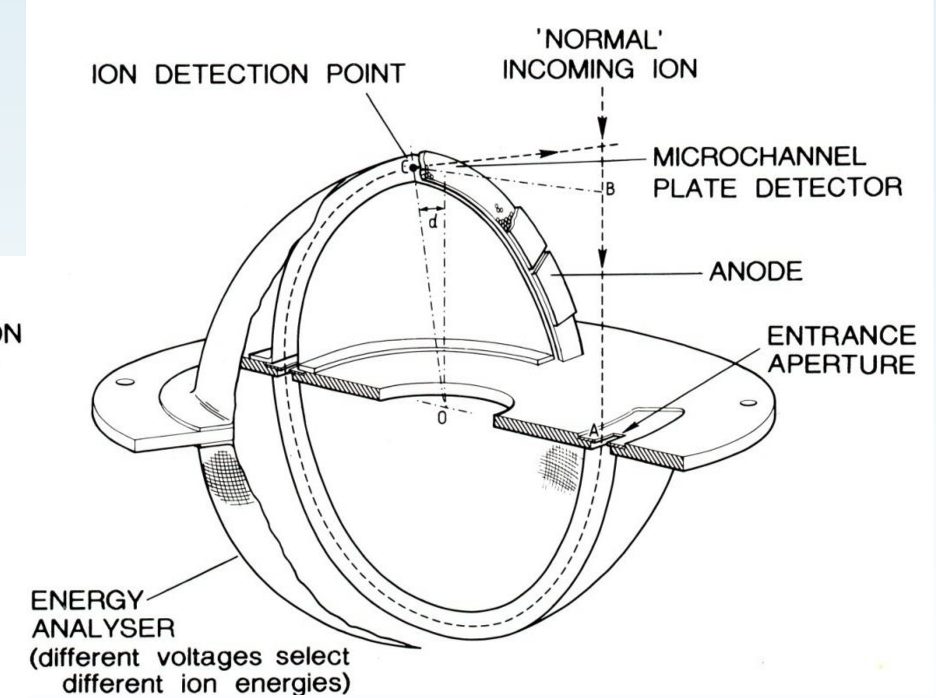
- Integrating
  - RPA
- Differential
  - Planar
  - Spherical

- Quadrispheric
- Hemispheric
- Tri-quadrispheric



Giotto Fast Ion Sensor: Tri-quadrispheric

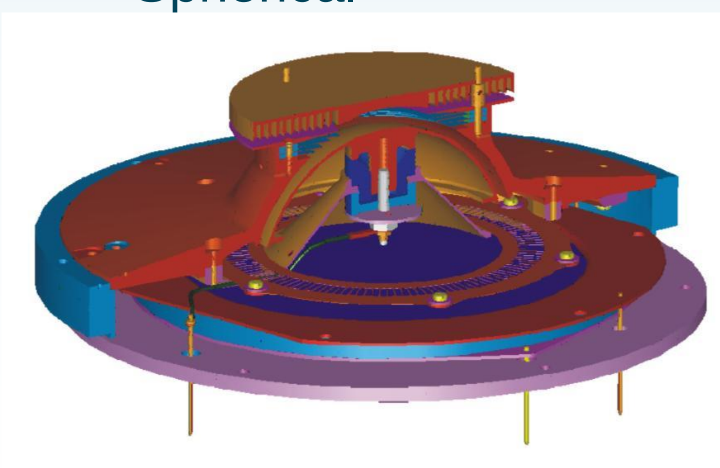


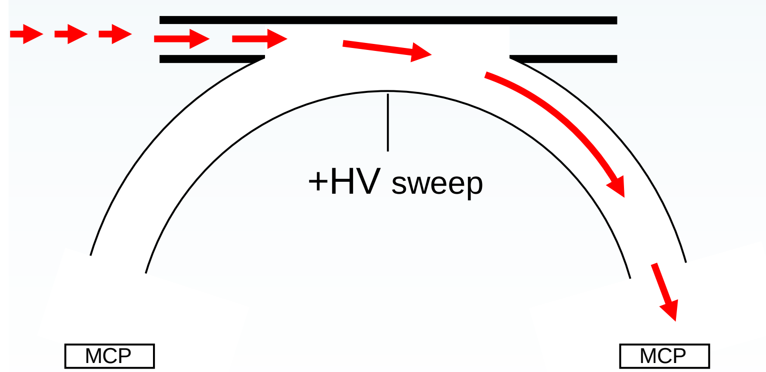


Electrostatic Analysers

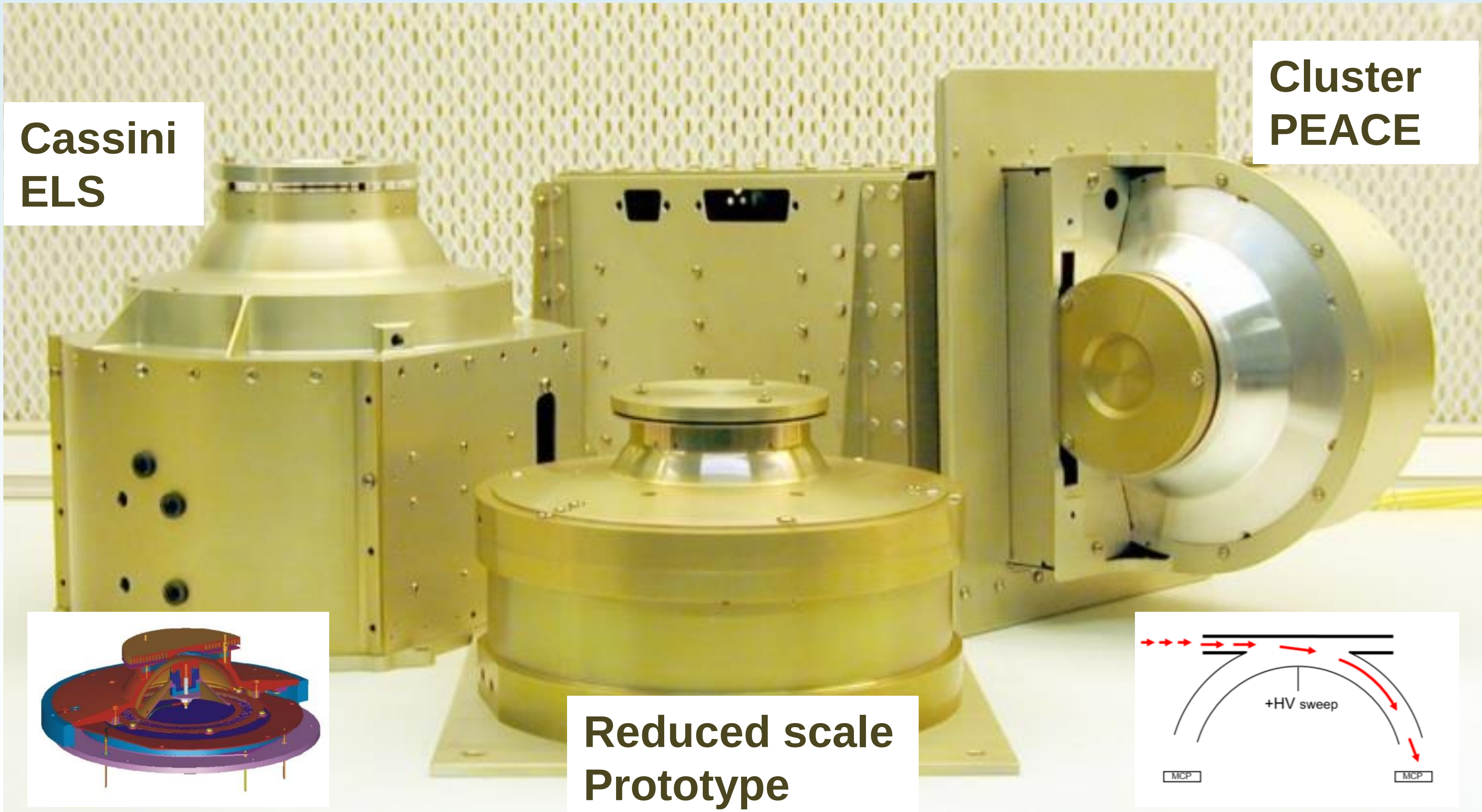
- Integrating
  - RPA
- Differential
  - Planar
  - Spherical

- Quadrispheric
- Hemispheric
- Tri-quadrispheric
- Top hat or Symmetric quadrispheric
  - Visit in detail in next section





Top hats: Symmetric quadri-spheric



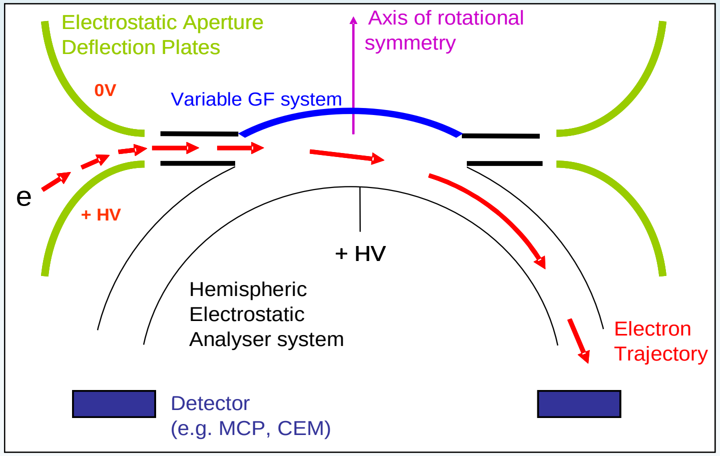
Electrostatic Analysers

- Integrating
  - RPA
- Differential
  - Planar
  - Spherical (k-factor)
  - Cylindrical, toroid

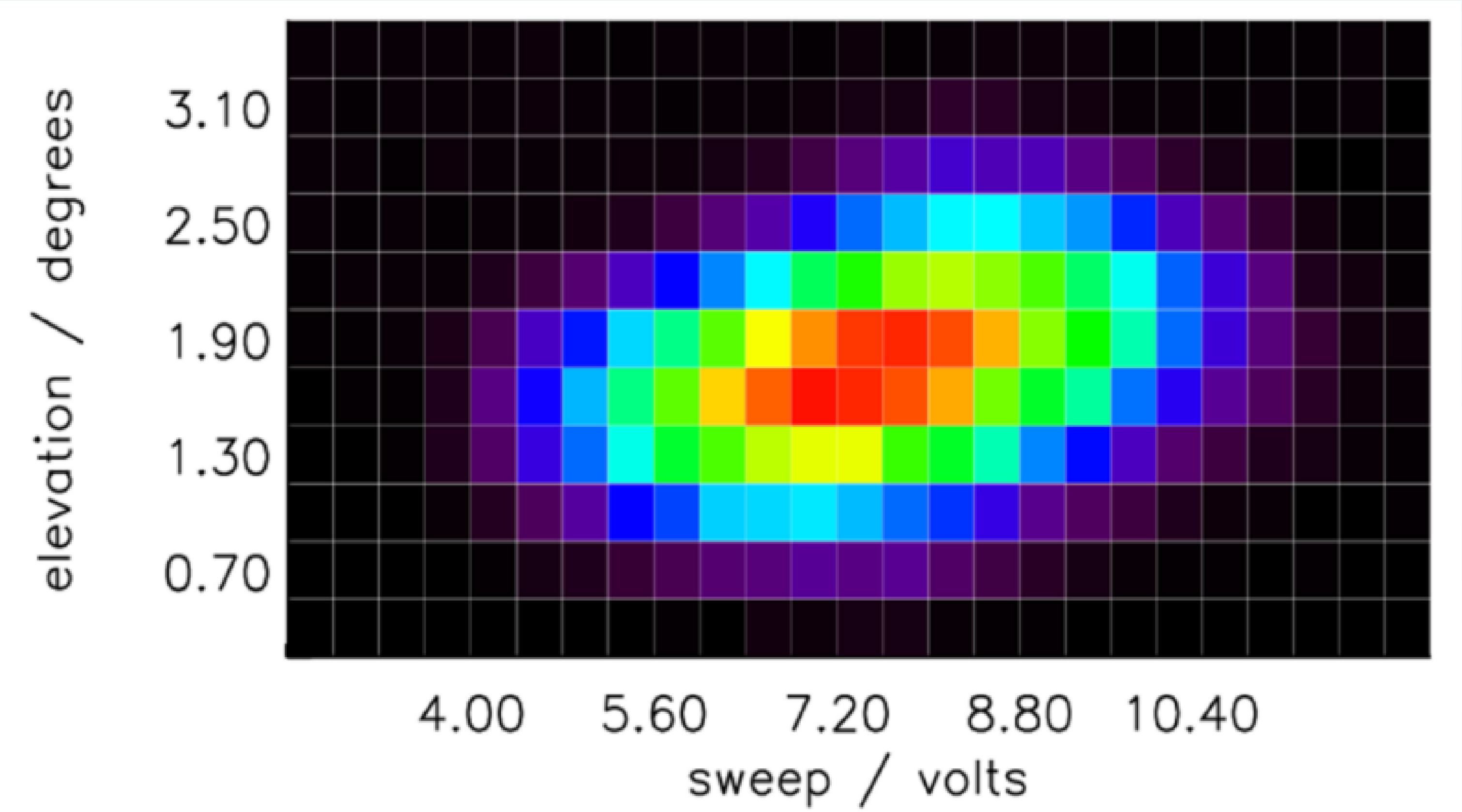
- Cylindrical: e.g. INMS on QB50, discussed later
- Toroid: e.g. TIMAS instrument on the Polar satellite discussed later

Electrostatic Analysers

- Acquiring an energy distribution
  - Voltages stepped to cover the desired range
    - E.g., k-factor 10
  - Data acquired by the detector for desired time period at each step
    - Sampling statistics vs temporal resolution
    - Spacecraft motion: temporal and spatial resolution



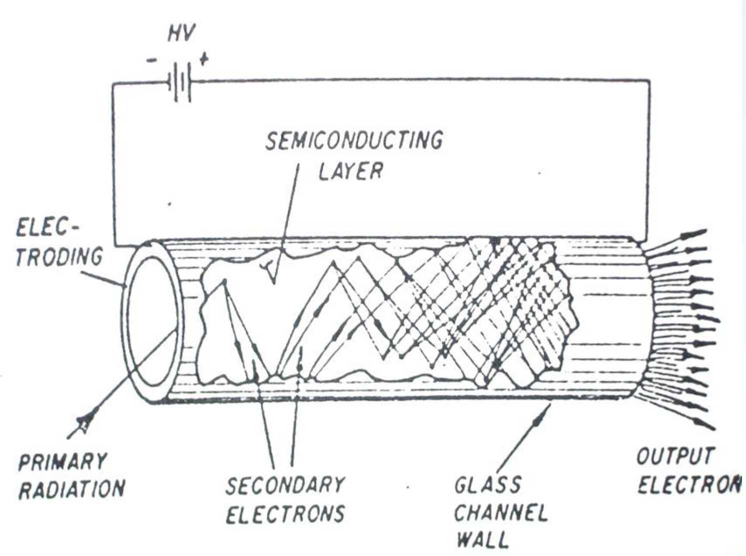
Electrostatic Analysers



Ground Calibration Performance

Micro-Channel Plates

- Micro-Channel Plates (MCPs) and Channel Electron Multipliers (CEM)

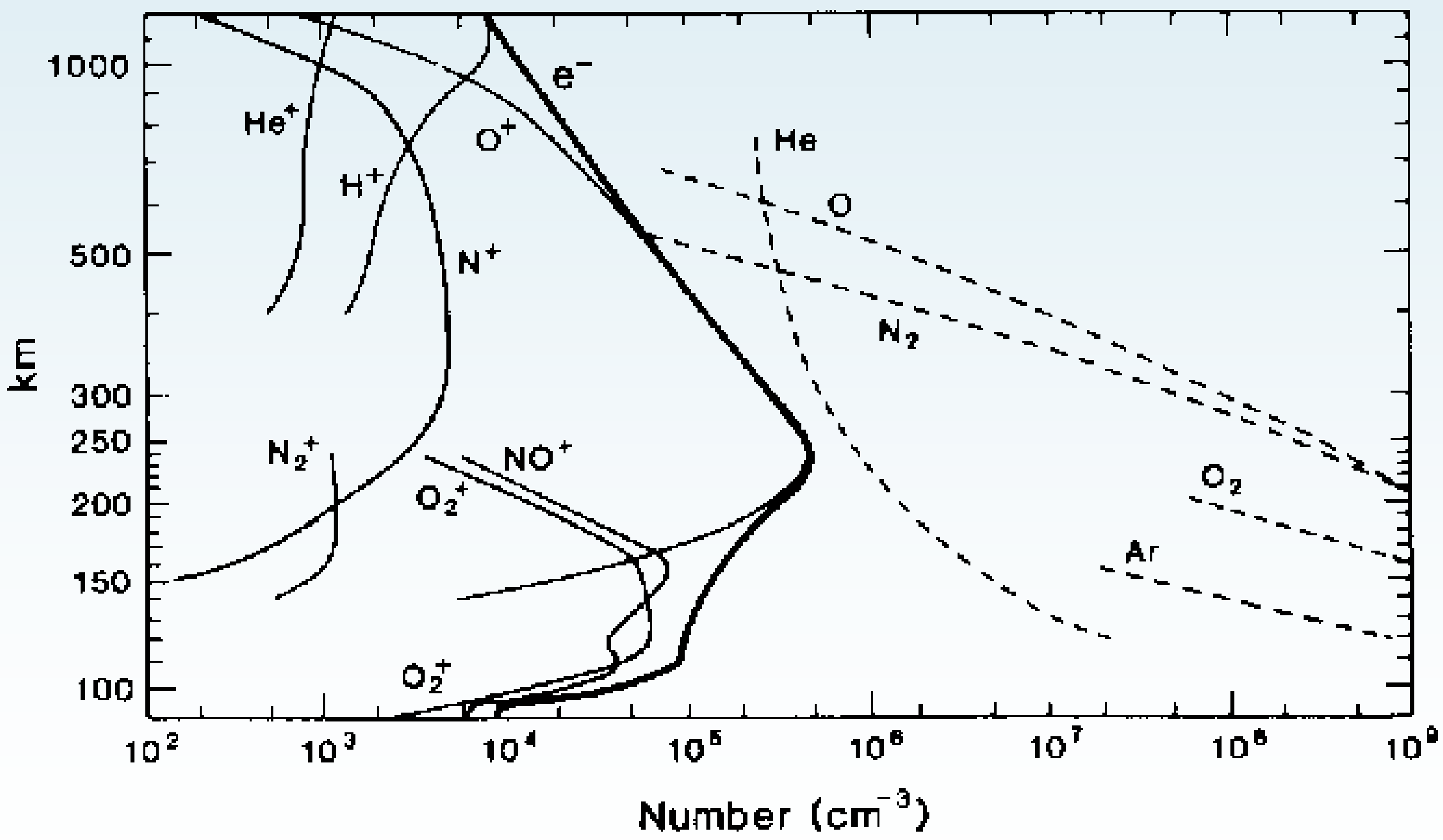


- Typical CEM gain
  - $10^6 - 10^8$ e
  - Independent of incident energy
- Signal read out by a charge sensitive preamplifier and leading edge discriminator
- Counts acquired for fixed acquisition time

In-situ Plasma Measurements

- Design an In-situ Instrument
  - Requirement Definition, Geometries and Fields
- In-situ Measurement Techniques
  - What and How with Examples
- Instrument Sub-systems: Brief Introduction
  - Plasma Detectors, Electronics
- Instrument Acceptance Parameters
  - Extracting the answers

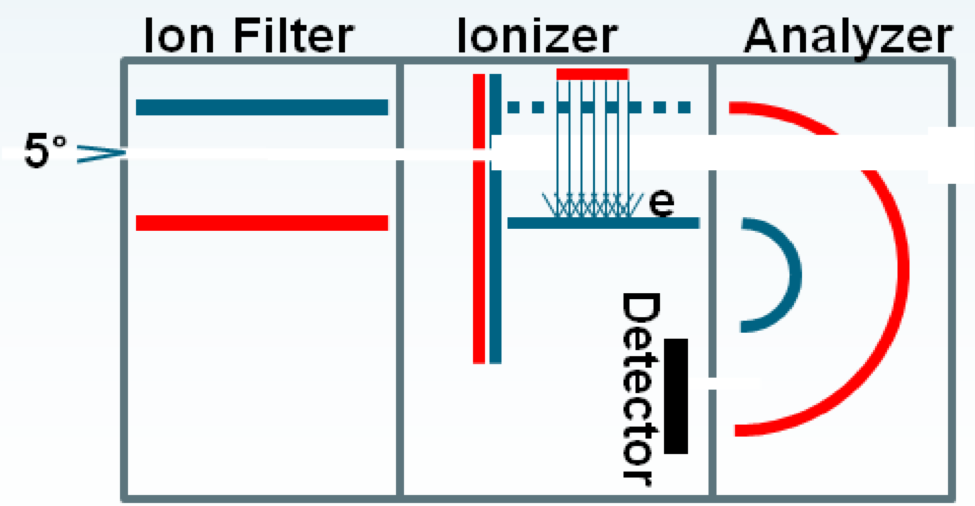
Near-Earth environment

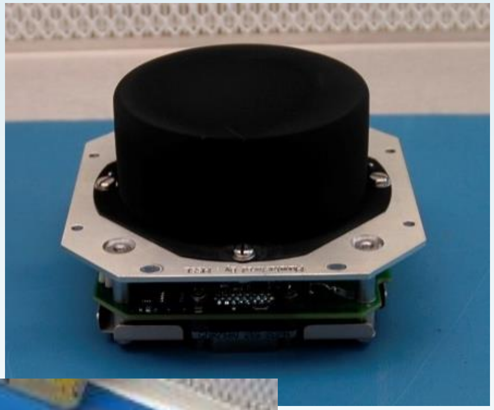


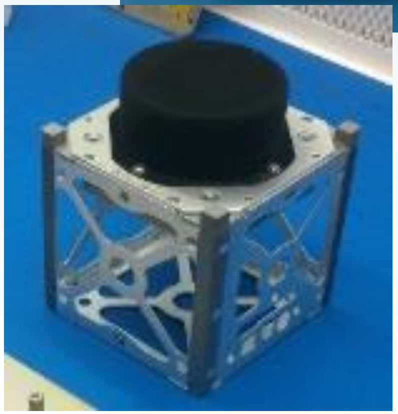
- Near Earth
- No Angular information

QB50 INMS: Cylindrical Analyser

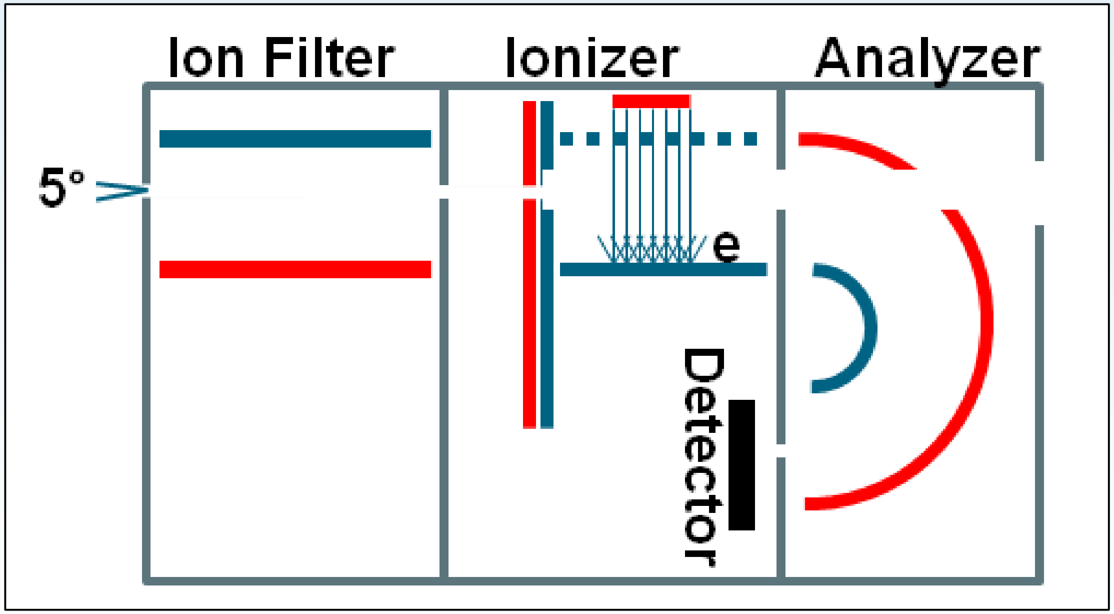
- Ion and Neutral Mass Spectrometer
- Measure density of dominant species
  - O, O_2, N_2, NO
- Spacecraft ram velocity for mass identification
- Cylindrical electrostatic analyser





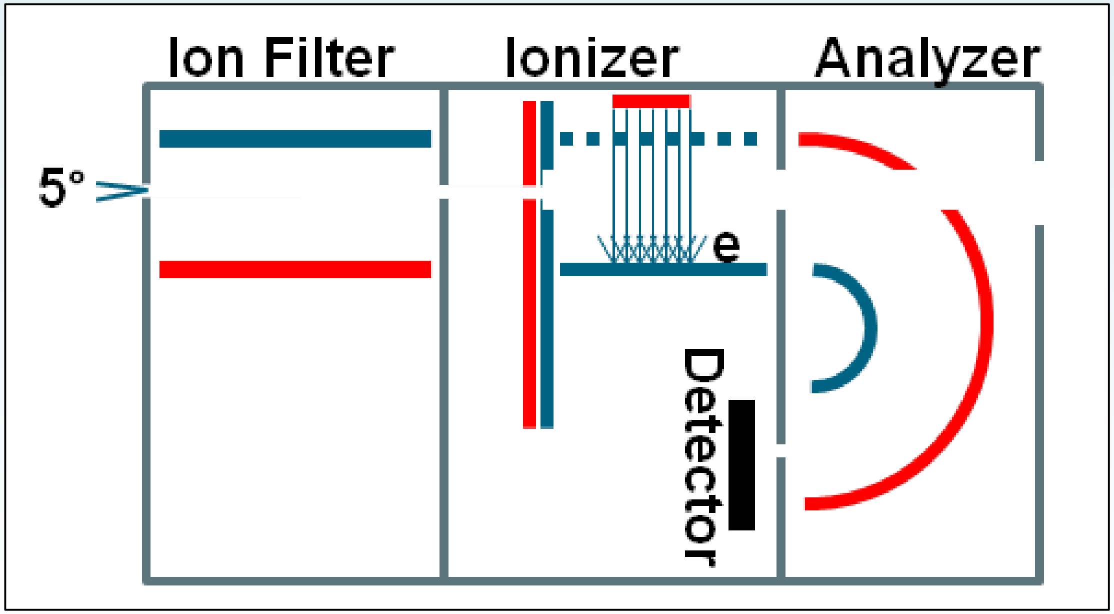


QB50 INMS: Cylindrical Analyser



- Ions and neutral particles pass through the aperture
- Ion mode: Ion Filter and Ionizer off
- Neutral mode: Ion Filter and Ionizer on
- Analyser selects energy
- Detector counts number of arriving particles

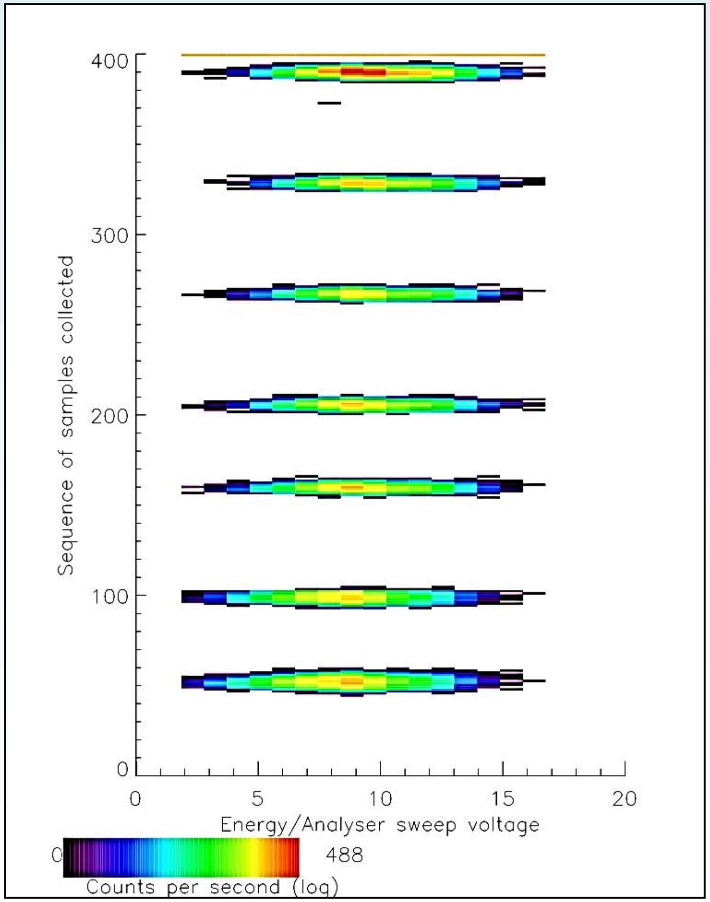
QB50 INMS: Cylindrical Analyser

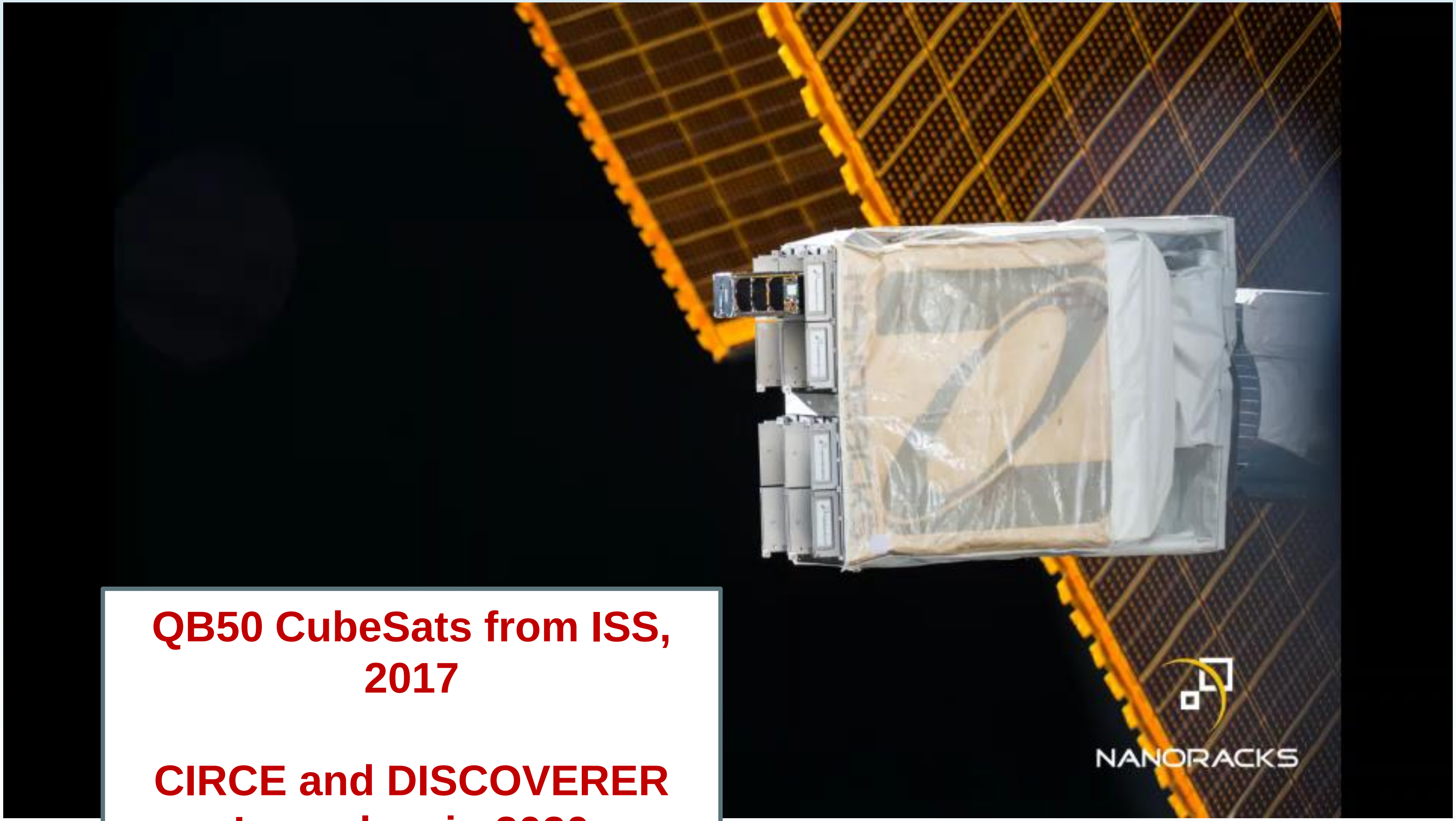


- Mass identification
  - $E = 0.5mv^2$
  - Energy from Analyser
  - Velocity from orbital dynamics
  - Energy resolution is critical – discussed in next lecture
  - Why can't this technique be used all the time for mass identification?

Data from Phoenix (Taiwan)

- Satellite in Y-Thomson spin
  - Particles enter aperture when instrument faces spacecraft ram direction measured only
- Data from 16th January 2018
  - Instrument set for O+
  - X-axis – Voltage (Energy)
  - Y-axis - Time

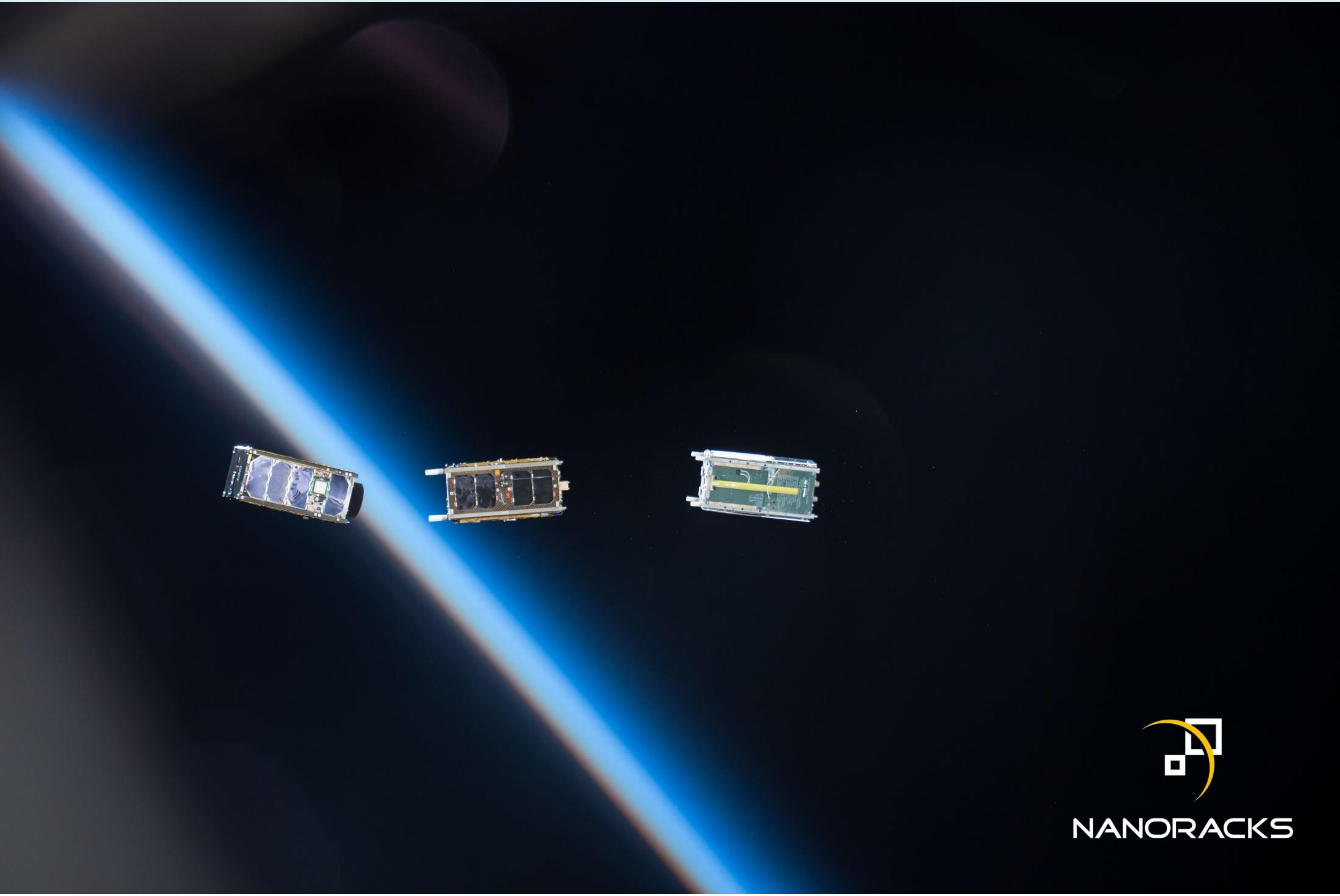




QB50 CubeSats from ISS, 2017

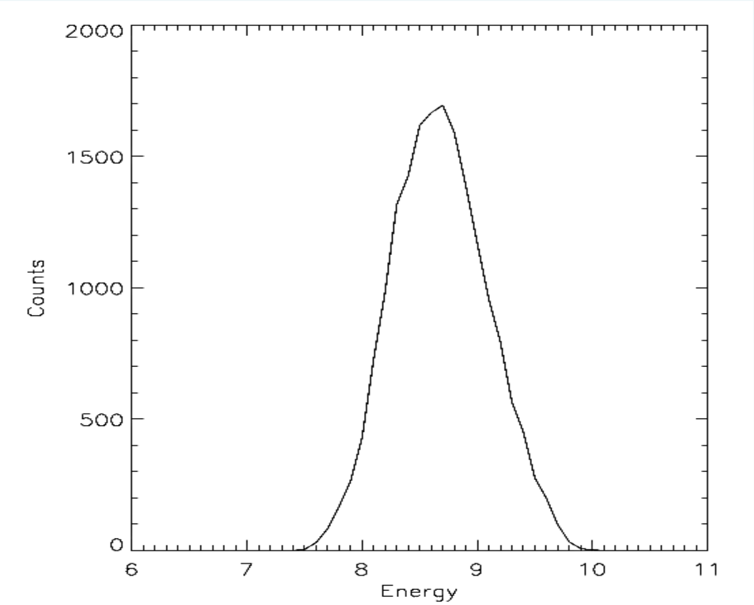
CIRCE and DISCOVERER Launches in 2020

UCL



Velocity measurement

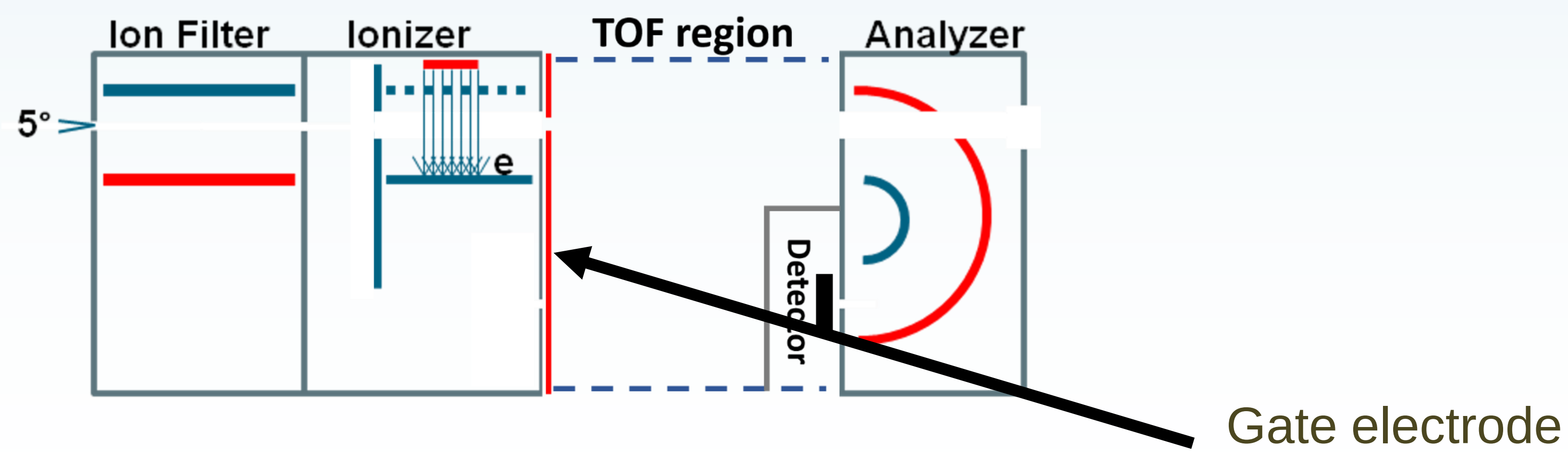
- AtOx in LEO ~ 5eV, due to spacecraft ram velocity
- 40 m/s ⇔ 0.05 eV dK_e for AtOx in LEO
- Instrument energy resolution 10%
  - FWHM ≈ 0.5 eV
- Required resolution <1%
- Measure velocity instead
  - Time-of-flight technique



Time-of-flight

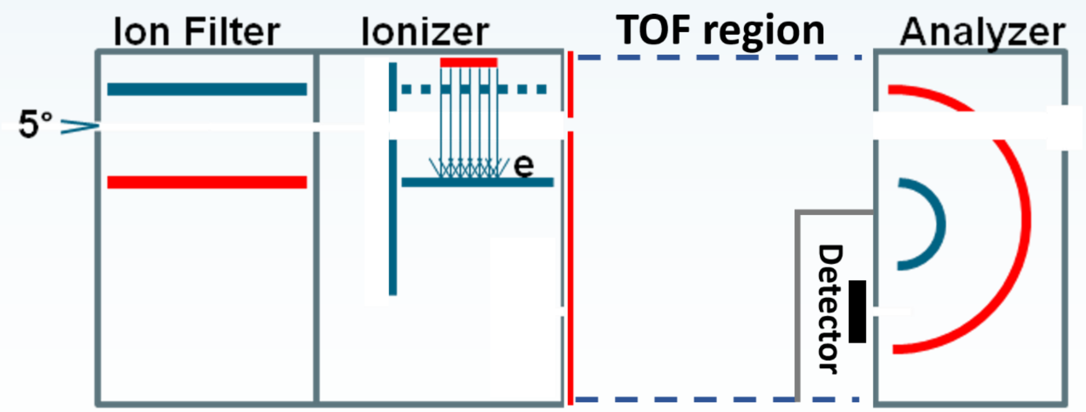
- Electrostatic gating technique
  - Incoming AtOx +ve ion ~5 eV
  - Positive 10V on gate electrode
  - 0V “window” opened for m x 12.5ns
  - Build histogram for n x 200 ns

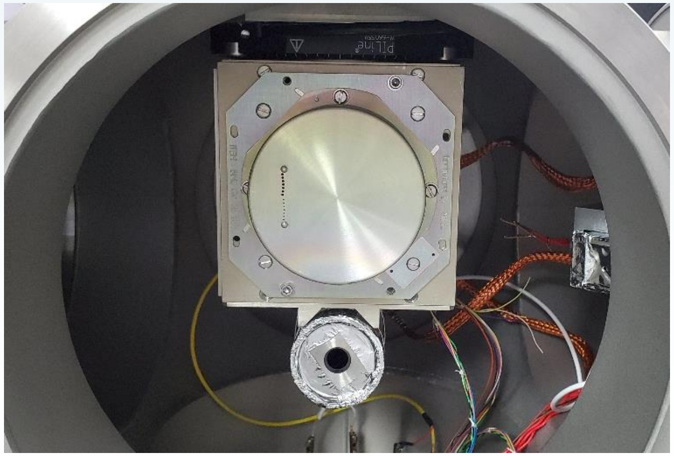
Energy	36 mm TOF (ns)	dt (ns)
3.5	5557.29	
5	4649.56	907.72
8	3675.80	973.76
4.4	4956.45	306.88
5.6	4393.42	256.13



DISCOVERER

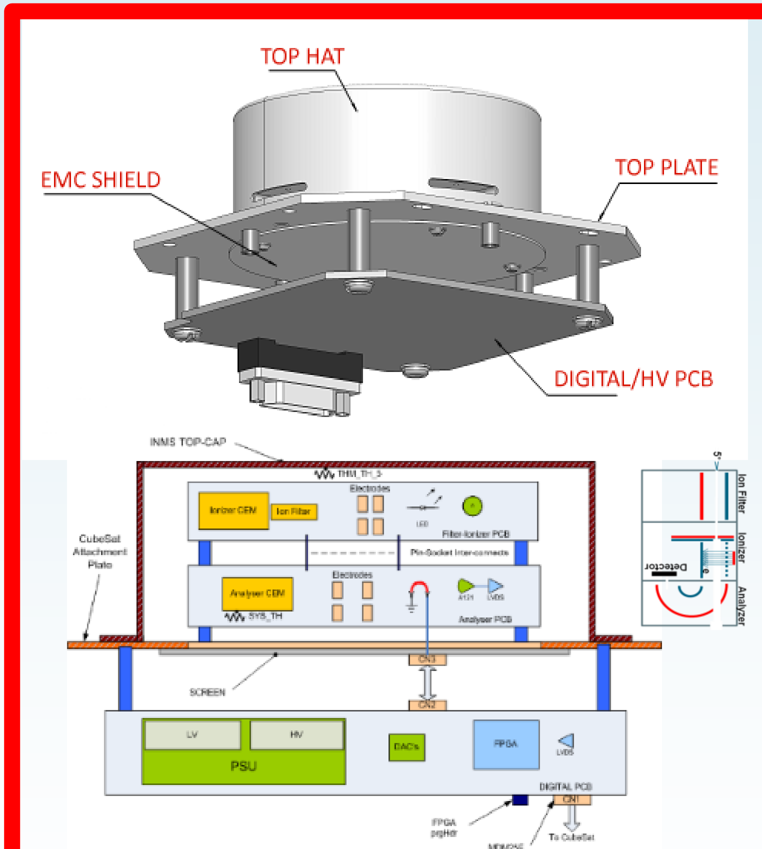
- INMS for SOAR
  - Satellite for Orbital Aerodynamics Research
  - Time-of-flight
  - In-flight velocity measurement
    - Needs high resolution position knowledge



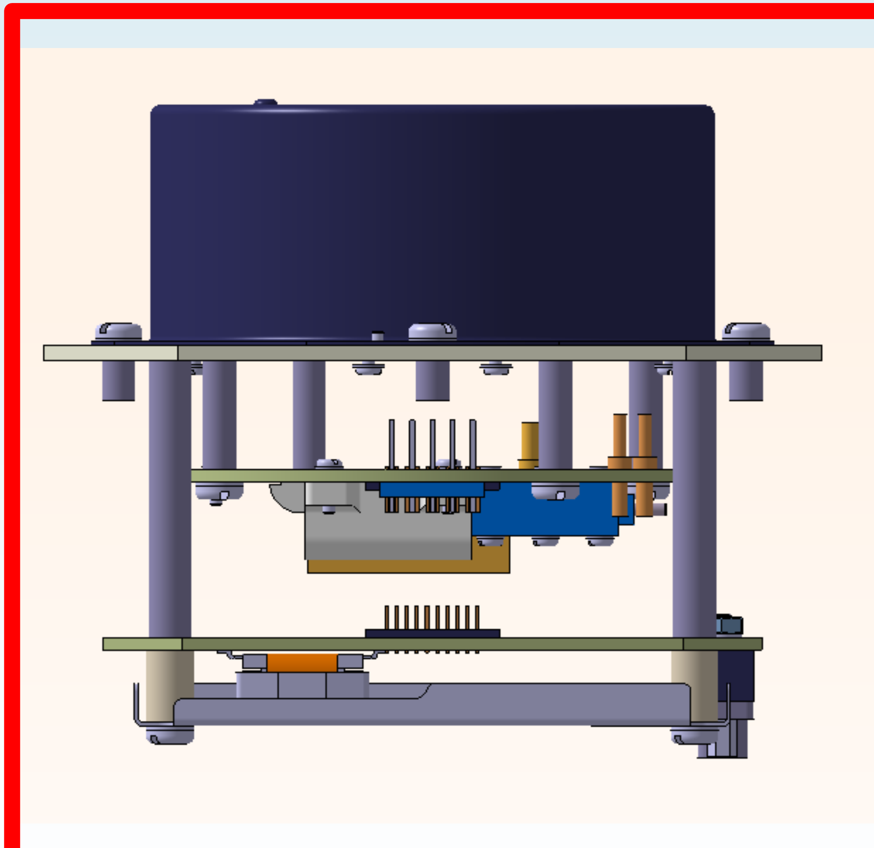


DISCOVERER – ROAR and SOAR units

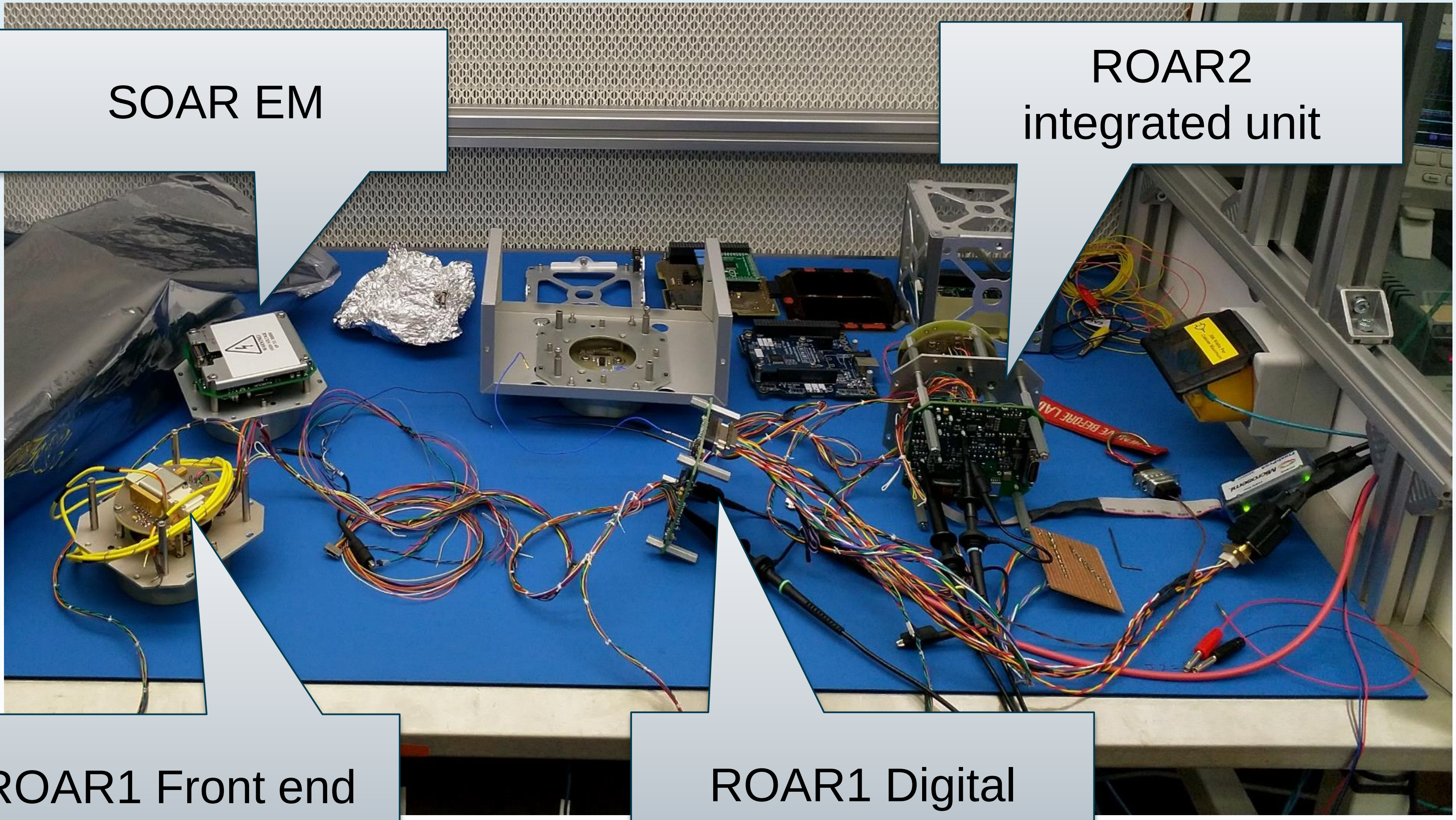
QB50 design



DISCOVERER design

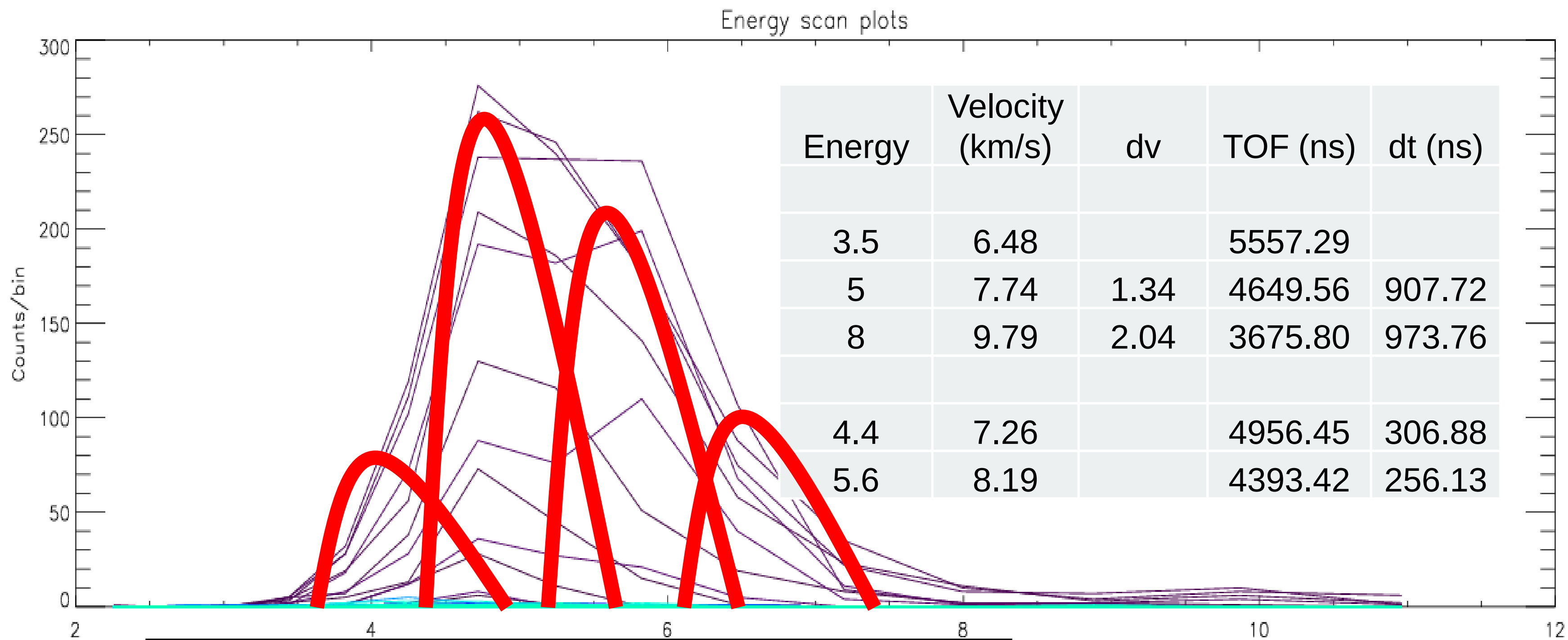


Flow Characterisation Hardware

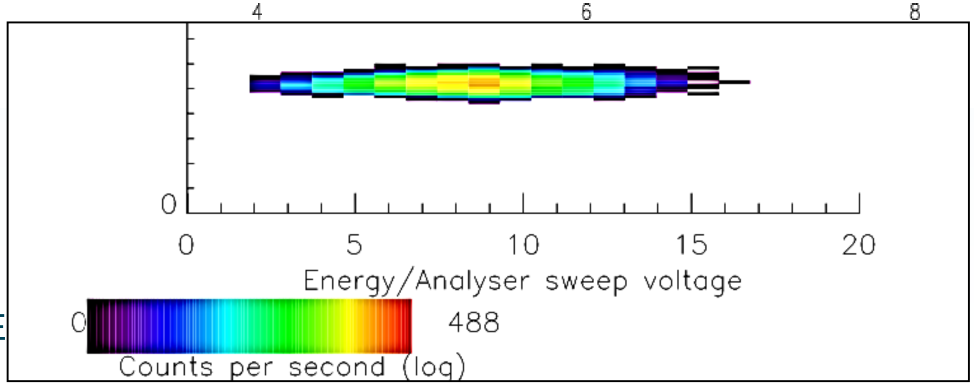


Time-of-flight and in-flight data

Typical in-flight energy spectrum from QB50 INMS



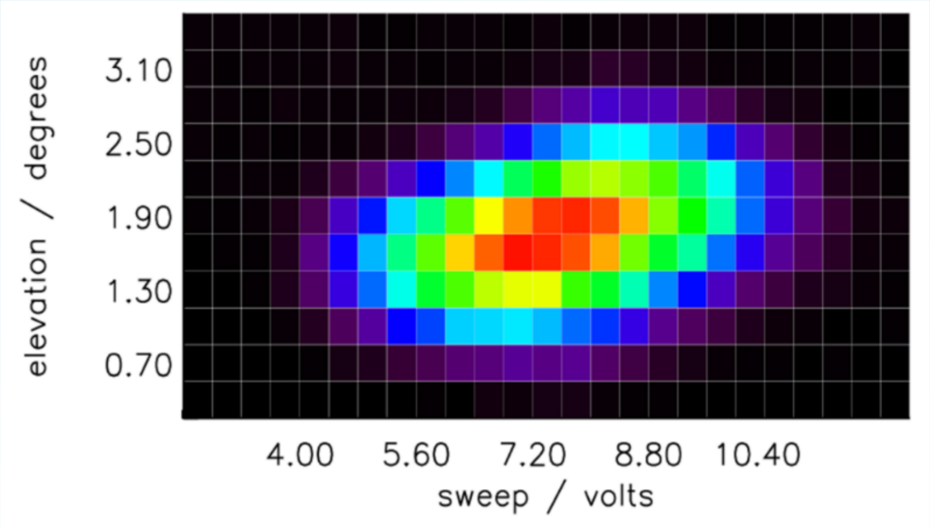
Energy	Velocity (km/s)	dv	TOF (ns)	dt (ns)
3.5	6.48		5557.29	
5	7.74	1.34	4649.56	907.72
8	9.79	2.04	3675.80	973.76
4.4	7.26		4956.45	306.88
5.6	8.19		4393.42	256.13



DISCOVE

Sources of errors

- Spacecraft pointing knowledge
- Instrument resolutions
- Width of gating window
  - 12.5 ns ⇔ ~20 m/s
  - DISCOVERER measurement goal - 250 m/s
- Detection efficiency
- Ionization efficiency



Somewhere in the TOF/Energy spectrogram is plasma temperature and velocity

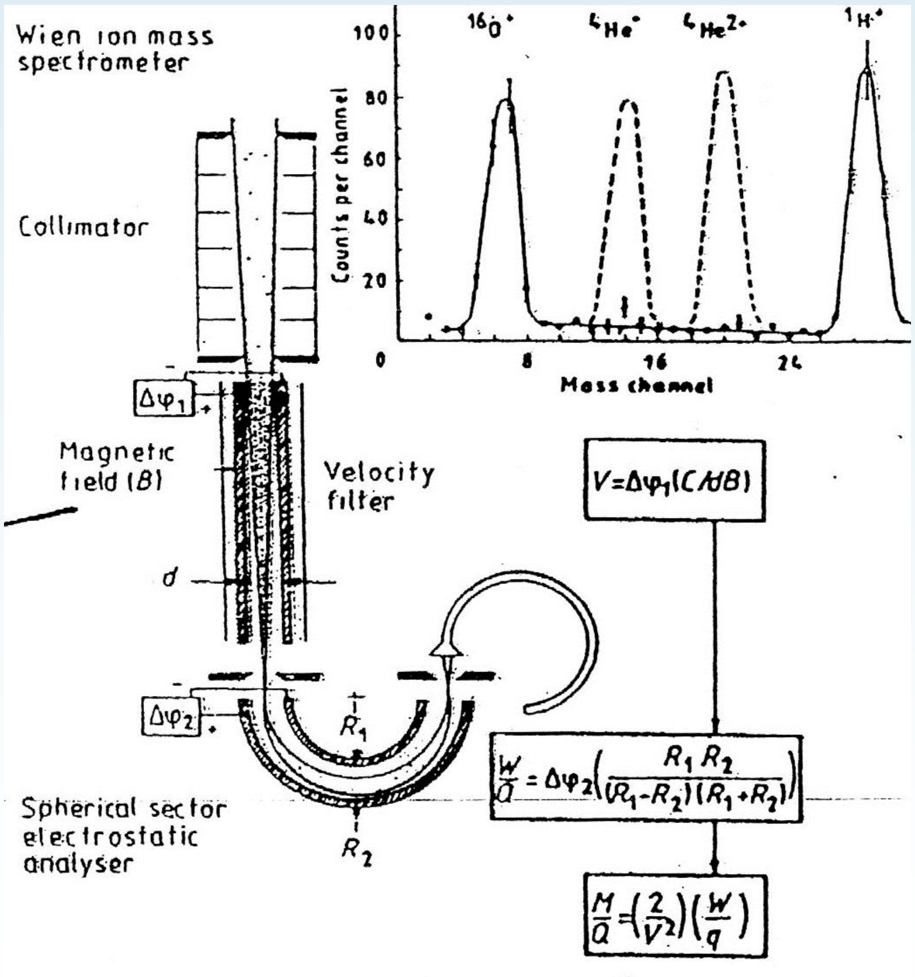
In-situ instrumentation

- $E = \frac{1}{2}mv^2$
- Analysers:
  - Electrostatic: energy, angle (Θ,Φ)
- Sufficient for electron and some ion measurements
- Driven by mission science
- For ions, may need species identification
  - Usually done by measuring velocity v

In-situ instrumentation

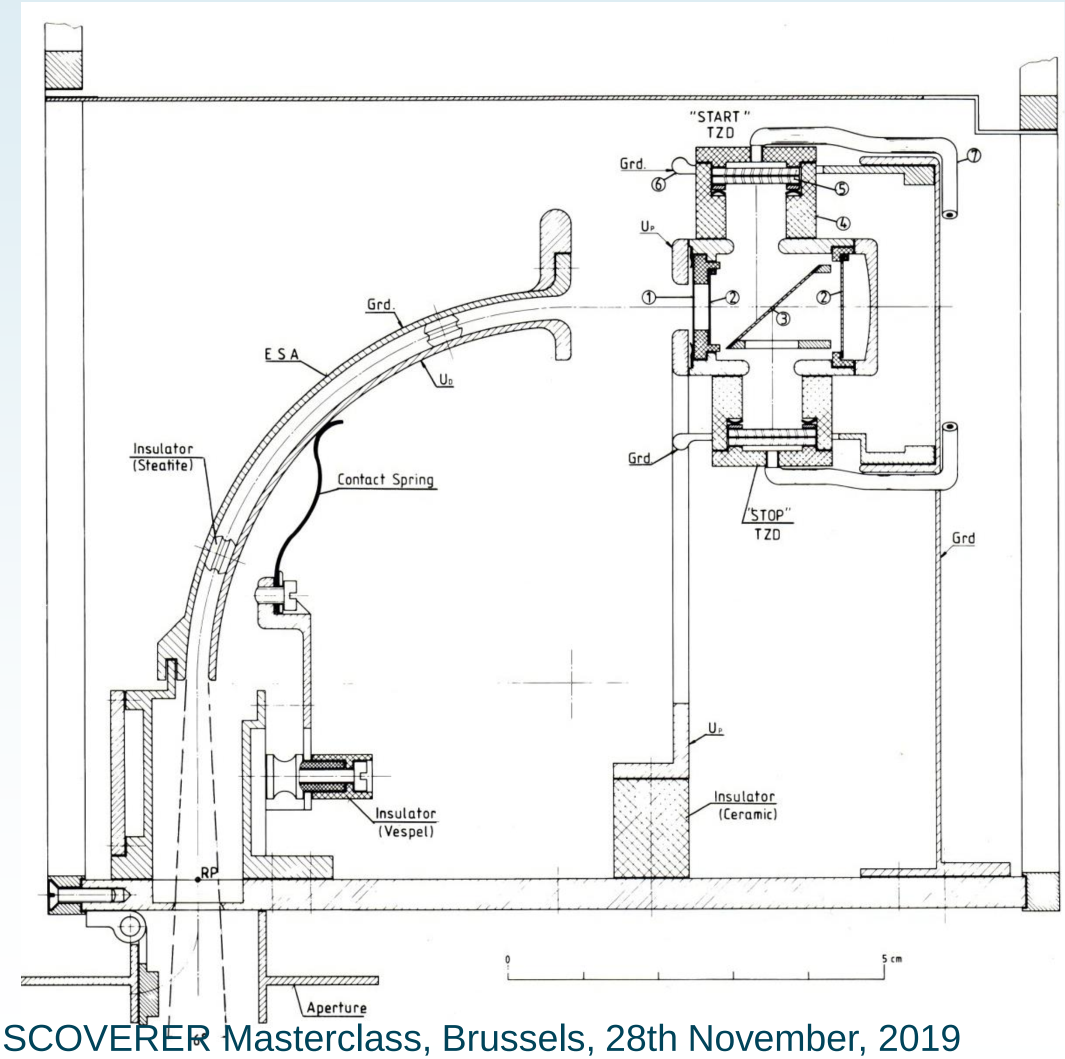
- Techniques for species identification
  - Energy analysis followed by
    - Velocity selection
    - Mass selection
    - Time of flight – velocity measurement
- Former two use magnetic field
  - $\vec{E}$ x $\vec{B}$ – Wien filter
  - $\vec{E}$ // $\vec{B}$
  - $\vec{E}$ followed by $\vec{B}$

Species identification - ExB



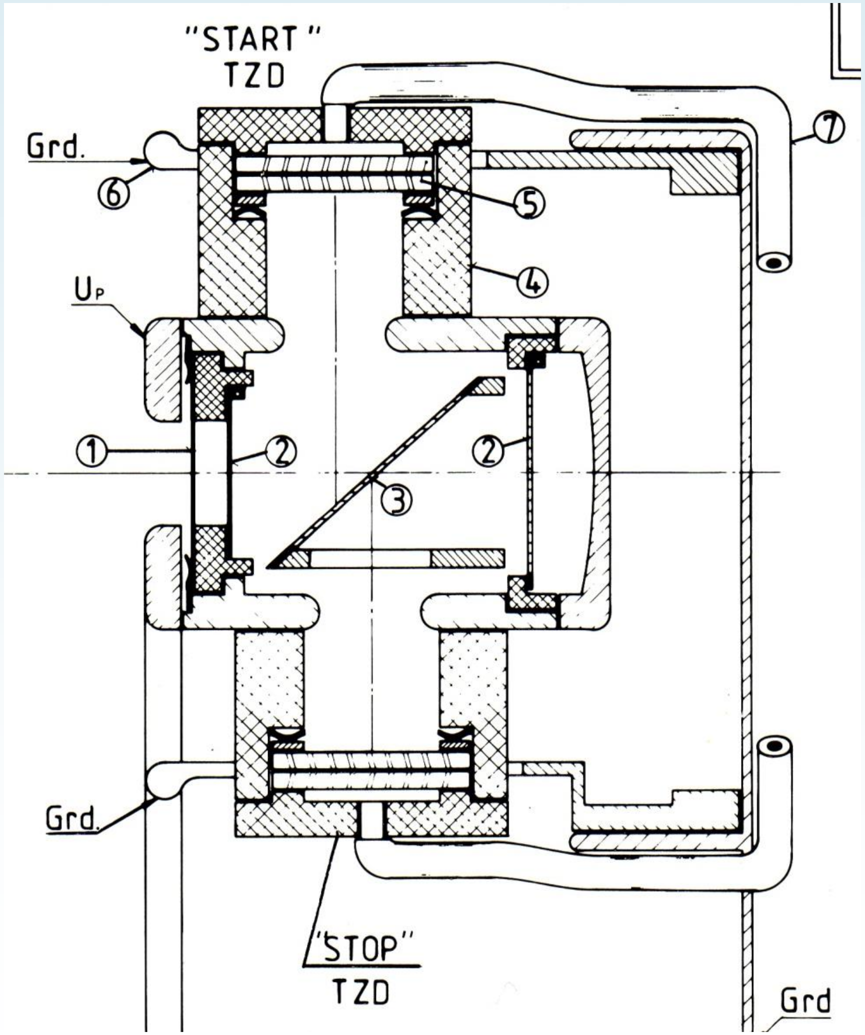
- Velocity selection using a Wien filter.
- $\vec{E}$ x $\vec{B}$ field
  - q$\vec{E}$ – Electric field
  - q (v x $\vec{B}$) – magnetic field
  - If q$\vec{E}$ = q(v x $\vec{B}$) or v = $\vec{E}$/$\vec{B}$
    - Forces are balanced
    - Particle trajectory unaffected
- Permanent magnet
  - $\vec{B}$ is known
- v proportional to $\vec{E}$ or applied voltage
- Wein filter followed by energy analyser to achieve m/q identification

Species identification - TOF



- Time-of-flight (TOF)
- e.g., Giotto Implanted Ion Sensor
- Electrostatic analyser -Energy
- TOF - velocity

Giotto Implanted Ion Sensor

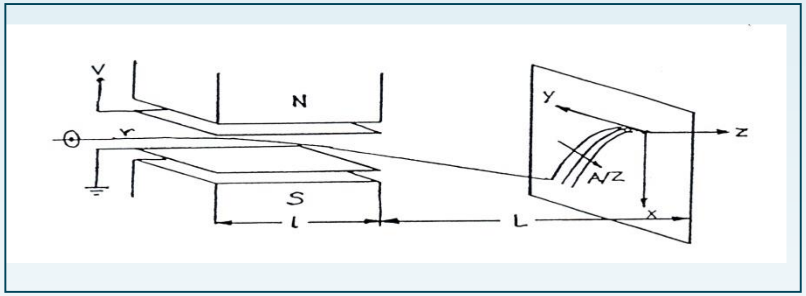


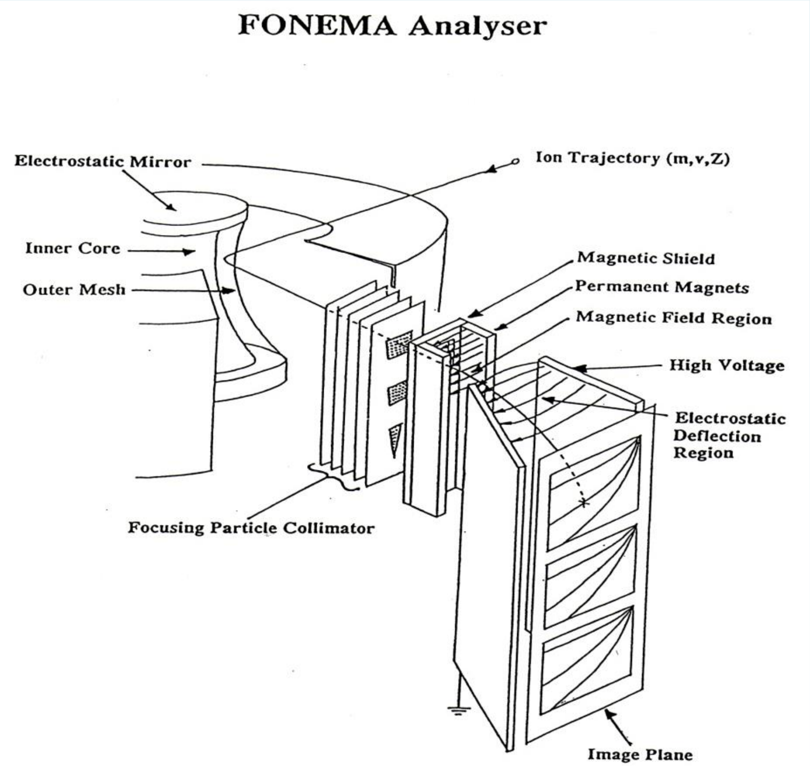
TOF section

- Time of flight technique
  - Record the time a particle takes to "fly" through a known length
  - Passage of particle through a material emits electrons
    - Carbon foils
    - Silicon detectors
  - Two detectors provide fast signals to start and stop a time-to-amplitude converter
  - Charge a capacitor or start and stop a counter

Species Identification – E//B

e.g., Mars 96 mission

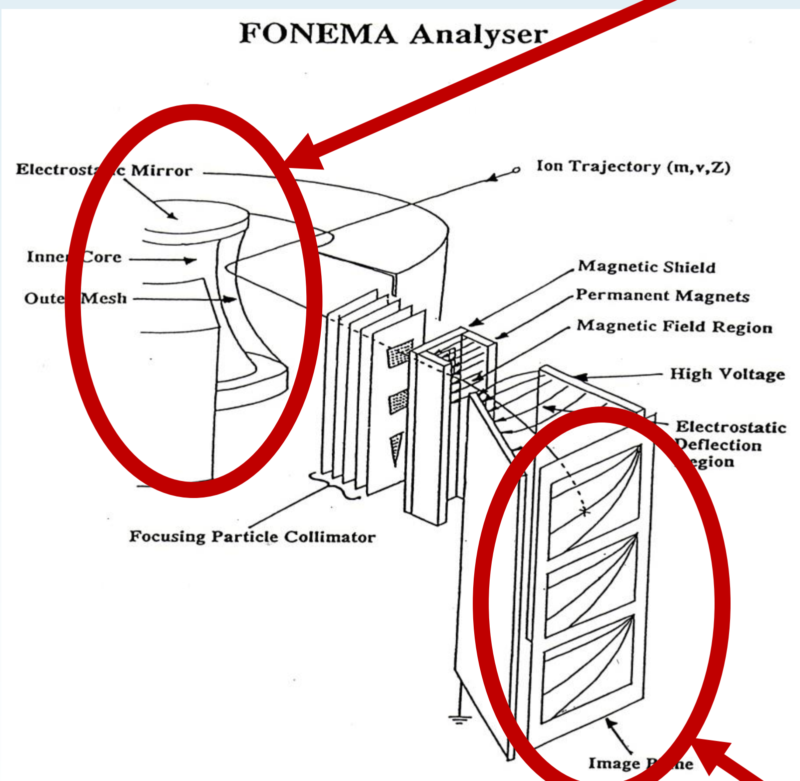


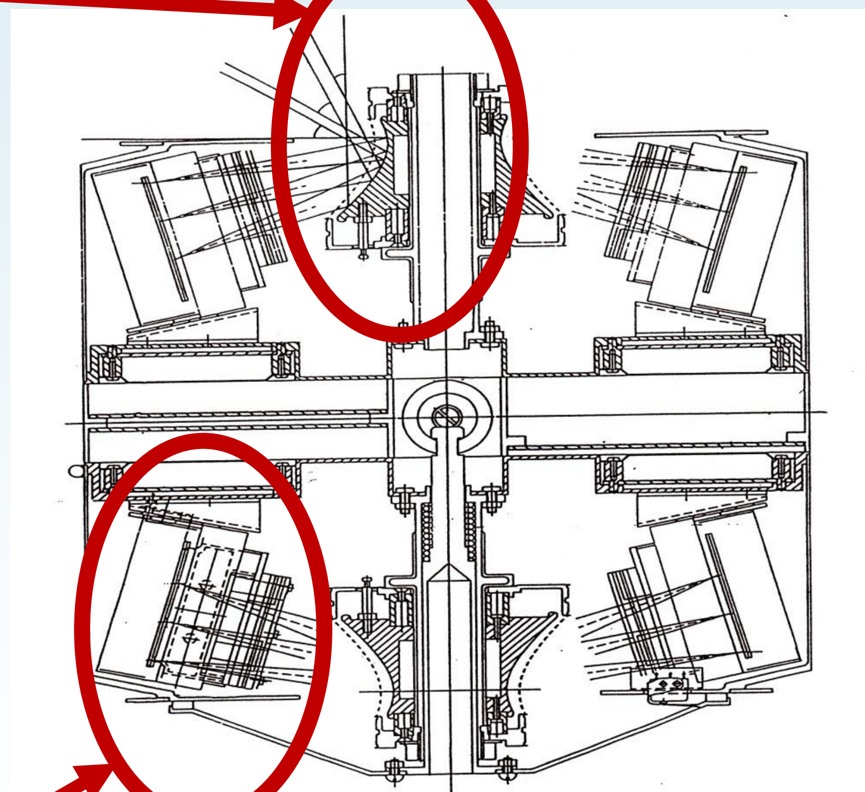


- Thompson parabolas
- Each curve is energy dispersion of a different mass/q

FONEMA instrument

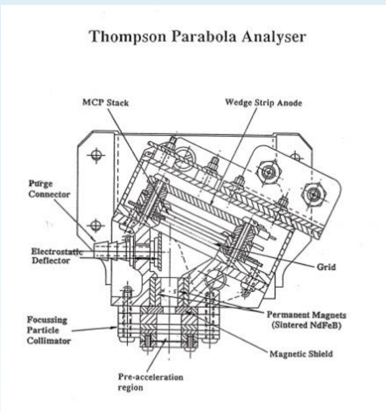
Hyperbolic electrostatic mirror
for increased angular coverage

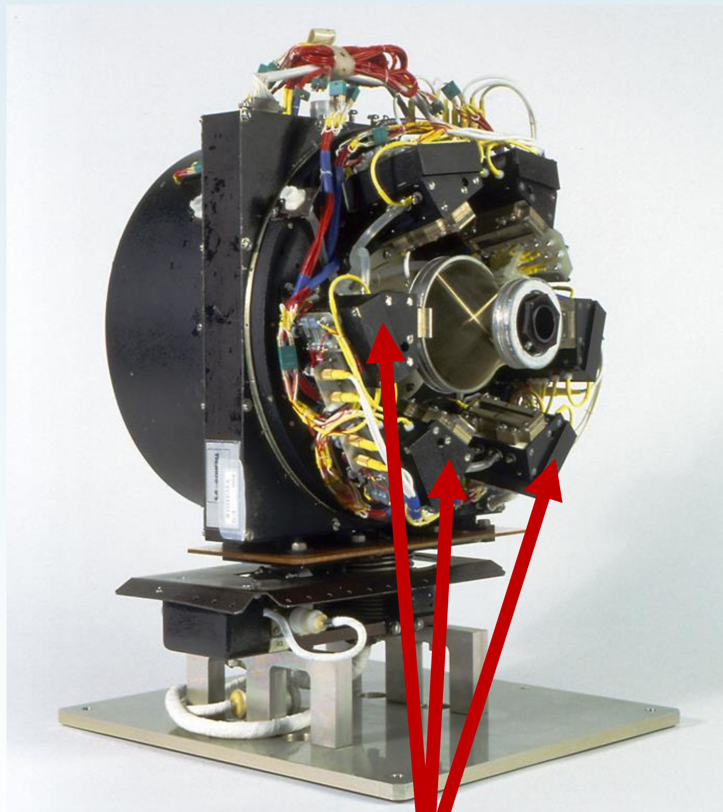


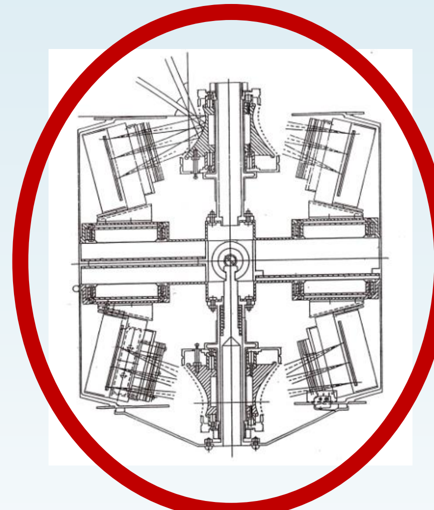


Position sensitive detector
at image plane

FONEMA



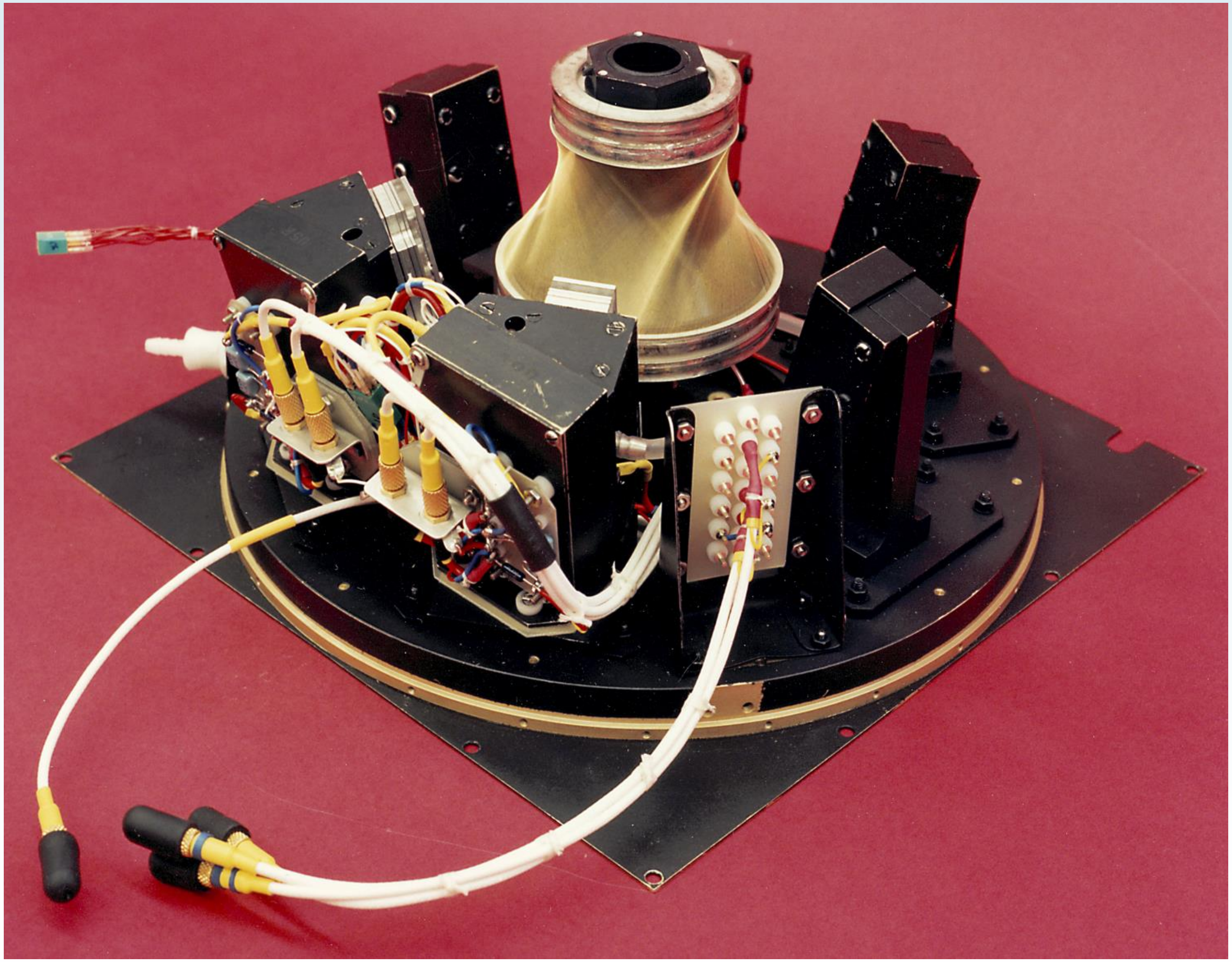




Back-to-back mirrors and focal plane detectors to sample large fraction of 4π

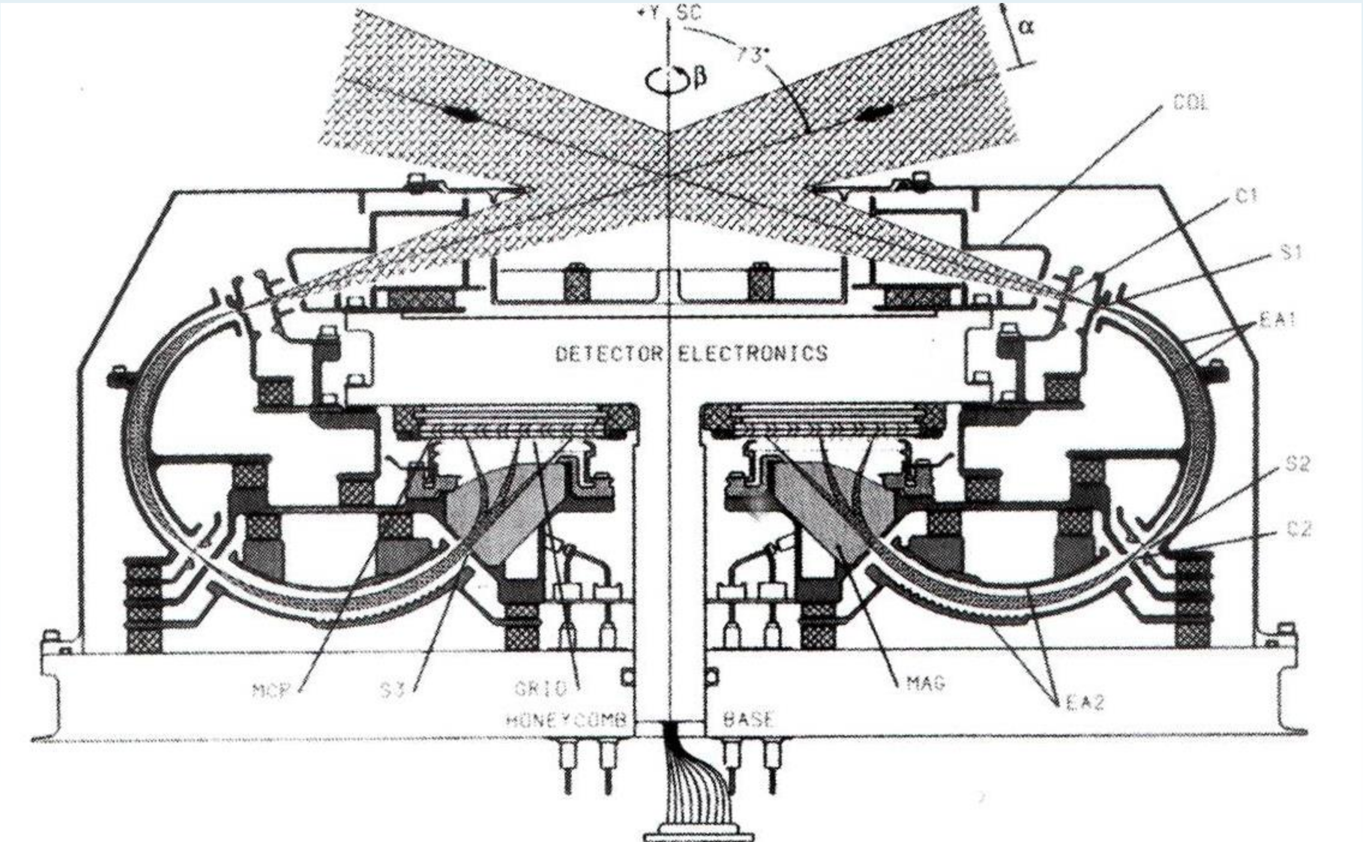
Six position sensitive detectors around the “focal image plane”

FONEMA

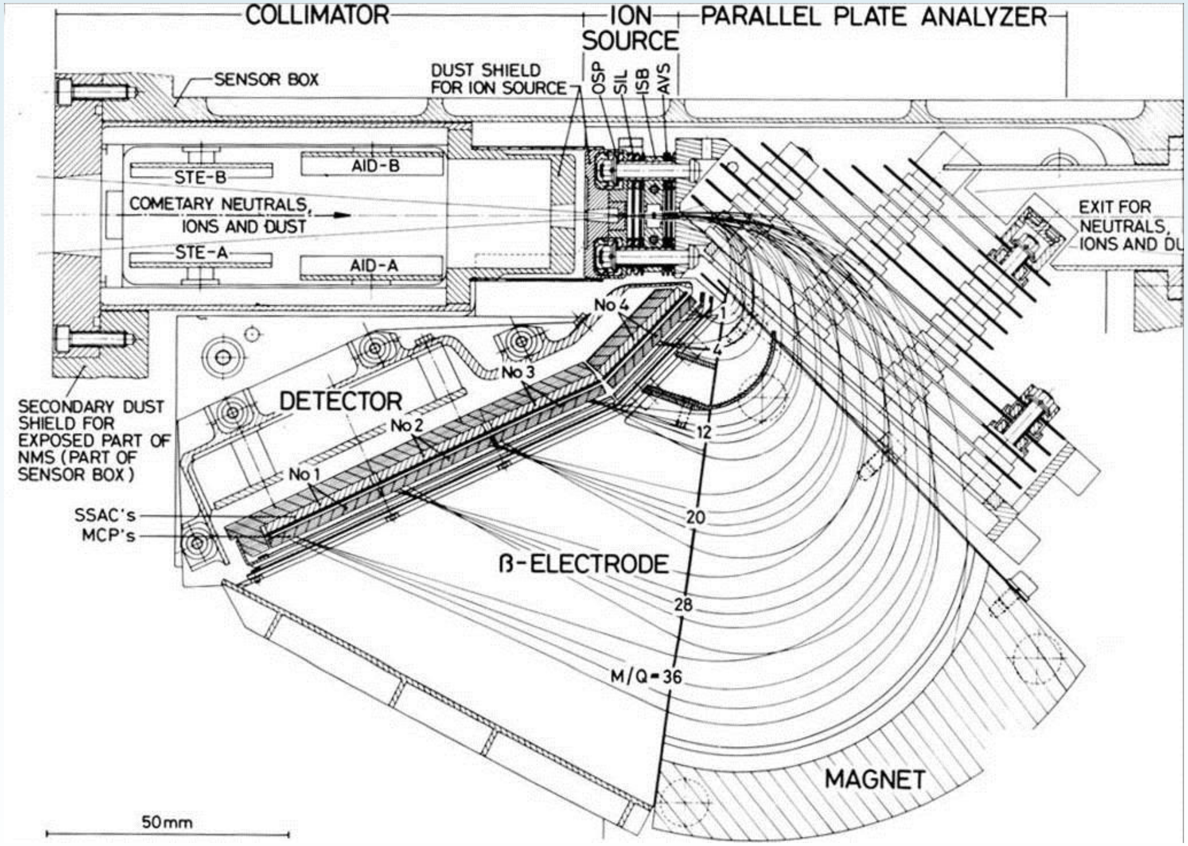


TIMAS

- Toroidal Imaging Mass-Angle Spectrograph
- POLAR mission

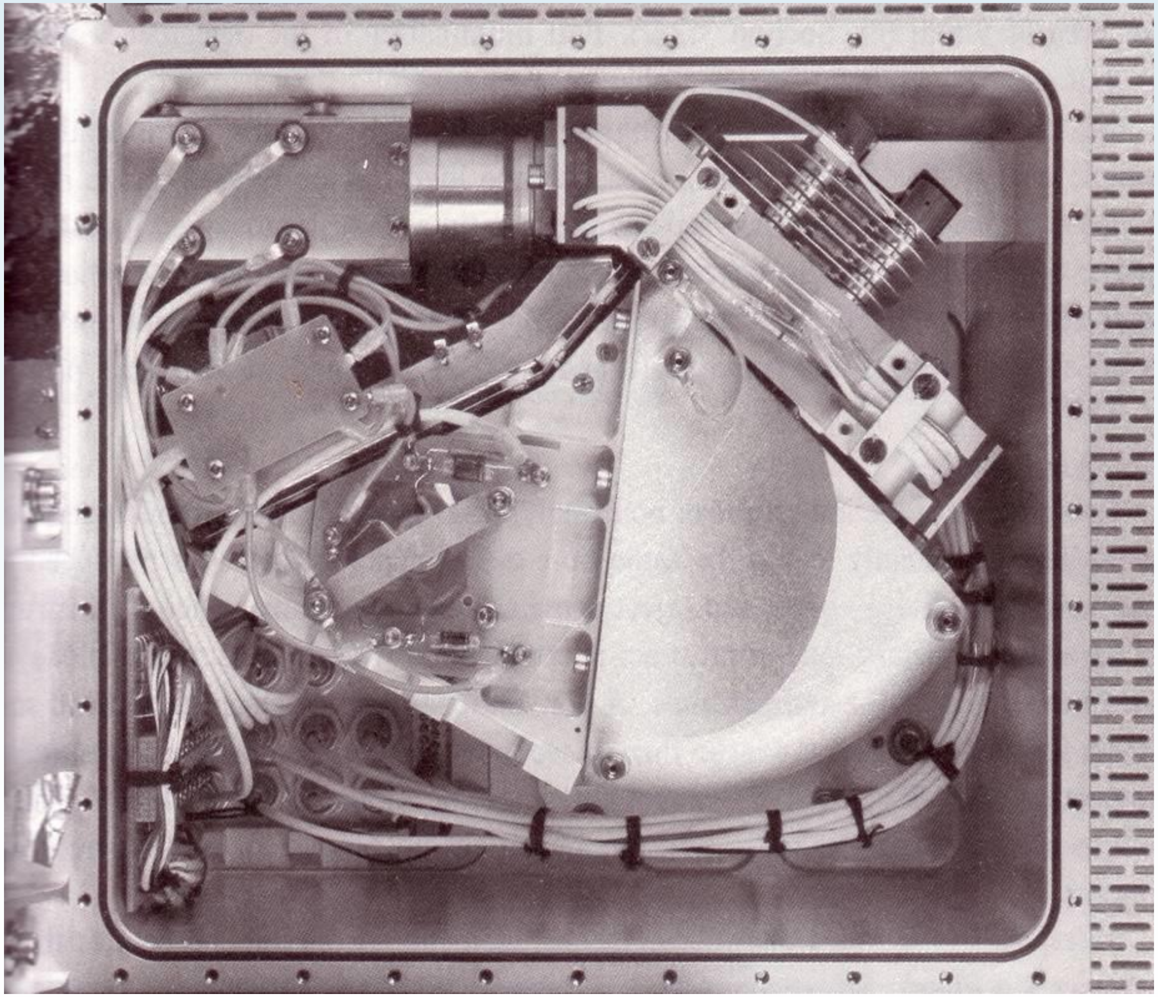


Neutral particles



- Giotto NMS
- Describe the different components

Neutral particles



Recapitulate

- In-situ instrumentation
  - Analysers
    - Electrostatic
    - Species identification
      - TOF – velocity measurement
      - Velocity selection
      - Mass selection
    - Magnetic
    - Combinations
  - Neutral Particle instrument

Recapitulate

- In-situ instrumentation
  - Principle of operation
    - Energy analysis
    - Mass identification
      - E-M techniques
      - TOF techniques
  - Examples
    - Cylindrical/Top Hat with additional electrodes – Energy analysis
      - INMS, Top-hat
    - GIOTTO TOF analyser – Mass identification
    - FONEMA – Thompson parabola – Mass identification

References

- B. Wilken, Reports on Progress in Physics, Vol 47, p 767-853
- G.Gloeckler, Rev. Sci. Inst. Vol. 61, p3613 – 3620(1990)
- R.F. Pfaff, J.E. Borovsky and D.T. Young ed., Measurement techniques in Space Plasmas, AGU monograph series, Vol 102
- Solar System Plasma Physics, Geophysical Monograph 54, Ed. J.H.Waite, Jr, J.L.Burch, R.L.Moore
- The Giotto Mission, J.Phys. E, Vol 20 (1987), 795,etc
- Glenn F Knoll, Radiation Detection and Measurement, Publisher John Wiley and Sons, ISBN 0470131489, 9780470131480
- J.L.Wiza, Microchannel Plate detectors, Nuclear Instruments and Methods, Volume 162, Issues 1–3, 1–15 June 1979, Pages 587-601