Mass Spectrometers for Cubesats

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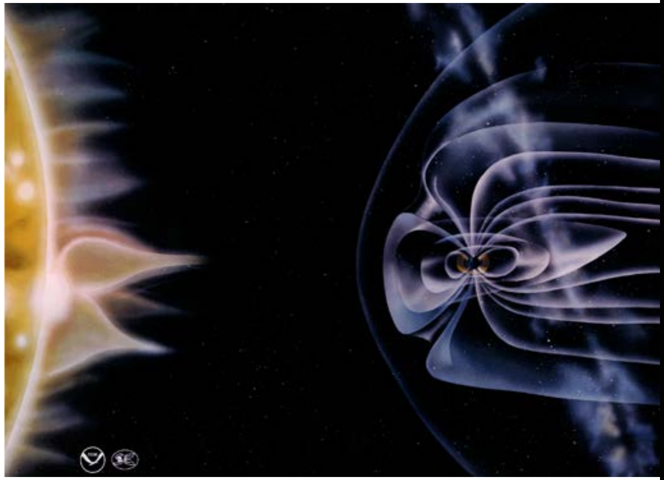
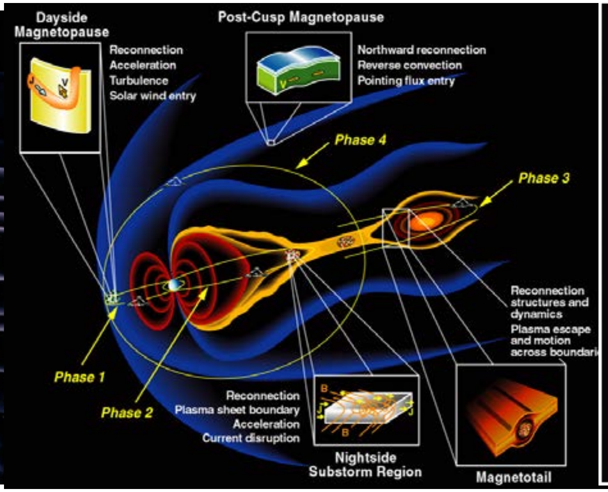
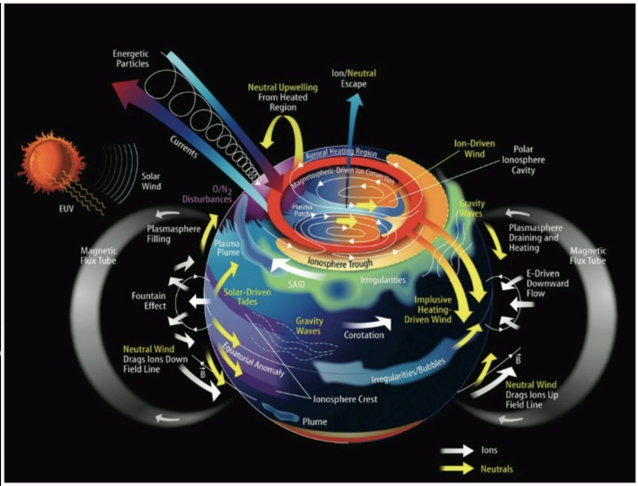
2nd Planetary CubeSat Science Symposium
PCSI: the Planetary CubeSat Science Institute
NASA Goddard Space Flight Center

Solar Terrestrial Connection





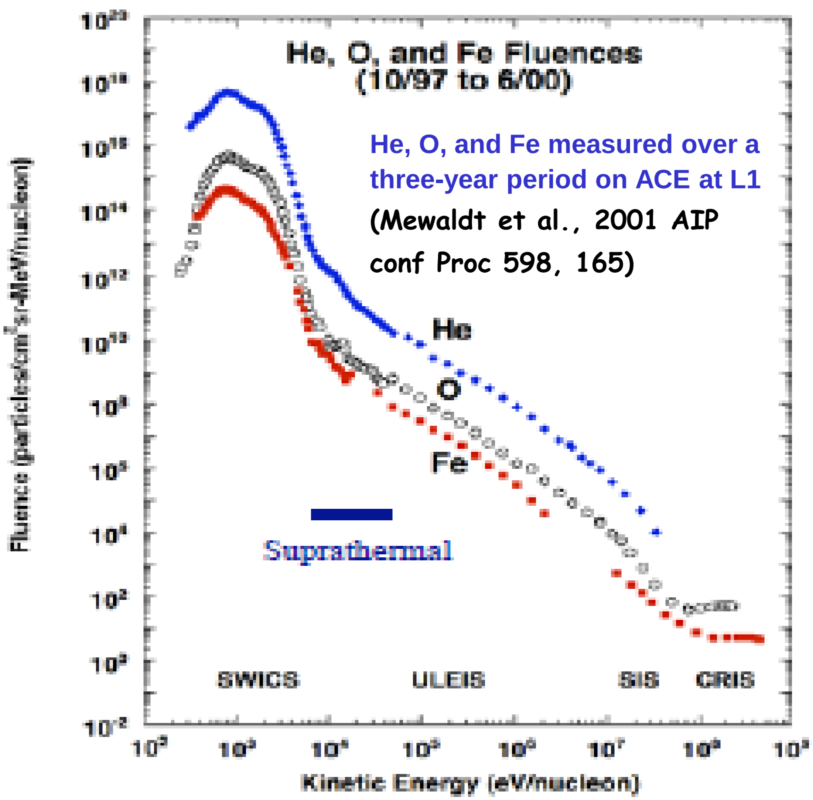


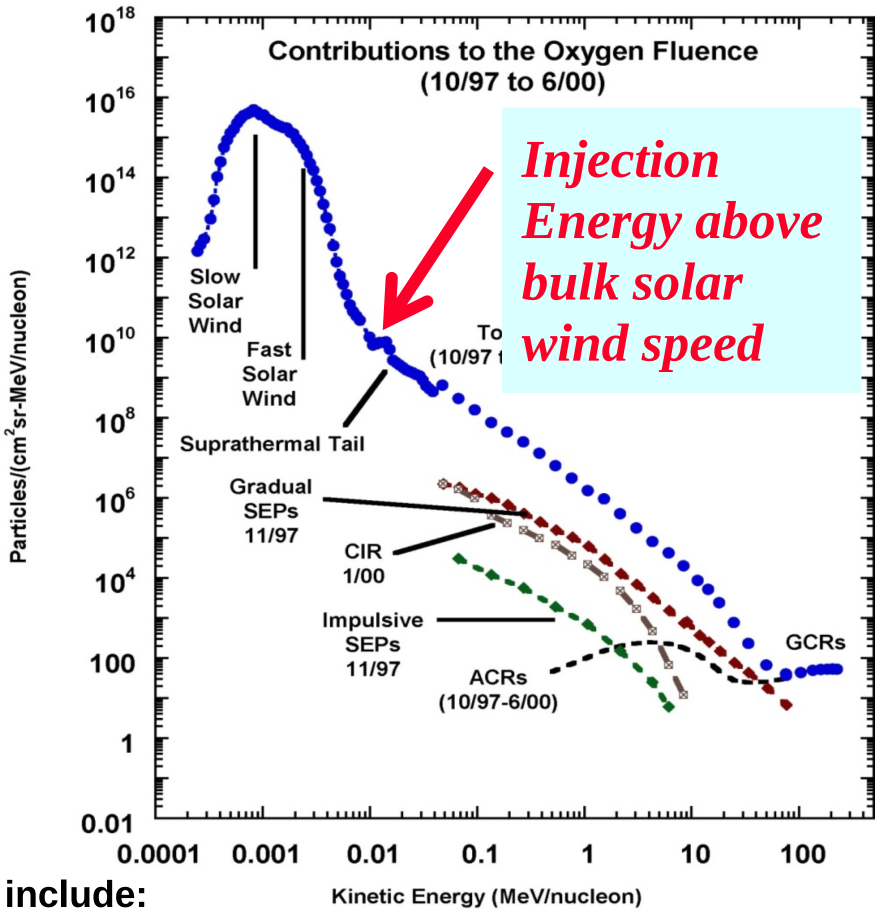
- The SW flows radially outward from the rotating sun at slow and fast streams originating at the solar corona.

- The SW slows down and heats up on encountering Earth's magnetosphere driving several current systems, waves and acceleration phenomena. Ultimately some of the SW energy is deposited in the ionosphere, causing currents, heating, bulk flows etc

- Similar processes apply to the rest of the planets depending on the existence of own magnetic fields and neutral atmospheres

Fluence and Energy Dynamic Range of Particle Distributions in the Solar Wind





Particle distributions in the solar wind generally include:

- **A thermal core which can be characterized by a drifted maxwellian with temperature 1-2x10^5 K, bulk velocity 450km/sec, density ~5-10/cm^3 (94% H, 5% He, 1% minors) B= 5-10nT; plasma flow speeds in CMEs can reach 2000 km/sec**
- **A high energy tail produced by acceleration processes (free energy of the distribution) at > 10KeV to >100MeV with differential intensity dynamic range >10e12**

Typical space environment conditions in the earth's day side magnetosheath, magnetosphere and ionosphere

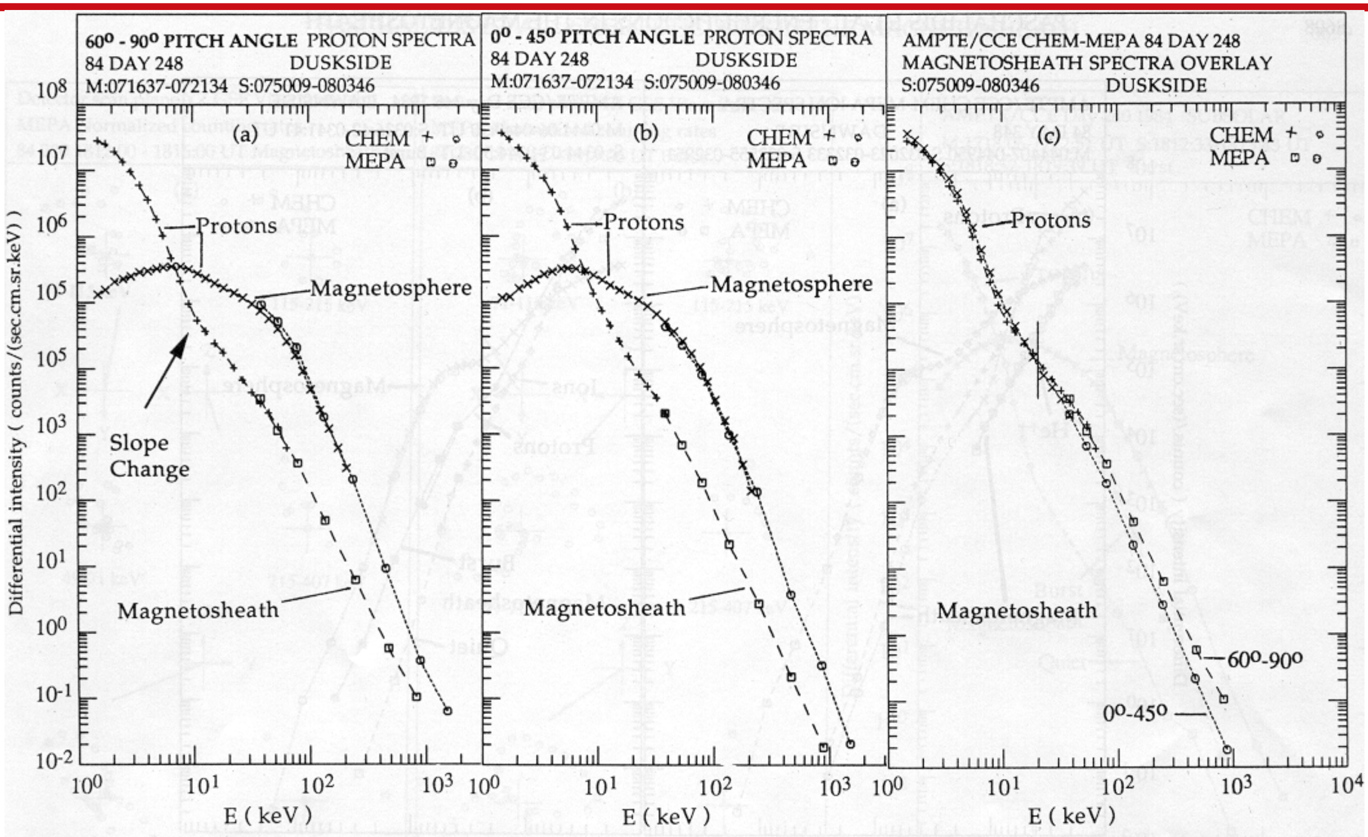


Figure 11. Pitch angle averaged spectra on the duskside magnetosheath (Figure 2 bottom); (a) 60° to 90° pitch angles, (b) 0° to 45°, and (c) overlay of the two spectra. Note that the large pitch angle spectrum is harder than the other.

Differential intensities of protons (dominant ion) in earth's day side magnetosheath and magnetosphere

Paschalidis, N. P. et. al., *JGR - Space Physics*, vol. 99, pp. 8687-8703, May 1, 1994

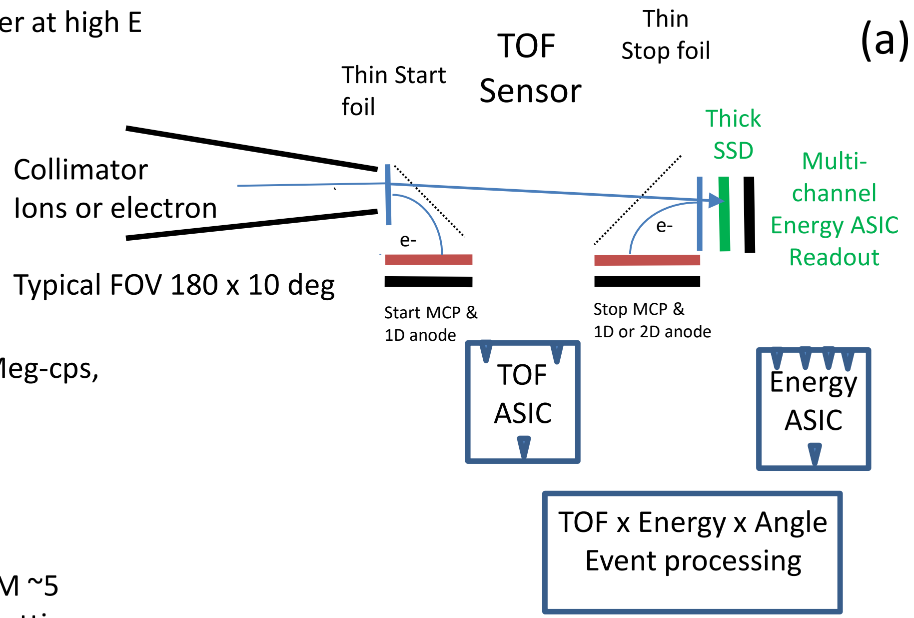
- **The solar wind in the earth's magnetosheath is shocked, slowed down and thermalized: typical bulk flow velocity ~200km/sec, temperature 10^6K, density 10-30/cm^3, B ~10nT**
- **Just inside in the dayside magnetosphere plasma conditions are dominated by maghetospheric processes: typical temperatures 10^8K, density ~1/cm^3, B 100-200nT**
- **Typical ionospheric LEO conditions at 450-700km: Ion density 1e3 to 1e8 /cm^3 , neutral density 1e4-1e9/cm^3 O+, O dominated, temperature ~1000K, horizontal ion drifts up to 2000m/sec, horizontal neutral winds up to 500m/sec, B~ 10^4nT**

Categories of TOF x E x Angle Particle Spectrometers

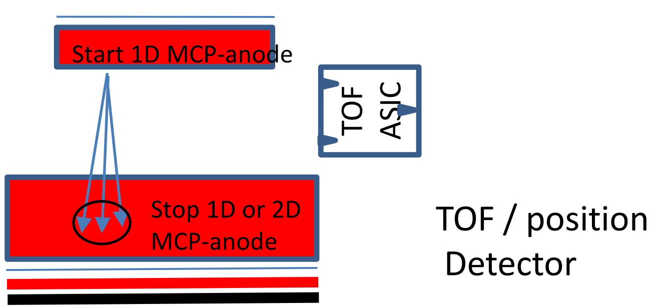
Medium energy range and Low energy range

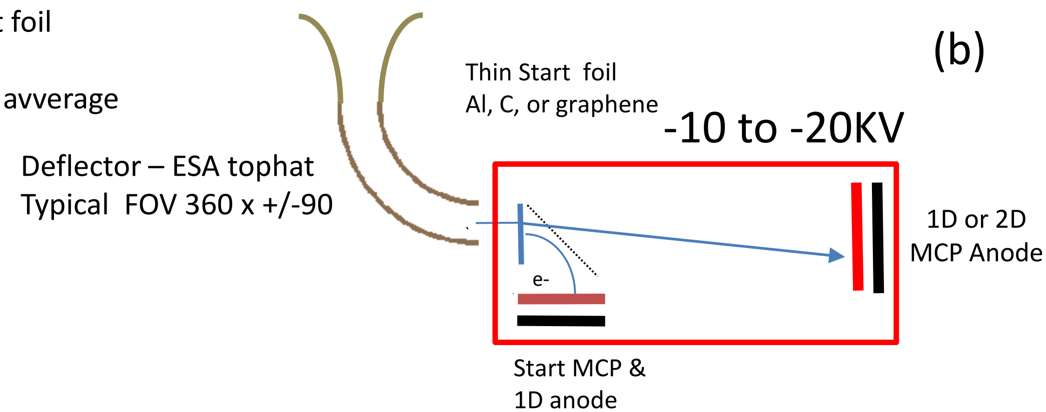
M/dM ~5 limited by DE, Foil strangling and TOF path errors

(a) Medium Energy ~20KeV to 20MeV
Typical FOV 2pi x 10 deg, DE/E typical 30-50% at low energies, much better at high E
TOF with foil – foil - MCP-anode, Energy with Solid State Detectors
Angle with collimation & position sensing
M/DM ~5 separates H, He, CNO, Sulfur
Primary noise source: straight UV, foreground/background particles
Noise rejection: multiple time/ position coincidence
Low energy limitations: energy straggling and scattering at foil,
dead layer of SSDs and electronic noise.
High energy rage range limitations: detector thickness, small TOFs
Dynamic range limitations: max detector counting capability average <1Meg-cps,
Electronics shaping, noise and power.



(b) Low Energies: few eV/q to ~50KeV /q, DE/E ~10-15% typical
E/Q analysis w ESA , 4pi FOV with deflectors
TOF: foil – foil - MCP and **~20KV post acceleration**, mass resolution M/dM ~5
Azimuth angle: 1D start position circular sensing , elevation by deflector setting
Primary instr noise: attenuated UV / penetrators, Noise rejection: multiple time/ position coincidence
TOF correction by 1D/2D stop anode
Energy Thresholds: SC potential, energy straggling/scattering at foil
Low and Upper Energy: limited by max HV and fast scanning HV
Dynamic range limit: GF and ~1meg-cps detector counting limit avverage

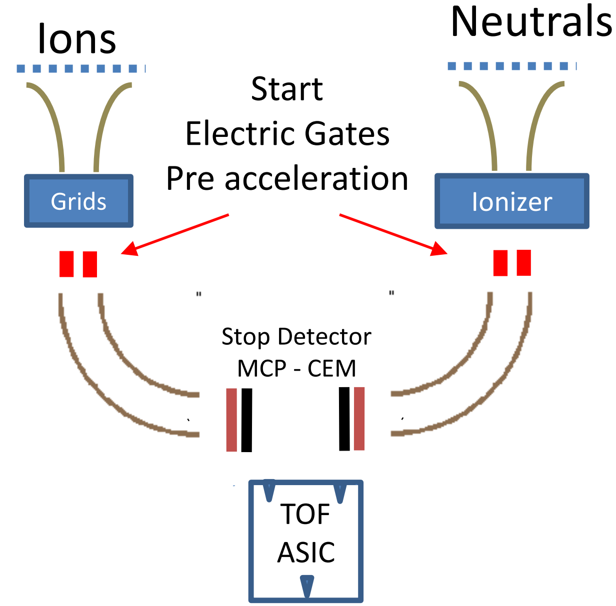




Low Energy Ion Neutral Mass Spectrometer 0.1eV to 20eV
Wide Aperture Low Energy Energetic Neutral Atom Imager

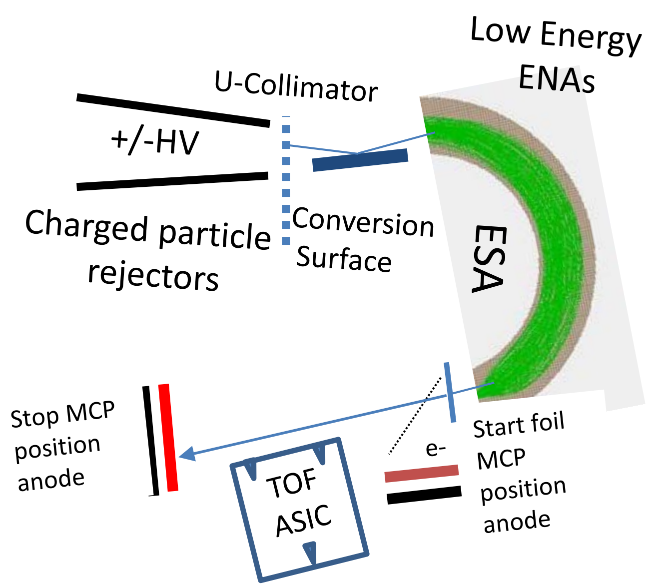
Gated TOF Ion and Neutral Mass Spectrometer

Fast electric gate replaces start foil to **eliminate ~20kV HVPS, does not** interfere with molecules
Pre acceleration ~200V for moderate mass resolution ~10-20 M/dM
Primary noise source: UV and scattering
Optional ESA for UV rejection and out of band particle noise rejection
Mass resolution limitations: size of gate and instrument, improved mass resolution w TOF path correction, Limitation: Fast HV electric gate
Thermionic ionizer for neutrals – emission current ~1mA
TOF binning for mass analysis according to tof~ sqrt(m)
Advantages: non-distractive, electronic sensitivity control



Large aperture Low Energy Energetic Neutral Atom Imager

Large aperture for high sensitivity
Charge particle rejector with HV plates abd grids
Composition H, He, CNO, Ne
Highly polished surface converts neutrals to ions at low energies, foil at higher energies
Micro collimator defines angular resolution in the range of 2-10 deg
Wide gap ESA for signal collection, energy analysis DE/E 20-30% and UV attenuation
Post acceleration ~20KV, Foil – foil MCP TOF system
Magnets for electron rejection
Triple time coincidence + position anode coincidence for high S/N >10^4
Fast TOF ASIC electronics

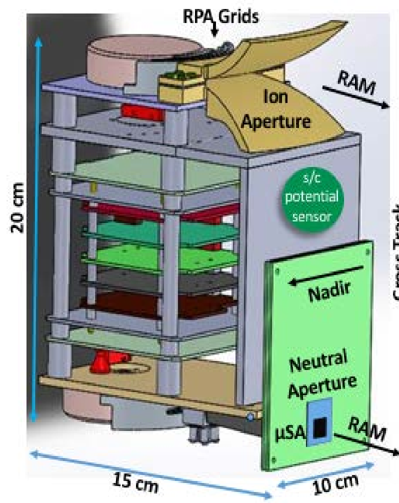


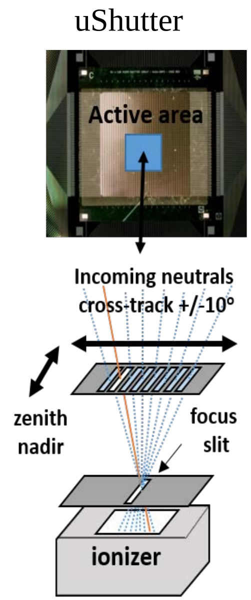
Low Energies 0.1eV to 10eV

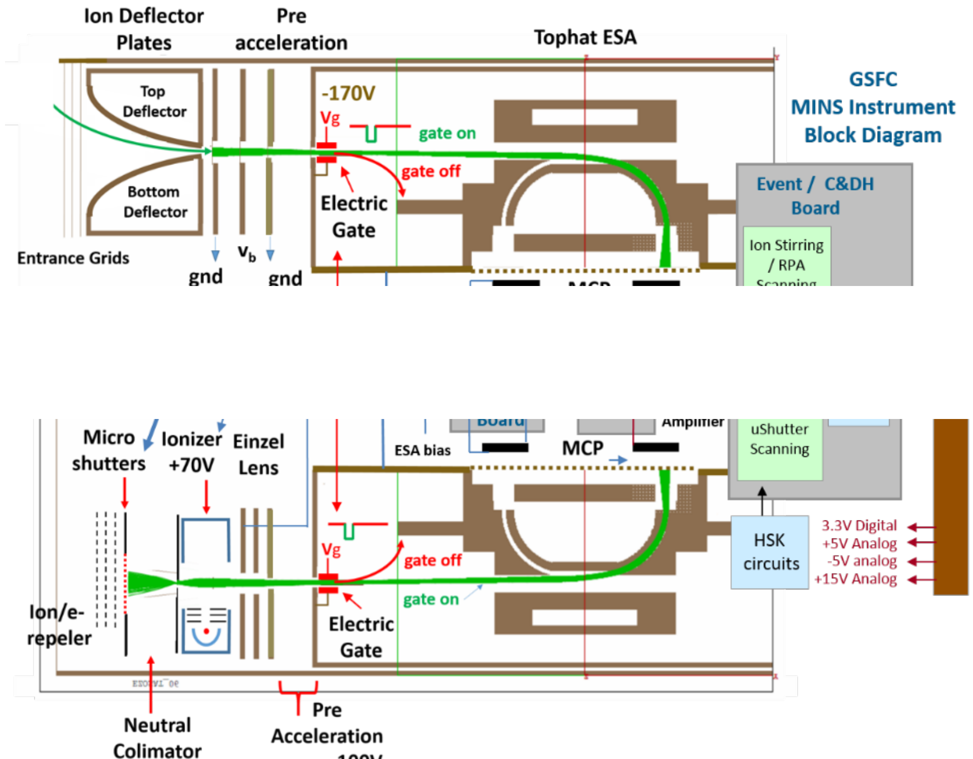
Ionospheres: Ion & Neutral Composition, Flow Velocities, and Temperatures

Ions: Density 10^3-10^8/cm^3, Temp 500 to 3000K, Ion drifts up to 2000m/sec

Neutrals: Density 10^4-10^9/cm^3, Temp 500 to 2000K, winds up to 1000m/sec







Design for 3-axis stabilized platform at LEO

Neutral FOV in the range +/- 10 deg horizontal and vertical w micro–shutter array

Ion FOV +/- 25 horizontal and vertical

Electron impact ionization for the neutrals

Pre acceleration and TOF mass analysis

Delay line – TOF electronics for time of flight and position

Mass range 1-40amu, M/DM~12

Further miniaturization

$$M/q = 2 \times E/q \times t^2 / d^2$$

<u>**On Going Instrument Development**</u>

- Ultra compact Ion and neutral
- Mass spec
- Winds and drifts
- Temperatures

$$\Delta\left(\frac{m}{q}\right)\Big/\frac{m}{q} = \sqrt{\left(\Delta\left(\frac{E}{q}\right)\Big/\frac{E}{q}\right)^2 + \left(\frac{2\Delta t}{t}\right)^2 + \left(\frac{2\Delta d}{d}\right)^2}$$

Miniaturization Technologies

Gated Time of Flight for Ion and neutral mass spectrometry with non distractive non-foil methods

Eliminating ~20KV HVPS required for foils

Make use of advanced time of flight – position sensing – delay line imaging technologies for low power small size and high speed measurements

MEMS micro shutter technology for particle colimation

S. Jones, M. Rodriguez, E. Sittler et all

Nick Paschalidis

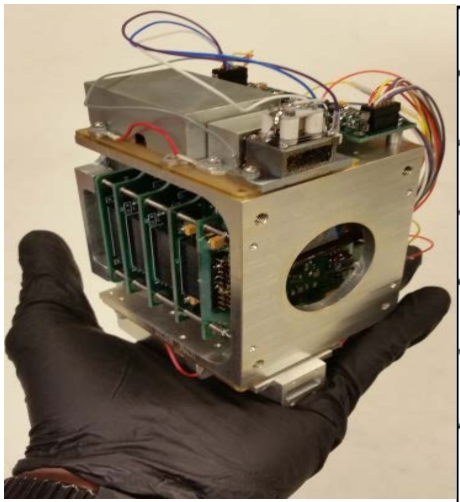
Very Low Energies 0.1eV to 20eV

Ionospheres: Ion & Neutral Composition Mass Spec

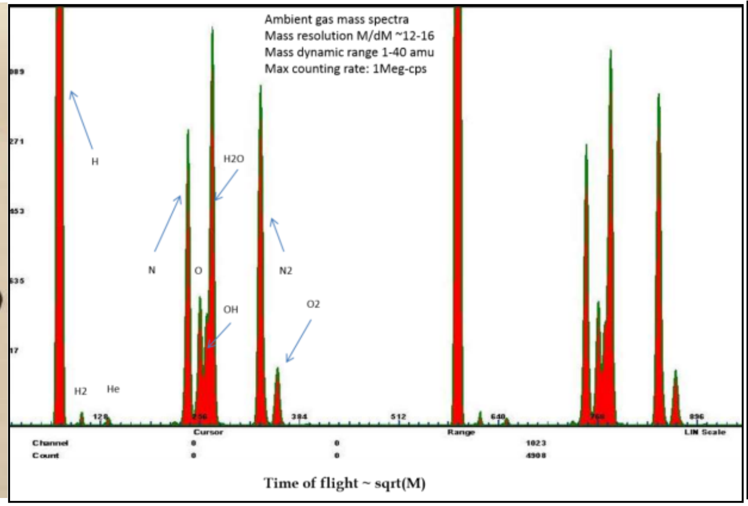
Ions: Density 10^3-10^8/cm^3, Neutrals: Density 10^4-10^9/cm^3

The mini-INMS includes on front optics, gated time of flight, ESA, CEM/MCP detectors, TOF electronics, FPGA event processing and binning and HV for optics and detectors. The mass spectra are measured in time of flight ~ sqrt(Mass).

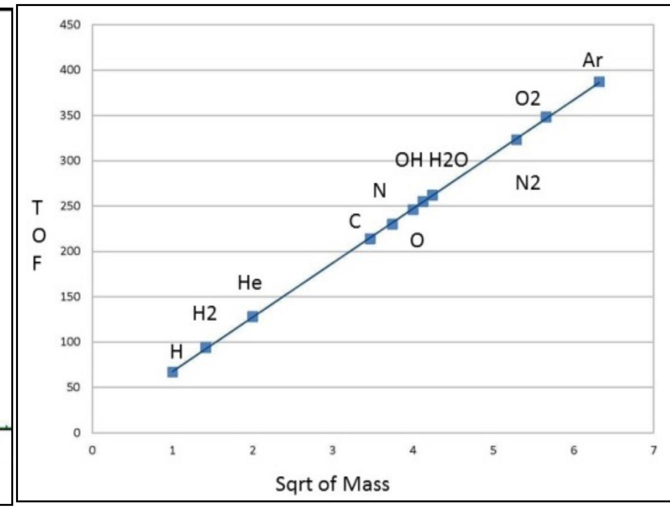
Dellingr FM unit



Lab spectra of neutral gas



TOF ~ sqrt(M)



Science Specs

Ram facing FOV
10° x 10°
Mass resolution M/dM ~10-12
Mass range 1-40 amu
Densities Ions 1e3 to 1e8 /cm3, neutrals 1e4 to1e8 /cm3
Sampling time 0.1-10s

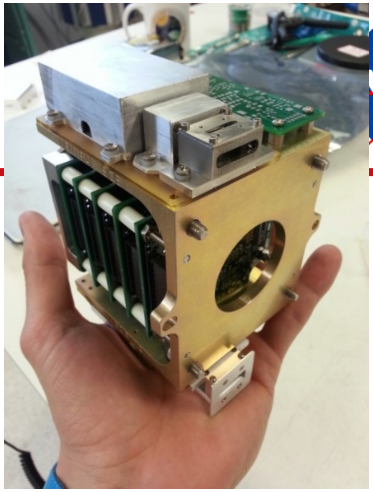
Engineering Specs

1.3U volume, 9 x 10 x 13 cm
Mass 560 g
Power 1.8W
Nominal data rate 13.7kbps
Data interface LVDS and SPI serial
Power Supplies +3.3V, +/-5V, +12VOption for internal LVPS card with single +12V from Spacecraft

Funded Flight Missions

- Exocube 3U CubeSat launched in Jan 2015 got flight data and validated the instrument
- Dellingr 6U to be launched in Aug 2017
- Exo2 to be Launched Jan 2018
- PETIT Sat to be launched in 2020-

NSF EXOCUBE
GSFC mini - INMS



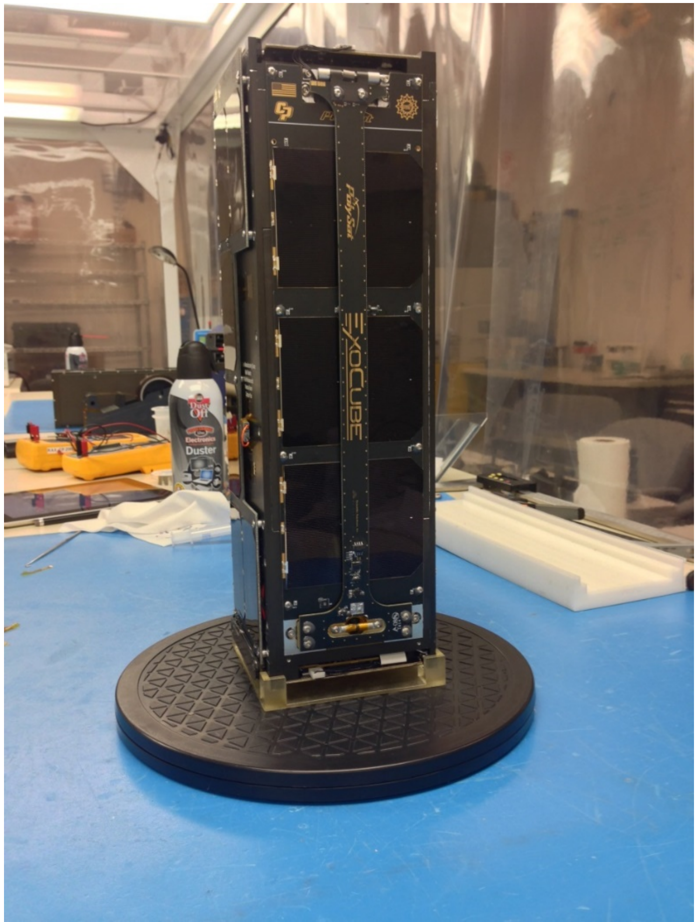
- A compact INMS has been developed at the Heliophysics Science Division of GSFC for the EXOCUBE mission

- The INMS is capable of making high-resolution, *in-situ* measurements of [H], [He], [O], [N2], [O2] & $[H^+]$, $[He^+]$, [O+], [N2+], [O2+]

- The INMS is fully redundant for ions and neutrals

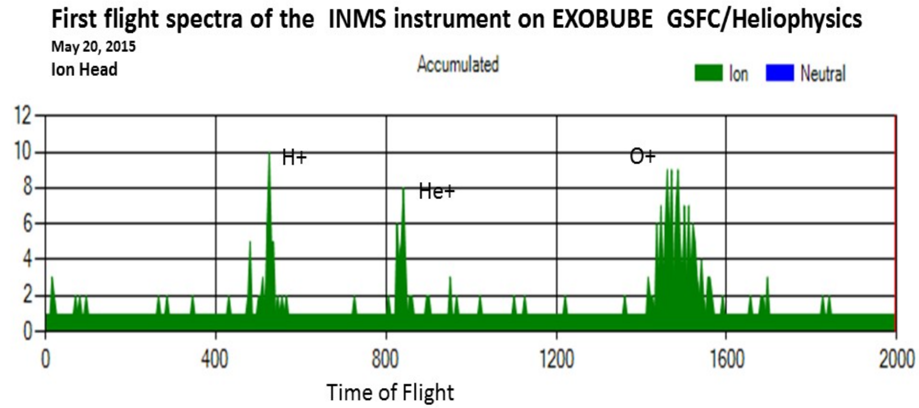
- The instrument occupies 1.5U of volume in the central portion of the CubeSat

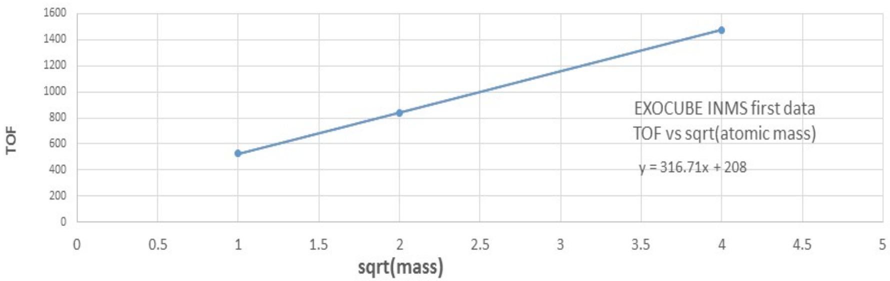
- The complete EXOCUBE has passed I&T and environmental testing and is scheduled for launch in Jan of 2015

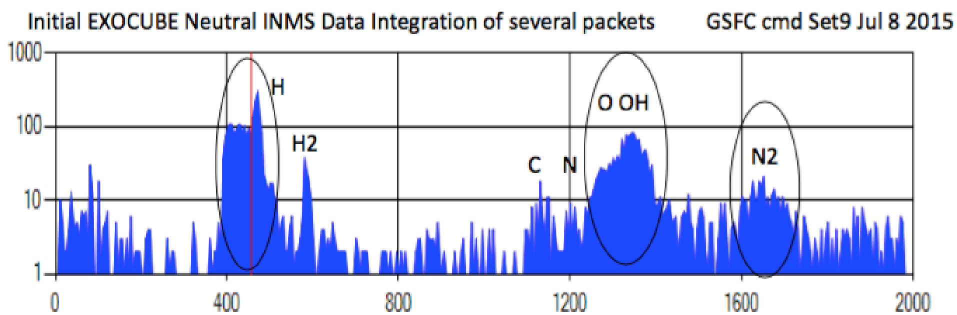


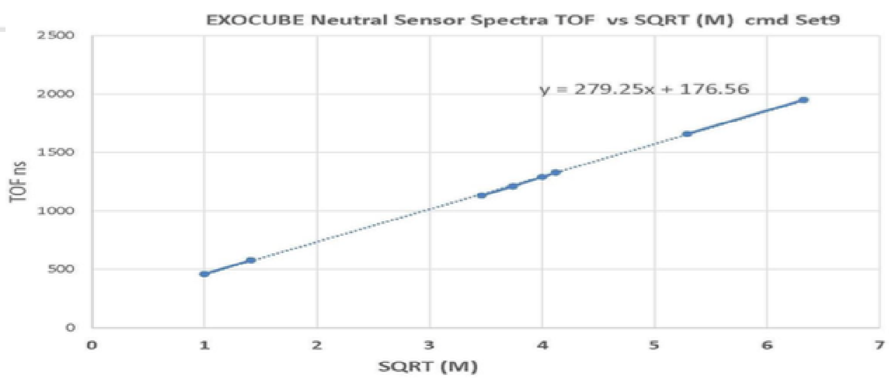
EXOCUBE 1 MISSION
Flight Data

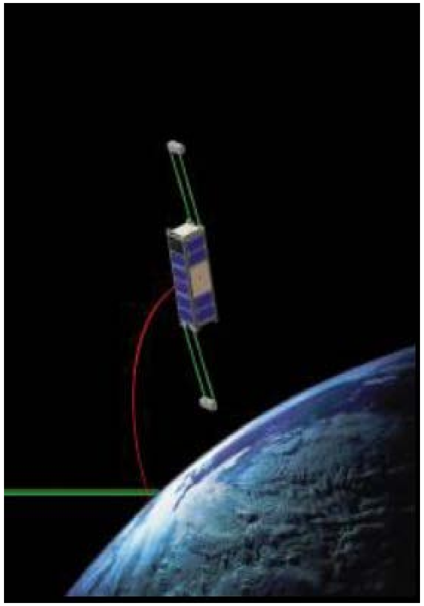
Mission PI	John Noto SSC
CubeSat Bus	California Polytechnic
	3U gravity stabilized
Compact INMS	GSFC / HSD
Launch Date	Jan 2015
Primary mission	NASA/SMAP
Orbit	450km x 680km, 98º inclination, sun-synchronous
INMS	Occupies the central 1.3U

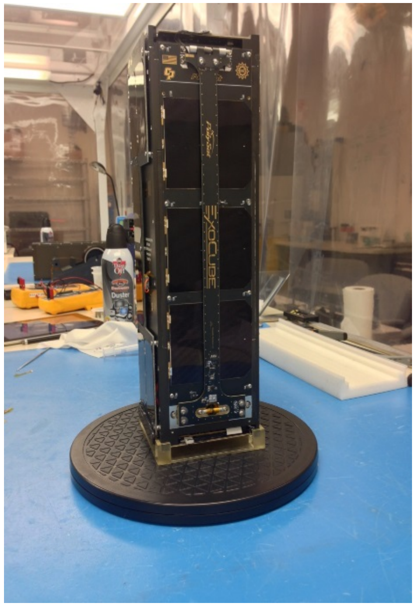












The GSFC Dellingr 6U satellite
Payload: INMS and Magnetometers – Launch date Aug 16 2017

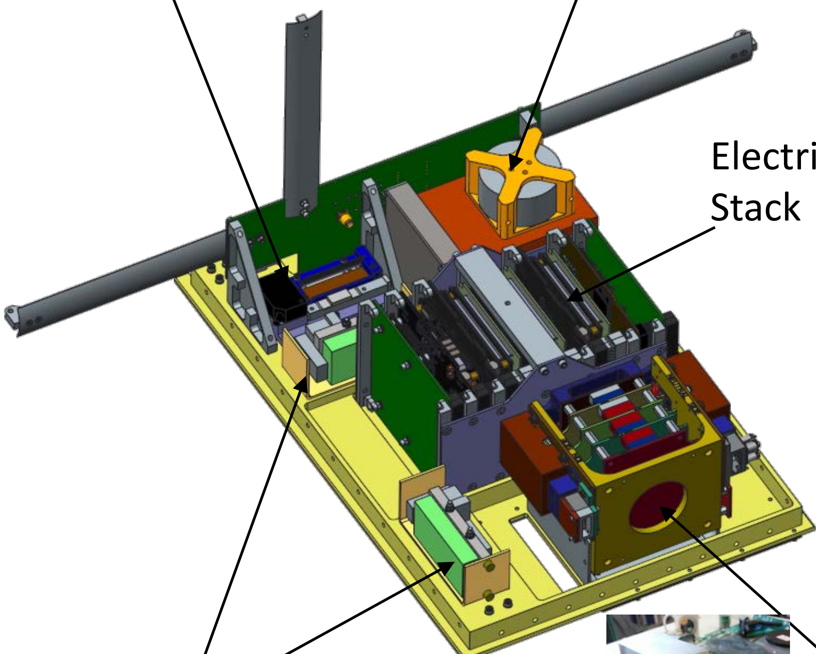
Thermal Louvers Experiment

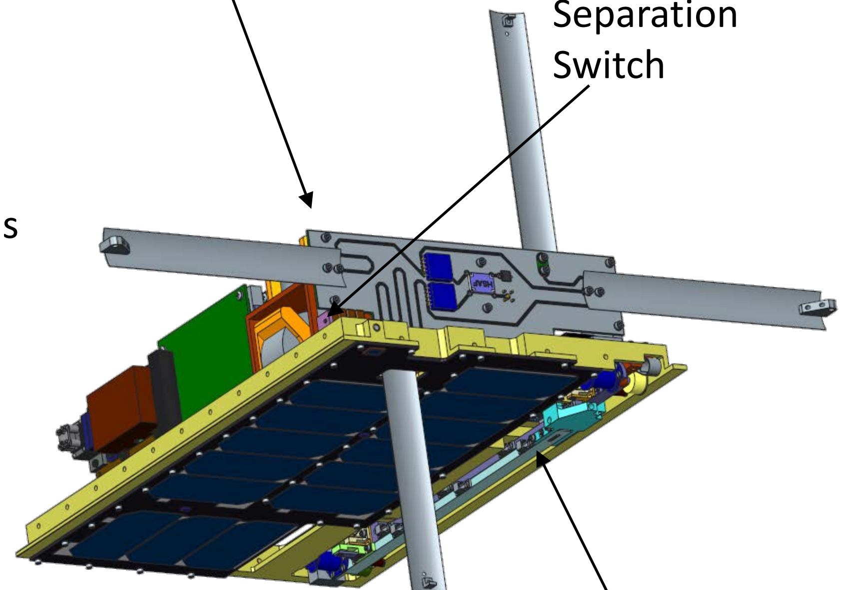
Reaction Wheels and Radio Assembly

UHF Antenna Assembly

Separation Switch

Electrical Cards Stack





-Y Solar Panel

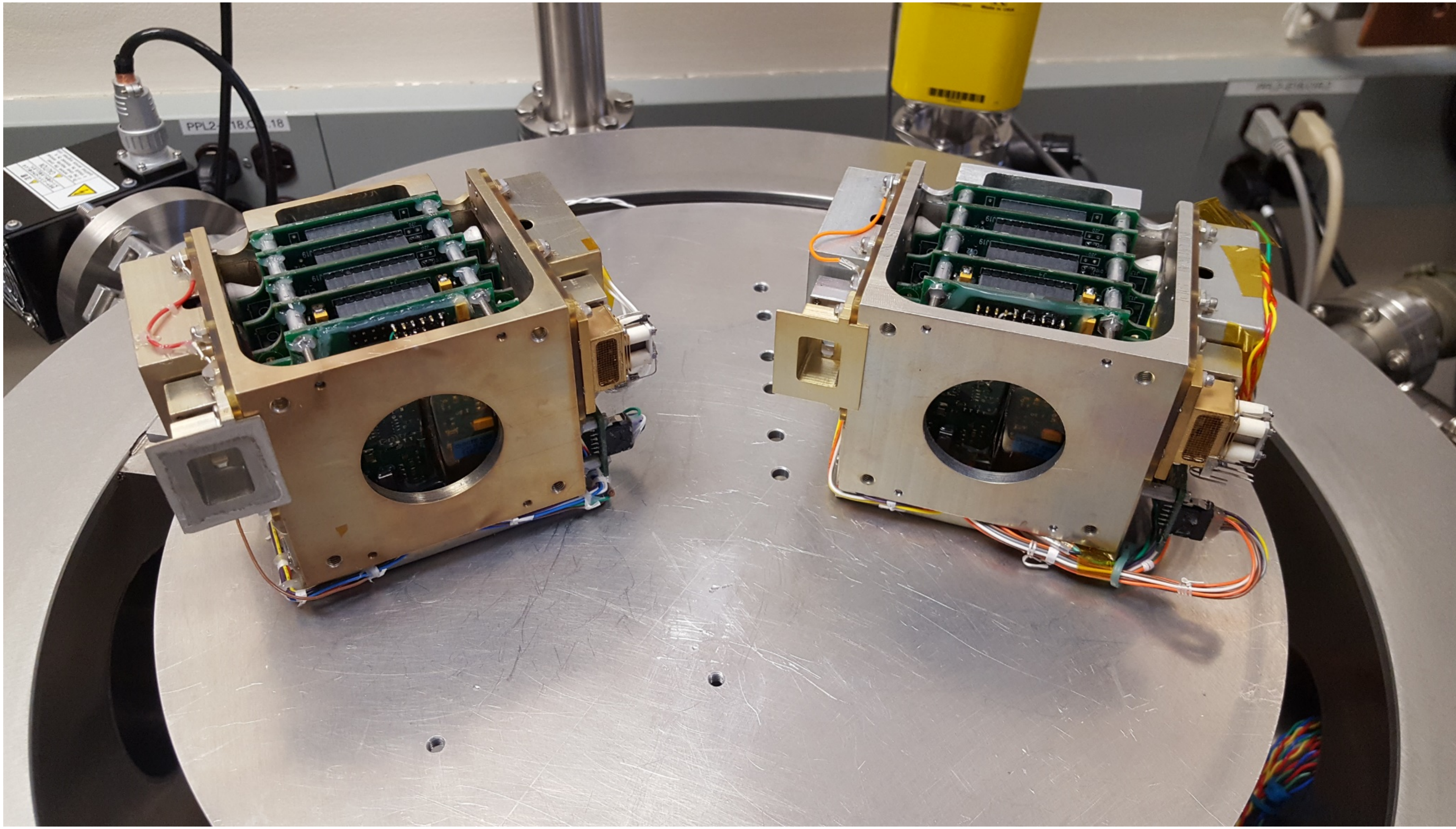
Science Magnetometer Boom

Science Magnetometers

INMS

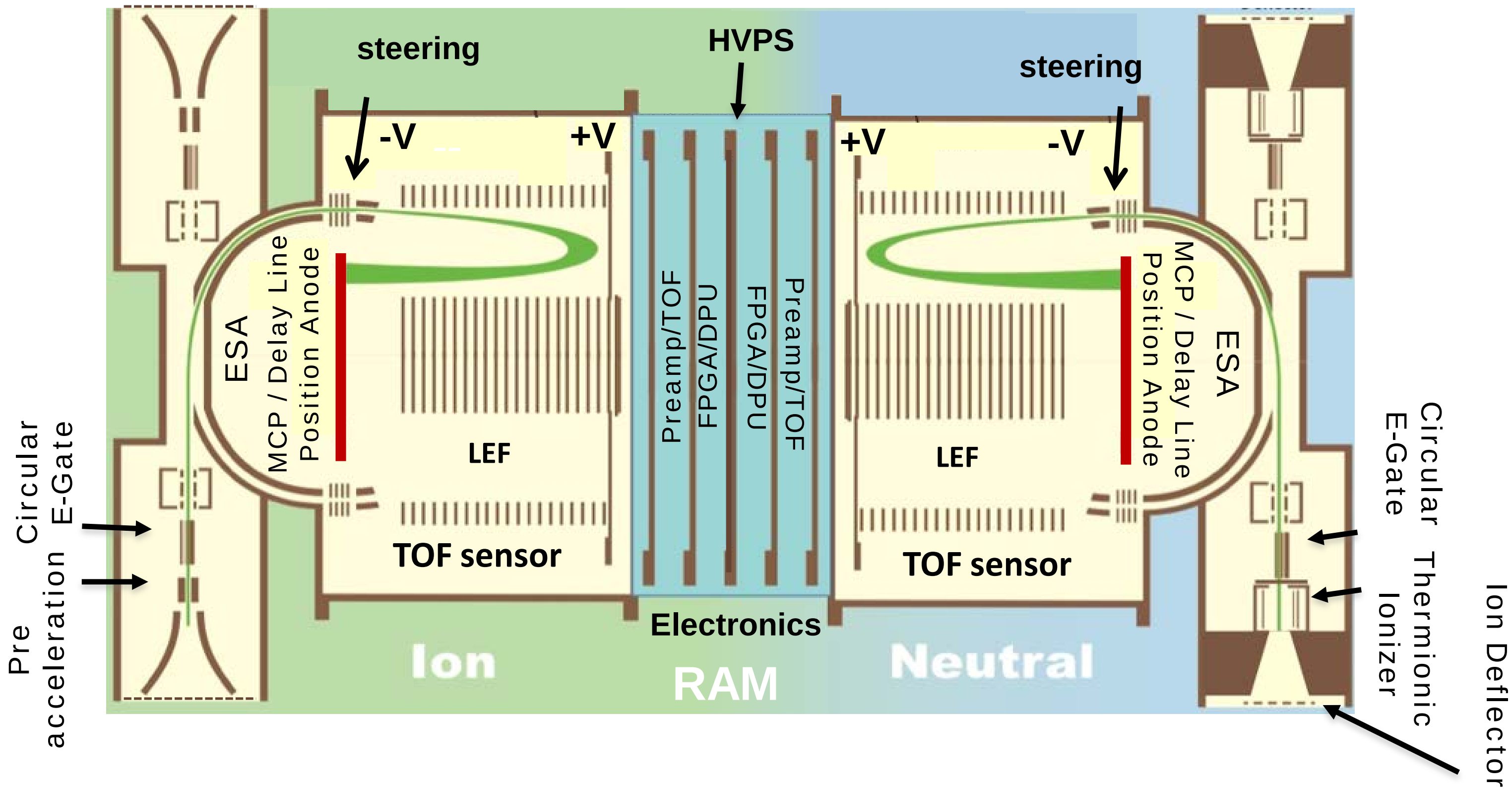
Ion and Neutral Mass (INMS) Spectrometer- nickP, SJones, MRodriguez, et al., NASA/GSFC

Two Flight INMS instruments for the GSFC Dillinger 6U (left) and the NSF Exocube 2 (right) to be lunched in Spring 2018



Energy range 1-1000eV Wide FOV compact IMS & INS Mass resolution M/dM ~20
Standard Deflectors / ESA for Energy analysis
Gated TOF and LEF for high resolution mass analysis, LEF compensates for DE/E errors

E. Sittler, S. Jones, M. Rodriguez, Nick P

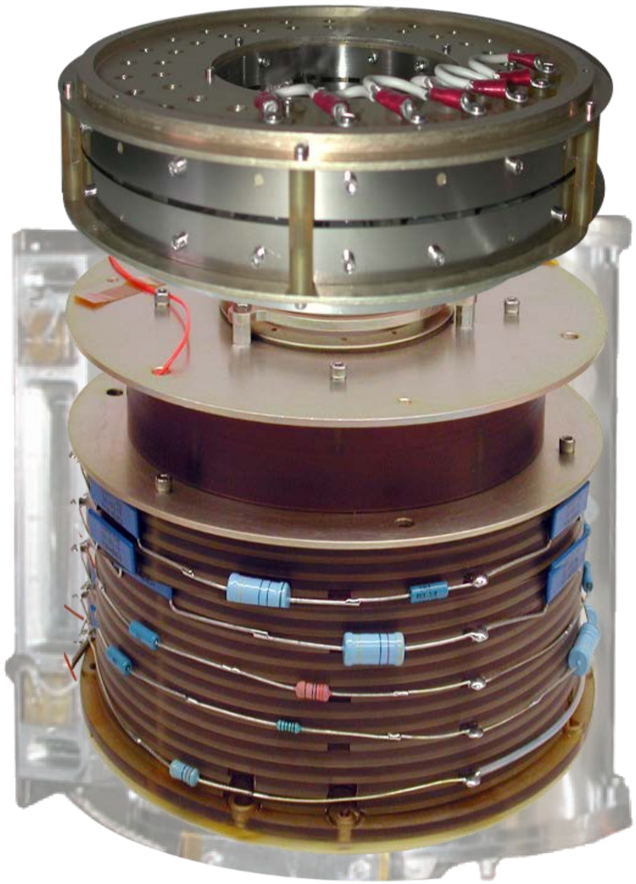


Energy/charge Range (eV/e) 0-1000eV
Field of View (°) 360°AZ x 90°EL
Angular Resolution (°) 5°AZ x 5°EL
Mass/charge Range 1-40 amu

$$\Delta\left(\frac{m}{q}\right)\Big/\frac{m}{q} = \sqrt{\left(\Delta\left(\frac{E}{q}\right)\Big/\frac{E}{q}\right)^2 + \left(\frac{2\Delta t}{t}\right)^2 + \left(\frac{2\Delta d}{d}\right)^2}$$

Entrance Aperture Sensitive Area:
0.1cm x 10 cm
Electric Gate Duty Cycle (%) 0.1 – 10
Detector/electronics counting rate:
1 meg-cps

Lab prototype and testing
Ed Sittler, NickP



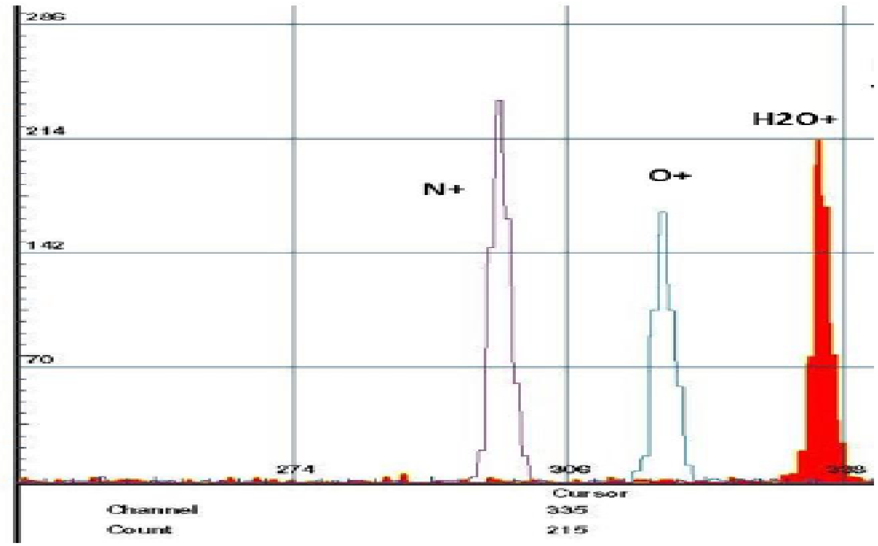


Figure E - 3: laboratory measurements of the instrument prototype with N^+, O^+ and H_2O^+ beams using circular electric gate; results show a mass resolution $M/\Delta M \sim 30$ using 10% rule which applies to detection thresholds for small peaks. Large peaks of comparable amplitudes can be separated by $M/\Delta M \sim 100$ at the peak FWHM.

Laboratory WIMS prototype with cylindrical steering lens and aperture (top) section and ESA/TOF section (bottom)

Test results with ion beam of ~400eV, DE/E ~10% WIMS design, including circular electric gate replacement for carbon foil sto $M/\Delta M \geq 20$ °

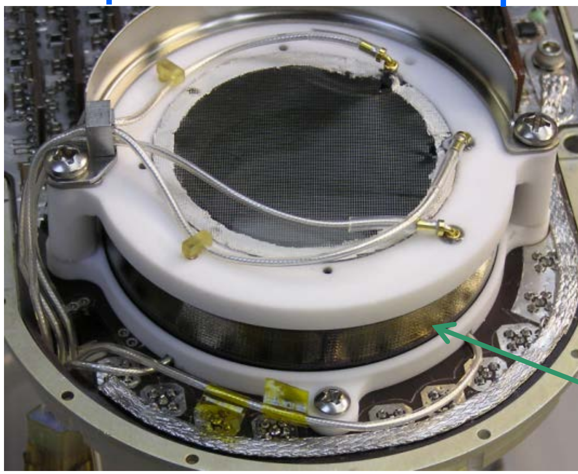
The JHU/APL Energetic Particle Analyzer

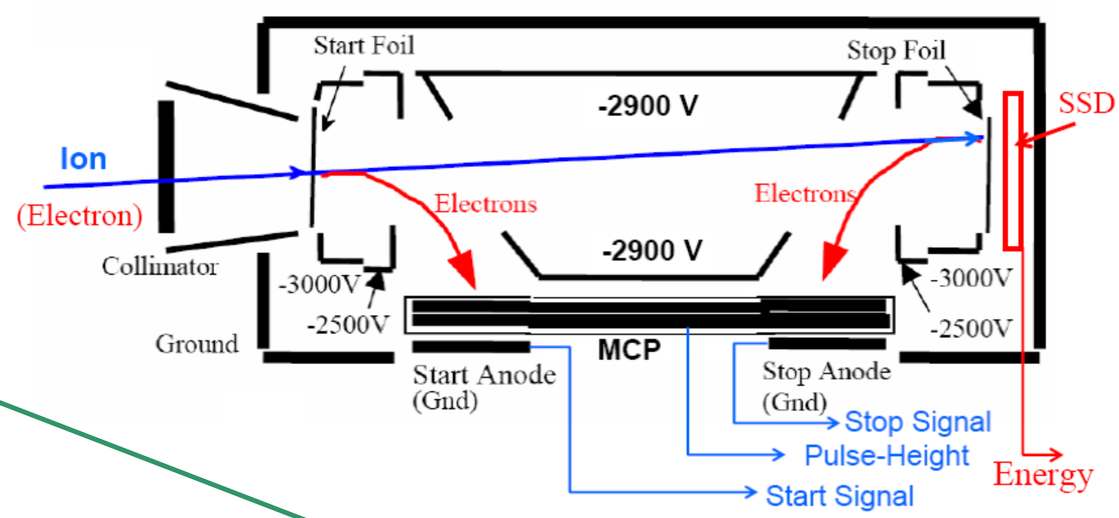
TOF x E x Angle (foil-foil-SSD- 1D delay lines) Ions >30KeV to ~5MeV, Electrons ~30KeV to 500KeV

Missions: MMS, VanAllen Probes, New Horizons, JUNO

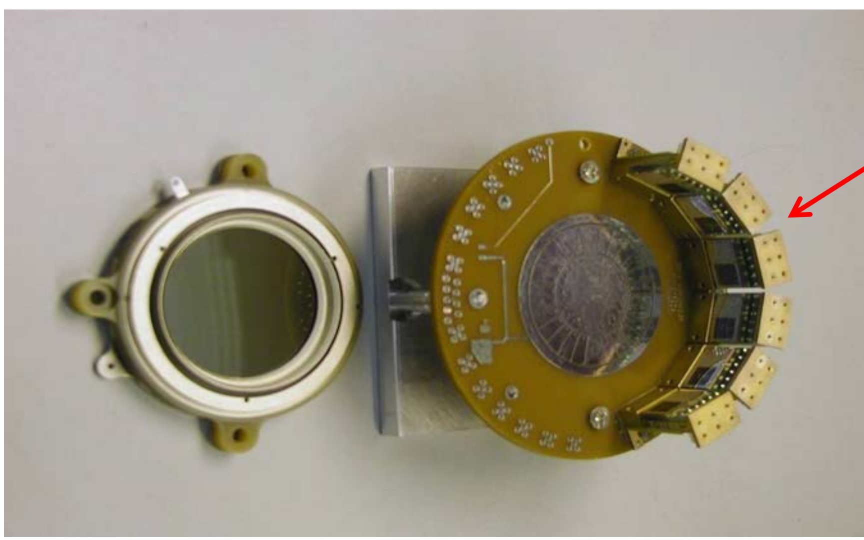
DM/M ~5

~6 cm

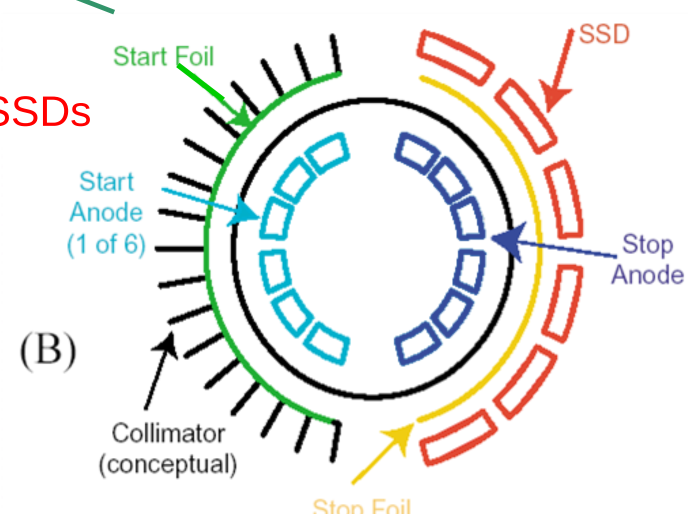




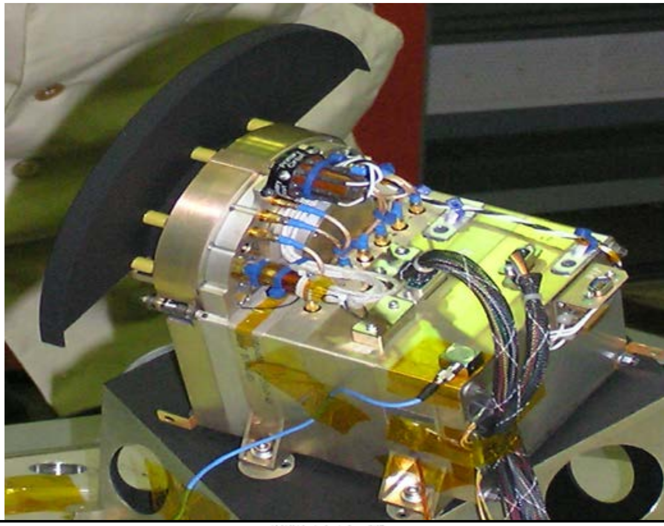
New Horizons PEPSSI, JUNO/JEDI
Van Allen/RBSPICE, MMS/EPD

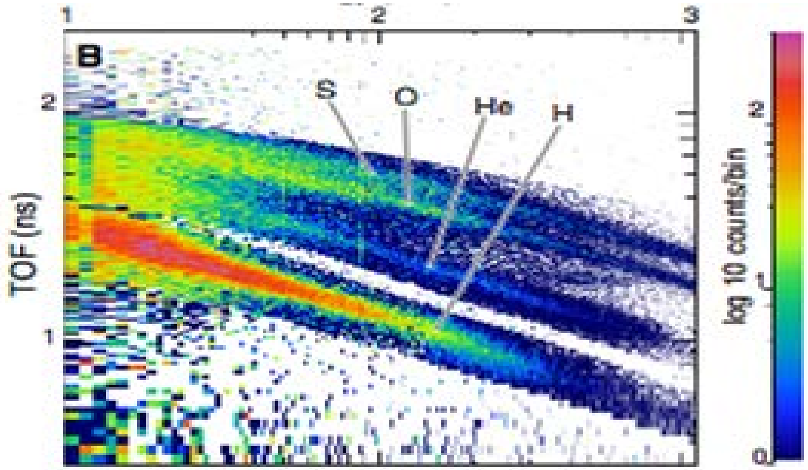


SSDs

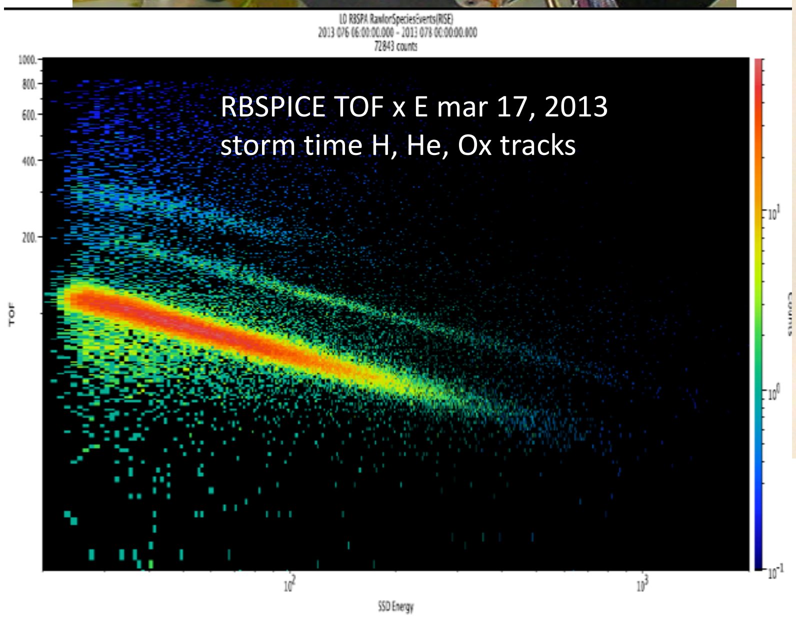


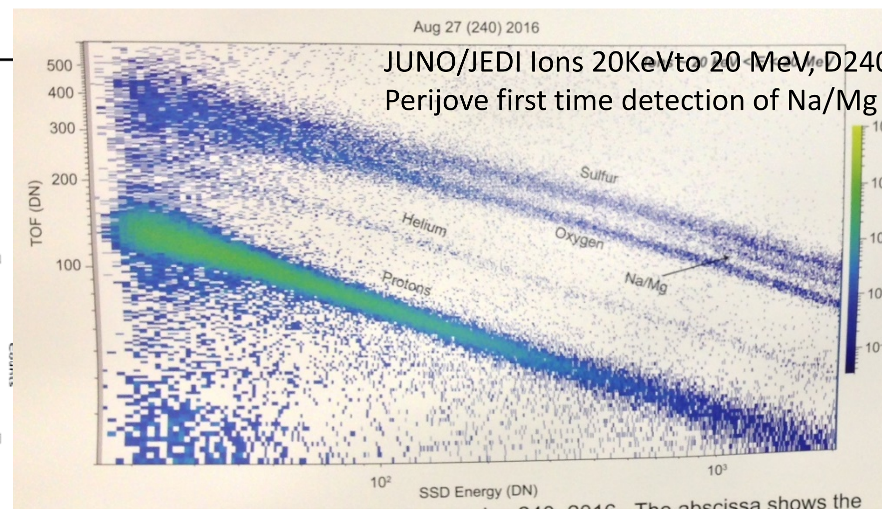
JHU/APL Energetic Particle Analyzer 30KeV to 30MeV
Foil/MCP and SSD detectors, M/DM ~5
APL D. Mitchel, B. Mauk, R. McNutt et al.,
Nick Paschalidis TOF postionon and energy read out





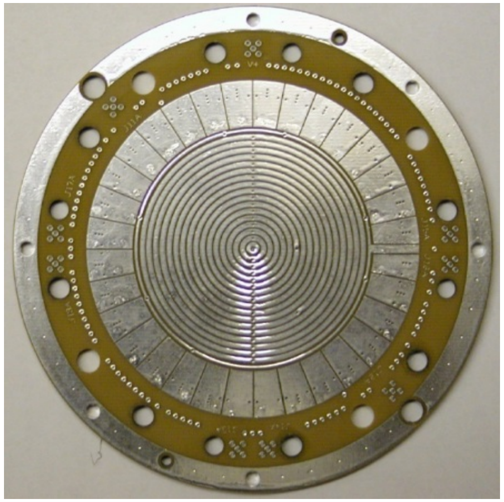
PLUTO / NH encounter w Jupiter PEPSSI E 20KeV to 1 MeV





Haggerty, et al. AGU 2016 P33C-2159
Note clear Na/Mg track between Sulfur and Ox.
The extended energy range and the fine mass separation was enabled by the expended energy of the SSD/ASIC and the <100ps time resolution of the TOF chip

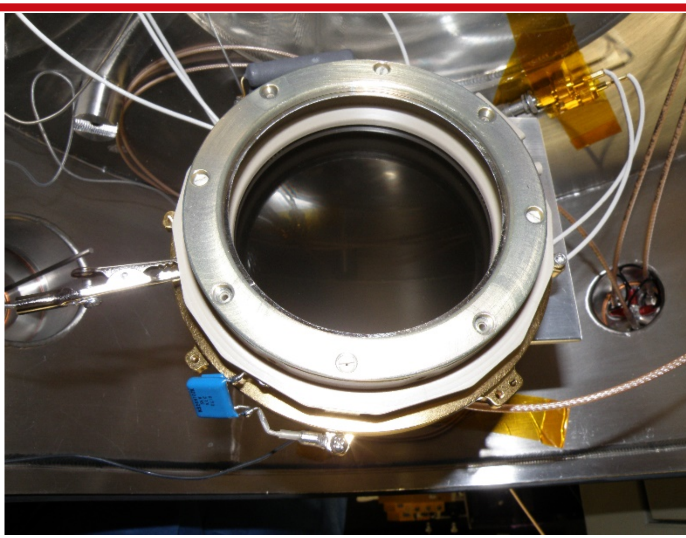
SWRI Plasma Composition Analyzer HPCA
SWRI D. Young, S. Fusellier et al.,
Nick Paschalidis nasa/gsfc
Deflectors, 2pi ESA, TOF sensor – foils – MCP DM/M ~5

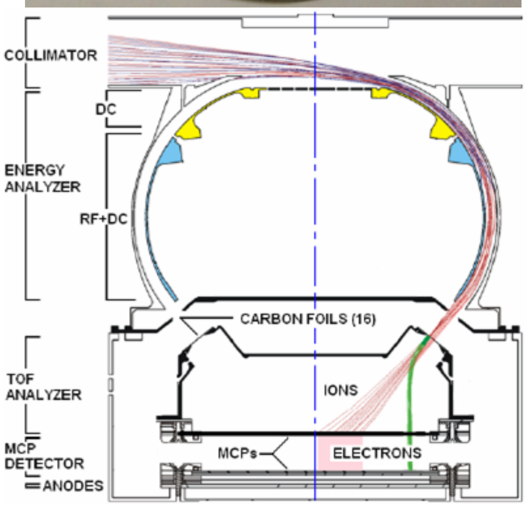


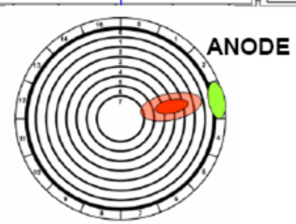
MCP assembly by SWRI

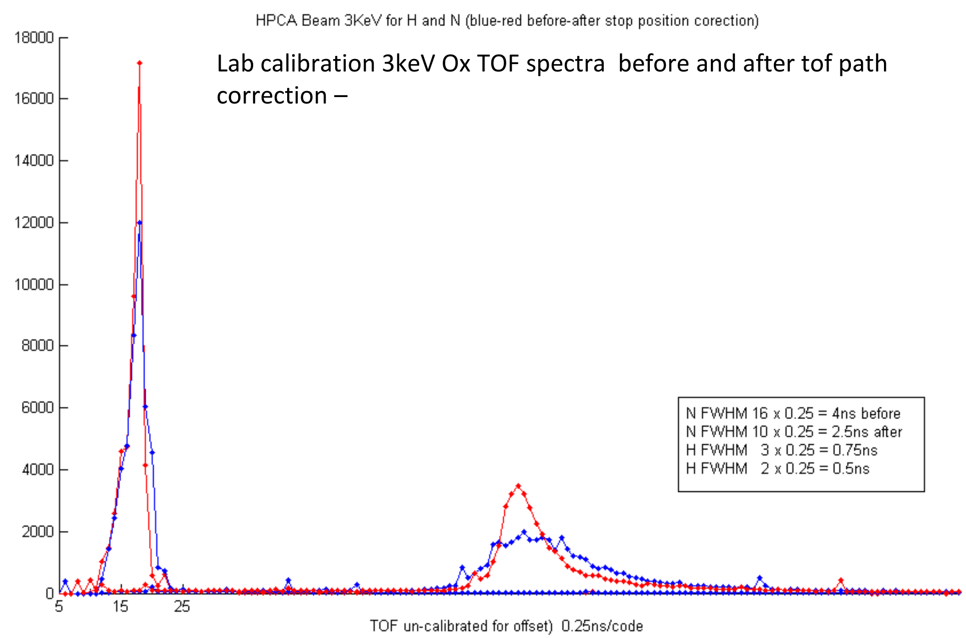
The 1D delay line / TOF measures the azimuth 360 FOV in 32 sectors of 11.25 deg

The concentric ring anode compensates for time of flight path variation due to foil scattering

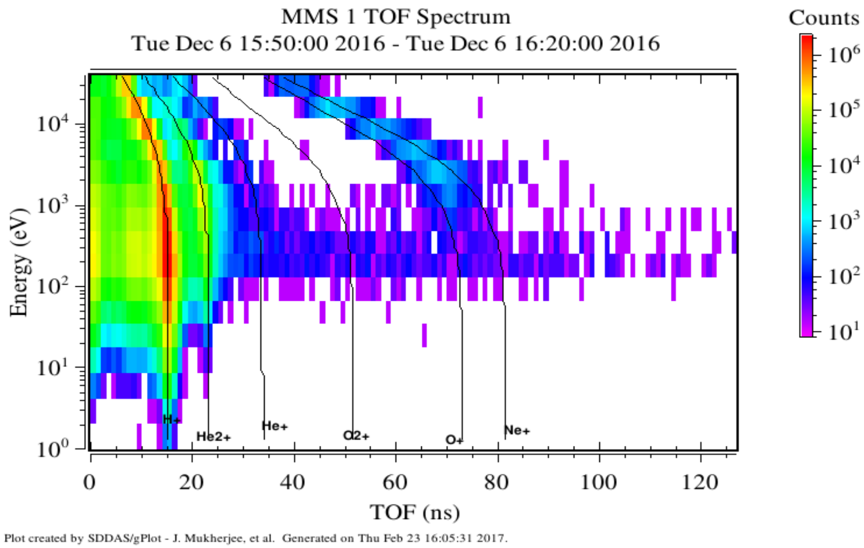


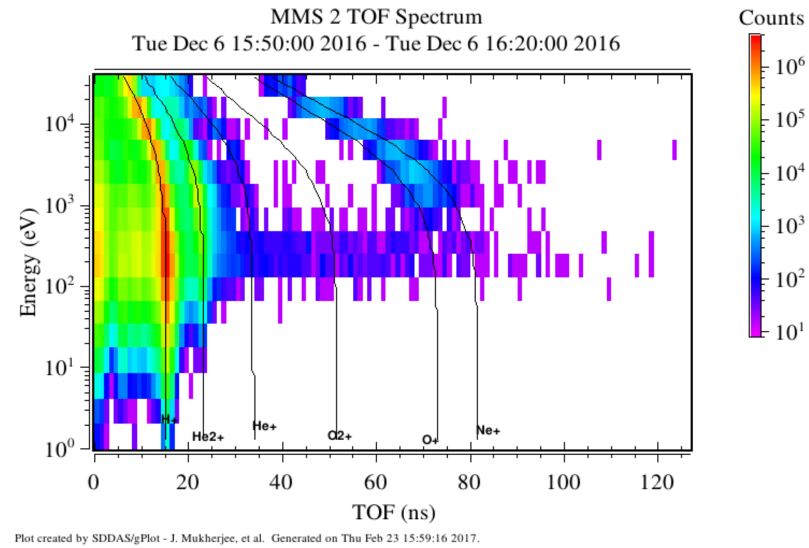


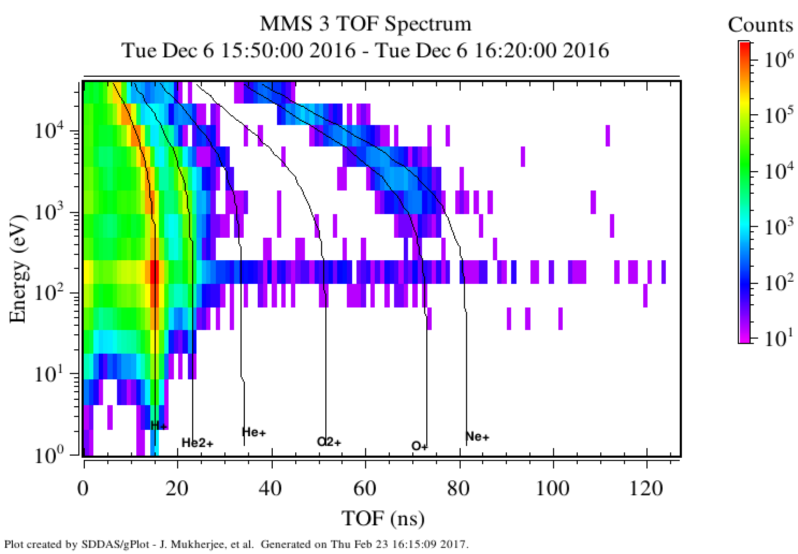


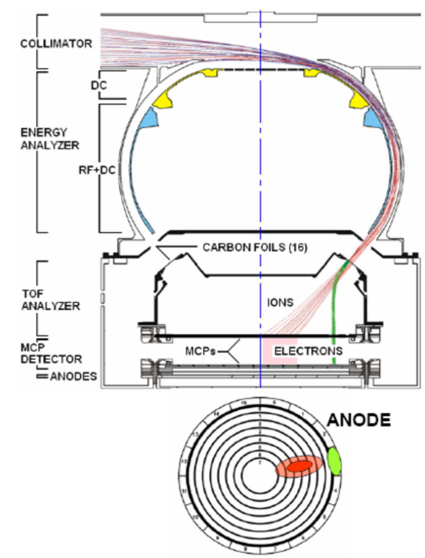


MMS Hot Plasma Composition Analyzer
Deflector/ ESA Post Acceleration, TOF Foil/MCP
SWRI S. Fuselier et al.,
Nick Pascalidis TOF read out

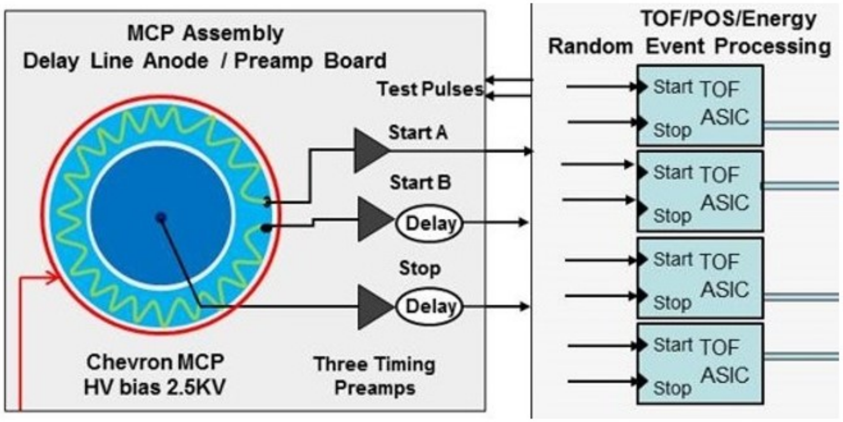




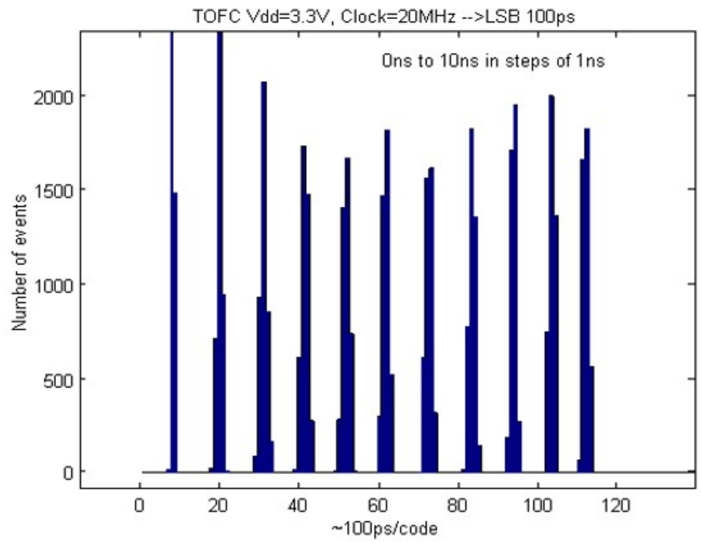


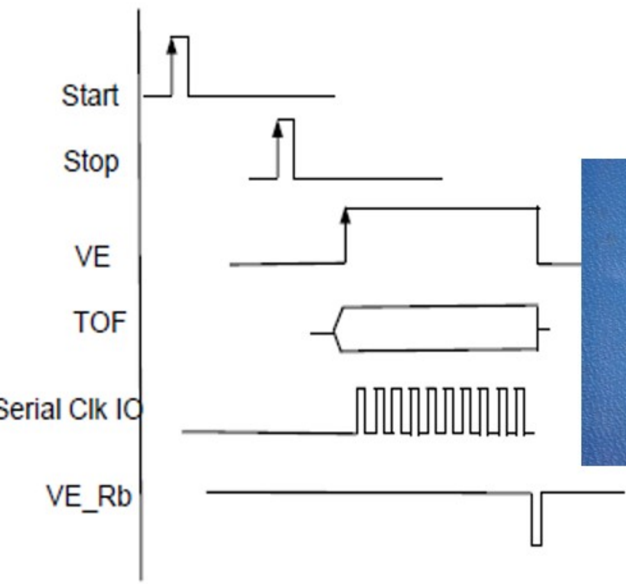


Miniaturization, high performance and low power
Time of Flight and and Delay Line Imaging with TOF ASIC
nickP

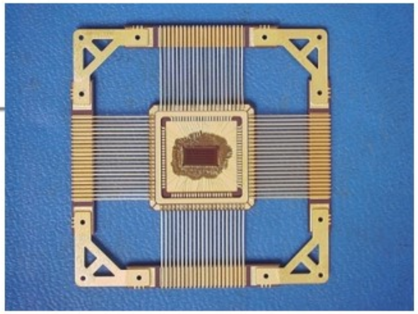


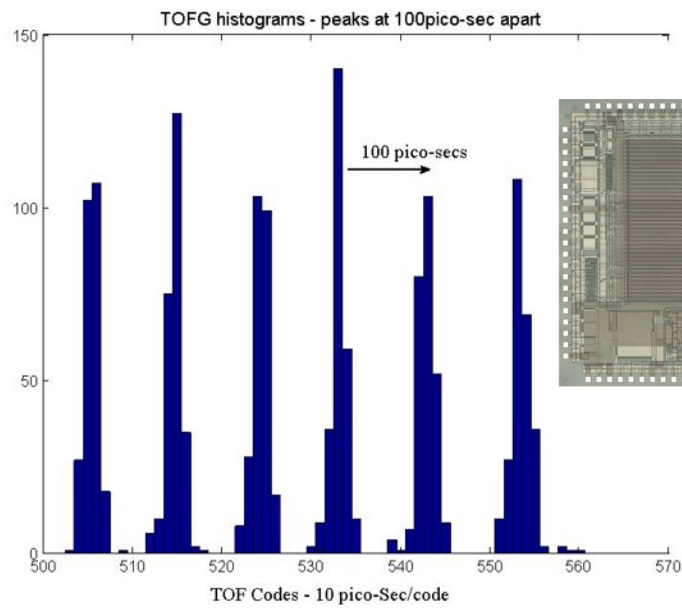
nickP

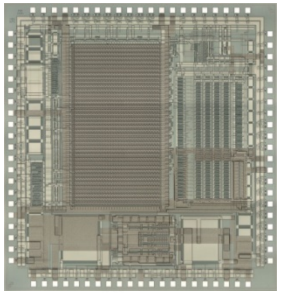




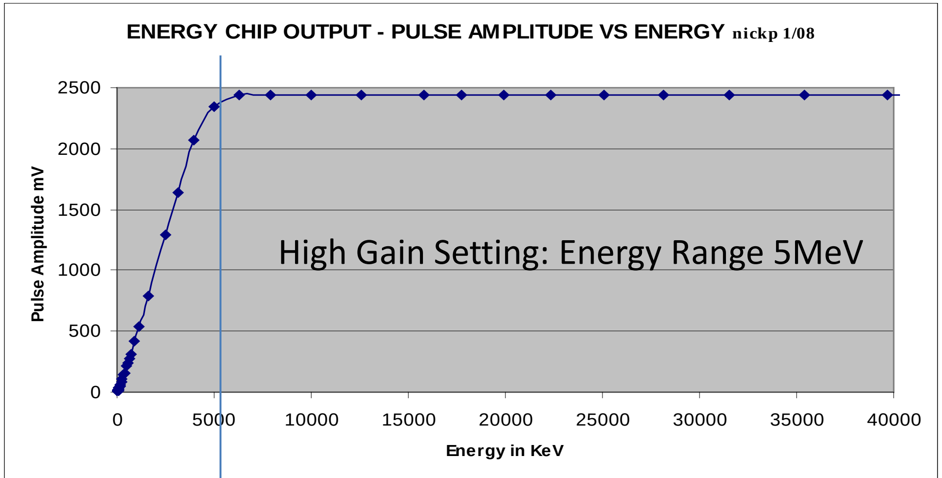
TOF-G ASIC <10ps

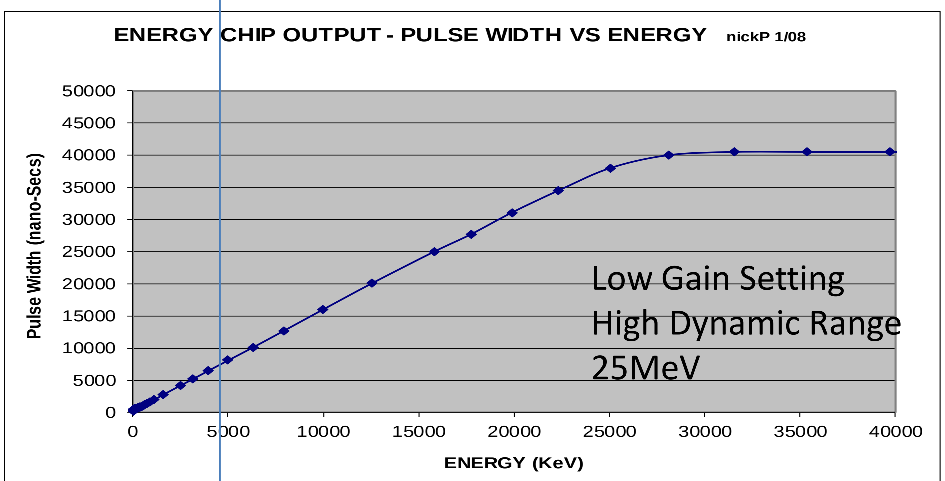


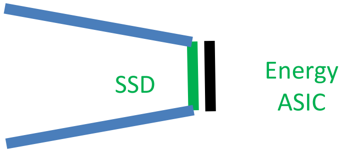




Miniaturization, High Performance and low power SSD Telescope with the Energy ASIC Energy Dynamic Range 10KeV to 20 MeV – noise ~2-5KeV FWHM nickP







Energy Spectrum 2KeV per Code