The Proton and Alpha Sensor (PAS) of Solar Orbiter Mission: design, operation, scientific return simulation, and first flight data

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Solar Orbiter is an ESA/NASA mission that will provide an unprecedented opportunity to discover the fundamental connections between the rapidly varying solar atmosphere and the solar wind. The Solar Wind Analyzer (SWA) plasma package shall provide comprehensive in-situ measurements of the solar wind. In particular, the Proton-Alpha Sensor (PAS) will determine the properties of the dominant solar wind ion population through the measurement of the D distribution function, density, bulk velocity, temperature, and heat fluxes, at temporal cadences ranging form 4s to ~0.1 s. The closest approach of Solar Orbiter to the Sun is .28 AU. At this distance the solar wind Vow, solar UV, and solar infrared fluxes increase by a factor compared to near-Earth space. The PAS instrument will provide high cadence 3D distribution function measurements (up to 10 per second) all the way from closest approach to AU. This paper give a basic information about PAS design, and describes the PAS measurement scheme adopted for varying solar wind conditions and our approach to the fast sampling of D distribution functions. We also provide a simulations of the expected scientific return. A first glance of PAS commissioning results is presented.

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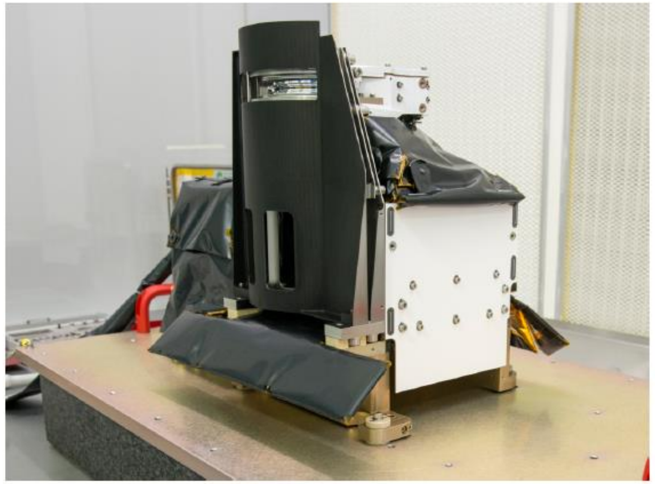
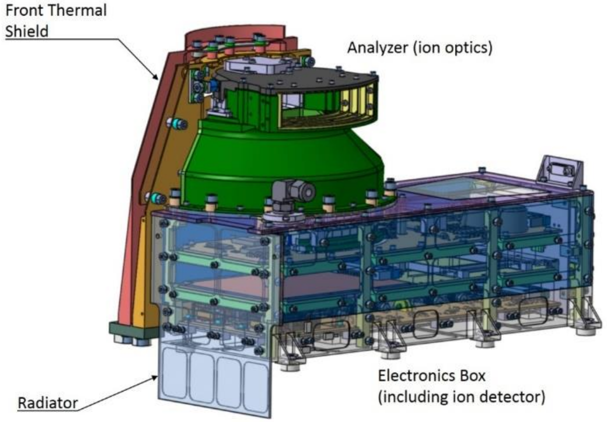
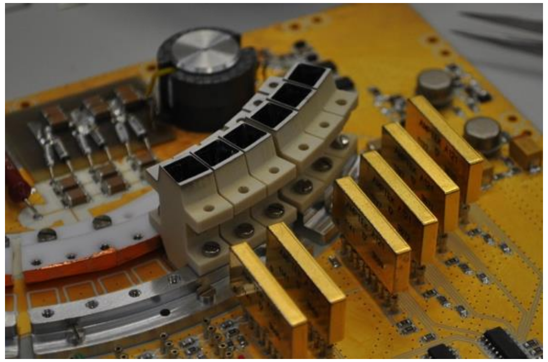
PAS : Principles of measurements

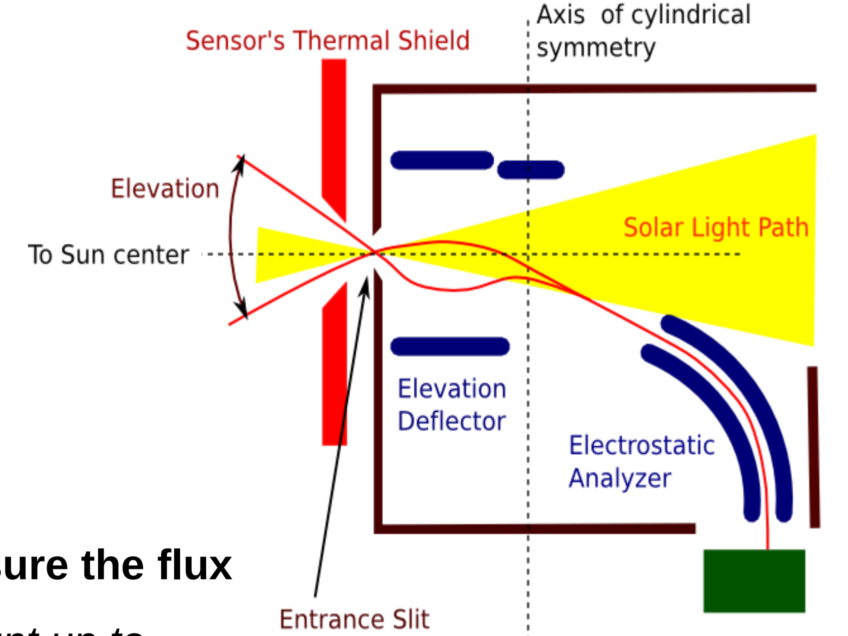
PAS Flight Model with MLI



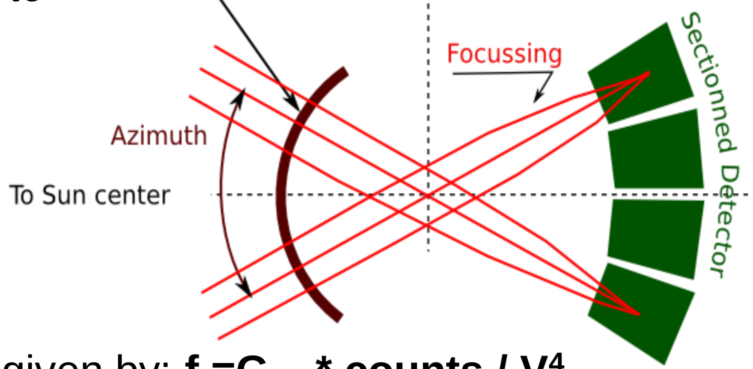




PAS combines an **electrostatic deflector** and **energy analyzer** to select the **energy** and **direction** of incident particles (selection of a portion of phase space) . *Done by sweeping the **high voltages** applied on the electrodes. (12 kV, 4-5 ms rising time, accuracy > 1%)*



11 detectors (one per azimuth sector) then **measure the flux** of selected particles *(use of channeltrons that count up to 10^7 counts/s with 'exposure time' of 1 ms) .*



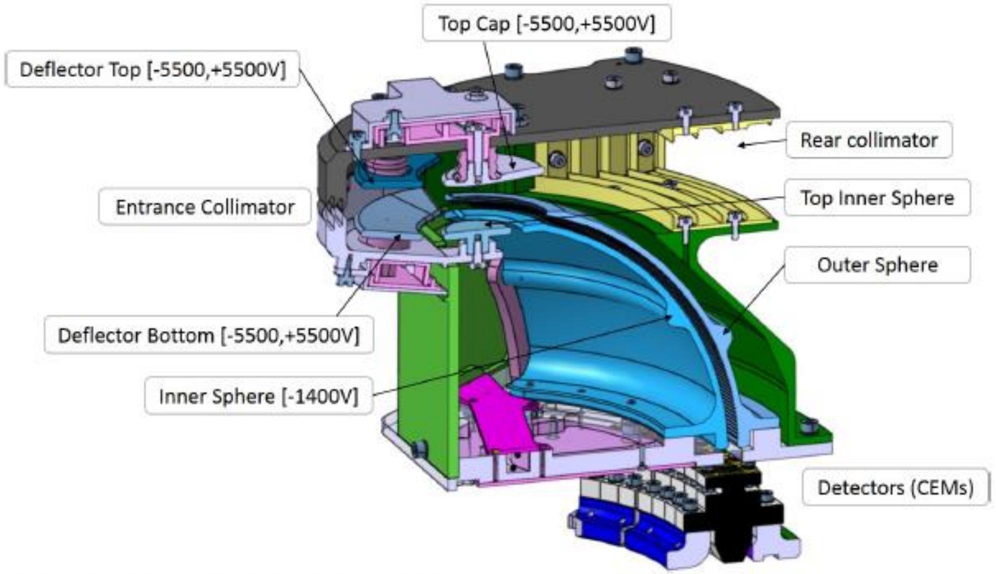
The basic product of PAS is then a 3D matrix (N_energy, N_elevation, N_azimuth) **of counts (c/s).**

Using the **'geometrical factor'** of the instrument **(G_{eff}~ 5. 10^{-6}** cm^2 sr eV/eV per pixel), the distribution is given by: **f =G_{eff} * counts / V^4** .

Characteristics: FOV: 45° in Elevation, 66° in Azimuth. Energy range: 200 eV – 20 keV; Energy res.: ΔE/E: 8% ; Angular res.: 6° Elev/Azim. Time res.:1 full 3D in 1 s.

Elements of PAS Optics design

Conception and model by A. Fedorov

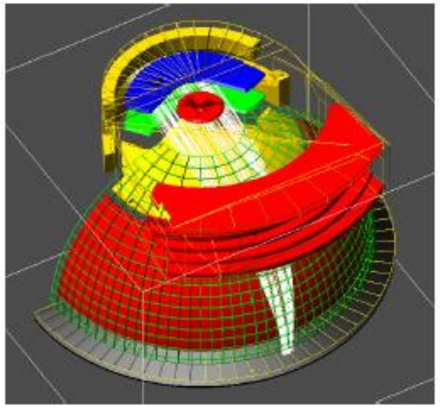


PAS analyzer ion optics elements.
Deflector system designed to fit the maximal possible HV.
CEMs ion detectors chosen with very wide dynamic range (0.1 to $10^7\ s^{-1}$) count rate and a long time of life.

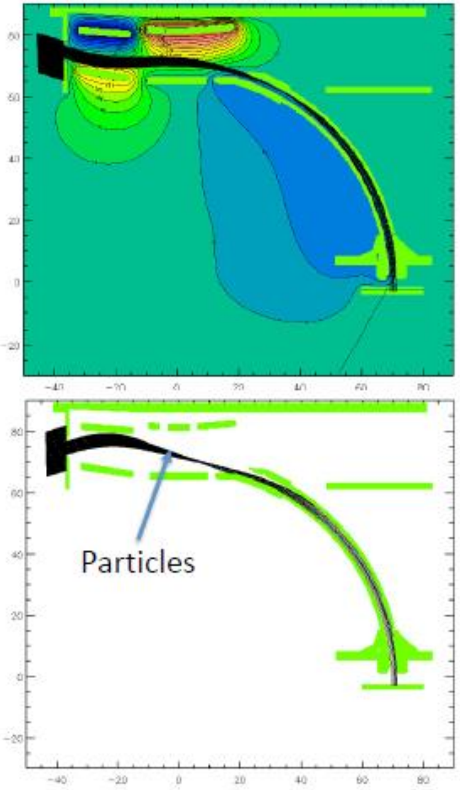
- Particle elevation steering via a thin slit
- Azimuthal information from detectors

Combination of a special deflector with a regular top-hat does the job

Analyzer for Heavy Ion Sensor (HIS)



Electrostatic particle tracing

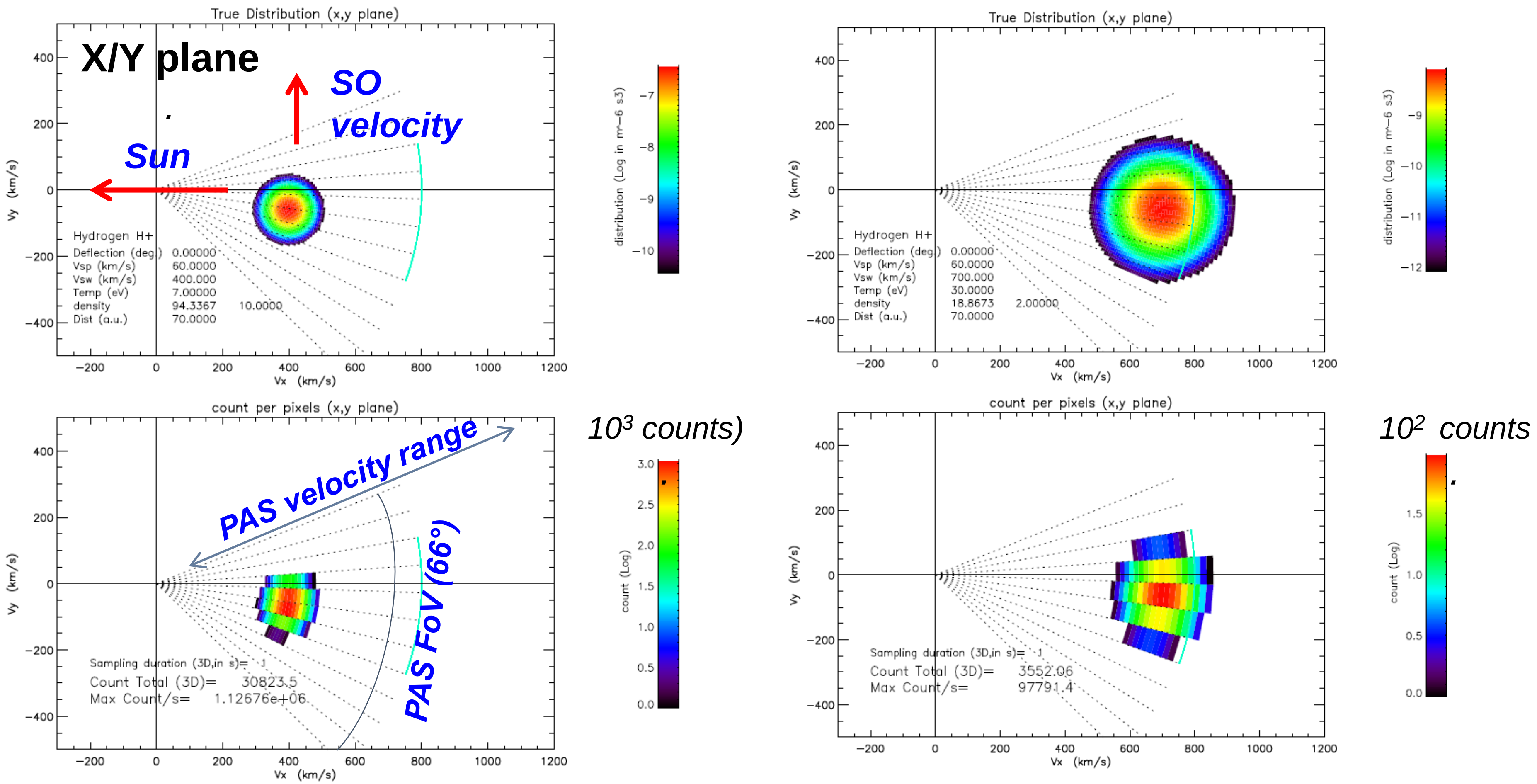


Measuring an 'ideal' Solar wind – Simulation 1

Slow 400 km/s, 7 eV, (10 cc at Earth) | Fast 700 km/s, 25 eV, (2 cc at Earth)

The 'simplest' Solar Wind (a shifted maxwellian) as seen with an ideal sensor (no limitation of sampling)

What should be seen by PAS



PAS measurements: ***96 energies*** *from 200 eV to 20 keV, 6x6° angular resolution,* ***11 azimuths and 9 elevations****, with ~ 1 ms elementary sampling time.* ***1s for a full 3D****.*

Note the dynamics, the statistics, the FOV to accomodate deviation

10^2 - 10^3 cts on 1 pixel at central peak, few 10^4 for a complete distribution

(would be 10 times less at Earth)

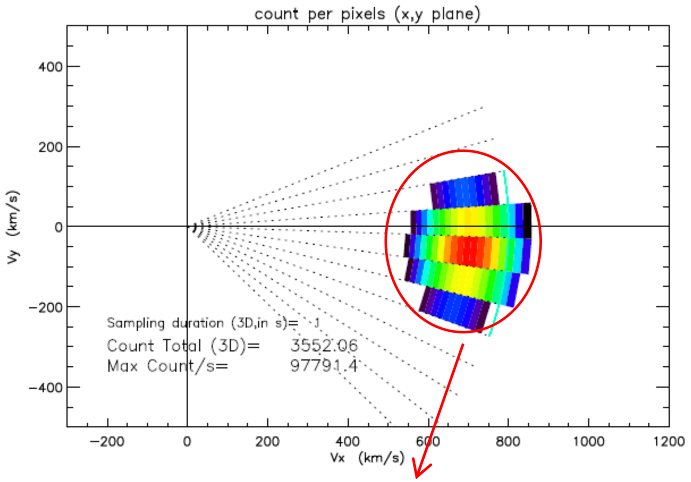
PAS perspective of the Solar wind.

1) Measurements at a **4s cadence of N, V, T and anisotropy**

2) With counts > 10^2 per pixels near the peak (~few 10^3 to 10^4 in total), **accuracy should not be a problem…**density should be measured at 1 %. Velocity should be determined at 20-30 km/s and 2-3° in direction.

Capability to investigate subtle modifications in the characteristics of the solar wind at accuracy of 1-2 % …

What about time resolution and Burst Modes ?



The 'ideal' solar wind only fills a small portion of the phase space. ***PAS will have the capability to 'zoom' on it*** *. By autonomous identification of the peak and proper operation of HT, measurements can be focussed at 24 or 32 energies and 5 elevations.* ***(Peak Tracking)***

Gain ~5-10 in time cadence

In burst modes, using the **'peak tracking'** scheme, measurements of (32,11,5) samples at 0.2 s (5 Hz) are possible. A jump in time and space resolution !

In principle, N,V,T fluctuations at ~ 50-100 km along flow and 10-20 km perp. to the flow

An analysis of the fluid characteristics down to 'microscopic' scales (Larmor radius)

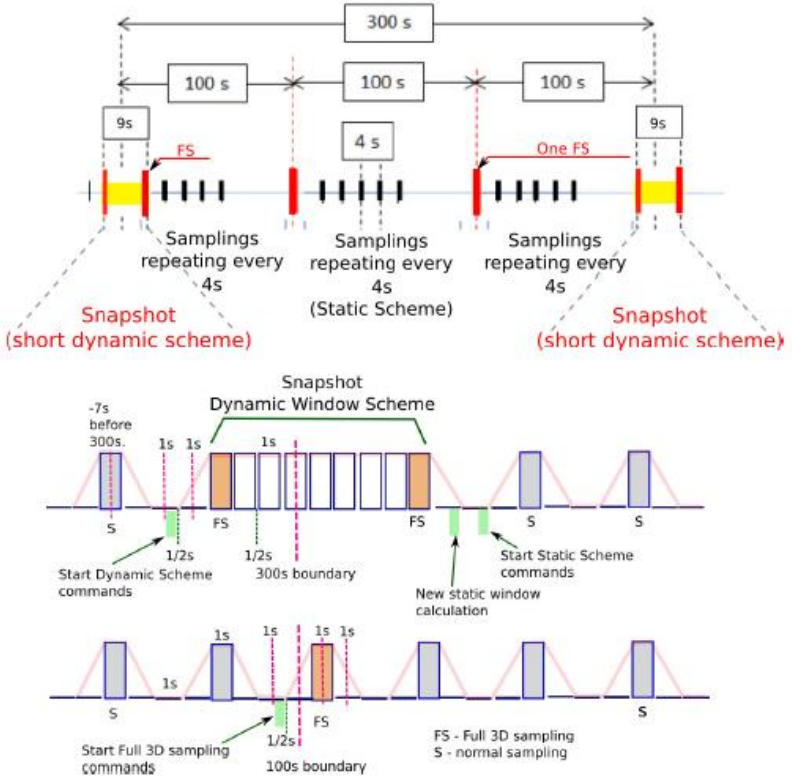
A much more accurate vision of Structures, Turbulence, Gradients etc…

Operation scheme

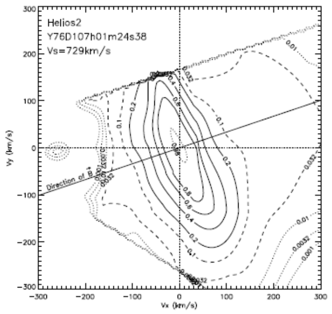
To cover both fluid and kinetic scales, the operation scheme is adapted to:

(1) make regular measurements at 4 s cadence

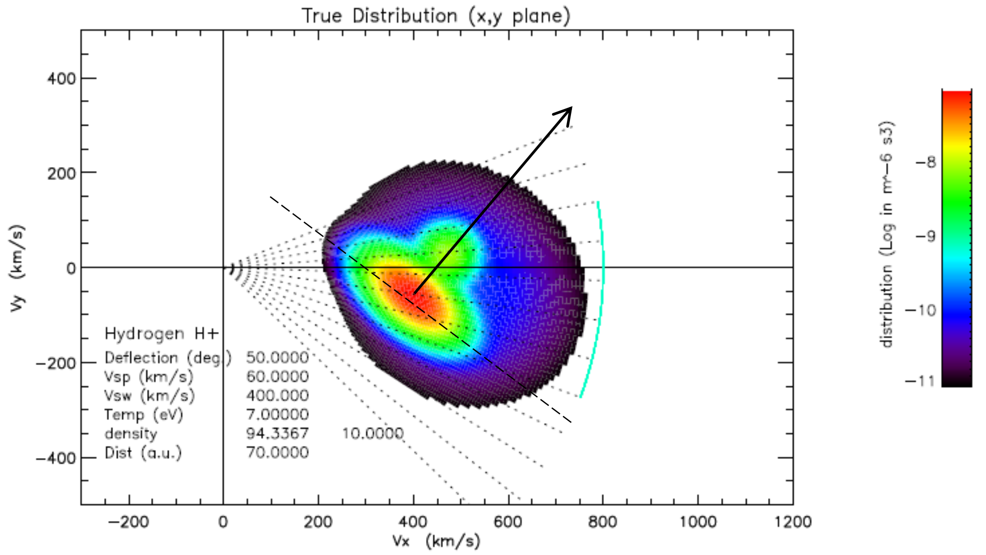
(2) get high time resolution ‘snapshots’ for 8 s each 300s. (up to 10 Hz)

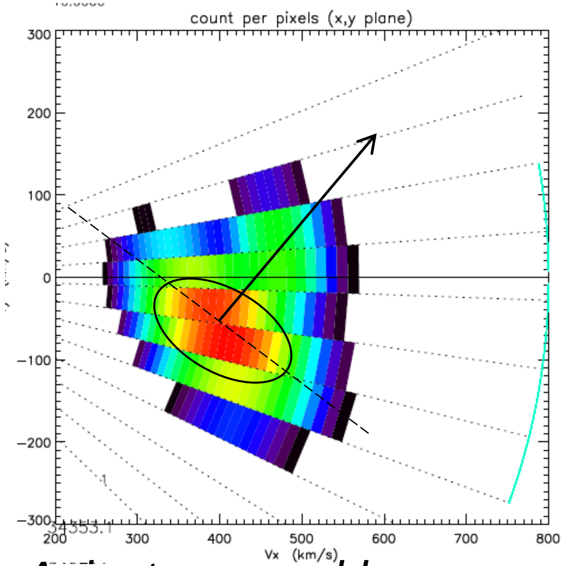


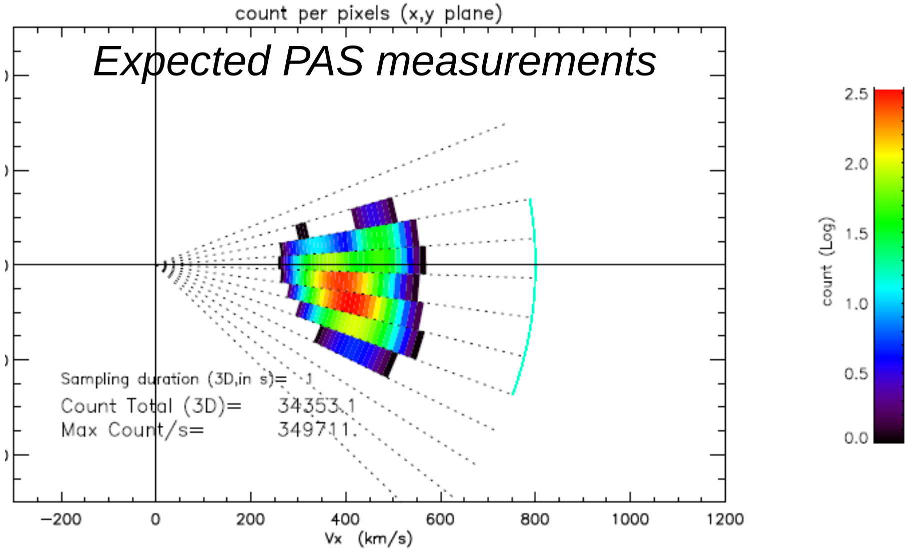
Example: Tpe=2 Tpa; tiny beam along B (5% of total density)



Highly anisotropic distribution from Helios *(Tu and Marsch, 2002)*





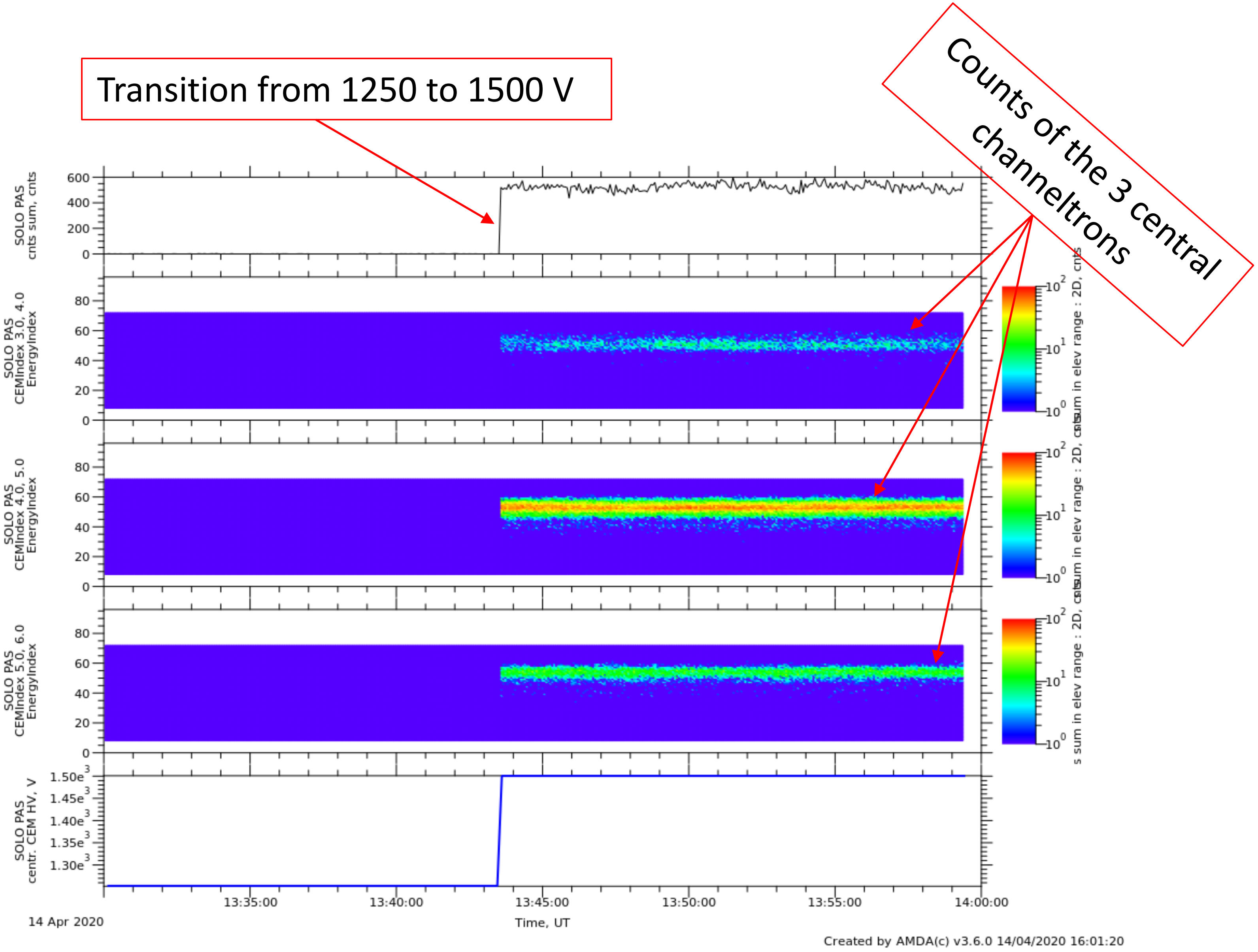


Anisotropy and beam are easily seen, at resolution < 1 second

More than 1000 counts to characterize the beam.

After ~10 years of design, conception, construction, calibration, what is the reality ?

First results from PAS commissioning

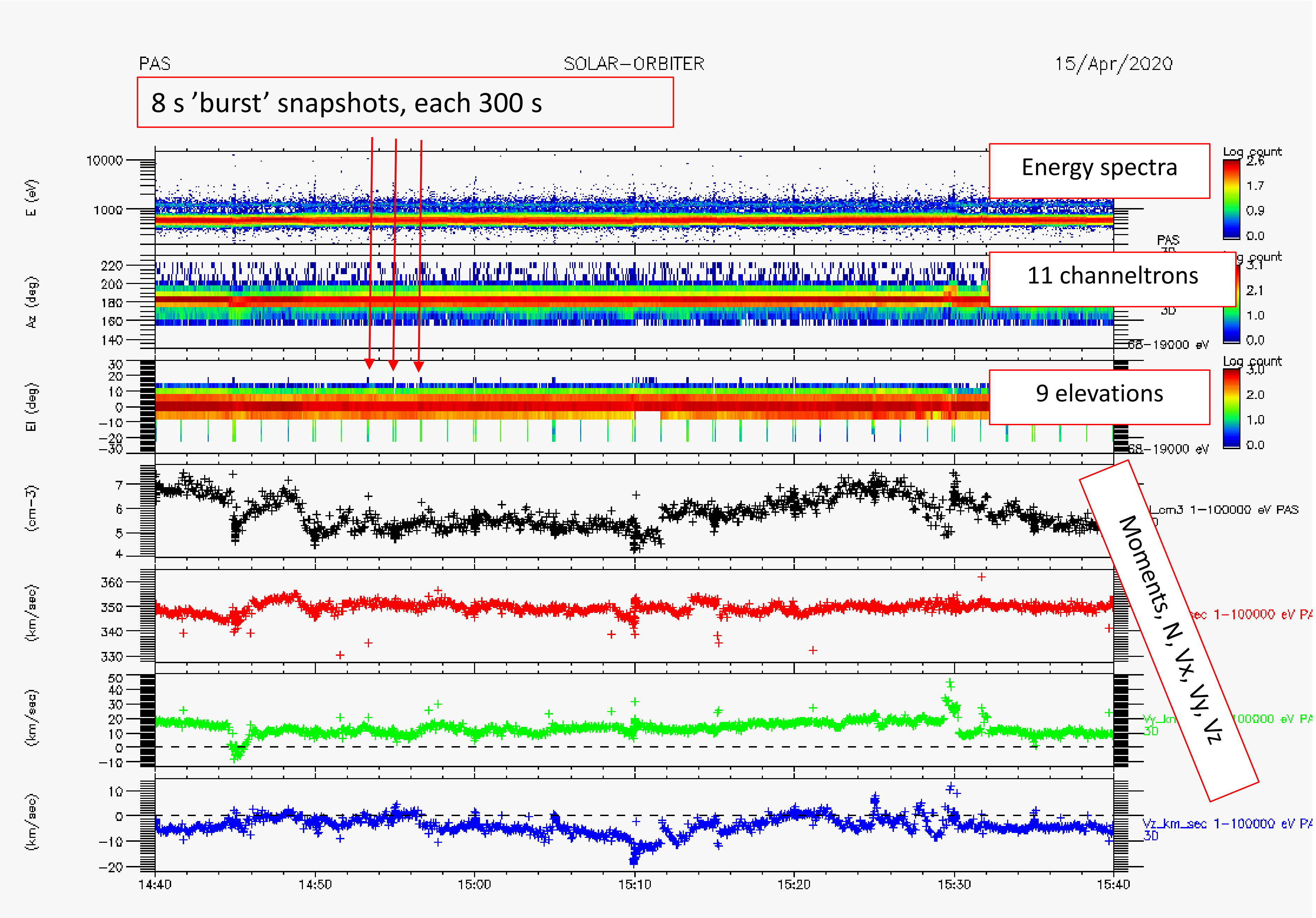


April 14th : FIRST LIGHT of PAS

Starting at ~11 UT, after several hours of slow ramping of the HVPS, from 0 to 6500 V for the main HT and 0 to 1250 V for the channeltrons, we finally approach the working point. This was a very smooth wake-up of the instrument, nominal in any respects.

Exactly at the transition to 1500 V, **PAS starts to see the Solar wind.**
This is the ‘first light’ of the sensor.

April 15th : PAS working in nominal scientific mode.



The first hour of PAS working in nominal scientific mode.

The nominal mode consists in

1) Reduced distribution each 4 s (5 elevation, 11 channeltrons and 48 energies)
2) 8 s snapshots each 300 s. Here, we run a fast mode, with reduced distributions at 4 Hz cadence!
3) A full 3 D distribution each 100 s to re-calibrate the peak tracking (how the center the 5 elevations and the 458 energies)

This works very well.

Moments seem very fine. *The variations seen at time of snapshots are normal.*

PAS working in nominal scientific mode (2)

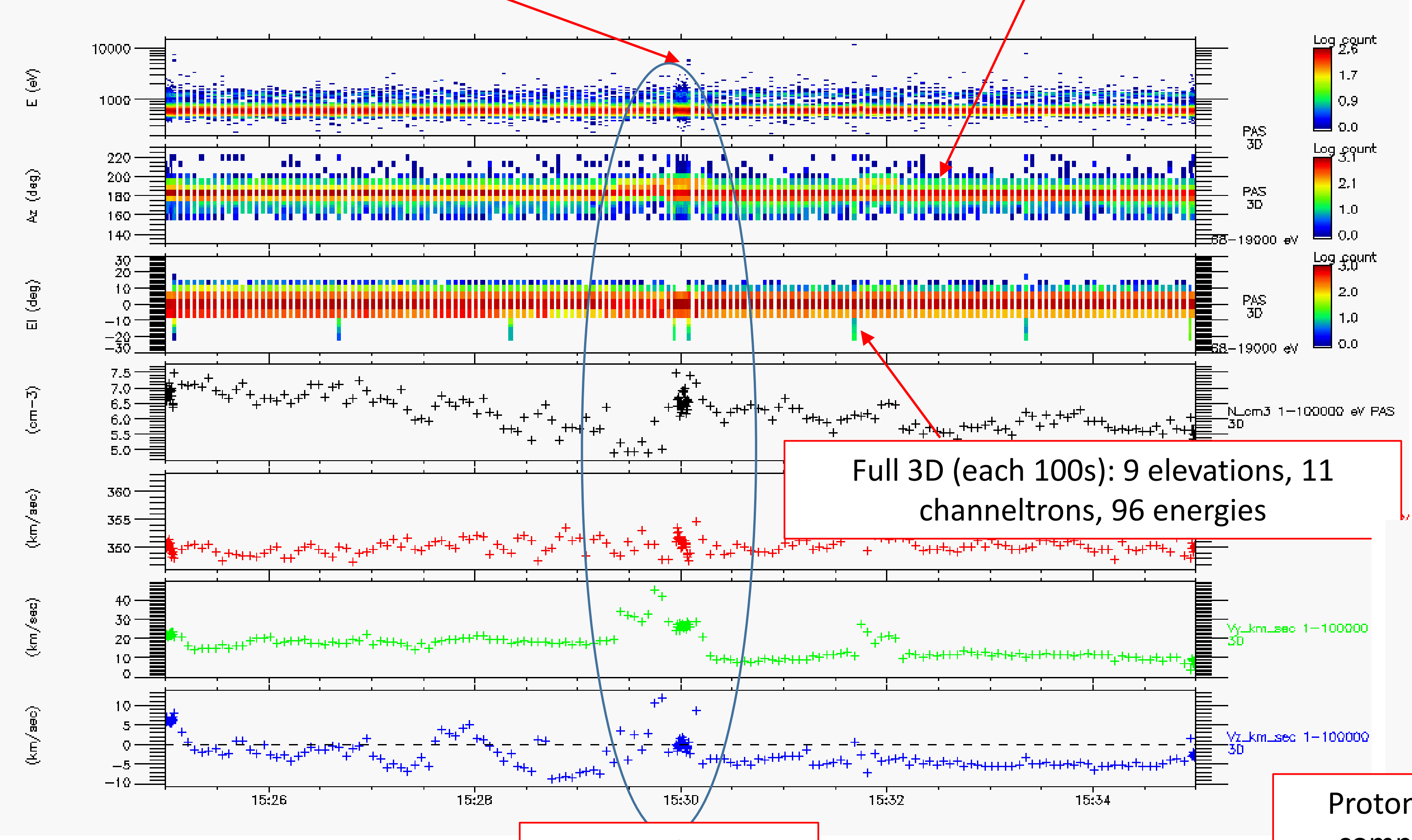
Details of 10 minutes of acquisition.

Given the count rates, we think that the few % variations in the moments are realistic. The instrument is indeed extremely stable (to be quantified).

Here, a real perturbation in SW at 15:30

Snapshots (each 300s): 1 full 3D + 28 reduced distribution (4 hz: 3 elevations, 11 channeltrons, 48 energies)

Nominal reduced distribution (each 4 s): 5 elevations, 11 channeltrons, 48 energies

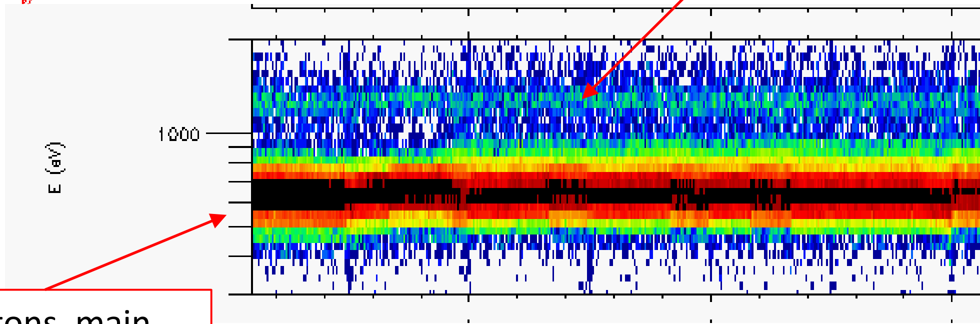


Full 3D (each 100s): 9 elevations, 11 channeltrons, 96 energies

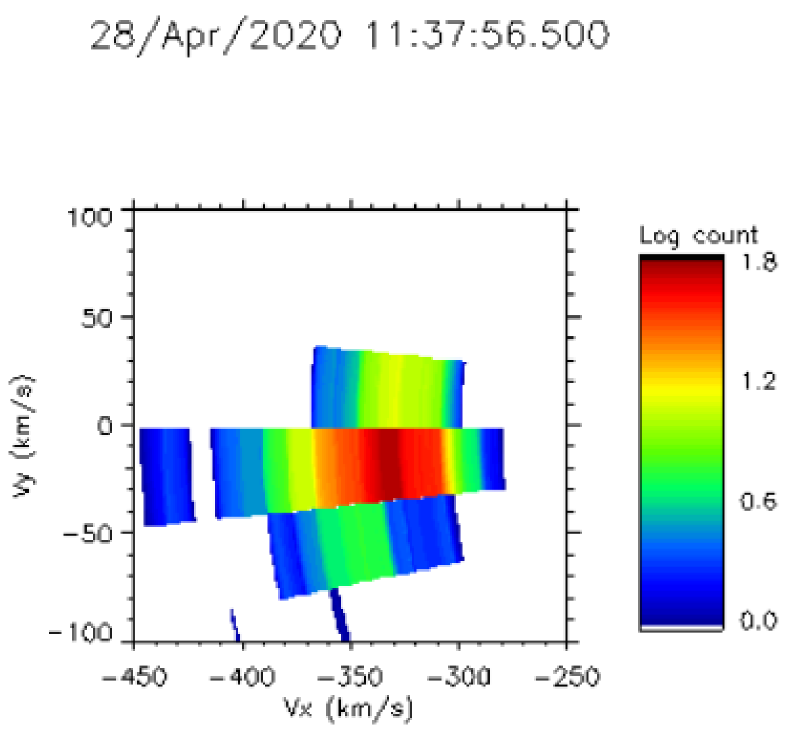
A perturbation !

Zoom on energy spectra

He ++



Protons, main components



Example of measured distribution function.
The counts are those expected from design.
Note the very rare isolated 1 count ‘event’

Conclusion:

After ~10 hours of measurements and several commissioning sequences, PAS appears to work extremely well, very close to what was designed and foreseen.

Very stable and low noise sensor

Excellent data have already been obtained, with complete 3D distributions at 4 s cadence.

A new vision of SW, at subsecond cadence !