INTERPRETATION AND MODELING OF PARTICLE SPECTRA

FROM COUNTS TO PHYSICAL UNITS

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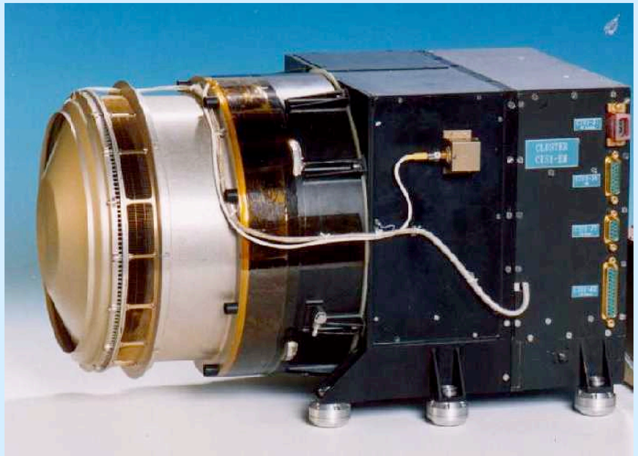


Solar-Terrestrial Interactions:

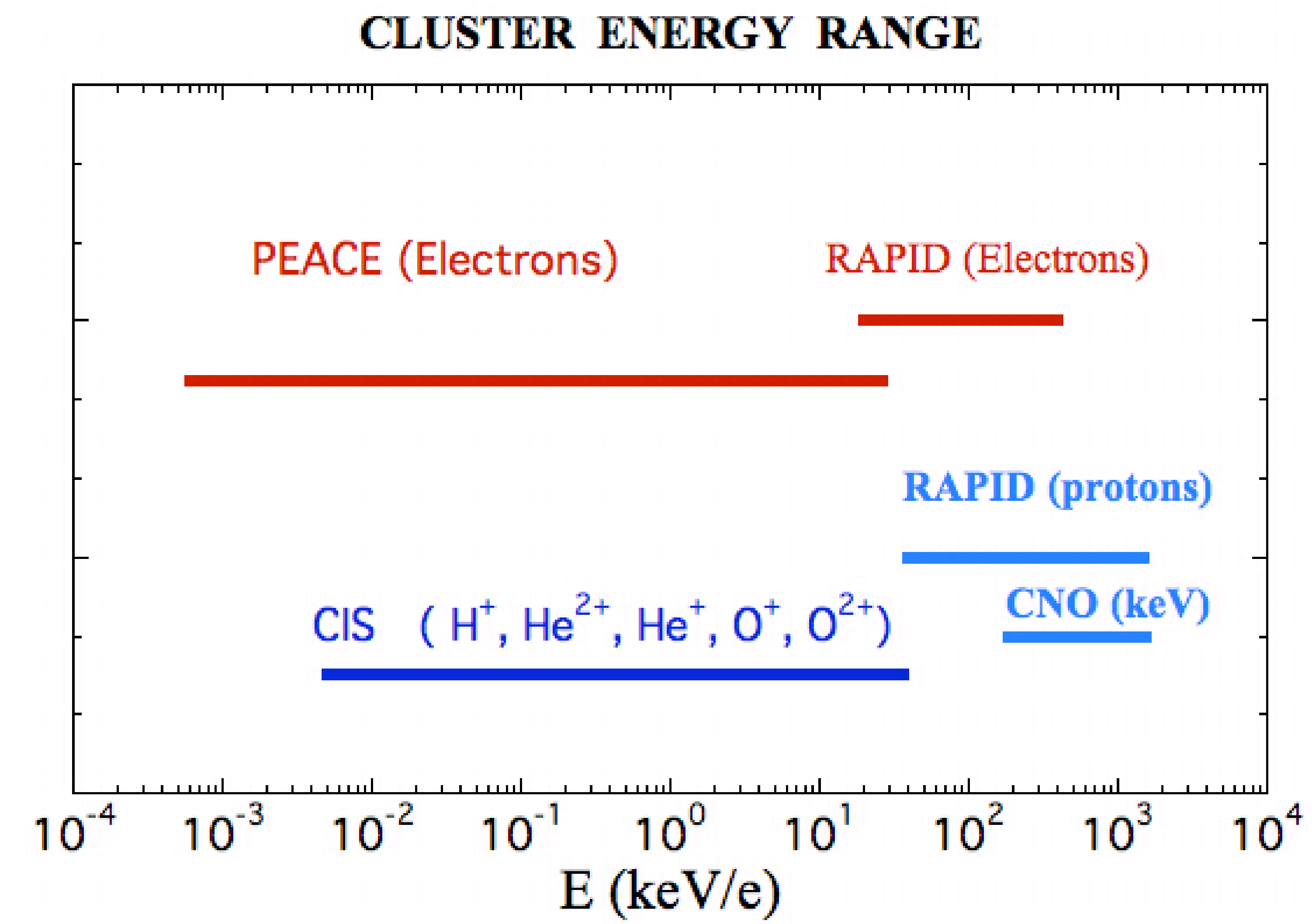
Instruments and Techniques (STIINTE)

Sinaia, Romania, June 4 - 16, 2007

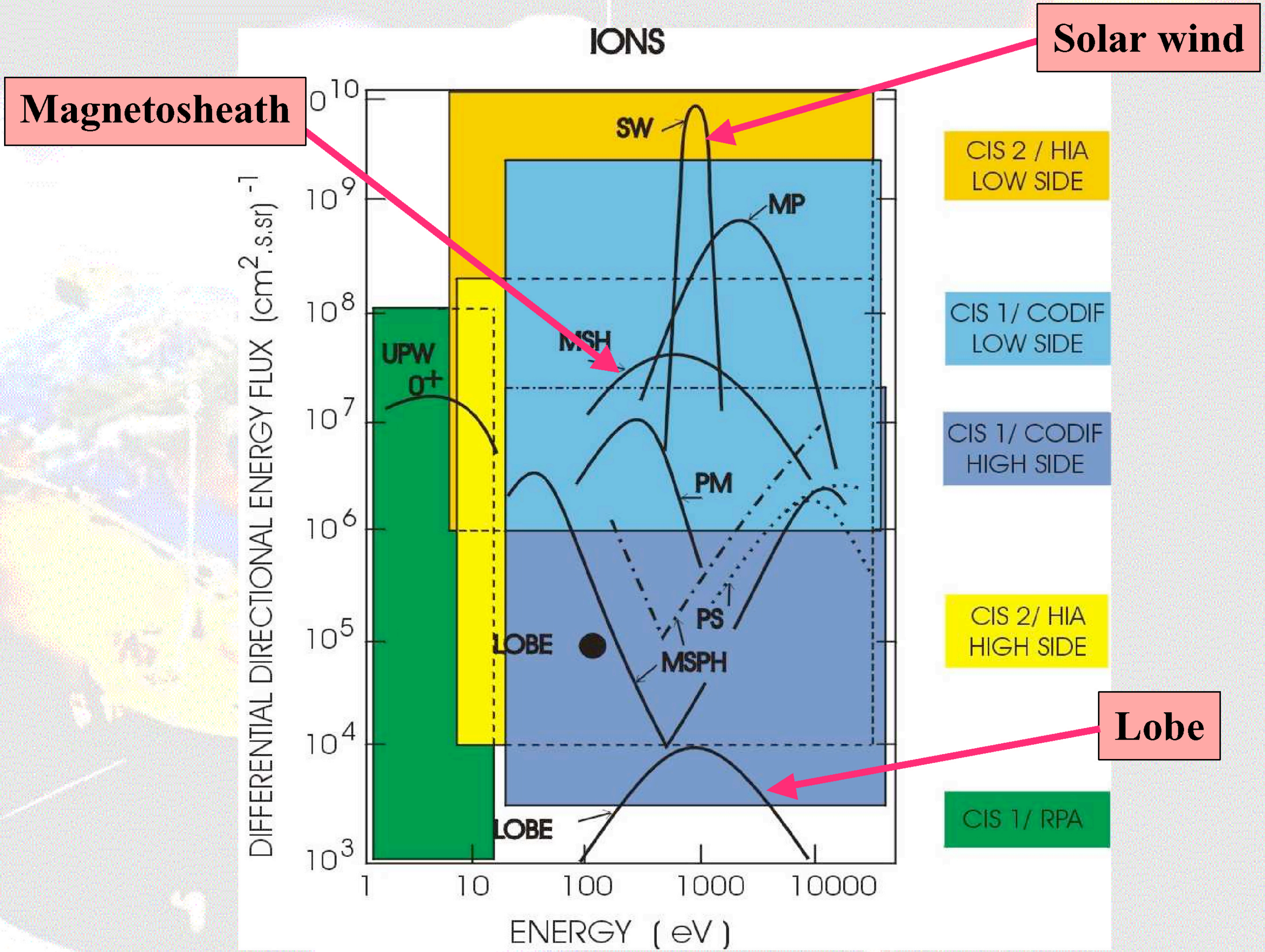
OUTLINE

1. The Cluster Particle Experiments
   The Ion Spectrometry Experiments
2. Onboard Data Processing - a Necessity
3. From Counts to Physical Units
4. Sensor Calibration
5. Some Examples of Spectrograms and 3D Distributions
6. Outlook to Computer Session

THE CLUSTER PARTICLE EXPERIMENTS

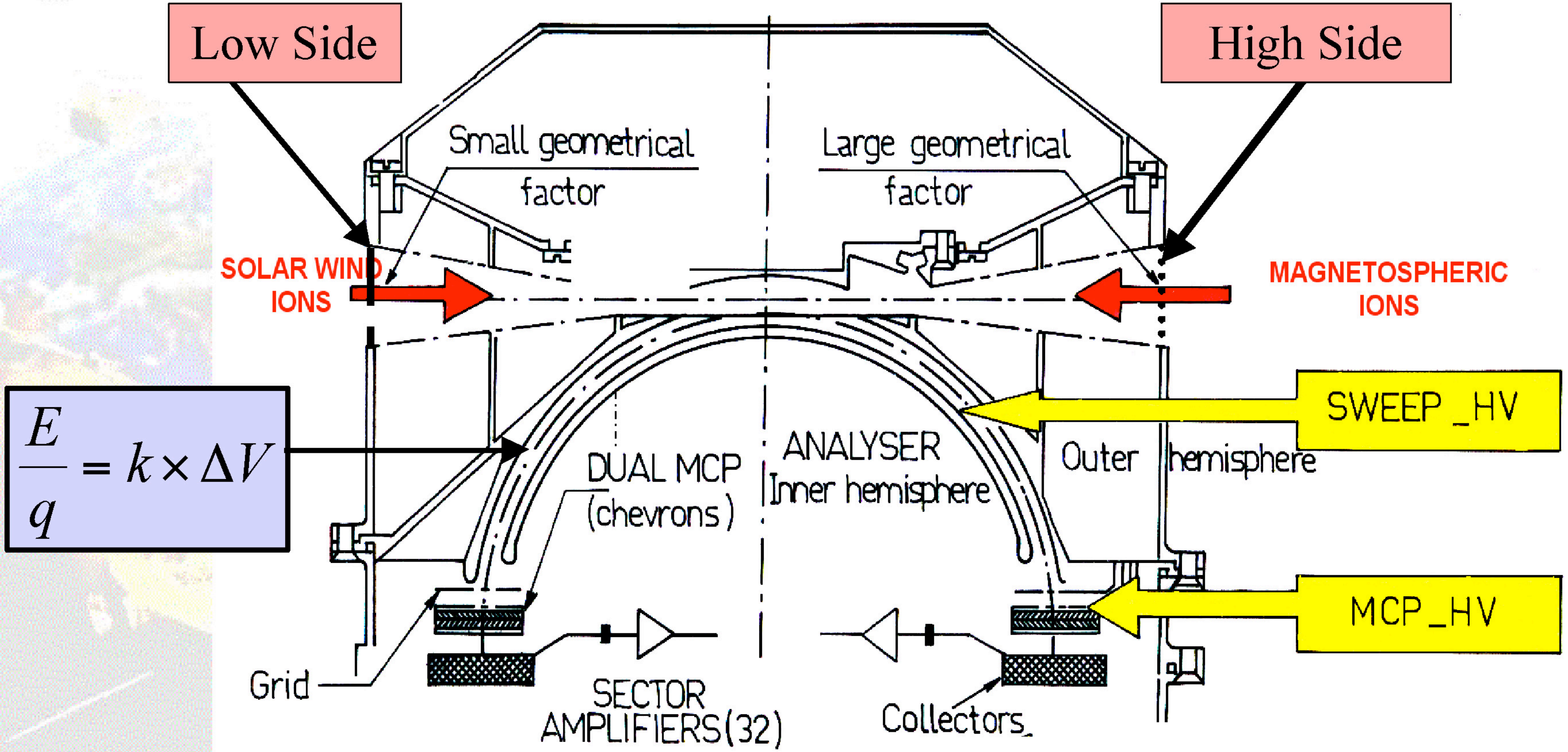


PARTICLE POPULATIONS IN THE MAGNETOSPHERE



Cluster Ion Spectrometry:

HIA: Hot Ion Analyser



E/Q, Φ, θ

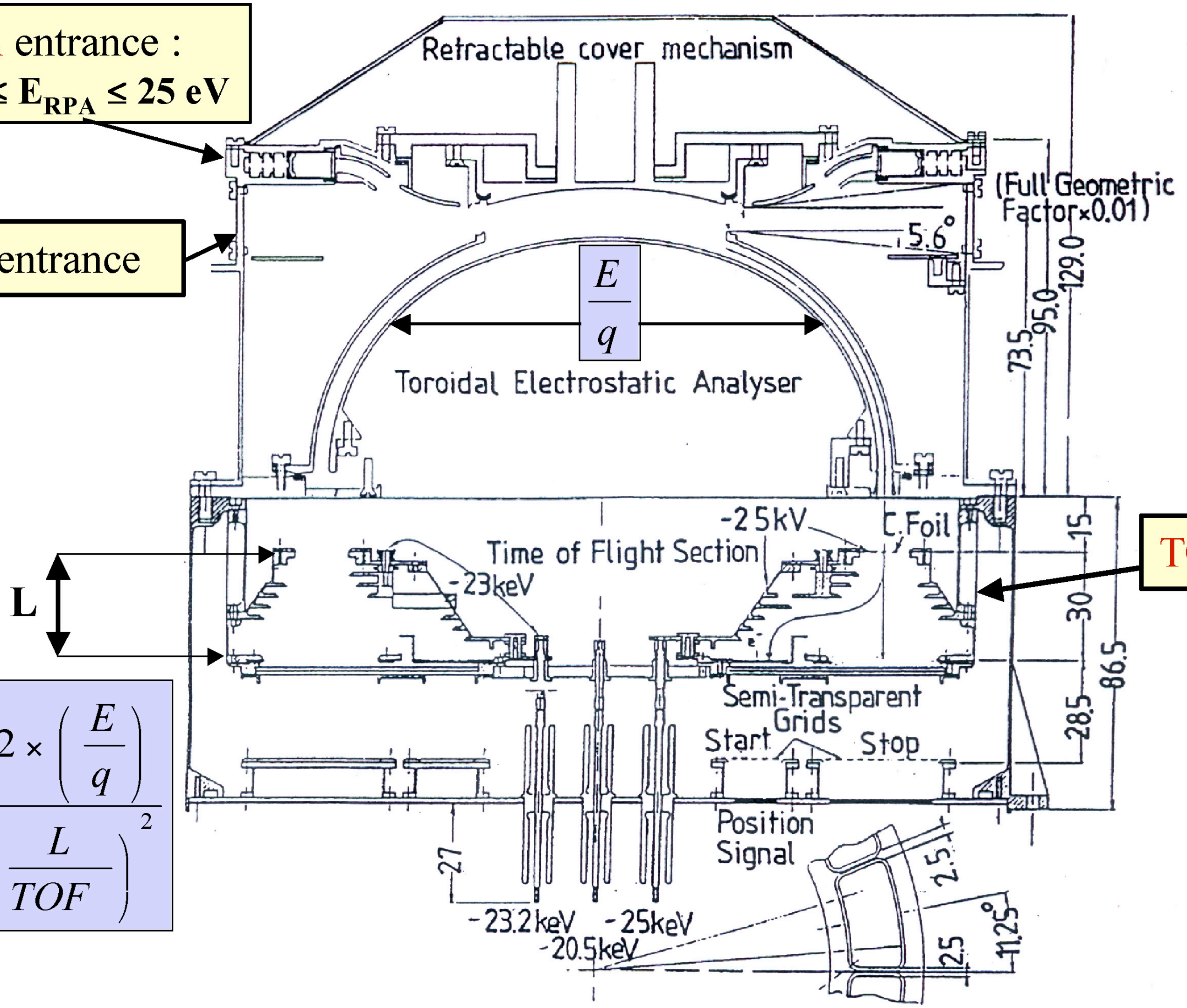
CODIF: Ion Composition and Distribution Function Analyser

RPA entrance :
≈ 0 eV ≤ E_{RPA} ≤ 25 eV

Main entrance

Reduced Entrance

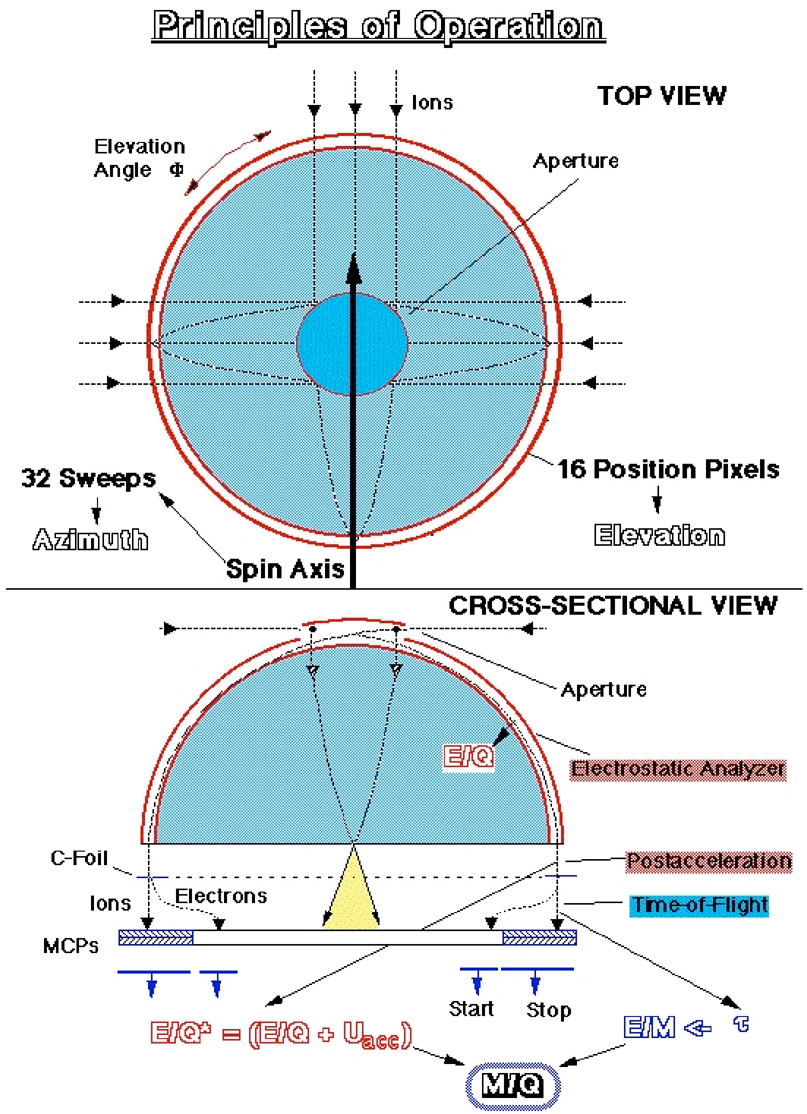
TOF system



$$\frac{m}{q} = \frac{2 \times \left(\frac{E}{q}\right)}{\left(\frac{L}{TOF}\right)^2}$$

E/Q, Φ, θ, TOF -> M/Q

CODIF SENSOR
Dynamic Range Improvement



SPIN AXIS

Measurement:

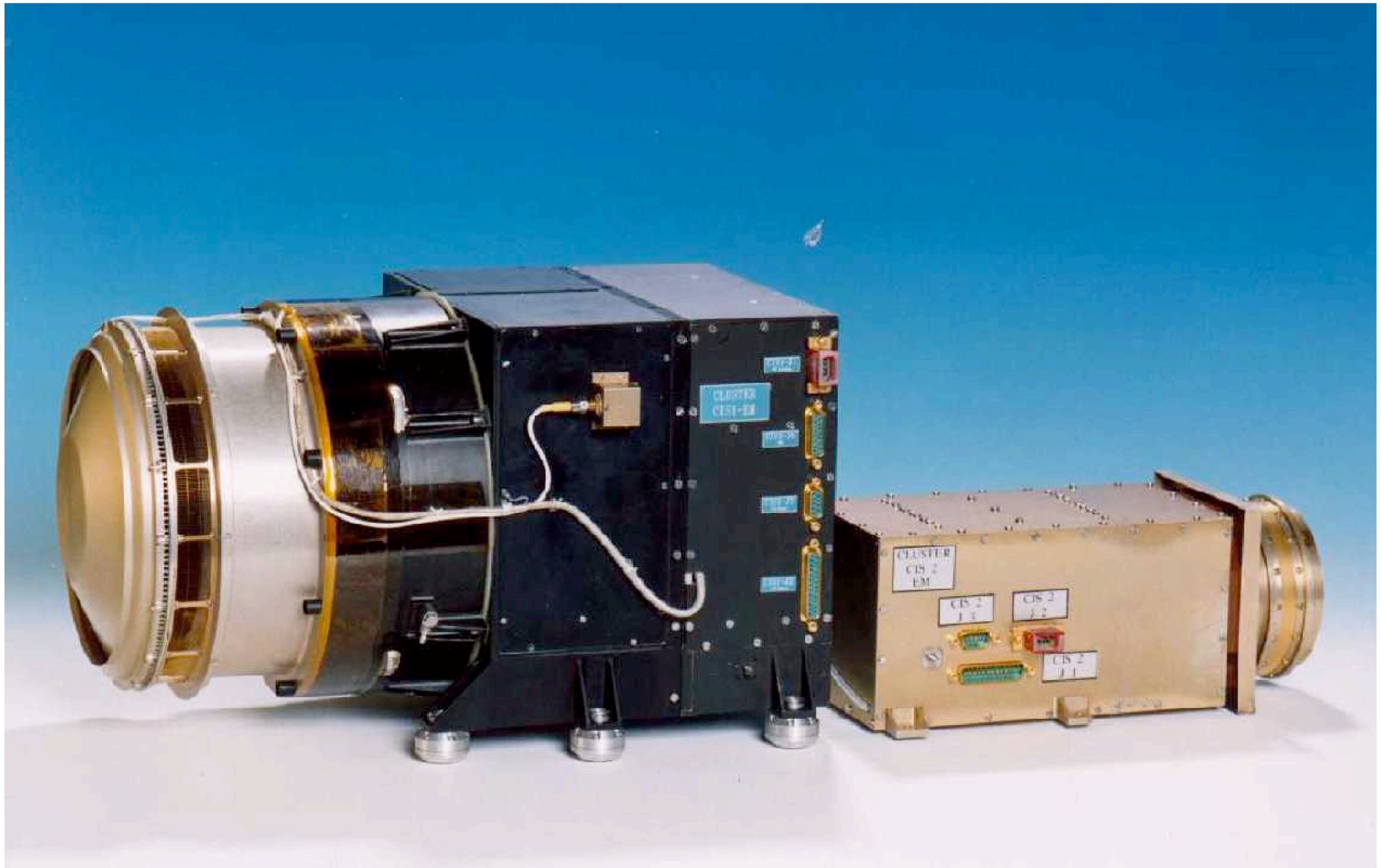
E/Q

Φ from Spin

θ from Position Pixel

TOF

Cluster Ion Spectrometry Experiment (CIS



CIS-1 (CODIF) **CIS-2 (HIA)**

ON BOARD DATA PROCESSING

Full Information for Each Ion

Parameter	Range	Bits
Time-of-Flight	0-255	8
Azimuth (Φ)	0-31	5
Mode Bit	0-1	1
Energy Step	0-127	7
Elevation (θ)	0-7	3
Total		**24**

+ time information

Event Rate:

up to several 100 kHz

Telemetry needed for full transmission:

several MB/s

Typical available: 5 - 10 kB/s

Onboard Processing is essential for data reduction !

ON BOARD DATA PROCESSING

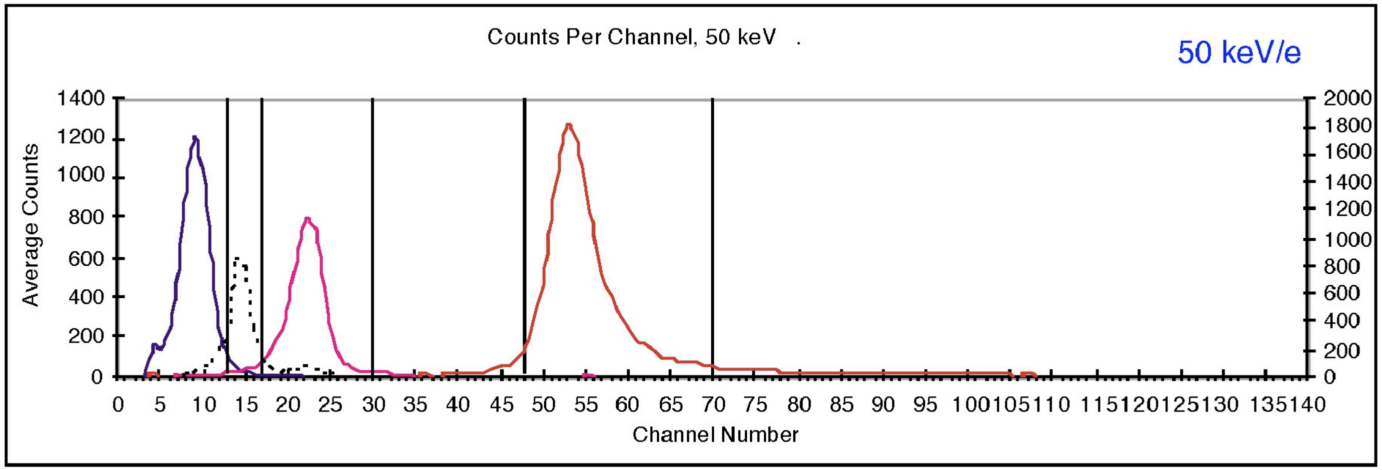
Measurement:

E/Q, Φ, θ, TOF → **E/Q, M/Q, Φ, θ (H^+, He^{2+}, He^+, O^+)**

M/Q: 1 2 4 16

Step 1: Fast M/Q Identification

$TOF_{MIN/MAX}$ (E/Q): **Thresholds for M/Q = 1, 2, 4, 16**



ON BOARD DATA PROCESSING

Step 2:

Accumulation of Count Arrays $C_{M/Q}$ (E/Q, Φ, θ)

M/Q = 1, 2, 4, 16		**4 bins**
E/Q:	**20 eV - 38 keV in**	**128 energy steps**
Φ:	**0 – 360° in**	**32 bins**
Θ:	**0 –180° in**	**8 bins**

4 x 128 x 32 x 8 x 4 = 131072 words /4s

too much for transmission

ON BOARD DATA PROCESSING

Step 3:

Compression in Energy:	**128**	→	**32**
Compression in Φ and Θ:	**32 x 8**	→	**88**
Compression of Φ and Θ to pitch angle α:	**128**	→	**16**

4 x 32 x 88 = 11264 * 16 bits / 4 s = 45 kBs

Still too large for transmission at full (1spin) resolution, but promising!

Step 4

Digital compression of 3D distributions

ON BOARD DATA PROCESSING

Step 5:

Transmit Plasma Characteristics at Full Time Resolution (1 spin = 4s)

Full Information on Plasma:

f(**r**,**v**,t) **Distribution Function**

(or phase space density) (p s^3 /m^6)

Examples: Maxwell-distribution,

Drifting Maxwell Distribution,

Kappa-distribution, etc.

THE MOMENTS OF THE DISTRIBUTION FUNCTION

Moments of the Distribution Function:

$$\int v^k f\,(r,v)\, d^3v,\ k = 0, 1, 2, 3, \ldots$$

K = 0: Density $N = \int f(r,v)\, d^3v$

K = 1: Bulk Velocity $w = 1/N \int v\ f(r,v)\, d^3v$

With $u = v - w$

K = 2: Pressure Tensor: $P = \int u \otimes u\ f(r,v)\, d^3v$

K = 3: Heat Flux: $H = \int u^2\ u\ f(r,v)\, d^3v$

Temperature: $N\,k\,T_i = P_{ii}$ **(from Pressure Tensor after diagonalization)**

DISTRIBUTION FUNCTION AND DIFFERENTIAL FLUX

Full Information on Plasma:

$f(\mathbf{r},\mathbf{v},t)$	Distribution Function	$(p/m^3\ m^3/s^3)$

Other Related Quantities:

$J(E)$	differential Particle Flux	$(p\ /\ cm^2\ s\ sr\ keV)$
$J(E) * E$	differential Energy Flux	$(p\ /\ cm^2\ s\ sr\ keV/keV)$

$$J(E,\mathbf{r})\ dE\ d\Omega = f\ (v)\ v^3\ dv\ d\Omega$$

$$J(E,\mathbf{r}) = v^2/m\ f(v,\mathbf{r})$$

ON BOARD DATA PROCESSING
DPU Tasks

- **Fast Particle Identification (M/Q) Using Time-of-Flight Measurement**
- **Compute Plasma Parameters (N, V, T, P) for H^+, He^{2+}, He^+, O^+**
- **Compute 3D Distributions (E/Q, θ, Φ) for H^+, He^{2+}, He^+, O^+**
- **Compute 2D Pitch Angle Distributions (E/Q, α) for H^+, He^{2+}, He^+, O^+**
- **Accumulate (small) Sample of Events with full (24 bit) Information**
- **Accumulate all Plasma Parameters once per Spin (4s)**
- **Accumulate 3D and 2D Distributions of H^+, He^{2+}, He^+, O^+ over several Spins (can be adjusted by command)**
- **Transmit All Telemetry Products to Ground**

The various Data sets (2D, 3D, Mom) are accumulated in pre-defined Products

ON BOARD DATA PROCESSING

Telemetry Products

Table 6. CODIF scientific telemetry products

Quantity	Product no.	Packet numbers	Basic Time (spins)	Total bits	bit/s
I. HOT POPULATIONS					
Moments 3ΔE(n,3v,6P,3H) × 4M	P7	1	1	1872 + 32	476
3D 64M×8E×6Ω *(6Ω: 2 polar, 4 perpendicular)*	P11	2	2	24 576 + 64	3080
3D protons 1M × 16E × 88Ω	P12	1	1	11 264 + 32	2824
3D protons 1M × 31E × 88Ω	P13	2	1	21 824 + 64	5472
3D protons 1M × 31E × 24Ω	P14	1	1	5952 + 32	1496
3D He^{++} 1M × 16E × 88Ω	P15	1	1	11 264 + 32	2824
3D He^{++} 1M × 31E × 88Ω	P16	2	1	21 824 + 64	5472
3D He^{+}, O^{+} 2M × 16E × 88Ω	P17	2	1	22 528 + 64	5648
3D He^{+}, O^{+} 2M × 31E × 88Ω	P18	4	1	43 776 + 128	10 944
3D He^{+} 1M × 16E × 88Ω	P32	1	1	11 264 + 32	2824
3D O^{+} 1M × 16E × 88Ω	P33	1	1	11 264 + 32	2824
3D He^{+} 1M × 31E × 88Ω	P34	2	1	21 824 + 64	5472
3D O^{+} 1M × 31E × 88Ω	P35	2	1	21 824 + 64	5472
2D 4M × 31E × 16ϕ* 2D 2M × 16E × 16ϕ (protons + He^{++})** or 4M × 16E × 8ϕ **	P19 P21 P20	1 1 1	1 1 1	15 872 + 32 4096 + 32 4096 + 32	3976 1032 1032
2D protons 1M × 31E × 32ϕ	P22	1	1	7936 + 32	1992
2D PAD Cut 4M × 16E × 8θ (2 slices/spin when B is in the field of view)**	P23	1/slice	0.5	4096 × 2 + 2 × 32	2064 (1032/slice)
2D PAD Cut 4M × 31E × 8θ (2 slices/spin when B is in the field of view)*	P24	1/slice	0.5	7936 × 2 + 2 × 32	3984
Monitor Counting Rates 18 signals × 16E × 16ϕ	P27	8	32 spins	36 864 + 256	290

A Mix of products can be transmitted by selecting specific MODES

ON BOARD DATA PROCESSING

Instrument Modes

Table 7. Cluster-2 CIS operations modes

			Telemetry modes Cis-2 bitrate (bps)				Telemetry modes Cis-1 bitrate (bps)			
Mode		Mode Name	NM1	NM2	NM3	BM1	NM1	NM2	NM3	BM1
0	SW-1	Solar wind / SW tracking	1 272	1 272	1 272	7 000	4 255	5 252	3 231	19 762
1	SW-2	Solar wind / 3D backstreaming ions	1 272	1 272	1 272	7 000	4 255	5 252	3 231	19 762
2	SW-3	Solar wind / SW tracking	2 135	2 135	2 135	13 162	3 392	4386	2 368	13 600
3	SW-4	Solar wind / 3D backstreaming ions	2 135	2 135	2 135	13 162	3 392	4386	2 368	13 600
4	SW-C1	COMPRESSION SW-3 (+3Ds) solar wind tracking	2 135	2 135	2 135	13 162	3 392	4386	2 368	13 600
5	SW-C2	COMPRESSION SW-4 (+3Ds) backstreaming ions	2 135	2 135	2 135	13 162	3 392	4386	2 368	13 600
6		RPA								
7	PROM	PROM operation								
8	MAG-1	Magnetosphere 1	1 272	1 272	1 272	7 000	4 255	5 252	3 231	19 762
9	MAG-2	Magnetosphere 2	2 135	2 135	2 135	13 162	3 392	4386	2 368	13 600
10	MAG-3	Magnetosphere 3	3 124	4 148	2 135	13 162	2 403	2 373	2 368	13 600
11	MAG-4	MAG-1 sheath/tail	1 272	1 272	1 272	7 000	4 255	5 252	3 231	19 762
12	MAG-5	MAG-2 sheath/tail	2 135	2 135	2 135	13 162	3 392	4386	2 368	13 600
13	MAG-C1	Compression MAG-1 + 3Ds	1 272	1 272	1 272	7 000	4 255	5 252	3 231	19 762
14	MAG-C2	Compression MAG-4 + 3Ds sheath/tail	1 272	1 272	1 272	7 000	4 255	5 252	3 231	19 762
15	CAL	Calibration								

RELATION BETWEEN MEASUREMENT AND PLASMA PARAMETERS

SENSOR

$A\Omega$	Geometric Factor
ε	Efficiency (< 1)
$\Delta E/E$	Energy Resolution

J(E) → SENSOR → C (E Φ, θ , M/Q)

C: COUNTS

$$J(E) * A\Omega * \varepsilon(E, \theta, M/Q, t) * \Delta E * \Delta t = C$$

(p / cm^2 sr s keV) * (cm^2 sr) * keV * s = particles (or counts: C)

$$J(E) * E * A\Omega * \varepsilon * (\Delta E/E) * \Delta t = C$$

MOMENT COMPUTATIONS

Density: $N = \sum_E 1/V/(E) \sum_{\Phi} \sum_{\theta} C(E\ \Phi, \theta) / \Delta t\ / \varepsilon (E\ \Phi, \theta)$

Velocity: $N V_X = \sum_E \sum_{\Phi} \cos(\Phi) \times \sum_{\theta} \cos(\theta) \times C(E\ \Phi, \theta) / \Delta t\ / \varepsilon (E\ \Phi, \theta)$

$N V_Y = \sum_E \sum_{\Phi} \sin(\Phi) \times \sum_{\theta} \cos(\theta) \times C(E\ \Phi, \theta) / \Delta t\ / \varepsilon (E\ \Phi, \theta)$

$N V_Z = \sum_E \sum_{\Phi} \sum_{\theta} \sin(\theta) \times C(E\ \Phi, \theta) / \Delta t\ / \varepsilon (E\ \Phi, \theta)$

Heat Flux

$N H_X = \sum_E V^2(E) \sum_{\Phi} \cos(\Phi) \sum_{\theta} \cos(\theta) \times C(E\ \Phi, \theta) / \Delta t\ / \varepsilon (E\ \Phi, \theta)$

$N H_Y = \sum_E V^2(E) \sum_{\Phi} \sin(\Phi) \sum_{\theta} \cos(\theta) \times C(E\ \Phi, \theta) / \Delta t\ / \varepsilon (E\ \Phi, \theta)$

$N H_Z = \sum_E V^2(E) \sum_{\Phi} \sum_{\theta} \sin(\theta) \times C(E\ \Phi, \theta) / \Delta t\ / \varepsilon (E\ \Phi, \theta)$

Note: V(E/M) = V(E/Q * Q/M)

Moments will not be correct if M/Q is incorrect

MOMENT COMPUTATIONS

Pressure Tensor:

$N\ P_{XX} = \sum_E V(E) \sum_{\Phi} \cos^2(\Phi) \times \sum_{\theta} \cos^2(\theta) \times C(E\ \Phi, \theta) / \Delta t\ / \varepsilon(E\ \Phi, \theta)$

$N\ P_{YY} = \sum_E V(E) \sum_{\Phi} \sin^2(\Phi) \times \sum_{\theta} \cos^2(\theta) \times C(E\ \Phi, \theta) / \Delta t\ / \varepsilon(E\ \Phi, \theta)$

$N\ P_{ZZ} = \sum_E V(E) \sum_{\Phi} \sum_{\theta} \sin^2(\theta) \times C(E\ \Phi, \theta) / \Delta t\ / \varepsilon(E\ \Phi, \theta)$

$N\ P_{XY} = \sum_E V(E) \sum_{\Phi} \cos(\Phi) \sin(\Phi) \times \sum_{\theta} \cos^2(\theta) \times C(E\ \Phi, \theta) / \Delta t\ / \varepsilon(E\ \Phi, \theta)$

$N\ P_{XZ} = \sum_E V(E) \sum_{\Phi} \cos(\Phi) \times \sum_{\theta} \sin(\theta) \cos(\theta) \times C(E\ \Phi, \theta) / \Delta t\ / \varepsilon(E\ \Phi, \theta)$

$N\ P_{YZ} = \sum_E V(E) \sum_{\Phi} \sin(\Phi) \times \sum_{\theta} \sin(\theta) \cos(\theta) \times C(E\ \Phi, \theta) / \Delta t\ / \varepsilon(E\ \Phi, \theta)$

INSTRUMENT CALIBRATION

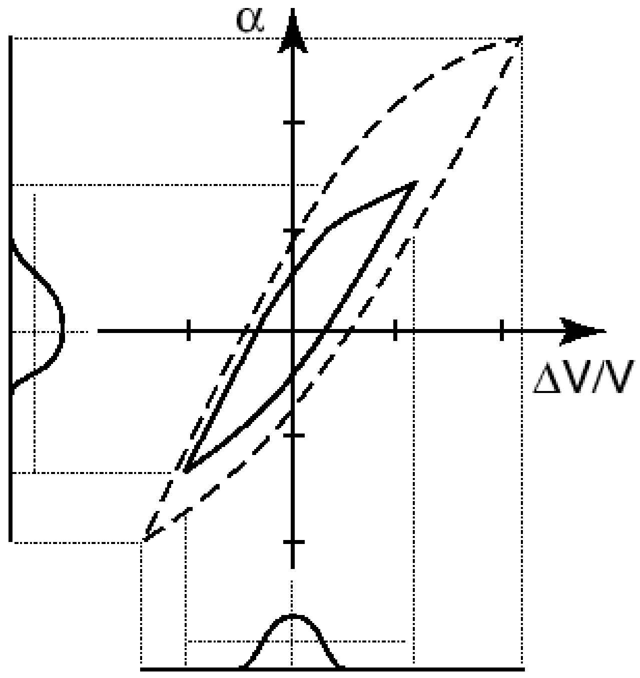
The Evaluation of the instrument response as a function of

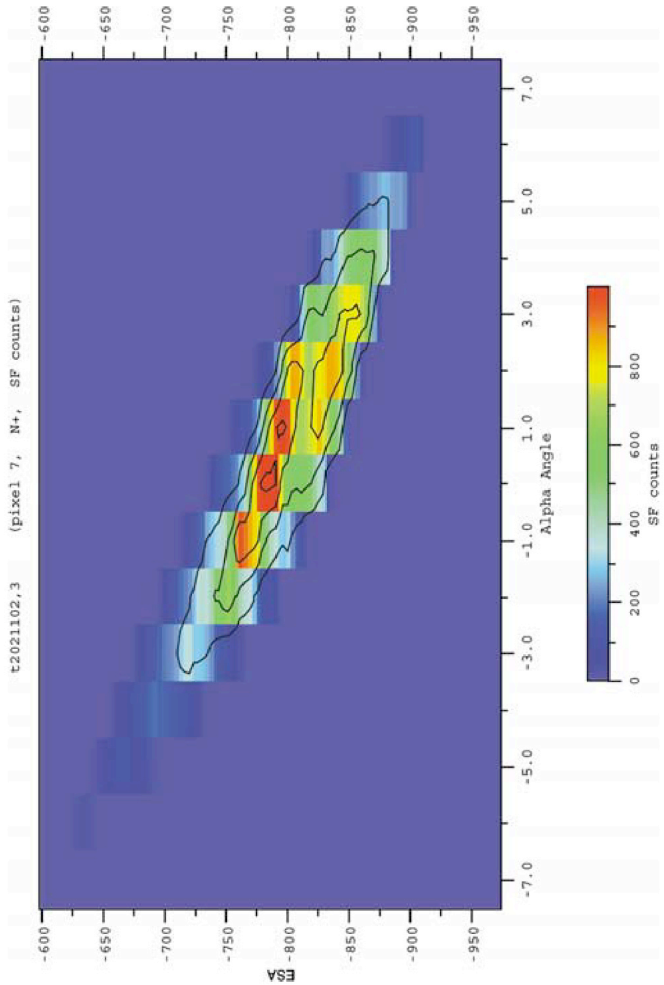
E, M/Q, Φ, θ

requires extensive calibration.

1. **Pre-Flight: Ion Beams (H^+, He^+, O) at various energies for**
   a) **calibration of the analyzer response: AΩ**
   b) **Calibration of the time-of-flight response ε (E, M/Q, Φ, θ)**
2. **In-Flight Calibration**
   a) **Cross calibration of CIS 1 / CIS 2 on each Cluster spacecraft**
   b) **Intercalibration of CIS on Cluster 1 - 3 - 4**
   c) **Intercalibration of CIS with other instruments onboard Cluster (e.g. for Density: WHISPER)**

INSTRUMENT CALIBRATION
Energy - Angle Response of an Electrostatic Analyzer





Klumpar et al., Space Science Rev, 98, 2001

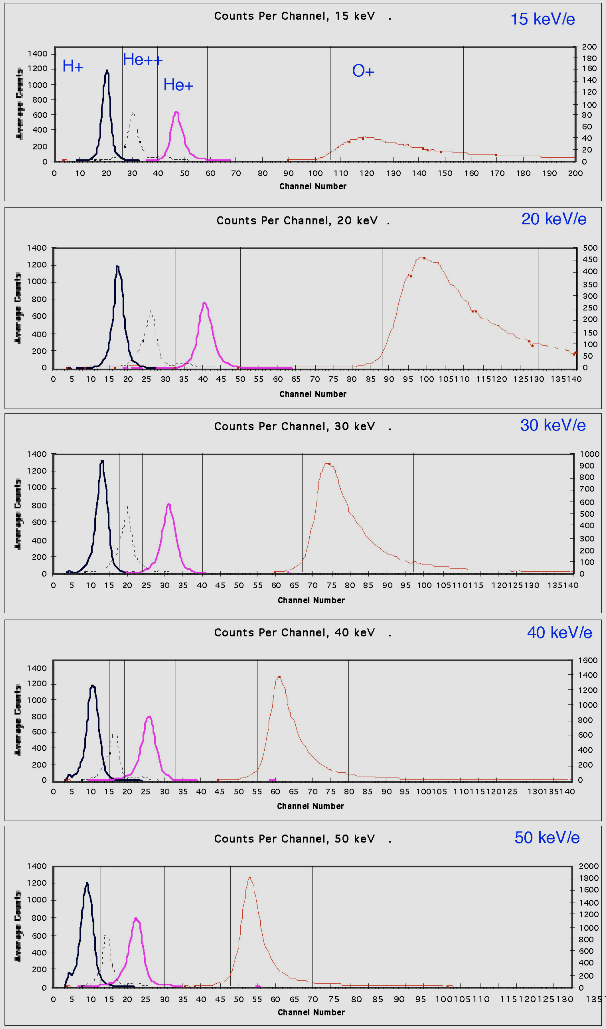
INSTRUMENT CALIBRATION
Time-of-Flight Response

Cluster II Calibration

FM 7

E/Q: 15, 20, 30, 40, 50 keV/e

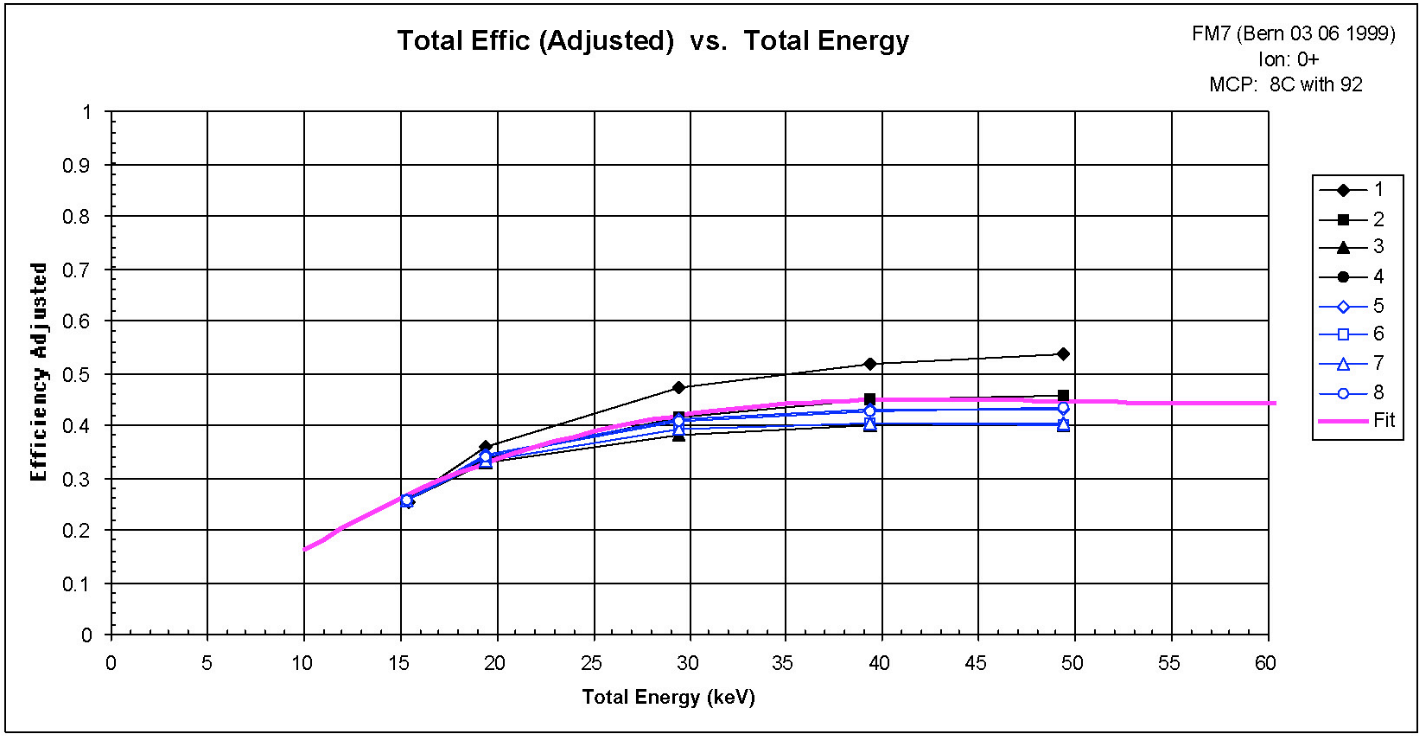
Ions: H^+, He^{2+}, He^+, O^+, O^{2+}, etc



CODIF CLUSTER FM7 time-of-flight spectra for the four major species at 4 energies.The lines show the thresholds used to distinguish species.

INSTRUMENT CALIBRATION

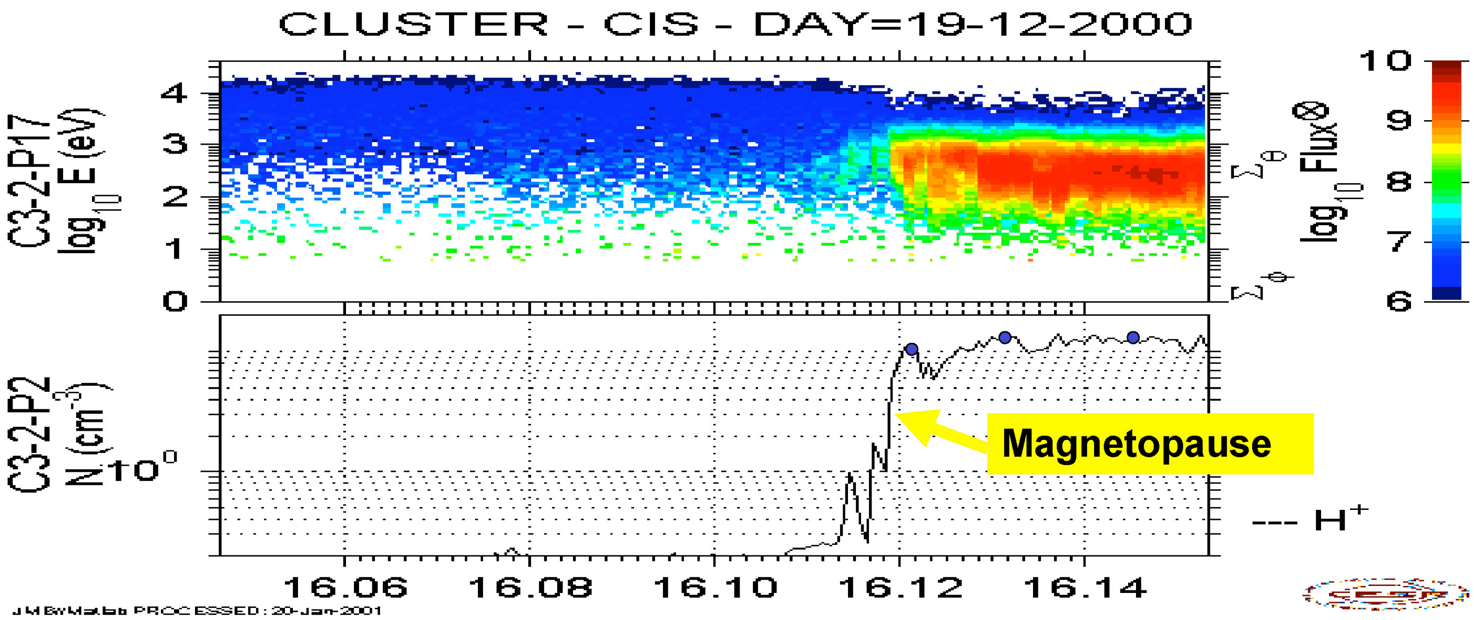
Pre-Flight Efficiency

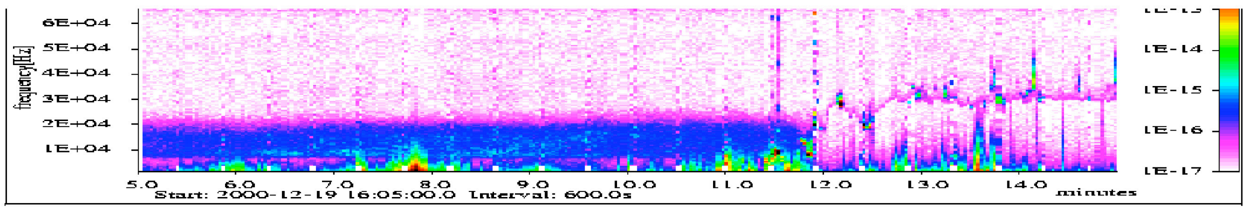


O^+

Klumpar et al., Space Science Rev, 98, 2001

INSTRUMENT CALIBRATION
Cross Calibration - Density (WHISPER)





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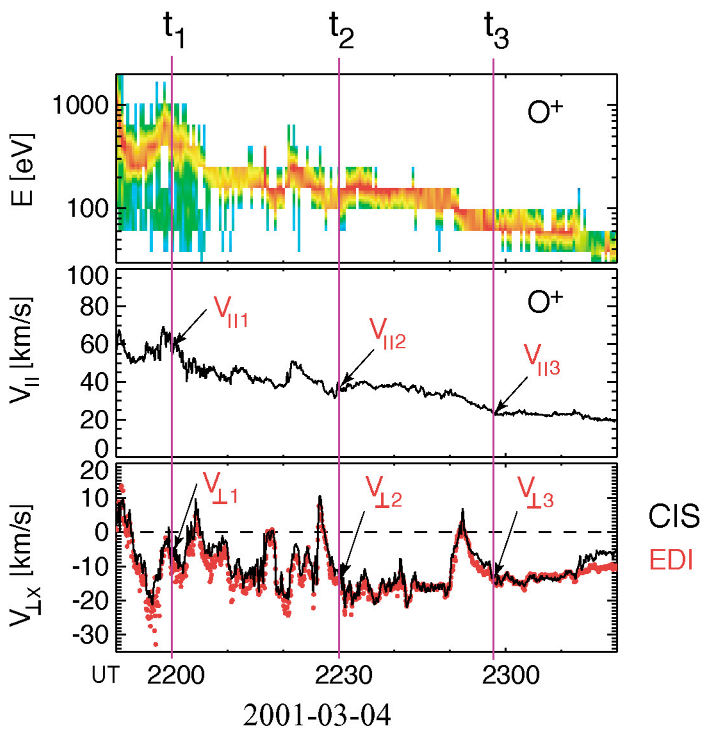
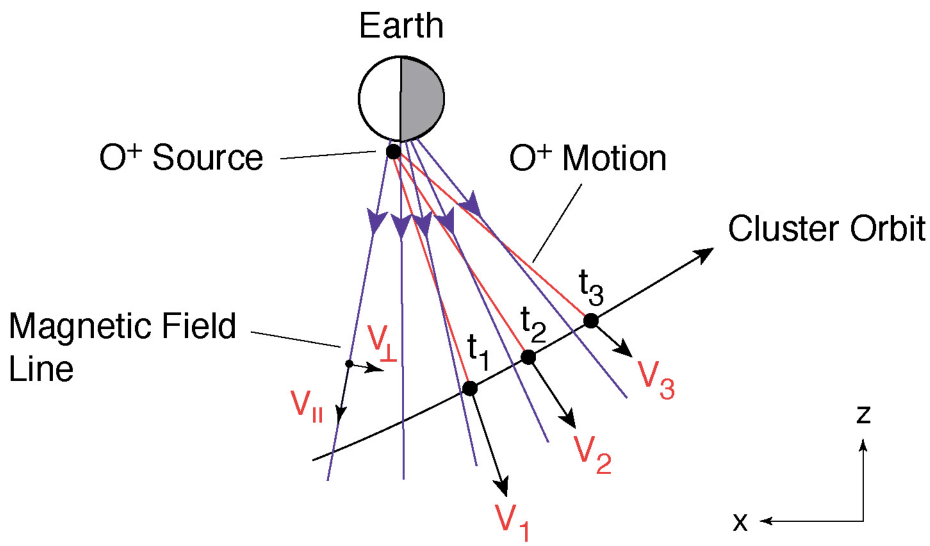
INSTRUMENT CALIBRATION
Cross Calibration - Velocity (EDI)

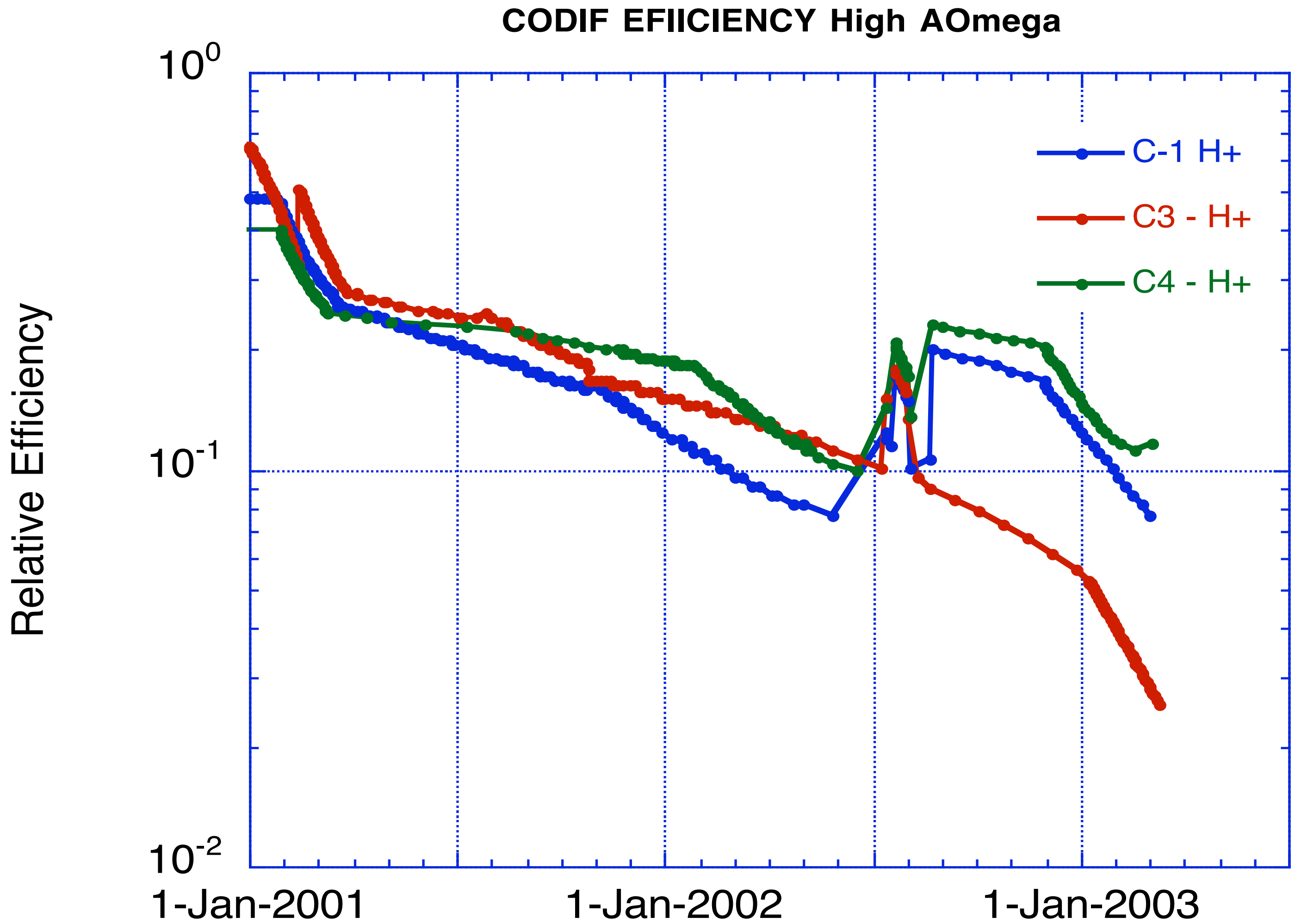




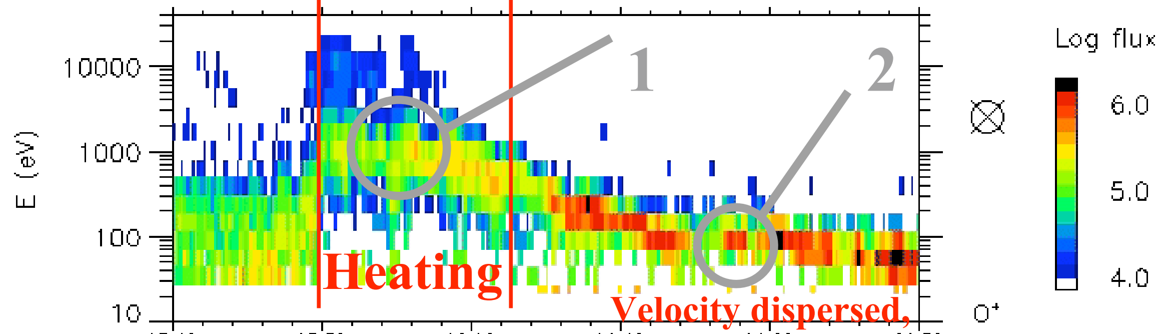
Localized Source of accelerated ionospheric ions

Convection in anti-solar direction across the polar cap

INSTRUMENT CALIBRATION
Efficiency Variation 2001 - 2003

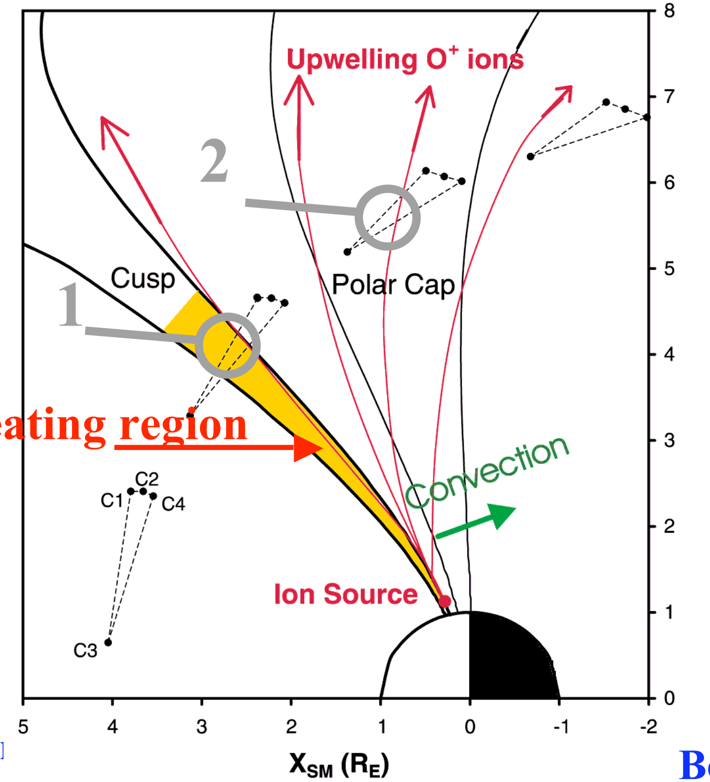


IONOSPHERIC OUTFLOW

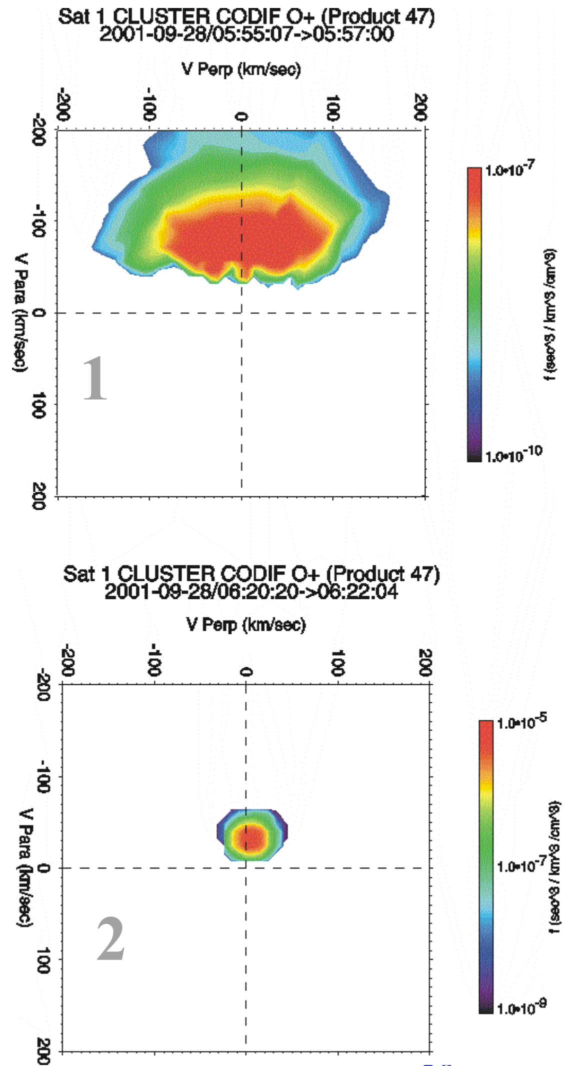


2001-09-28

R = 6R$_E$



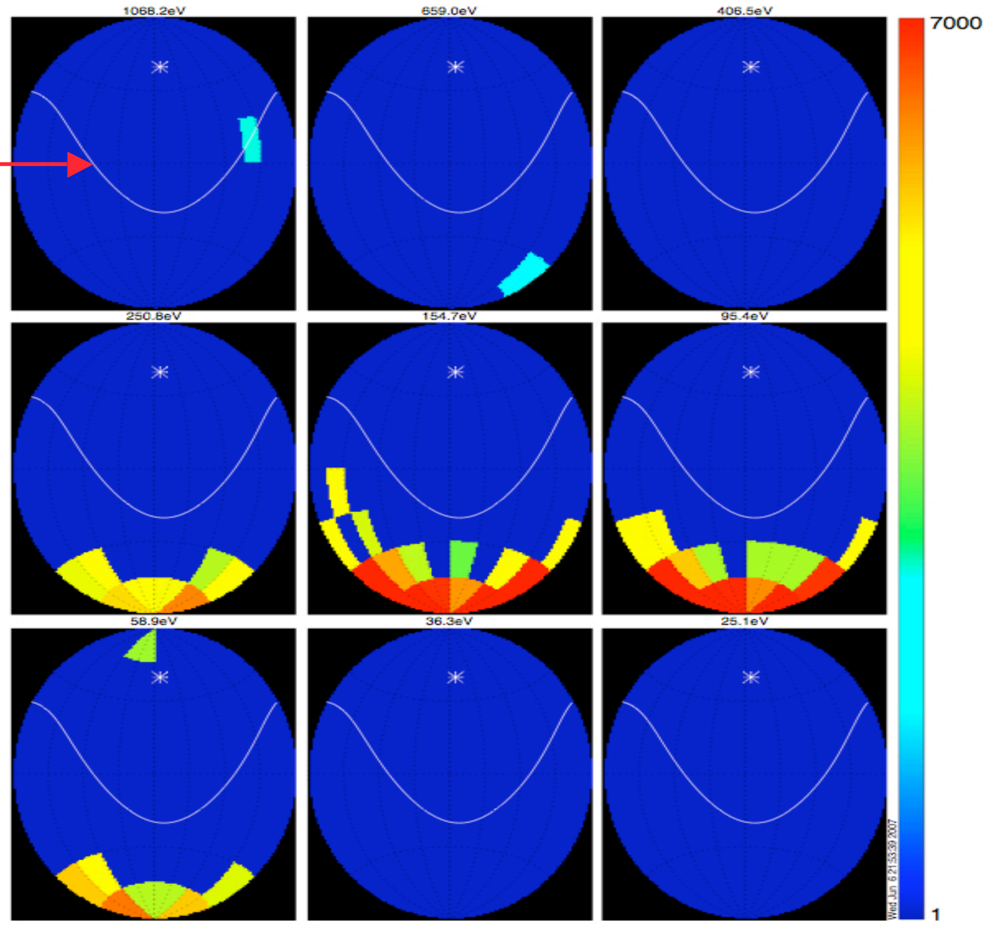
Transverse Heating region



Bouhram et al., 2004

ION BEAM IN 3D DISPLAY

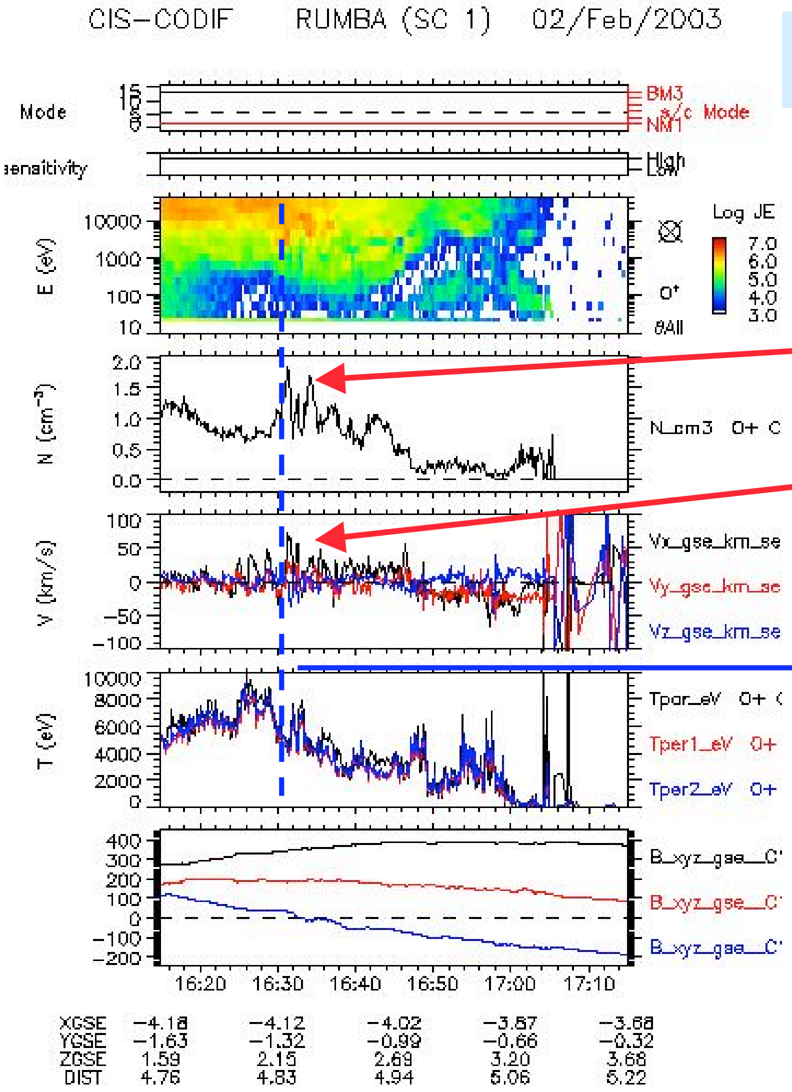
B



Ion Beam

anti-parallel to B

SOME EXAMPLES OF CIS DATA

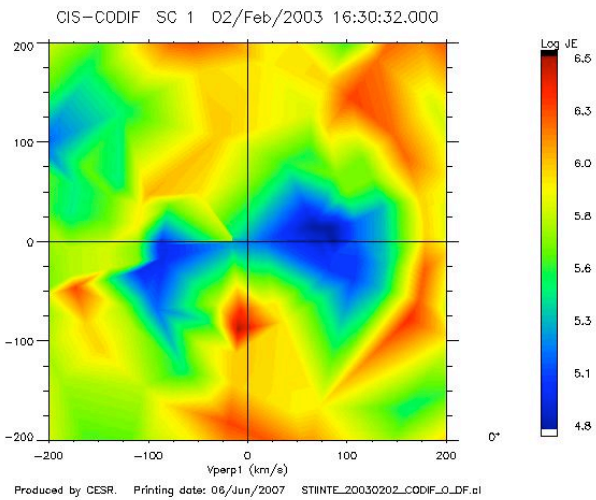


O^+

Cluster going from Perigee to the Cusp

O^+ Density Increase

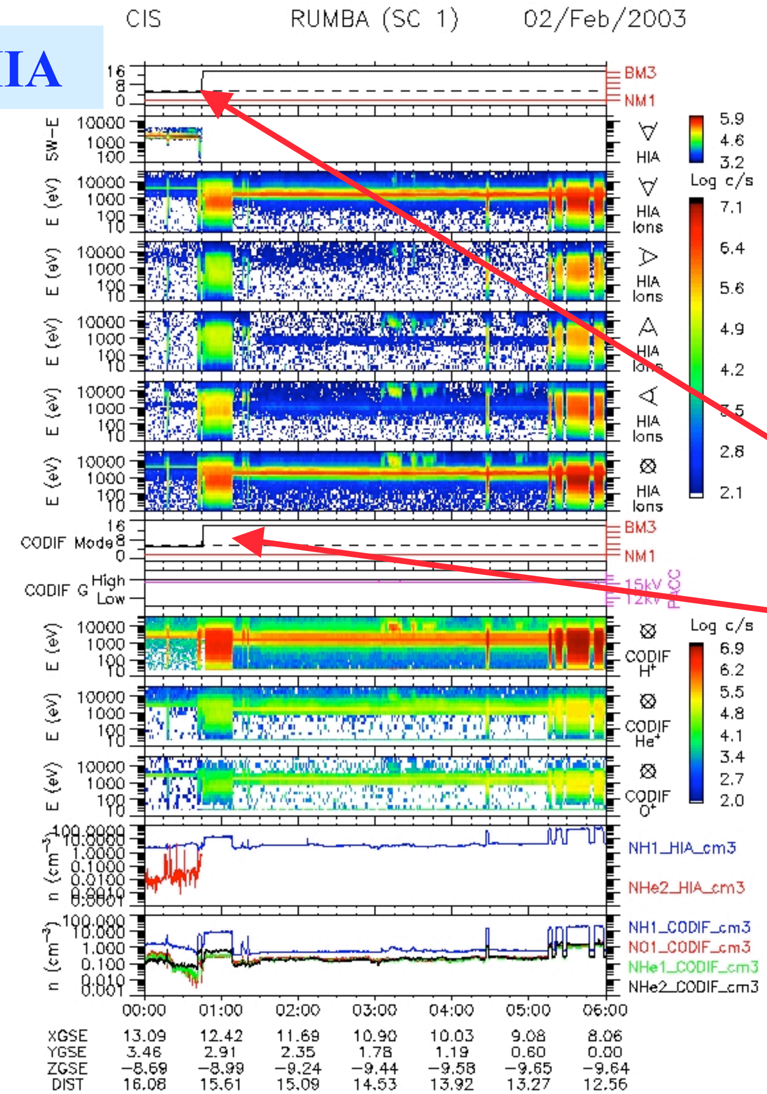
$V_x > 0$



V_{II}

V_{perp}

SOME EXAMPLES OF CIS DATA



HIA

CODIF

Cluster in the Solar Wind

Mode Changes

NEXT
COMPUTER SESSION

- Use Cluster Science Data System (CSDS) to display Cluster Orbit and Overview Plots of Particle and Field Data
- Use CIS/Cluster public archive at CESR to display Ion data for Summer and Winter Orbit (identify Solar Wind, Cusp, Tail, Boundary Crossings, Radiation Belt)
- Closer analysis of ion data using CL program (moment data, 3D data, distribution functions (Vper, Vpar)

REFERENCES

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Möbius, E., et al., In: “Measurement Techniques in Space Plasmas: Particles“, AGU Monograph, 102 , 243-248, 1998

Rème, H., et al., Space Science Rev. 79, 399-473, 1997

Rème, H., et al., Annal. Geophys., 19, 1303-1354, 2001

Wilken, et al., Space Science Rev. 79, 399-473, 1997

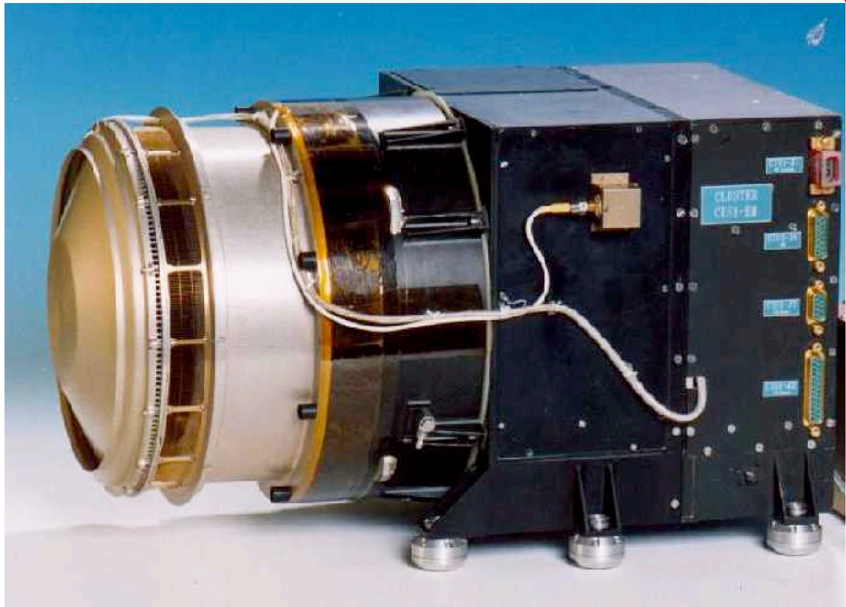
CODIF onboard FAST, Equator-S and Cluster

FAST:
Launch: 21.08.1996
Orbit: polar, 400 x 4000 km

Equator-S:
Launch: 2.12.1997
Orbit: äquatorial,
500 km x 11.3 R_E

Cluster
Launch: 16.7 + 9.8.2000
Orbit: polar, 4 x 19.5 R_E

ESA TOF EBOX DPU



SPIN AXIS

CODIF / CLUSTER

COmposition and DIstribution Function Analyzer