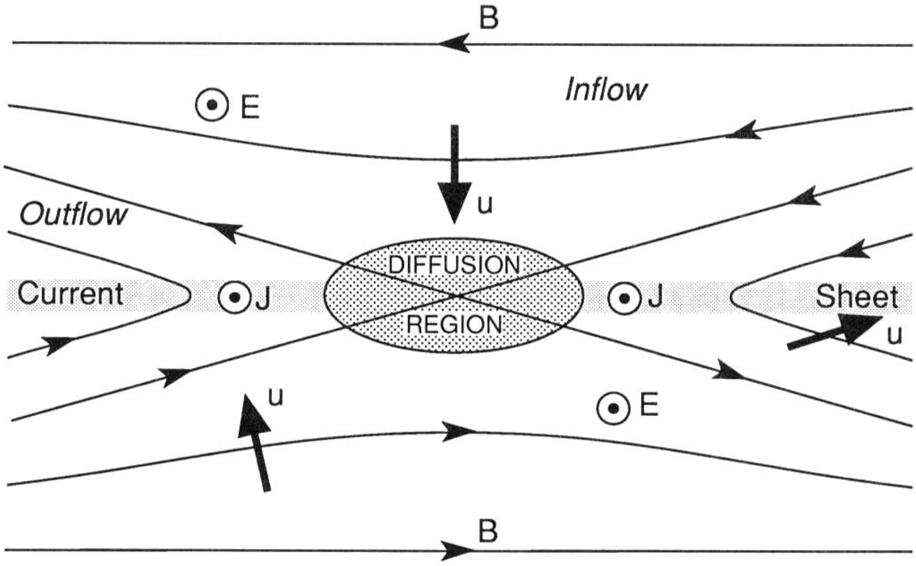
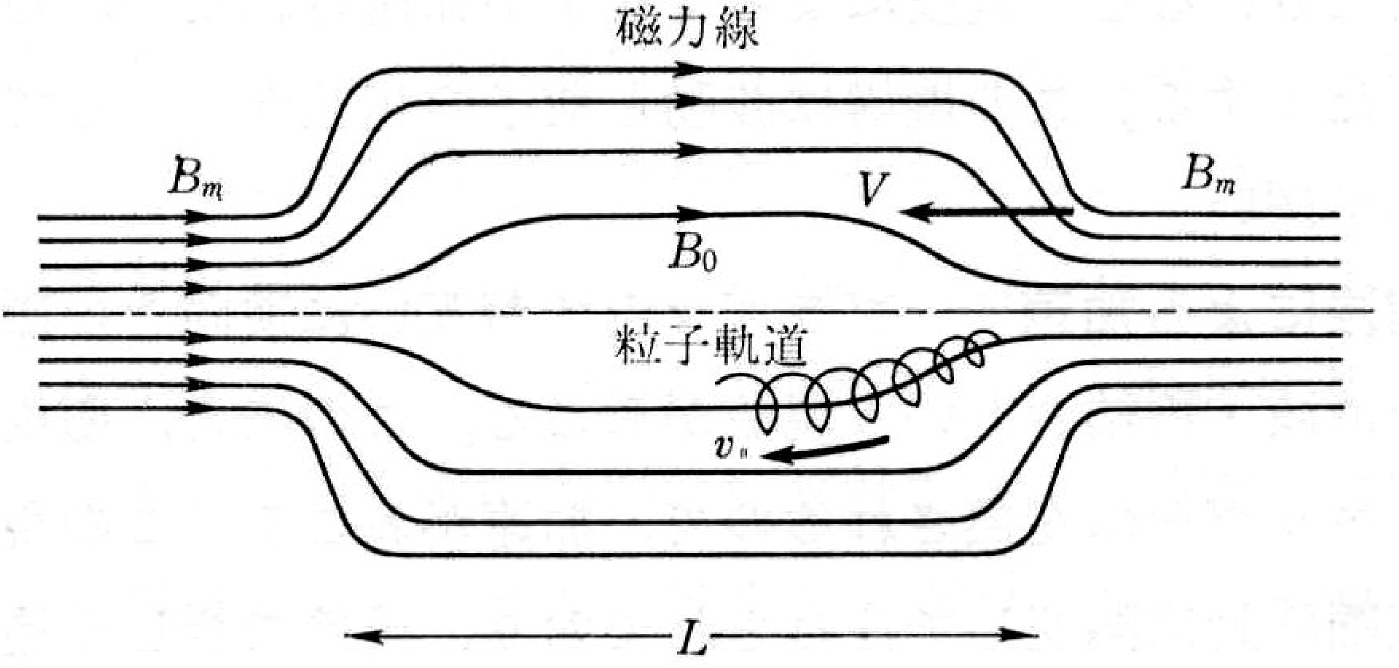
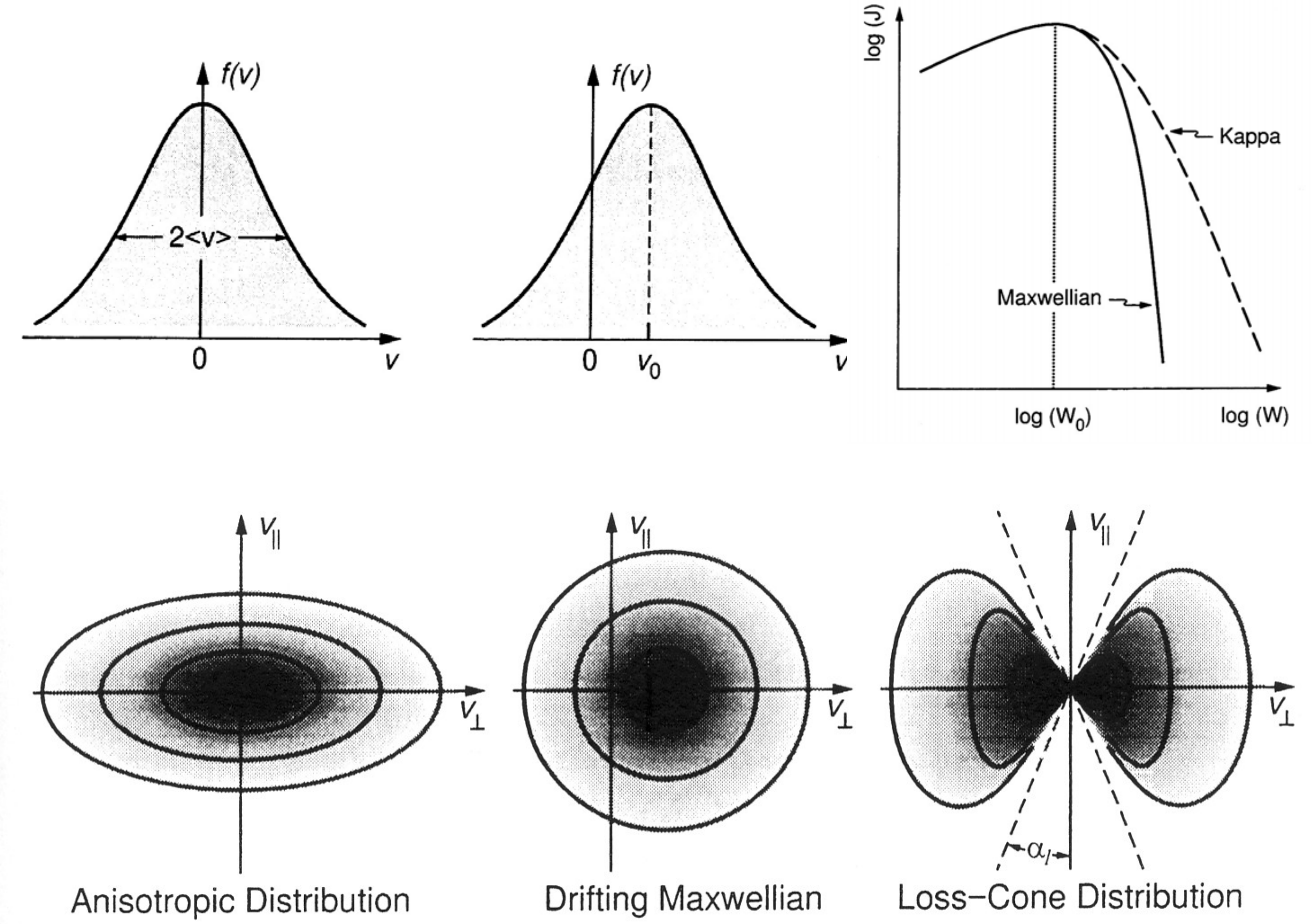
Illustration of magnetic reconnection occurring at an x-type magnetic neutral line. Plasma and magnetic field flow in from the top and bottom of the figure and flow out toward both sides. Only in the diffusion region, where $R_m < 1$, is plasma not tied to magnetic-field lines.





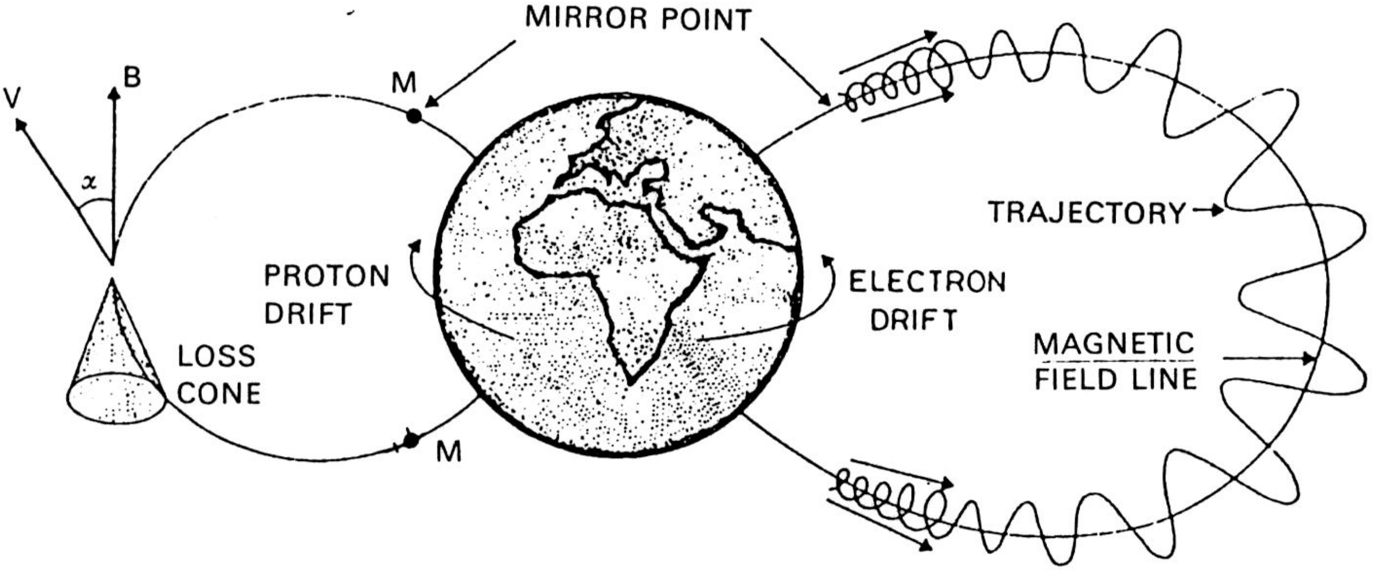
フェルミ加速



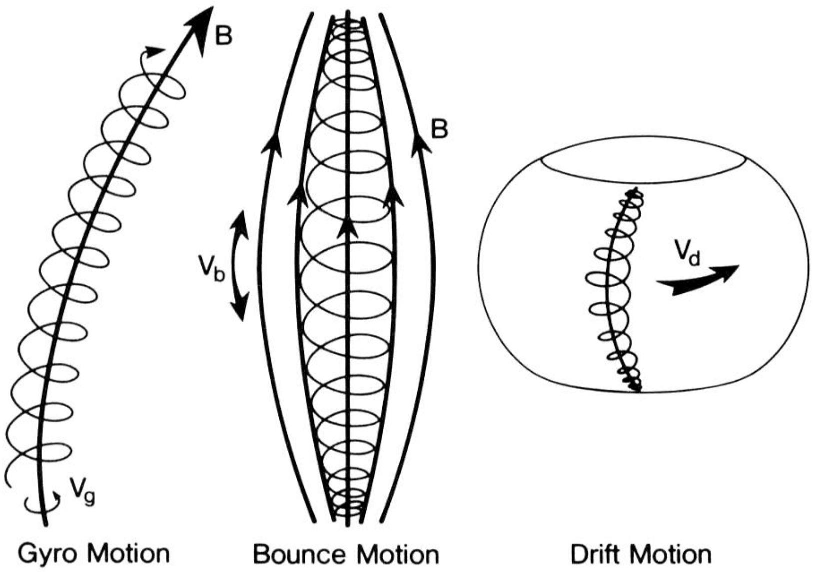
Anisotropic Distribution

Drifting Maxwellian

Loss–Cone Distribution

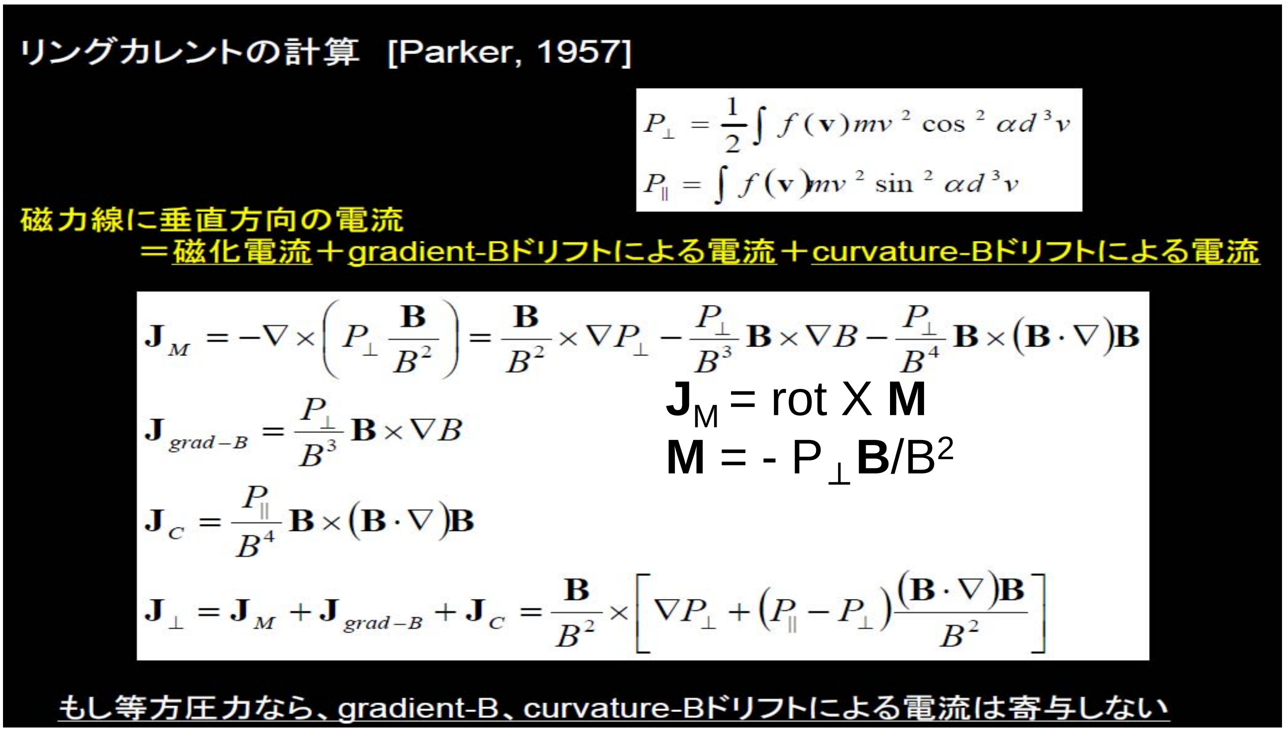


Trajectories of particles trapped on closed field-lines. (Reprinted with permission from J. Lemaire, *Advances in Space Research*, **2**, 3, copyright (1982) Pergamon Press PLC)



Schematic of particle motion in a magnetic field. On time scales of gyroperiods, the particle spirals about the magnetic field (see illustration of gyromotion at the left). If there is a field-aligned gradient of the field strength, the component of velocity parallel to the field decreases as the particle moves into regions of increasing field magnitude, although the total velocity is conserved. Eventually, the parallel velocity reverses. The reflection of the parallel motion is called "magnetic mirroring." Motion between mirror points is called bounce motion (central panel). As the particle bounces, it also drifts about the source of the field, tracing out a drift shell (see the right-hand illustration).

リングカレント（環電流）-1



リングカレントの計算 [Parker, 1957]

$$P_\perp = \frac{1}{2}\int f(\mathbf{v})mv^2\cos^2\alpha d^3v$$

$$P_\parallel = \int f(\mathbf{v})mv^2\sin^2\alpha d^3v$$

磁力線に垂直方向の電流

＝磁化電流＋gradient-Bドリフトによる電流＋curvature-Bドリフトによる電流

$$\mathbf{J}_M = -\nabla\times\left(P_\perp\frac{\mathbf{B}}{B^2}\right) = \frac{\mathbf{B}}{B^2}\times\nabla P_\perp - \frac{P_\perp}{B^3}\mathbf{B}\times\nabla B - \frac{P_\perp}{B^4}\mathbf{B}\times(\mathbf{B}\cdot\nabla)\mathbf{B}$$

$$\mathbf{J}_{grad-B} = \frac{P_\perp}{B^3}\mathbf{B}\times\nabla B$$

$$\mathbf{J}_C = \frac{P_\parallel}{B^4}\mathbf{B}\times(\mathbf{B}\cdot\nabla)\mathbf{B}$$

$$\mathbf{J}_\perp = \mathbf{J}_M + \mathbf{J}_{grad-B} + \mathbf{J}_C = \frac{\mathbf{B}}{B^2}\times\left[\nabla P_\perp + (P_\parallel - P_\perp)\frac{(\mathbf{B}\cdot\nabla)\mathbf{B}}{B^2}\right]$$

$\mathbf{J}_M$ = rot X $\mathbf{M}$

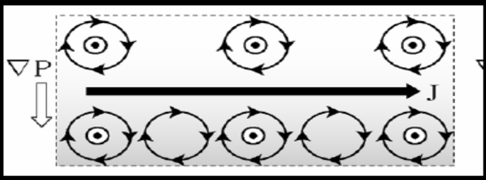
$\mathbf{M}$ = - $P_\perp\mathbf{B}/B^2$

もし等方圧力なら、gradient-B、curvature-Bドリフトによる電流は寄与しない

リングカレント（環電流）-2

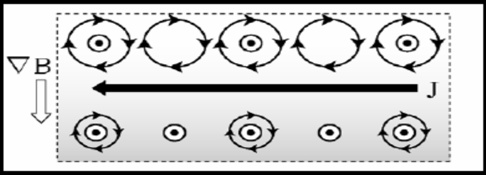
磁化電流の内訳

$$\mathbf{J}_M = -\nabla\times\left(P_\perp \frac{\mathbf{B}}{B^2}\right) = \frac{\mathbf{B}}{B^2}\times\nabla P_\perp - \frac{P_\perp}{B^3}\mathbf{B}\times\nabla B - \frac{P_\perp}{B^4}\mathbf{B}\times(\mathbf{B}\cdot\nabla)\mathbf{B}$$



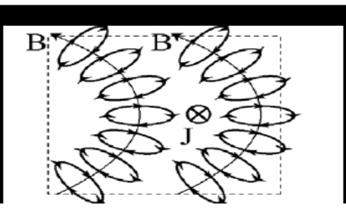
$$\frac{\mathbf{B}}{B^2}\times\nabla P_\perp$$

磁場が均一で圧力勾配あり。
電流は右に流れる



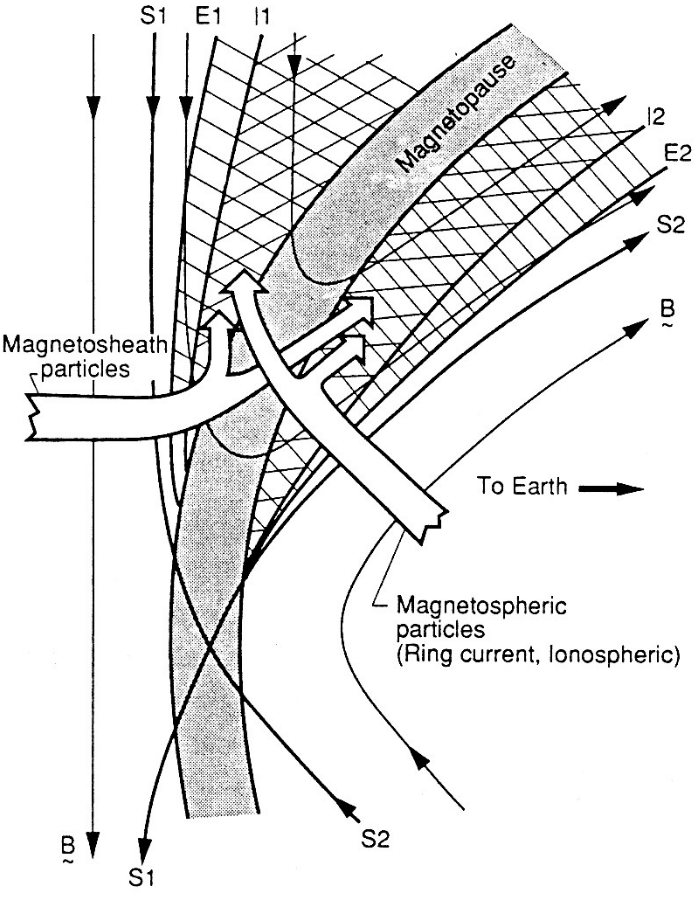
$$\frac{P_\perp}{B^3}\mathbf{B}\times\nabla B$$

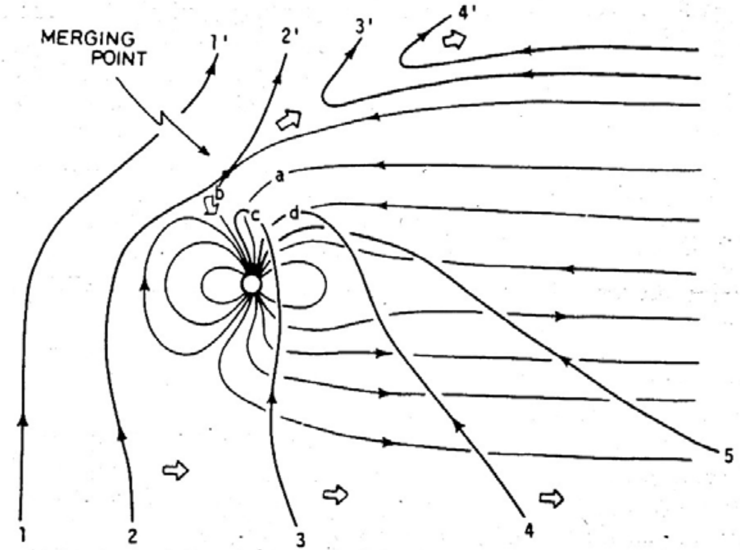
圧力が均一で磁場勾配あり。
電流は左に流れる

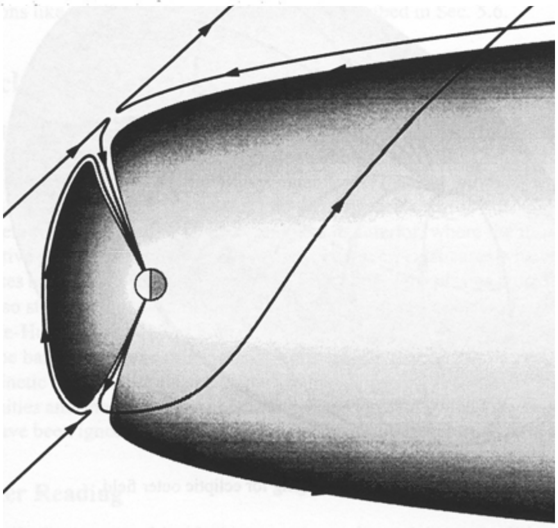


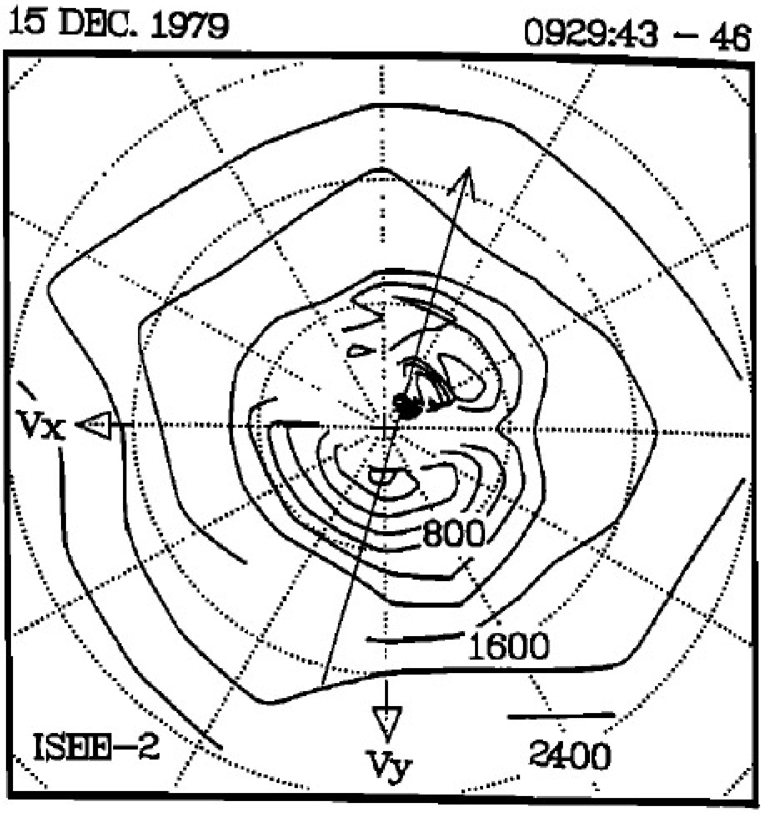
$$\frac{P_\perp}{B^4}\mathbf{B}\times(\mathbf{B}\cdot\nabla)\mathbf{B}$$

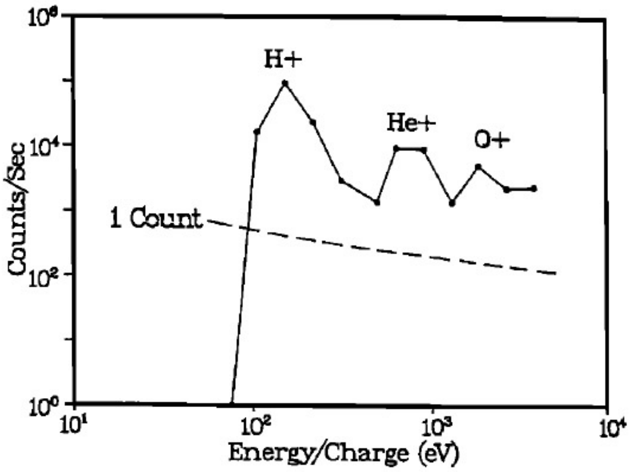
圧力が均一で磁場に曲率あり。
紙面を貫く方向に流れる

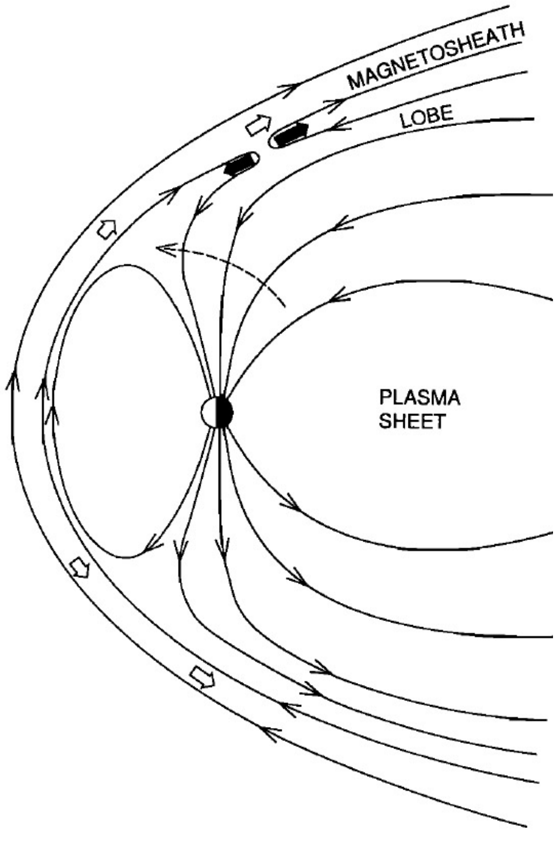


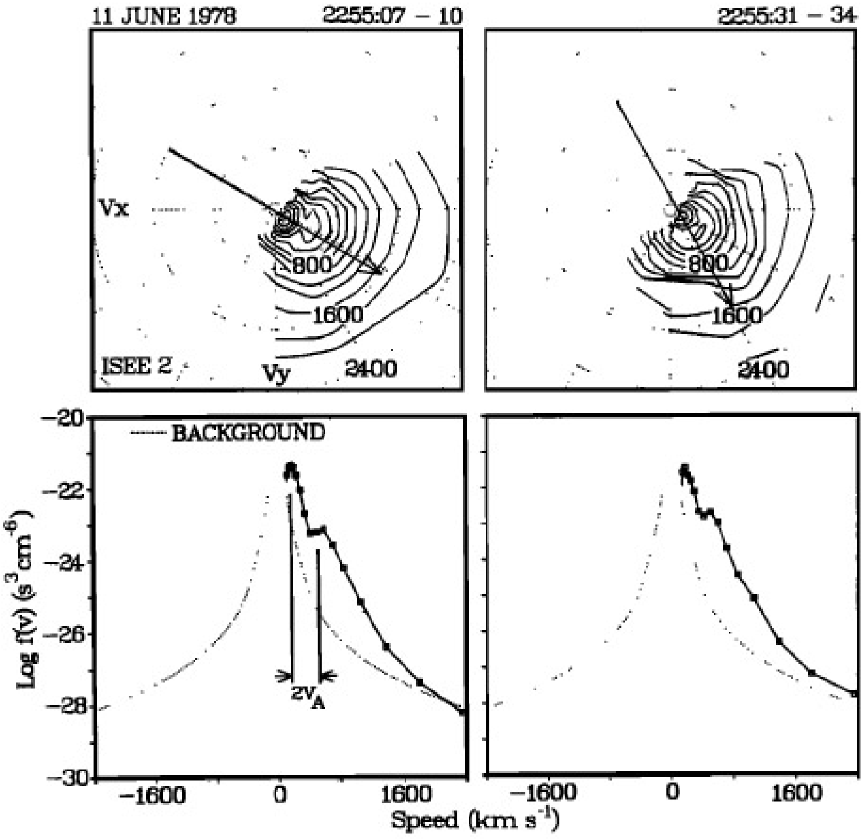




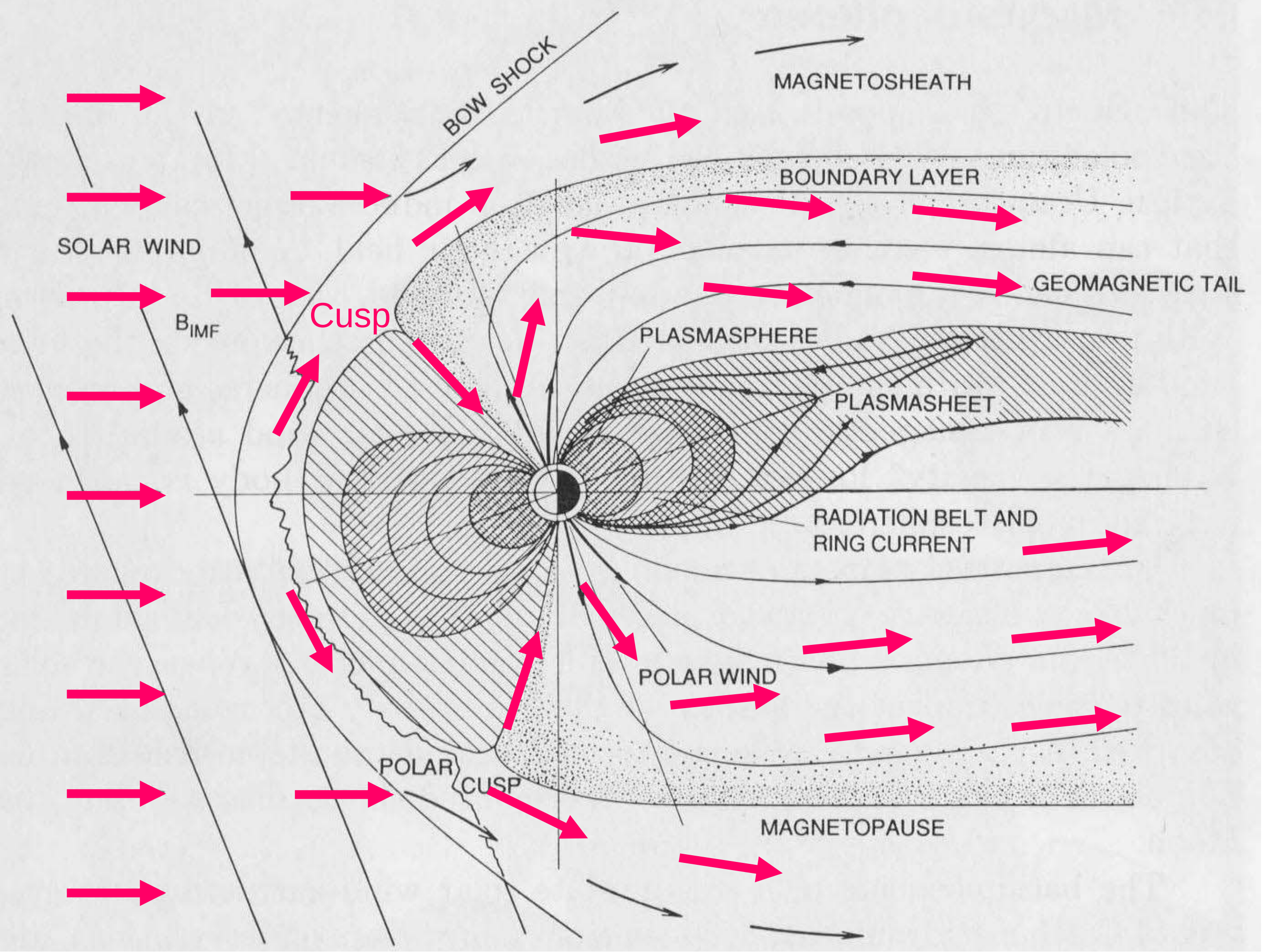

15 DEC. 1979
0929:43 – 46
Vx
Vy
800
1600
2400
ISEE-2


H+
He+
O+
1 Count
Counts/Sec
Energy/Charge (eV)
10^0
10^2
10^4
10^6
10^1
10^2
10^3
10^4

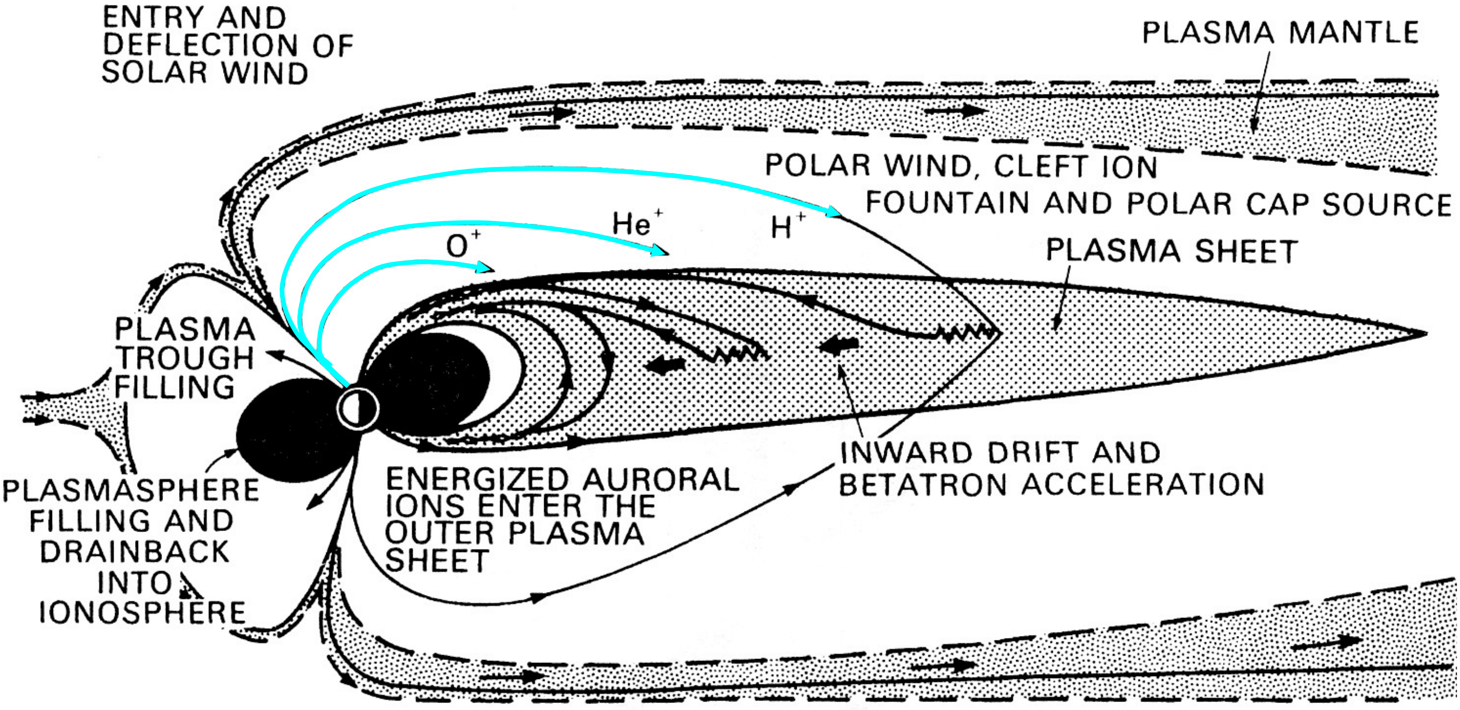

MAGNETOSHEATH
LOBE
PLASMA
SHEET


11 JUNE 1978
2255:07 – 10
2255:31 – 34
Vx
Vy
800
1600
2400
ISEE 2
BACKGROUND
Log f(v) ($s^3 cm^{-6}$)
–20
–22
–24
–26
–28
–30
$2V_A$
–1600
0
1600
Speed (km s^{-1})

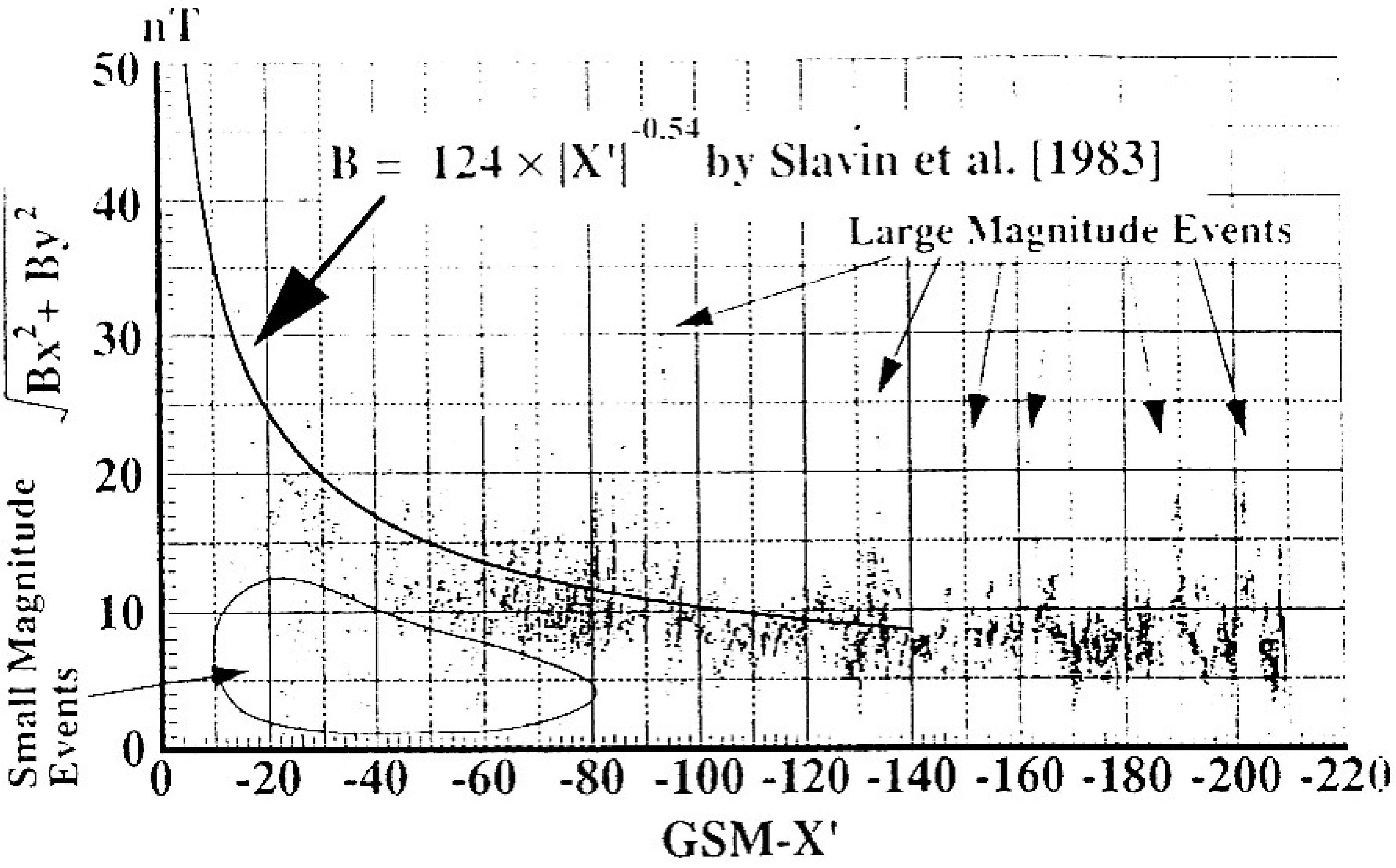
地球磁気圏の構造と太陽風侵入

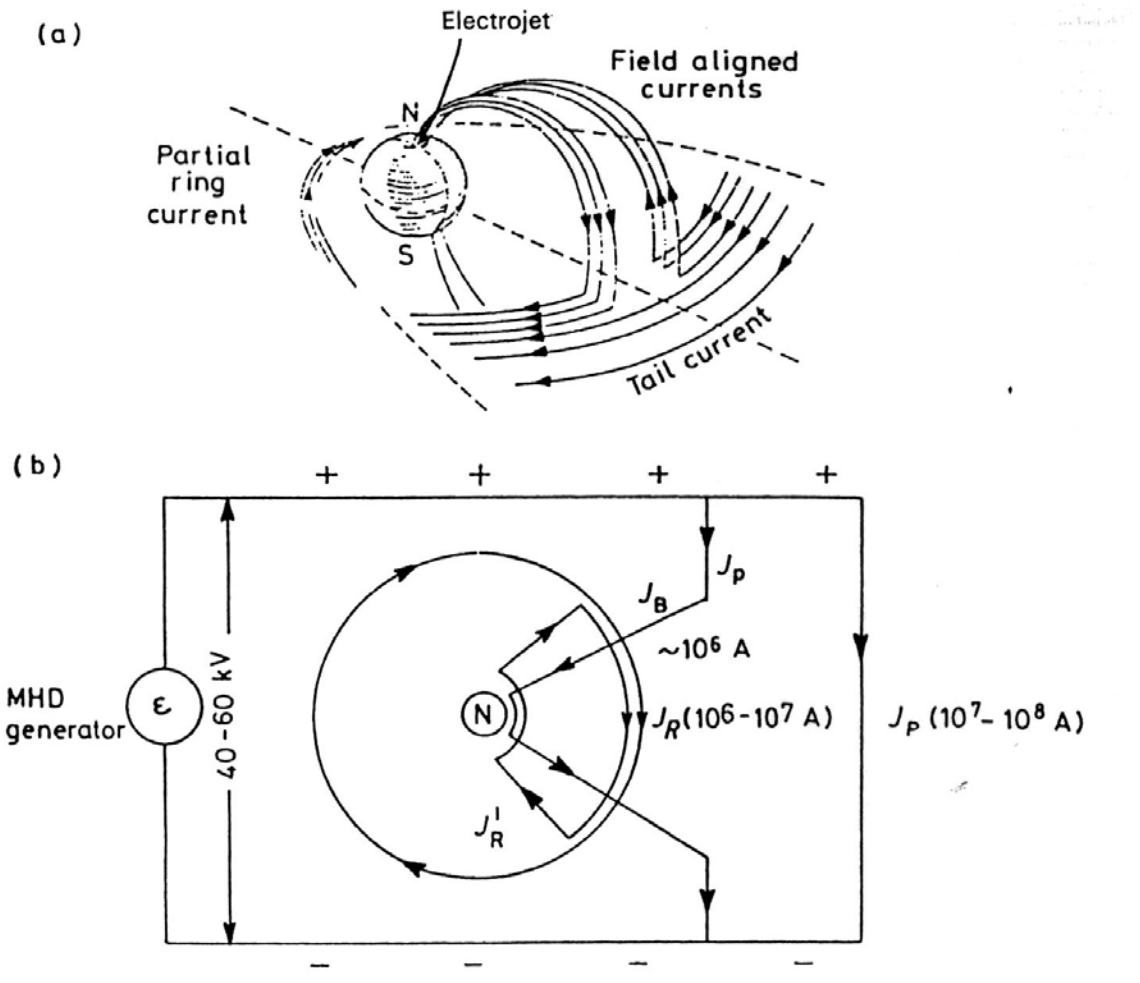


地球磁気圏への電離圏イオン流出



磁気圏ローブ中での磁場観測例





Substorm currents: (a) pictorial; (b) schematic. (After L. Svalgaard, *NASA Report SP*-366, 1975, and W. J. Heikkila, *J. Geophys. Res.* **79**, 2496, 1974, copyright by the American Geophysical Union)

IIJIMA AND POTEMRA: FIELD-ALIGNED CURRENTS DURING SUBSTORMS

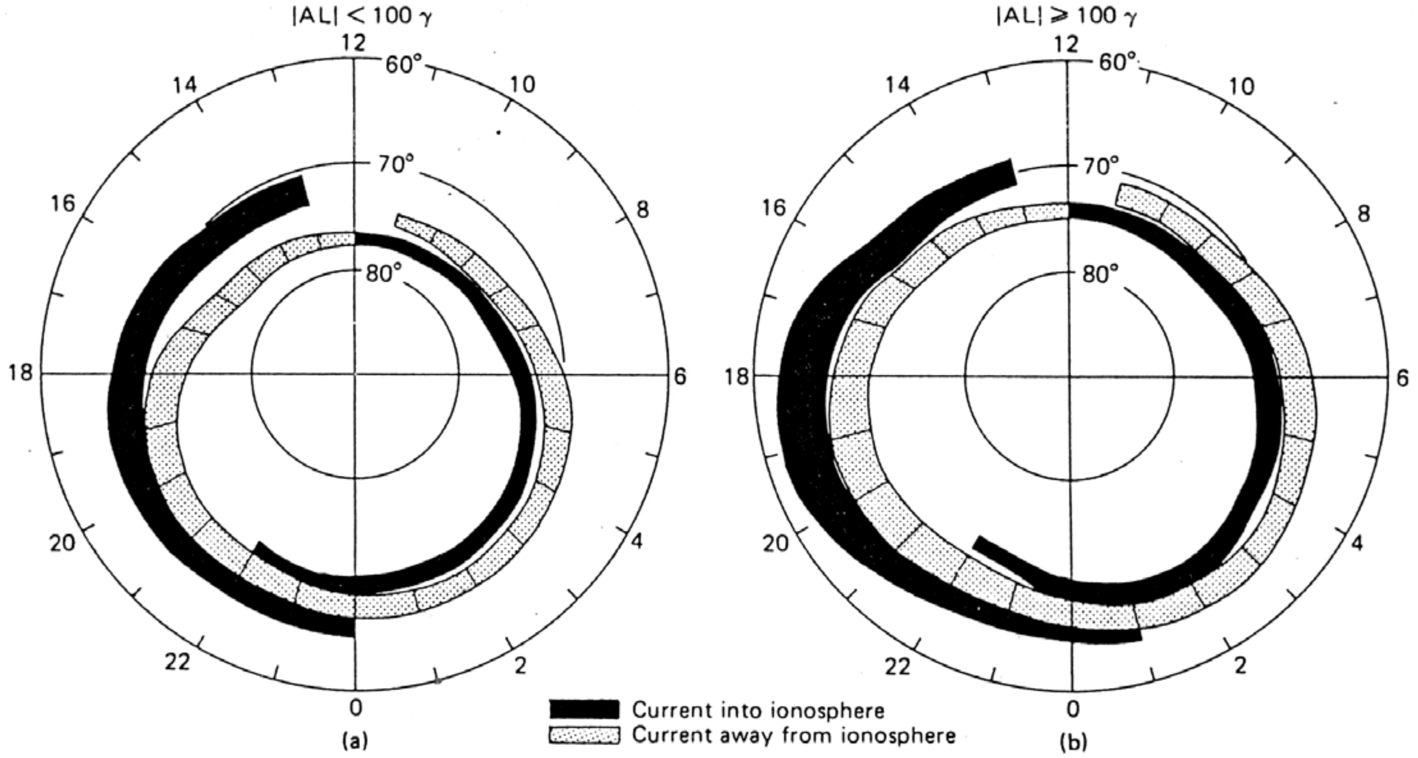
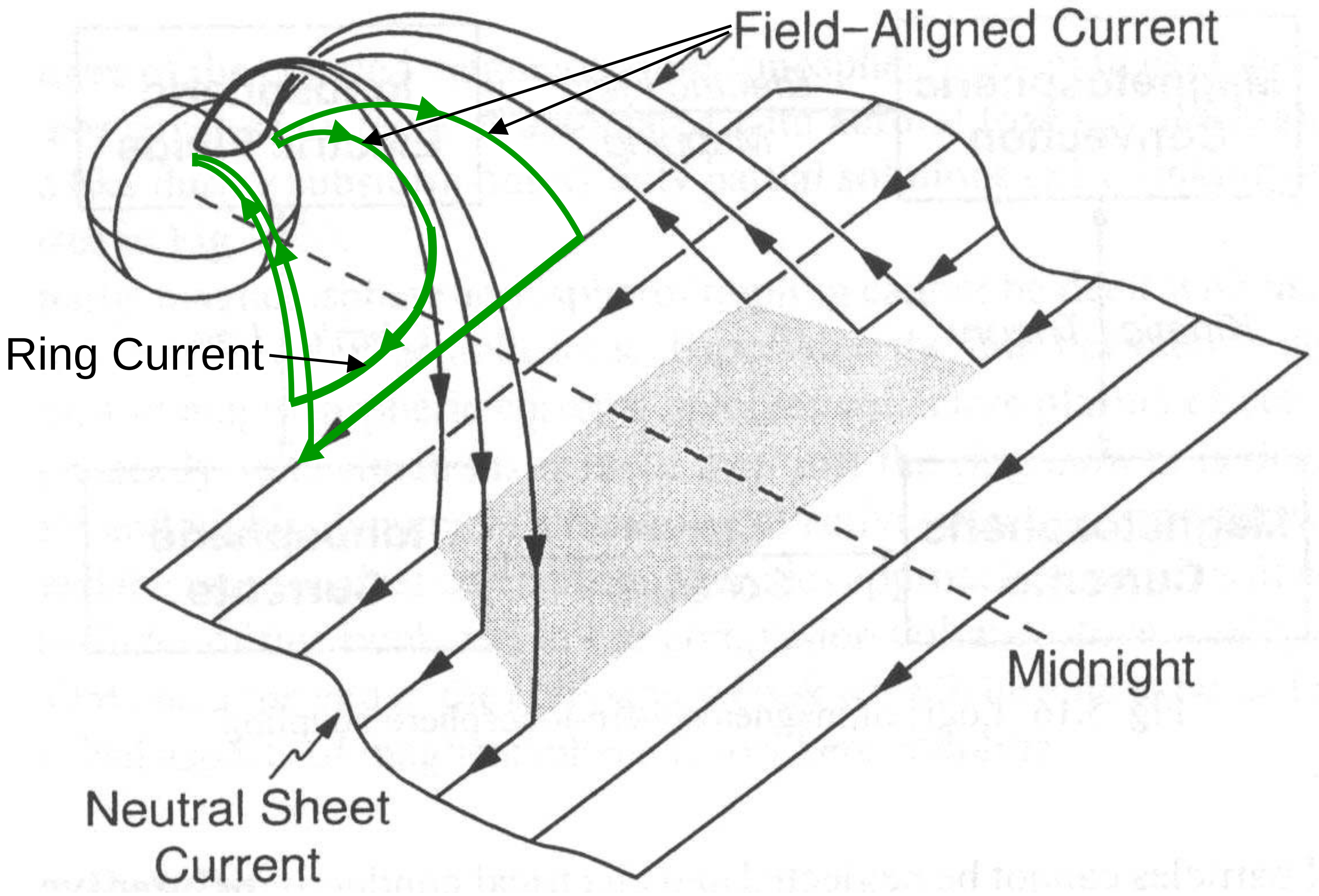
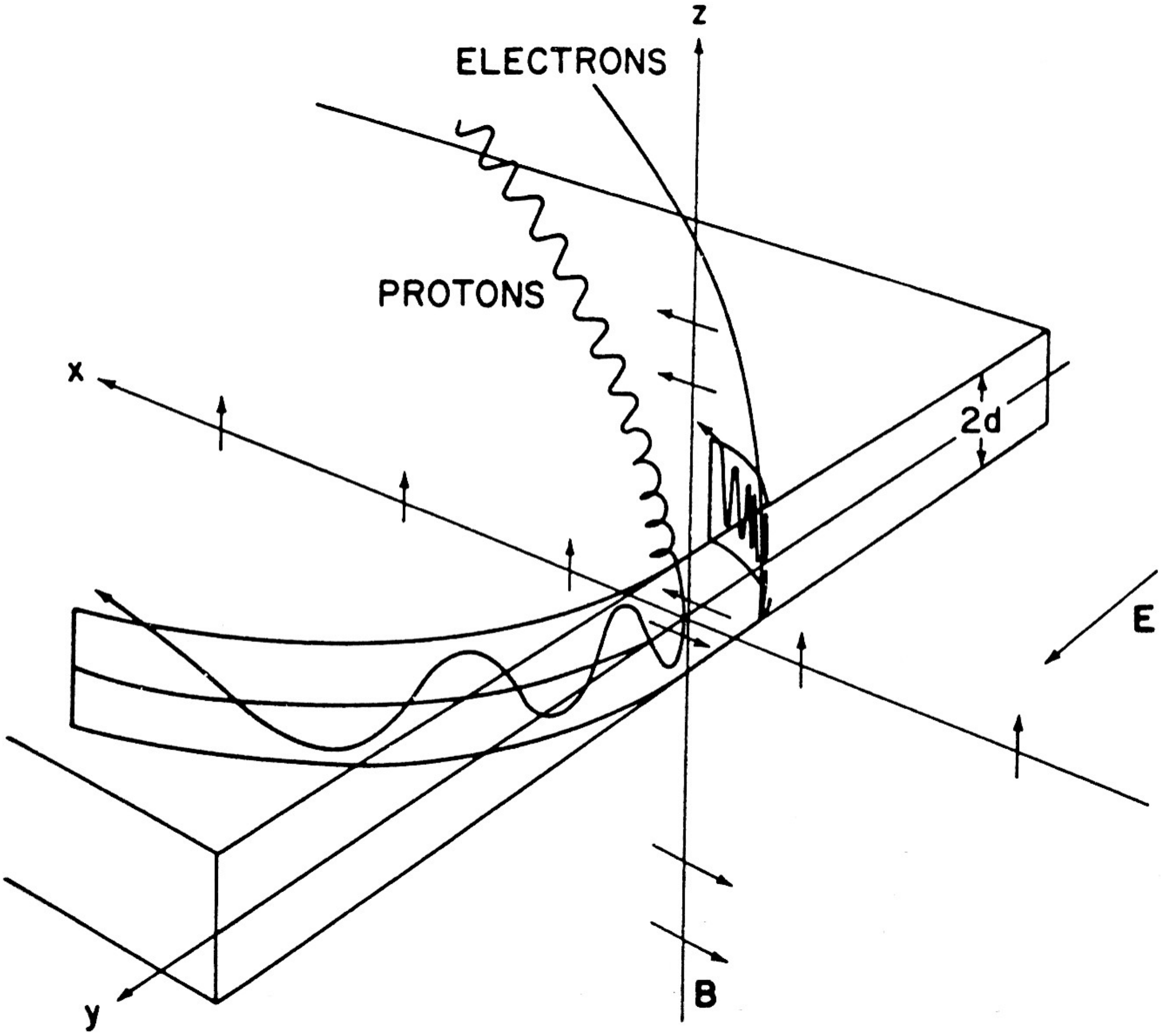
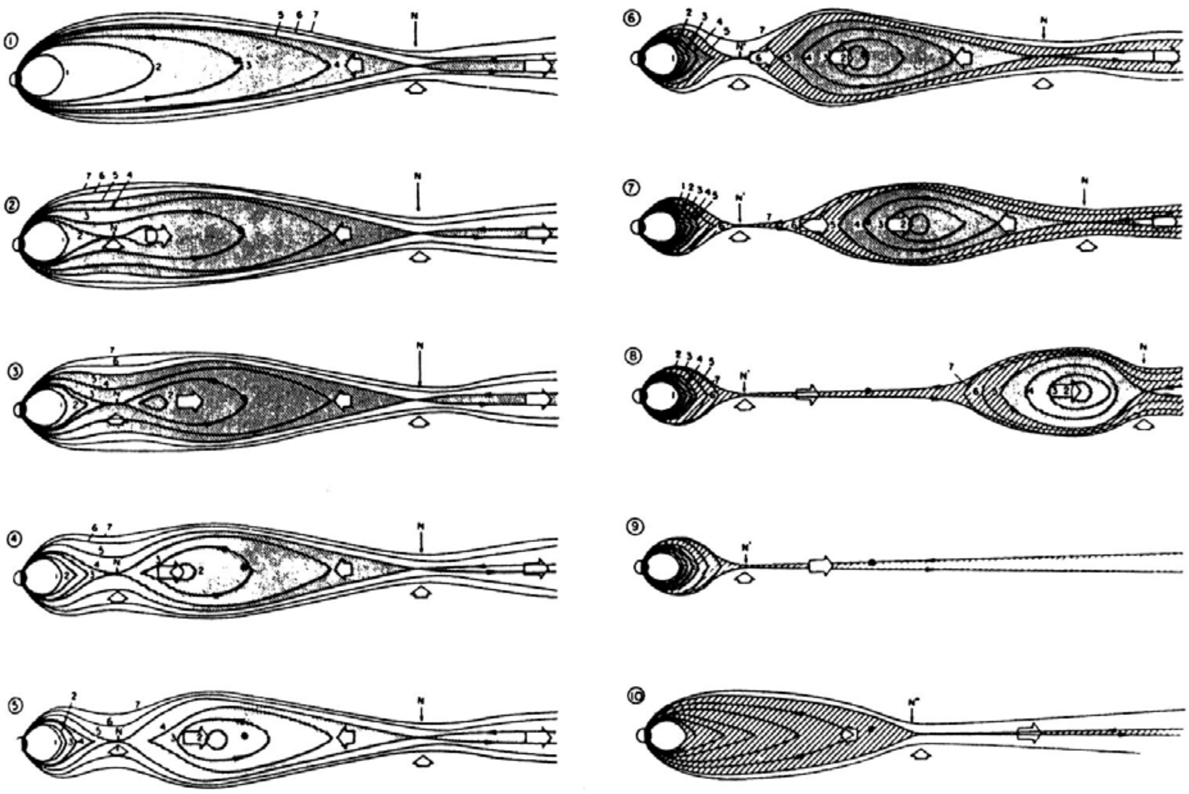


Fig. 13. A summary of the distribution and flow directions of large-scale field-aligned currents determined from (*a*) data obtained from 439 passes of Triad during weakly disturbed conditions ($|AL| < 100\ \gamma$) and (*b*) data obtained from 366 Triad passes during active periods ($|AL| \geq 100\ \gamma$).

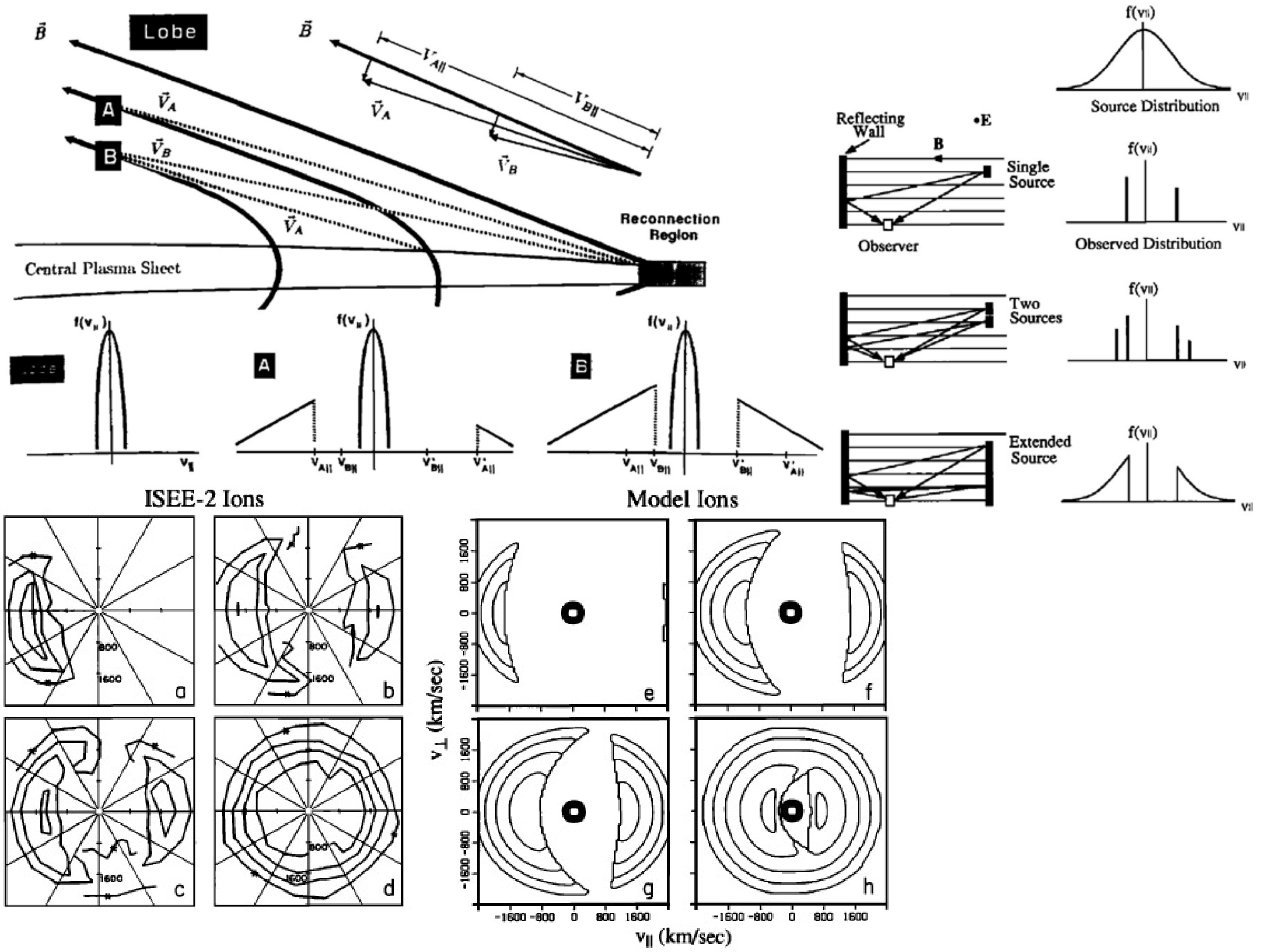
沿磁力線電流とCross-tail currentの結合







Sequence of events in the magnetotail during a substorm. White arrows indicate plasma flows. The plasma sheet is bounded by field-line 5. N′ is the second neutral line that forms in the substorm, and picture 8 shows the plasmoid being expelled down the tail. (E. W. Hones, in *Magnetic Reconnection* (ed. Hones). A.G.U. Monograph 30, 1984)



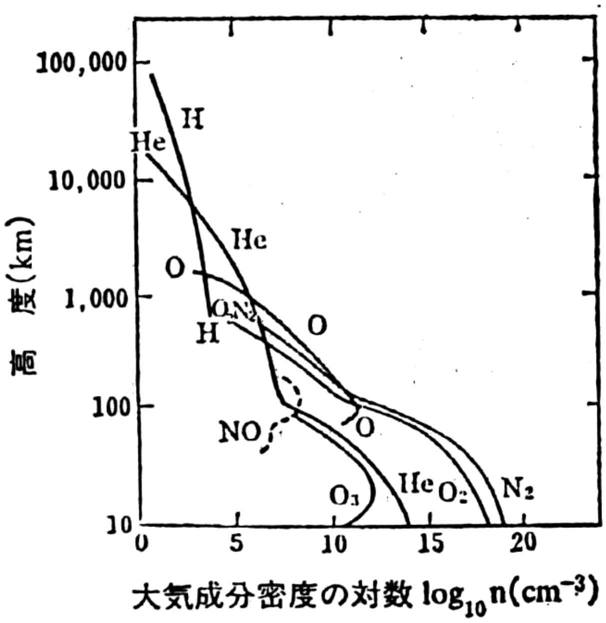


図 4.5 大気主要成分密度の高度分布（松浦，1978）.

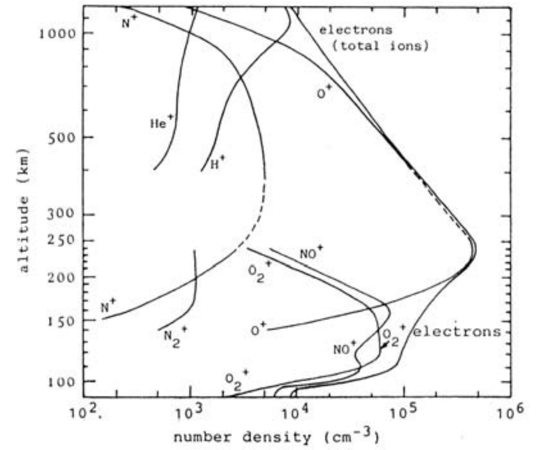


FIG. 5.24. Ion composition in the daytime ionosphere. After Johnson, *J. Geophys. Res.*, 71, 330 (1966).

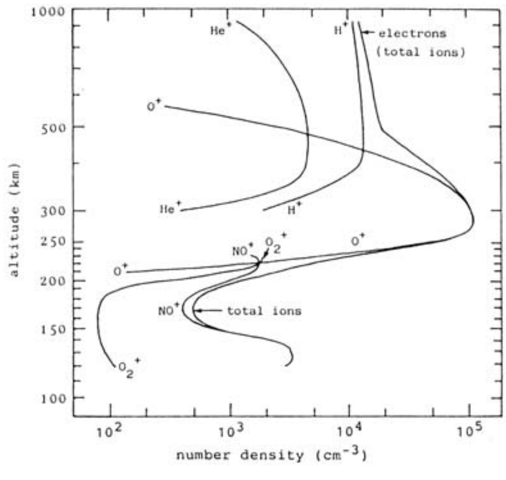
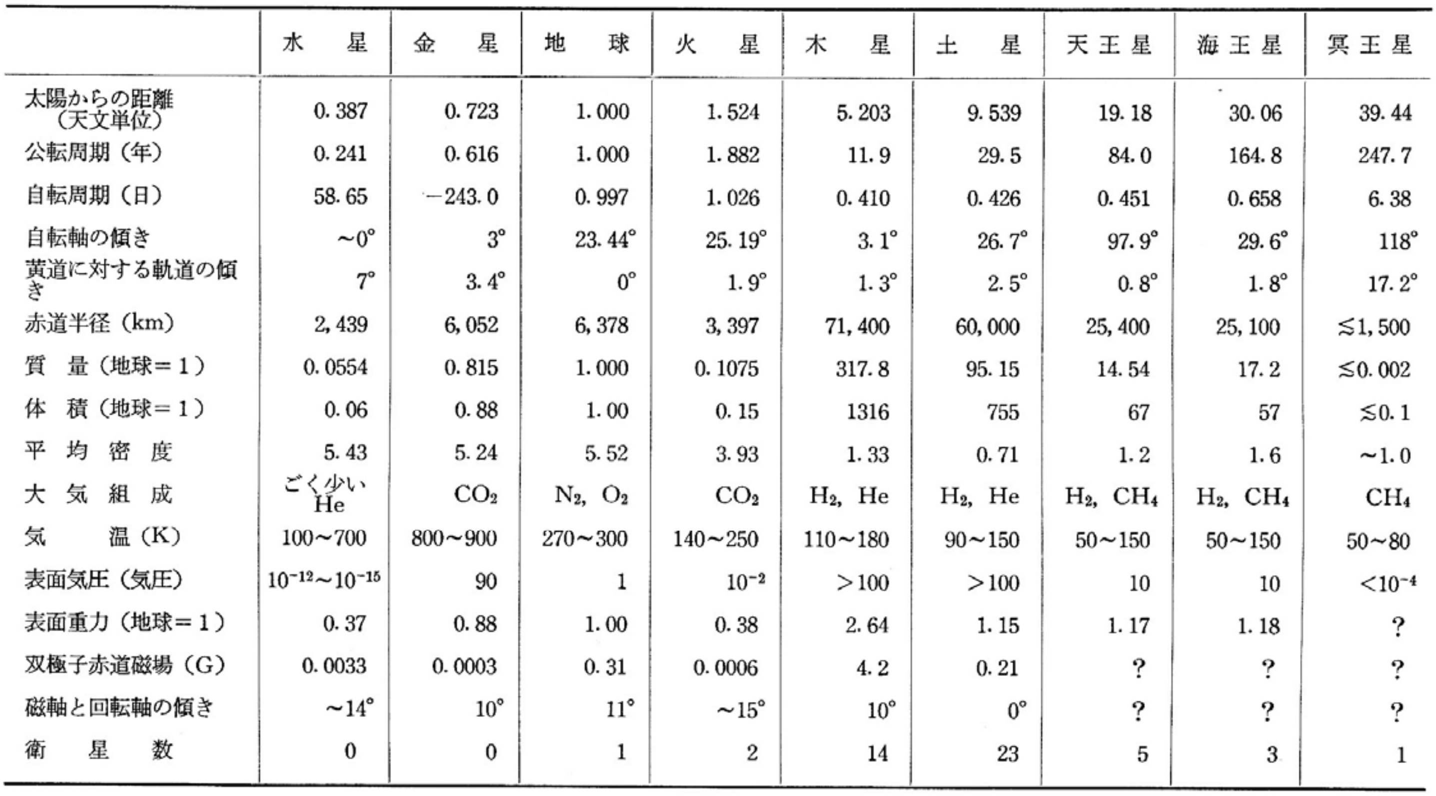


FIG. 5.25. Ion composition in the nighttime ionosphere. After Johnson, in *Annals of the IQSY*, Vol. 5 Solar-Terrestrial Physics: Terrestrial Aspect, MIT Press, 197 (1969).



	水星	金星	地球	火星	木星	土星	天王星	海王星	冥王星
太陽からの距離（天文単位）	0.387	0.723	1.000	1.524	5.203	9.539	19.18	30.06	39.44
公転周期（年）	0.241	0.616	1.000	1.882	11.9	29.5	84.0	164.8	247.7
自転周期（日）	58.65	−243.0	0.997	1.026	0.410	0.426	0.451	0.658	6.38
自転軸の傾き	～0°	3°	23.44°	25.19°	3.1°	26.7°	97.9°	29.6°	118°
黄道に対する軌道の傾き	7°	3.4°	0°	1.9°	1.3°	2.5°	0.8°	1.8°	17.2°
赤道半径（km）	2,439	6,052	6,378	3,397	71,400	60,000	25,400	25,100	≲1,500
質量（地球＝1）	0.0554	0.815	1.000	0.1075	317.8	95.15	14.54	17.2	≲0.002
体積（地球＝1）	0.06	0.88	1.00	0.15	1316	755	67	57	≲0.1
平均密度	5.43	5.24	5.52	3.93	1.33	0.71	1.2	1.6	～1.0
大気組成	ごく少い He	CO_2	N_2, O_2	CO_2	H_2, He	H_2, He	H_2, CH_4	H_2, CH_4	CH_4
気温（K）	100～700	800～900	270～300	140～250	110～180	90～150	50～150	50～150	50～80
表面気圧（気圧）	10^{-12}～10^{-15}	90	1	10^{-2}	＞100	＞100	10	10	＜10^{-4}
表面重力（地球＝1）	0.37	0.88	1.00	0.38	2.64	1.15	1.17	1.18	?
双極子赤道磁場（G）	0.0033	0.0003	0.31	0.0006	4.2	0.21	?	?	?
磁軸と回転軸の傾き	～14°	10°	11°	～15°	10°	0°	?	?	?
衛星数	0	0	1	2	14	23	5	3	1

Coordinate System

- Geocentric (Geographic), Geodetic
- Centered Dipole (Geomagnetic, MAG)
- Invariant latitude (McIlwain L-value)
- Eccentric Dipole/Geomagnetic (EDM/EGM)
- Corrected Geomagnetic (CGM)
- Altitude Adjusted Corrected Geomagnetic (AACGM)

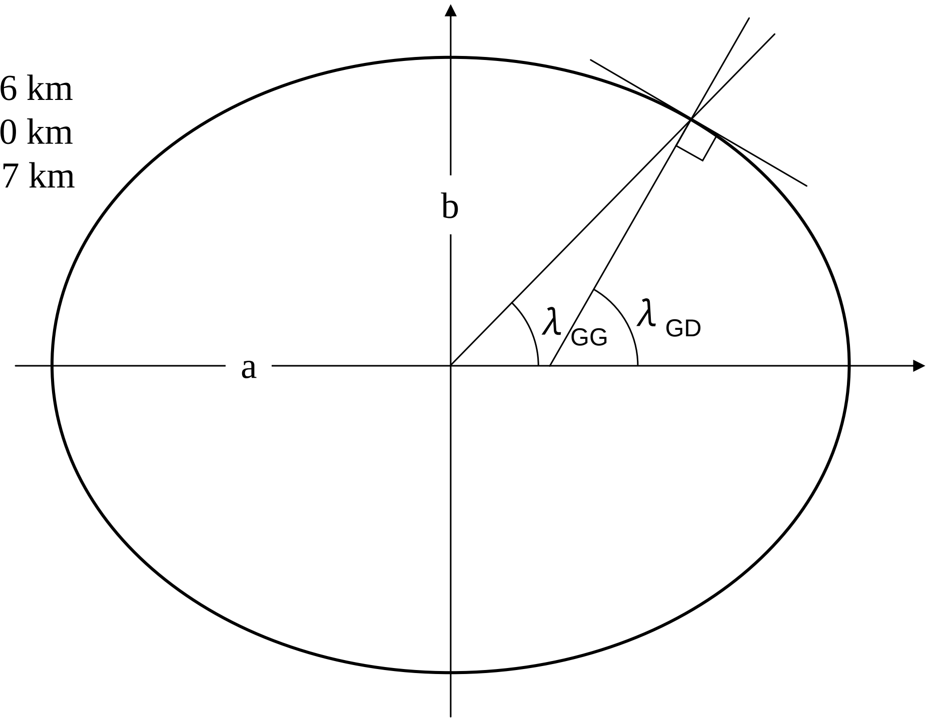
- SM(Solar Magnetic)
- GSE(Geocentric Solar Ecliptic)
- GSM(Geocentric Solar Magnetospheric)

Geomagnetic Field Model

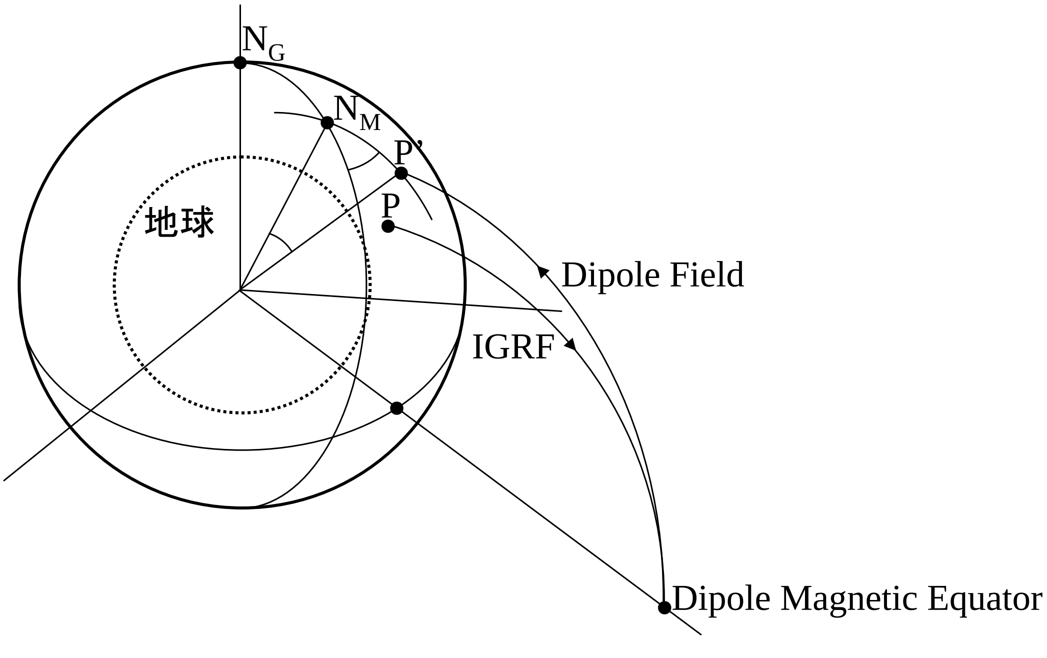
- IGRF (International Geomagnetic Reference Field)
- Tsyganenko field model

Geographic & Geodetic

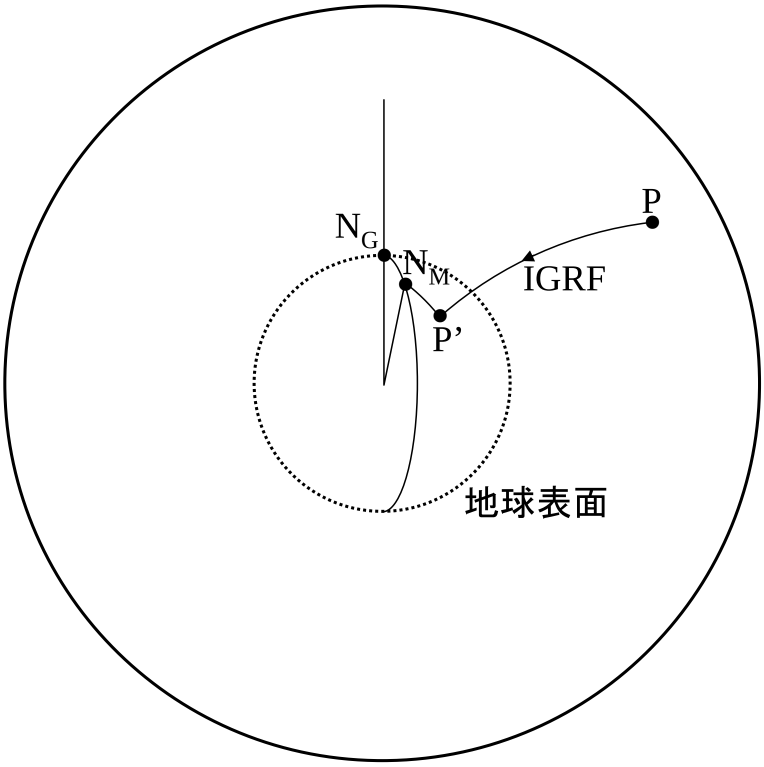
a = 6378.16 km
$\bar{a}$ = 6371.20 km
b = 6356.77 km



Geomagnetic & Corrected Geomagnetic



Altitude Adjusted Corrected Geomagnetic



Geomagnetic (MAG)

- Definition:
  - Z axis goes thru the center of the earth and is aligned with the magnetic dipole (as defined by the IGRF model).
  - Let D be vector from origin to south magnetic pole. Let S be vector from origin to south geographic pole. Y = D x S
    - » So X is in the plane defined by D and S.
- Convert from Cartesian to Spherical coordinates to determine magnetic latitude and longitude.

Eccentric Dipole (EDM)

- Find Z (not thru center of earth) such that if you expand the magnetic field in spherical harmonics, the quadrupole term is minimized.
- Once Z is determined, X and Y are defined as in MAG.

MAG advantages and disadvantages

- Advantages
  - Very easy to calculate
  - Orthogonal system and transformation from geographic to MAG is simply a rotation matrix.
  - Inverse transformation is the transpose (inverse) matrix.
- Disadvantages
  - Ignoring the non-dipole terms of the magnetic field leads to serious inaccuracies.
  - Coordinates are NOT constant along a field line.

EDM advantages and disadvantages

- Advantage:
  - More accurate that MAG for ordering data (but still not really accurate enough).
- Disadvantages
  - Transformation from geographic to mag is more difficult because a translation as well as a rotation is involved.
- Advantage
  - Orthogonal system with well defined inverse

McIlwain B,L

- Based on adiabatic invariants. Defines drift-shells.
- L is the measure of the distance from center of earth to the drift shell in the magnetic equator IF THE FIELD IS A DIPOLE.
  - L can still be defined for non-dipole fields and still defines a drift shell
  - Drift shells are NOT magnetic shells (defined by field lines)

(B,L) advantages and disadvantages

- Excellent coordinate system for describing particle drifts in the magnetosphere.
- Does not exactly show magnetic conjugate relationships, however.
  - If your data is organized by particle drifts then this is an excellent coordinate system to use.
  - If your data is organized by magnetic conjugacy it is not so good.
- For non-dipole field it is not orthogonal and does not have a simple inverse. And it is complicated to calculate.

Corrected Geomagnetic Coordinates

- Introduced by Hultquist and and Gustafsson [*JATP*, 1960]
- Start at a point, P (in the ionosphere at some altitude)
- Follow the magnetic field line out to the Dipole equator using the full magnetic field model.
- Trace back to your original altitude, but using only the Dipole field.

CGM definition

- The new point, P* will be at the same altitude as P, but at a different latitude and longitude.
- Assign the MAG latitude and longitude of P* to the original point P.
- NOTE: the tracing backwards isn't really necessary. We know the equation defining a dipole magnetic field line, so the calculation is trivial.

CGM advantages and disadvantages

- Advantage: Very good for working on data in the ionosphere.
- Disadvantages:
  - Points on the same field line have different coordinates – does not show conjugate relationships.
  - Not an orthogonal coordinate system
    - » Calculation is difficult
    - » Inverse is difficult to determine

More on CGM disadvantages

- You must trace to dipole equator
  - If you use a strictly internal magnetic field model (IGRF) there are no open field lines [so that's OK], but there are low latitude field lines that never cross the magnetic equator.
  - If you want to include the effects of external fields then the high latitude lines can be open field lines and don't cross the equator.
    - » Papitashvili, et al. have suggesting tracing to the minimum B point.
  - You therefore have patches where CGM is not defined.

Altitude Adjusted Corrected Geomagnetic Coordinates (AACGM)

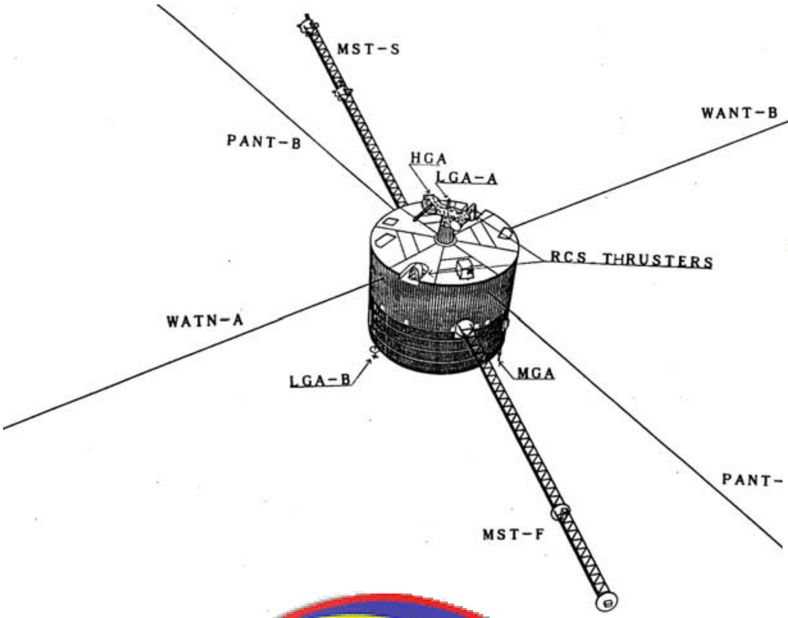
- Originally referred to as the PACE (Polar Anglo-American Conjugate Experiment) Geomagnetic (PGM) coordinate system.
- Original reference:
  - Baker, K. B. and S. Wing (1989). "A new magnetic coordinate system for conjugate studies at high latitudes." Journal of Geophysical Research **94**(A7): 9139 - 9144.

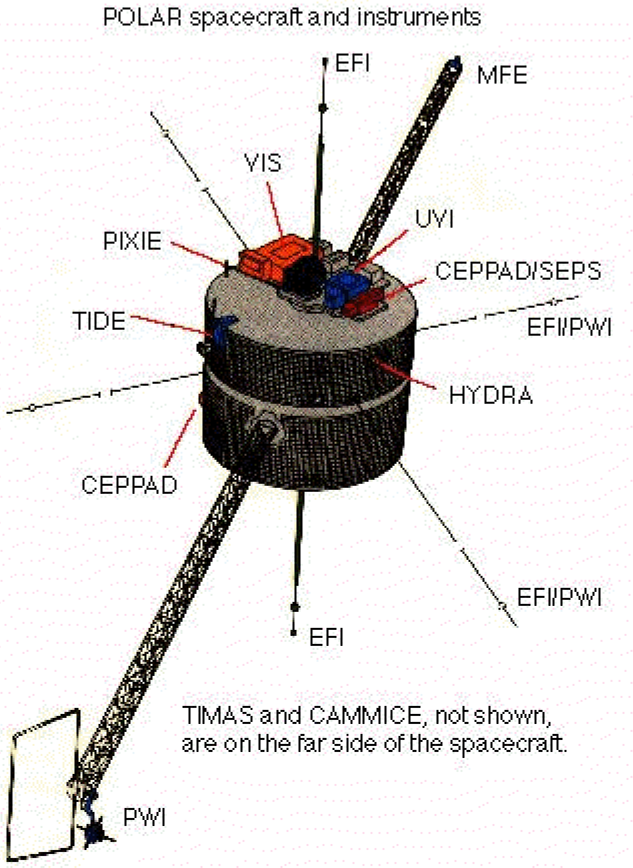
AACGM Concept

- Use the same basic approach as CGM but with differences:
  - No matter what point you start at, trace back all the way to the ground. This means all points on a field line have the SAME latitude and longitude.
- Define the coordinate transformation in terms of an expansion in Spherical Harmonics.

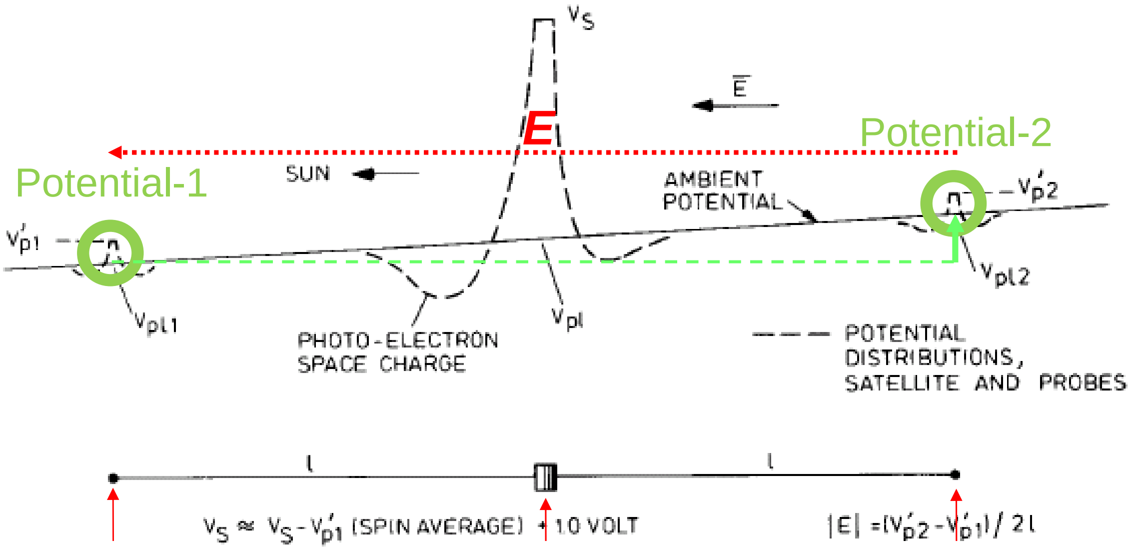
電場計測器

- ダブルプローブ法
  - あけぼの：30m×2本×2対（Wire+Wire）
  - Geotail：50m×2本×2対（Wire+Sphere）
  - Polar: 100, 130m（tip-to-tip, Sphere）
- イオン・電子ドリフト法
  - Geotail, Cluster-II





Principle and Technique for Space Electric Field and Plasma Wave



E

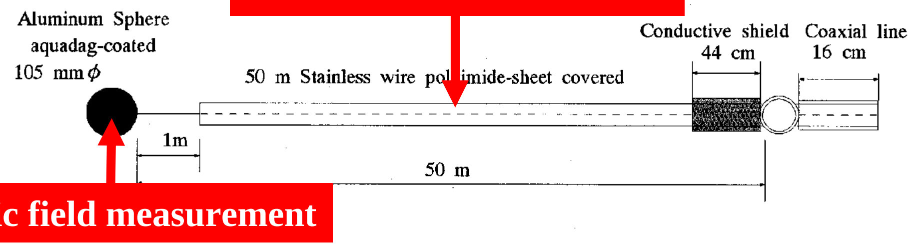
Potential-1

Potential-2

Probe-1

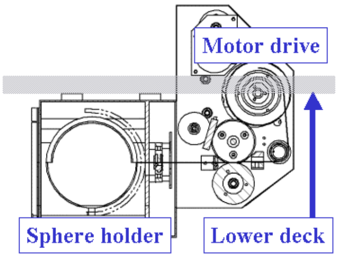
Spacecraft

Probe-2

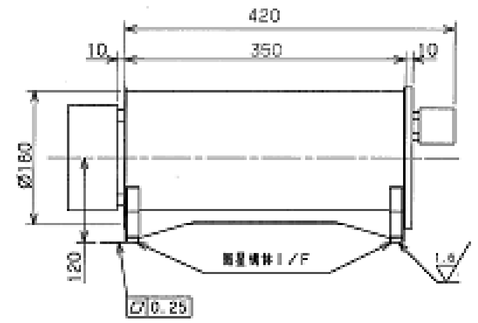


Plasma wave measurement

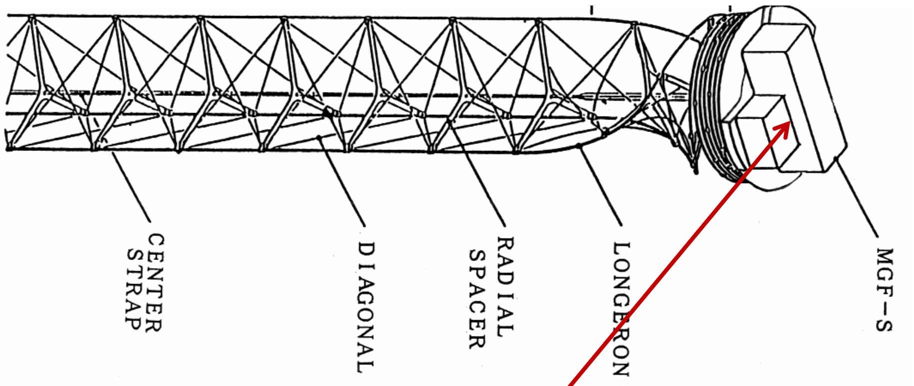
Electric field measurement

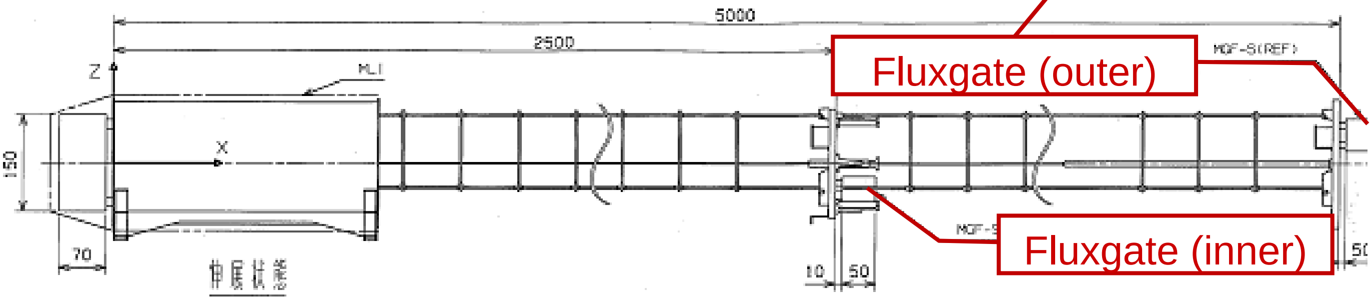


Fluxgate-type Magnetometers on Extensible (Coilable) Mast



STORED





Fluxgate (outer)

Fluxgate (inner)

DEPLOYED

観測手法

- ファラデーカップ電流計
- ラングミュアプローブ（Langmuir Probe）
- RPA（Retarding Potential Analyzer）
- Electrostatic Energy Analyzer（ESA）
  - 静電型荷電粒子エネルギー分析（E/q分析）
  - Channel Electron Multiplier (CEM, Channeltron)、MCP (Microchannel Plate)等の開発で粒子計数測定による詳細なエネルギー分析が実現
  - 2次元の視野を衛星スピンを利用し3次元速度分布を取得
- 質量分析
  - 磁石によるM/q分析・TOFによる速度分析
  - 質量別の3次元速度分布
- SSDによるエネルギー分析
  - E/q、M/qあるいはv、Eからイオン価数同定

FARADAY CUP RESPONSE TO POSITIVE IONS

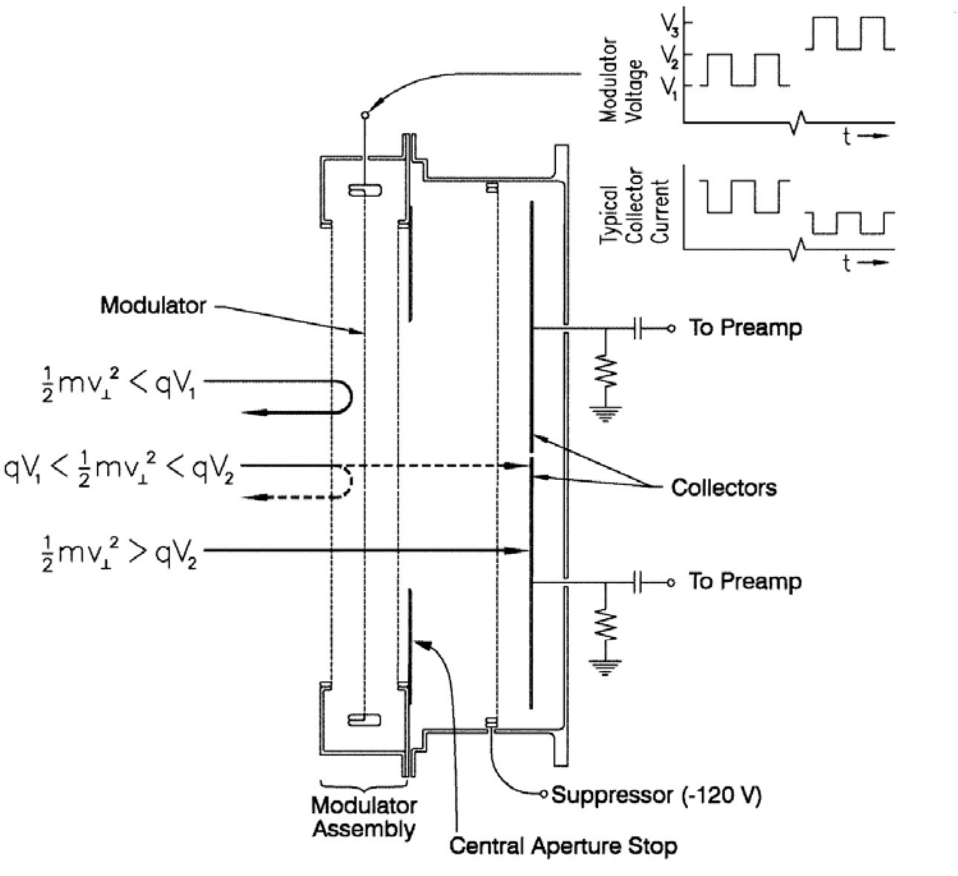
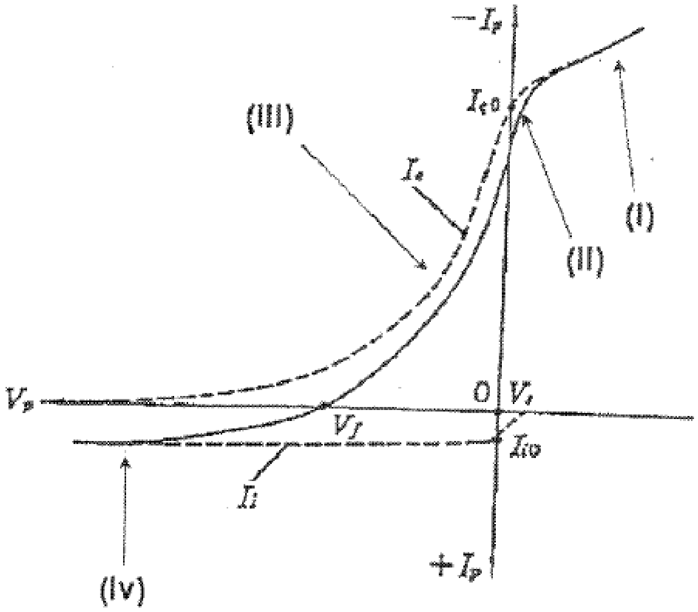


Figure 2.23: A schematic cross section of the Wind FC instrument along its symmetry axis showing the entrance aperture, the modulator assembly, the limiting aperture, the suppressor grid, and the collector plate (oriented perpendicular to the page), which is split into two semicircular plates.

Langmuir Probeの測定原理



プラズマ中に導体(プローブ)をおくと、導体はそのプラズマが持つ電位(空間電位V_s)と同じ電位になるまで電荷がたまる。プローブに印加電圧を加えて電圧を変化させると電流値は変化するため、その変化を見ることでプラズマの様子を知ることができる。

空間電位をV_s、プローブにかける印加電圧をV_pとして、V_pを変化させると電流値は図3.1のように変化する。これをLangmuir Probeの電流-電圧特性という。

この特性曲線を3つの特徴的な領域に分けて考える。電子温度を求めるために用いる領域は(Ⅲ)である。

(Ⅰ)プローブ電位がプラズマ電位よりも高いとき

プローブは相対的に正に帯電しているため電子が引きよせられ、結果的にプローブ表面に電子の過剰な層ができる(電子シース)。過剰に集まった電子の遮蔽効果によって、電場はシース内に閉じ込められるので(Ⅱ)のときと同じように荷電粒子の熱拡散電流のみが流入する。この電流は飽和電流と呼ばれる。平板プローブでは、飽和電流は理論上一定だが、実際はプローブ電流の上昇とともに増加する。

(Ⅱ)プローブ電位とプラズマ中の電位が等しいとき

プローブと荷電粒子の間に電気的な力は働かない。従って、プローブには熱運動によってのみ荷電粒子が浸入する。この電流は熱拡散電流と呼ばれる(B章参照)。

$$I_{e0} = \left[\frac{kT_e}{2\pi m_e}\right]^{\frac{1}{2}} N_e \cdot eS$$

$$I_{i0} = \left[\frac{kT_i}{2\pi m_i}\right]^{\frac{1}{2}} N_i \cdot eS$$

Sはプローブの表面積である。プローブ電流I_pはI_{e0}とI_{i0}の総和で表される。

$$I_p = -I_{e0} + I_{i0}$$

(Ⅲ)プローブの電位が空間電位よりも低くなる領域

電子の運動エネルギーが

$$\frac{1}{2}m_e v_e^2 < e(V_p - V_s)$$

を満たす電子がプローブ内に浸入する。

電子のエネルギー分布がマクスウェル分布に従うとすると(A章参照)、この領域でのプローブの電流-電圧特性は

$$I_e = I_{e0} \exp\left[-\frac{e(V_p - V_s)}{kT_e}\right]$$

である。両辺の対数をとり、$V = e(V_p - V_s)$で微分することにより

$$\frac{d\ln I_e(V)}{dV} = -\frac{e}{kT_e}$$

となり、T_eが求まる。

(Ⅳ)プローブの電位が空間電位よりも十分に低いとき

電子は電場の影響で浸入できないので、ほとんどはイオン電流となる。プローブ周辺にイオンシースができるので、プローブ内にはイオンの熱運動による飽和イオン電流のみが流れる((Ⅰ)と同じ原理)。ここで得られたイオン電流を外挿することによって電子電流を求めることができる。

Requirements for Space Plasma Particle Instruments onboard Spacecraft in Space

- Wide energy coverage is necessary because the space plasma distribute over the wide energy range.
- Wide field-of-view (FOV) is required because the velocity distributions of the space plasma could be anisotropic or drifted in a certain direction.
- 3- or 2-dimensional velocity distribution functions should be obtained independently for electrons and ions discriminated by their species.
- ✓ Several types of instruments for electrons and ions based on appropriate techniques for energy/flight direction/mass analyses and particle detection are applied in each mission.
- ✓ The combination of wide FOV, for instance, using a planar FOV up to 2π rad. with only a half spin motion of spacecraft can realize the whole coverage over the full solid angle, 4π sr.

静電型荷電粒子エネルギー分析器の測定原理

エネルギー弁別・掃引
入射角弁別・掃引
質量弁別・掃引
価数弁別
カウント・フラックス・PSD換算

プラズマ・粒子観測器の特徴・原理

電子のピッチ角・3次元速度分布

・熱的エネルギー　　0.1 〜 10eV
  I. Langumuir probe
・低エネルギー　　10 eV 〜 30 keV
  I. Electrostatic energy analyzer

・中エネルギー　　10 keV 〜 100 keV
  I. Electrostatic energy analyzer
  II. SSD or APD

・高エネルギー　　30 keV 〜 2 MeV
  I. SSD energy analysis

・超高エネルギー　　300 keV 〜 20 MeV
  I. APD + Scintillator

プラズマ・粒子観測器の特徴・原理

主要イオン種別のピッチ角・3次元速度分布

- 熱的エネルギー　0.1 ～ 30eV
  1. Gated electrostatic energy analyzer or RPA(+Mirror)+TOF
- 低エネルギー　10 eV ～ 30 keV
  1. Electrostatic energy analyzer
  2. TOF mass(velocity) spectrometer
- 中エネルギー　10 keV ～ 180 keV
  1. Electrostatic energy analyzer
  2. SSD
  3. TOF mass(velocity) spectrometer
- 高エネルギー　30(60) keV ～ 1 MeV
  1. SSD energy analysis
  2. TOF mass(velocity) spectrometer

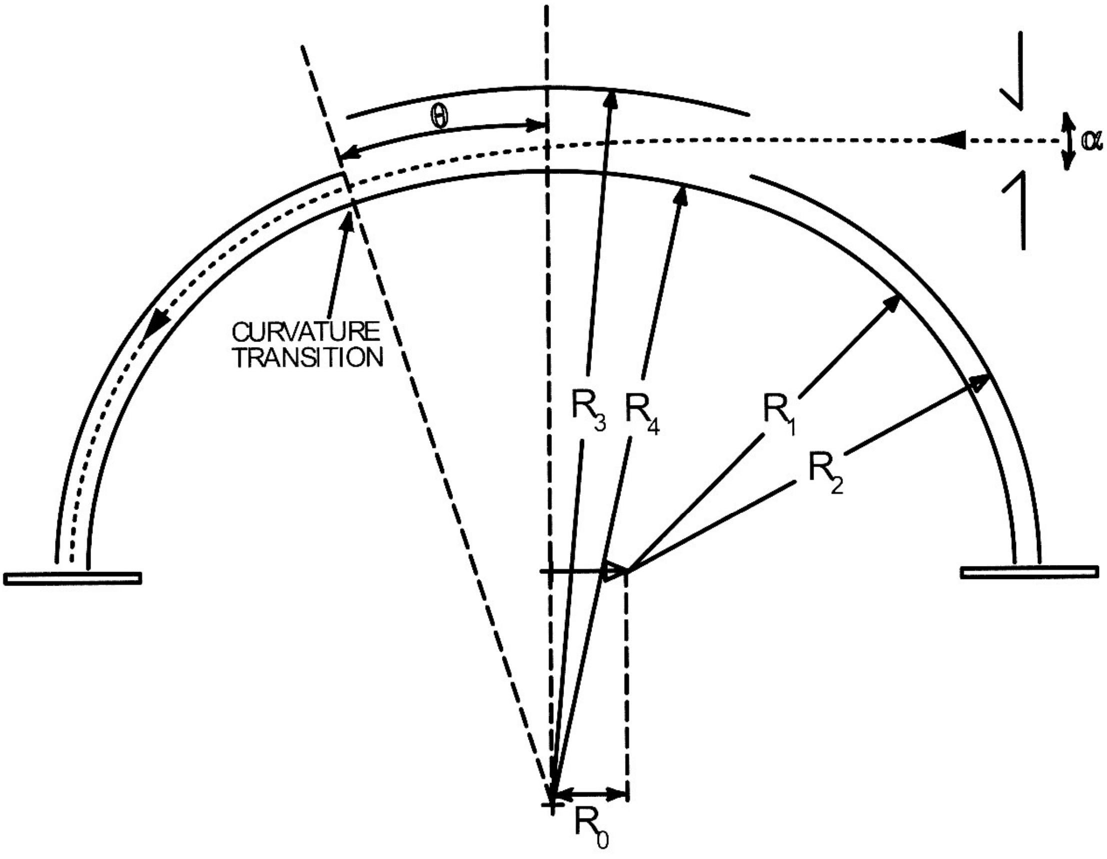


Figure 2.33: Schematic diagram of a toroidal top-hat analyzer with a spherical top-hat. The radius R_4 is chosen to provide a continuous curved surface by matching slopes at the interface between different curvatures. From *Carlson and McFadden* [1998].

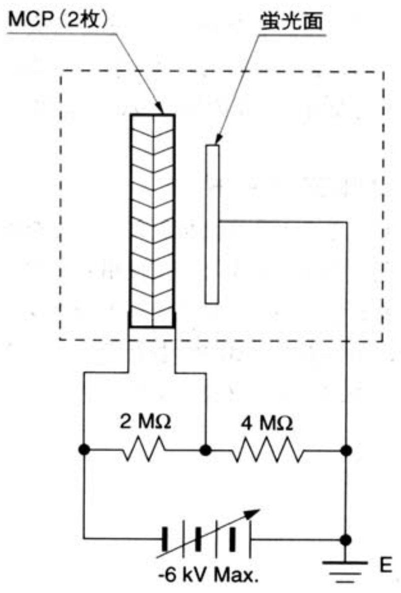


図25：蛍光面アッセンブリの結線例

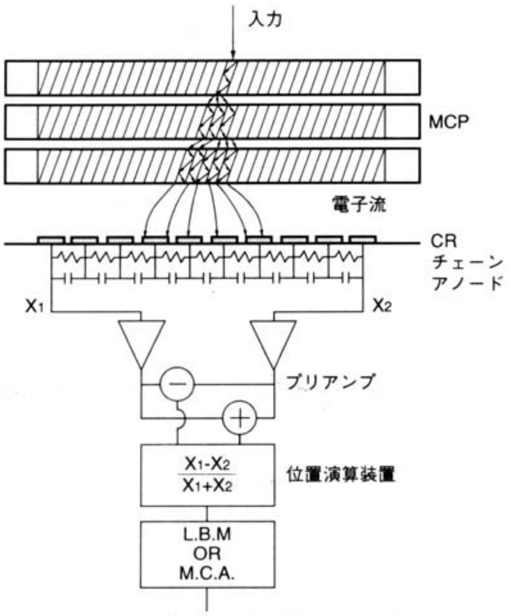


図28：CRチェーンアノードMCPアッセンブリ
の構成および処理系

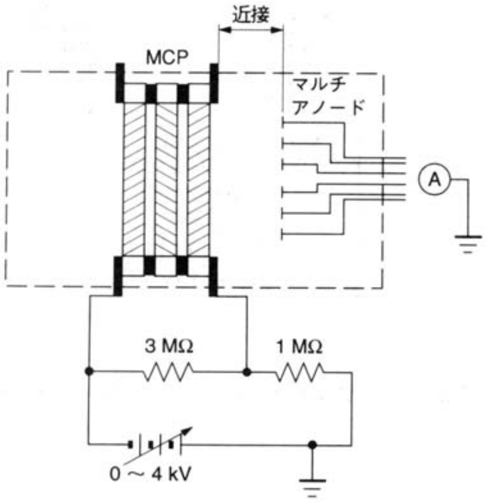
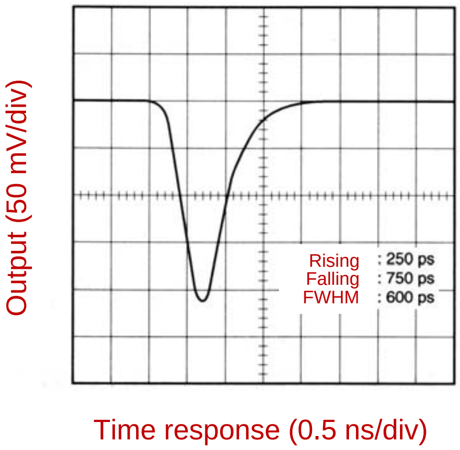


図24：マルチアノードアッセンブリ結線例

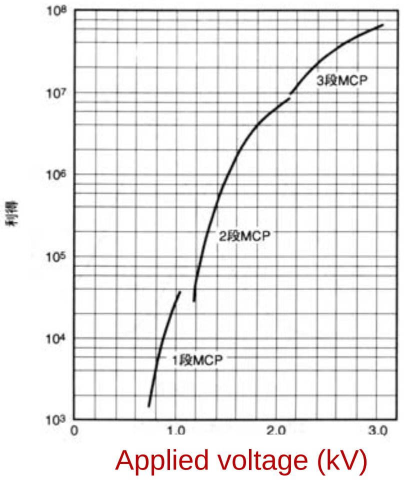
Micro Channel Plates (MCP)

- Sensitive to low-energy neutral/charged particles and photons
- Effective areas are wide and various in shape.
- Generate fast sharp pulse signal with high gain up to $10^{7\text{-}8}$
- Not capable of discriminating incident particles/photons
- Pulse height varies one by one, independently, e.g., of energy.
- High voltage must be applied.

Examples of circular MCPs



Example of pulse signal



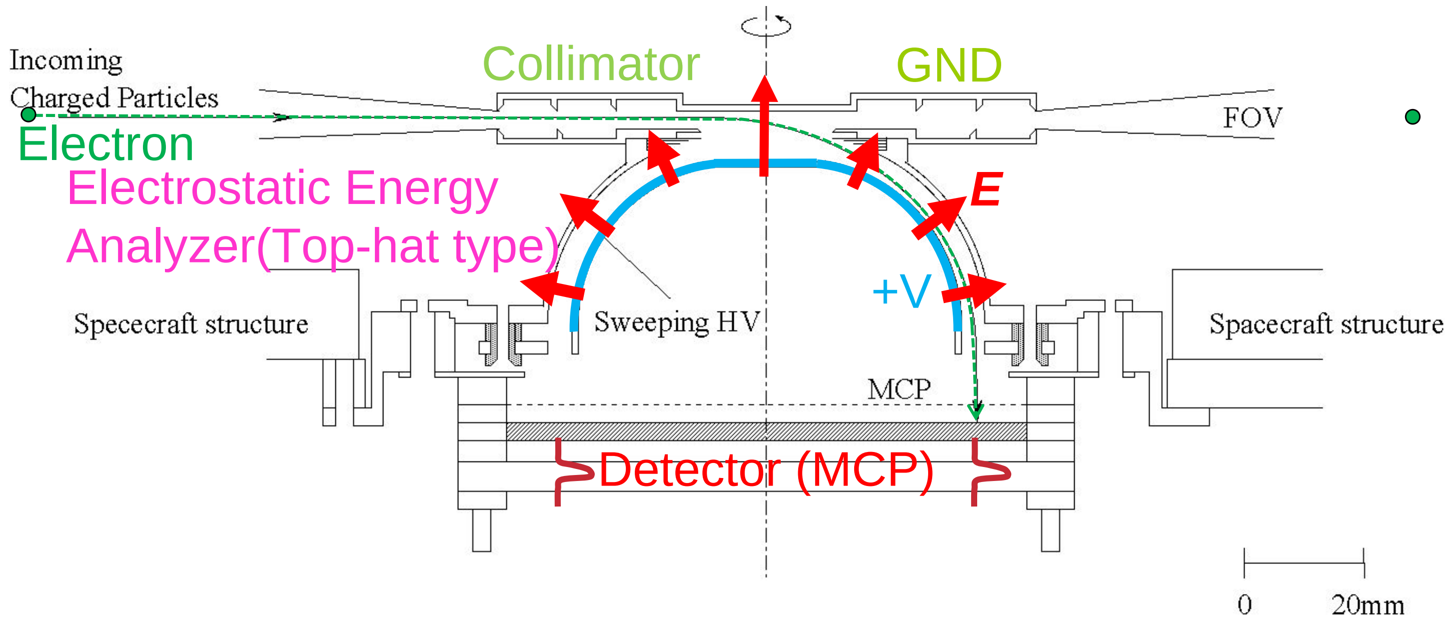
Examples of gain

Low-Energy Electron Instrument (Reimei Satellite, ISAS/JAXA)

Electron energy (*K*)
12 eV ～ 12 keV

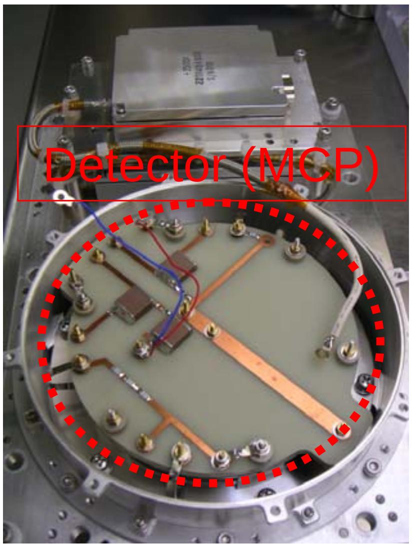
+3～+3000 V

Cylindrically symmetric



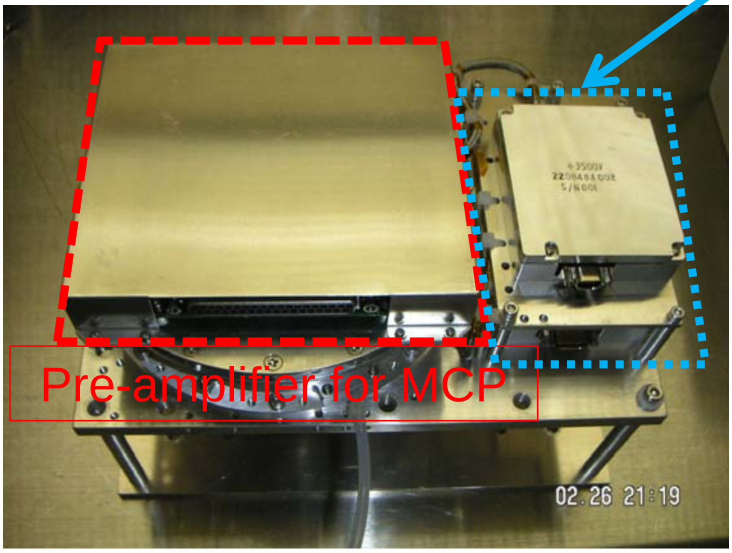
Pulses dependent on flight directions

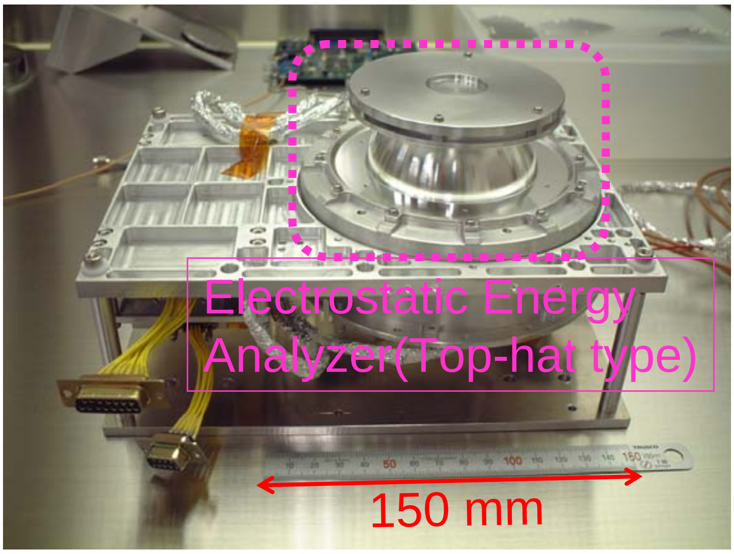
Pictures of Low-Energy Electron Instrument (Reimei Satellite, ISAS/JAXA)



Weight: 1.4 kg
Power: 2.4 W

High-voltage power supplies for electrostatic energy analyzer (lower) and MCP (upper)





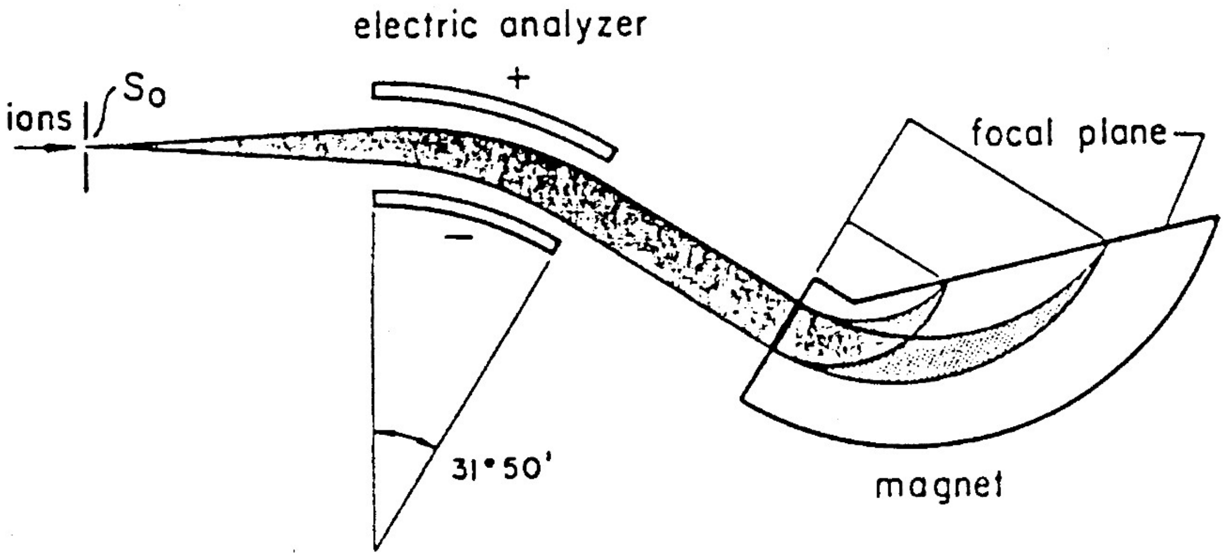
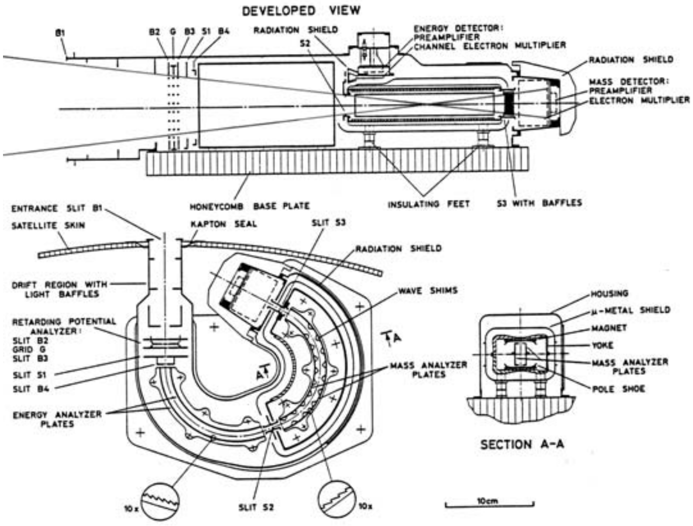
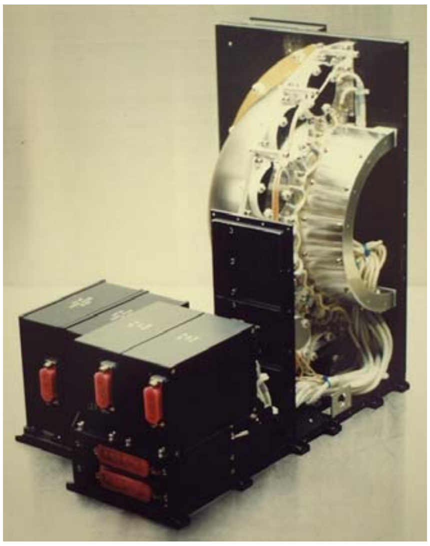
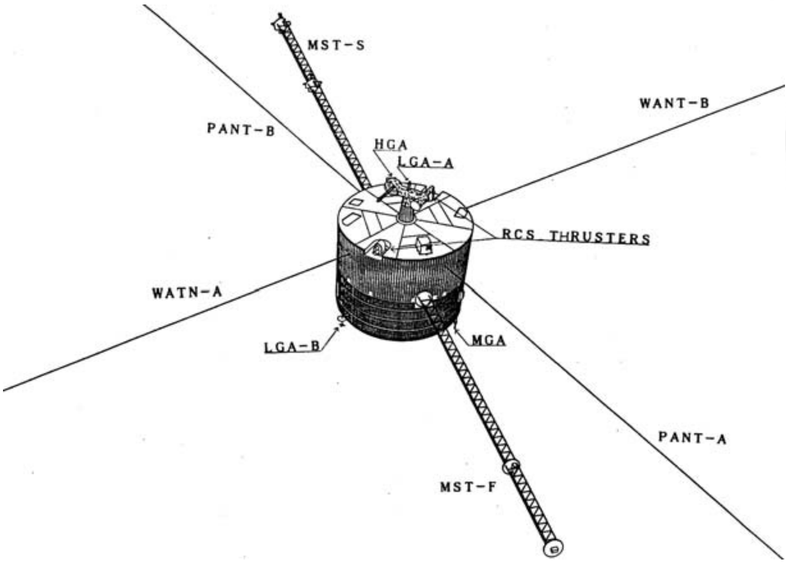
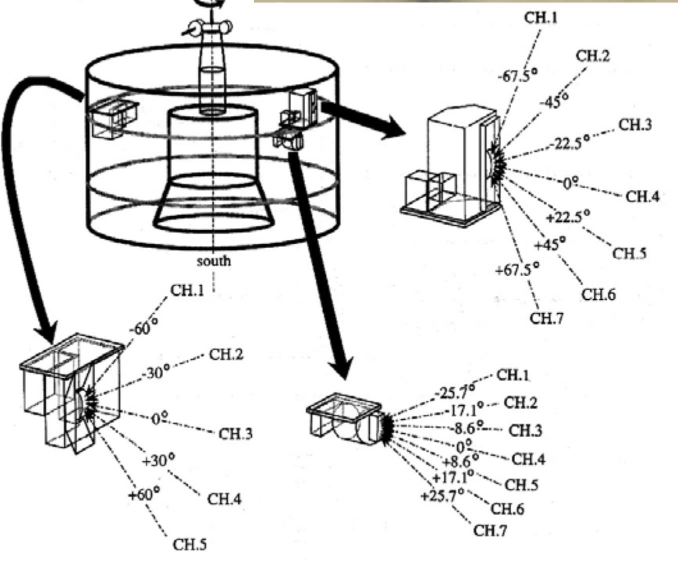


Figure 2.38: High-performance double focusing mass spectrometer of the Mattauch-Herzog design. From *Nier and Schuttler* [1985].

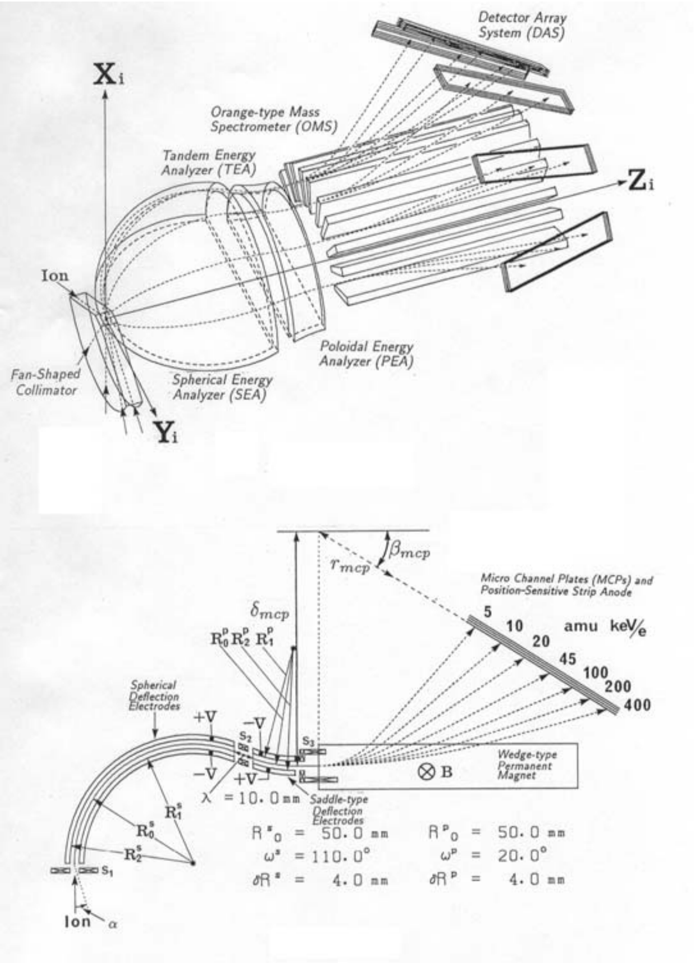


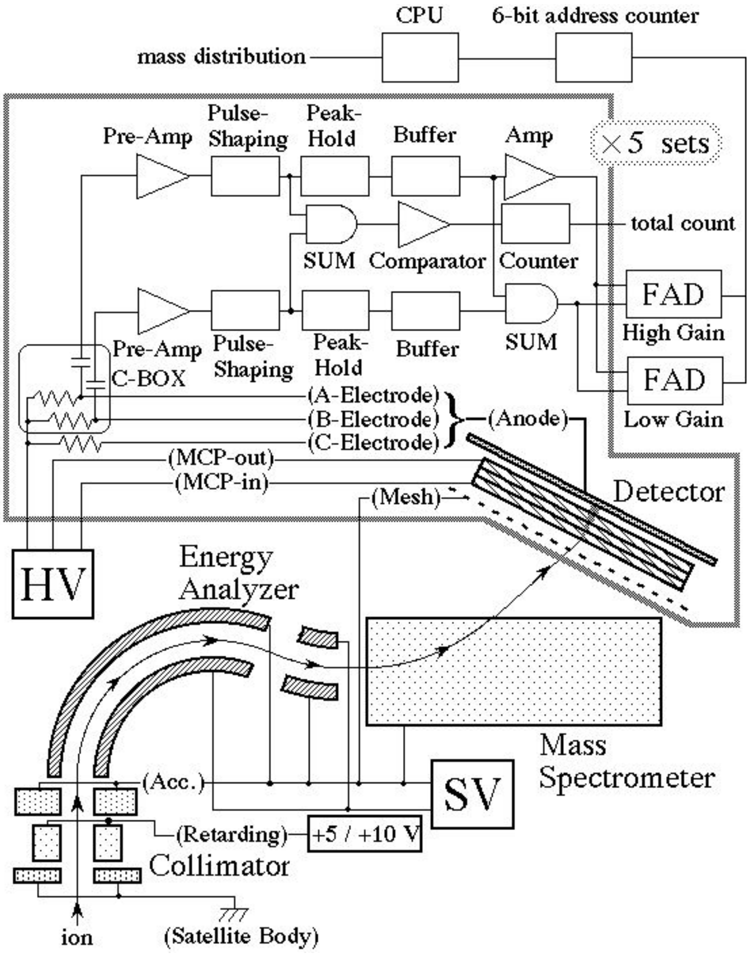




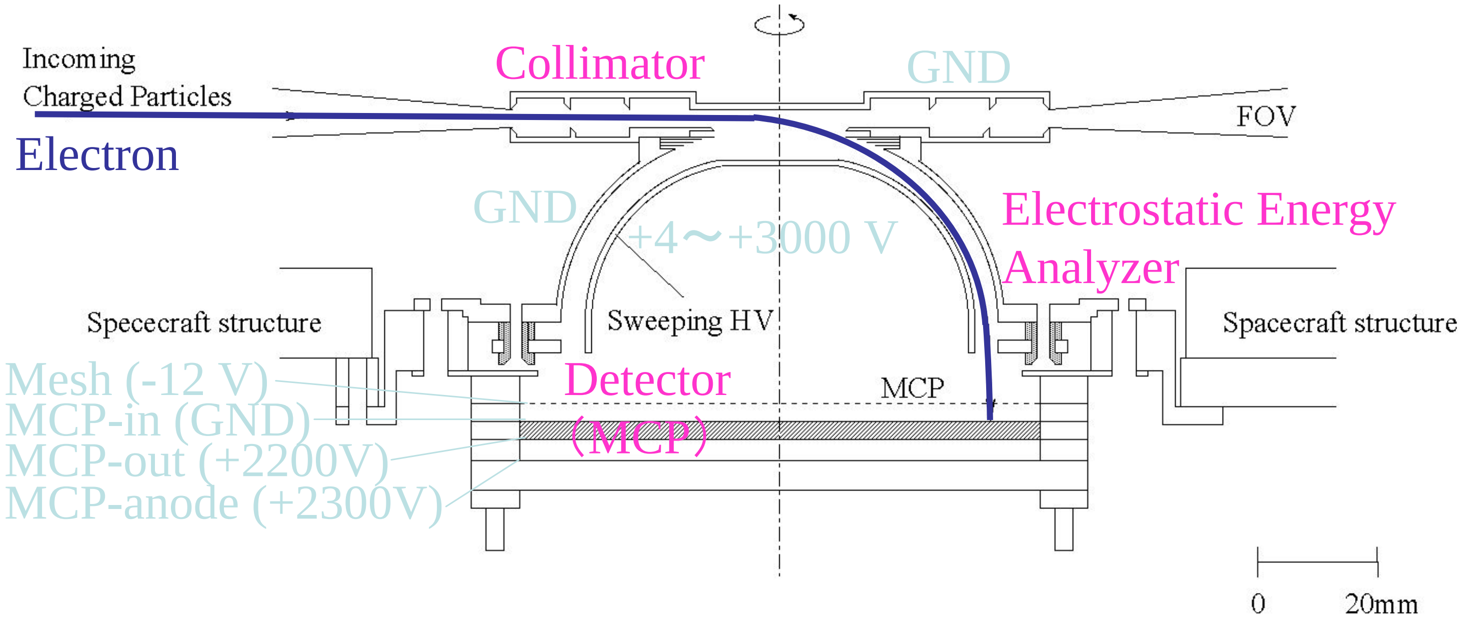


Geotail搭載イオンエネルギー質量分析器





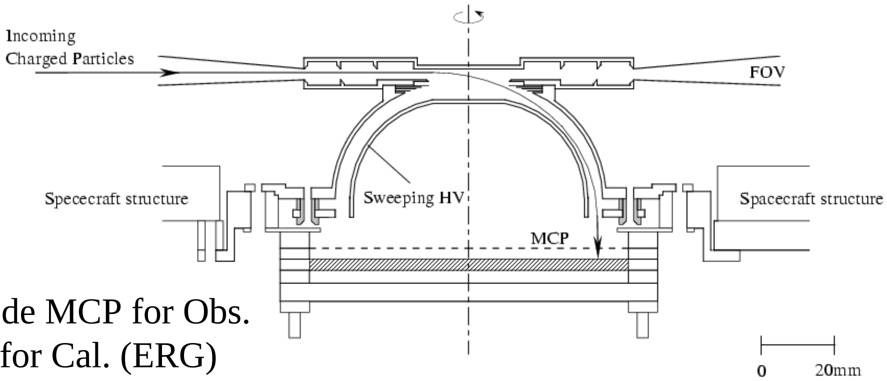
れいめい搭載用荷電粒子エネルギー分析器（Electron/Ion Energy Spectrum Analyzer: ESA/ISA）

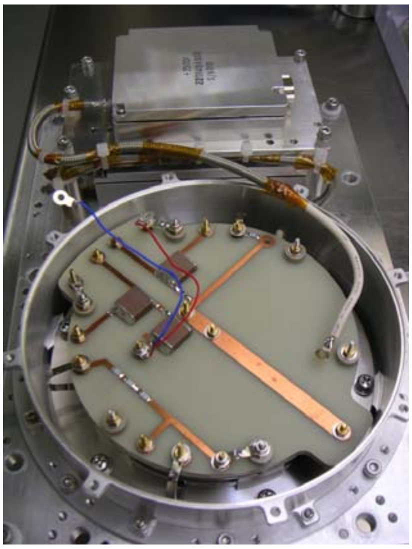


3000 V * 20 keV/12 keV = 5 kV

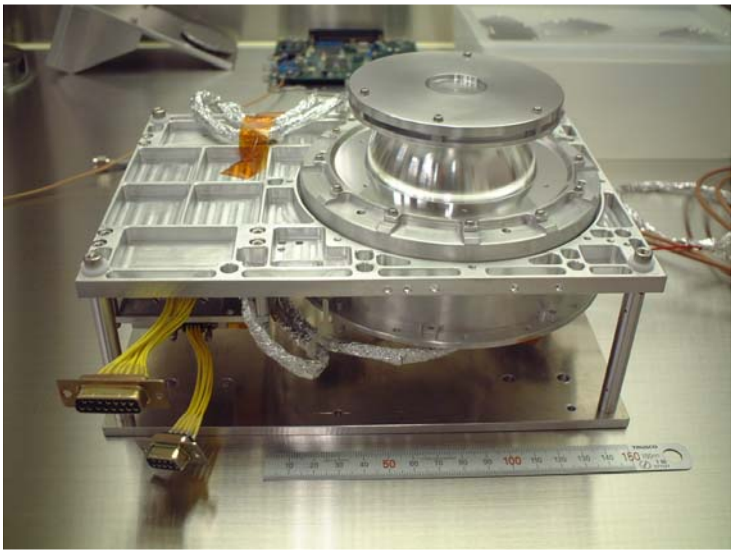
3000 V * 16 keV/12 keV = 4 kV

Sectional view of ESA/ISA

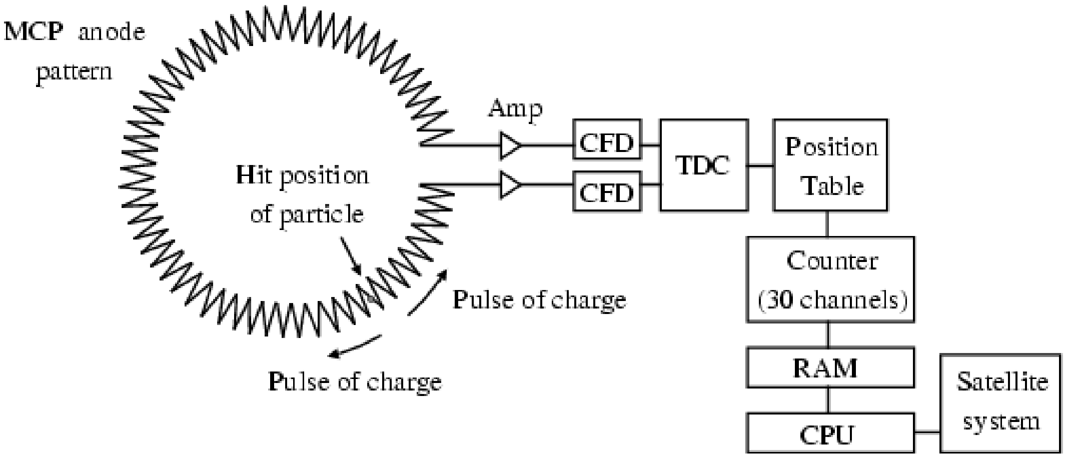


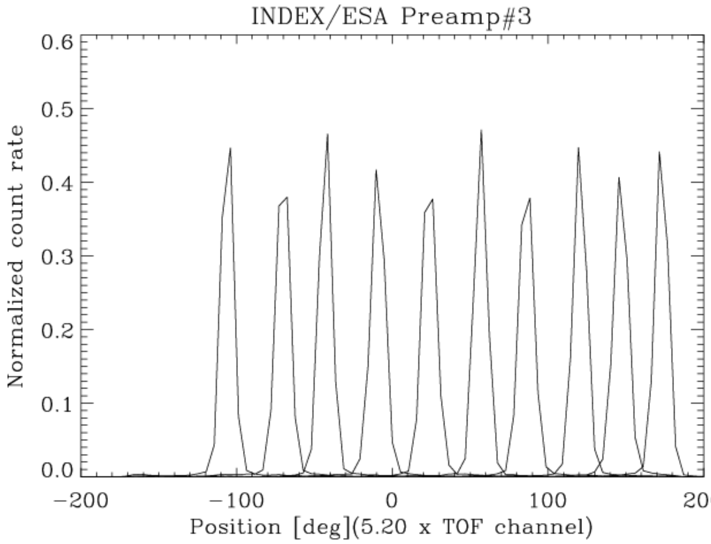


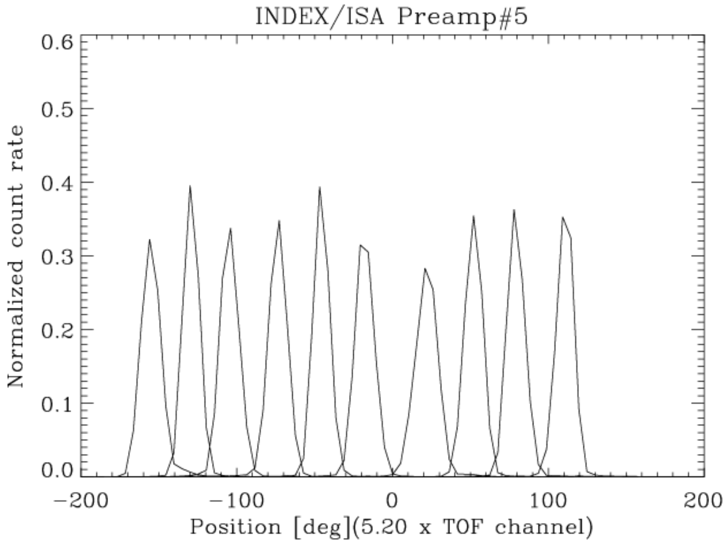
Multi-anode MCP for Obs.
and APD for Cal. (ERG)



ESA/ISAの位置検出方法と実験結果



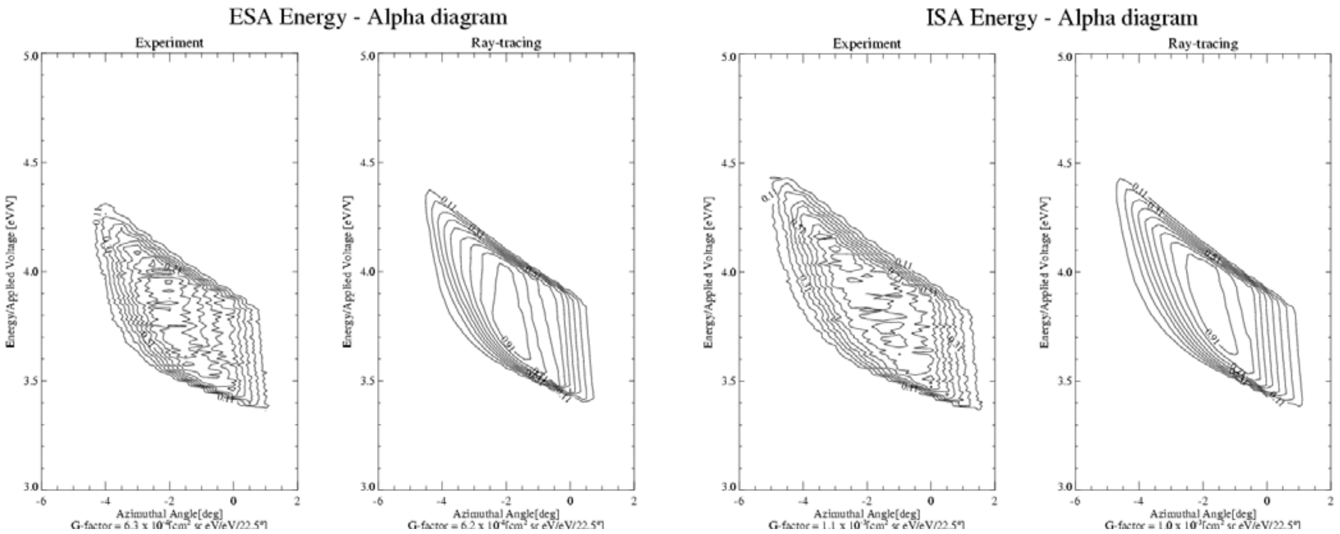




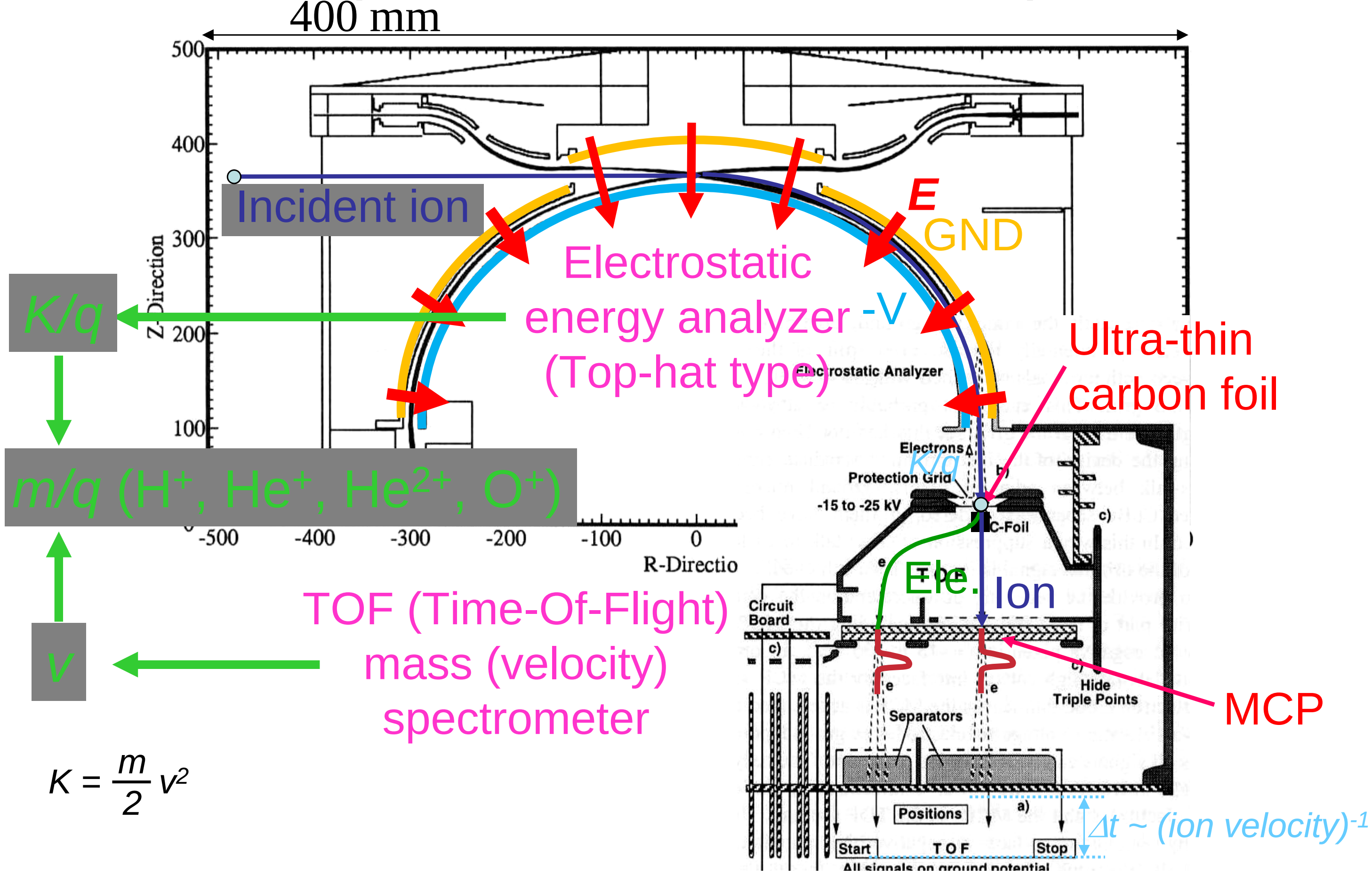
ESA/ISAのエネルギー・角度応答

ESA　　　　　　　　ISA

実験結果　計算結果　実験結果　計算結果



Low-Energy Ion Instrument (FAST Satellite, NASA)



Incident ion

E

GND

-V

Electrostatic energy analyzer (Top-hat type)

Ultra-thin carbon foil

K/q

m/q (H^+, He^+, He^{2+}, O^+)

v

TOF (Time-Of-Flight) mass (velocity) spectrometer

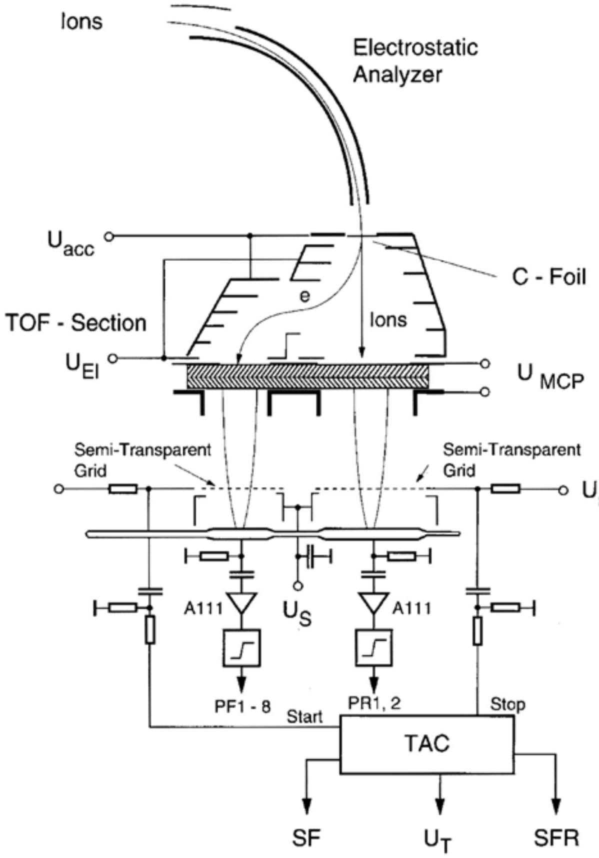
Ele.

Ion

MCP

$\Delta t \sim$ *(ion velocity)*$^{-1}$

$$K = \frac{m}{2} v^2$$



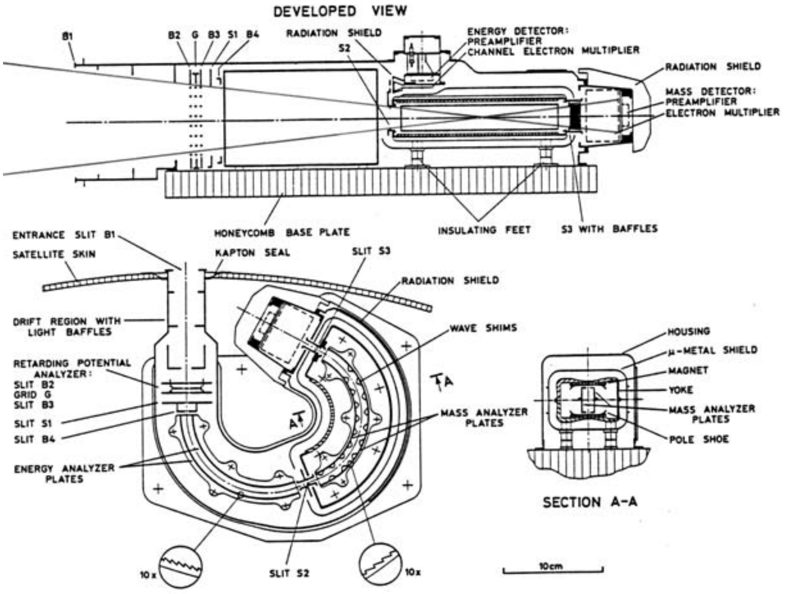
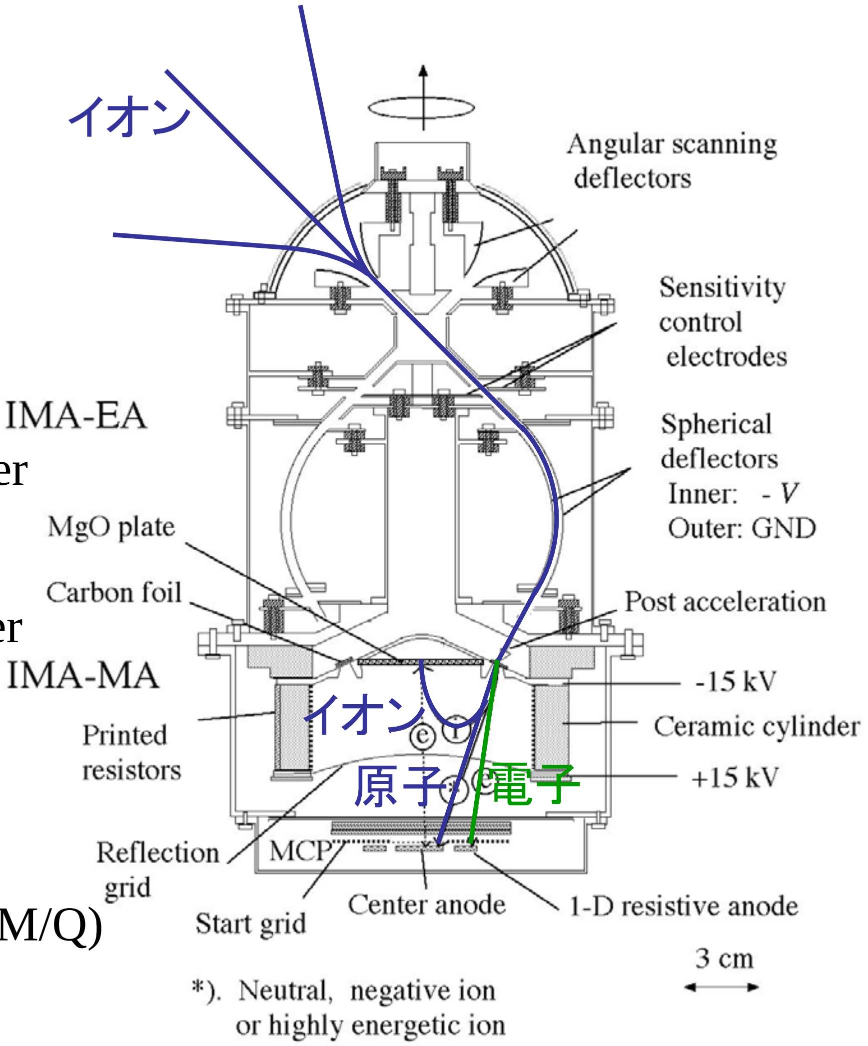


Figure 2.43: A schematic showing the Cluster CODIF TOF principle of operation. The top portion of the figure depicts the motion of an ion through an electrostatic analyzer and accelerated by the electrically biased carbon foil. The secondary electrons produced by the ion passing through the foil are steered by biased electrodes to the left hand side of the MCP to create the START signal while the ion continues on a linear path to the right hand side of the MCP to produce the STOP signal. The bottom portion of the figure shows the processing of the signals from each side of the MCP to the Time-to-Amplitude Converter (TAC) that provides the measure of the time-of-flight of the ion. From *Rème et al.* [1997].

SELENE搭載用 低エネルギーイオン 分析器（IMA） （ES-Deflector・RPA・ ESA・EF-TOF）

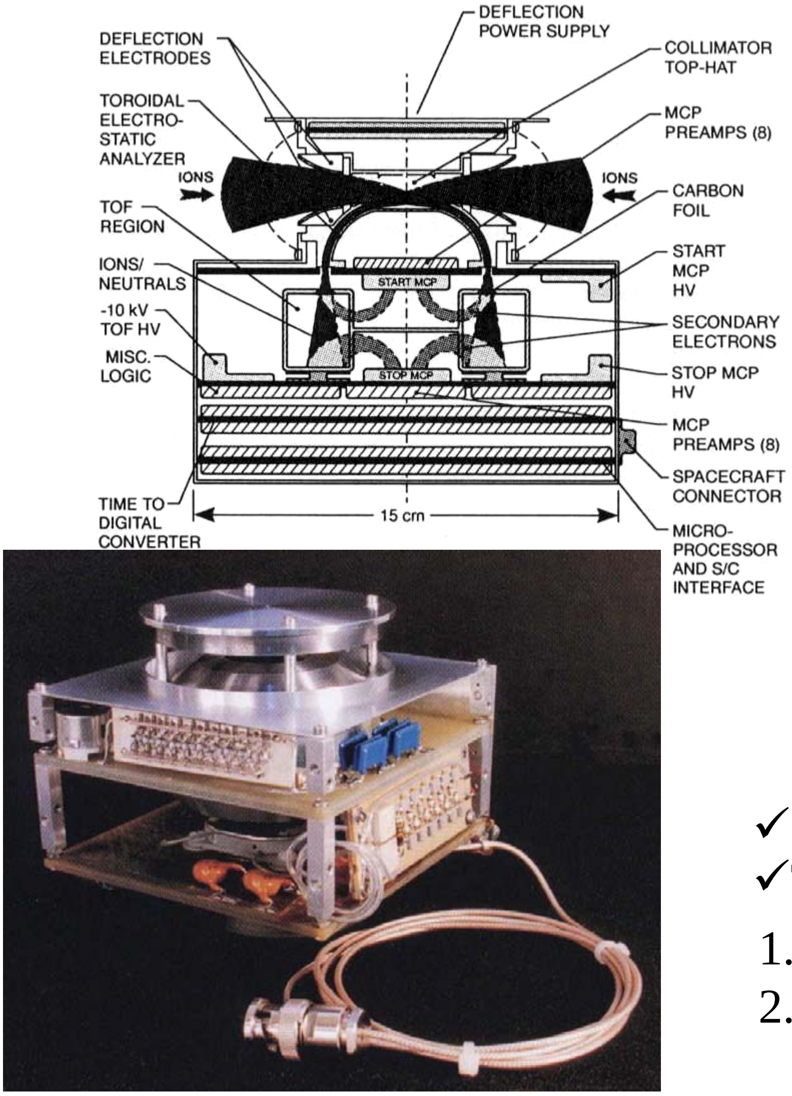


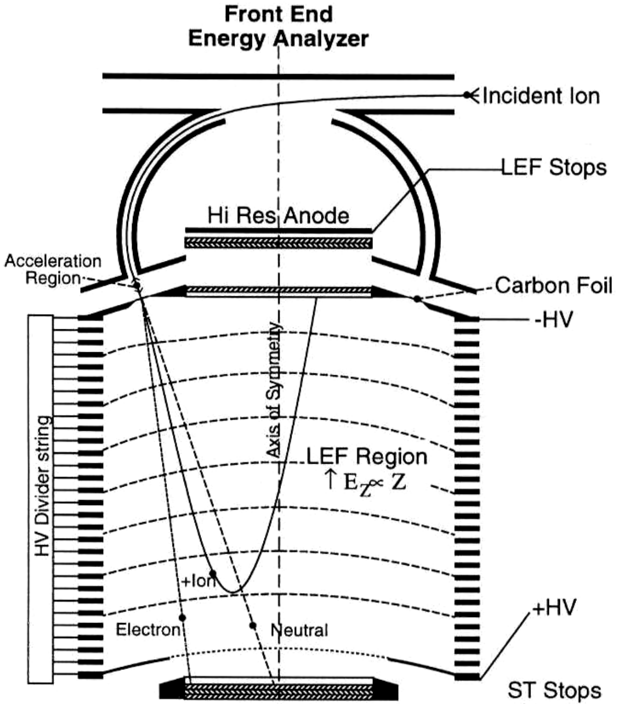
- ✓Electrostatic energy analyzer
- ✓Angular scan
- ✓LEF(Linear Electric Field) TOF velocity spectrometer
- ✓Sensitivity control

1. Energy per charge (E/Q)
2. Velocity

1 & 2 → Mass per charge (M/Q)

小型化と高性能化の例





✓Electrostatic energy analyzer
✓TOF velocity spectrometer

1. Energy per charge (E/Q)
2. Velocity

1 & 2 → Mass per charge (M/Q)

中エネルギーイオン観測器

エネルギー分析技術（10keV～100keV）

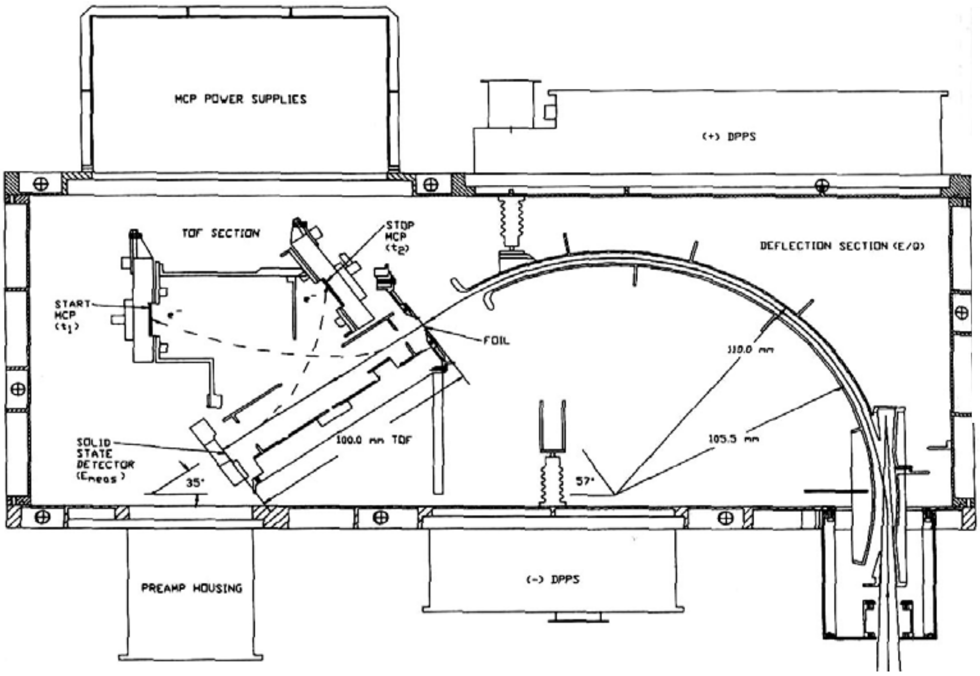
1. SSD　　エネルギー分解能が不十分
2. 静電型分析器・TOFユニット　　大きな容積・電圧が必要

→ 新規技術、小型・軽量化問題

対応

1. SSDのピクセル化、アンプ系の多チャンネル・チップ化
2. 小型高圧電源・TOFユニットの開発

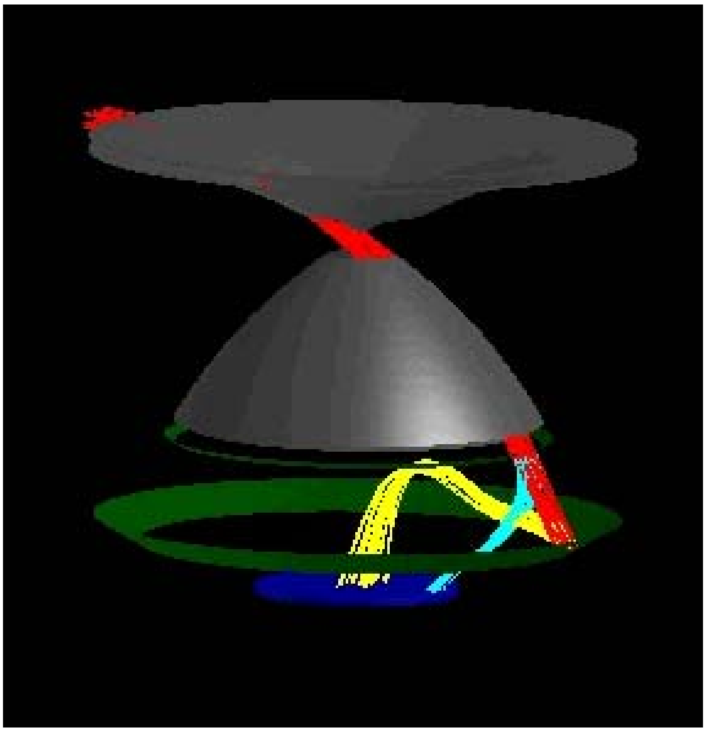
Geotail搭載用中エネルギーイオン観測器（STICS）
（ESA･TOF･SSD）

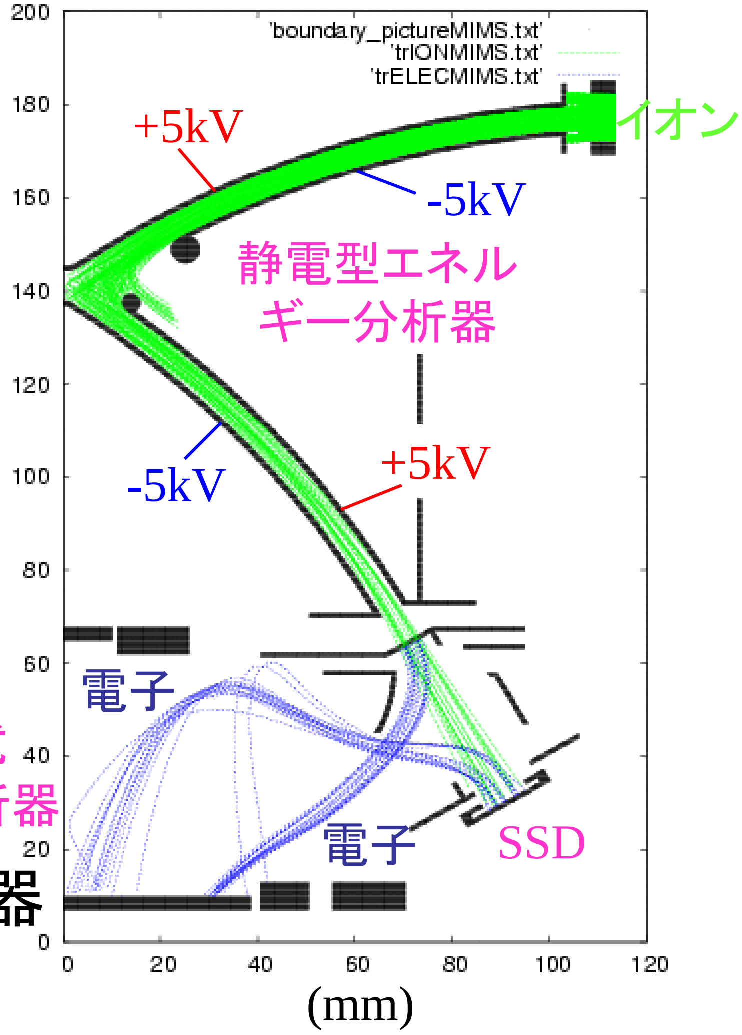


✓Electrostatic energy analyzer
✓SSD energy analysis
✓TOF velocity spectrometer

1. Energy per charge (E/Q)
2. Energy (E)
3. Velocity

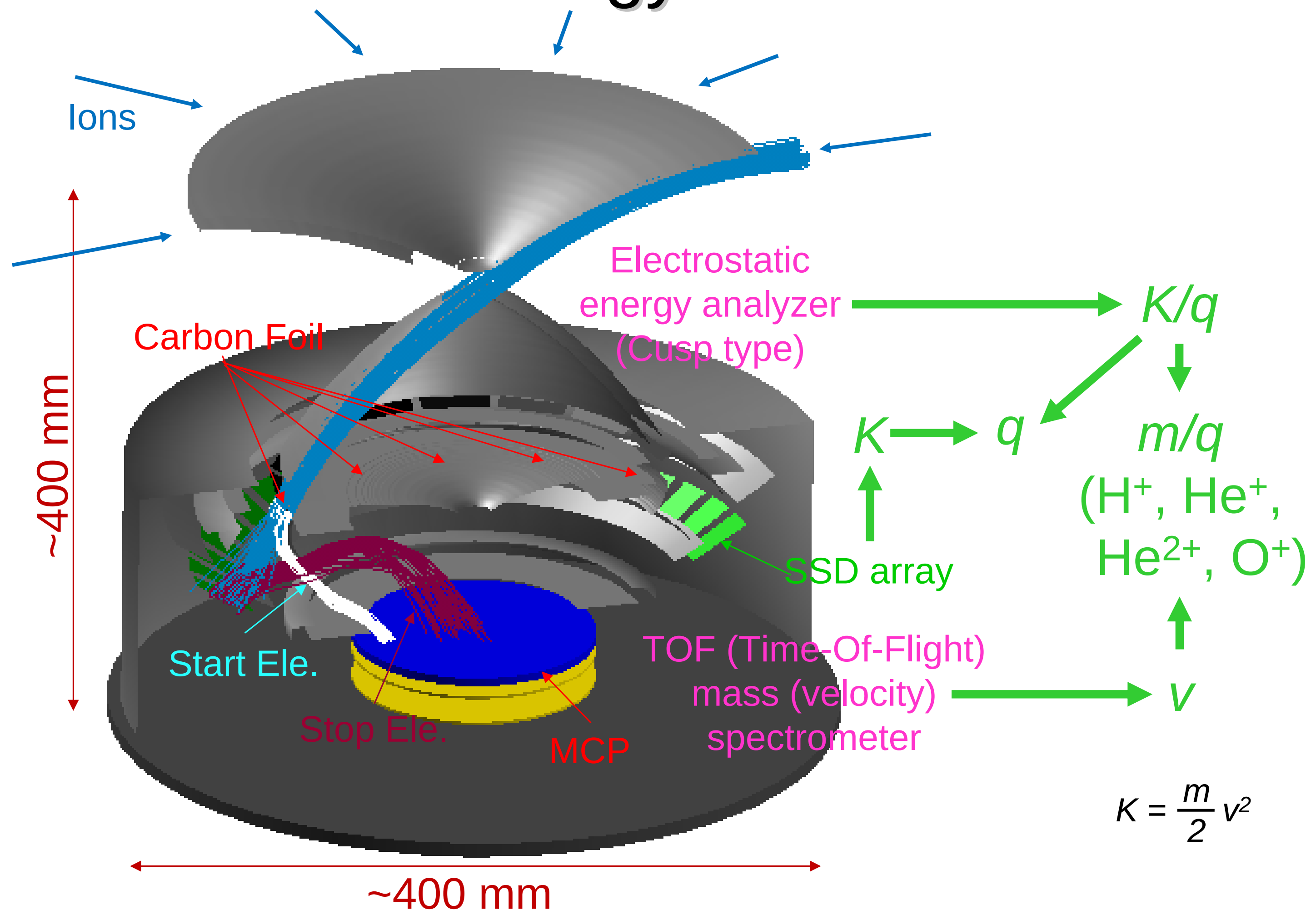
1& 2 & 3→ Mass (M) and charge (Q)



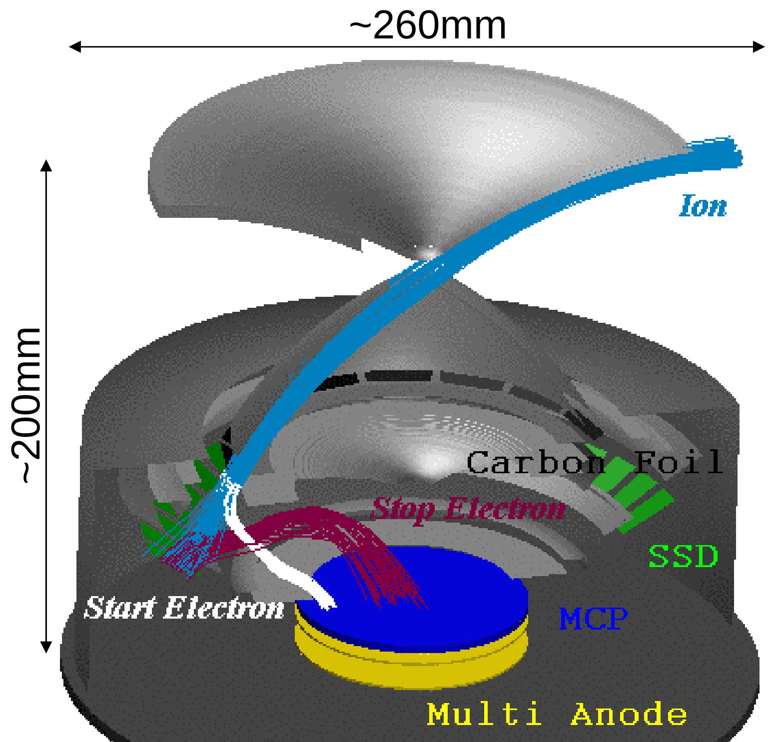


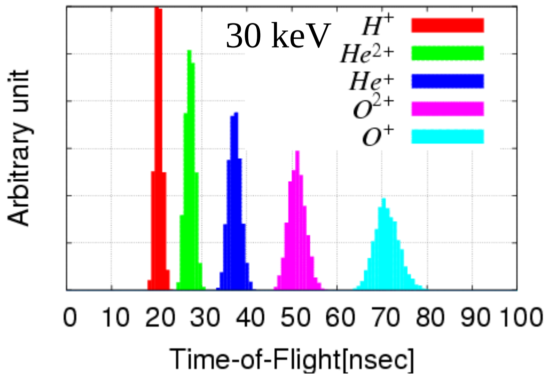
中エネルギーイオン観測器
（ESA･TOF･SSD）

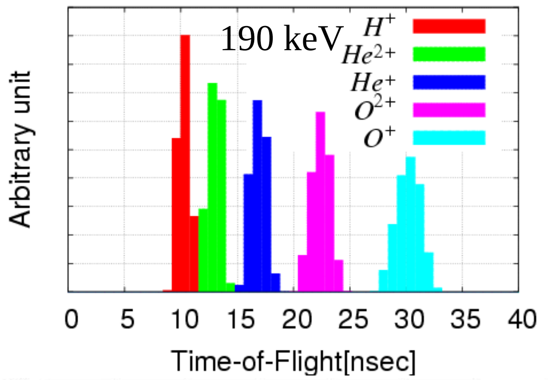
Medium-Energy Ion Instrument

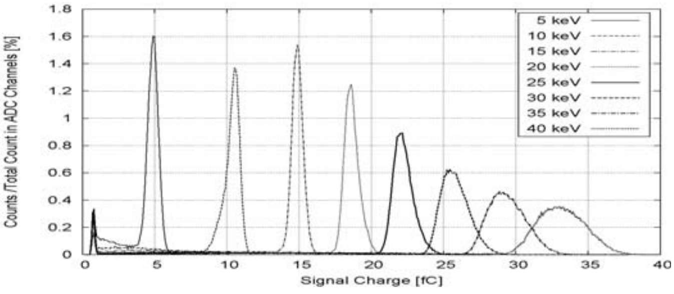


$$K = \frac{m}{2} v^2$$







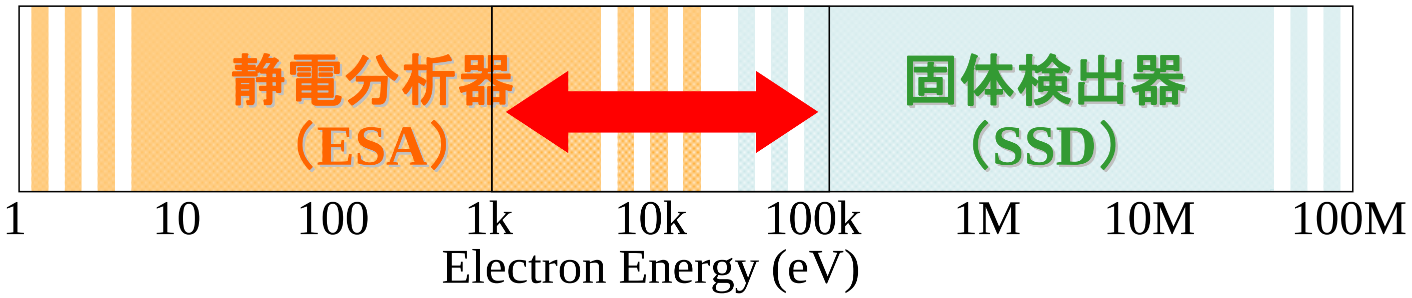


中エネルギーイオン観測器

（ESA･TOF･SSD）

中エネルギー帯域電子観測器

数keVから数十keVの電子

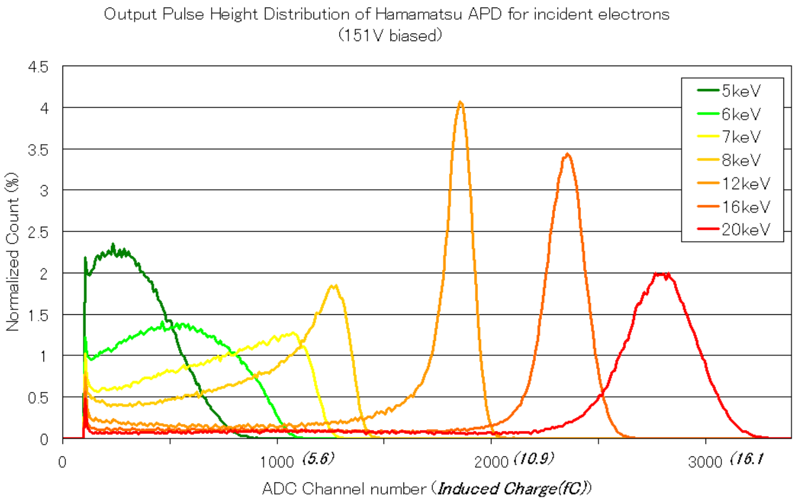


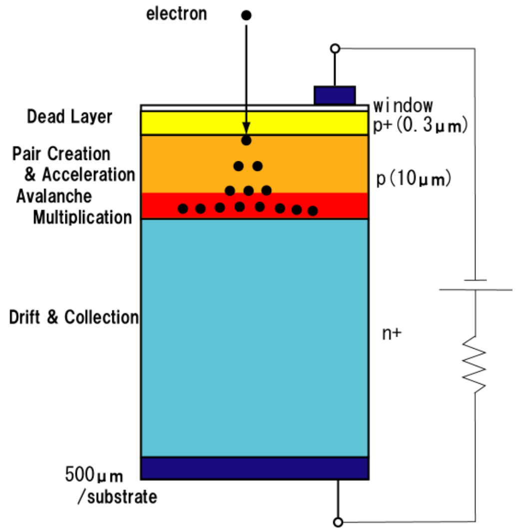
SSD …低エネルギー側にノイズの影響の問題

ESA …MCP等の検出部の検出効率の問題

電子計測用APD
（アバランシェ・フォトダイオード）

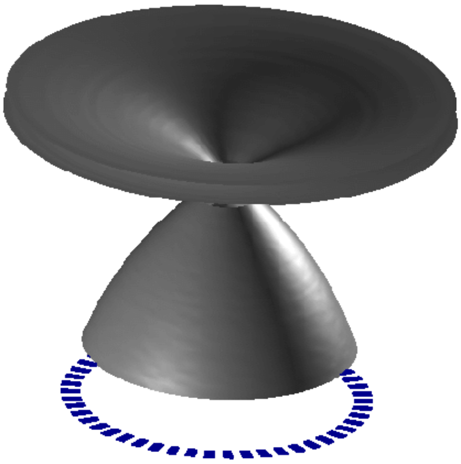
- ✓ 数keV～30keV付近電子のエネルギー測定を実現させ、プラズマ検出器とのエネルギー連続性を達成可能である。
- ✓ APDは固体光検出器で、内部利得があるためノイズに強い。





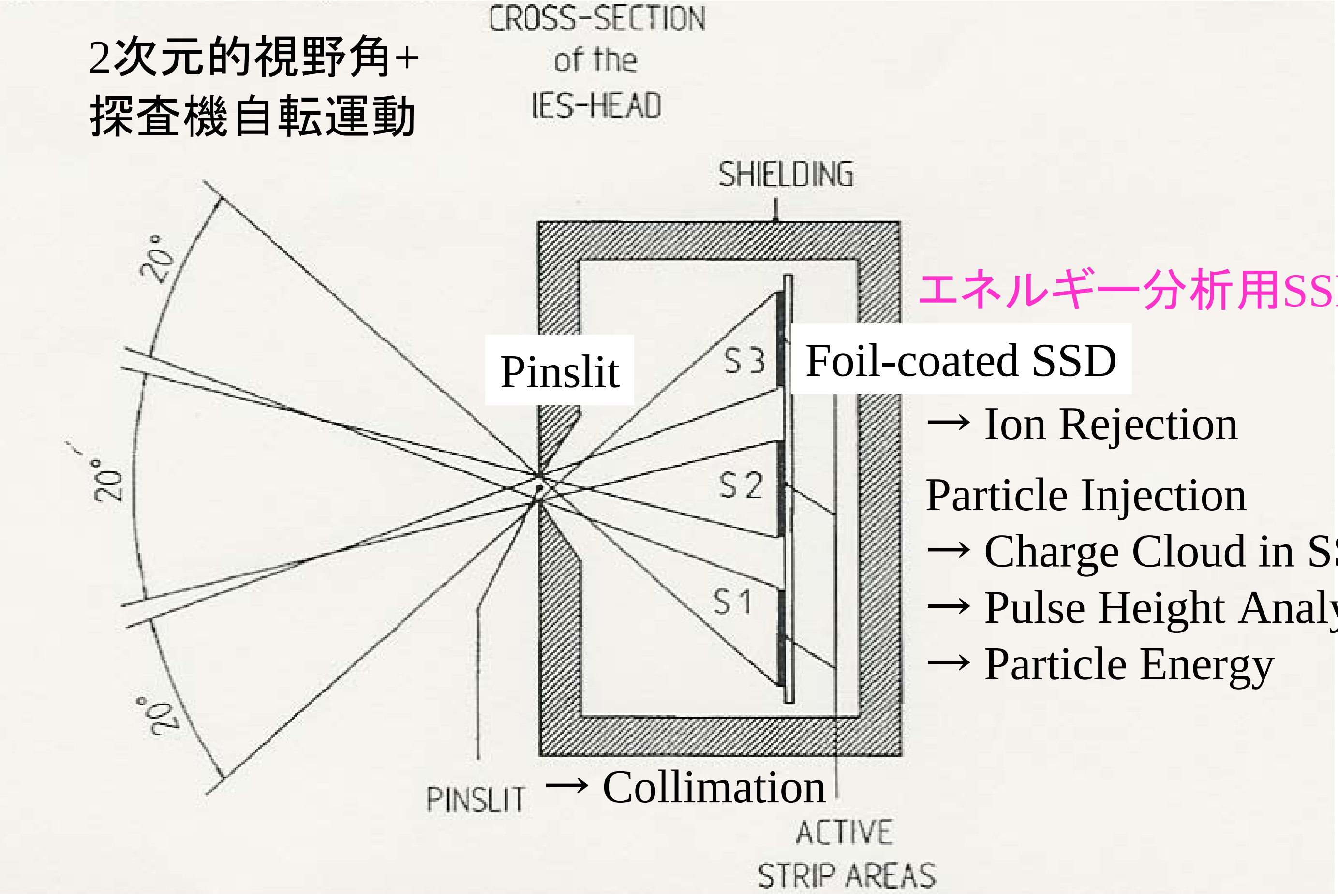
MEP-e

Electrostatic Energy Analyzer



APD Array

CLUSTER-II搭載用高エネルギー電子分析器（RAPID IES）



2次元的視野角+
探査機自転運動

Pinslit

エネルギー分析用SSD

Foil-coated SSD
→ Ion Rejection

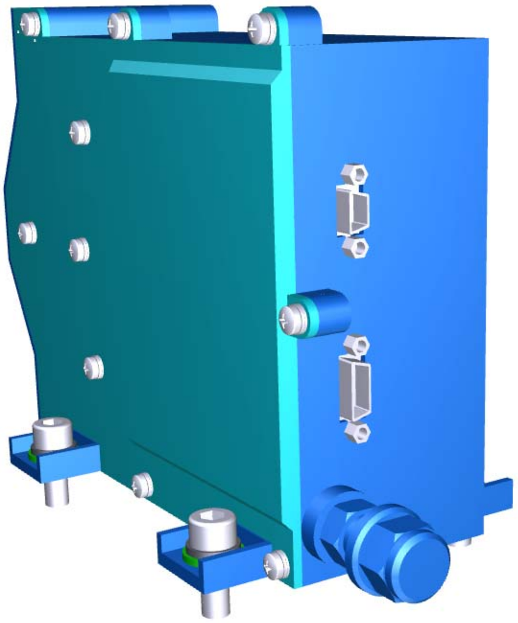
Particle Injection
→ Charge Cloud in SSD
→ Pulse Height Analysis
→ Particle Energy

→ Collimation

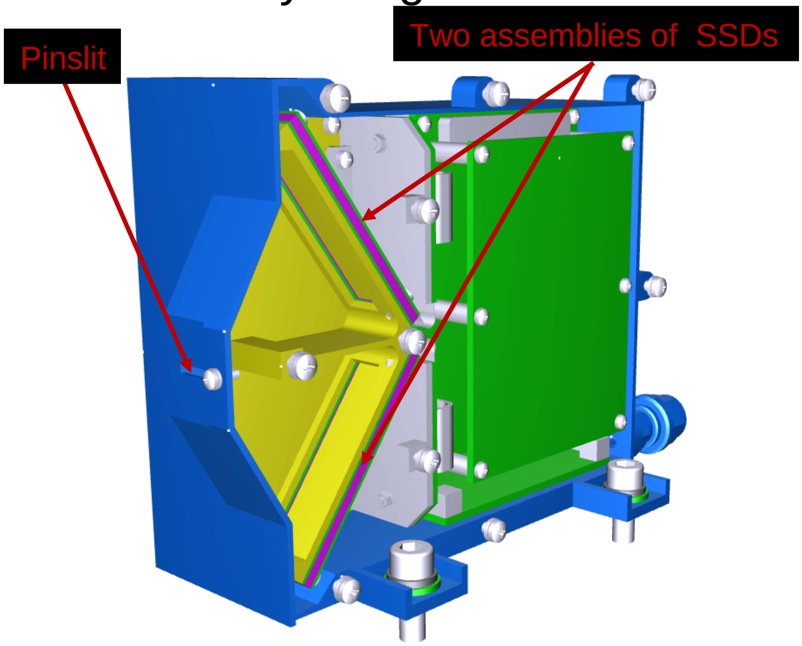
High-Energy Electron Instrument (BepiColombo MMO, ISAS/JAXA)

1. Pinslit-type Collimator
2. Energy Analysis with Strip-type SSD
3. Ion Rejection

Appearance of HEP-e

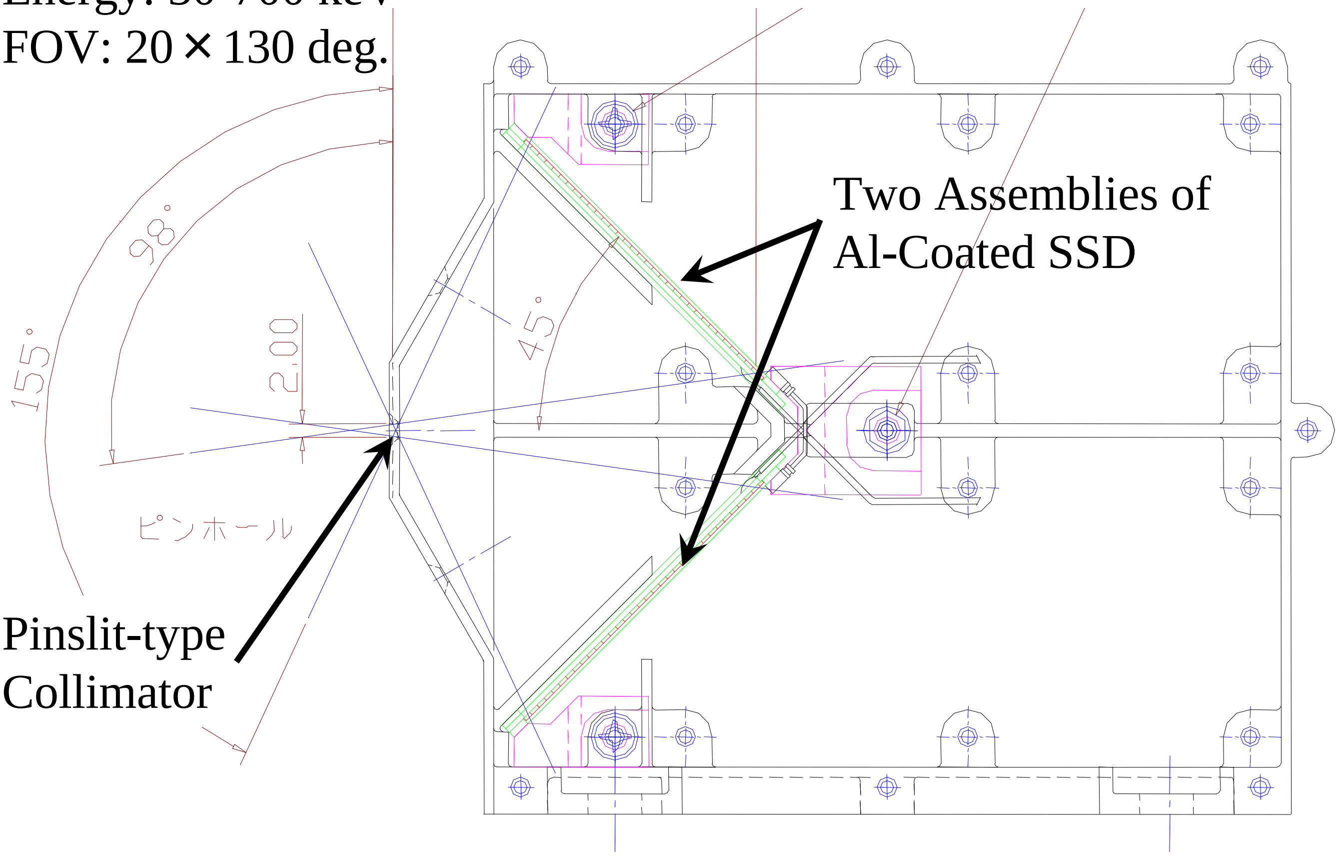


Cutaway Image of HEP-e



BepiColombo-MMO搭載用 高エネルギー電子観測器（HEP-Ele）（SSD）

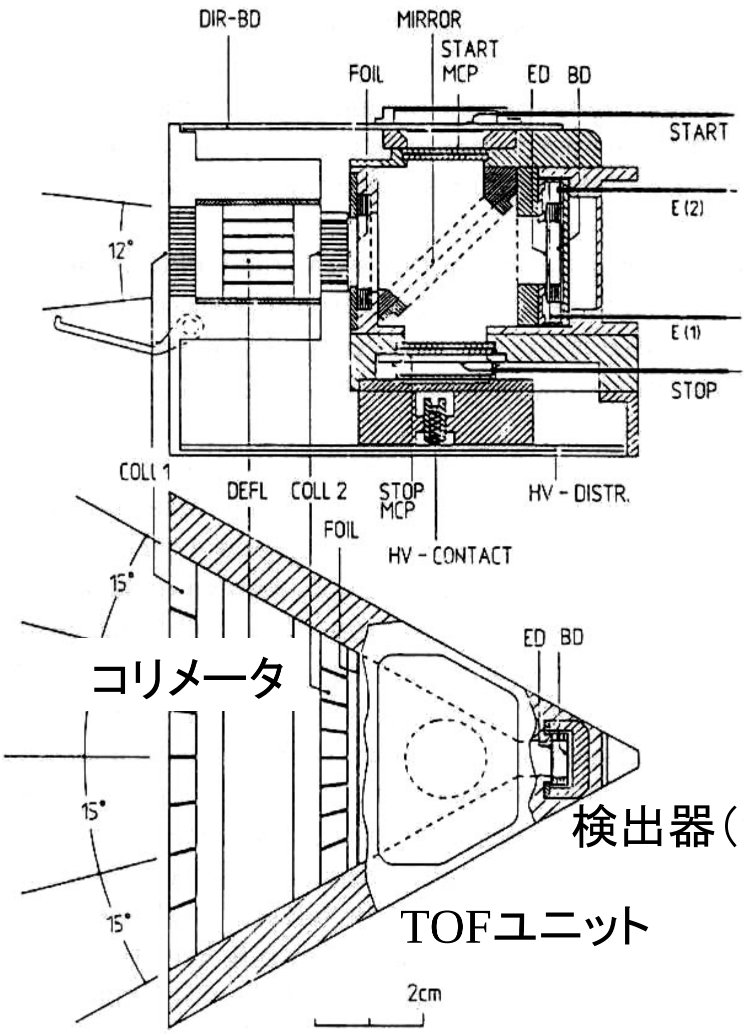
Energy: 30-700 keV
FOV: 20×130 deg.



Two Assemblies of Al-Coated SSD

Pinslit-type Collimator

Geotail搭載用 高エネルギー 粒子観測器 （TOF・SSD）



コリメータ

検出器（SSD）

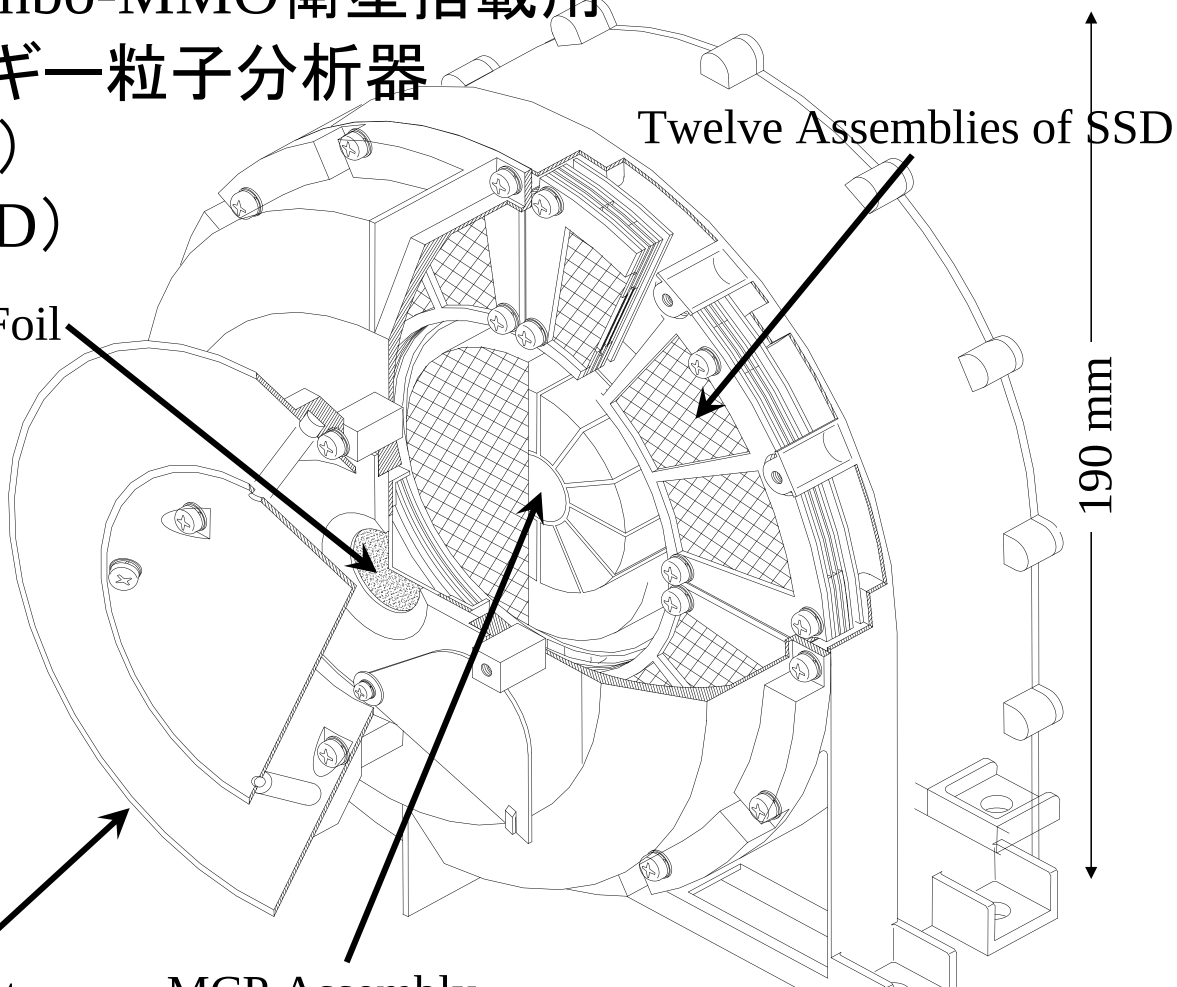
TOFユニット

✓No electrostatic energy analyzer
✓SSD energy analysis
✓TOF velocity spectrometer

1. Energy (E)
2. Velocity

1 & 2 → Mass (M)

BepiColombo-MMO衛星搭載用 高エネルギー粒子分析器 （HEP-Ion） （TOF・SSD）



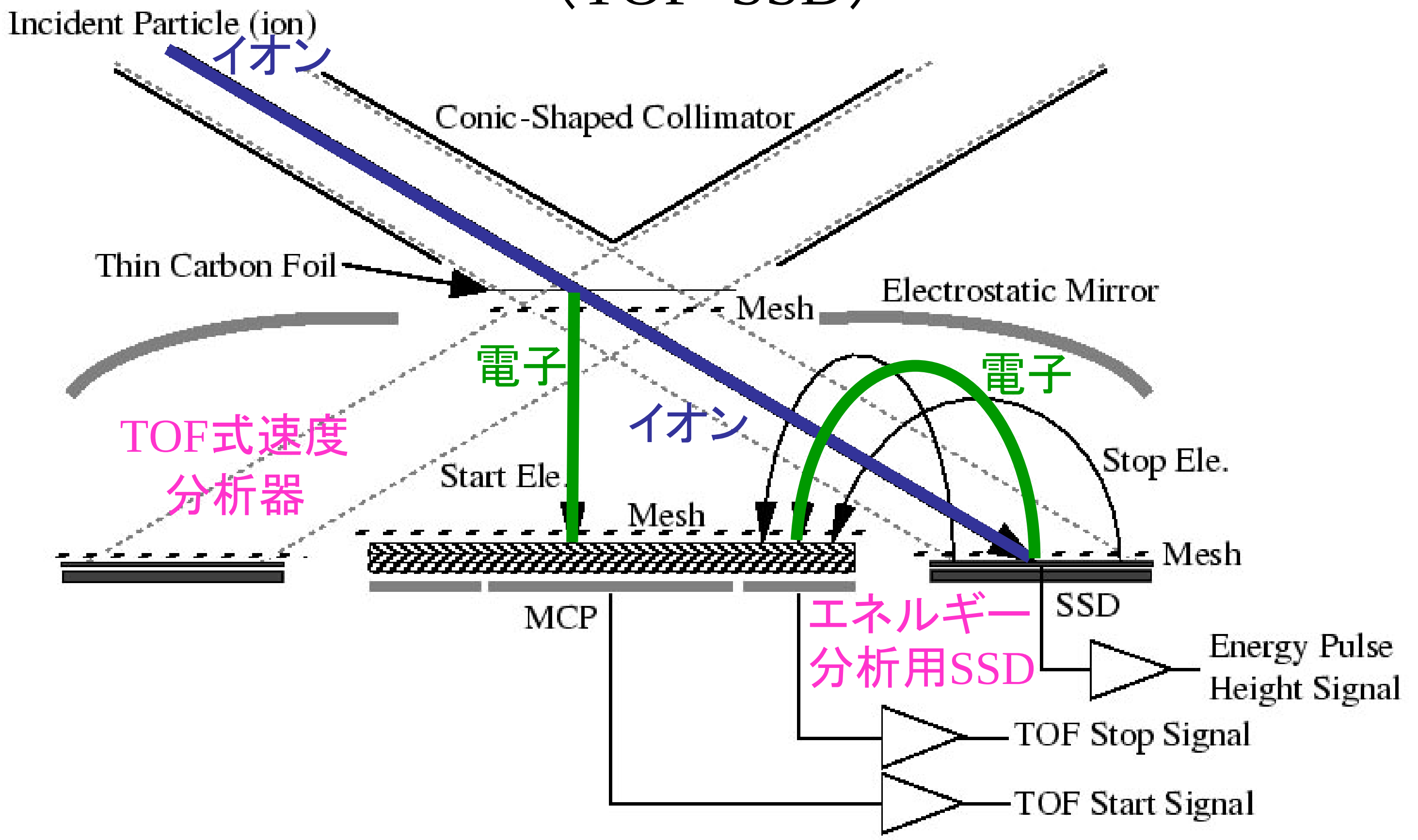
Twelve Assemblies of SSD

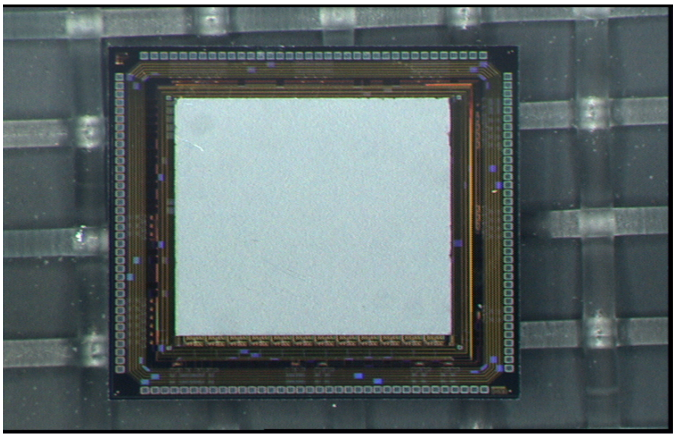
Carbon Foil

Collimator

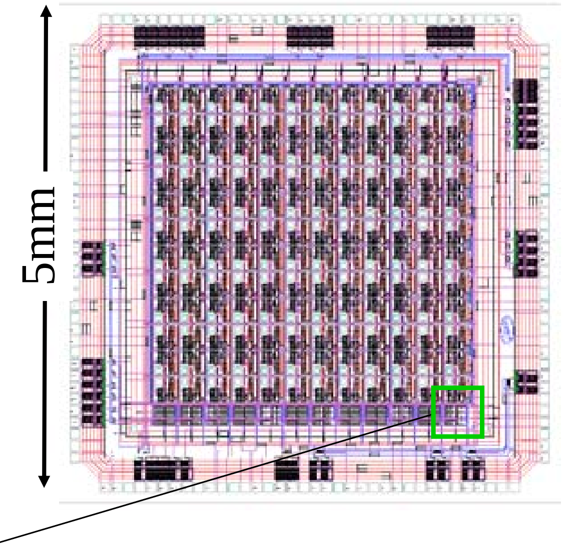
MCP Assembly

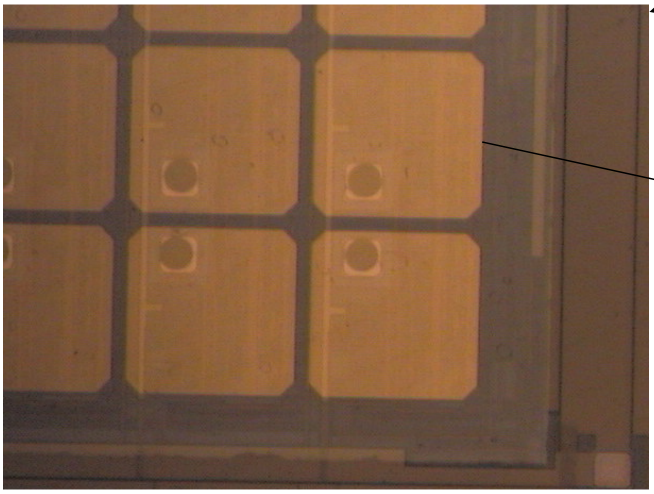
BepiColombo-MMO衛星搭載用高エネルギー粒子分析器（HEP-Ion）（TOF・SSD）



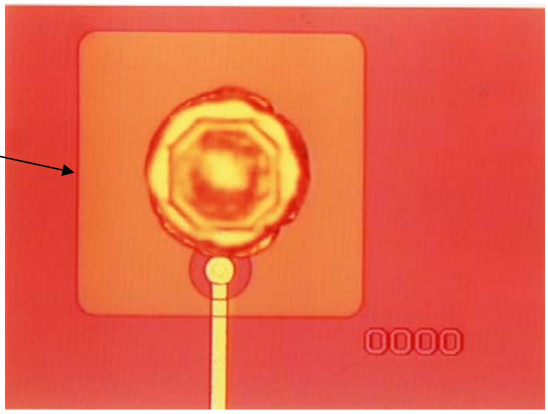


プロトタイプモデル・ピクセルSi検出器

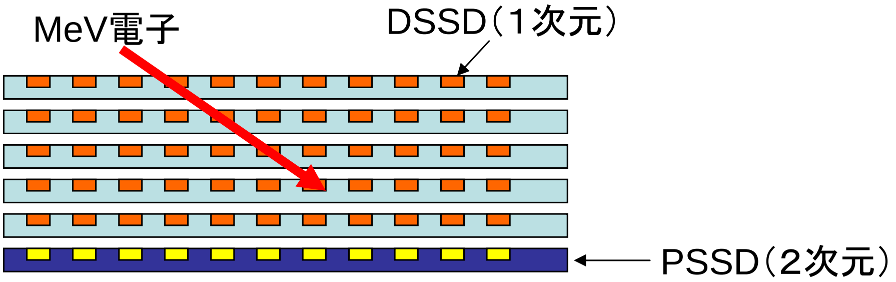




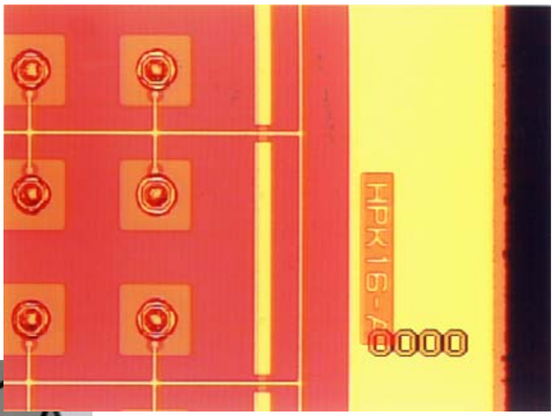
1ピクセルの様子

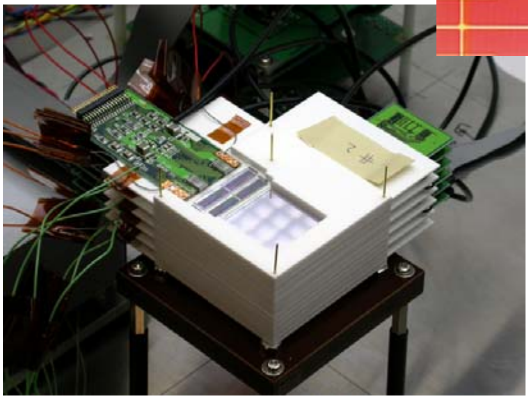


高エネルギー電子（＞MeV）検出に向けて



高エネルギー粒子測定のために
検出器を積層（例えば、6層）





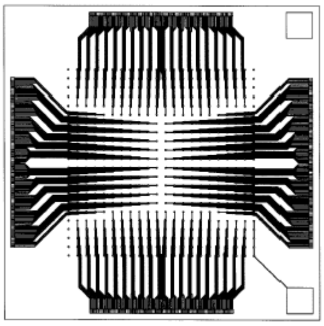


Fig. 5. Layout of the fanout board for the CdTe pixel detector. The total number of bump pads is $22 \times 22 = 484$. 400 pads are used for pixels and 84 pads are used for the guard ring. The size of the substrate ceramic board is 24 mm $\times$ 24 mm.

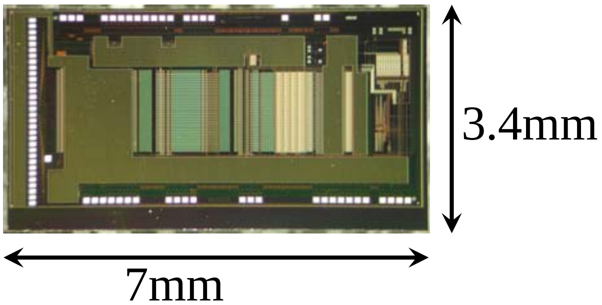
1次元検出器の積層
↓
電極配置の2次元化
↓
2次元（Pixel）チップで読み出し

非常にコンパクト
入射方向の精密決定
↓
詳細なピッチ角分布取得・バックグランド除去が可能

SSDの小型化・高エネルギー分解能実現に向けて

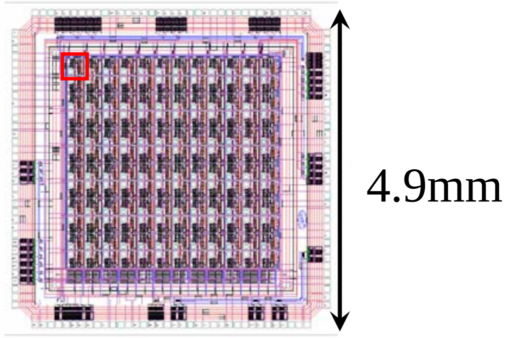
HEP用専用読み出し回路の開発（ASIC@ISAS）

- １次元多チャンネル読み出し



32チャンネル読み出し
→A4基板1枚分の回路が集積！
電力は300 μ W/ch
→従来の1/100以下
ノイズ特性は0.7keV@0pF

- ２次元多チャンネル読み出し

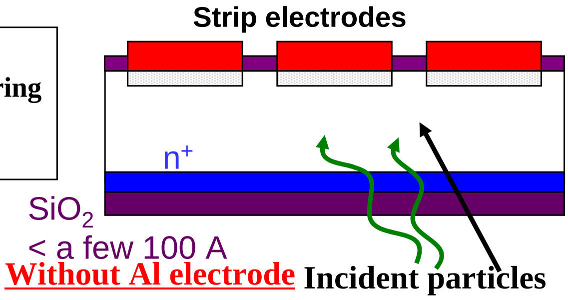


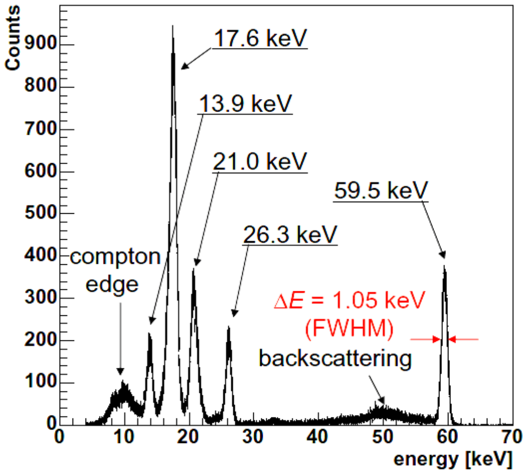
12 x 12チャンネル読み出し回路
→2次元タイプで粒子のイメージングが可能
各チャンネル部分に検出器を直接マウント
→非常に小型の検出器が可能
多層1次元検出器の読み出し回路としても
機能する

SSDによる低エネルギー検出に向けて

- Single-sided Si Strip Detector（SSSD）
  - 15mm角の大きな入射面を持ちながら、入射面側の電極を無くし、20keV付近から測定可能

Size : 15 mm x 15 mm
Strip : 32strips with guard-ring
Pitch : 400 μm
Thickness : 300 μm





熱的イオン観測器

衛星電位問題

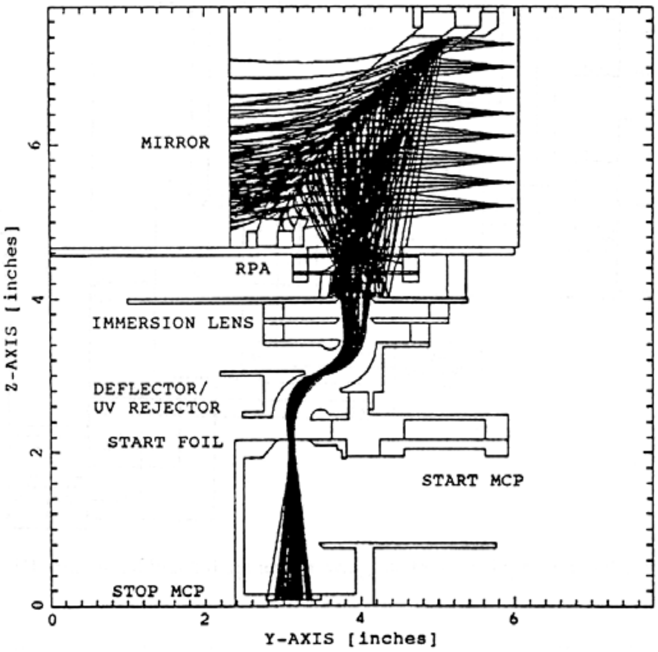
1. イオン放出による衛星電位制御（Polar）
2. 観測器のブーム伸展と電位制御（Freja、のぞみ）

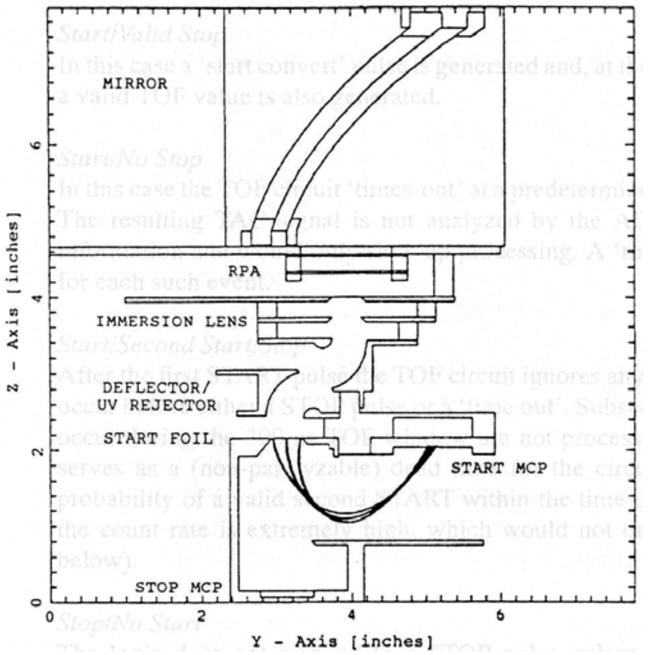
→ 小型・軽量化問題

例

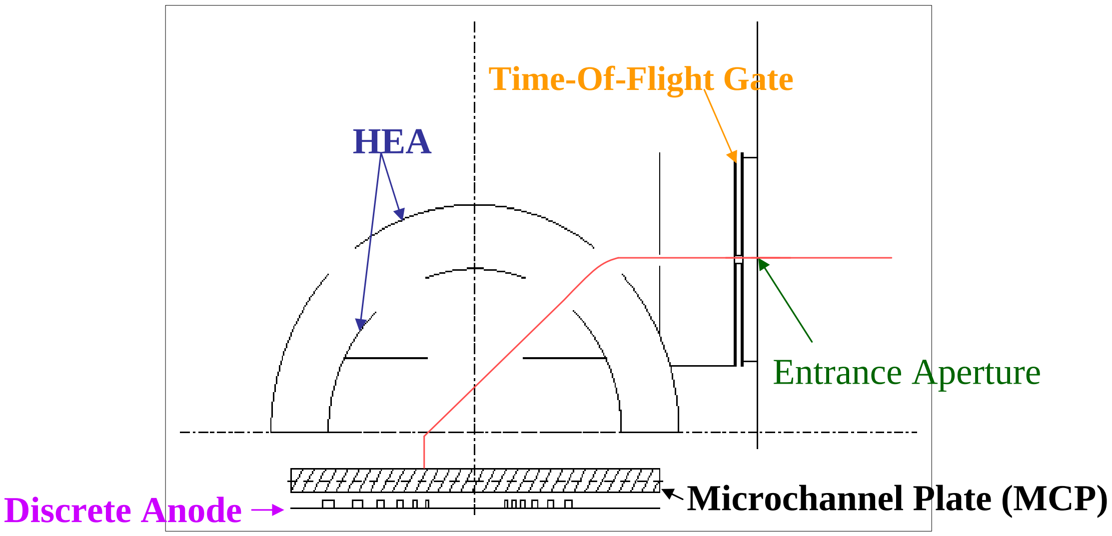
1. Polar搭載 TIDE 17 kg + PSI 数 kg
2. Freja搭載 CPA+boom 5kg

Polar衛星搭載用熱的イオン質量分析器（TIDE）
（ES-Mirror・RPA・TOF）



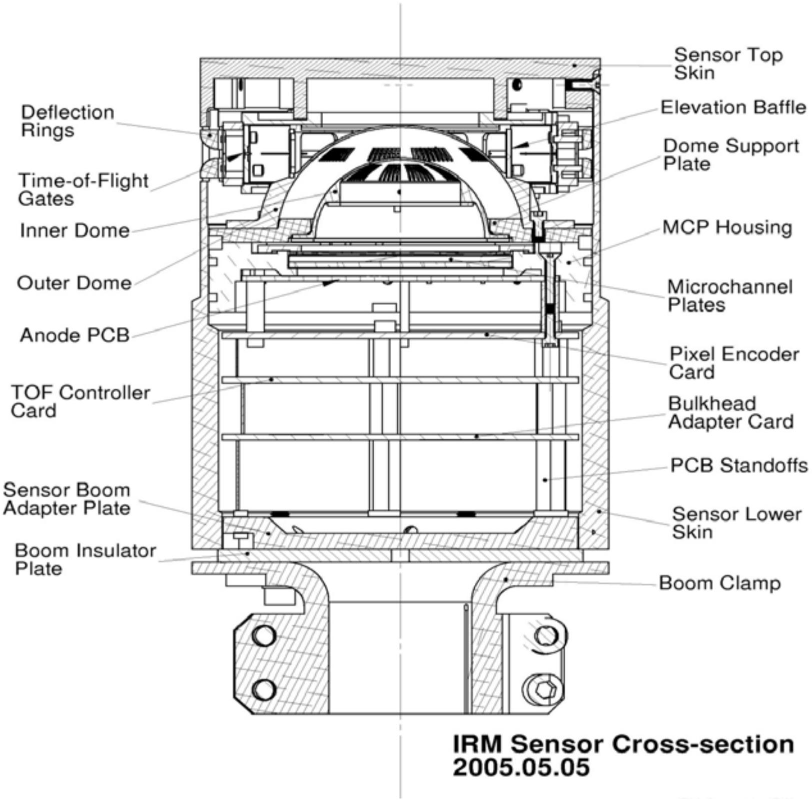


衛星搭載用熱的・超熱的イオン質量分析器
（ES-gate・ES-deflector）

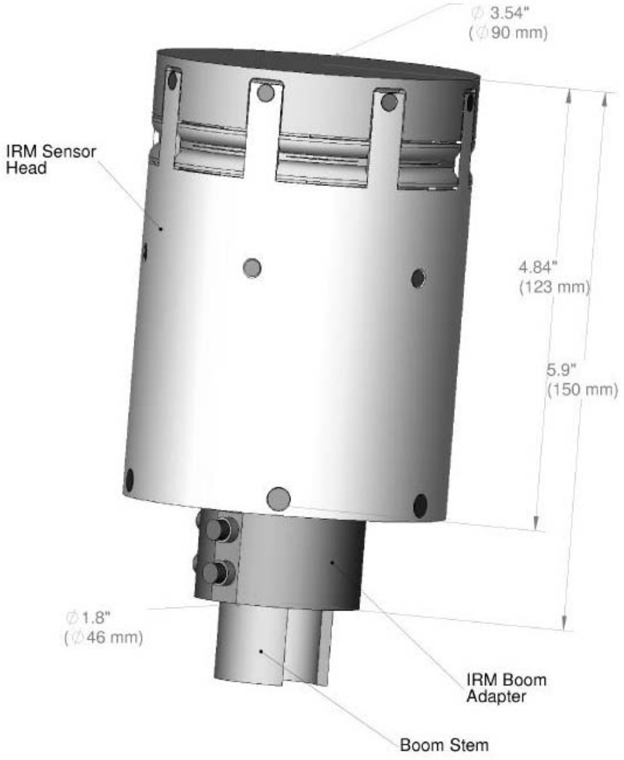


- Time of Flight ➔ Mass (Ion Type)
- Landing position ➔ Energy

衛星搭載用熱的・超熱的イオン質量分析器

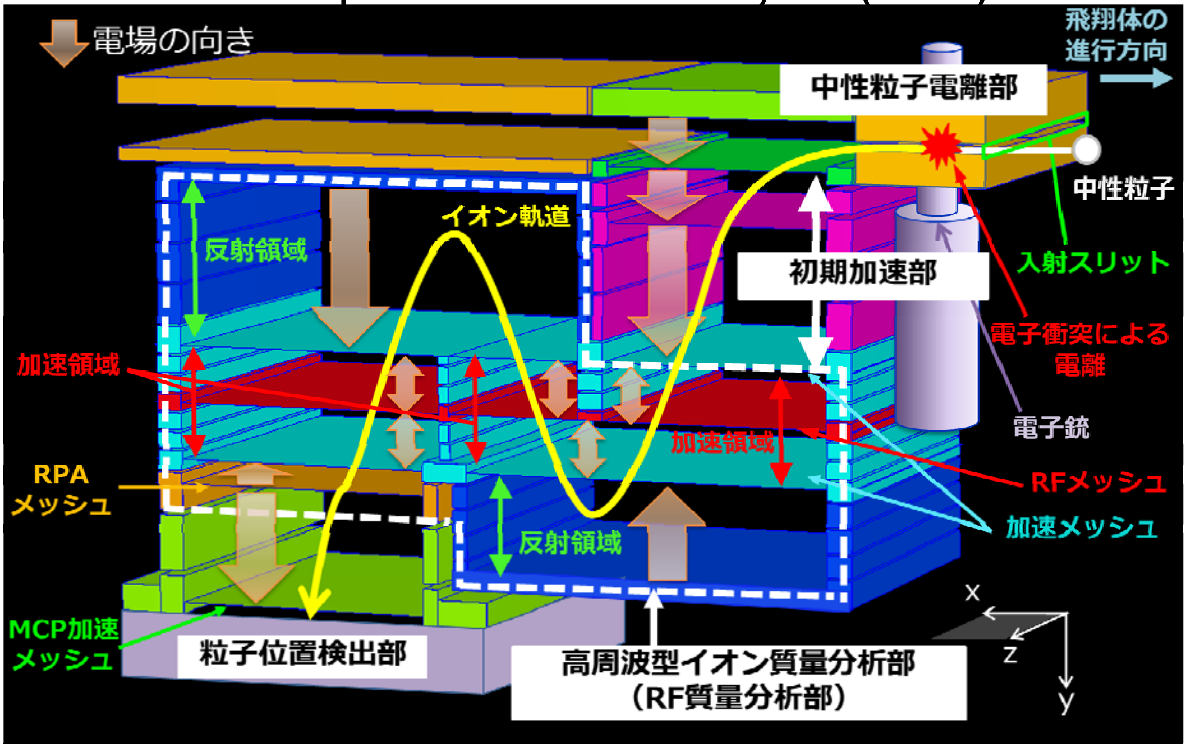


IRM Sensor Cross-section
2005.05.05



中性粒子質量分析器

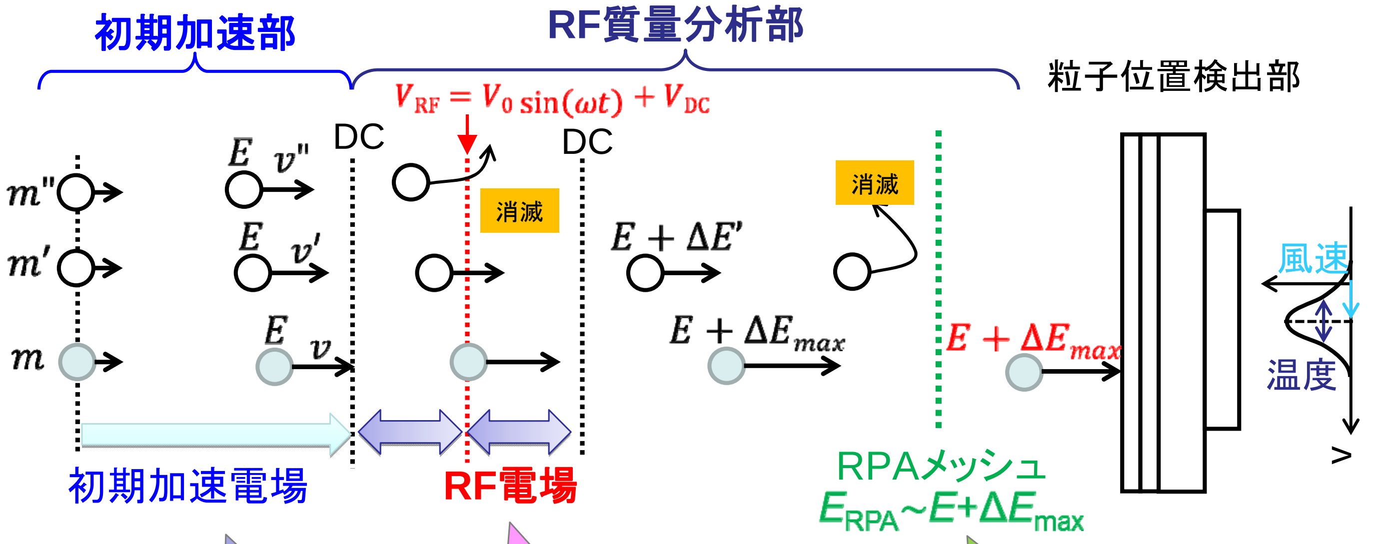
“Atmospheric Neutral Analyzer (ANA)”



- ■ Y方向にのみイオンを加減速（質量分析）
- ■ X, Z方向のイオン速度は保存
- ■ 二次元速度分布（V_x,V_z）を取得

⇒ 中性粒子種毎の温度、風速、密度を同時に測定可能

ベネット型質量分析

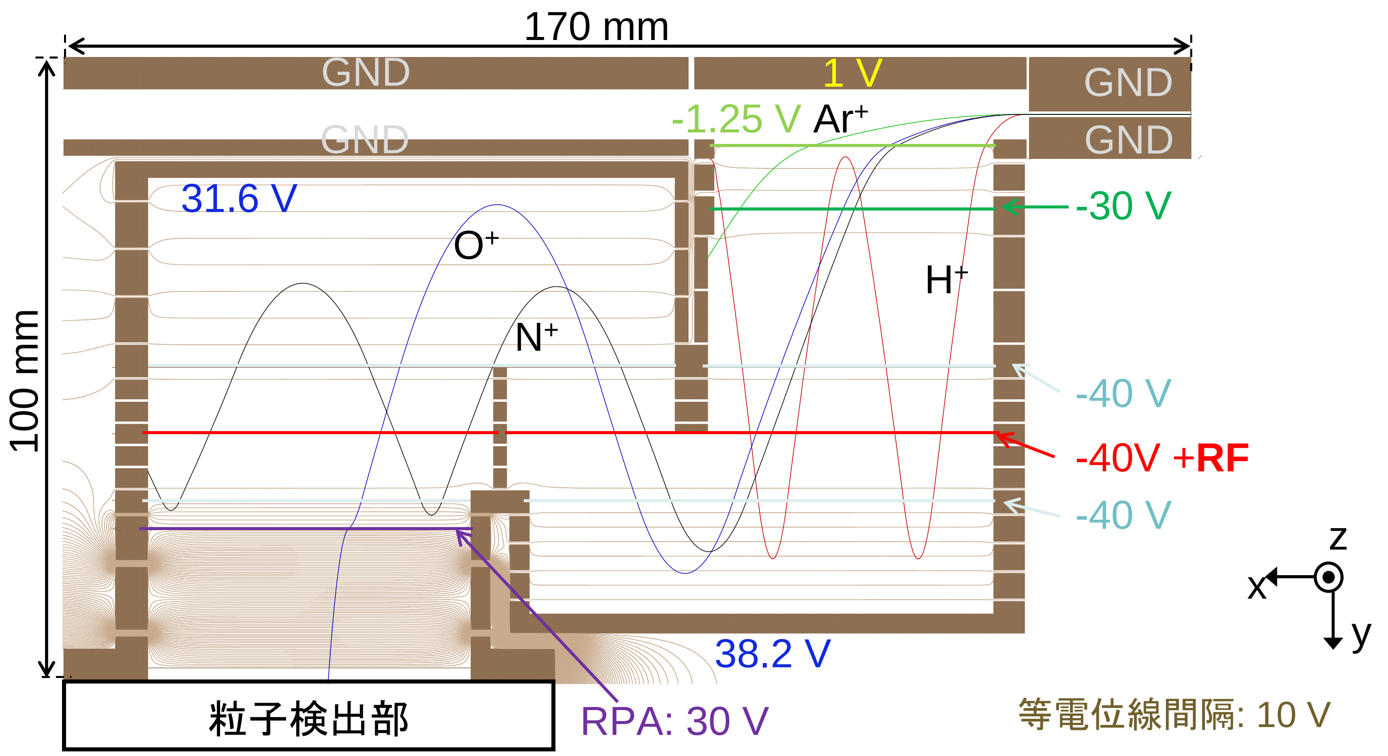


質量分析したいイオンが**特定の速度**になるよう電場で初期加速

特定速度のイオンはRF電場で**効率よく加速**される

RF電場で選択的に加速されたイオンは**RPAを通過**して**粒子検出部に到達**

電極配置と電圧（O分析の例）



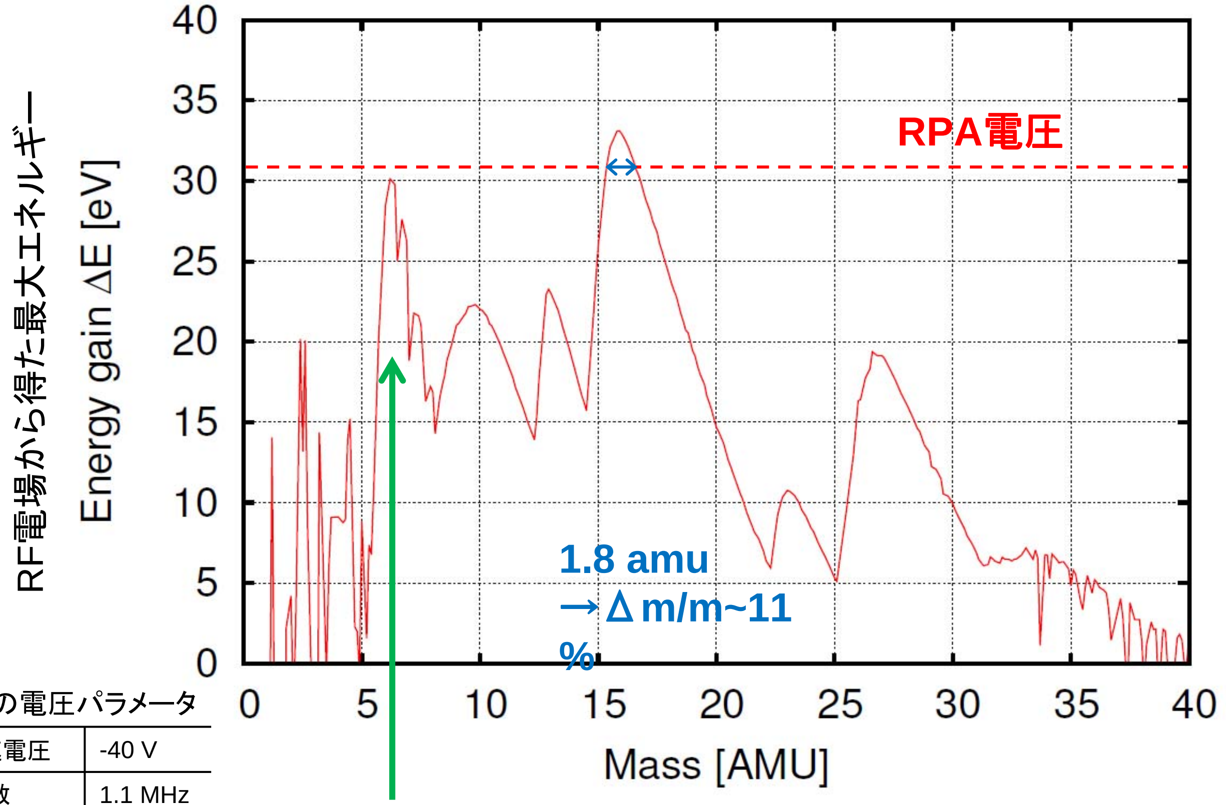
RF電圧の周波数	1.10 MHz
RF電圧の振幅	8 V
飛翔体速度	8 km/s

$$f \cong \frac{v_y}{2L_{\mathrm{RF}}}\ [\mathrm{Hz}]$$

L_{RF}:メッシュ間距離　10.5 mm

v_y: RF電場中のイオンのy方向平均速度 23 km/s

粒子軌道計算による性能評価【質量分解能】



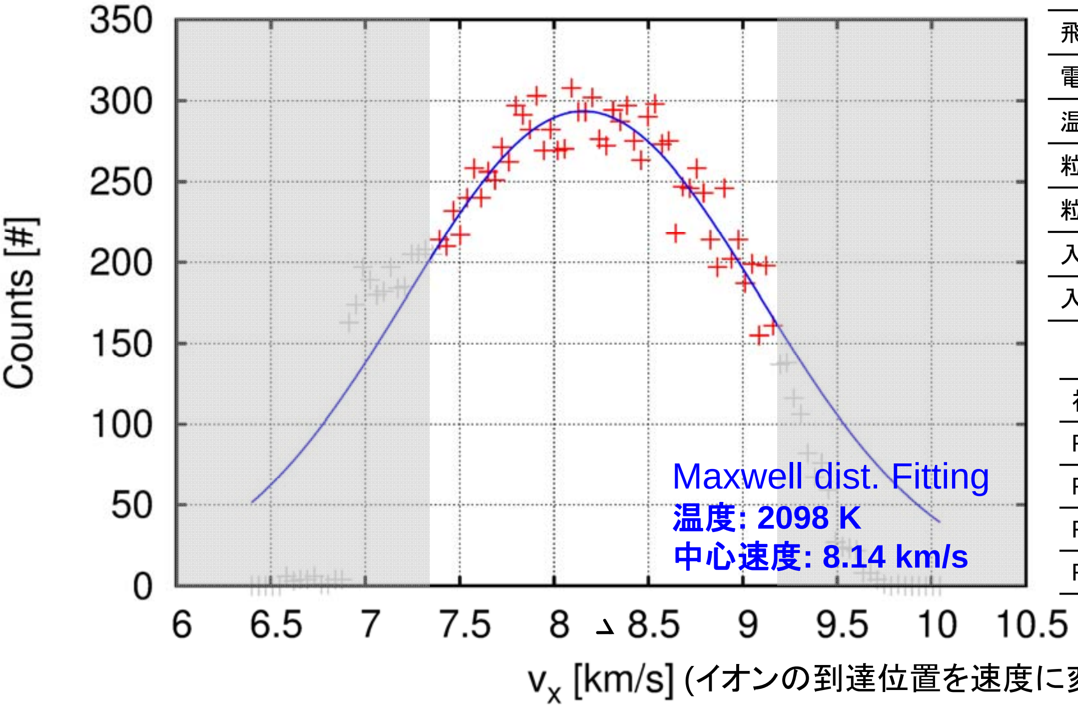
1.8 amu
→Δm/m~11 %

6 amuのイオンの内、30 eVに近いエネルギーを獲得するイオンの確率は小さい

分析器の電圧パラメータ

初期加速電圧	-40 V
RF周波数	1.1 MHz
RF振幅	8 V
RFの基準電位	-40 V

粒子軌道計算による性能評価【速度分布】



Maxwell dist. Fitting
温度: 2098 K
中心速度: 8.14 km/s

シミュレーション条件

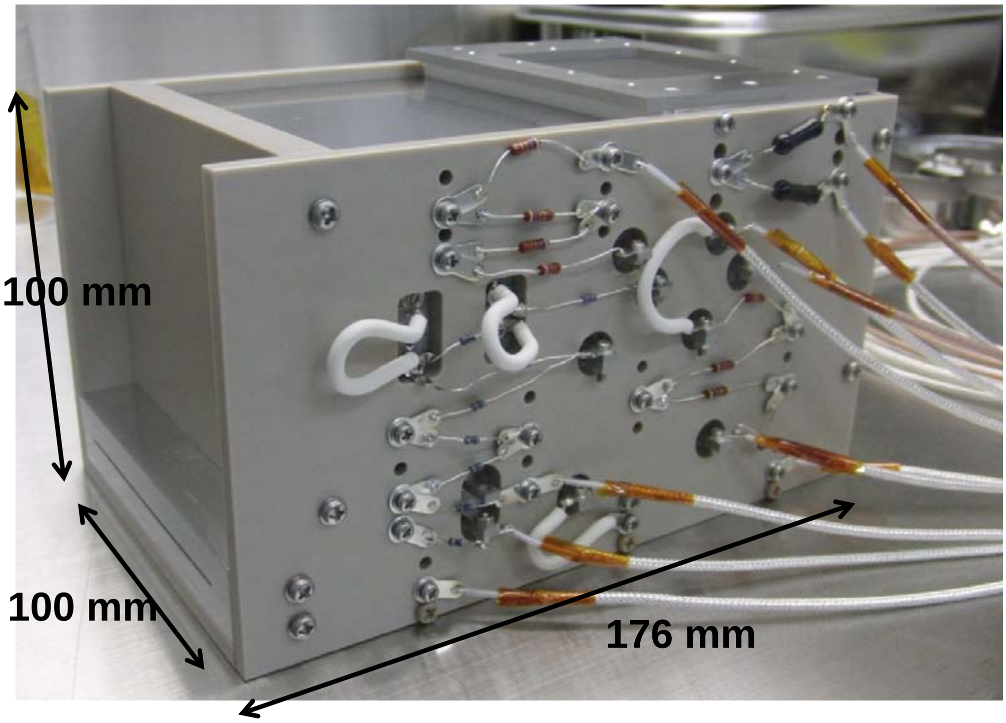
飛翔体速度	**8 km/s**
電圧値	**O^+質量分析モード**
温度	**2000 K**
粒子数	10^6 個
粒子種	O^+ (m=16 amu)
入射時間	0-1 sec
入射位置	x=0mm, y=0±0.5mm

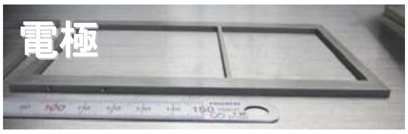
分析器の電圧パラメータ

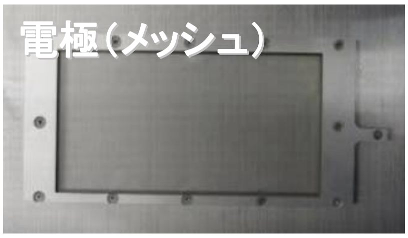
初期加速電圧	-40 V
RF周波数	1.1 MHz
RF振幅	8 V
RFの基準電位	-40 V
RPA電圧	31 V

グレー領域:X-Z平面内の非一様な電場の存在や、
4回以上のRF部通過により軌道が歪められたため、
フィッティングには用いないデータ

試作器





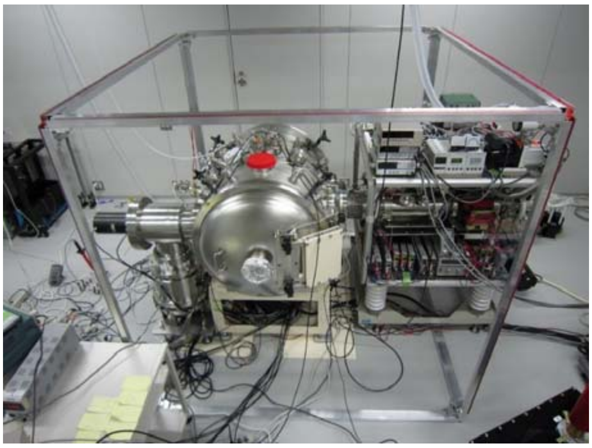


プラズマ・中性粒子分析器用較正実験装置

高エネルギーイオン・電子ビームライン

10keV/q～150keV/qのエネルギー範囲のイオン・電子ビームを照射する高エネルギーイオン・電子ビームライン

数eV/q程度の超熱的・低エネルギーイオン及び100eV/q程度以上の低エネルギー電子が照射可能な超熱的イオン・低エネルギー電子ビームライン

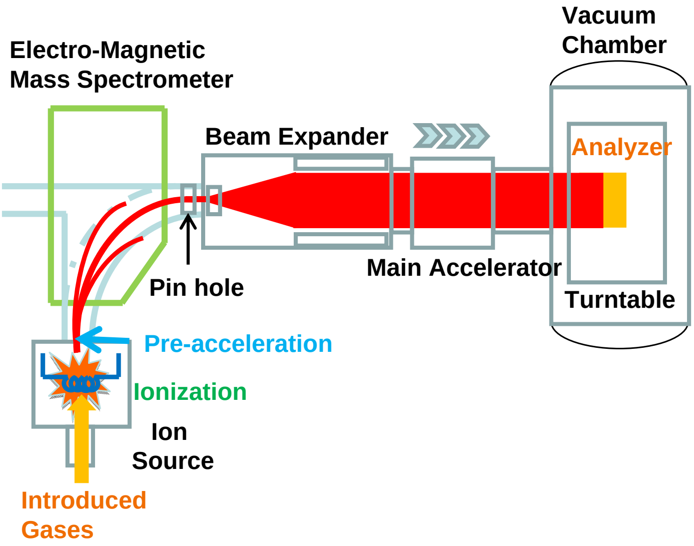


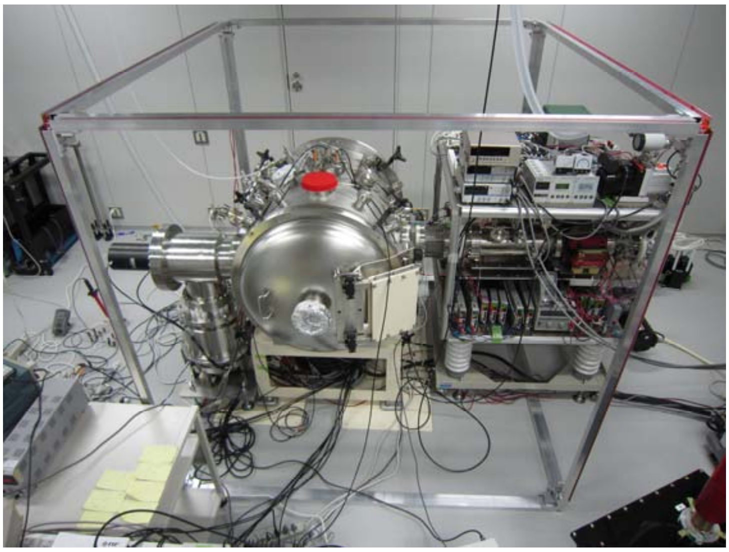
超熱的イオン・低エネルギー電子ビームライン

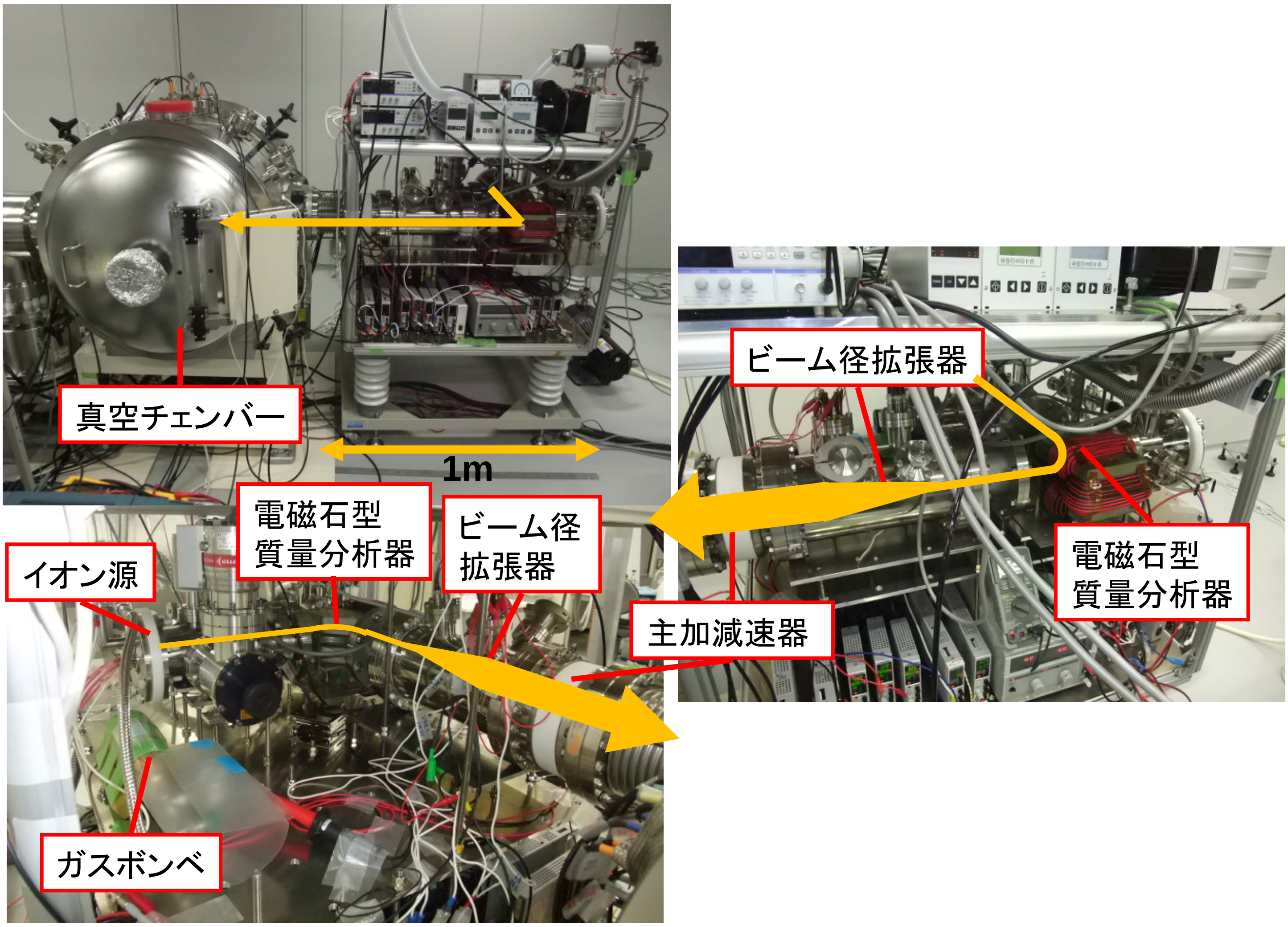
- 世界的にも超熱的イオンビームラインは極めて希少。
- 2つのビームライン(10eV～10keV, 10keV～150keV)を共同利用できる環境は希有。

超熱的イオンビームライン

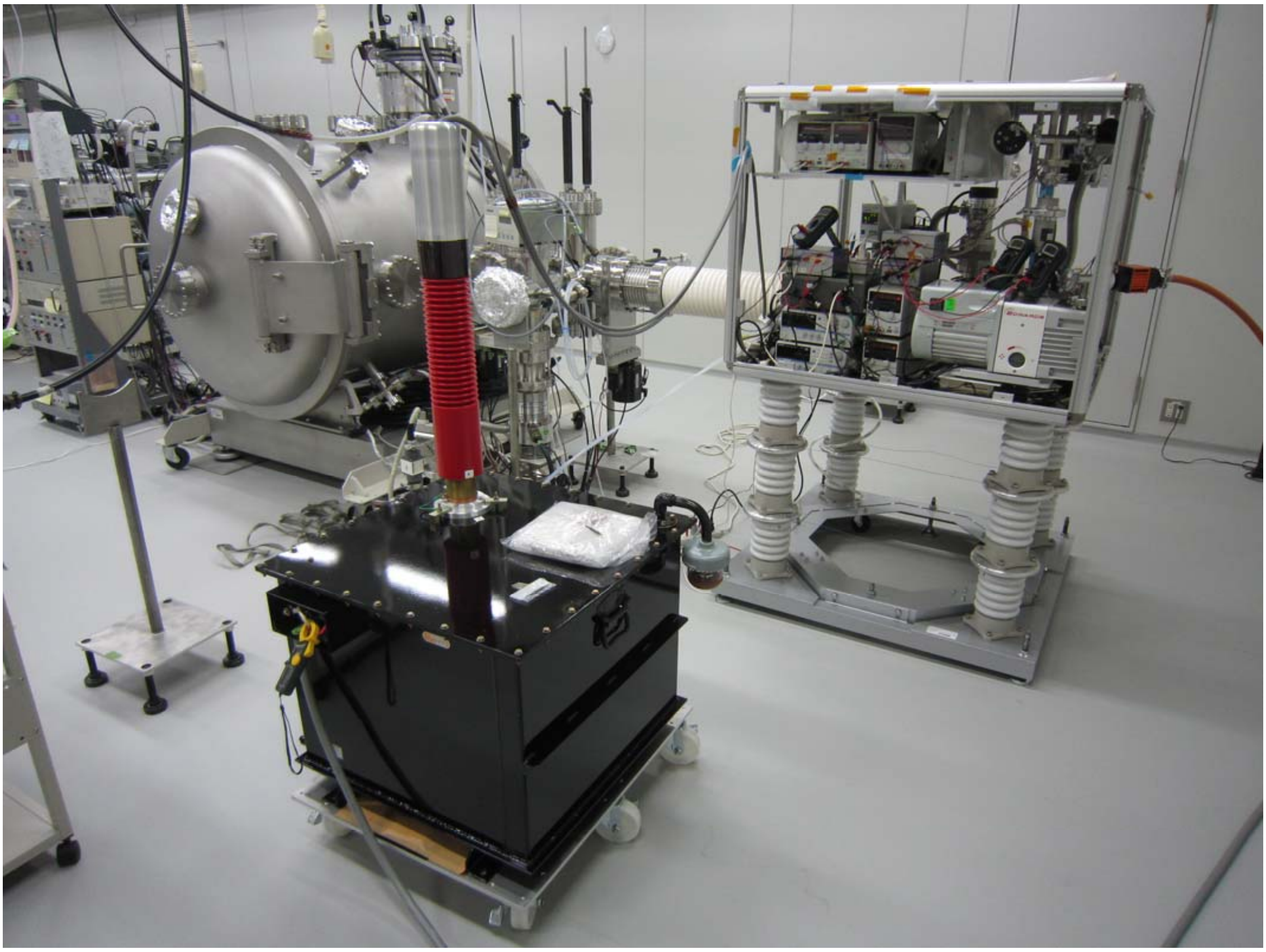
- 数 eV～10 keV程度のイオンを照射可能な超熱的イオンビームラインを開発・改良中
- 衛星速度8 km/s程度のイオンビームを照射し、電離部を除く中性粒子質量分析器の特性試験を目指す

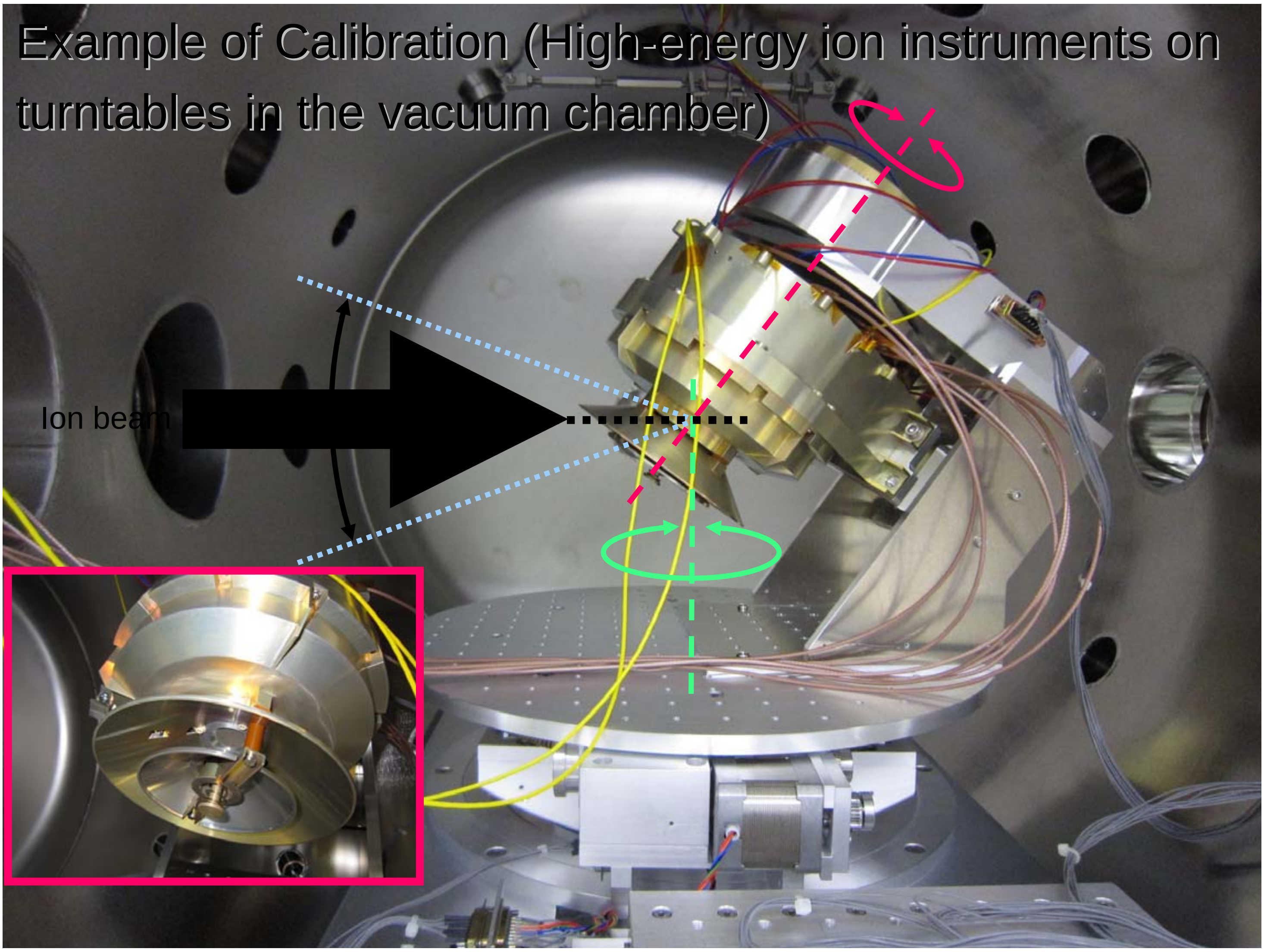






高エネルギーイオン･電子ビームライン

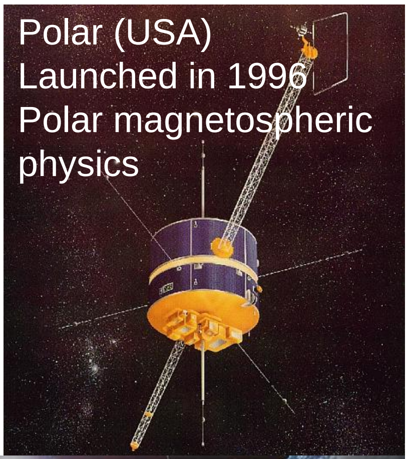


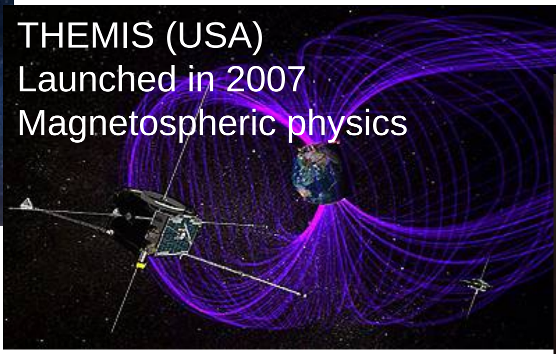


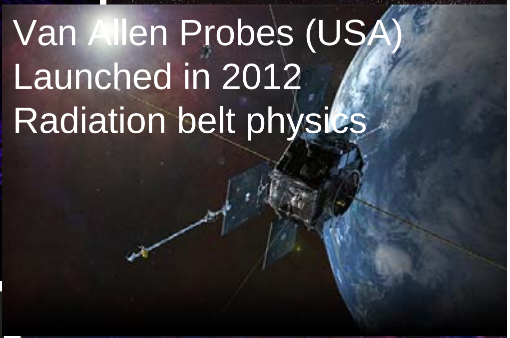
Example of Calibration (High-energy ion instruments on turntables in the vacuum chamber)


Akebono (Japan)
Launched in 1989
Auroral physics

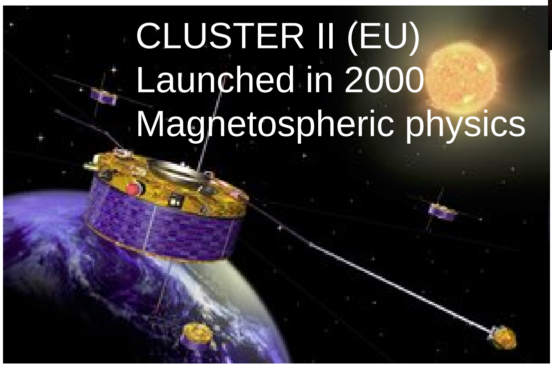

Geotail (Japan)
Launched in 1992
Magnetospheric physics

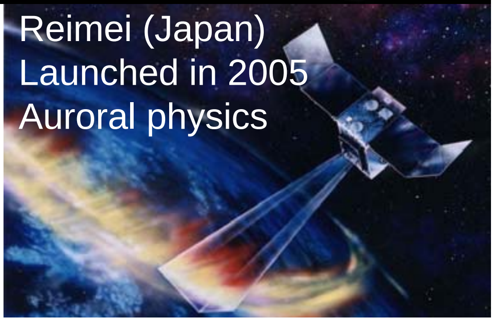

Polar (USA)
Launched in 1996
Polar magnetospheric physics


THEMIS (USA)
Launched in 2007
Magnetospheric physics


Van Allen Probes (USA)
Launched in 2012
Radiation belt physics

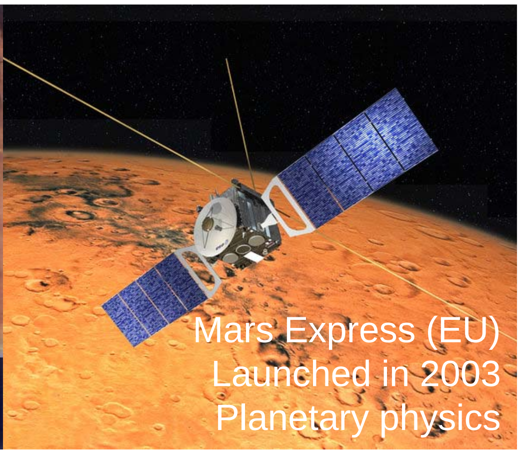

FAST (USA)
Launched in 1996
Polar magnetospheric physics


CLUSTER II (EU)
Launched in 2000
Magnetospheric physics


Reimei (Japan)
Launched in 2005
Auroral physics

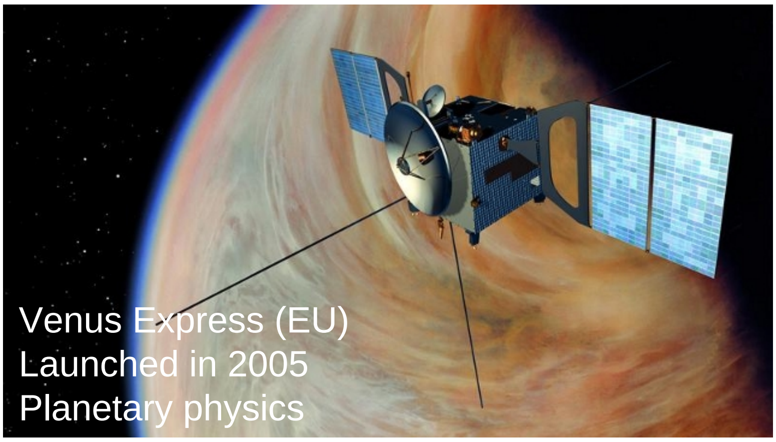

Phobos 2 (USSR)
Launched in 1988
Upper atmospheric physics

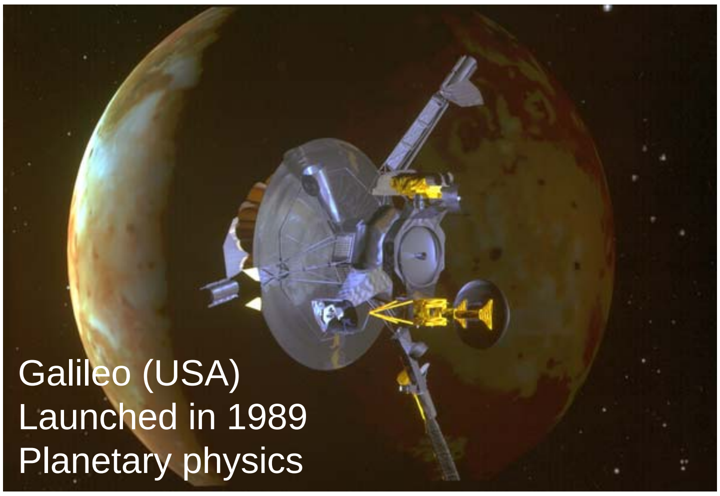

Nozomi (Japan)
Launched in 1997, but failed
Upper atmospheric physics


Mars Express (EU)
Launched in 2003
Planetary physics

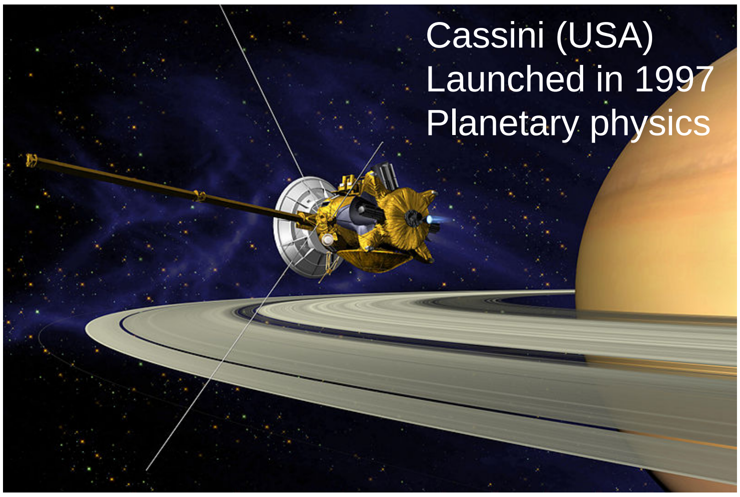
Planetary Exploration Missions (Space plasma observations at Mars/Venus)


Mars Global Surveyor (USA)
Launched in 1996
Planetary physics


Venus Express (EU)
Launched in 2005
Planetary physics

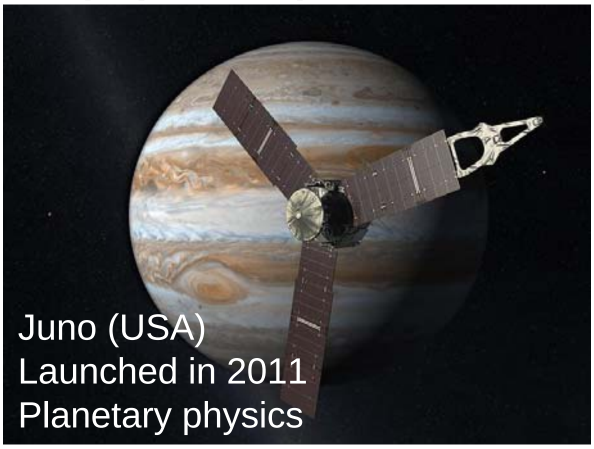


Galileo (USA)
Launched in 1989
Planetary physics

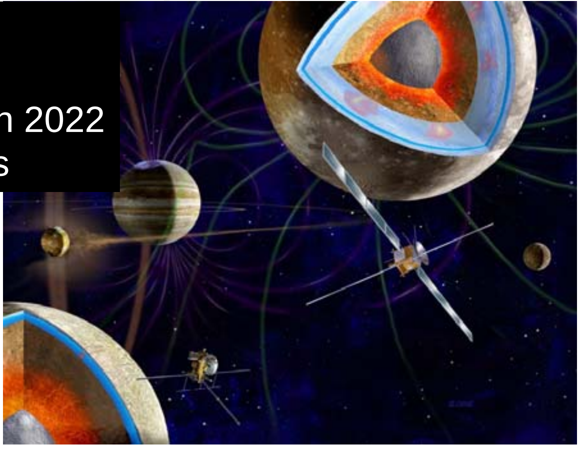


Cassini (USA)
Launched in 1997
Planetary physics

Planetary Exploration Missions (Space plasma observations at Jupiter/Saturn)



Juno (USA)
Launched in 2011
Planetary physics



Under planning
JUICE (EU)
To be launched in 2022
Planetary physics