Observational Heliophysics I: Particles, Plasma, and Fields

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July 23, 2026

Introduction

Why Not?


dBC
%RH
TRIPLETT
9055
HOLD
Lux
RANGE
REL
Hz%
HOLD
MODE
Auto Power Off
OFF
10A
CAP

Some Random Numbers

- Temperature of solar corona = 1-2 million degrees K
- Solar wind speed = 1 million mph
- Solar wind ram pressure at 1 AU = 1 nPa
- Magnetospheric plasma density ~0.01-1000 cm^{-3}
    - Compared to Earth surface atmospheric density of 2.5×10^{19} cm^{-3}

- Typical solar wind motional electric field at 1 AU = 1 mV/m
- Typical solar wind parallel electric field = <1 nV/m
- Solar wind magnetic field at 1 AU = 10 nT

Space Plasma Physics: How Hard Could it Be?

Maxwell's Equations for the Fields

$$\nabla \cdot \mathbf{D} = \rho$$

$$\nabla \cdot \mathbf{B} = 0$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

$$\nabla \times \mathbf{H} = \mathbf{J} + \frac{\partial \mathbf{D}}{\partial t}$$

Here be dragons

Charge and Current Density

$$\rho = \sum_s q_s n_s = e\left(Z n_i - n_e\right)$$

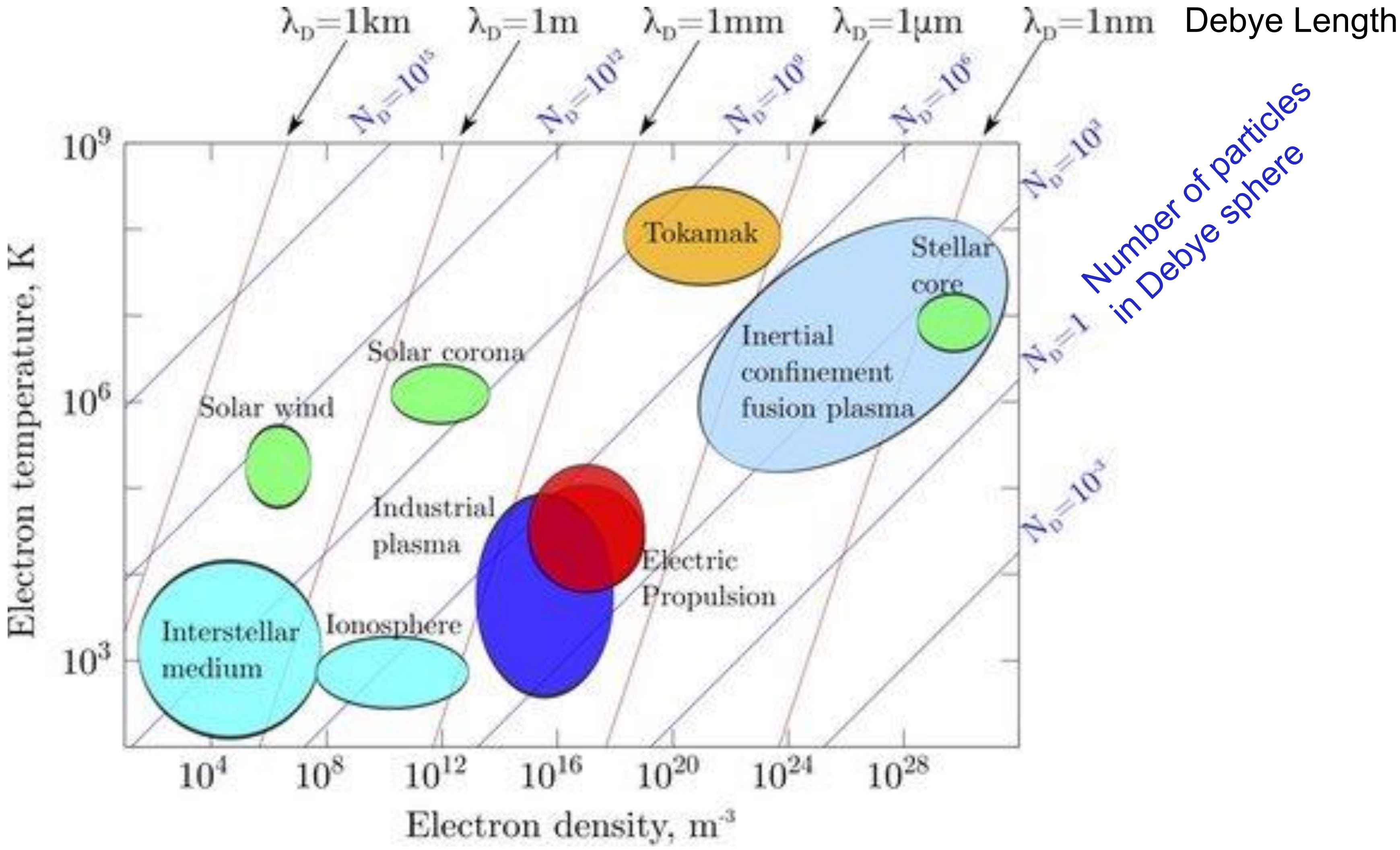
$$J = \sum_s q_s n_s v_s = e\left(Z n_i v_i - n_e v_e\right)$$

Equation of Motion (Lorentz Force)

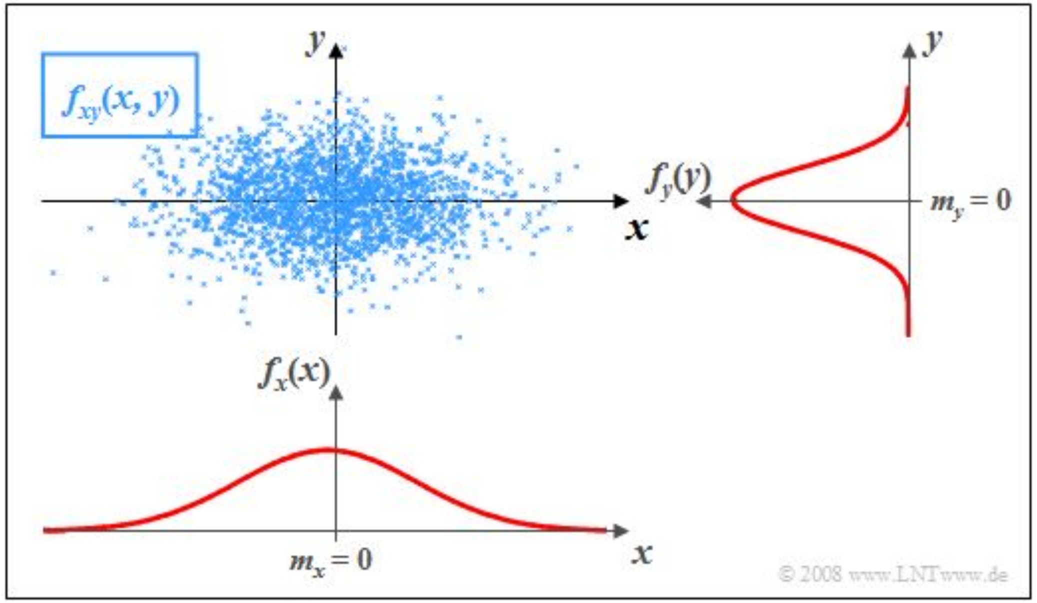
$$\mathbf{F} = m\frac{d\mathbf{v}}{dt} = q\left(\mathbf{E} + \mathbf{v} \times \mathbf{B}\right)$$

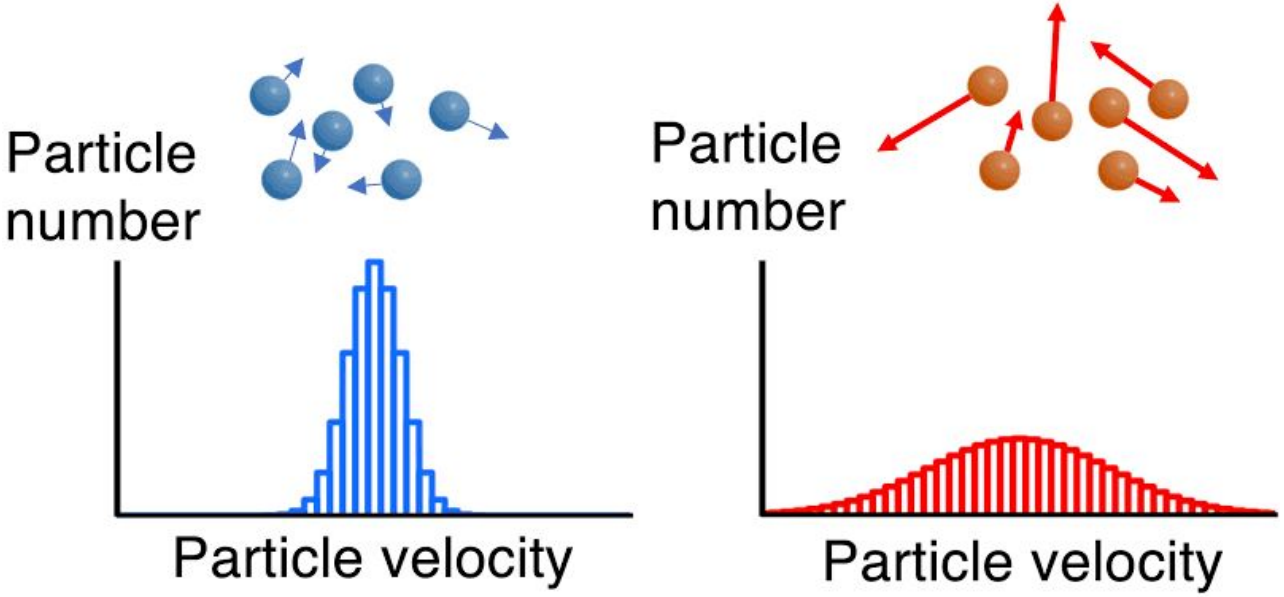
+ *sprinkle in collisions, other forces as needed*

So Many Particles…



The Distribution Function





$$f(\mathbf{r}, \mathbf{v}, t) = \frac{dN}{d^3\mathbf{r}\, d^3\mathbf{v}}$$

$$\frac{\partial f}{\partial t} + \mathbf{v} \cdot \nabla_{\mathbf{x}} f + \frac{\mathbf{F}}{m} \cdot \nabla_{\mathbf{v}} f = \left(\frac{\partial f}{\partial t} \right)_{\text{collisions}}$$

Boltzmann Equation

Moments of the Distribution Function

(a) Particle density,

$$n = \int f(\vec{v})d\vec{v}$$

(b) Particle flux density,

$$\vec{\Gamma} = \int \vec{v} f(\vec{v})d\vec{v}$$

(c) Flow velocity,

$$\vec{u} = \vec{\Gamma}/n$$

(d) Current density,

$$\vec{j} = Ze\vec{\Gamma}$$

(e) Stress tensor (diagonal components only),

$$P_{xx} = m\int v_x^2 f(\vec{v})d\vec{v}$$
$$P_{yy} = m\int v_y^2 f(\vec{v})d\vec{v}$$
$$P_{zz} = m\int v_z^2 f(\vec{v})d\vec{v}$$

(f) Pressure tensor (diagonal components only),

$$p_{xx} = m\int (v_x - u_x)^2 f(\vec{v})d\vec{v}$$
$$p_{yy} = m\int (v_y - u_y)^2 f(\vec{v})d\vec{v}$$
$$p_{zz} = m\int (v_z - u_z)^2 f(\vec{v})d\vec{v}$$

(g) Scalar pressure (from the trace of the pressure tensor),

$$p = \frac{1}{3}(p_{xx} + p_{yy} + p_{zz})$$

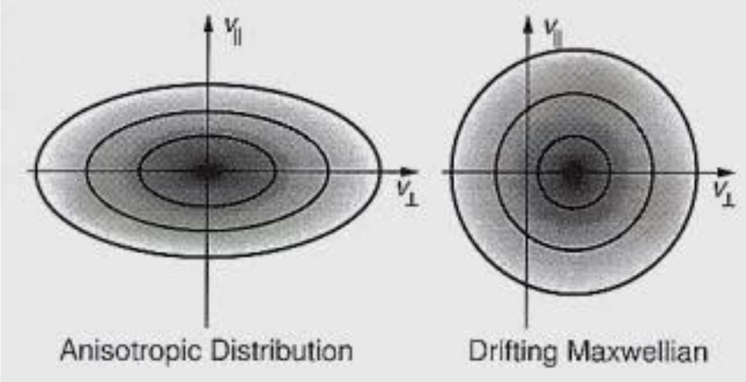
(h) Energy flux density

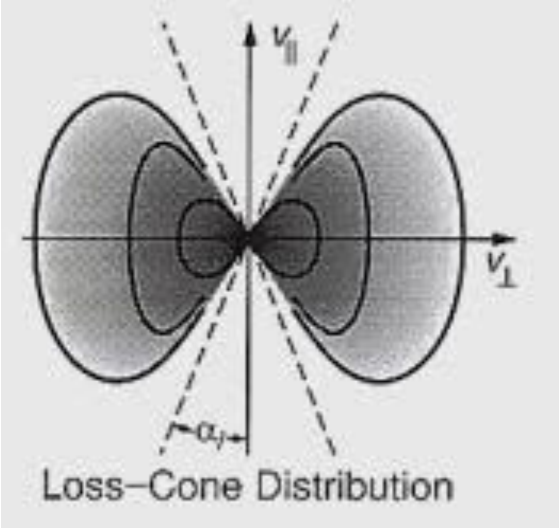
$$\vec{Q} = \frac{1}{2}m\int v^2\,\vec{v} f(\vec{v})d\vec{v}$$

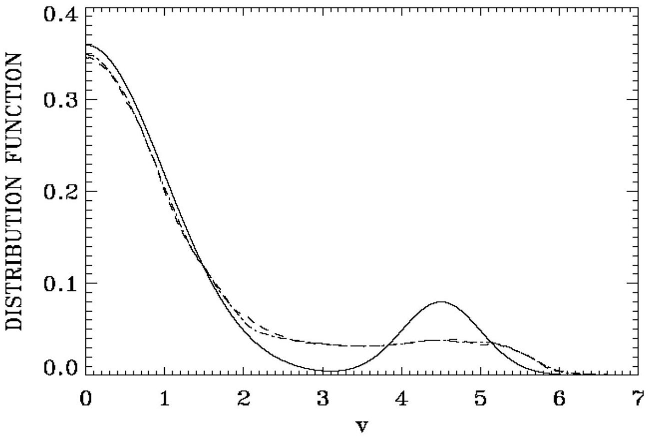
(i) Heat flow

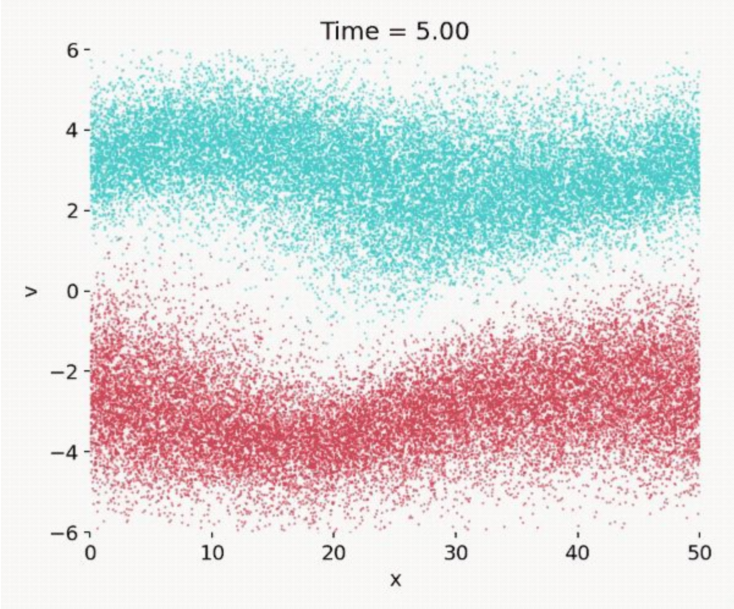
$$\vec{q} = \frac{1}{2}m\int w^2\,(\vec{v} - \vec{u}) f(\vec{v})d\vec{v}$$
$$w^2 = (v_x - u_x)^2 + (v_y - u_y)^2 + (v_z - u_z)^2$$

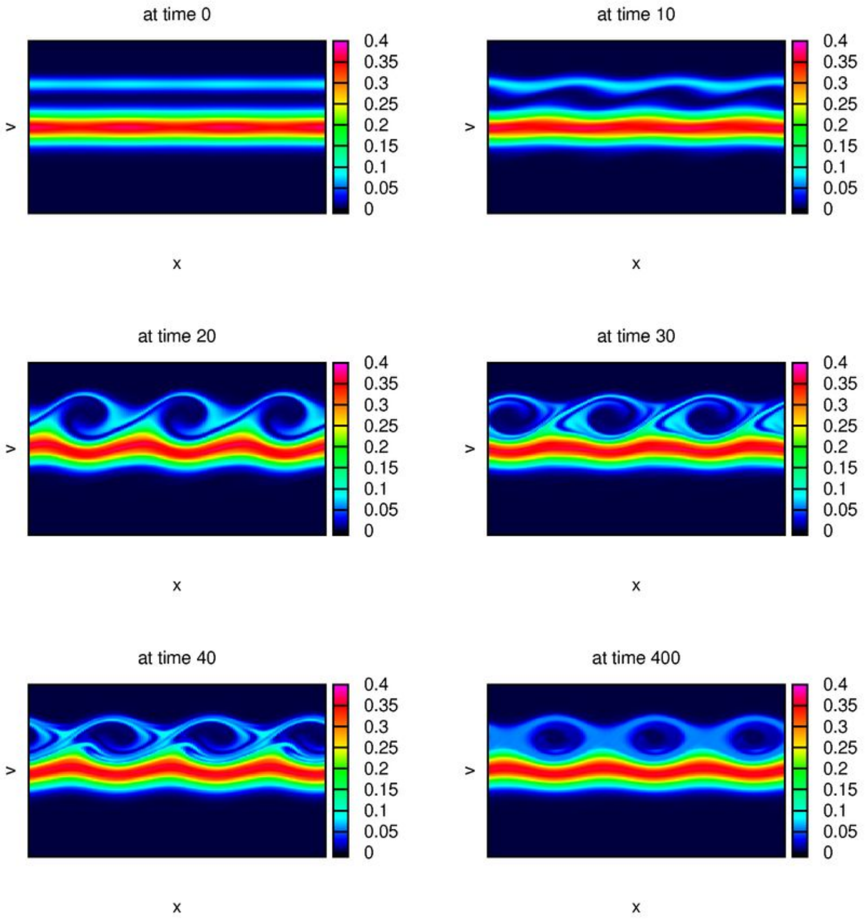
Beyond Moments

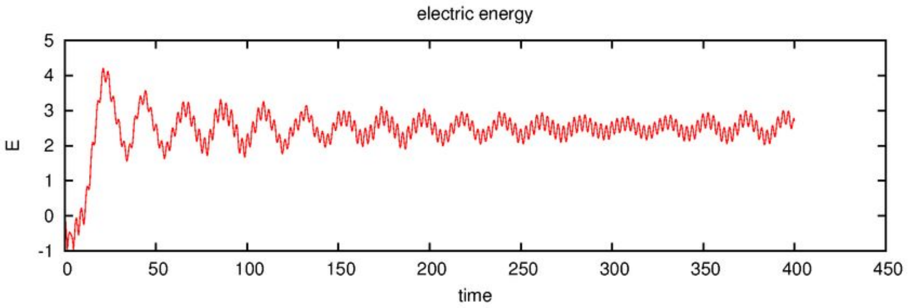








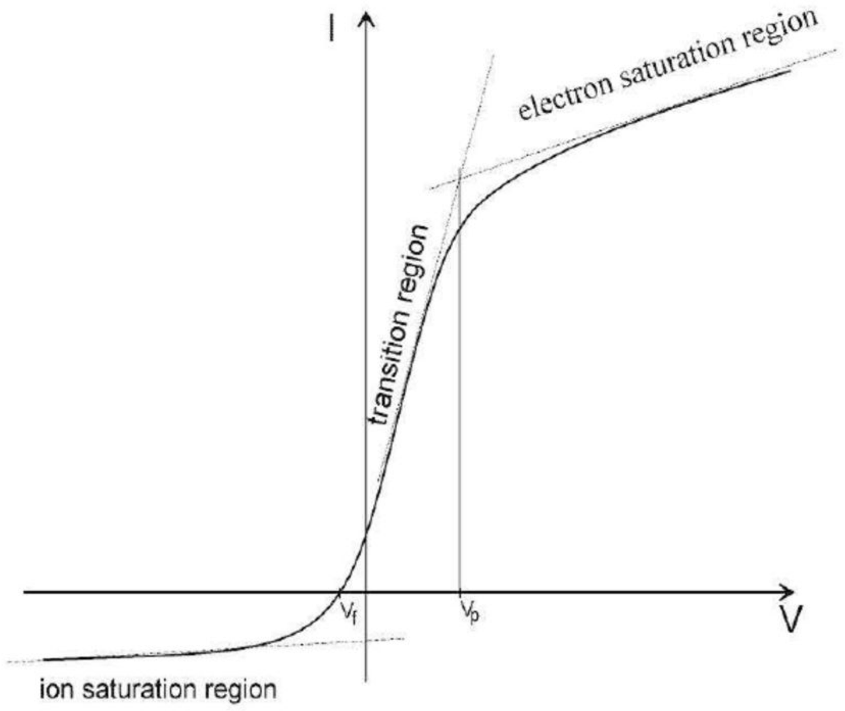




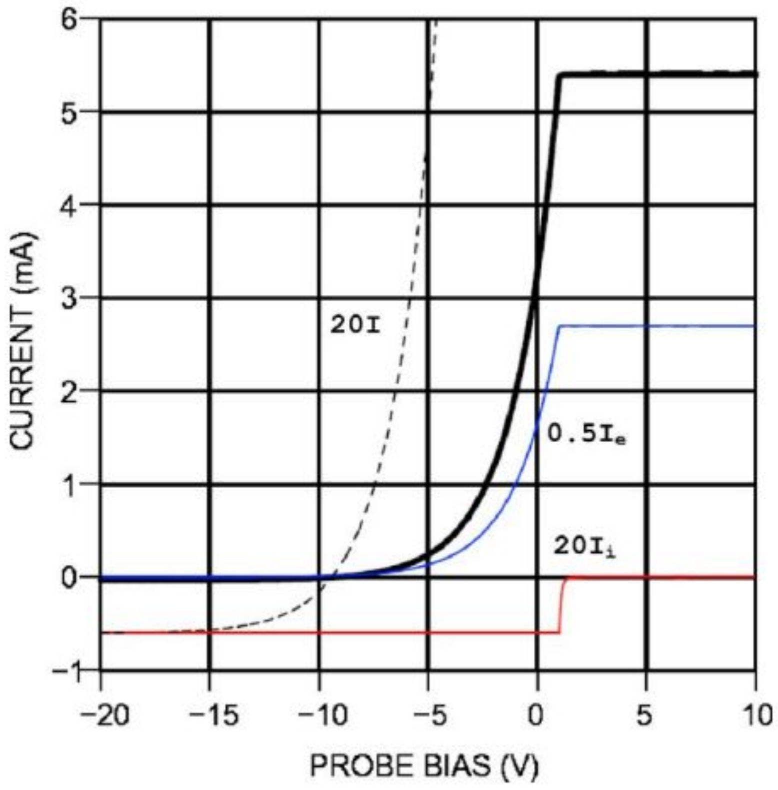
Plasma and Particles

In Situ Techniques: Measuring Current – Langmuir Probe

Thick Sheath

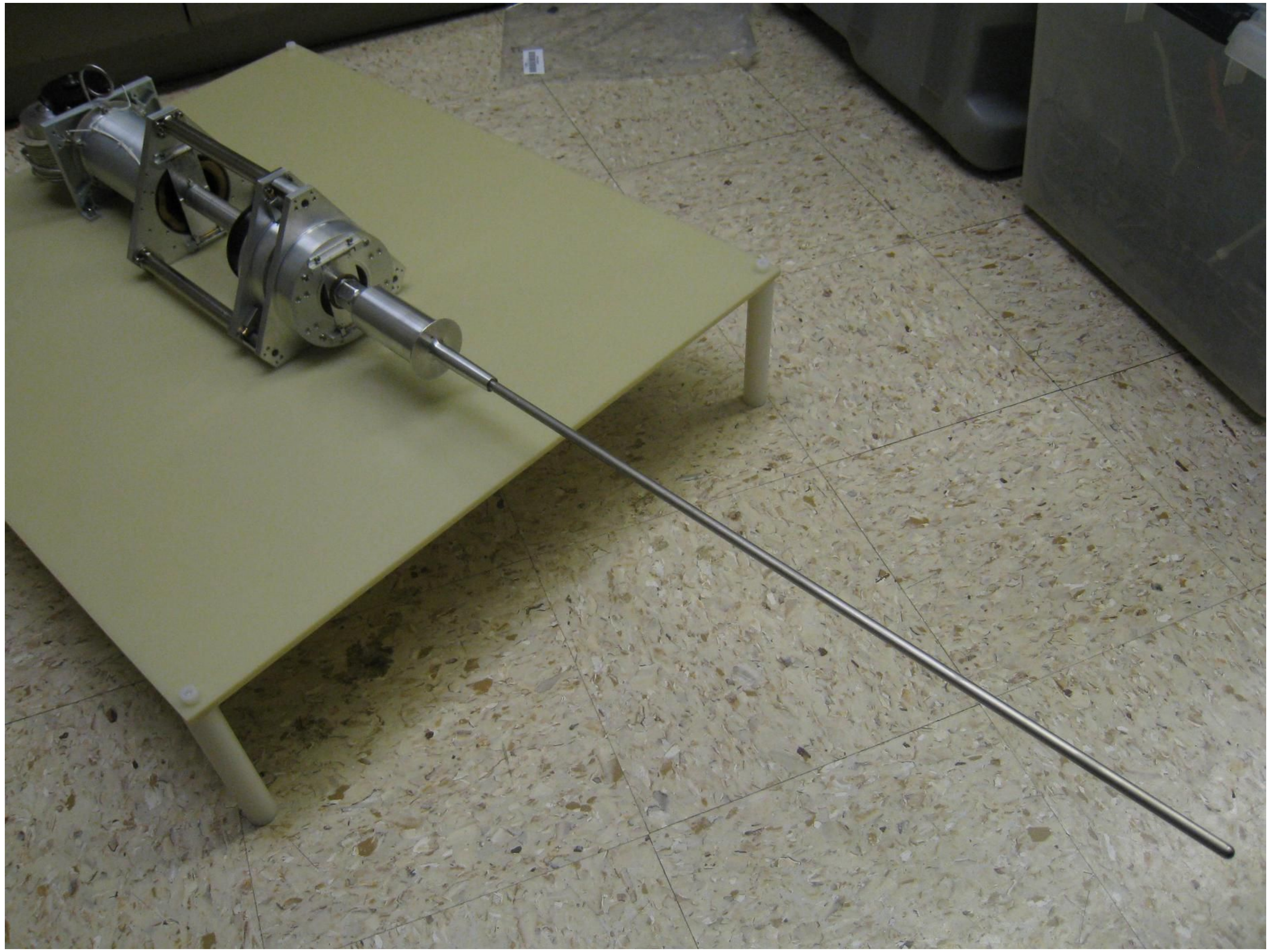


Thin Sheath

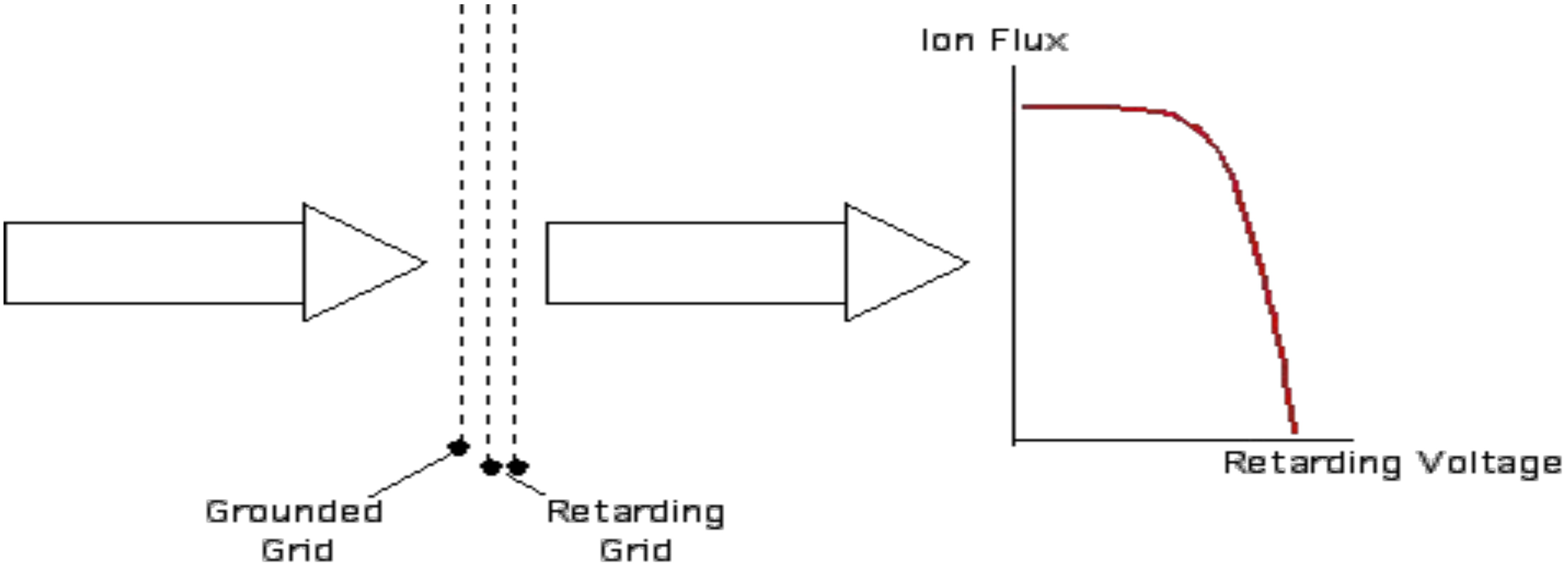


V_f = Probe Floating Potential, V_p = Plasma Potential

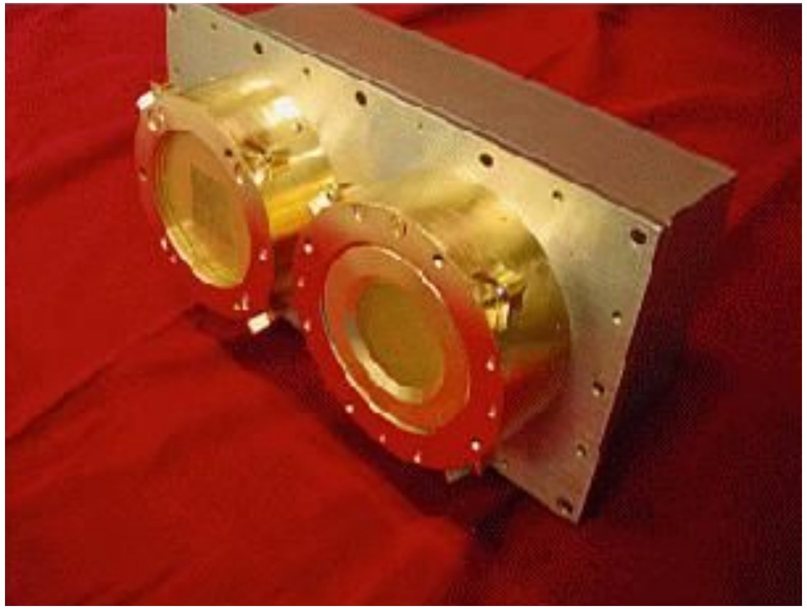
In Situ Techniques: Measuring Current – Langmuir Probe

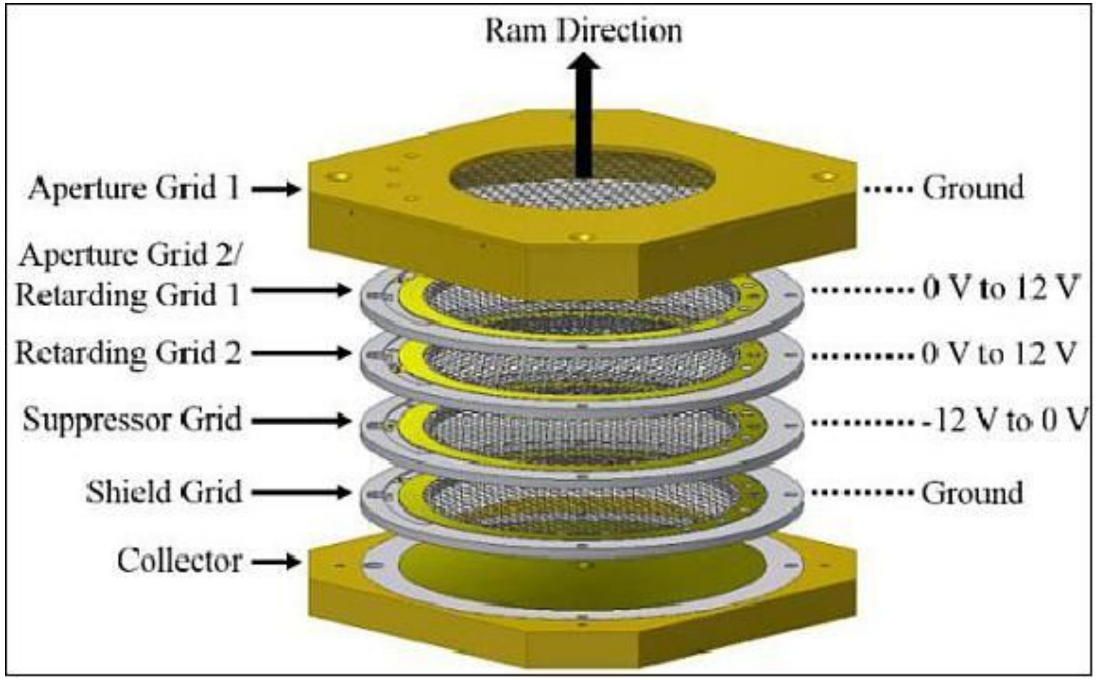


In Situ Techniques: Measuring Current - Retarding Potential Analyzer

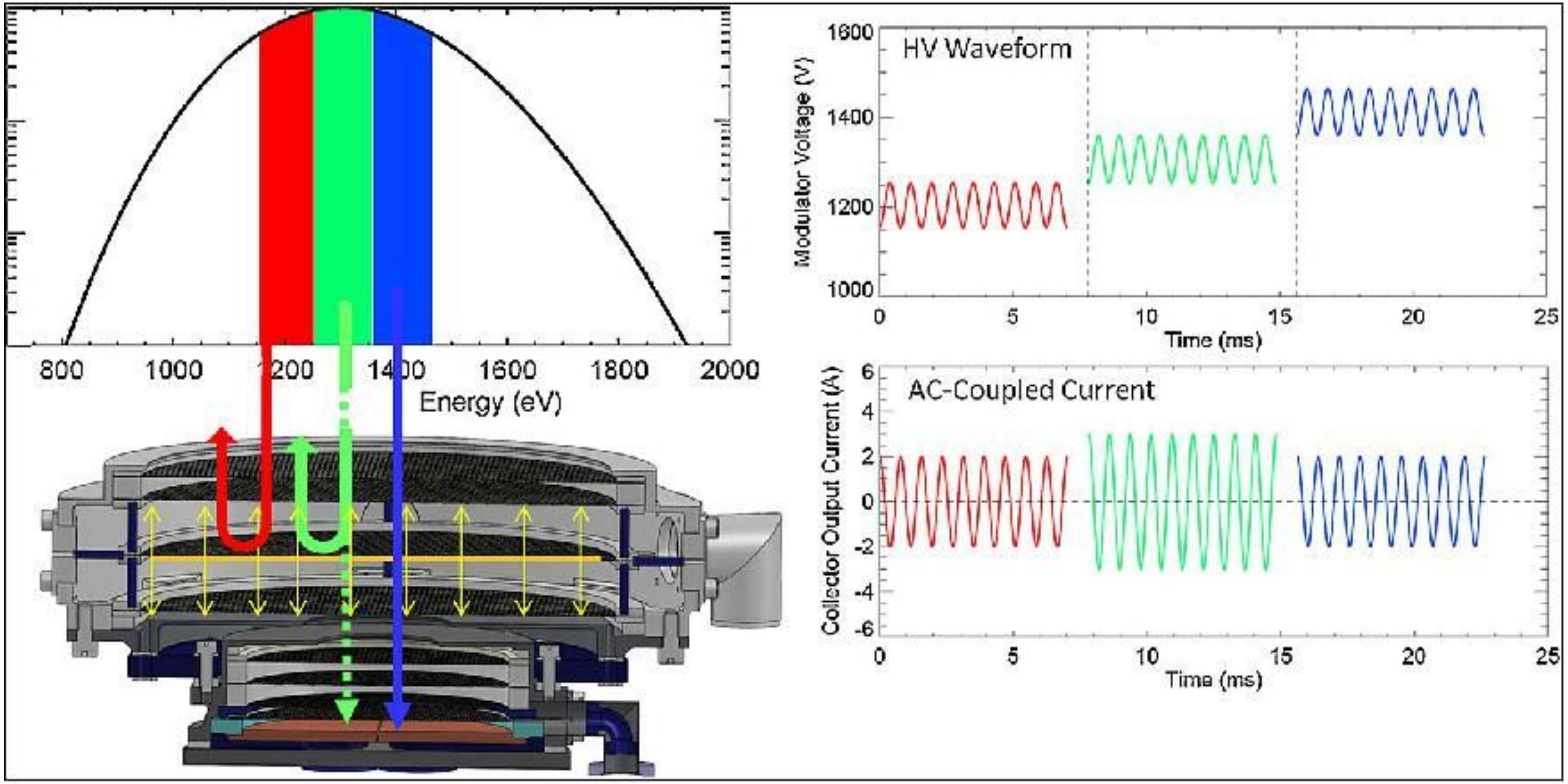


In Situ Techniques: Measuring Current – Retarding Potential Analyzer

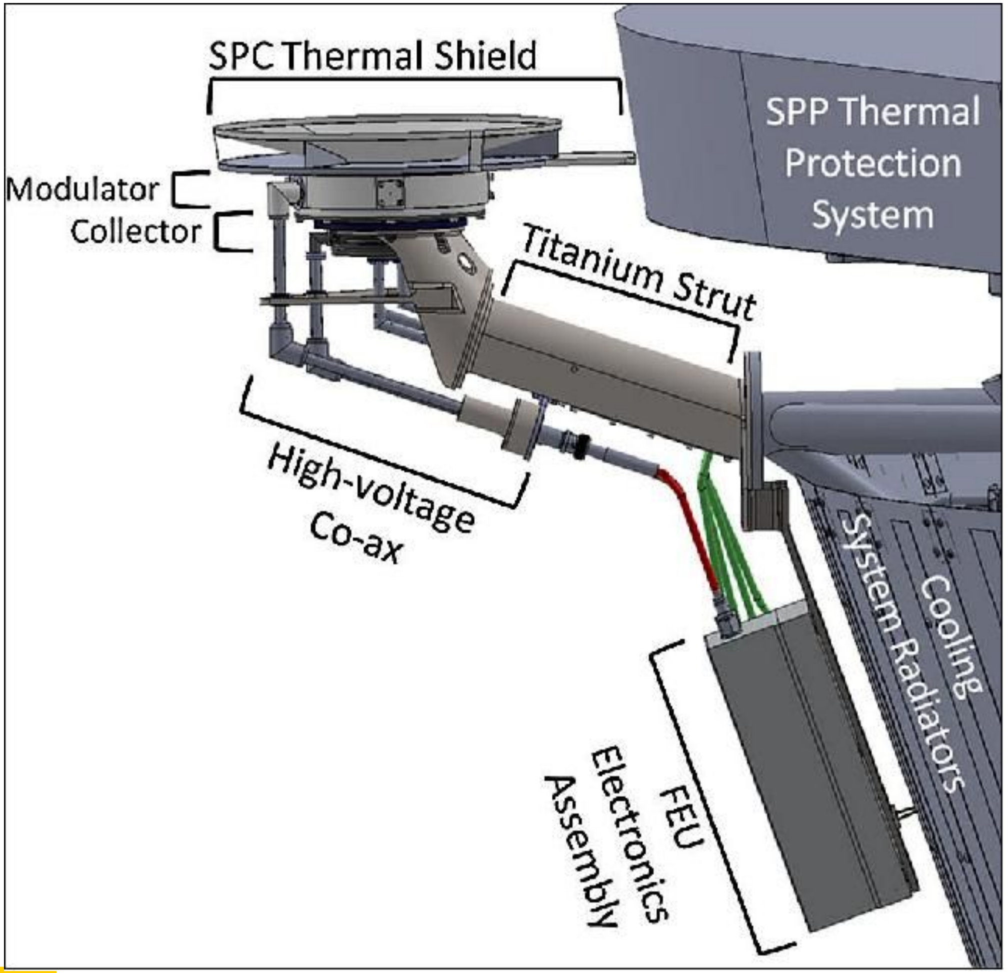




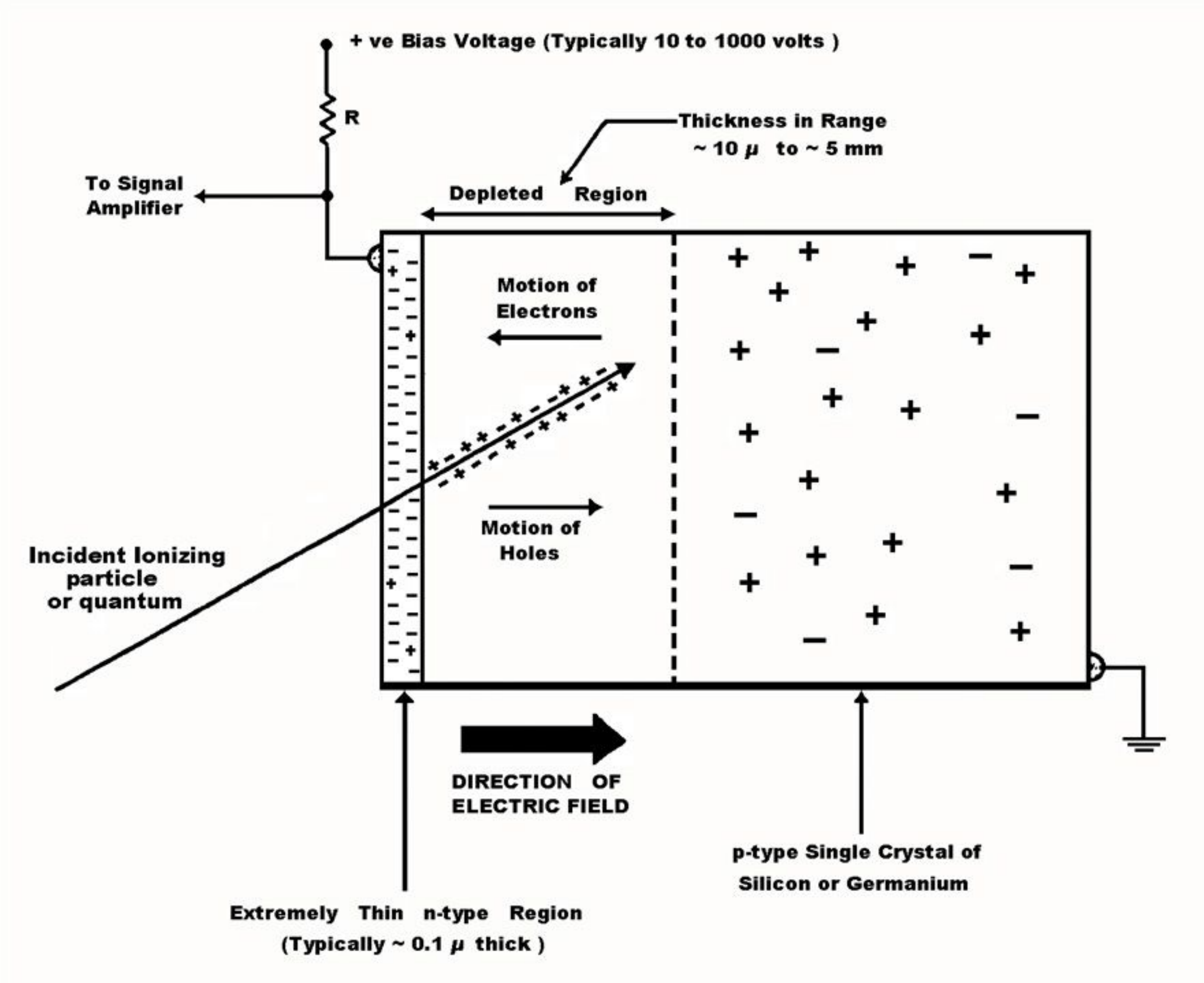
In Situ Techniques: Measuring Current – Faraday Cup



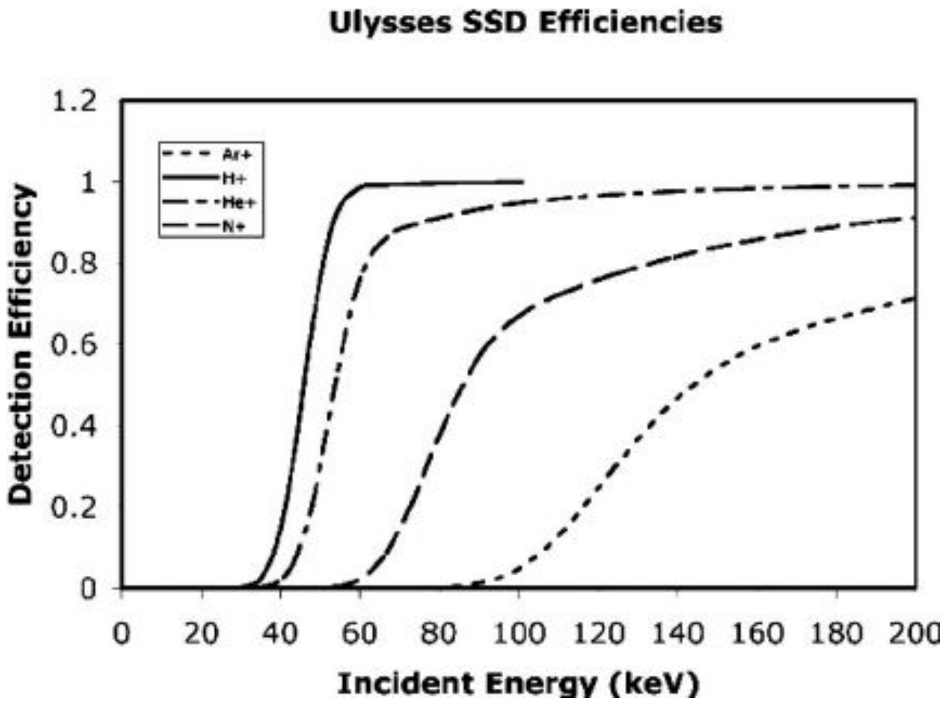
In Situ Techniques: Measuring Current – Faraday Cup

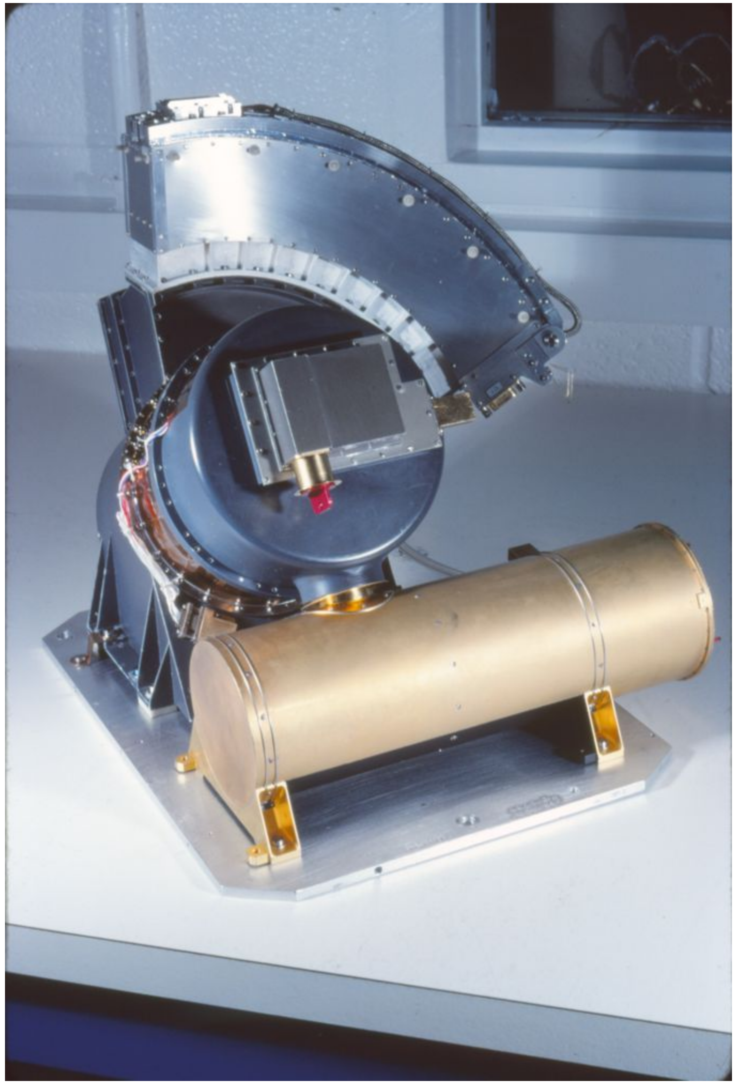


In-Situ Techniques: Counting Particles – Solid-State Detectors



In-Situ Techniques: Counting Particles – Solid-State E Deposition





Bethe-Bloch Formula

$$\boxed{-\frac{dE}{dx} = 2\pi N_a r_e^2 m_e c^2 \rho \frac{Z}{A}\frac{z^2}{\beta^2}\left[\ln\left(\frac{2m_e\gamma^2 v^2 W_{max}}{I^2}\right) - 2\beta^2 - \delta - 2\frac{C}{Z}\right],}$$

with

$$2\pi N_a r_e^2 m_e c^2 = 0.1535\ \mathrm{MeVcm^2/g}$$

r_e: classical electron radius $= 2.817 \times 10^{-13}$ cm
m_e: electron mass
N_a: Avogadro's number $= 6.022 \times 10^{23}\ \mathrm{mol}^{-1}$
I: mean excitation potential
Z: atomic number of absorbing material
A: atomic weight of absorbing material
ρ: density of absorbing material
z: charge of incident particle in units of e
$\beta = v/c$ of the incident particle
$\gamma = 1/\sqrt{1-\beta^2}$
δ: density correction
C: shell correction
W_{max}: maximum energy transfer in a single collision.

The maximum energy transfer is that produced by a head-on or *knock-on* collision. For an incident particle of mass M, kinematics gives

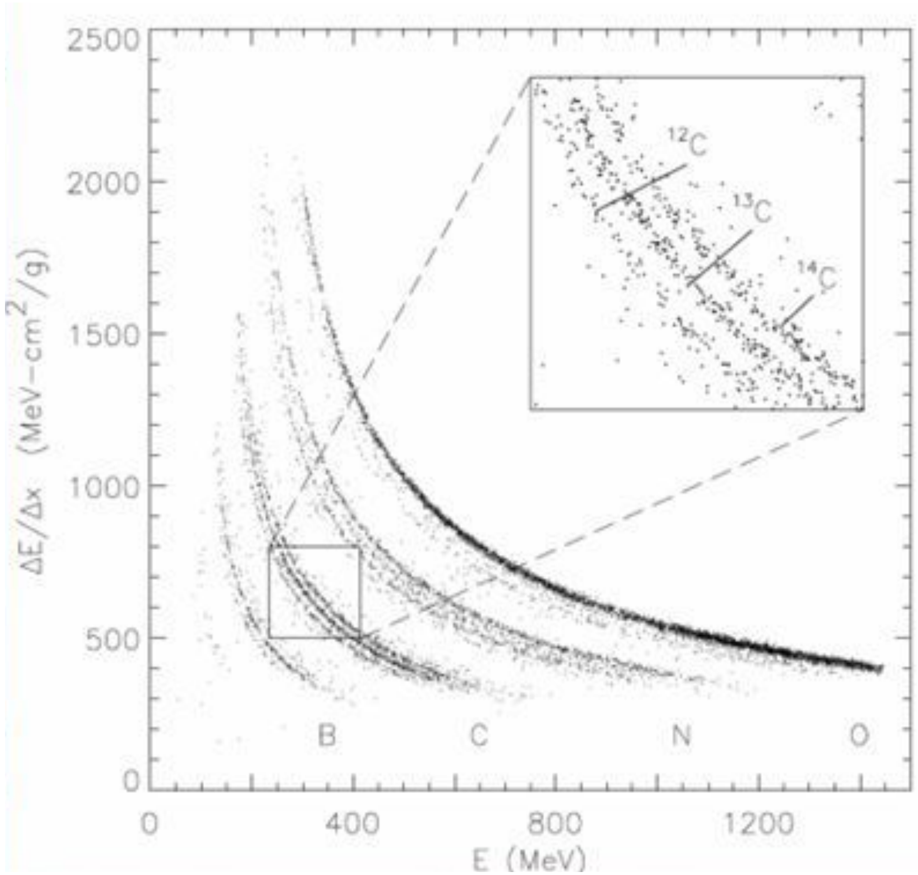
$$\boxed{W_{max} = \frac{2m_e c^2 \eta^2}{1 + 2s\sqrt{1+\eta^2} + s^2},}$$

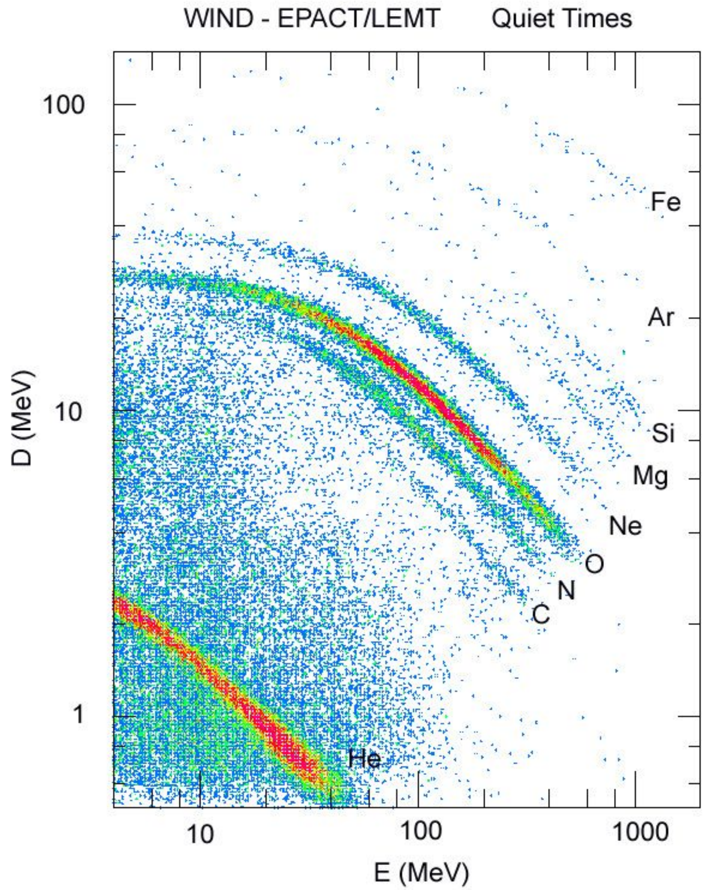
$$\frac{I}{Z} = 12 + \frac{7}{Z}\ \mathrm{eV} \qquad Z < 13$$

$$\frac{I}{Z} = 9.76 + 58.8 Z^{-1.19}\ \mathrm{eV} \qquad Z \geq 13$$

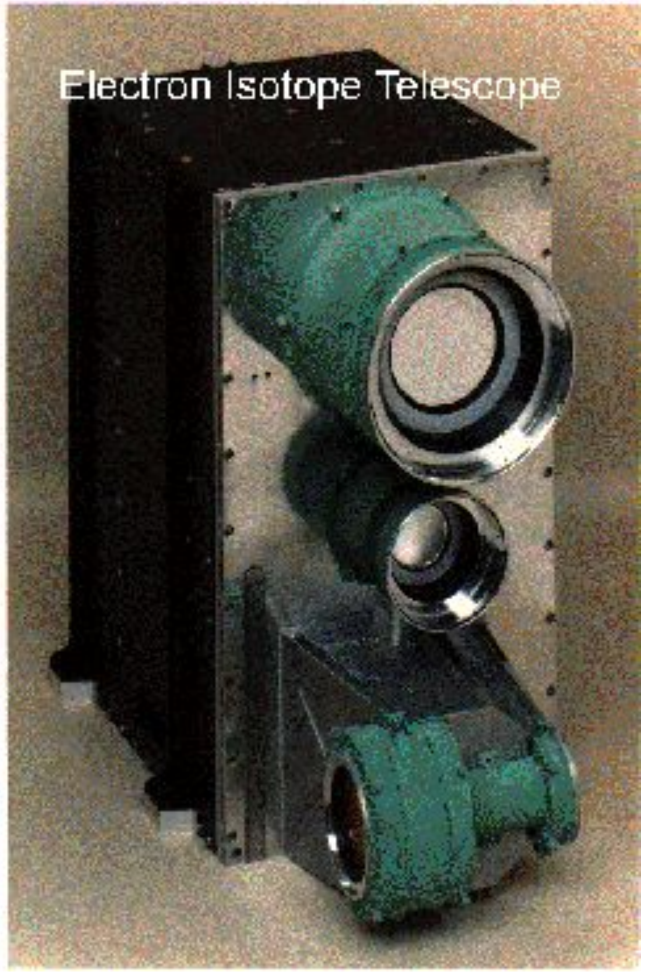
where $s = m_e/M$ and $\eta = \beta\gamma$. Moreover, if $M \gg m_e$, then $W_{max} \simeq 2m_e c^2 \eta^2$

In Situ Techniques: Counting Particles – Solid State dE/dx

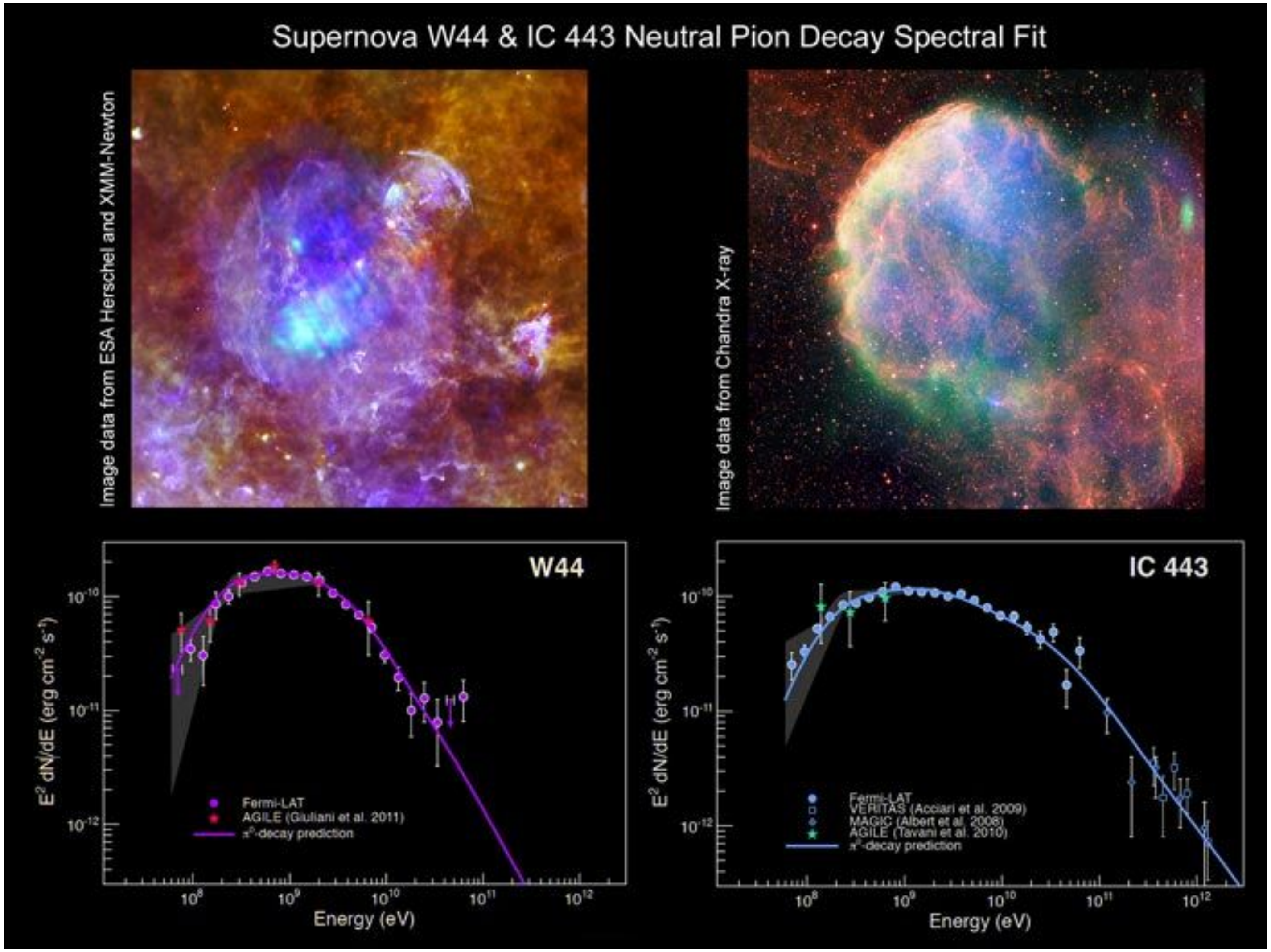




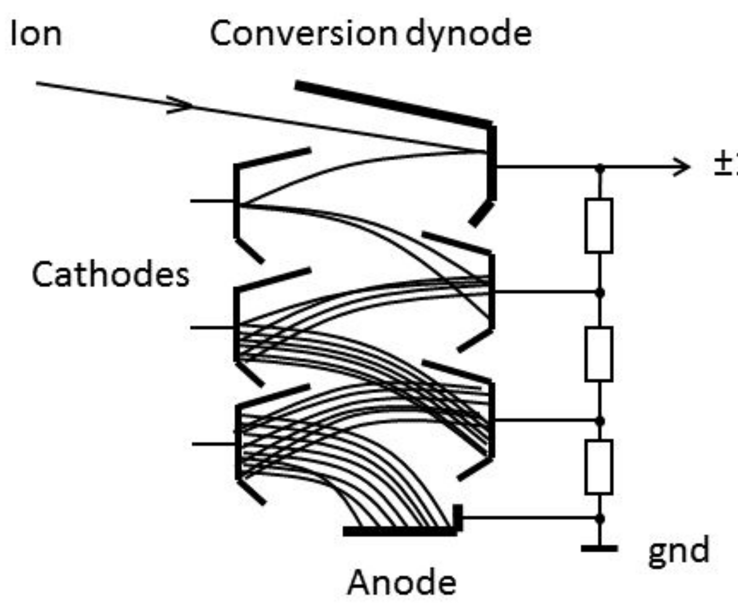
In Situ Techniques: Counting Particles – Solid State dE/dx

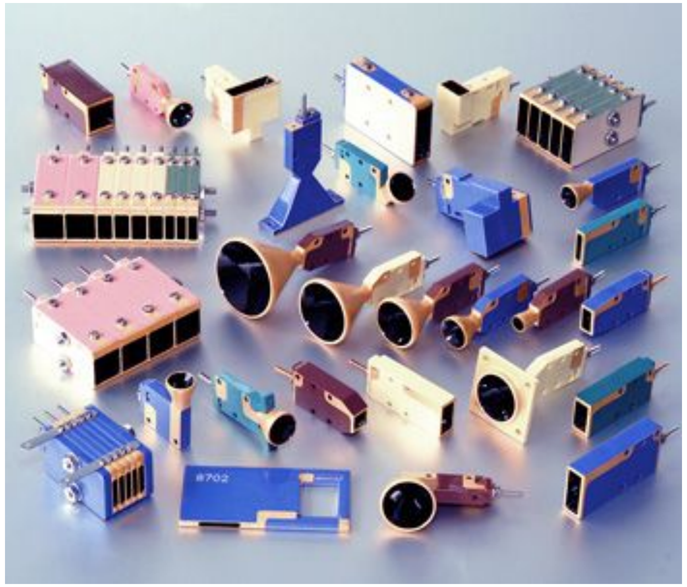


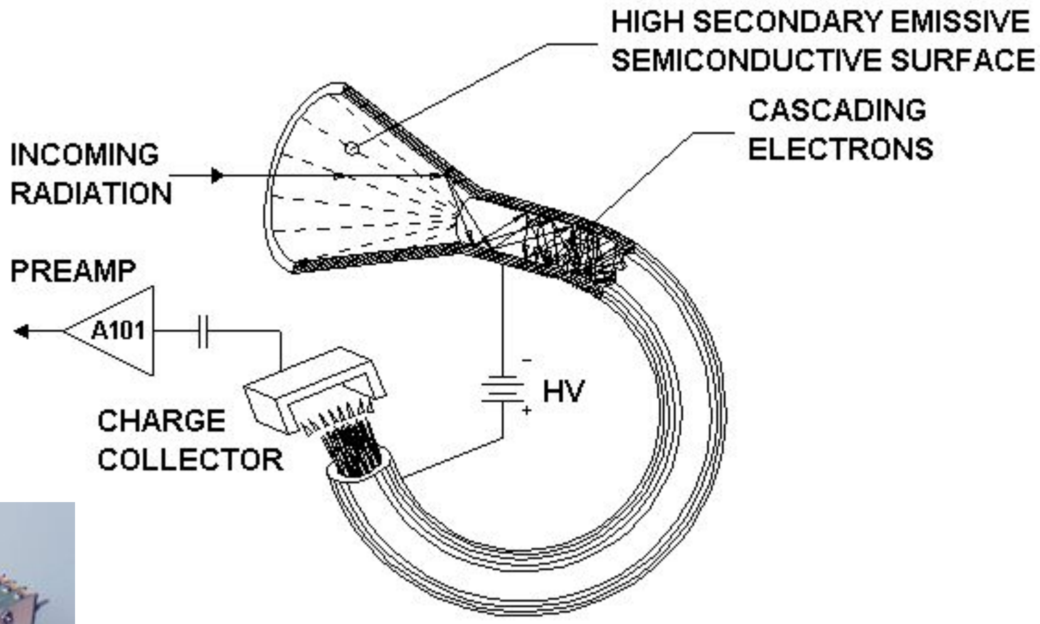
In Situ→Remote Techniques: Cosmic Rays



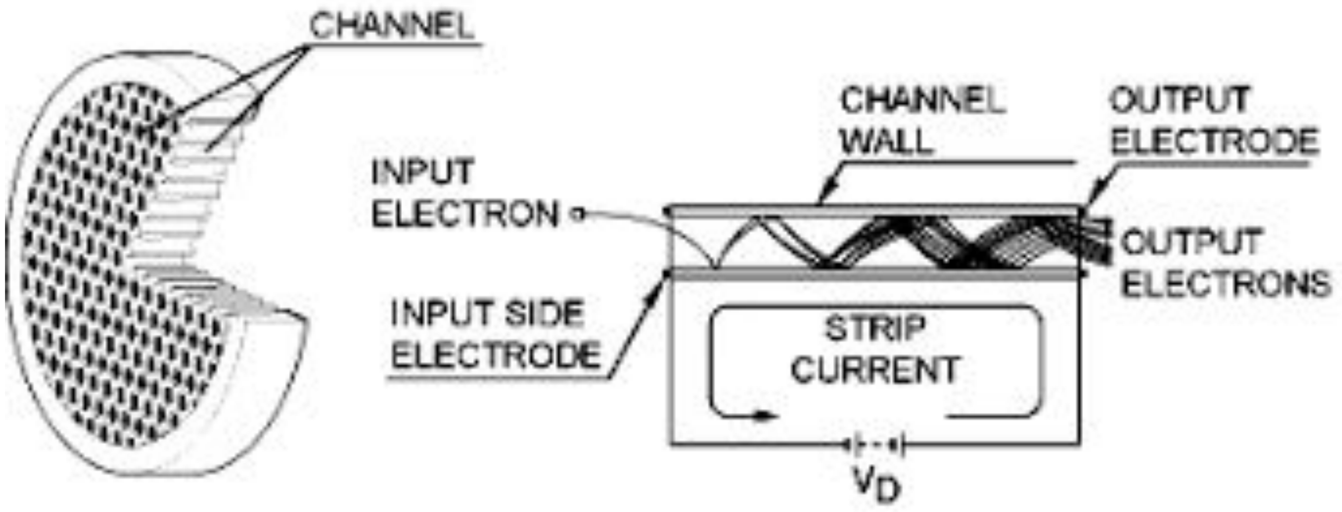
In Situ Techniques: Counting Particles – Dynodes & CEMs



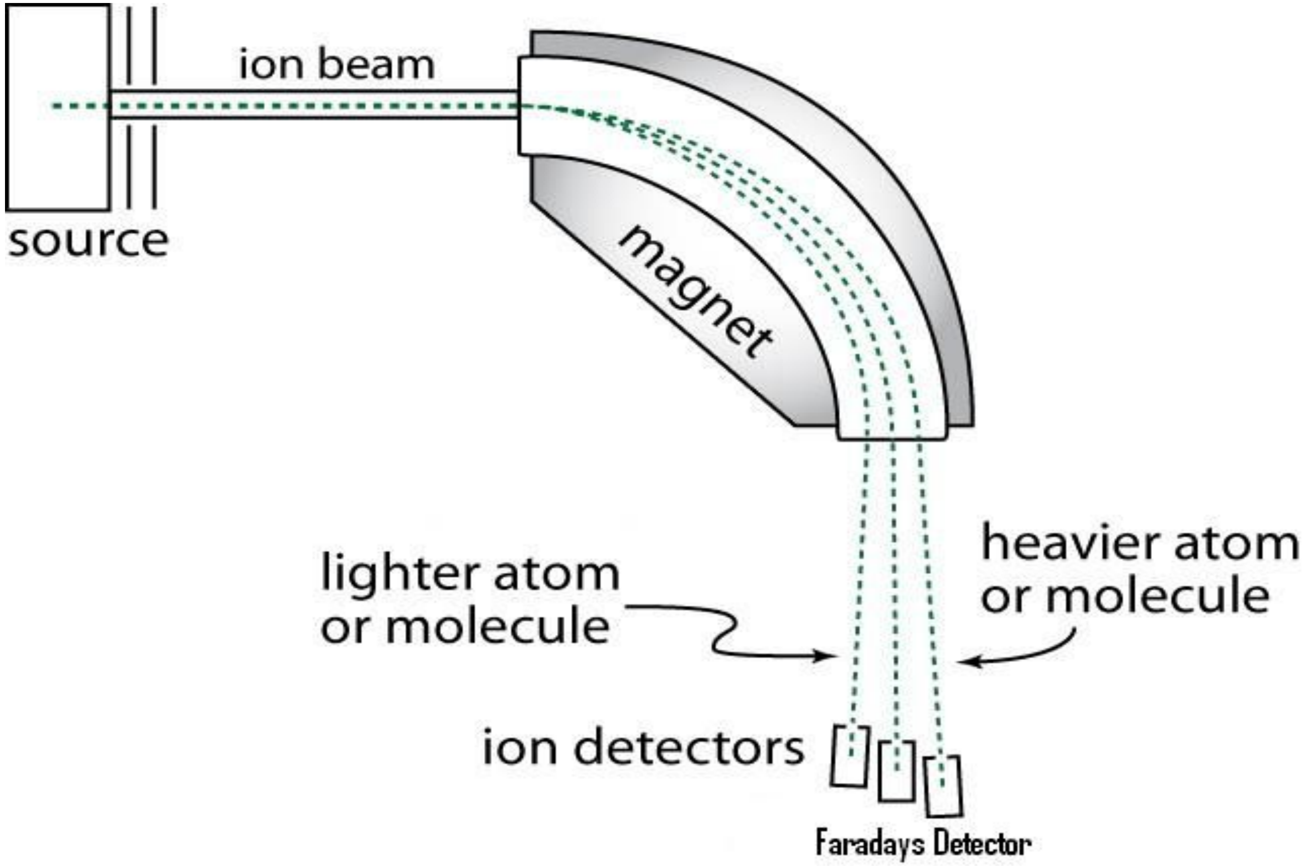




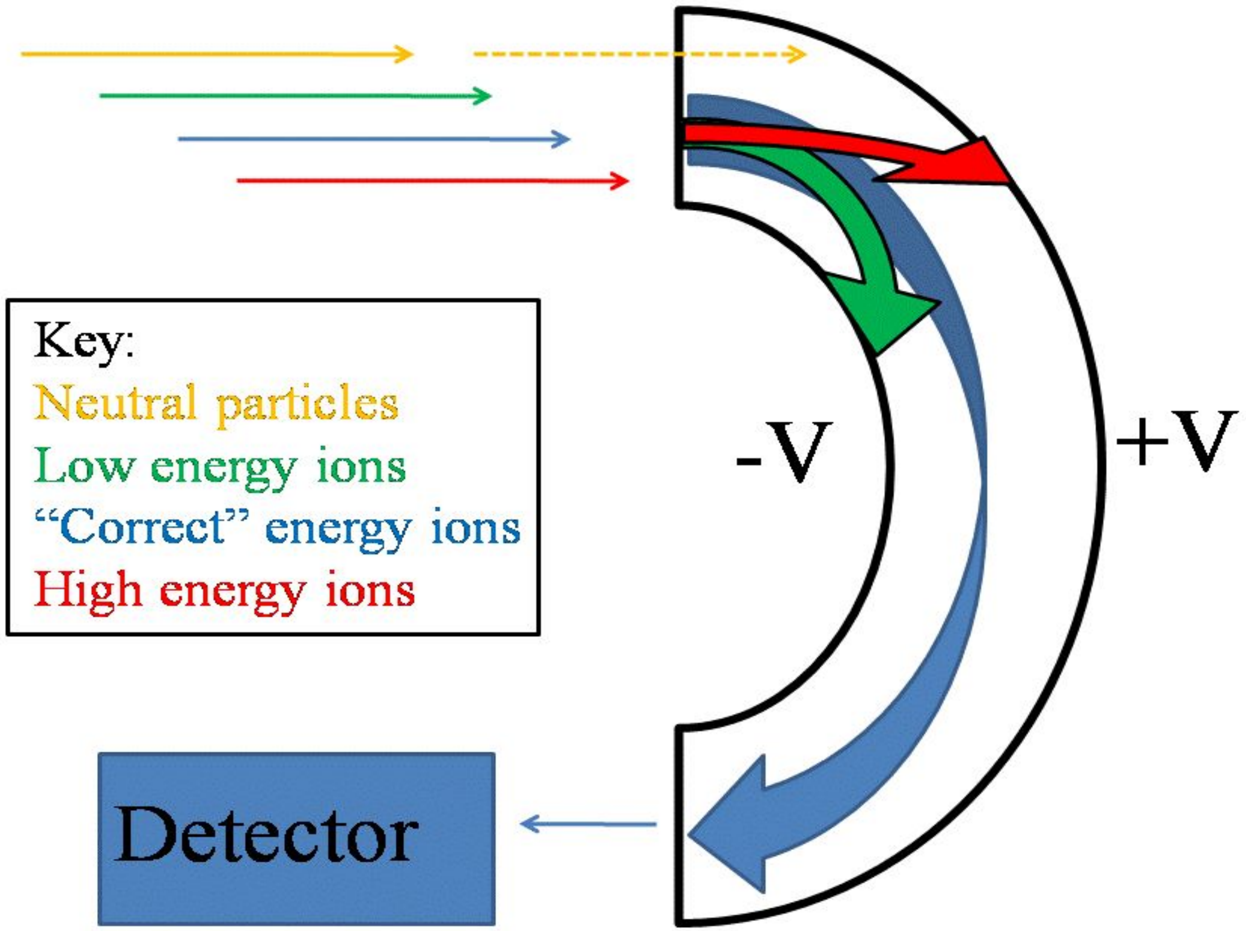
In Situ Techniques: Counting Particles – Microchannel Plates



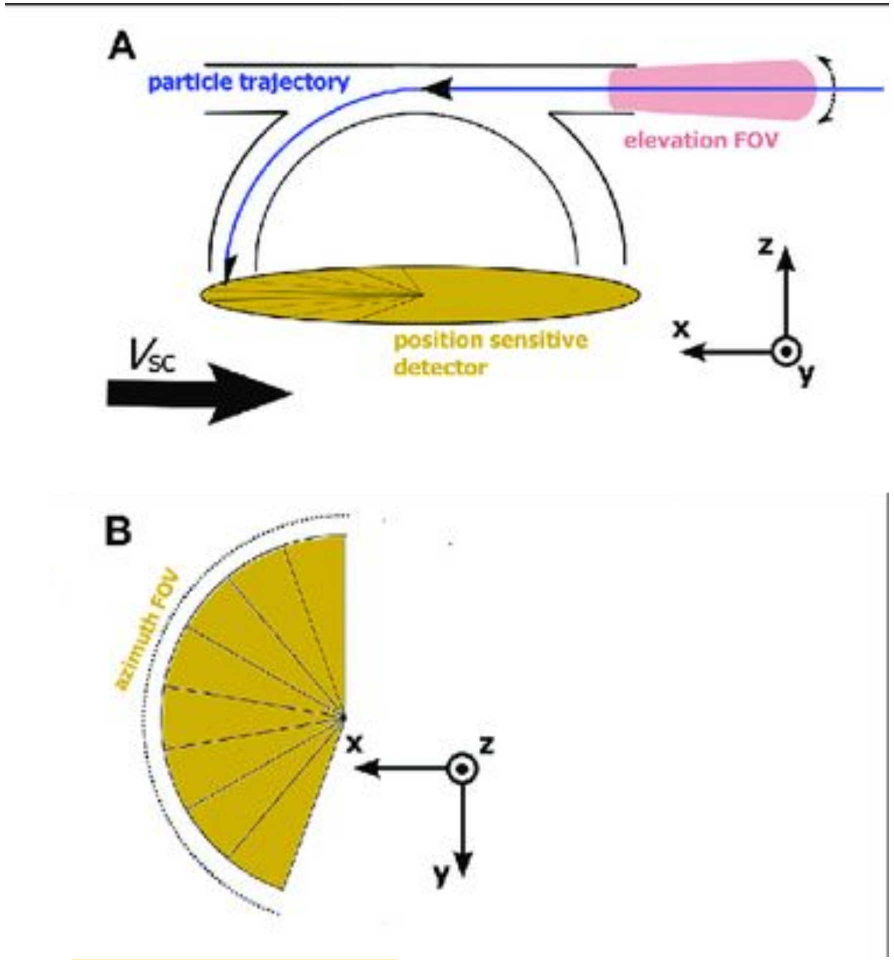
In Situ Techniques: Magnetic Optics

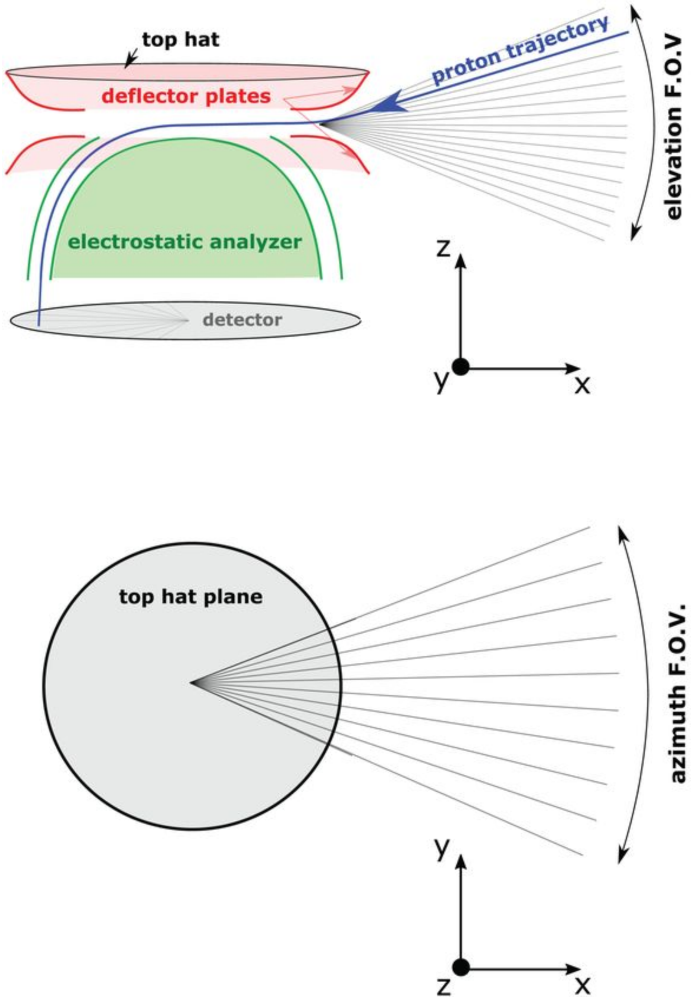


In Situ Techniques: Electrostatic Optics

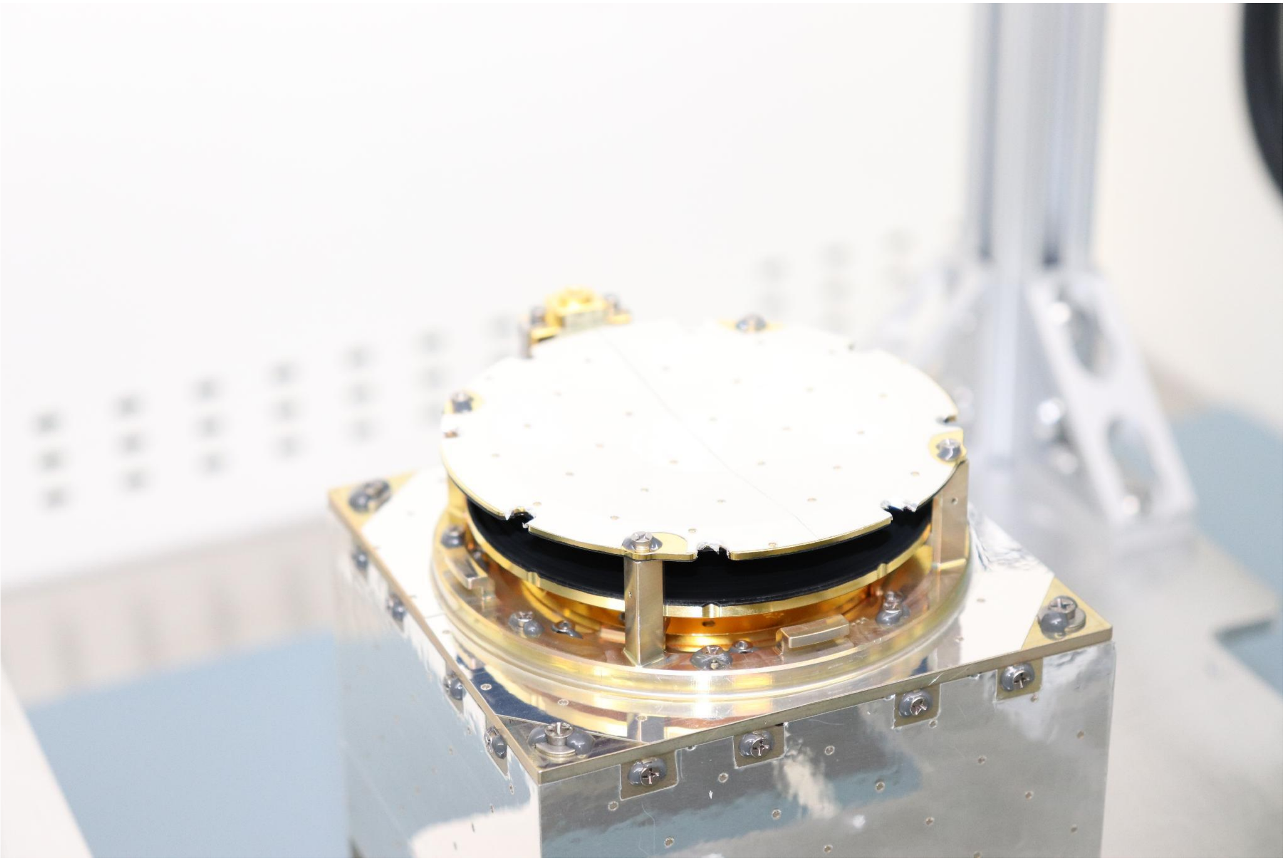


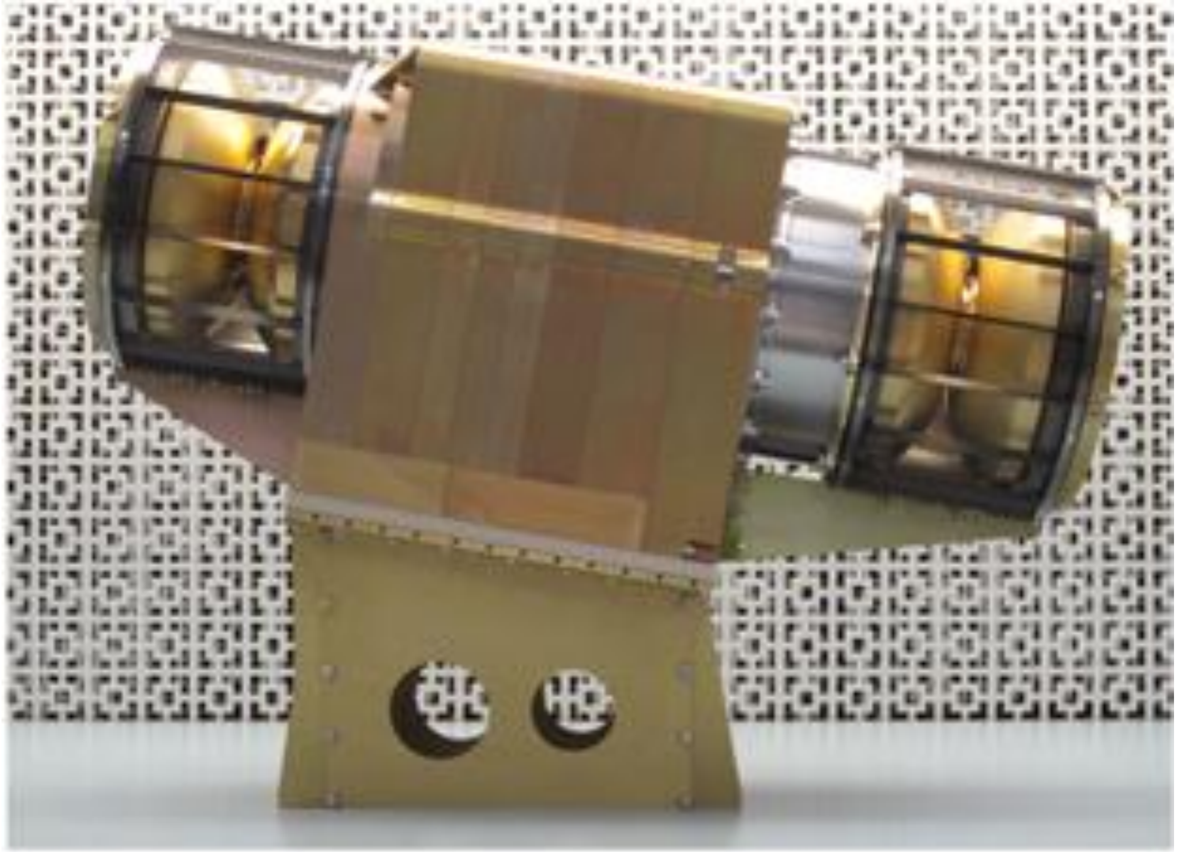
In Situ Techniques: Top-Hat Electrostatic Optics



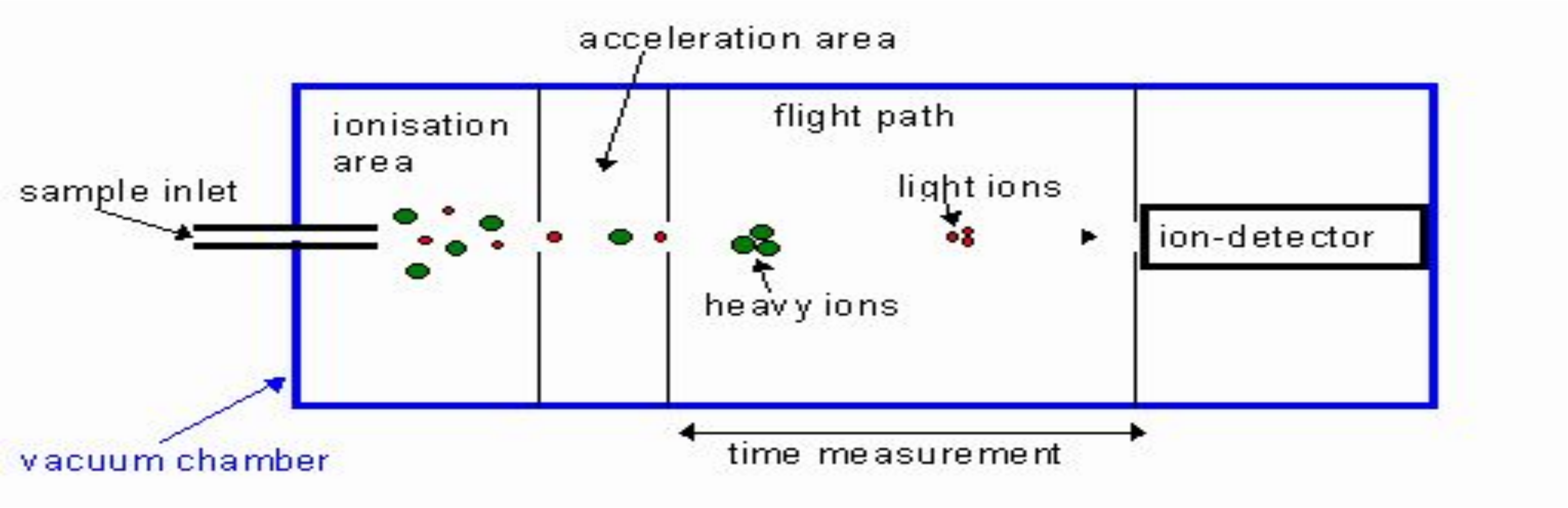


In Situ Techniques: Top-Hat Electrostatic Optics

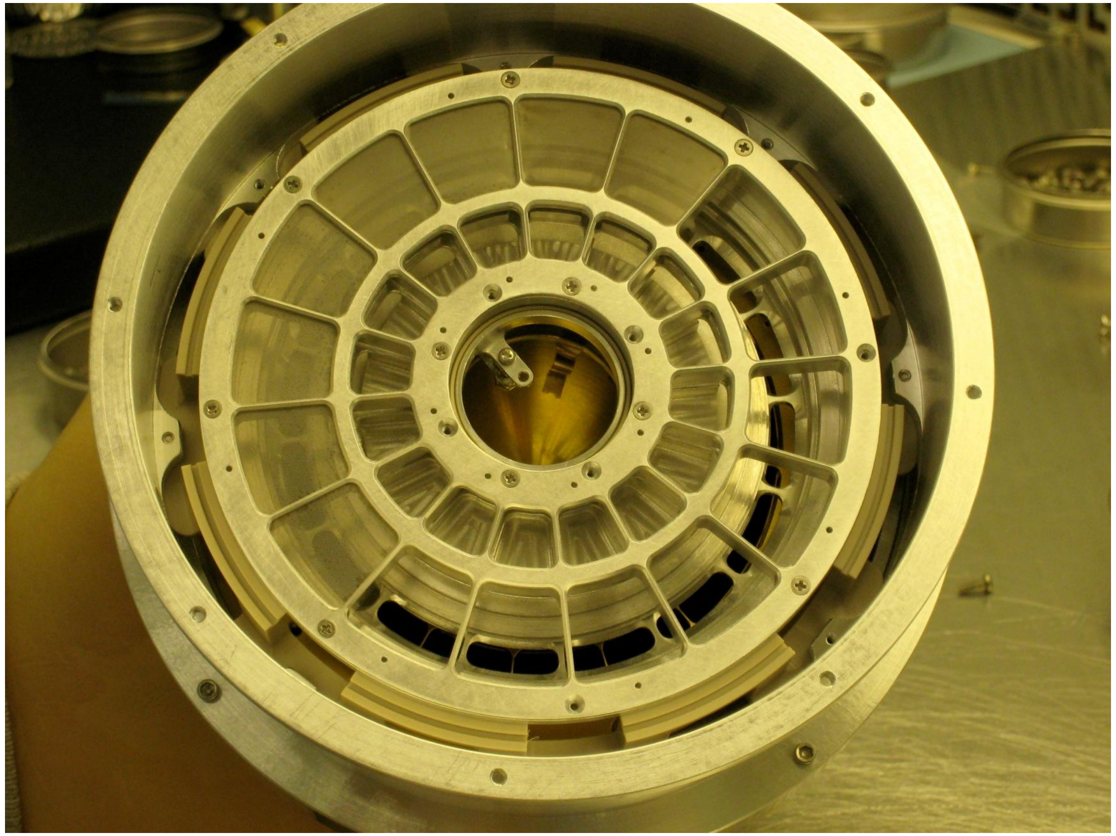


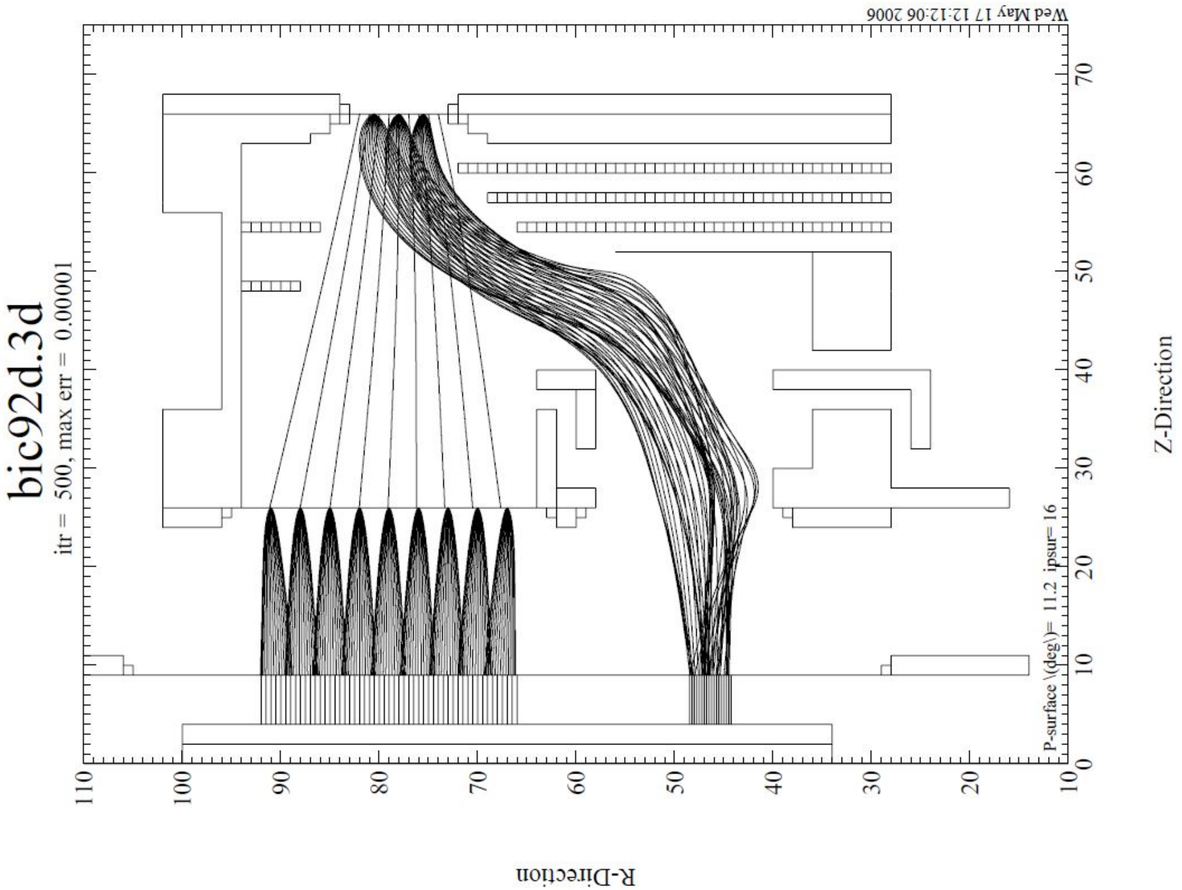


In Situ Techniques: Counting Particles - Time-Of-Flight

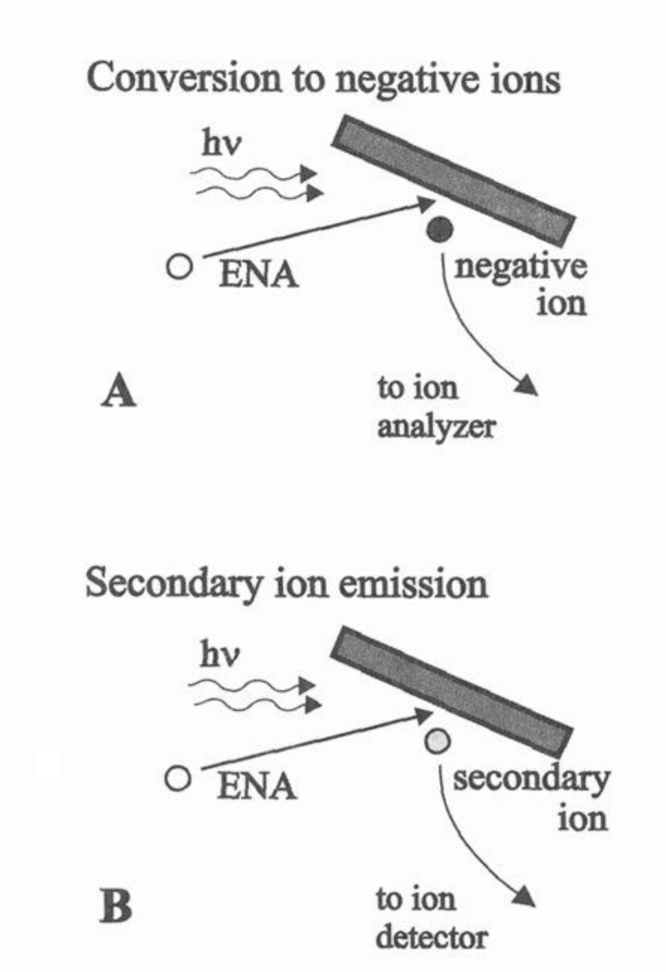


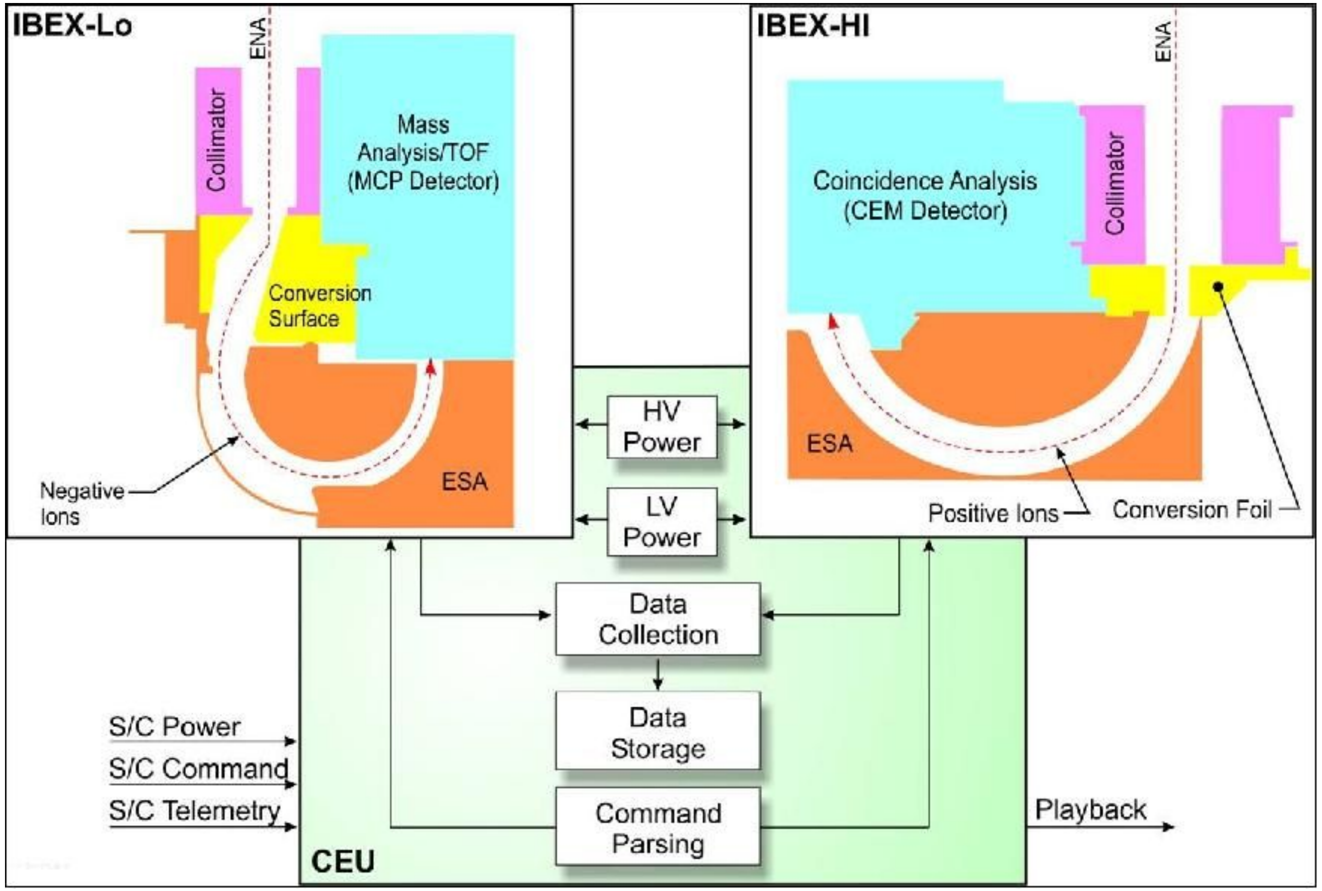
In Situ Techniques: Carbon Foils



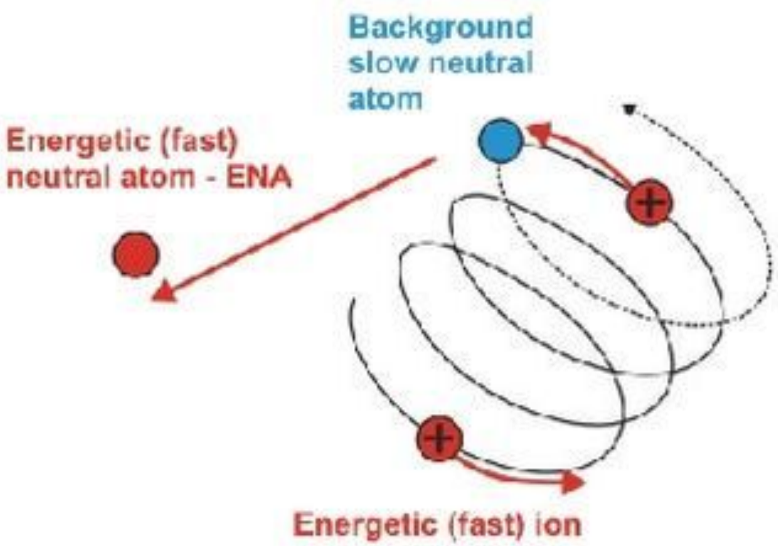


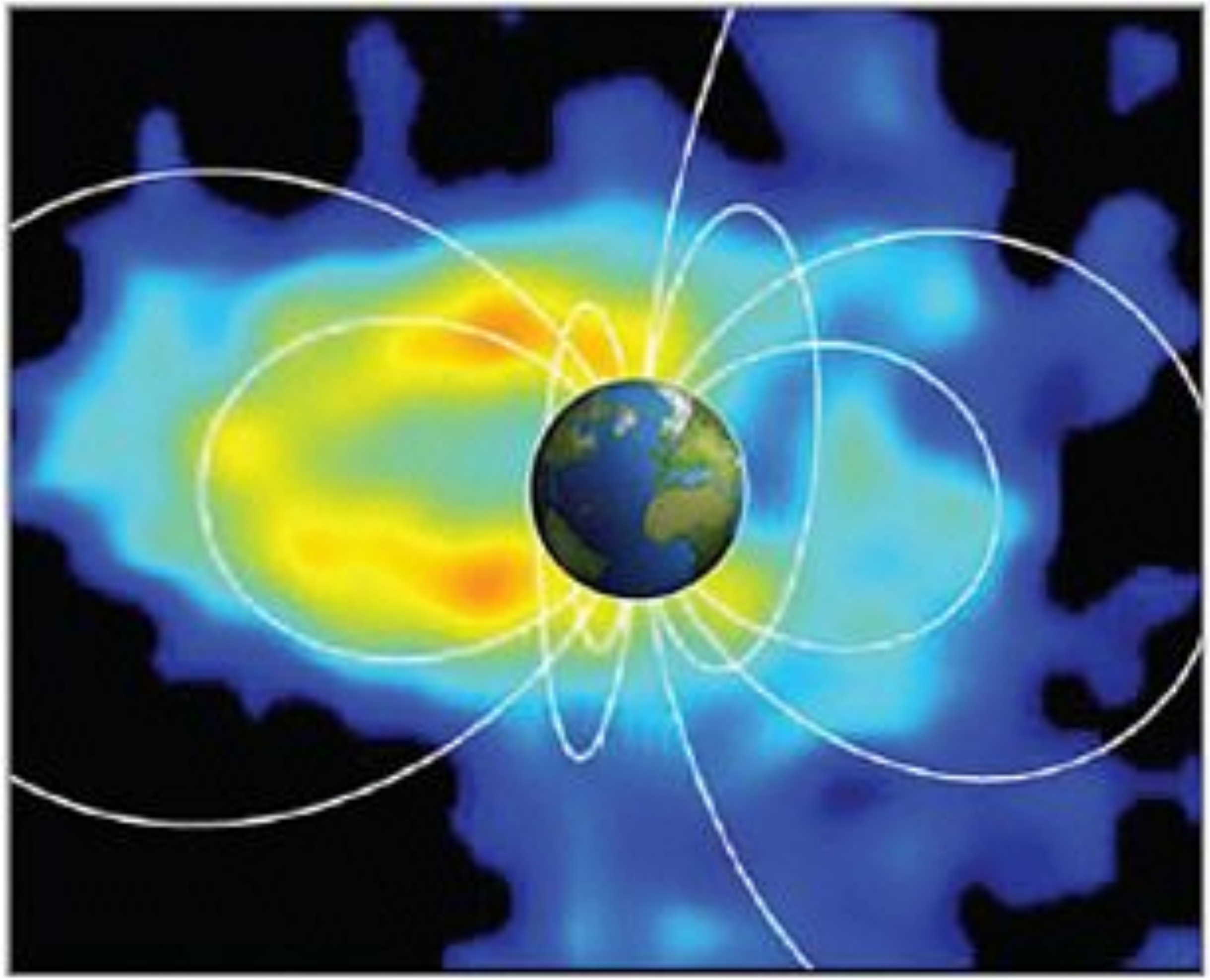
In Situ Techniques: Conversion Surfaces





In Situ→ Remote Techniques: ENA Imaging





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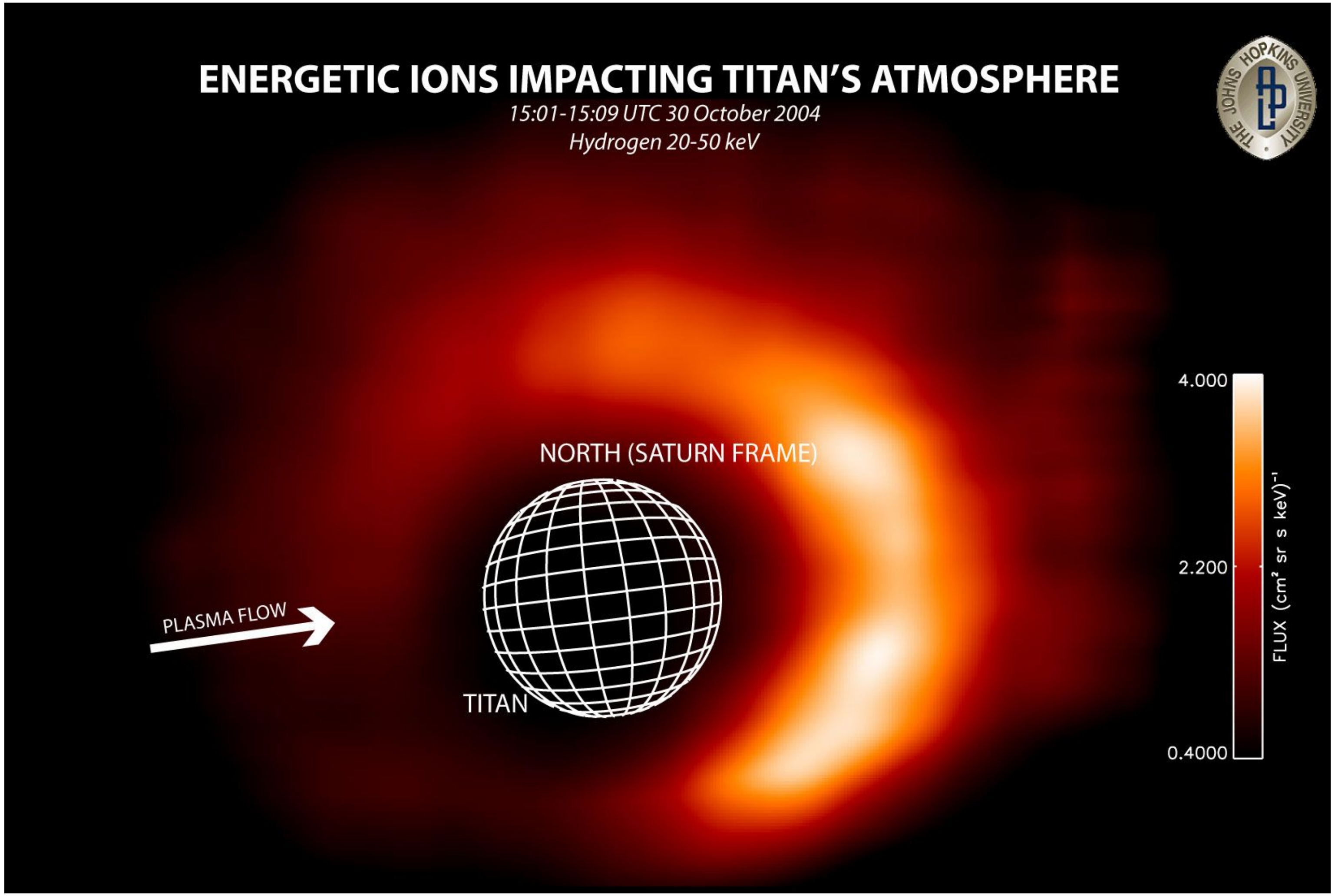

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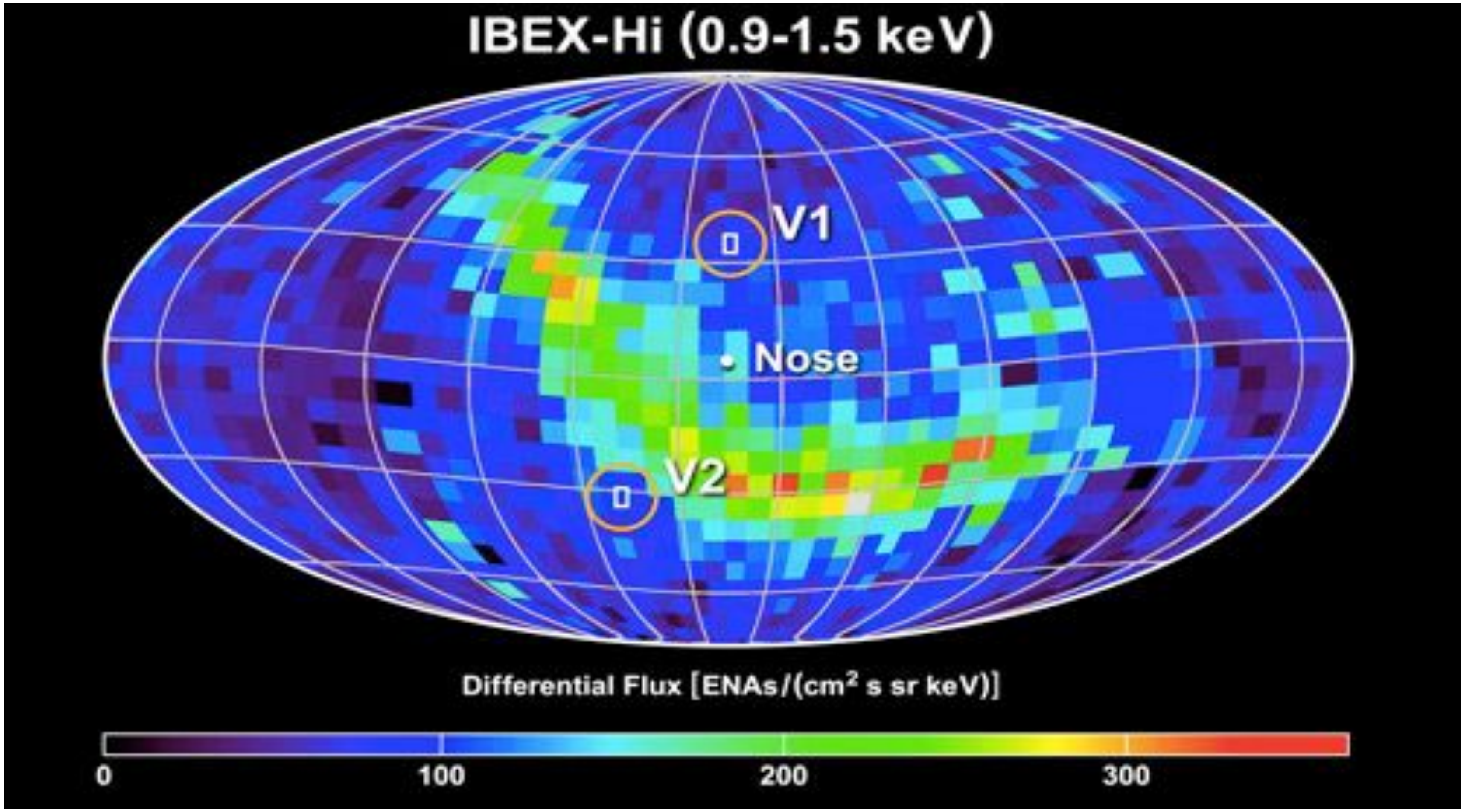
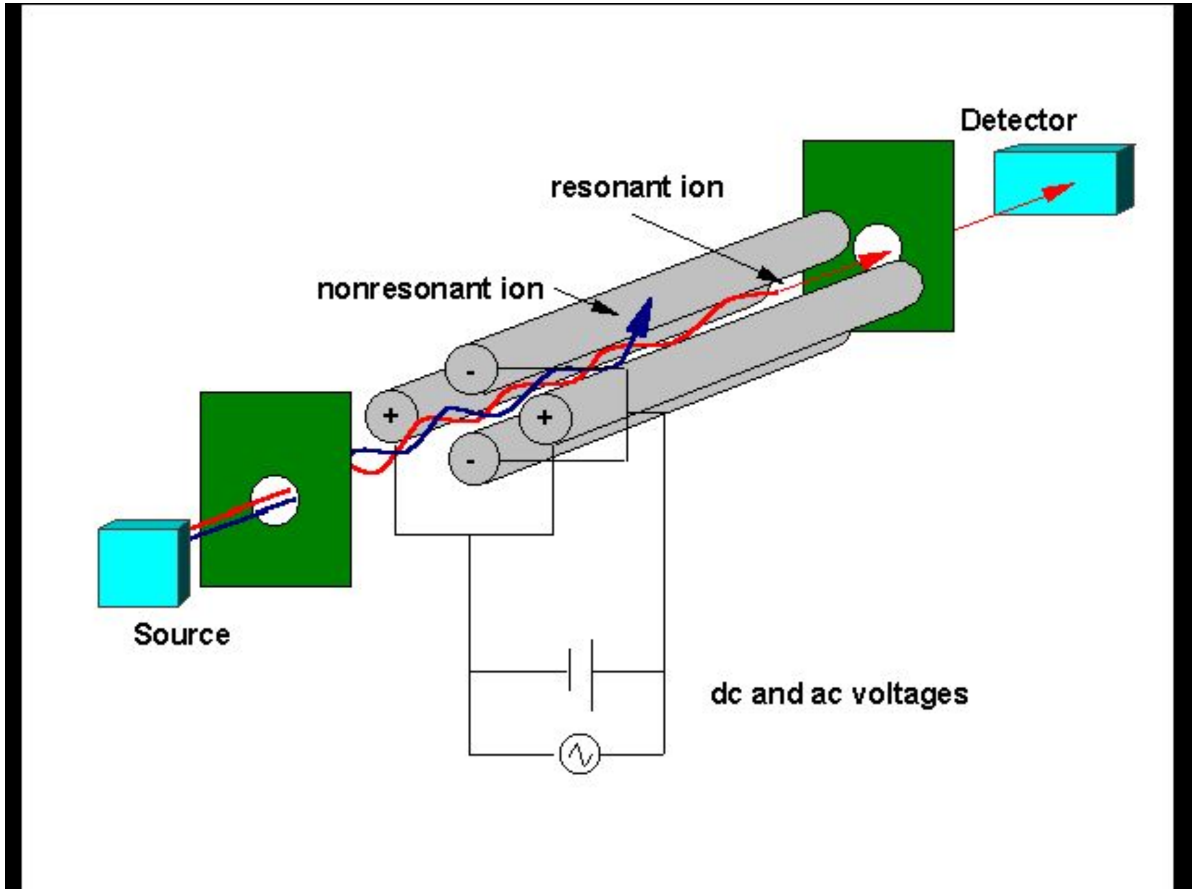
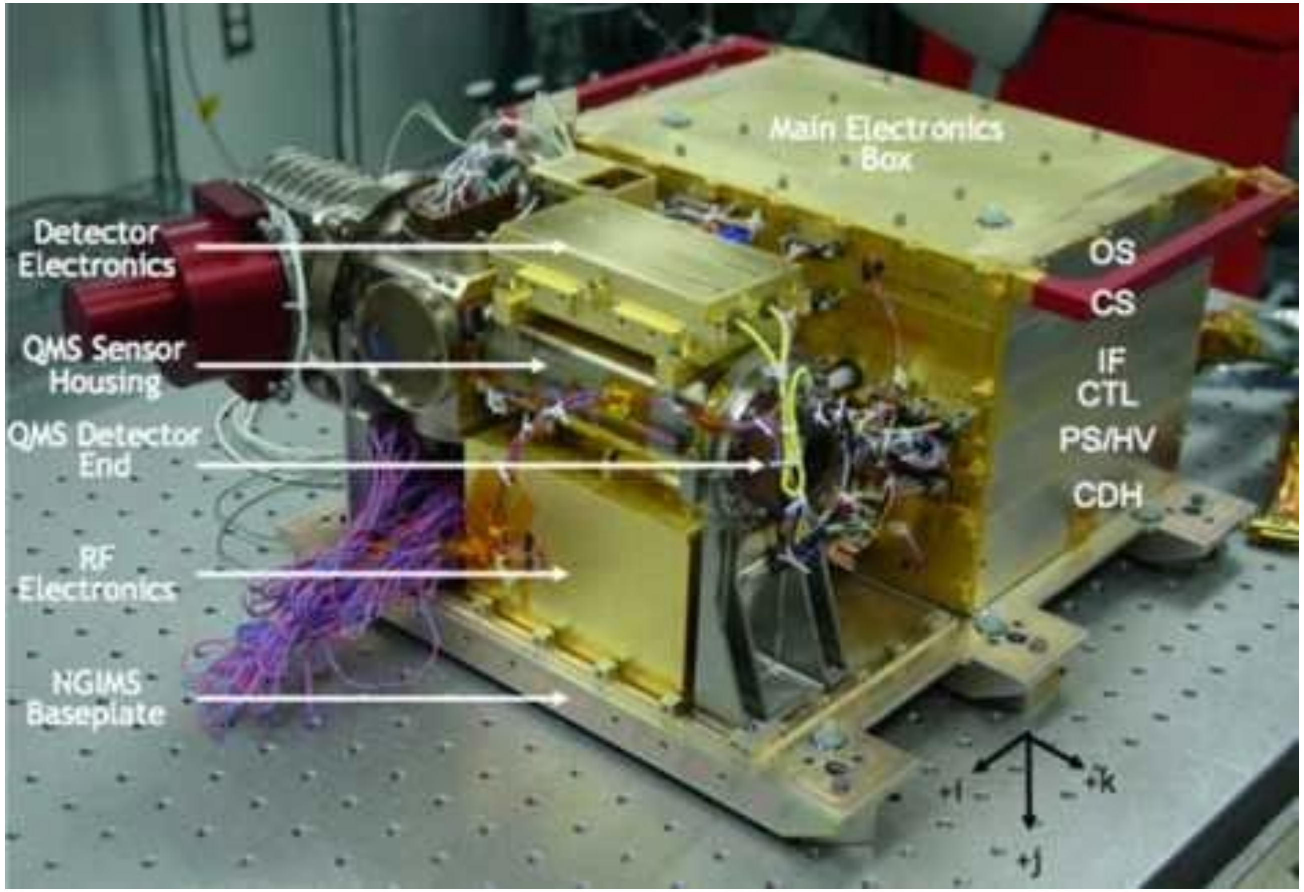
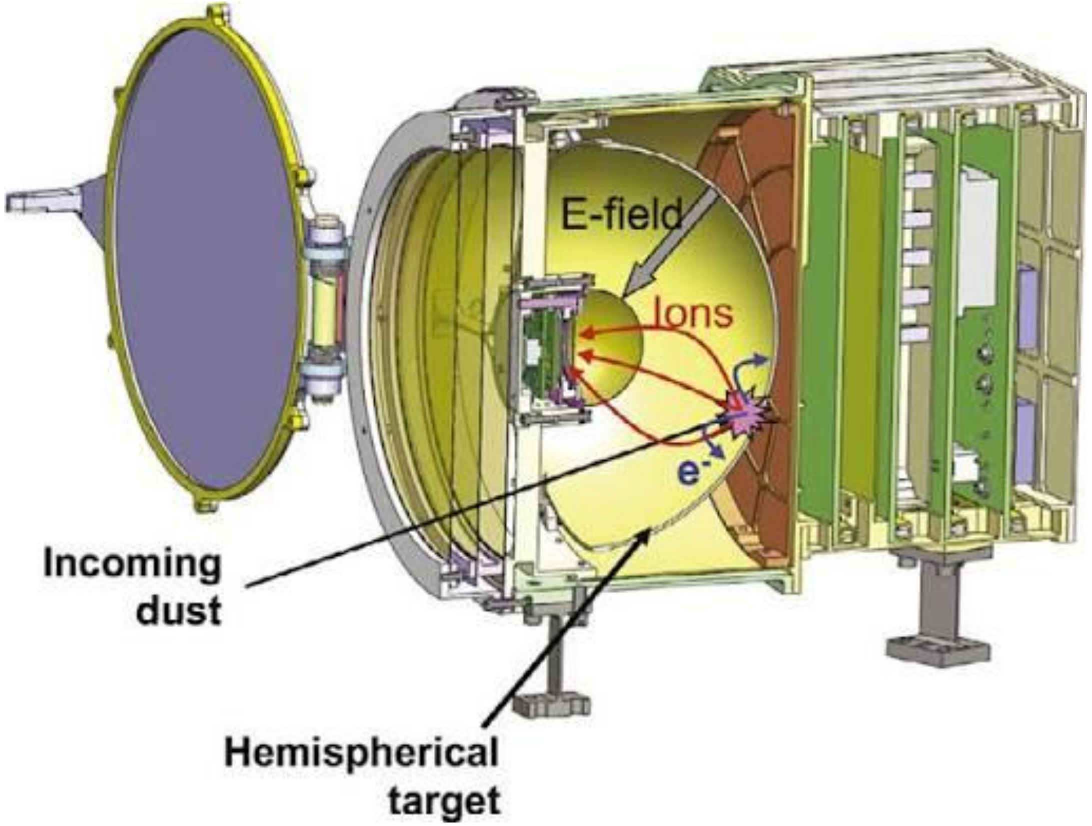


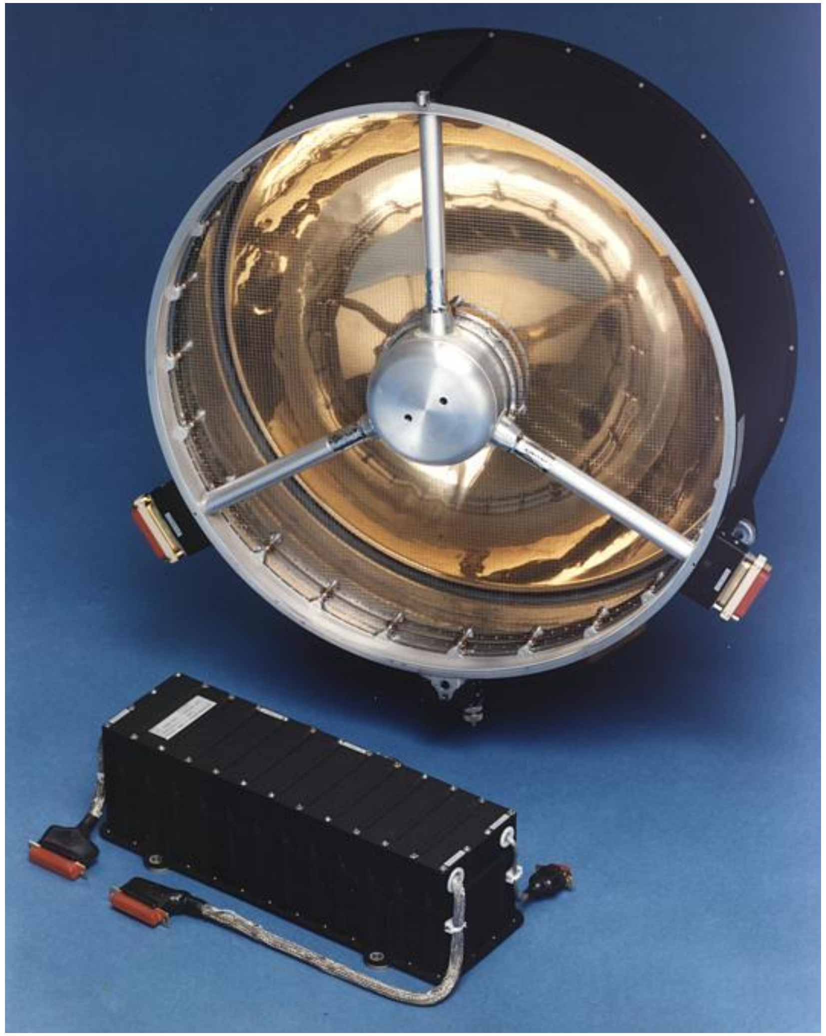
In Situ Techniques: RF Resonance





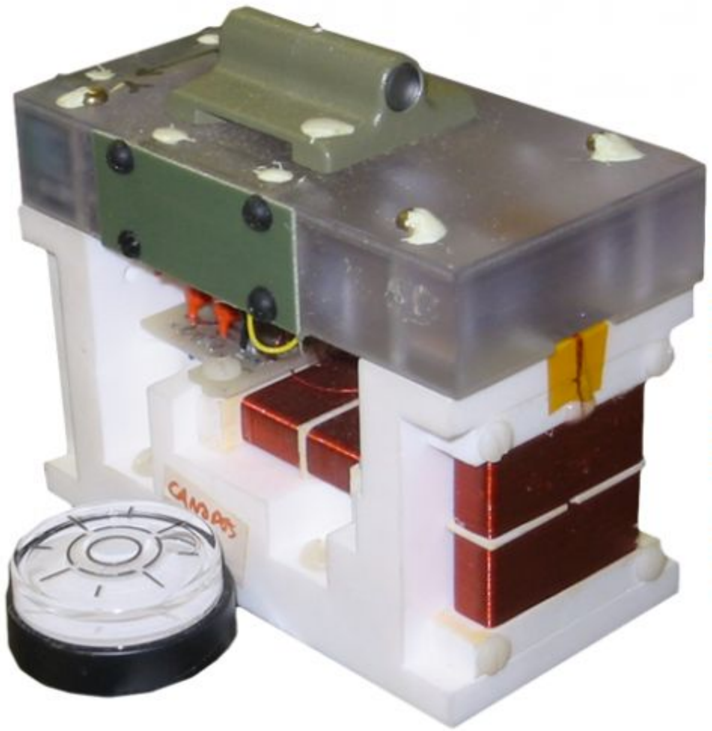
In Situ Techniques: Dust Impact Sensors

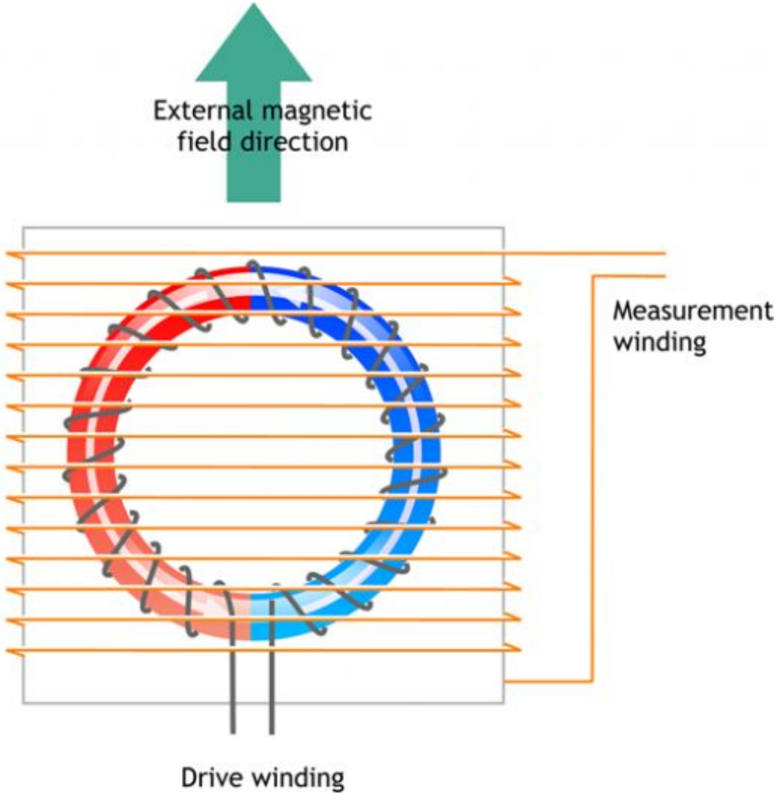




Fields

In Situ Techniques: Magnetic Field - Fluxgate



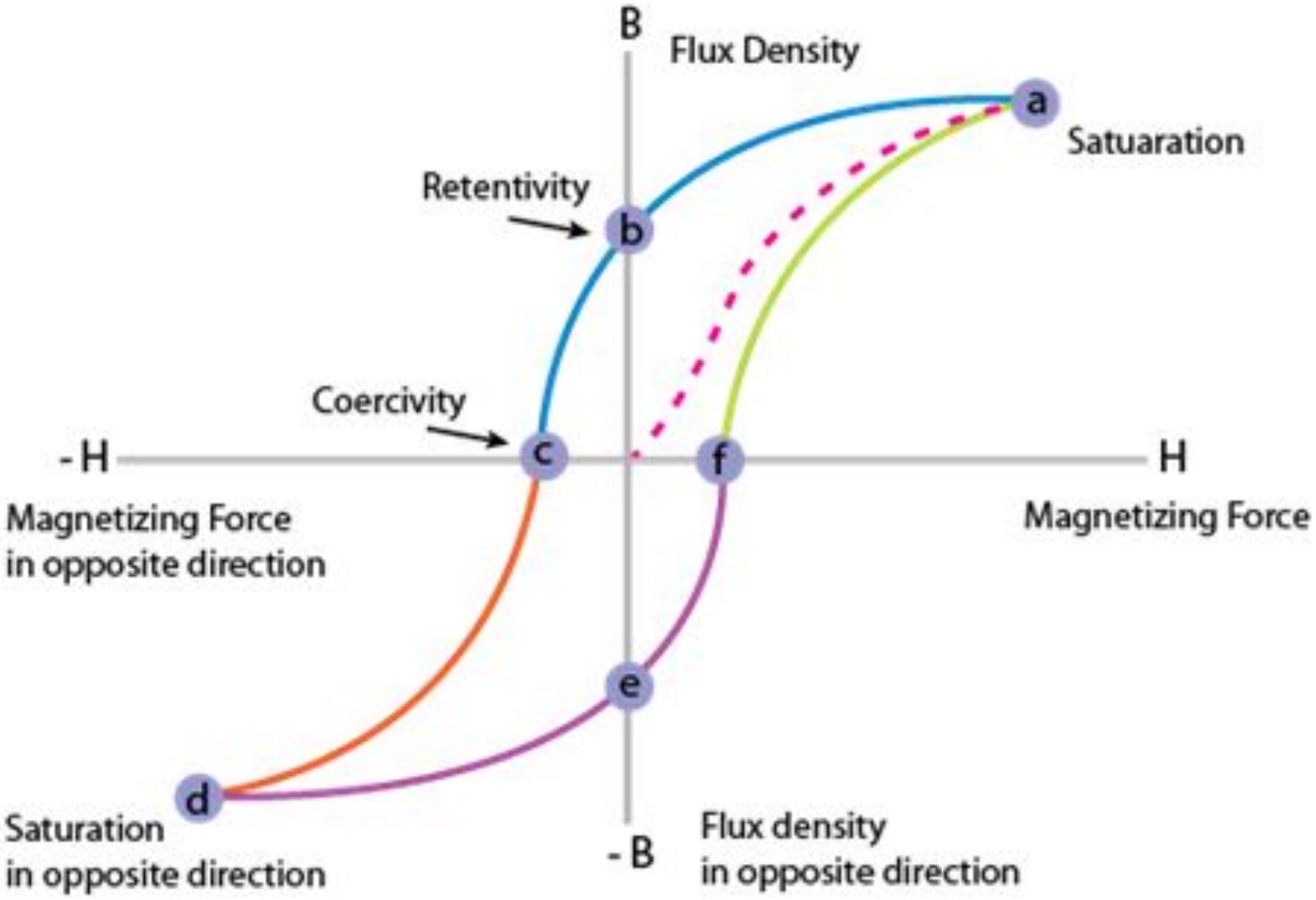


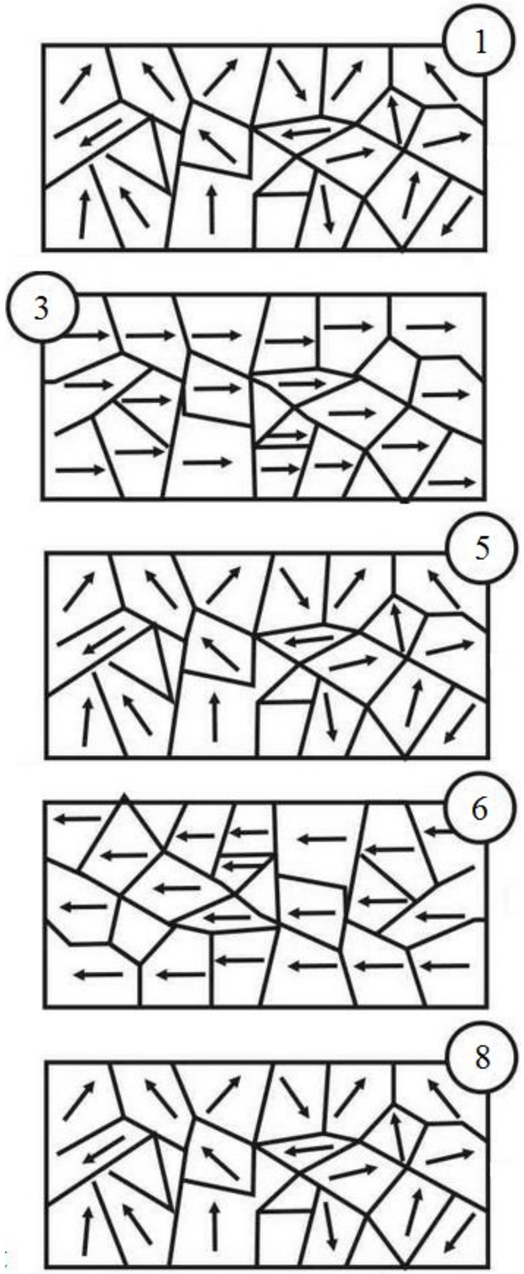
$$\mathcal{E} = -\frac{d\Phi_B}{dt}$$

$$= -\frac{d(\mu HNA)}{dt}$$

$$= -(\mu NA)\frac{dH}{dt} - (NHA)\frac{d\mu}{dt}$$

Magnetic Hysteresis





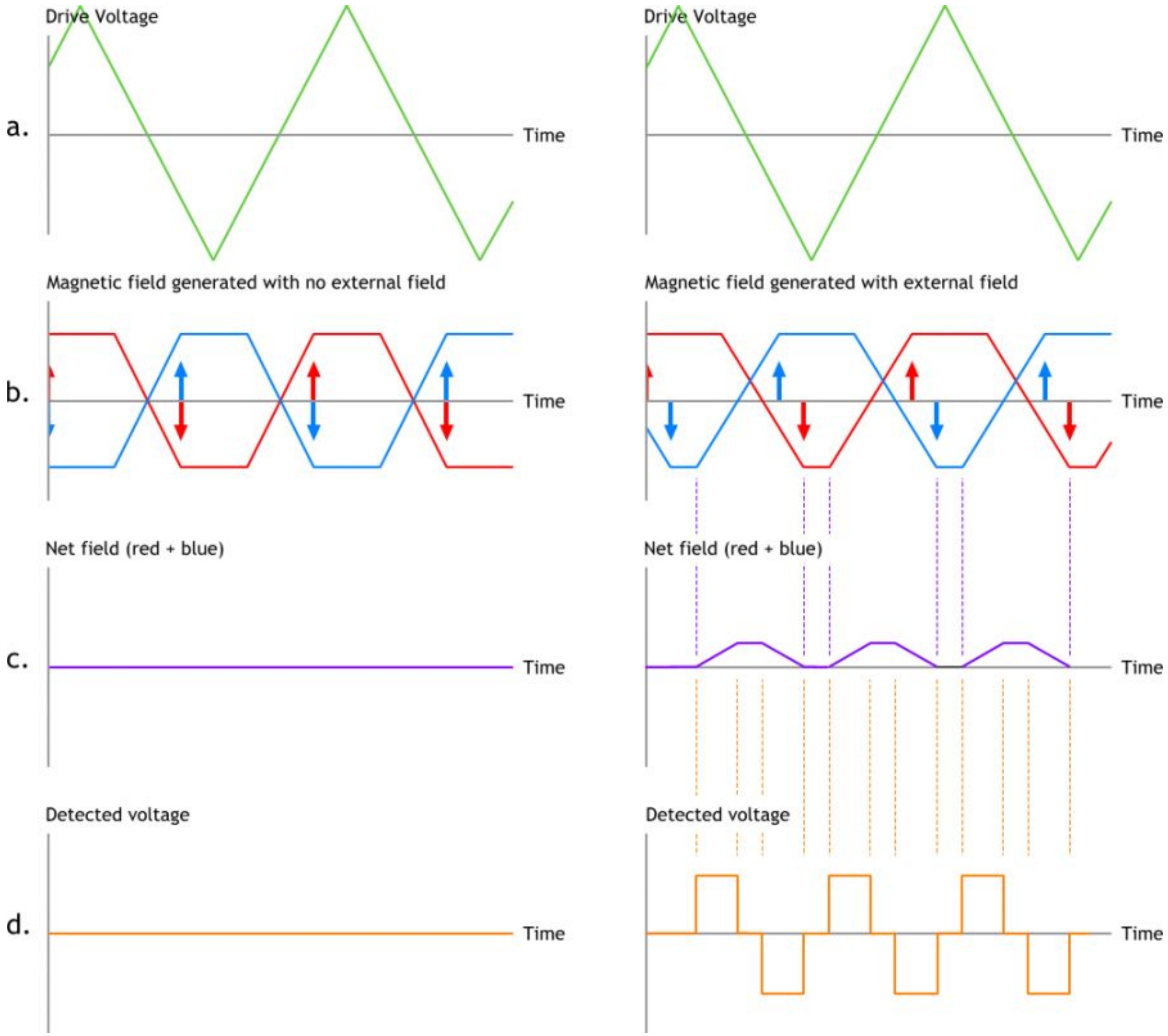
a

c

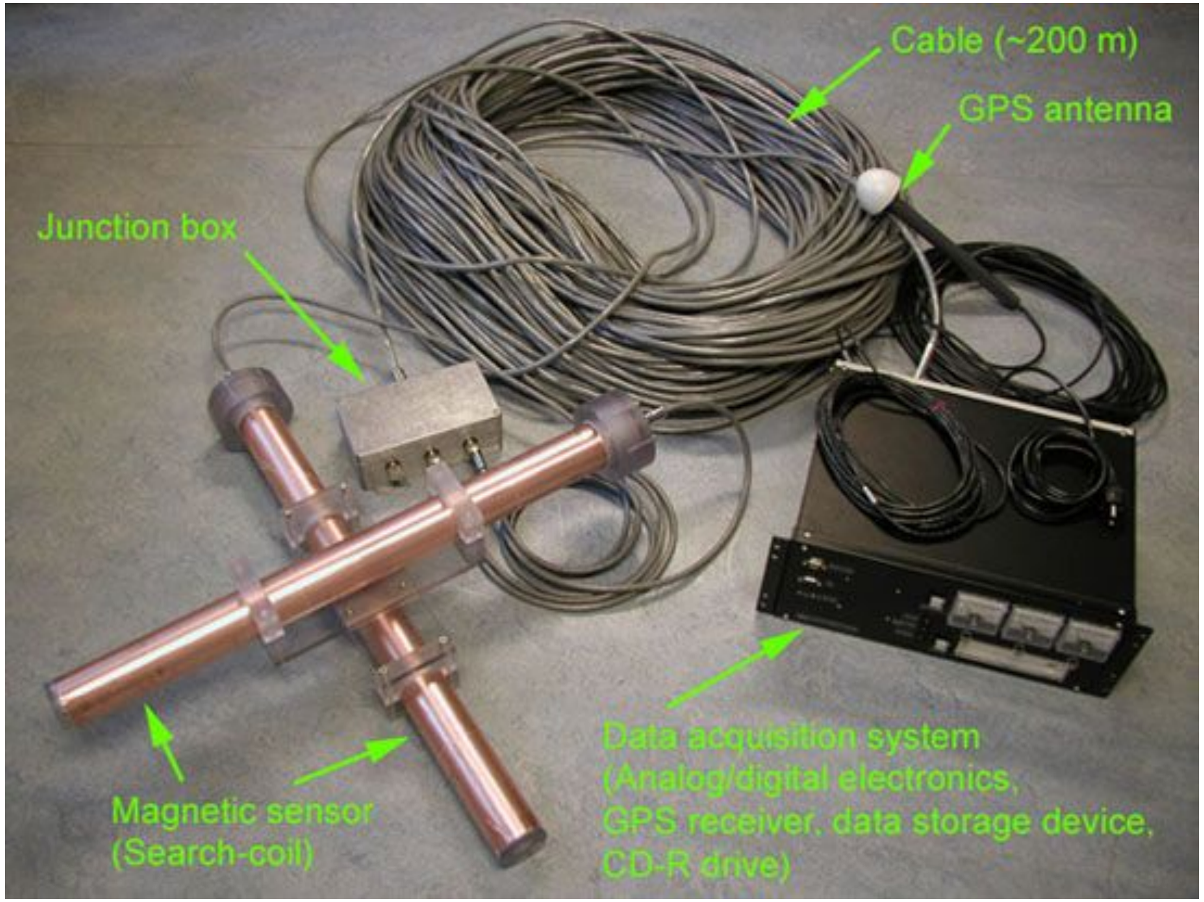
d

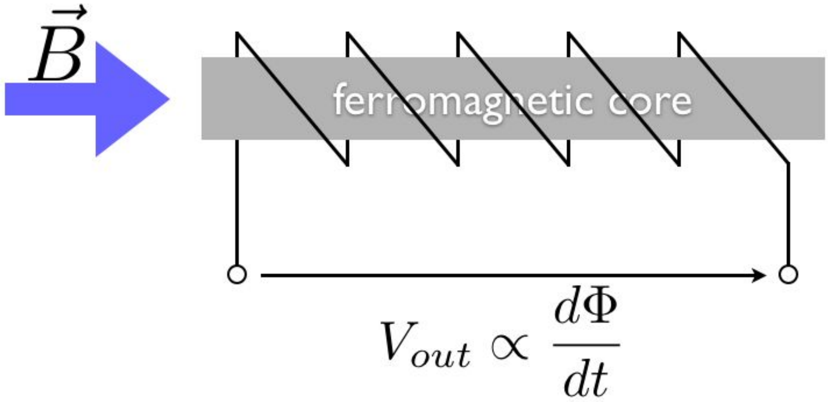
f

In Situ Techniques: Magnetic Field - Fluxgate

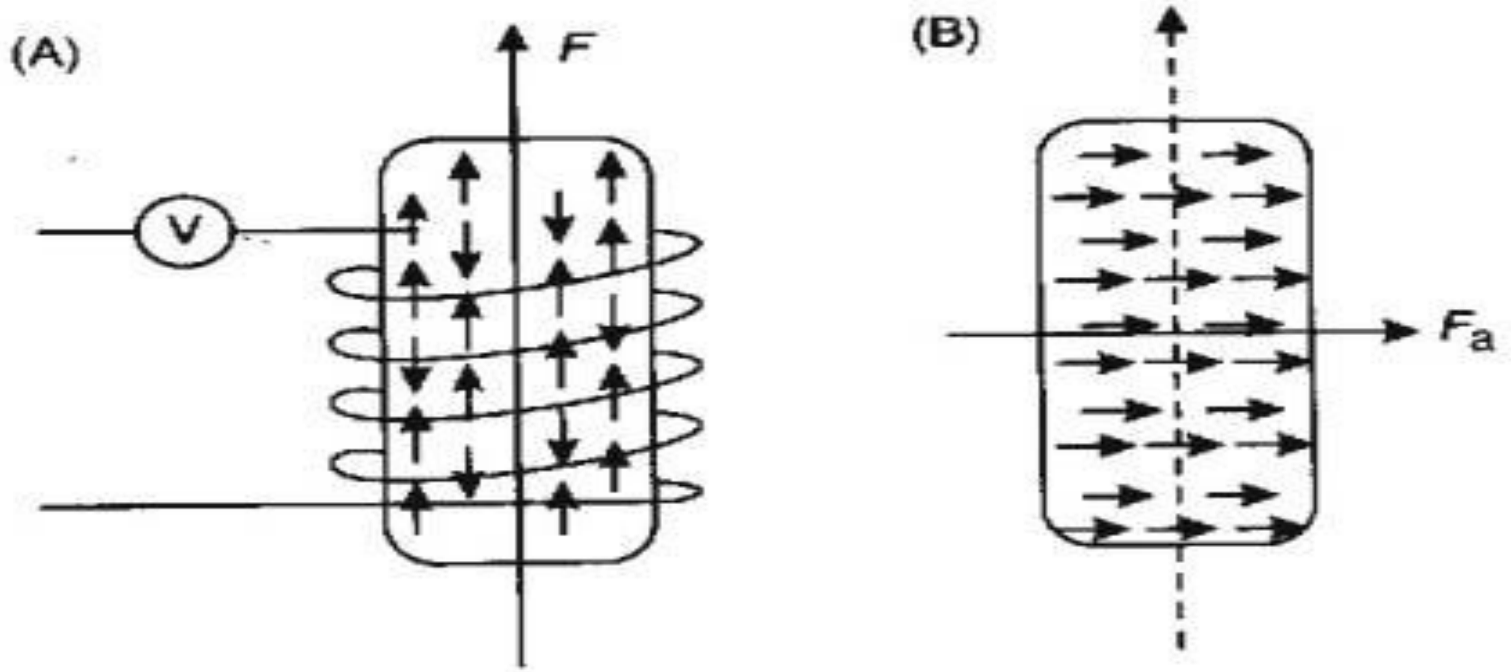


In Situ Techniques: Magnetic Field – Search Coil

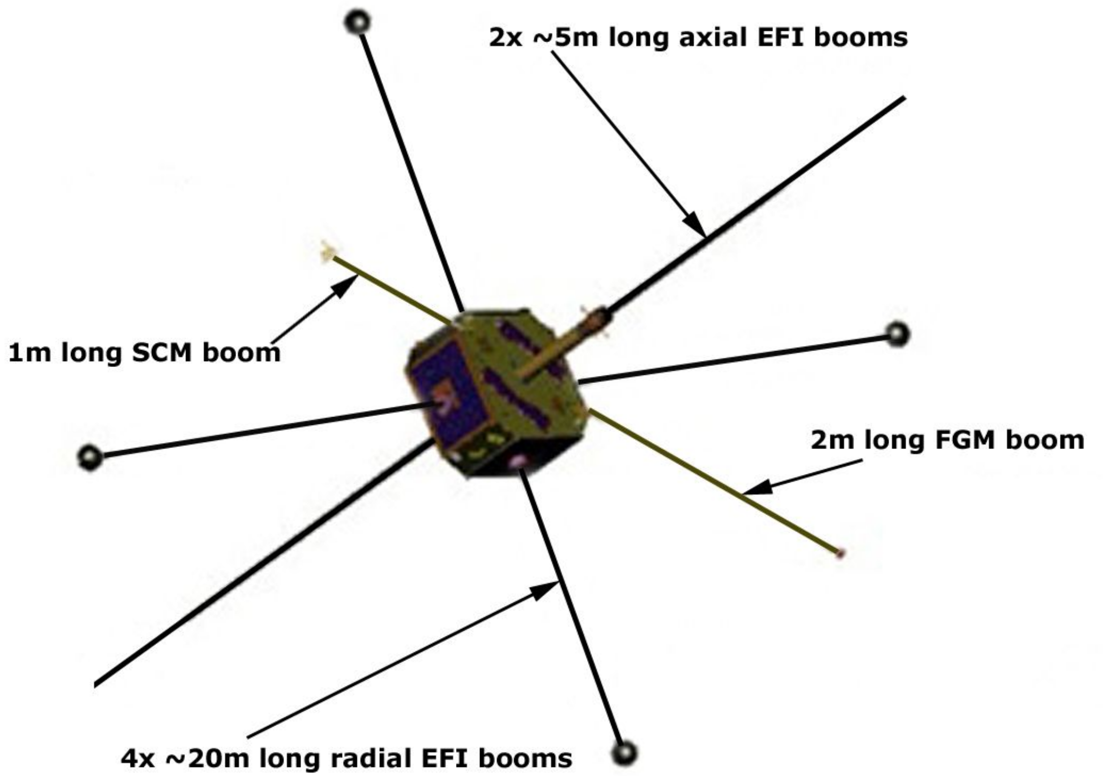


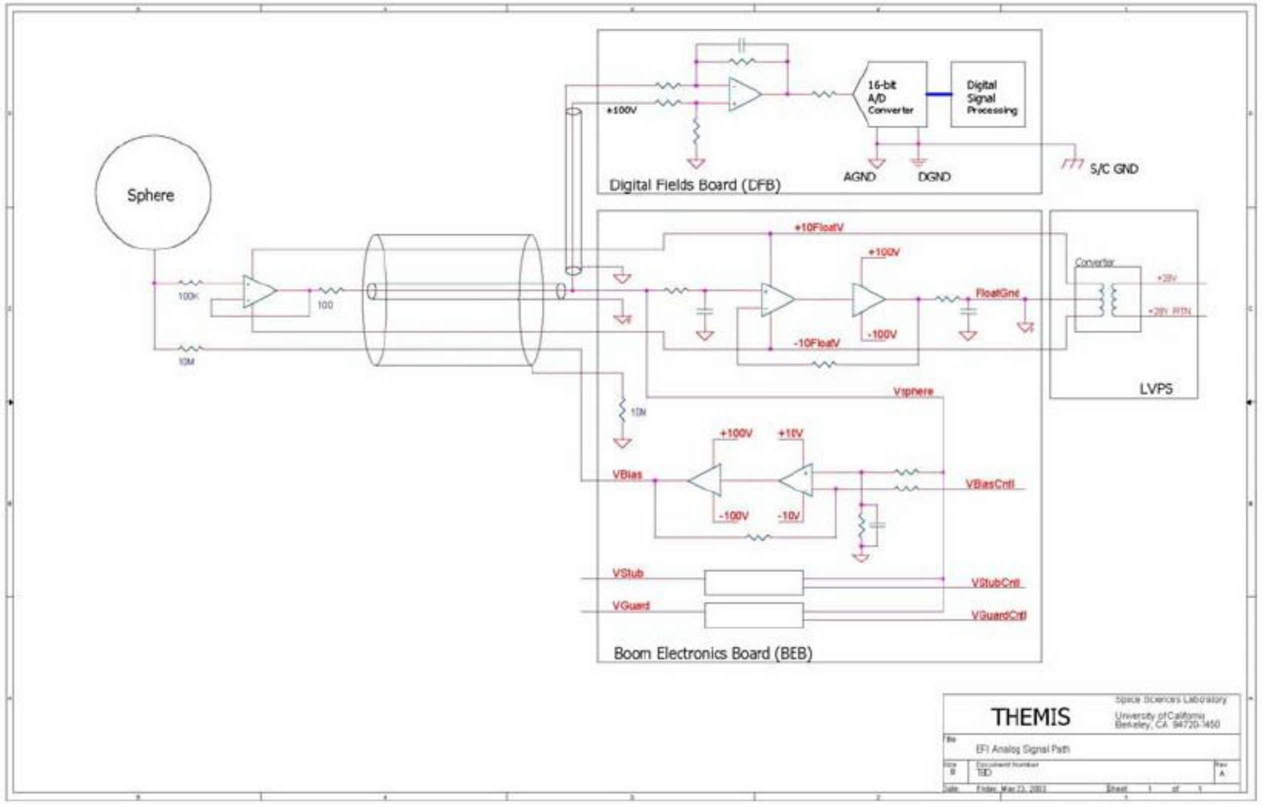


In Situ Techniques: Magnetic Field – Proton Precession

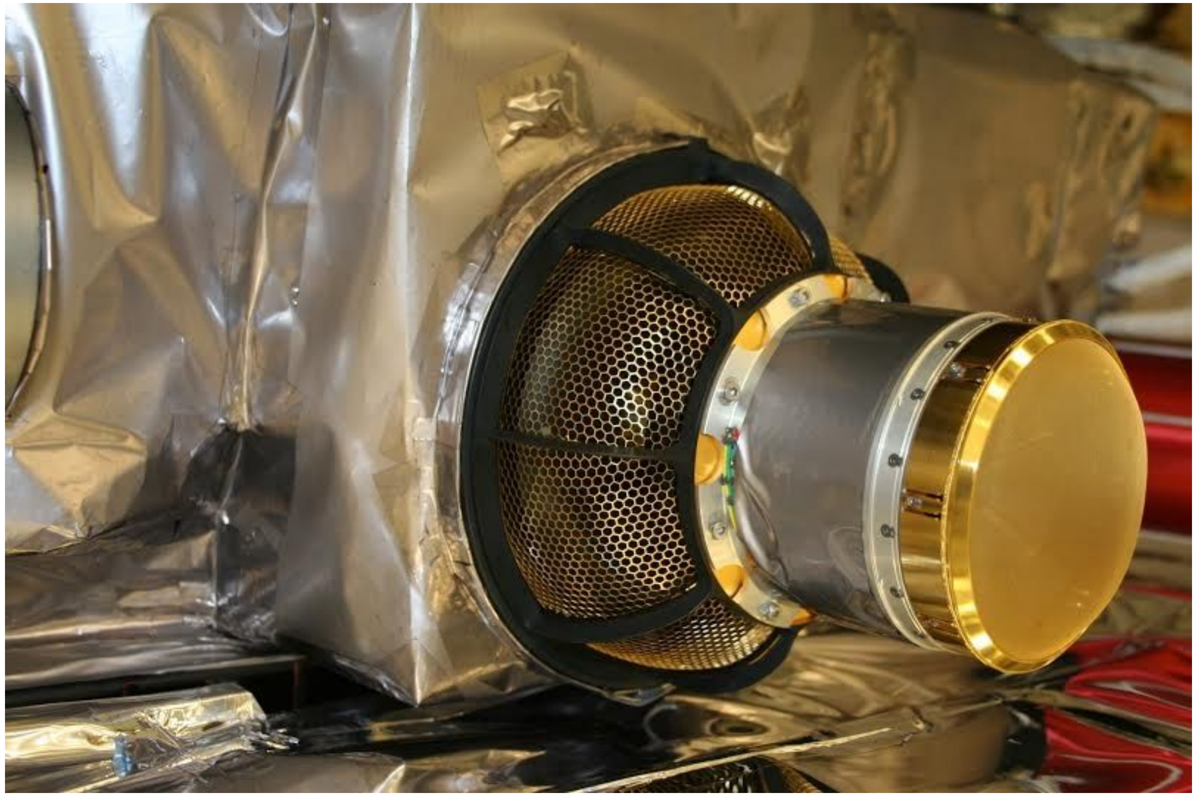


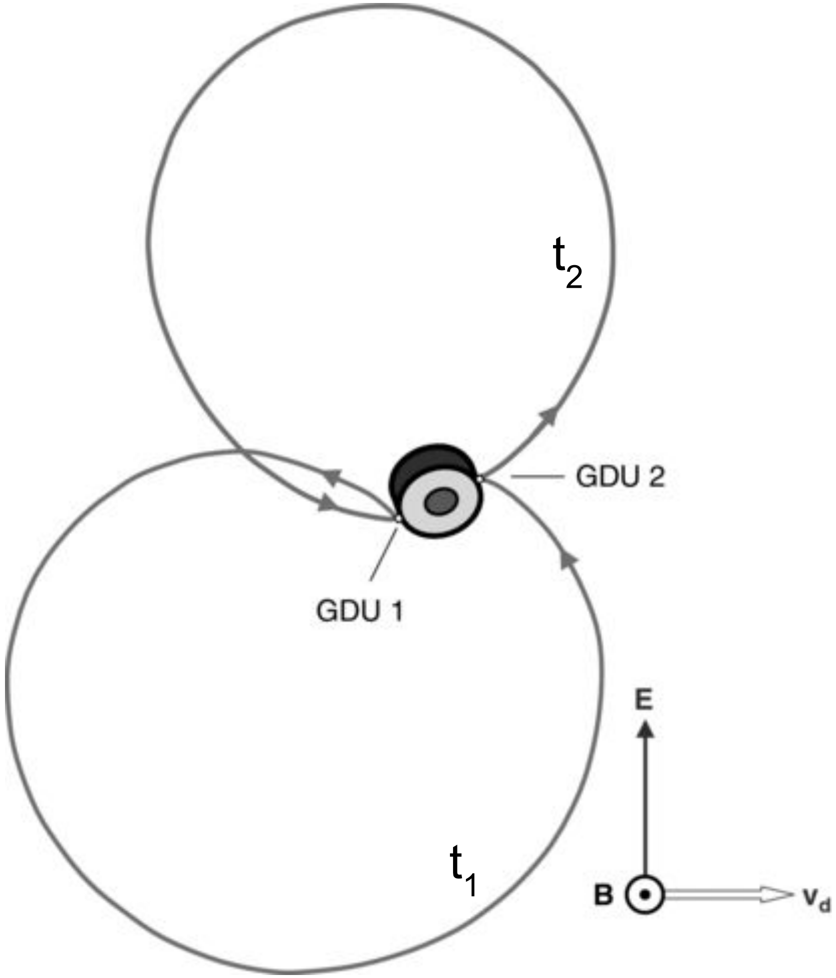
In Situ Techniques: Electric Field Measurements





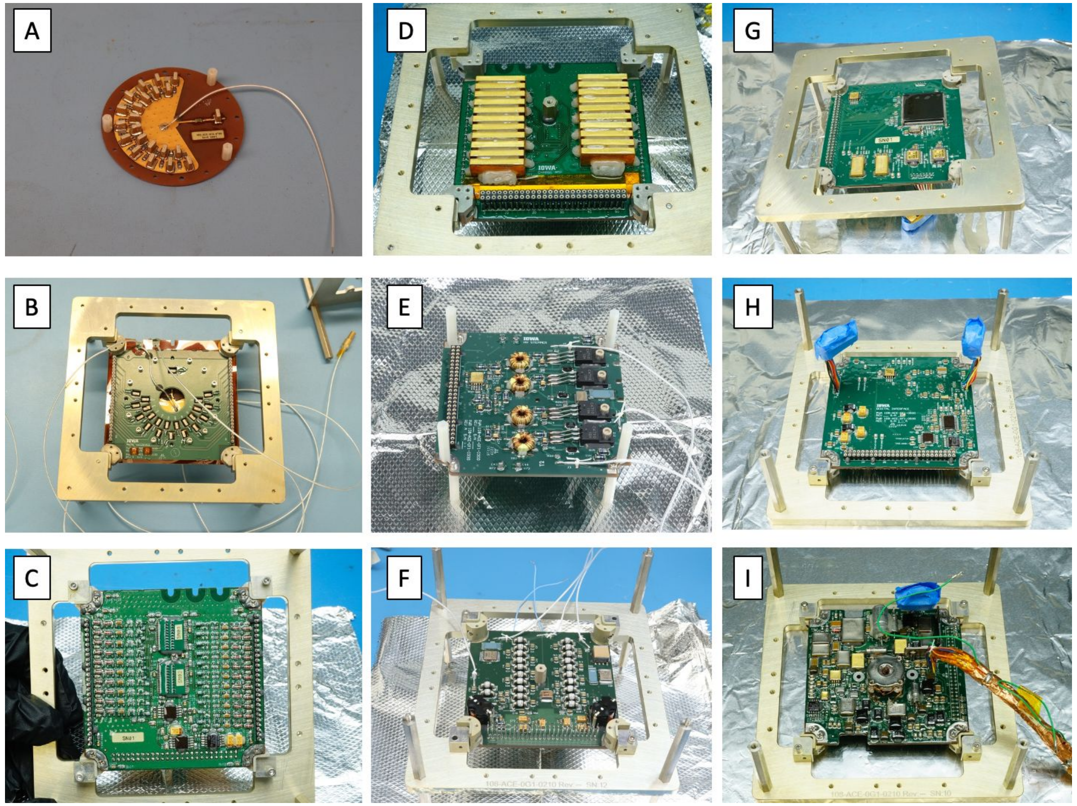
In Situ Techniques: Electric Field Measurements w/ Particles

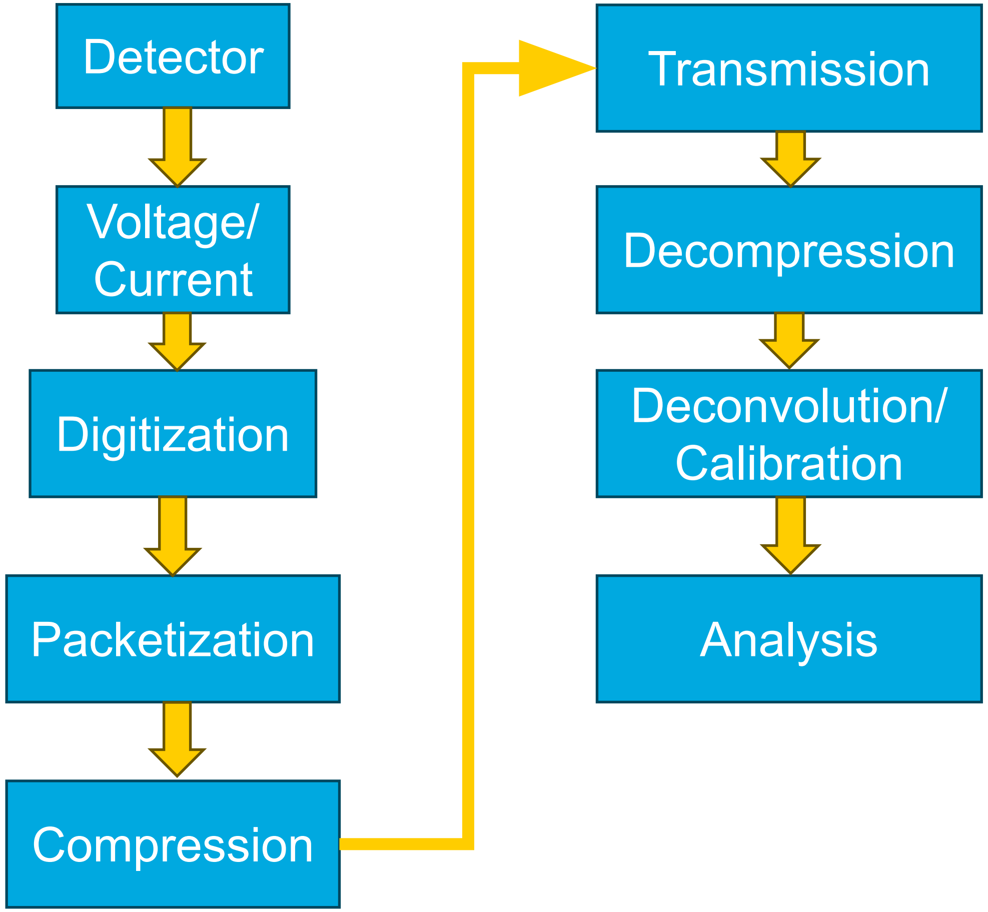




Some Issues

How to Make a Measurement

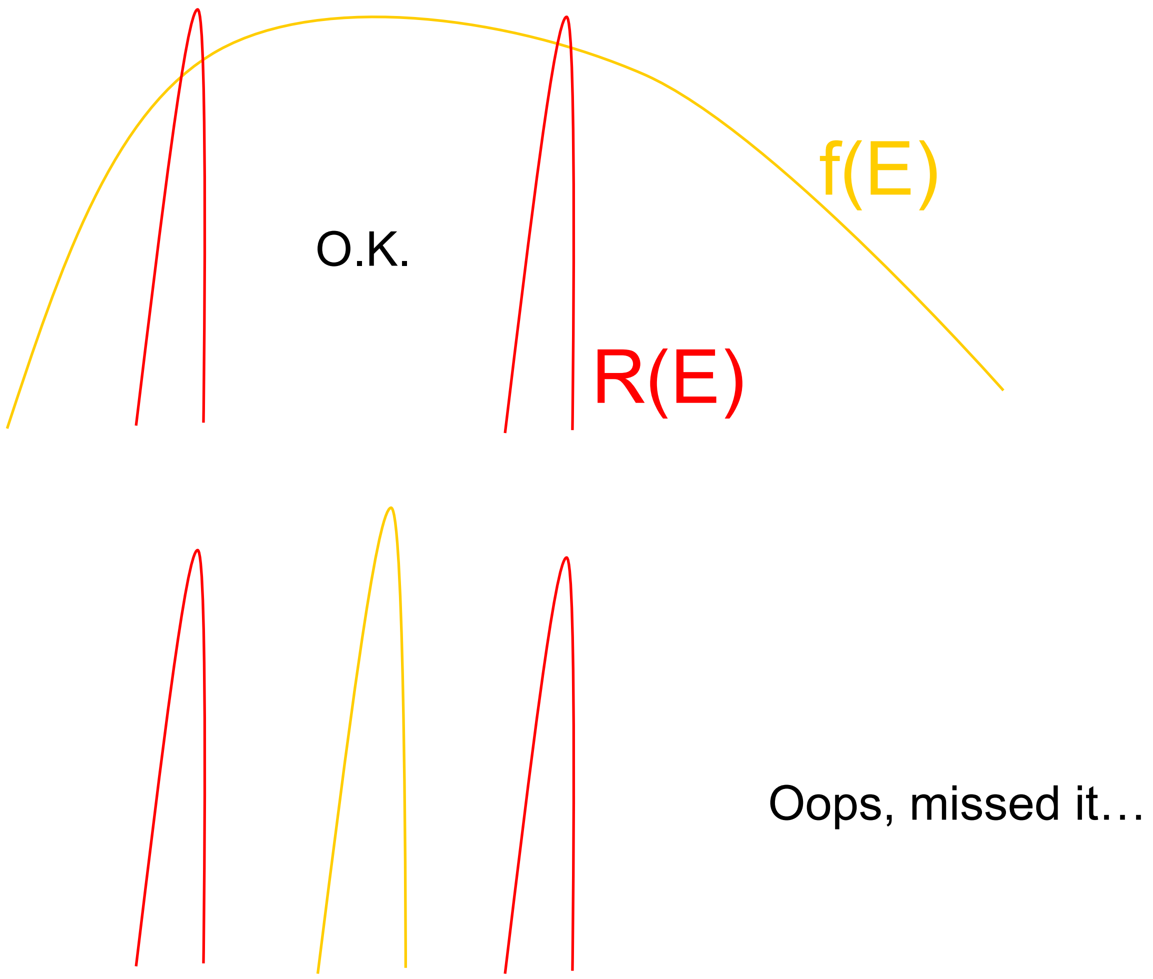




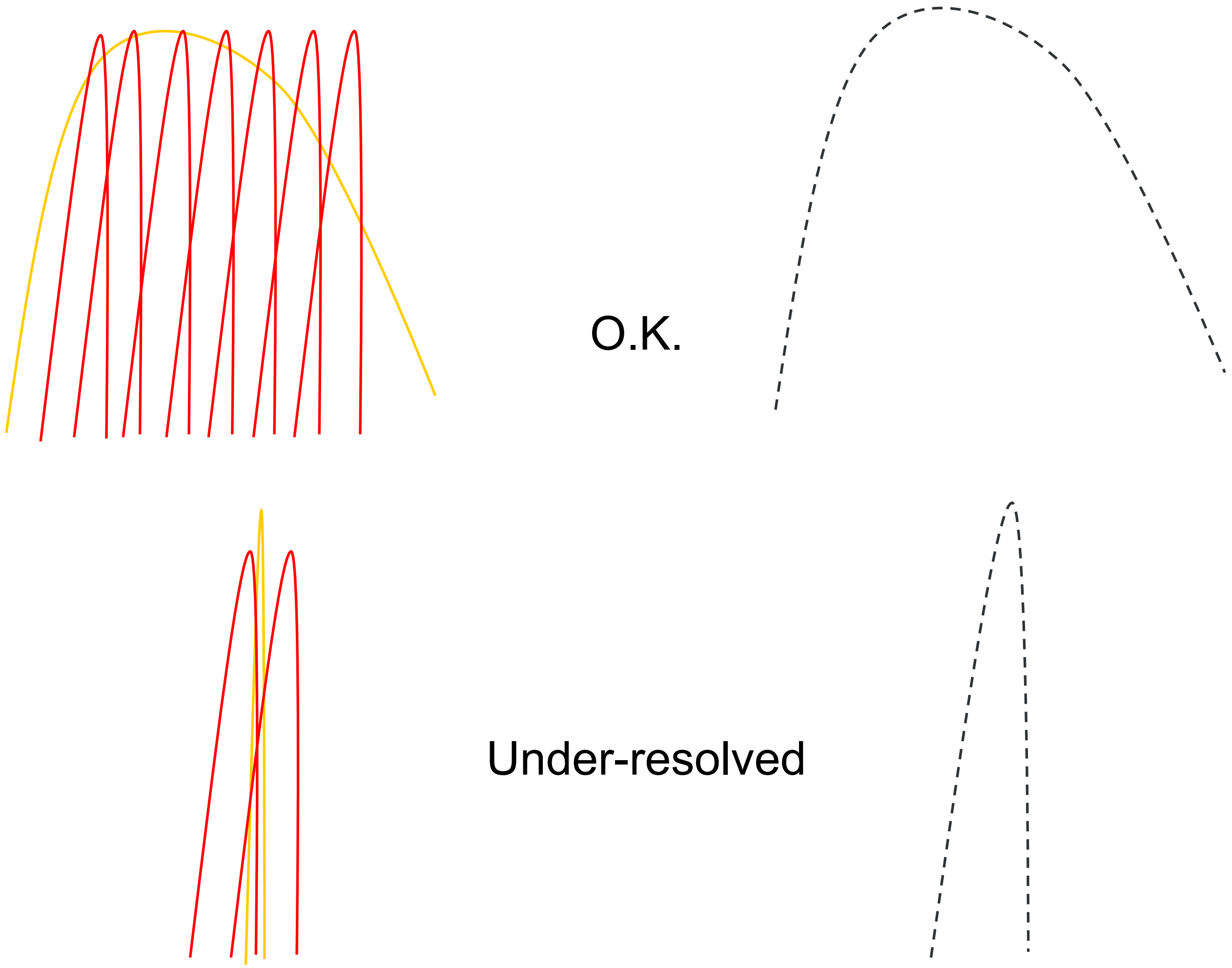
Every step may introduce errors…

IOWA

Sampling Issues

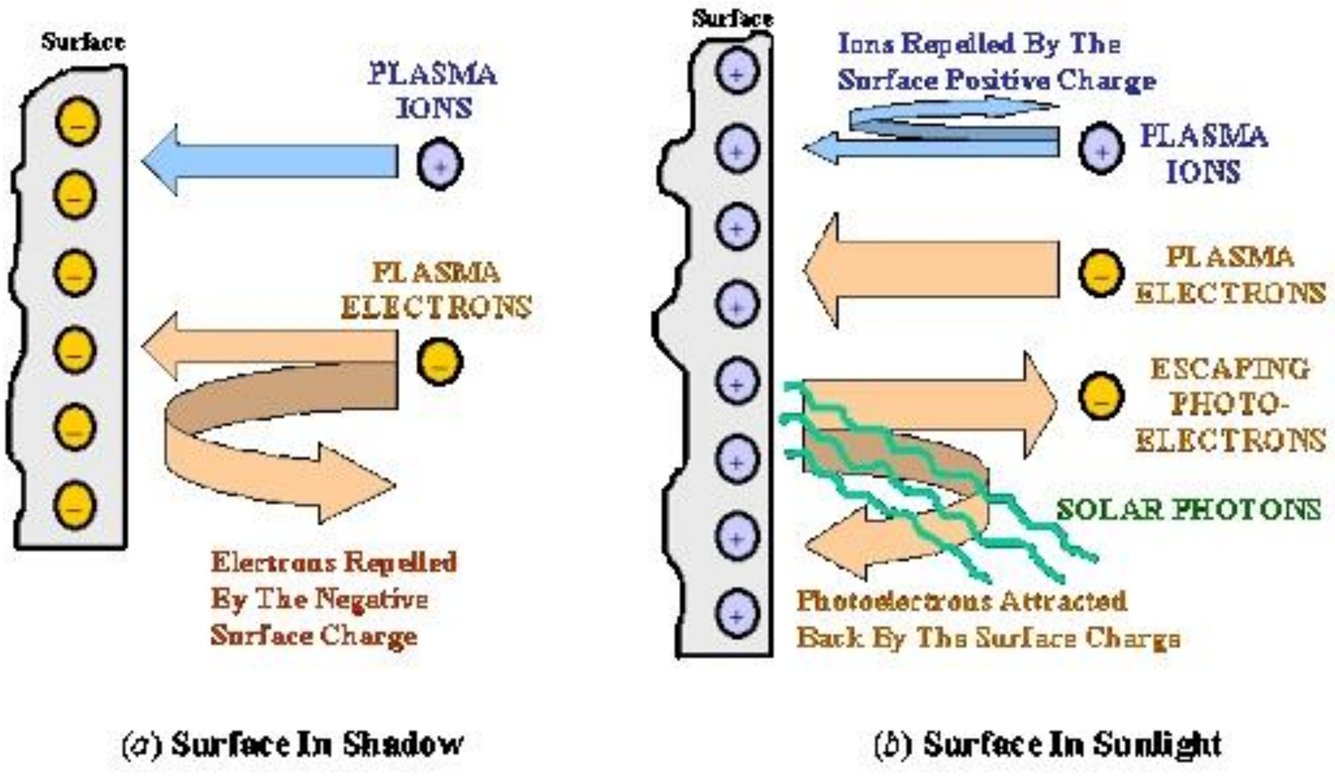


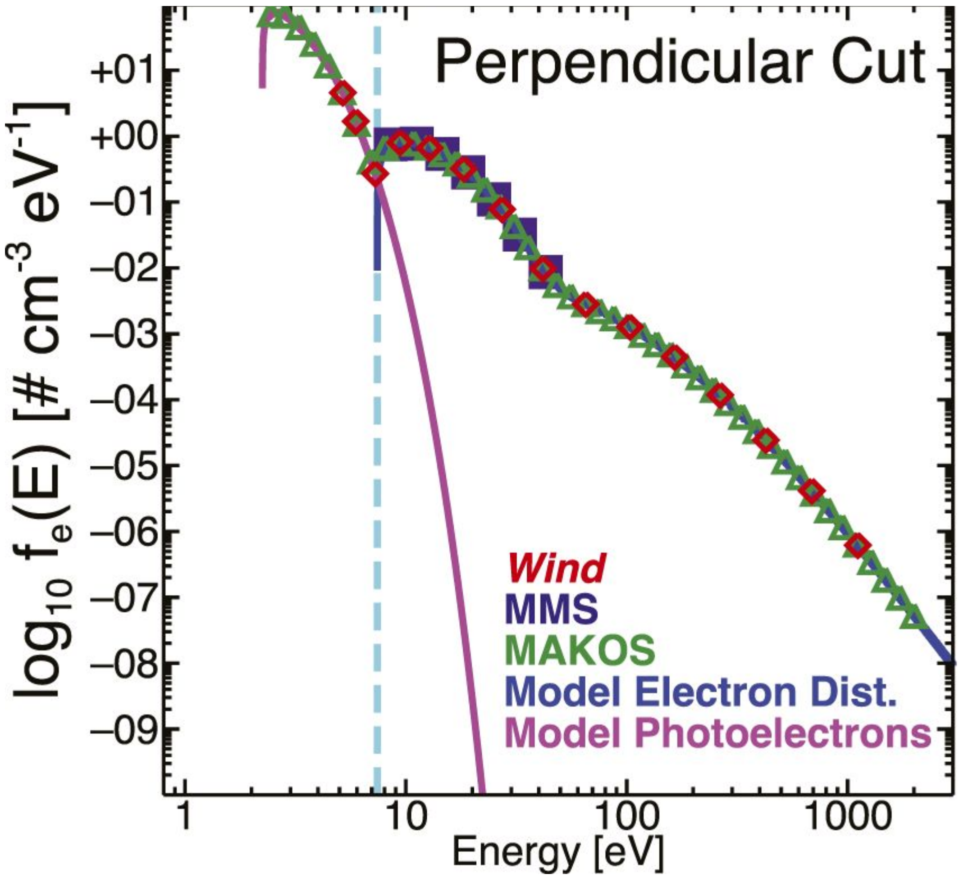
Deconvolution Issues



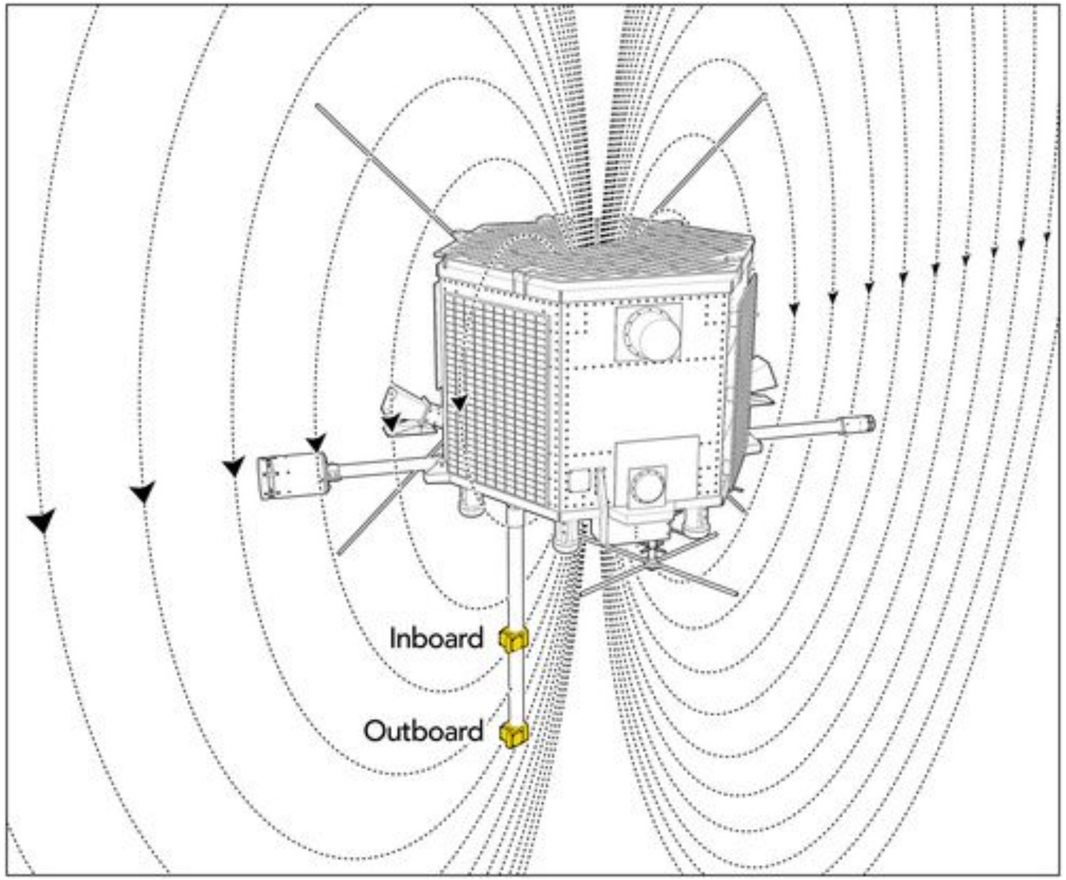
IOWA

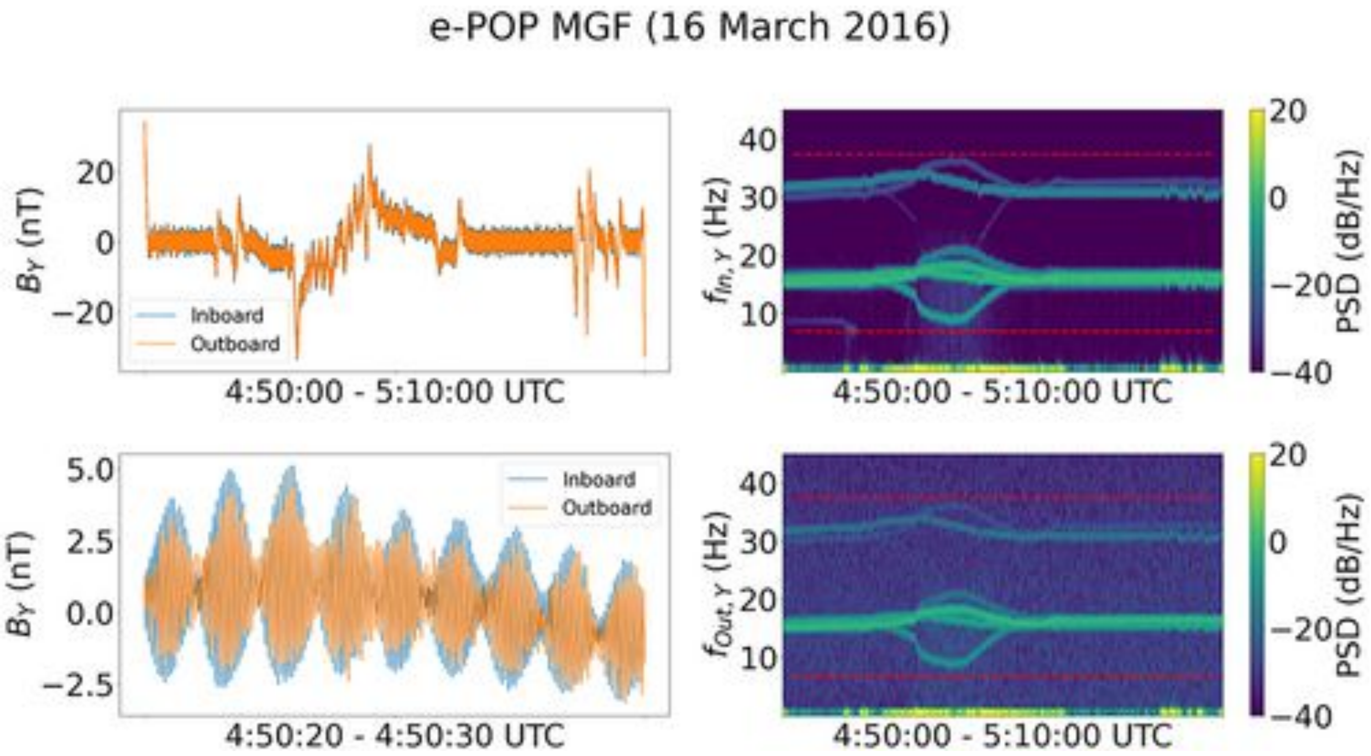
There's a Spacecraft in the Way





There’s a Spacecraft in the Way





Key Takeaways

- The physics of measurement devices can be as complex as the physics of the systems they measure
  - To understand the measurement, you have to understand the device and its limitations
- No measurement device is perfect
  - Limited by sensitivity/dynamic range
  - Limited by finite resolution – in all dimensions
  - Limited by counting statistics
  - Limited by systematic errors, offsets, and/or background
  - Limited by calibration uncertainties
- The measurement platform affects the measurement
  - Every measurement platform produces its own electromagnetic fields
  - Every measurement platform is both a source and a sink of particles
  - The measurement platform affects the surrounding plasma over at least a Debye length, and sometimes more

Backup

The Problem

- Plasma instruments do not measure the distribution function

- Plasma instruments usually measure something related to flux
  - Typical observable:
    - Number of particles entering aperture with area A per measurement period T
    - Normalize by A, T to get flux $J = \#/[cm^2\ s]$

Differential Measurements

- Charged particle measurements are differential
  - We only measure part of the distribution at a time
- Measurement are often stated in terms of differential energy flux [dJ_E/dE]:
  - $eV/[cm^2\ s\ sr\ eV]$
  - Count Rate = #/s = $dJ_E/dE * A * \Delta E/E * \Delta\Omega = G*dJ_E/dE$
  - G = Geometric Factor [units of area]

Converting Units

- Measured flux $J = n\langle \mathbf{v \cdot dA} \rangle = \text{int}\, [f(v)\, \mathbf{v \cdot dA}\, d^3\mathbf{v}] = \#/(cm^2\, s)$

- $\mathbf{v \cdot dA}\;\; d^3\mathbf{v} = \mathbf{v \cdot dA}\;\; v^2 dv \sin\theta\, d\theta\, d\varphi = v^3 dA\, dv\, d\Omega$
- $E = \frac{1}{2} mv^2 \Rightarrow mv\, dv = dE$
- $v^3 dA\, dv\, d\Omega = 2E/m^* dE/m\; dA\, d\Omega = 2E/m^2\; dE\, dA\, d\Omega$

- $J = \text{integral}[f^*2E/m^2\, dE\, dA\, d\Omega]$
- $dJ/dE = f\, {}^*2E/m^2$ [differential in E, Ω, A]
- $dJ_E/dE = f^*2E^2/m^2$