"Charged Particle Detection -- Thermal to GeV-plus"

(Focus on mid-range (keV) Energies)

David, M. Klumpar

Research Professor of Physics

Space Science and Engineering Laboratory

Montana State University

Bozeman, MT

July 31, 2010

Outline

- Motivation and setting the stage -- the tremendous challenge
- Breaking down the problem (somewhat arbitrary)
  - Thermal plasma regime ⟶ briefly
  - Hot plasmas
  - Medium energy particles
  - Very high energy particles ⟶ briefly
- Fundamentals of particle detection:
  - Electric and magnetic fields
  - Interactions with matter
- The Meat: Particle detection from ~1 keV to ~100 keV
  - Hot plasmas (non-thermal)
  - Accelerated Particles (plasmasheet, auroral regions, etc)
- Engineering challenges
- Homework Problems

Setting the stage

- The task is to identify: At an arbitrary point is space, how are the plasmas and charged particles at that location distributed, accelerated, and lost; where have they come from, … going to, and what is their "history"

- In what ways are the charged particles interacting with their surroundings (collisions -- or not?; wave/particle energy exchange?, etc)

- and … How are these characteristics varying in time and in space?

What needs to be learned to fully characterize the particle environment?

- How many particles are there?

- What directions are they coming from?

- What is their distribution in energy?

- What is the sign of their charge?

- What are their charge states (for positive ions)?

- What is their species distribution (for positive ions)?

- How are they varying in time and space (separately!!)

The charged particle environment in space:
- electrons (e^-)
- protons (p^+)
- positive ions
  - elemental composition (H, He, O, N, …Fe)
  - isotopic composition (e.g. He, He3, He4
  - charge states (e.g. O^+, O^{++}, … O^{6+})

The particle environment is fully described by the particle distribution function, or phase space density (Ref.Text Vol II pg 46)

Distribution function or *phase space density(f):*

$$f(\boldsymbol{v},q,m) = f(v,\theta,\phi,q,m) = d^6 n(\boldsymbol{v},q,m)/d^3\boldsymbol{x}d^3\boldsymbol{v} \qquad (s^3/km^6)$$

The right hand side is the number of particles with charge=q, mass=m, and velocity=$\boldsymbol{v}$ per unit volume in space and per unit volume in velocity space.

Practically speaking: We count the number of particles impinging on our detector during a chosen time interval. Ideally, we look in a specific direction. We use some clever techniques (to be described) to select a particular mass, charge, and energy.

What we receive on the ground is the number counts the detector registered, coming from that instantaneous direction in each measurement interval for the selected m, q, and v.

getting the data -- continued

So we have raw counts that depend on the size of our detector (aperture), its angular field-of-view, and the detection efficiency (a number between 0 and 1), which may be a function of energy, angle-of-arrival, mass, etc). The count rate is thus:

$$dR(E, q, m)/dt$$

To get rid of instrumental characteristics, we want calculate a quantity that is independent of the instrument. We are usually interested in the differential intensity at each energy ($E=mv^2/2$) between E and E+dE is:

$$dj/dE=[dR(E, q, m) / dt]/[dS \, d\Omega \, dE]$$

where $d\Omega$ is the solid angle, and dS is the aperture area.

The units are: particles/(cm^2 s sr keV). Now we've described how many particles per second of each type are crossing a unit area at our instantaneous location coming from a specific set of directions having energy between E and E + dE. We do this for as much of the energy range as our instrument is good for.

(Ref.:Gloeckler,"Text", Vol II -- section 3.2)

The challenge is (at first glance) stupefying!!

- The energy regime to be covered, from cold plasma to the most energetic Cosmic Rays is very broad: -- effectively from 0.01 eV to 10^{20} eV (22 orders of magnitude, or more!)

- The intensity range is equally broad: (in terms of particle density) from ***cm^{-3} to ***cm^{-3}

- No single instrument, no single technique can cover the range of energies and intensities required to fully characterize the particle environment.

- Fortunately nature is, to zeroth-order, somewhat well-behaved

Getting a handle on it.

- Break the problem down
  - Since particle kinetic energy dominates interaction physics; break the problem down -- by energy.
  - Use the well-established physics of particle interactions with matter and with electric and magnetic fields to guide the measurement approach.
    - At the lowest energies measure the bulk properties.
      - collect current (e.g. by biasing a probe)
      - utilize interactions between the plasma and electromagnetic waves (either directly or indirectly)
      - spacecraft velocity creates a bulk flow in the frame of the detector (another form of biased collector)
    - At Suprathermal Energies (tens to hundreds of eV to ~100 keV)
      - use electric or magnetic fields to push (guide) the particles around, separating them by charge sign etc
      - use atomic or molecular-level interactions in matter to detect the particles.
    - At high energies and very high energies (hundreds of kev to 10^{20} eV)
      - rely upon nuclear interactions with matter.

A Common Data Display:
The color spectrogram

- Large quantities of data require comprehensive display techniques

- "A picture is worth a thousand words" (or a million numbers)

- Time on horizontal axis

- Intensity represented by color

- energy, or pitch angle, on vertical axis

FAST ORBIT 1616
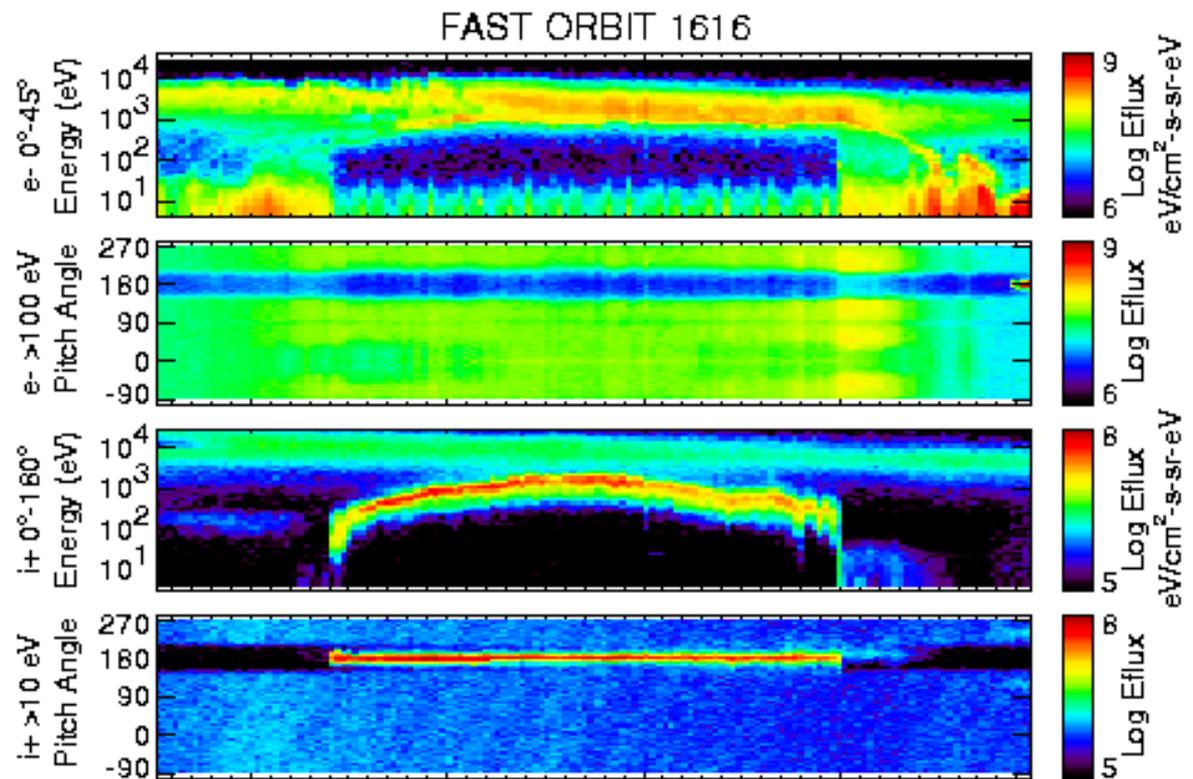
Universal Time (~45 seconds)

(Ref.: J. McFadden, 1998

Energy spectrum display

What characteristics of the natural universe can be counted on?

A "universal" energy spectrum here???

- The highest intensities occur at the lowest energies (with many exceptions).
- At the lowest energies bulk behavior dominates (measure fluid properties):
  - Temperature, density, bulk flow, departures from purely statistical distribution.
- At intermediate energies
  - departures from bulk dynamics begin to dominate, ***
- At highest energies the flux is very low
  - individual particles are "captured" and analyzed "one-by one".

Cosmic Ray Spectrum

(1 particle per m²-second)

Knee
(1 particle per m²-year)

Ankle
(1 particle per km²-year)
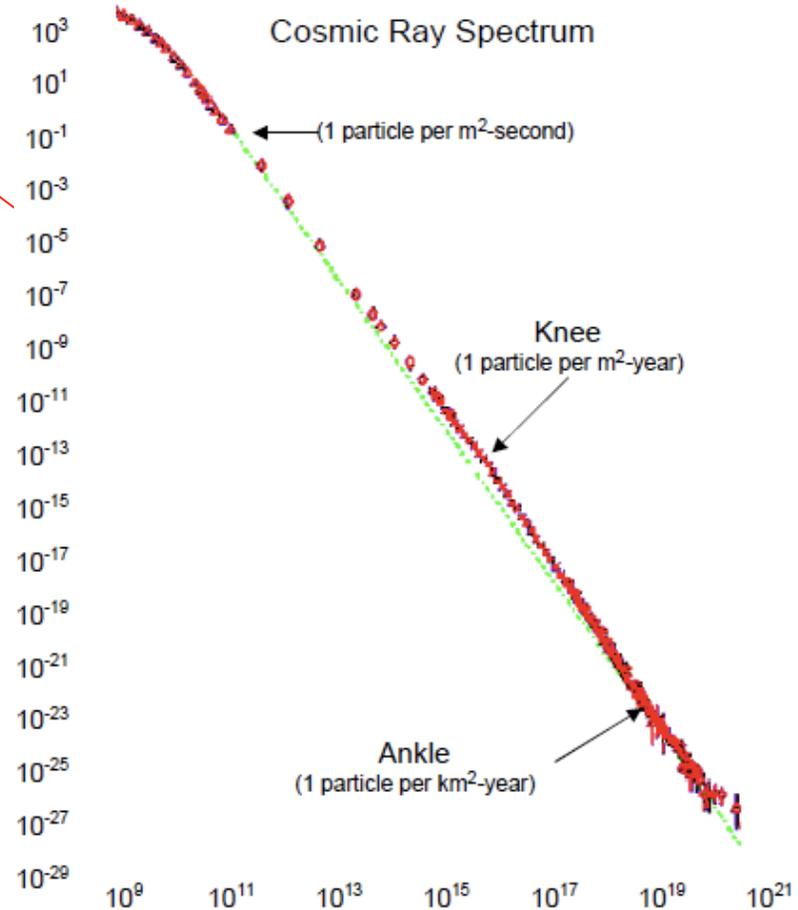
At the lowest energies: Cold/Thermal Plasmas

- Current collectors
  - Langmuir Probe
  - Faraday Cup
  - Retarding Potential Analyzers
- Utilize direct interaction with electromagnetic waves
  - RF probe
    - Launch a wave, see what happens
  - RF sounder
    - Sweep a transmitter over broad frequency regime.
    - Receive signals reflected from distant plasma boundaries.
    - Measure return times.

- Indirect interaction with electromagneitc waves

At the lowest energies: Cold/Thermal Plasmas -- More

- Direct interaction with electromagnetic waves
  - Topside Sounder
  - RF stimulation

- Indirect interaction with electromagnetic waves

-

Basic Langmuir Probe Operation

(The plasma has sufficient density that an electric current (nano-amps) can be drawn from the plasma.) Measure plasma parameters (density, $\Delta n/n$, temperature)

Basic Circuit

Current-Voltage Curve
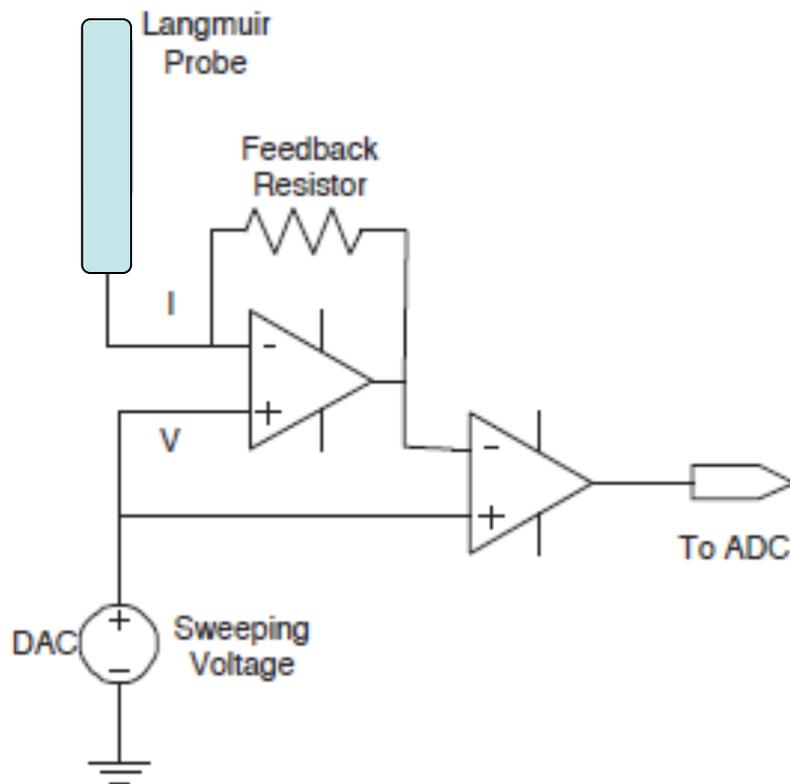
Cassini Langmuir Probe. Courtesy of Swedish Institute of Space Physics
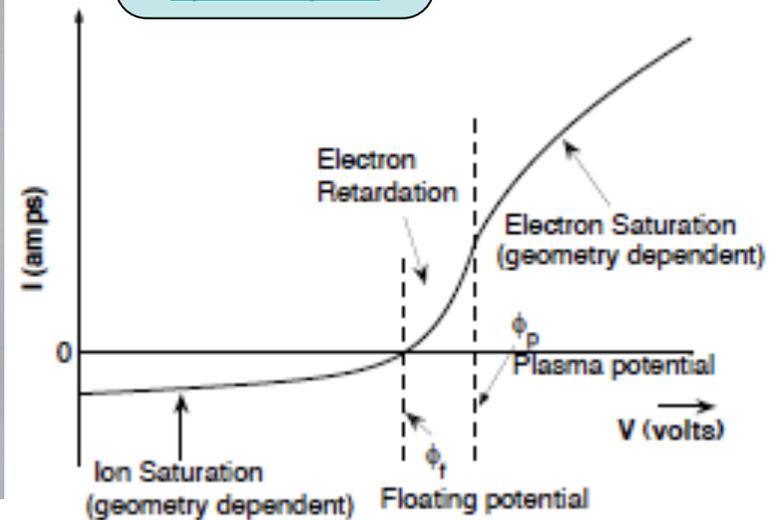
(Ref.:A. Barjatya,PhD thesis, 2007

The lowest energy particles- Continued
The Retarding Potential Analyzer

Retarding Potential Analyzer

Modulator Voltage

Aperture Stop

Modulator

$\frac{1}{2}mv_\perp^2 < qV_1$

$qV_1 < \frac{1}{2}mv_\perp^2 < qV_2$

$\frac{1}{2}mv_\perp^2 > qV_2$

Modulator Assembly

- The RPA consists of three highly transparent metal grids, an aperture stop (to define the acceptance geometry) and support structure

- It is a simple device with a large acceptance area and geometrical factor

- Its disadvantage are

  - upper energy range is limited to ~6 to 8 keV/e

  - UV suppression is very difficult

- The energy of incoming ions is determined by applying to the central metal grid a time-varying, dc-biased square wave potential that varies from V_1 to $V_1 + \Delta V$ (V and ΔV can be changed)

- Ions with 'perpendicular' energies, $mv^2_\perp < 2qV_1$, are rejected, those with $mv^2_\perp > 2q(V_1 + \Delta V)$ are accepted and ions with energies in between are either accept or reject depending on whether the modulating voltage is in its high or low step

The characteristics of charged particles that render them detectable:

- They are charged --> therefore they can be pushed around or guided by electric and magnetic fields.
- They can carry a current.
- They have kinetic energy and momentum
- They can interact with matter through:
    - Collisions with matter
    - Energy loss
    - ionization or charge exchange

Particle Motion in Electric and Magnetic Fields

- Consider a uniform electric field. The force on a particle is:

- **F** = q**E** (q is the charge, **E** is the field strength)
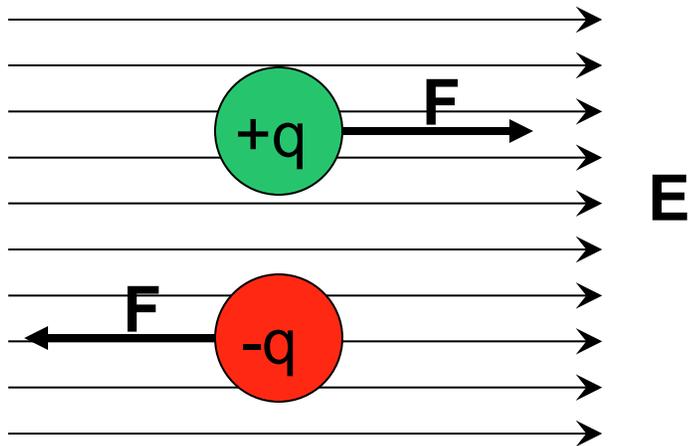
- In a uniform magnetic field the force is

- **F** = q (**v** x **B**) (v is velocity, B is magnetic field strength)
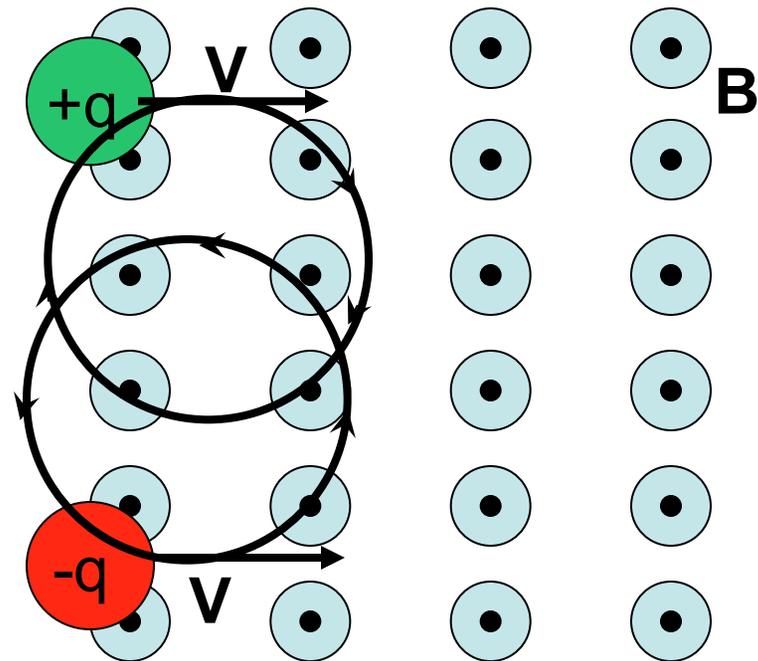
Particle Motion in Electric and Magnetic Fields

- Consider a uniform electric field. The force on a particle is:

- **F** = q**E** (q is the charge, **E** is the field strength)

- In a uniform magnetic field the force is

- **F** = q (**v** x **B**) (v is velocity, B is magnetic field strength)

Particle motion in a uniform magnetic field

So if the incident velocity is much higher, what happens?

The radius of the circular motion increases. We call this the gyroradius.

$mv^2/r = qvB$; ==> $r = mv^2/qvB$

note $r = mv/qB$ (momentum)

- What happens to the kinetic energy of the particle?

- In a uniform magnetic field the force is
- **F** = q (**v** x **B**) (v is velocity, B is magnetic field strength)
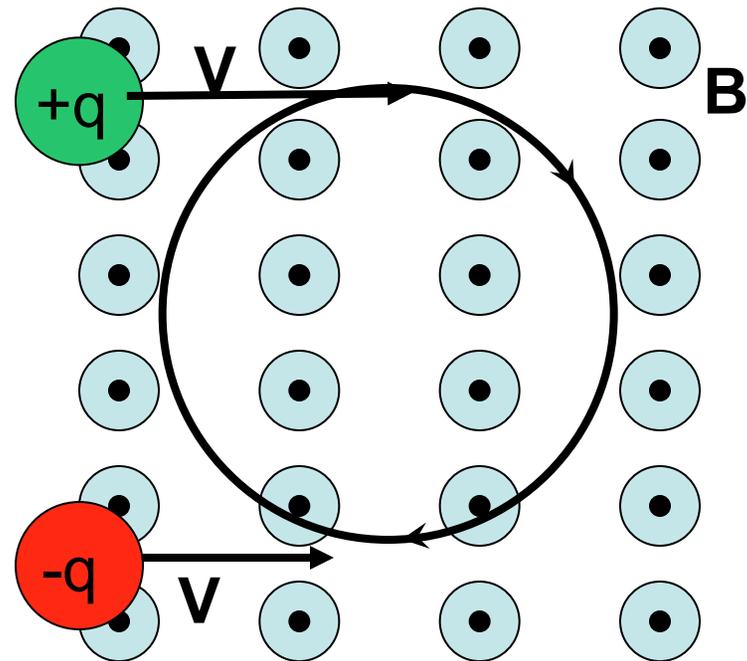
The concept of pitch angle

Interactions of energetic particles with matter

Energetic Particle

E_{in}

ion

e^-

e^-

e^-

e^-

ion

E_{out}
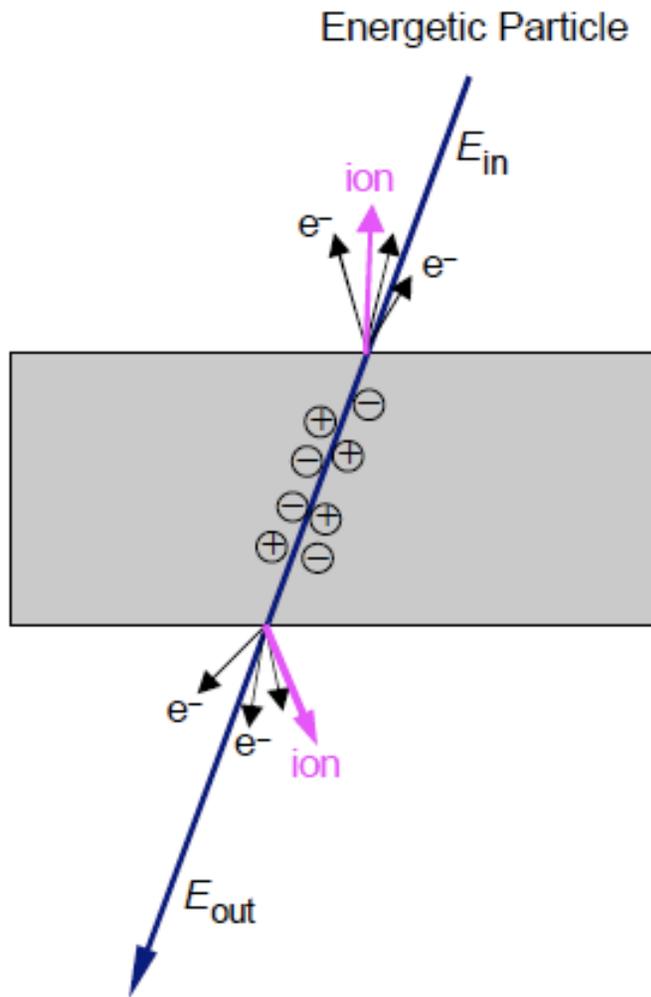
- An energetic particle (or photon) passing through a slab of material gives up some of its energy to eject electrons and ions from the surfaces of the slab

- Furthermore they ionize or excite some of the atoms or molecules of the material, or create charge carriers

- In this process they lose some or all (if they stop in the slab) of their energy

- This loss of energy is called *energy loss by ionization*

(Ref.:Gloeckler,"Text", Vol II -- section 3.4

Scintillation detector illustrates one use of interactions with matter (w/o using electric or magnetic fields)

- An energetic particle passing through a *scintillator* material excites atoms that then emit light as they decay to their ground states

- The light is then converted to an electrical signal that is amplified and recorded

- The scintillation material may be a solid, a liquid, or even a gas and the device converting light into an electrical signal is generally a photomultiplier tube, although in some applications photo-diodes (essentially thin window SSDs) are used
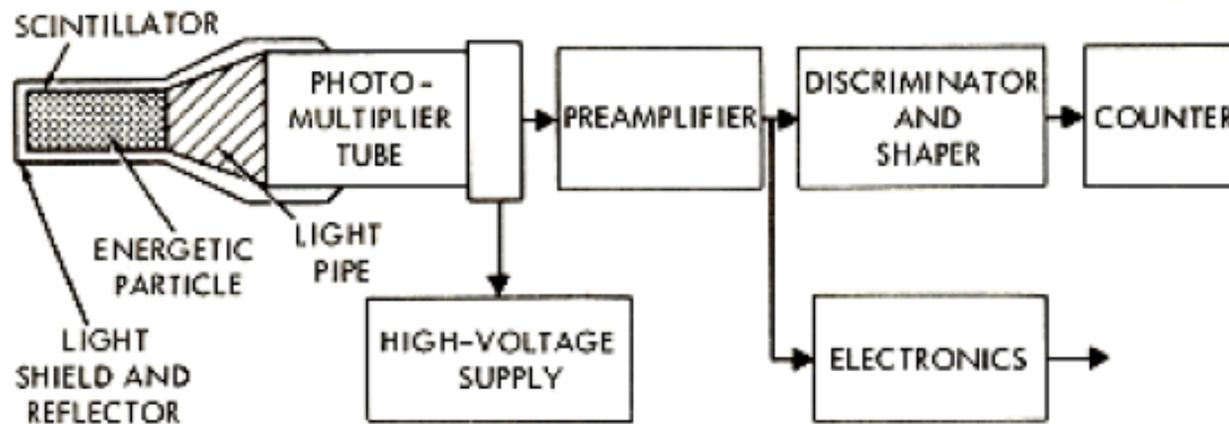
(Ref.:Gloeckler,"Text", Vol II -- section 3.5.5

Simple particle detectors that make use of interactions with matter

- Gas-filled counters
  - Geiger Tube
  - Ionization Chambers
  - Proportional counters
- Channeltron
- Microchannel Plate
- Solid State Detector
- Scintillation Detector
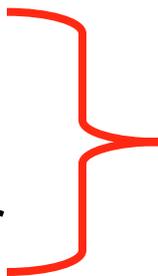
These three sensors are frequently used in combination withcomplex analyzer systems as the final sensor element

These are all covered pretty well in your textbook (Chapter 3). I'll only make a few remarks today about the three devices highlighted above, referring you to the text for details.

Channeltron

channel electron multiplier (CEM)

A simple and compact device that detects ~0.1 to ~ 100 keV ions and electrons

When several kilovolts are applied from one end to the other, a single electron produced at the low potential end will be accelerated down the tube and, at every collision with the tube wall, will produce several secondary electrons that continue that process

CEMs are curved to prevent *ion feedback* caused by cascading electrons that ionize some of the residual gas inside the device toward the high potential end of the devices

Positive ions are thus prevented from being accelerated toward the low potential input, where they could initiate a new cascade

For a fixed voltage, the gain (10^6 to $> 10^8$) depends on *length to diameter* ratio which sets the number of secondary electron multiplications

The CEM is a small, curved glass tube, ~1 mm inside diameter and several cm long

Inside surface is treated to have
- high resistivity
- large secondary electron yield
- stability when exposed to air

Microchannel Plates
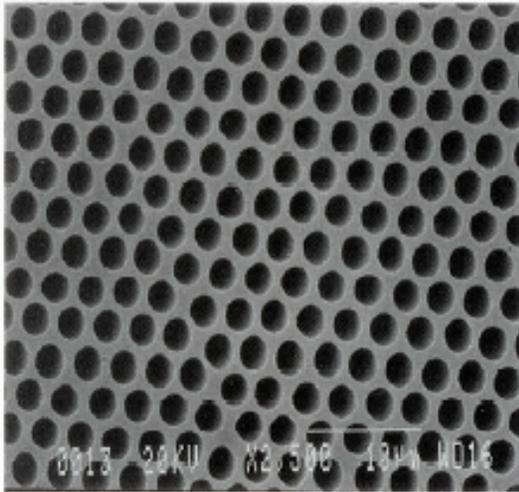
An array of microscopic glass tubes (12 to 25 μm spacing), hexagonally packed and sliced to thin (0.5 to 1.0 mm thick) wafers

Microchannel length to diameter (l/d) ratios range from 40:1 to 80:1

Wafers are treated at high (250-450°C) temperature in a hydrogen atmosphere to produce a resistive coating along the micro channels, and the top and bottom surfaces are metallized

Compact particle or photon detectors with a high signal to noise ratio allowing individual event counting

Low background rates (<1 cm^{-2} s^{-1})

Are often used as position sensing devices

As in CEMs, electron multiplication MCPs is produced by voltage bias across a resistive glass tube that generates an electron cascade through secondary electron production

(Ref.:Gloeckler,"Text", Vol II -- section 3.5.3)

Microchannel plates are often stacked
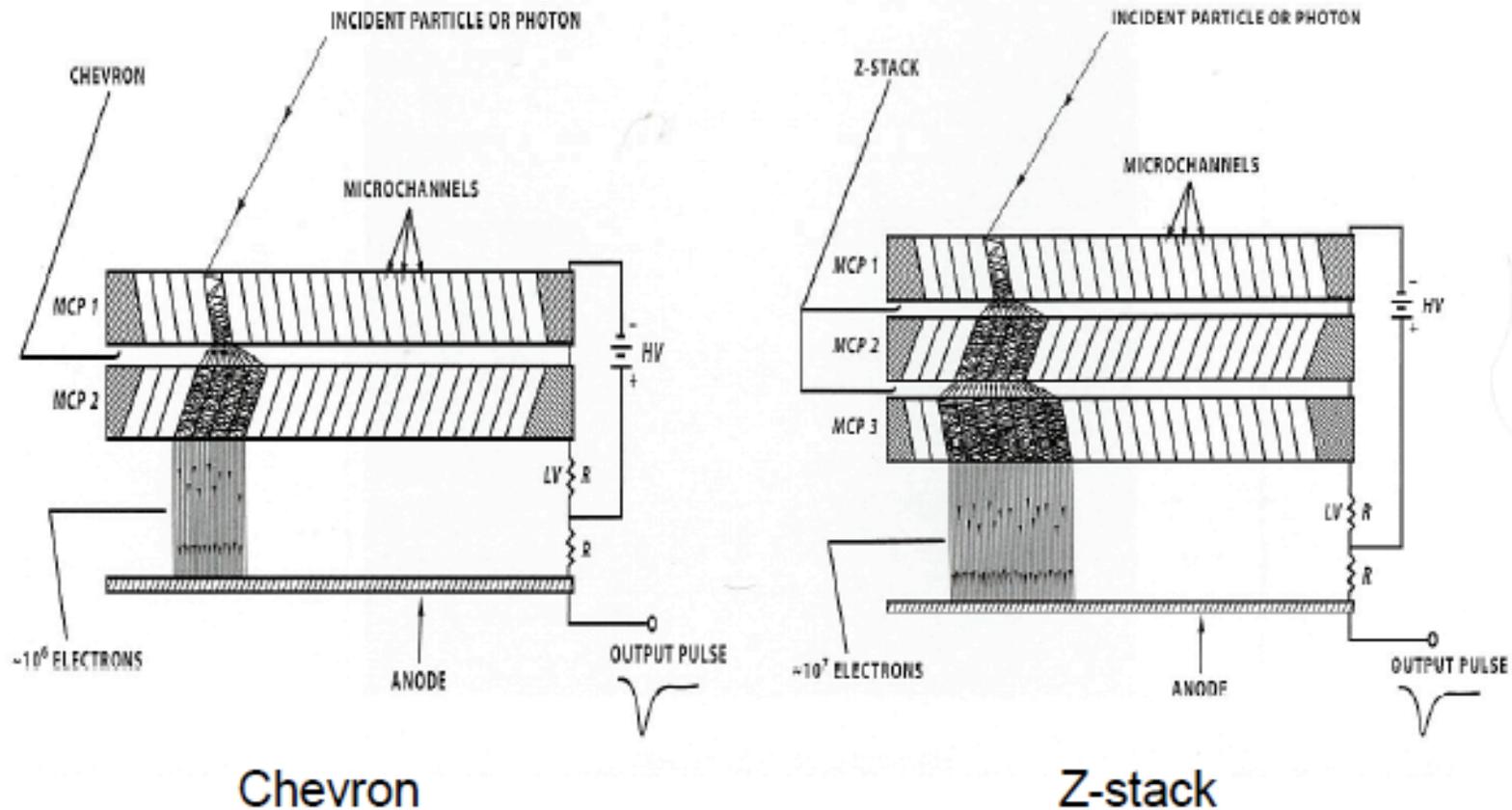
Chevron

Z-stack

MCP wafers are sliced at a small (8-12°) bias angle relative to the microchannel axis

They are stacked in pairs (Chevron configuration) or in triplets (Z-stack), with adjacent wafers having opposite bias angles to prevent ion feedback

Typical bias voltages are ~1 kV per plate and typical gains are ~1000 per plate.

Semiconductor (Solid State) Detectors

dE/dx by E technique

Essentially every particle detector has similar functional elements

- 1) An entrance system (a window) that defines the field-of-regard (or instantaneous FOV)
- 2) An energy selector, or energy analyzer (a gate that selectively passes desired energies)
- 3) Additional selection stages to ferret out other properties (i.e., for ions: mass, charge state, etc)
- 4) Amplification device (e.g. electron multiplier)
- 5) Detector

Randomly distributed particles in space

Electronic Output
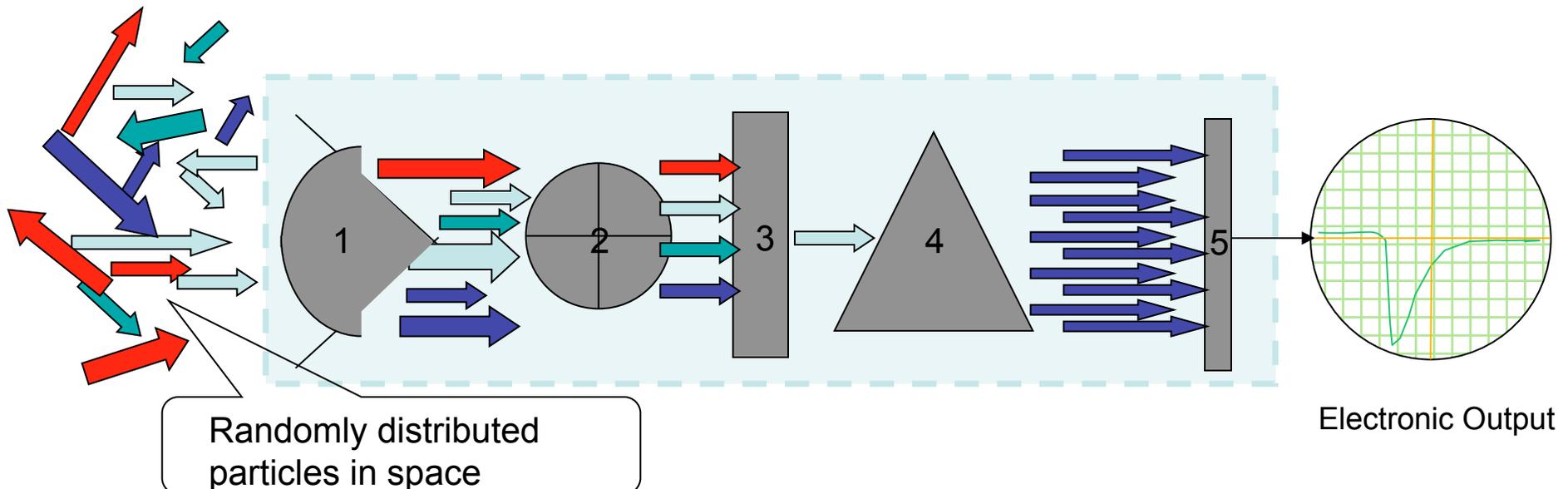
Electrostatic Analyzer 2D

- Two cylindrical plates. Potential applied. Electric field between plates is radial. Selects Energy per unit charge.

incident particle

Detector

(from Gloeckler,"Text", Vol II -- section 3.6.2

incident particle
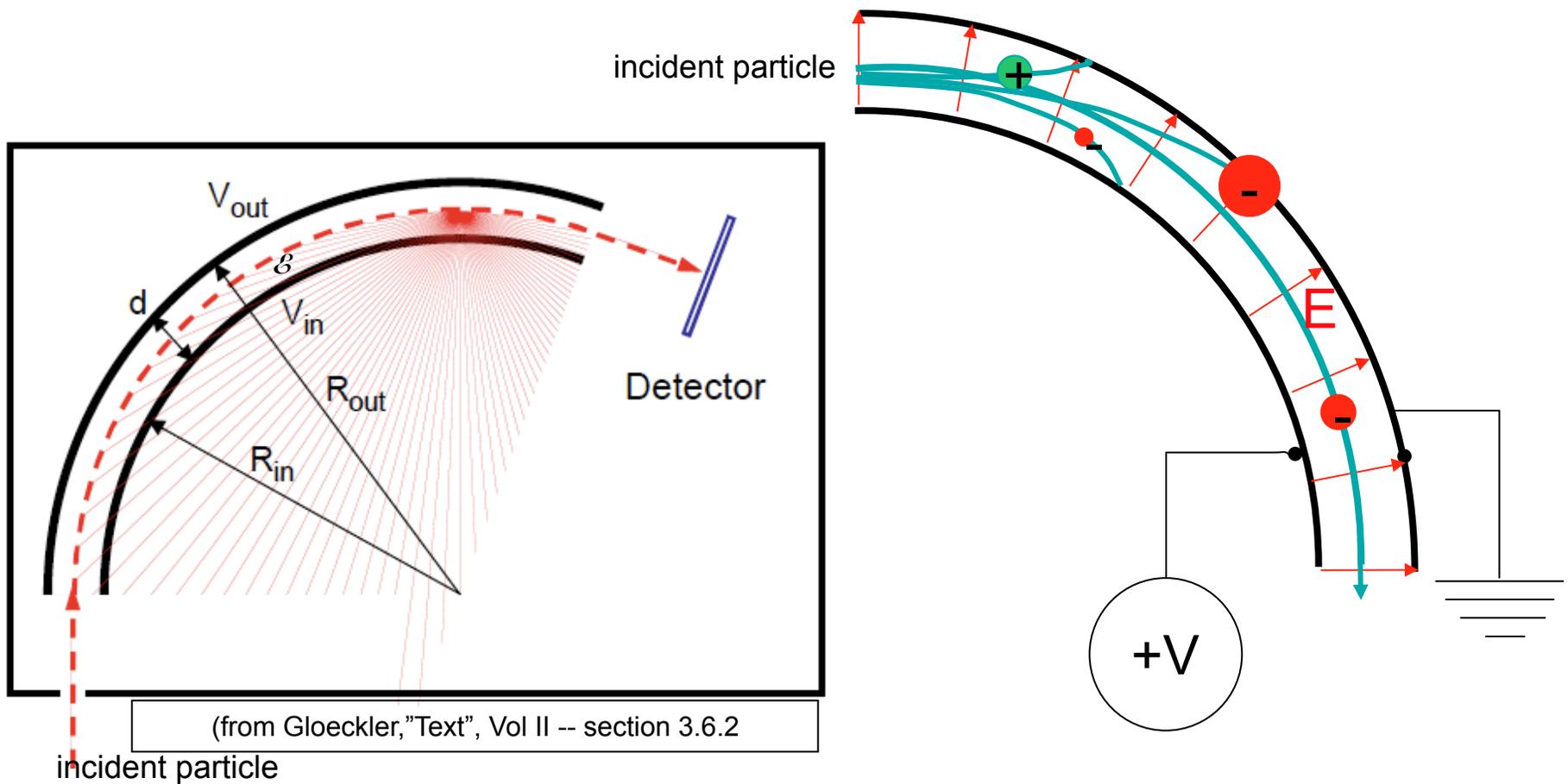
Electrostatic Analyzer - 3D

- The Time-of-flight Energy, Angle Mass Spectrograph (TEAMS) Experiment for FAST
  - A top-hat hemispherical analyzer
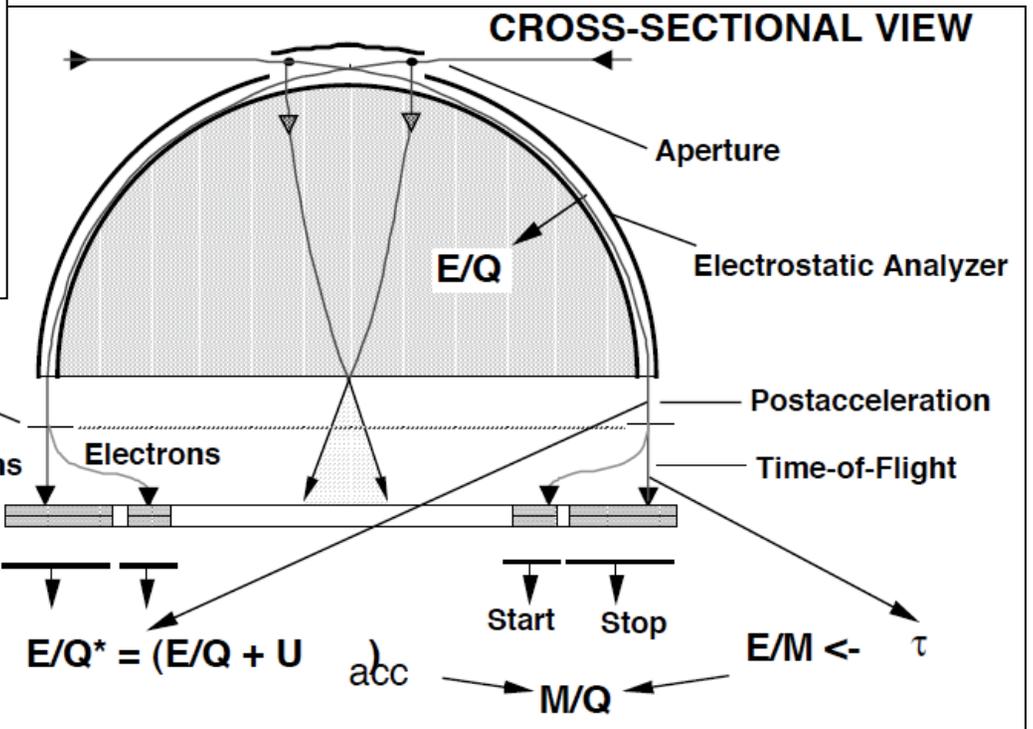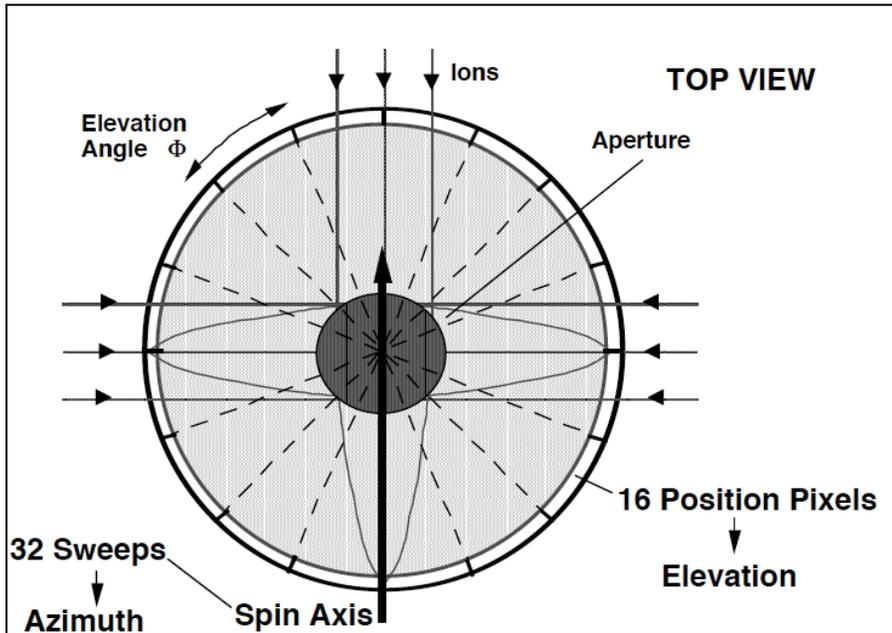
[Klumpar, et al., 2001]

TEAMS Ion Mass Spectrometer

It starts to get a little more complicated when you add many elements together to get energy, angle, mass simultaneously as a function of time.

Collimator to select angles

Energy analyzer to select E/q

Time-of-flight (Velocity selection)

Nevertheless, it is a combination of the basic building blocks
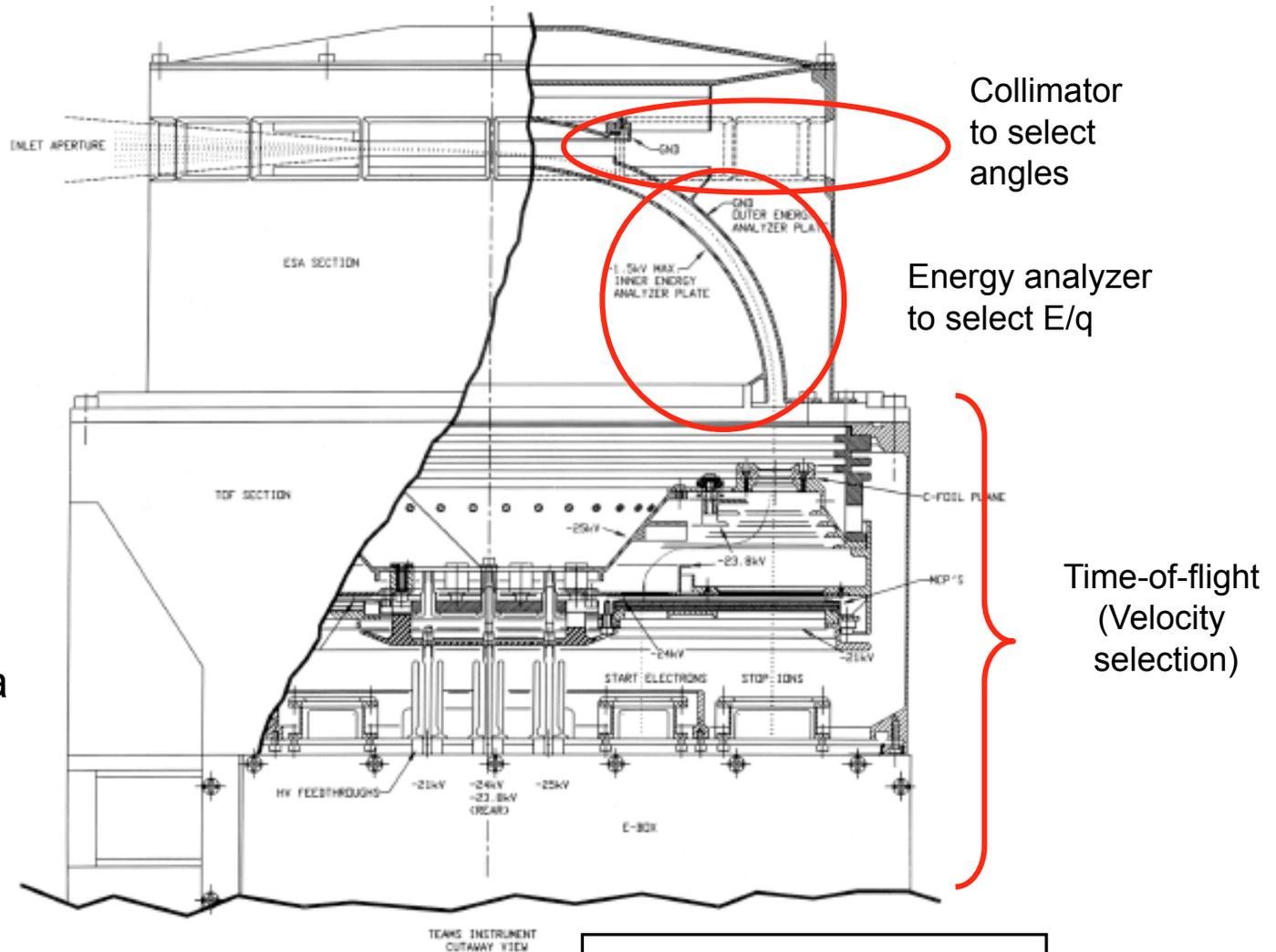
[Klumpar, et al., 2001]

The electronics in these time-of-flight energetic ion mass spectrometers logic can get really complicated, too.

It is a sectored top-hat instrument, with a 360 degree (in azimuth) x 12.5 degree instantaneous FOV. At the sensor plane there are 16 separate sensors. Providing 16 instantaneous 12.5° x 22.5° FOVs.

Engineers love this stuff!!

[Klumpar, et al., 2001]
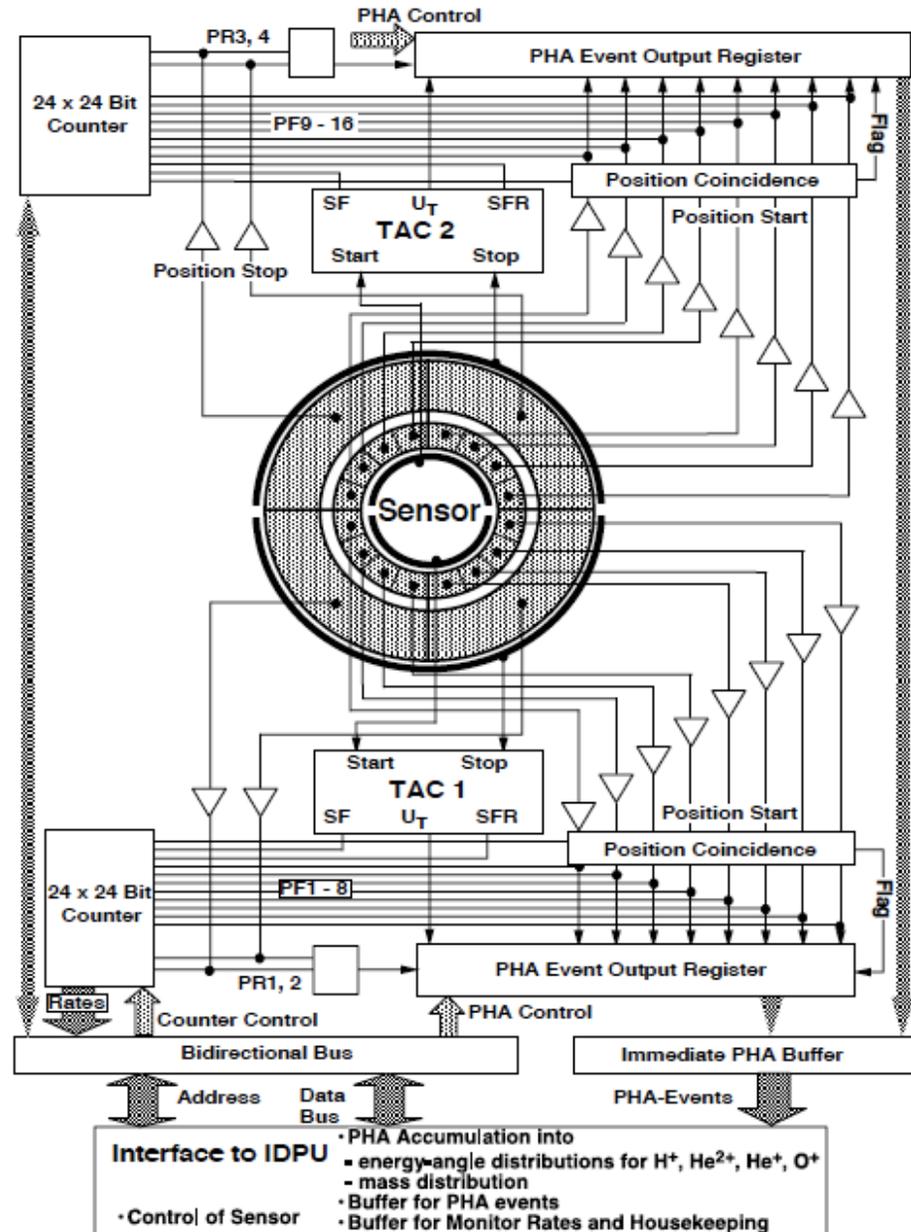
TEAMS sensor electronics block diagram

Flux-gate
Magnetometer

Electric Field Detector
and Langmuir Probes

Electrostatic
Analyzers
(4 places)

Search coil
Magnetometer

Ion Mass
Spectrograph

2010 Heliophy

34

But (amazingly) it works!

TOF Mass Spectra from Calibration Runs

TOF Mass Spectra from Flight

FAST Particles Energy/Angle Spec. Orbit 1676

[Klumpar, et al., 2001]   35
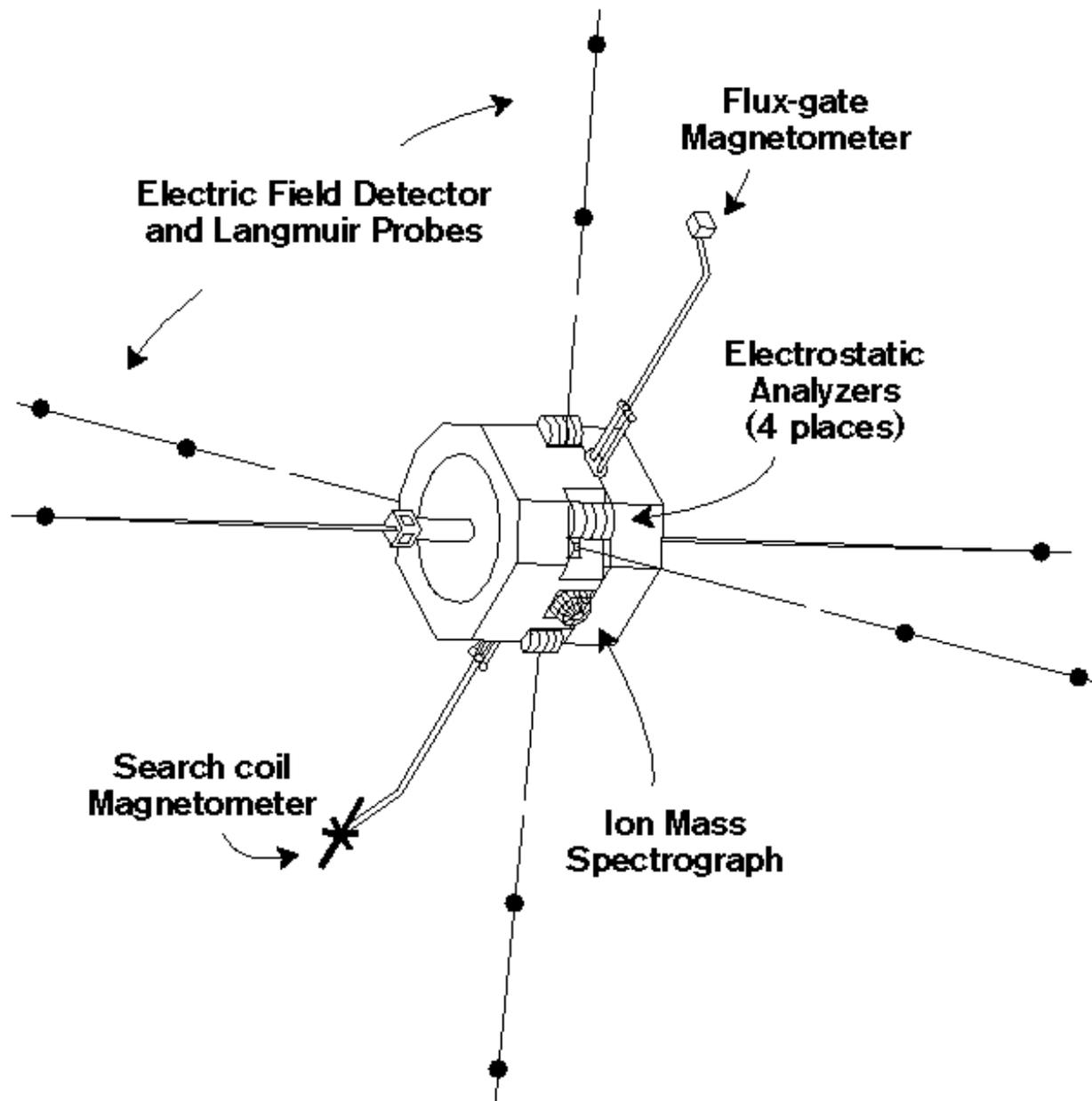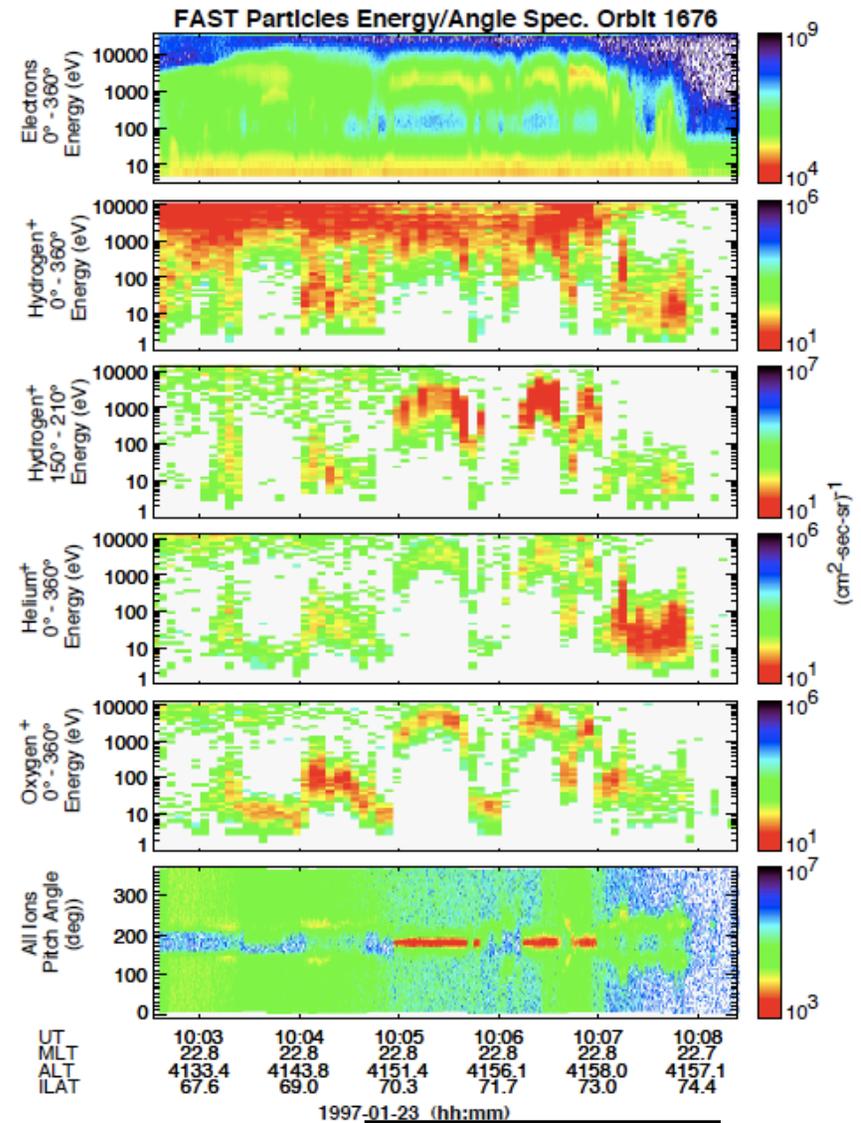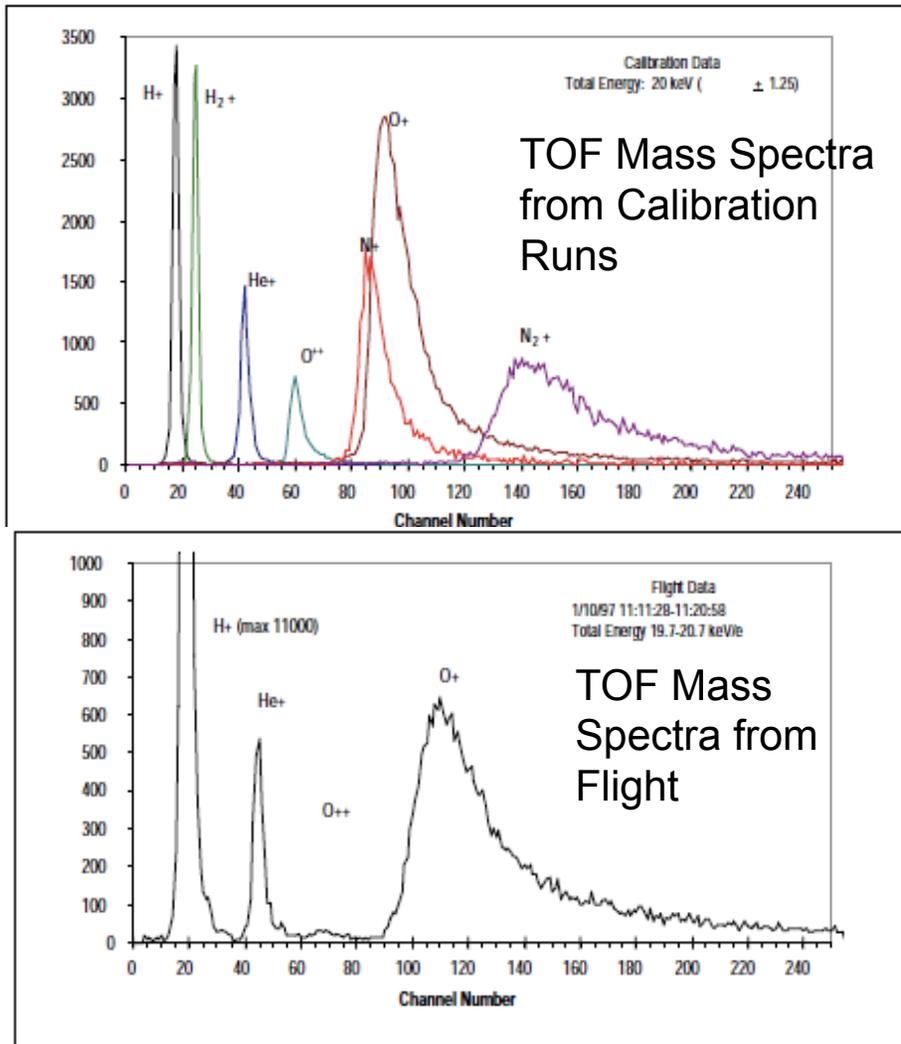
Magnetic Analyzer (Spectrometer)

- Utilize magnetic field to disperse particles

- F =ma = -q (**v** x **B**) Magnetic force is perpendicular to velocity

- Used for medium high energy particles

Collimator

Magnetic field region

B out toward viewer

2r
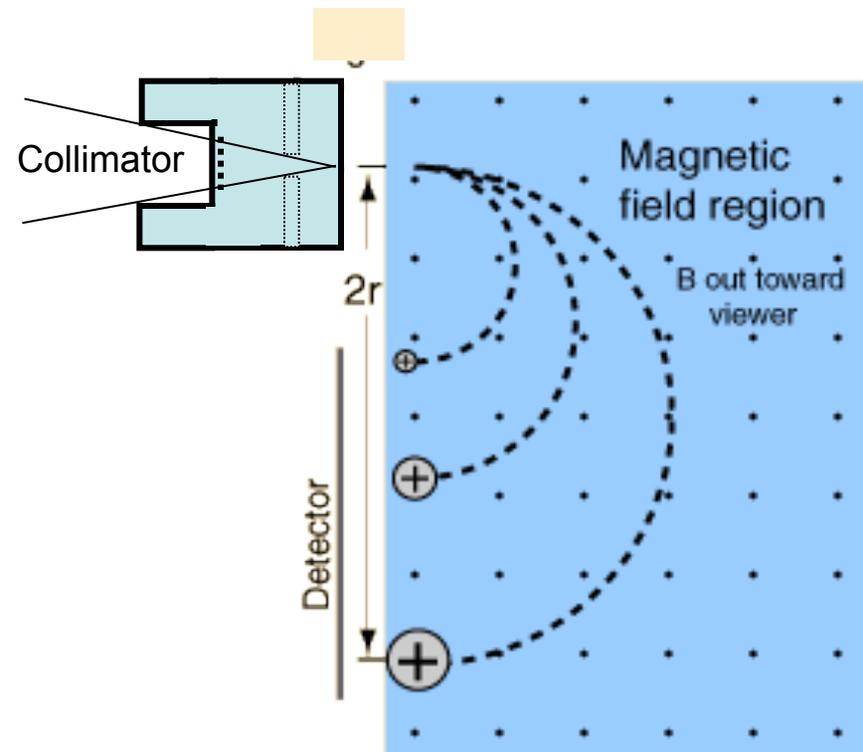
Detector

At the very highest energies (Cosmic Rays)

- The fluxes are very low.

- Electric and magnetic fields have minimal influence on charges particles at these very high energies (over the short distances that characterize a detector)

- Detectors utilize nuclear interactions with matter and need lots of material to effect an interaction.

- Geometric factors are comparatively huge (10's m^2-sr)
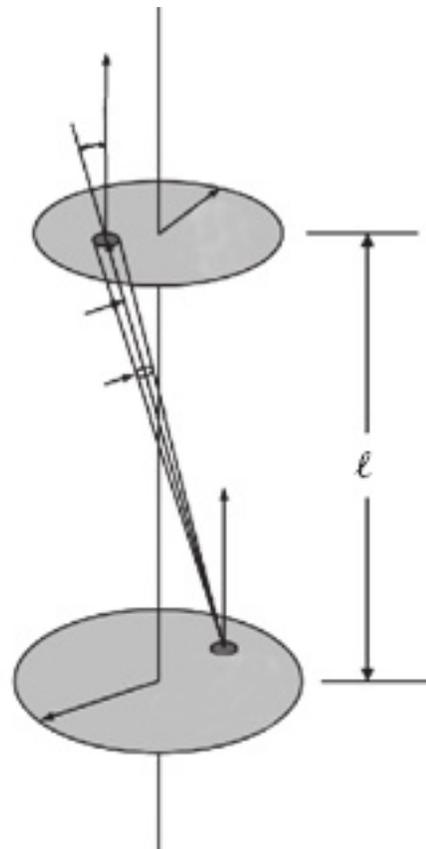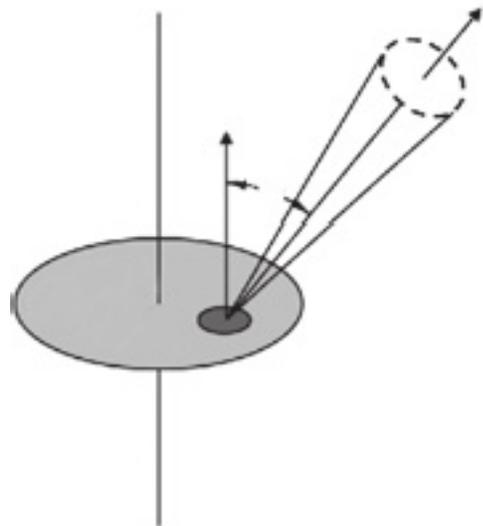
A few words about the "Engineering" aspects of building space in-situ particle detectors

- The space environment is inherently different than the environment here in this room. Your detector has to function properly (and stay well-calibrated) in this that not-so-benign environment:
  - Getting to space is a rough ride (high g-loads, vibrations and shocks, high acoustic levels, rapid decompression, …)
  - Once in space ….
    - No air --> thermal dissipation issues
    - Spacecraft charging, thruster plumes, outgassing, other bad effects of your immediate environment
    - Hot-cold cycles from full Sun to full eclipse and back ~14 times per day (relentless thermal cycling)
    - Penetrating radiation (sometimes the very thing you are trying to measure can be your worst enemy) Freezes your electronics and eventually kills it.
    - Atomic Oxygen corrosion (in LEO)

- AND WORST OF ALL: You gotta get it right the first time. No tweaking, no adjustments, no fixes or repairs possible once it is in orbit.

Homework Problems

- Pick up a sheet at the front of the room (Note it is copied double sided! – be sure to turn it over).

- You are going to "design" some particle detectors.

- You will use a few of the fundamental physics principles we have discussed here this morning.

- Let your imaginations run (but keep the physics in mind)   -- Who knows you might come up with an entirely new instrument concept