II. Plasma Instruments

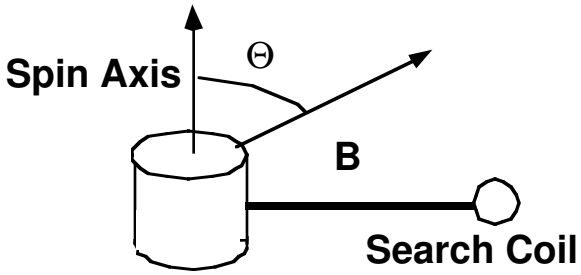
Instrumentation for space plasmas can be separated into Fields and Particle instruments. Generally, under fields we subdivide into magnetic and electric field measurements. Particle instrumentation is different for charged particles and neutrals. In this course we will concentrate on charged particle instrumentation. Electron instruments are not much different from ion instruments, except for the sign of the charge.
We will start with a brief survey of the field instruments, especially with the magnetometers.

II.1 Magnetometers, E-Field Instruments

Brandt, p. 142 – 145,
Measurement Techniques in Space Plasmas, Vol II, (Snare) p. 101-113

a) Search Coil

The simplest magnetometer is a search coil, i.e. a coil which spins with the S/C. Its axis is



inclined with respect to the spin axis, e.g.:
We make use of magnetic induction to deduce the magnetic field.

$$\nabla x \vec{E} = -\frac{\partial \vec{B}}{\partial t}$$

Because we measure the time derivative, the result needs to be integrated over the spacecraft (S/C) spin to return B. As sinΘ*B is measured, or in other words the components ⊥ to the spin axis, the component ||B is not returned by this method. This is a drawback of the method.

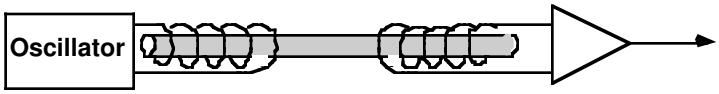
Because only time variations of B as seen by the coil are measured, any constant B-components on the S/C (e.g. permanent magnets, magnetized screws, etc.) do not matter. This is a substantial advantage. Only time varying fields from AC currents can contaminate the measured signal. To minimize this remaining problem calls for a careful wiring on S/C! For example, twisted pairs of wires are used to supply current.

A search coil sensor has several disadvantages. Let us summarize them:

- not an absolute instrument → must be calibrated
- low cadence of the measured signal (S/C spin): This means, faster frequencies in space are hard to untangle.
- component ||B is missing.

b) Flux Gate Magnetometer

The disadvantages have lead to the development of more advanced magnetometers, for example, the flux gate magnetometer. It makes use of the magnetization (with or without saturation) of a ferromagnetic core in a coil by a high frequency current.

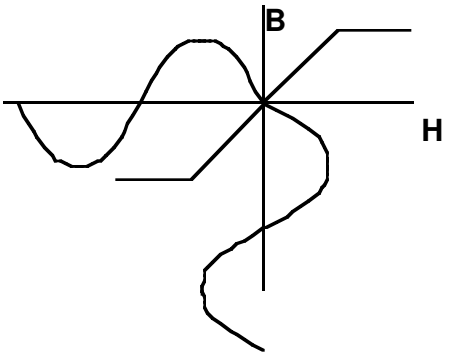


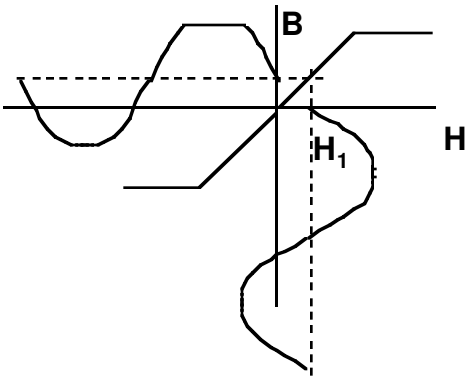
In a magnetic field $H(t) = H_o \sin \omega t$ that is generated with an oscillator in a coil with a ferrite in the center the magnetic induction $B(t) = B_o \sin \omega t$ follows according to the figure below. The wave may be clipped because of the finite permeability, but it remains perfectly symmetric, if there is no additional external field:

$H_1 = B_1/\mu_o = 0.$

With an ambient field B_1 this becomes

$H = H_1 + H_o \sin\omega t$ and thus: $B = B_1 + B_o \sin\omega t$



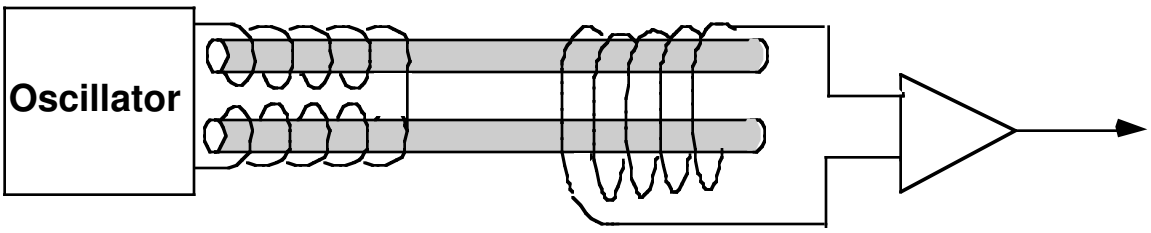


The AC field is shifted along the permeability curve. In any case (with or without saturation) the signal is asymmetric about 0 in B. Saturation is a complication that can be eliminated with the following argument:

If $B_1 = H_1 = 0$: $B(t) = -B(t + \pi/\omega)$,

whether the signal goes into saturation in the core or not. A Fourier series of the signal contains only odd harmonics. If 2 cores with opposite windings are used and the two signals are added in a coil across both cores, the two signals compensate each other perfectly for $B_1 = 0$ and $H(t) = 0$. If $H_1 \neq 0$, this symmetry is destroyed and a residual signal B_1 is measured that is proportional to the original magnetic field and modulated with the frequency 2ω.

$f_2(2\omega) \sim H_1$



The time resolution of the instrument is tied to the oscillator frequency ω. It can be used in a DC field. With 3 units, one gets all 3 directions. In a clever arrangement and making use of the spacecraft spin even less units are needed.

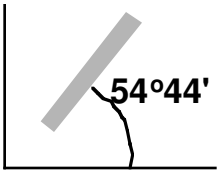
It is more accurate to measure an AC signal, in particular, after all other effects are compensated for. Therefore, a flux gate magnetometer:

- is very sensitive from 0.1 nT – a few 1000 nT
- is self-calibrating for the signal (depends only on physical constants)

However:

- it is also sensitive to residual S/C fields
  → calibration needed, but the magnetometer can be flipped mechanically to subtract residual static fields.

In principle, 1 magnetometer is sufficient on a spinning S/C to get the vector field.



An orientation of 54° 44 w.r.t. the plane perpendicular to the spin axis provides the same sensitivity in all directions.

However, B(t) must be slow compared to the S/C spin to get the complete picture. Usually two cores are sufficient in a time varying field on a spinning S/C, even for moderately high frequencies.

To cover even higher frequencies the search coil is the better choice, since it directly measures dB/dt. Thus very often both sensors are flown on space plasma missions.

c) Electric Fields

Electric fields are measured with probes on long boom antennas, by determining the voltage drop between them. The tricky part is that the potential of a probe in plasmas depends strongly on the environment (e and i temperatures, UV radiation, energetic particles) that charges up the probes. As noted before, generally the electron current is stronger in plasmas than ion currents. Therefore, a floating surface charges up negatively (more electrons hit the surface). To reach equilibrium, i.e. $j_e = j_i$, part of the electrons must be repelled. Given a Maxwellian with T_e for electrons and a probe potential U_p, the electron current varies as:

$$j_e(_{Up}) = j_{eo} * \exp(-eU_p/kT_e)$$

The total current is: $j = j_e - j_i = j_{eo} * \exp(-eU_p/kT_e) - j_i$ with an exponential characteristics. This is the well-known Langmuir Probe characteristics. To make use for an antenna the probes are biased with a power supply such that they are on the steepest point of this characteristics. This is a controlled potential close to what the local plasma potential is. Thus measuring the voltage between two probes provides the electric field between them.

A complication is that UV (e.g. form the sun) leads to emission of photoelectrons from all S/C surfaces, which then can lead to positive charging of the S/C and the probes. In addition, any probe in the S/C shadow may charge up differently. Therefore, operating an E-Field instrument and analyzing its data is a non-trivial exercise.

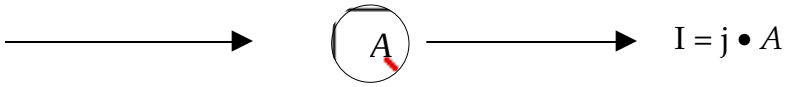
II.2 Plasma (Particle) Instruments

We distinguish between charge collecting sensors and particle counters. The first instruments in the 1950's and 60's were charge collectors. Only later particle counting could be done efficiently with new detectors.

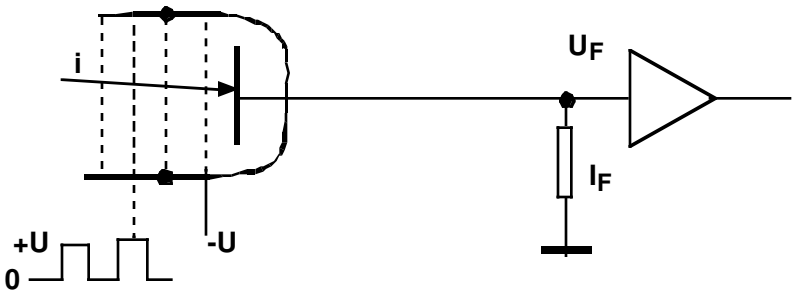
a) Faraday Cup

Measurement Techniques in Space Plasmas, Vol I, (Heelis&Hanson) p. 61-71

The Faraday cup is the typical charge collector. It works well in flowing plasmas. Therefore, it is still in use for solar wind measurements. The current into the known area *A* of the detector is measured:



This sounds simple. However, we need to distinguish between electrons and ions:



An alternating positive voltage is applied at the entrance to either allow ions in or repel them. A comparison is always better than an absolute measurement! In front of the collector an additional negative voltage repels electrons and suppresses the loss of secondary electrons, which would be counted as additional ions.

This instrument works fine for ions with

$10^2 < m_i/2\ v^2 < 10^4$ eV

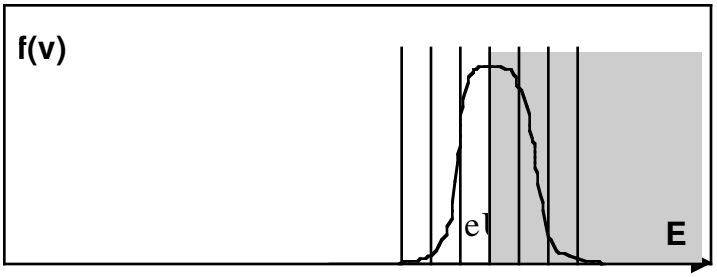
At lower energies a collimator is needed, because of the thermal spread. Then the velocity distribution (including direction) can be measured, if the satellite is spinning. At higher energies it becomes difficult to deal with the voltages. For electrons the voltages are flipped. Then the instrument is called a Langmuir probe (just mentioned under E-Fields), which usually is treated in a plasma physics course.

Let us look at typical energies and voltages in the solar wind:

-U: $T_e \approx 10 - 50$ eV U = -100 V o.k.

+U: $E_{sw} = m_i/2\ v_{sw}^2 \approx 1$ keV i.e. U ≈ 1.5 kV

Switching U+ on and off produces on/off signal, but if U is varied from 0-1.5 kV, the energy of the solar wind can be determined directly.



$$j(U_o) = e \int_{v_o = \sqrt{\frac{2eU_o}{m_i}}}^{\infty} f_x(v)\, v\, dv \quad \text{(II.2_1)}$$

In each voltage step U_o the integral flux up to the corresponding energy is measured. The distribution can be

determined by differentiation. For solar wind this is easy to determine the total flux we measure the current I:

$$n_{sw}\, v_{sw} = I/(A \cdot e) \qquad \text{(II.2_2)}$$

with the bias voltage $U_+ < E_{sw}/e$. a is the aperture area of the sensor.

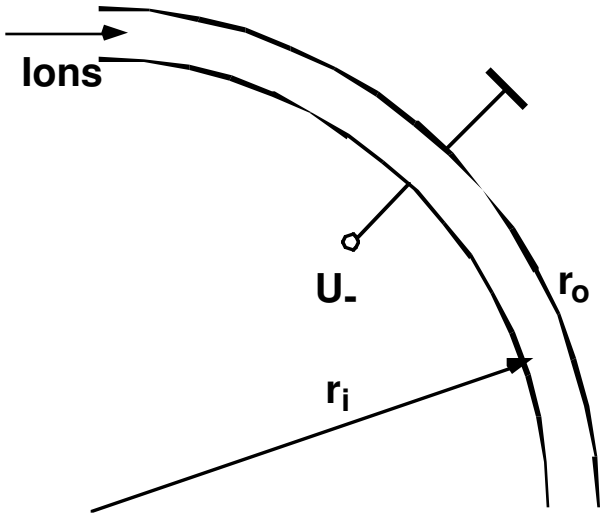
Disadvantages of Faraday Cups

- poor angular resolution
- Limited energy resolution and range
- photo effect (secondary electrons are produced)
- poor sensitivity at low fluxes (this needs counting of particles!)

To deal with the sensitivity particle counters are used that come from photon detection, i.e. from photo multipliers. When a photon or a particle hits a metal surface, one or more electrons are emitted, depending on the impact energy. Usually, it is more than one, if the energy exceeds 10 - 20 eV. Imagine that this process is repeated often enough. Then an electron cloud is created with enough charge to produce a detectable signal. In small glass tubes with a high resistivity coating this is achieved on the way from the entry to the rear end. Here the signal is collected. These devices are called channeltrons. They work with a total voltage across of 1 - 2 kV and achieve an amplification of the signal by 10^4 - 10^7. I.e. a single electron (ion) produces up to 1 pico Coulomb, enough for sensitive electronics to be detected.

b) Electrostatic Analyzer
Measurement Techniques in Space Plasmas, Vol I, (Carlson&McFadden) p. 125-140

Better energy and angular resolution is achieved with an electrostatic analyzer with curved plates.



$$r = \frac{r_o + r_i}{2}$$

$$\Delta = r_o - r_i$$

$$q\frac{U}{r_o - r_i} = F = \frac{2 m_i v^2}{r_o + r_i} \qquad (II.2_3)$$

$$E = \frac{m_i}{2} v^2$$

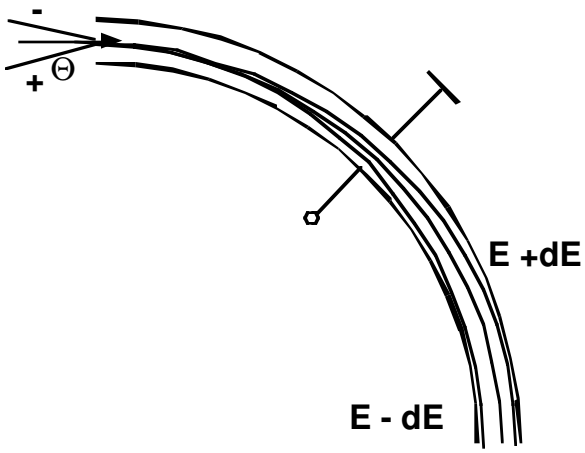
$$\frac{q \bullet U}{\Delta} = \frac{2E}{r} \qquad (II.2_4)$$

$$\frac{E}{q} = \boxed{\frac{r}{2\Delta}} U$$

A

A is the analyzer constant.

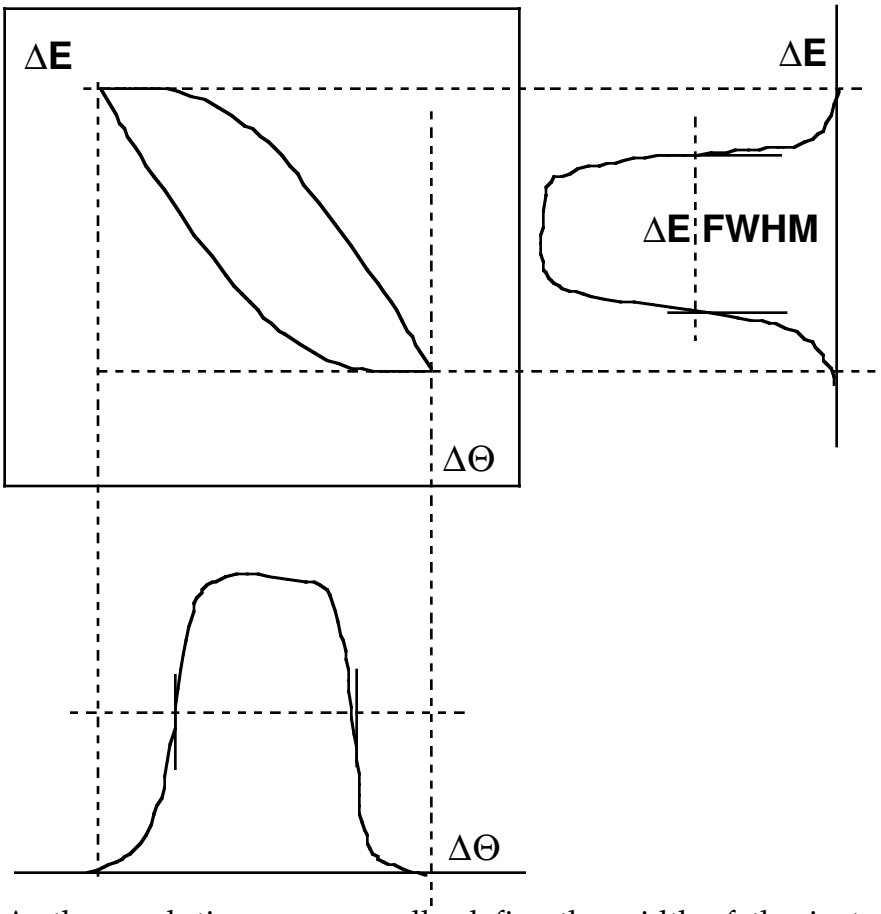
For a typical analyzer with r = 8 cm Δ = 4 mm: A = 10
Varying the voltage U- covers all energies E. Depending on the ratio Δ/r the analyzer will pass a certain energy range of the ions.



As can be seen from (II.2_4) a much lower voltage than E/q is needed. This allows an extension of the energy range to much higher energies than with a Faraday Cup.

Also ions with a slightly different incoming angle θ will pass the analyzer. Negative θ will increase the energy, which goes through the analyzer, and vice versa. Therefore, a much wider energy distribution will pass the analyzer than indicated by ± dE, because natural distributions have wide angle ranges.

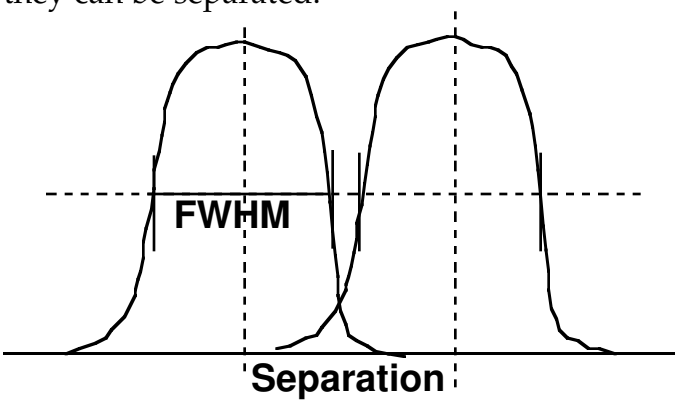
We end up with a response of the analyzer in θ and E, which looks like a magnetic hysteresis curve. Because generally the ions can arrive from all directions, we have to take this into account when we define the energy resolution of the analyzer.



As the resolution we generally define the width of the instrument response at half its maximum:

Full Width Half Maximum FWHM

If 2 distributions are separate by more than the FWHM of the instrument resolution, they can be separated:



Let us now use a hemispherical analyzer with a lifted top cap.

Viewgraph

The analyzer accepts ions from all directions, and by noting the position on the detector we get the incoming direction in polar angle Φ. It is called polar angle w.r.t. the spin axis of the satellite. By rotating the device with the satellite it covers the full sphere of the sky.

If we accumulate ions only for a fraction of a spin at a time, we keep the directional information. 8, 16 or 32 sectors/spin are typical numbers.

c) Conversion to Physical Units

With information about the energy E, and both directions Φ and θ we can determine the distribution function of the ions $f(\vec{v})$ or $f(v, \Phi, \theta)$.

How to get there from the number of particles detected per unit time?

Accumulating particles over a certain time Δt the instrument counts a certain number of ions N_p in each pixel p.
The accumulation time Δt is determined by the spin period t_{spin} and the number of sectors n_s:

$$\Delta t = t_{spin} / n_s \qquad (II.2_5)$$

We get a count rate in each pixel:

$$R_p = N_p / \Delta t = \frac{N_p \bullet n_s}{t_{spin}} \qquad (II.2_6)$$

in counts/sec.

The instrument collects the particles with an entrance aperture a ***Viewgraph***
out of an angular range Δθ (acceptance range of the analyzer) and ΔΦ (the size of the sector in polar angle). If the instrument has, for example, 16 sectors over 360°

$\Delta\Phi = 22.5°$

The combined angle

$\Delta\Omega = \Delta\theta \bullet \Delta\Phi$

is the solid (acceptance) angle of the instrument, given in steradian.

$$1\,\text{steradian (sr)} = \frac{1}{4\pi}\,\text{of full sphere}$$

Generally, any instrument will not detect 100% of the particles, which fall into its aperture and acceptance angle. For example an electrostatic analyzer passes typically only 25% of all particles within the acceptance angle because of the combined angle/energy response. In a real instrument additional grids etc. may reduce this value further. This is the transmission function T of the instrument. The effective geometric factor G of the instrument is therefore:

$$G = a \bullet T \bullet \Delta\theta\,\Delta\Phi = a \bullet T \bullet \Delta\Omega \qquad (II.2_7)$$

given in cm^2 sr

In addition, only ions in an energy band ΔE pass through. For an electrostatic analyzer this is

$$\Delta E = \frac{\Delta(E/Q)}{(E/Q)} \bullet (E/Q) \bullet Q \qquad \text{(II.2_8)}$$

We write it this complicated because:

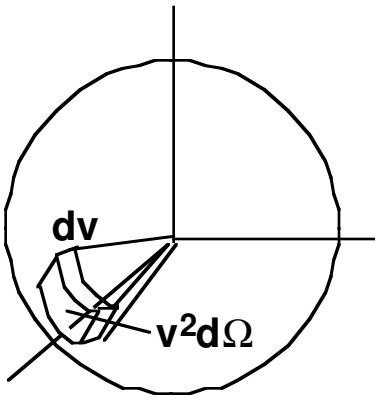
$\frac{\Delta(E/Q)}{(E/Q)}$ is a constant for each instrument, determined by its geometry, and we measure at fixed E/Q steps.

Now we can translate the count rate into the differential particle flux:

$$\frac{dJ}{dE d\Omega} = \frac{R_p}{\Delta E \bullet G} \qquad \text{(II.2_9)}$$

Let us now compute the flux **dJ** again from the velocity distribution function.

To get the flux we have to take f(v) • v and to integrate over a certain volume element $v^2 dv\, d\Omega$ in velocity space.



$$dJ = f(v) v \bullet v^2\, dv\, d\Omega$$

We want the differential flux in energy:

$$\frac{dE}{dv} = \frac{d\left(\frac{m}{2}v^2\right)}{dv} = mv \qquad dv = \frac{dE}{mv}$$

or

$$\frac{dJ}{dE\, d\Omega} = f(v) \bullet \frac{v^2}{m} \qquad \text{(II.2_11)}$$

Note: E has to be converted from keV to Joule, etc.!!

d) Mass Spectrometers

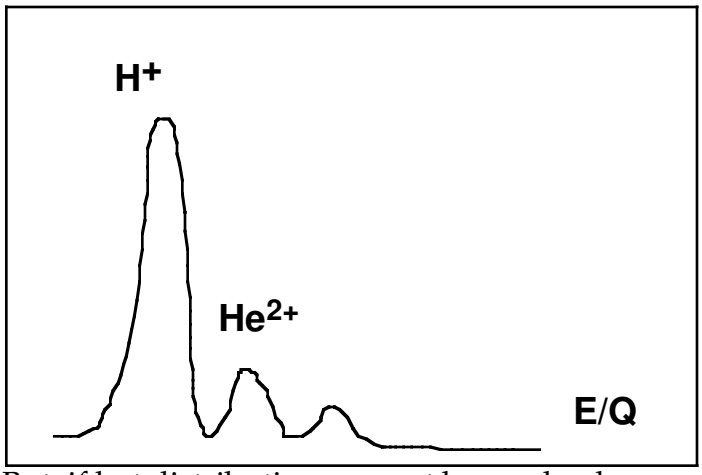
Measurement Techniques in Space Plasmas, Vol I, (Wüest) p. 141-155

(Möbius et al.) p 243-248 Using an electrostatic analyzer in the solar wind may produce already a mass spectrometer. We measure E/Q and solar wind with v_{sw} leads to:

$$2 v_{sw}^2 = \frac{E}{M}$$

$$\frac{E/Q}{E/M} = \frac{M}{Q} \qquad (II.2_12)$$

If the solar wind is cold $v_{th} << v_{sw}$



But, if hot distributions cannot be resolved:
-> measure velocity in instrument
-> measure time-of-flight

Linear Time-of-Flight Spectrometer

Viewgraph

We measure the time-of-flight between an entrance window and a stop detector. Then:

$$v = \frac{s}{\tau} \qquad \text{-> } E/M = v^2/2 \qquad (II.2_13)$$

The start pulse is created by the ion passing a thin carbon foil and knocking off secondary electrons. They are detected by micro-channel plates (MCPs).

The stop pulse can be either directly from the detector or again via secondary electrons.

The mass/charge resolution of the instrument depends on the E/Q resolution of the analyzer and the time-of-flight accuracy $\Delta\tau$:

$$\Delta\left(\frac{M}{Q}\right)\Big/\left(\frac{M}{Q}\right) = \sqrt{\left\{\Delta\left(\frac{E}{Q}\right)\Big/\left(\frac{E}{Q}\right)\right\}^2 + \left(\frac{2\Delta\tau}{\tau}\right)^2} \qquad (II.2_14)$$

The time resolution $\Delta\tau/\tau$ depends on:

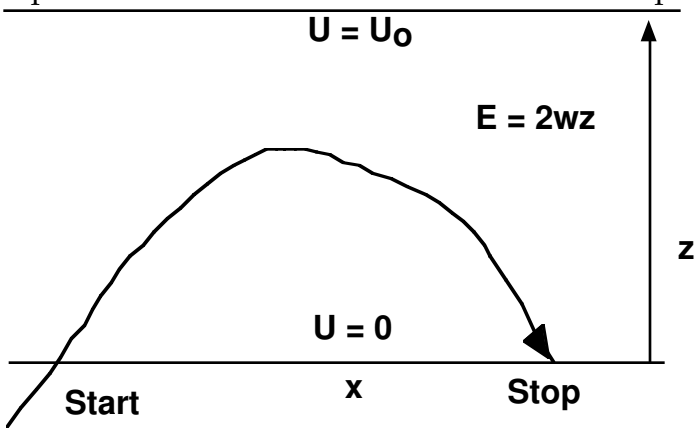
- accuracy of the time measurement (electronics, collection of secondary electrons)
- accuracy of the flight path (range of angles, homework)
- energy loss of ions in the C-foil (produces energy straggling, ions lose more or less energy).

The last effect is particularly bad at low energies, before the ions are finally stopped by the thin foil. Post-acceleration of the ions helps greatly to reduce this effect. It leads to:

- less energy straggling
- $\frac{\Delta(E/Q)}{(E/Q+U_{acc})}$ smaller!

Isochronous Time-of-Flight Spectrometers

This is still not good enough to separate the masses of neighboring heavy ions or isotopes. to overcome this hurdle we can use a repelling electric field:



The ions move like in a harmonic oscillator:

$$\frac{\partial^2}{\partial t^2} z(t) = \frac{Q_e}{A m_p} E(z) = \frac{Q}{A}\frac{e}{m_p} 2w \bullet z(t) \qquad (II.2_15)$$

where the oscillation frequency:

$$\omega^2 = \frac{Q}{A}\frac{e}{m_p} 2w$$

The time-of-flight is half a period.

$$\left(\frac{2\pi}{2\tau}\right)^2 = \frac{Q}{A}\frac{e}{m_p} 2w \qquad \text{or}$$

$$\tau = \pi\sqrt{\frac{A m_p}{Qe\,2w}} \qquad (II.2_16)$$

The constant w depends on the geometry and voltage in the instrument.

E is proportional to z (E linear in z), i.e. the potential $\phi(z) \sim z^2$ (quadratic in z). This could be realized with grids, but this is awkward and leads to many collisions of the ions with the grids.

How to get $\phi(z) \sim z^2$ without grids?
We have to solve the Laplace Equation with boundaries!

Consider the entry of particles from one direction. → We are interested in a linear geometry. (Works fine for solar wind)

$\phi(x, y, z)$ with no x dependence

$\phi(y, z)$

$$\Delta\phi(y,z)=\left(\frac{\partial^2}{\partial y^2}+\frac{\partial^2}{\partial z^2}\right)\phi(y,z)=0 \qquad (II.2_17)$$

Separation of variables

$$\phi(y,z)=\psi(y)+\xi(z) \quad with \qquad (II.2_18)$$

$$\xi(z)=wz^2$$

$$0 = 2w \sim + \sim \frac{d^2}{dy^2}\psi(y)$$

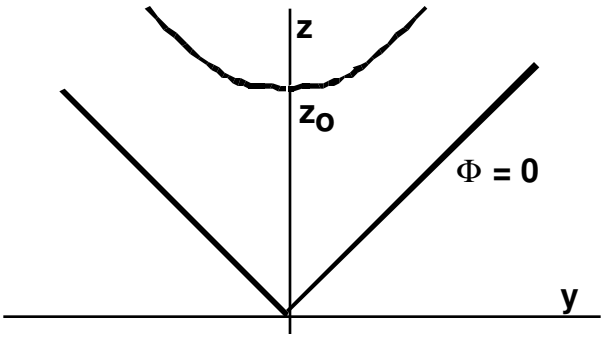
$$\psi'(y)=-2wy+A$$

$$\psi(y)=-wy^2+Ay+B \qquad (II.2_19)$$

A and B can be chosen.

B: potential: can be 0 anywhere

A: we choose a symmetric solution in y A = 0
$\phi(y, z) = w(z^2 - y^2)$ in y, z-plane



We set $\phi(0, 0) = 0$
This means:
$\phi = 0$
where z = y and z =- -y

Set $\phi(0, z_o) = U$

$$U = w \cdot z_0^2 \quad or \quad w=\frac{U}{z_0^2}$$

The equipotential surface with $\phi = U$ is at

$$z^2 = z_o^2 + y^2$$

Thus the time-of-flight volume is embedded in 2 equipotential surfaces which produce the z^2 dependence of the potential inside. The time-of-flight is:

$$\tau = \pi \sqrt{\frac{m_e}{e}} \sqrt{\frac{z_0^2}{2u}} \bullet \sqrt{\frac{A}{Q}} \qquad \text{(II.2_21)}$$

τ depends only on

- the geometry of instrument
- A/Q of the particle

but not on:

- the energy of particle
- the incoming angle of particle

This makes this configuration very convenient with a very high mass resolution.