Experimental Spectroscopy I

H.-J. Kunze

Institute for Experimental Physics V, Ruhr-University,
44780 Bochum, Germany

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Major goals of experimental plasma spectroscopy ?

Determination of the structure of atoms and ions and their radiative properties

Determination of collisional properties

Atoms and ions in plasma environment, influence of E and B fields

Testing of theoretical calculations and of simulations and complex codes

Plasmas as radiation sources from the x-ray region to the infrared

Plasma diagnostics determination of plasma parameters

Depending on the goal the most suitable plasma device has to be selected or designed

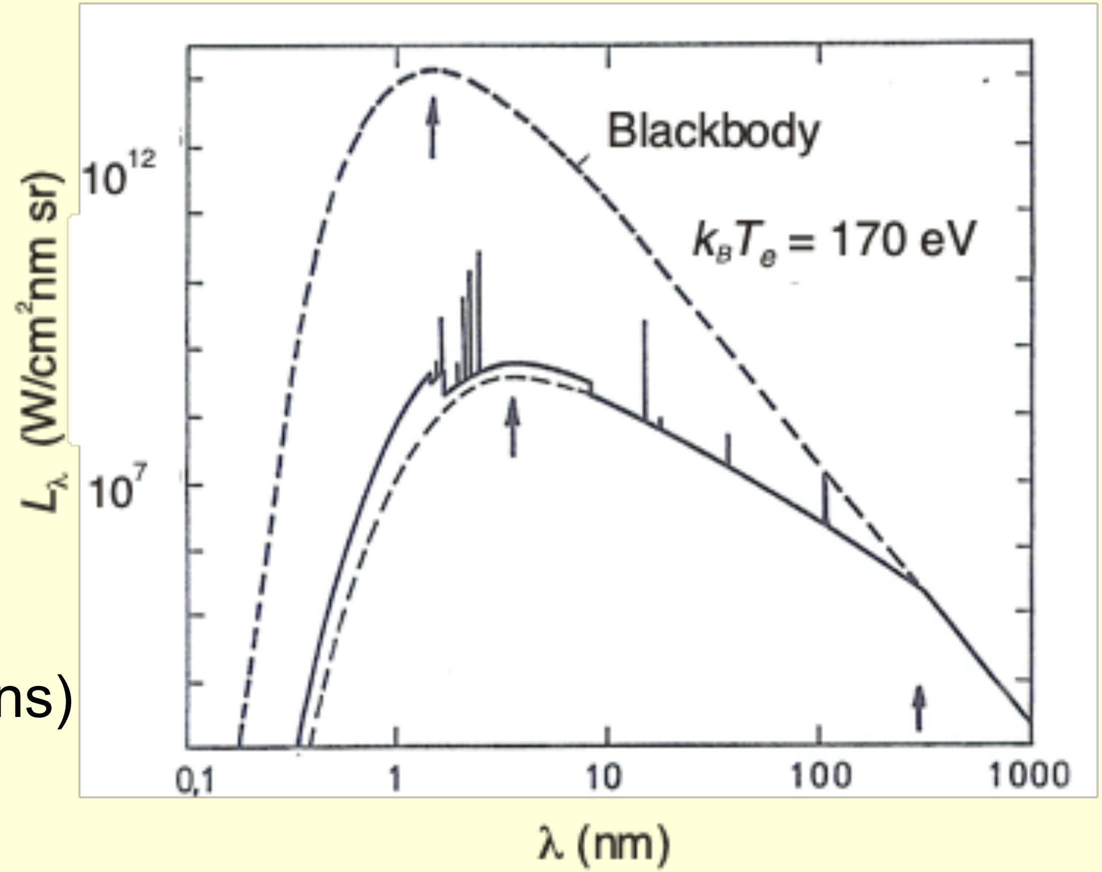
Typical spectrum of radiation emitted from a H-plasma with impurities

Continuum radiation

bremsstrahlung (free-free transitions)

recombination radiation (free-bound transitions)

Line radiation (bound-bound transitions)



At long wavelengths → self-absorption → blackbody limit

With increasing electron temperature the spectra shift to shorter wavelength (x-rays)

atoms exist in higher ionization stages

with lower temperature they shift to the visible and infrared,

atoms and even molecules may still exist

The tasks determine the choice of the spectroscopic equipment.

For the diagnostics of a plasma one should roughly know the electron temperature

Most plasmas are not homogeneous, and one measures only the spectral radiance $L_\lambda(\lambda)$ (*intensity*) at the surface of the plasma !

The quantity of interest, however, is the

local spectral emission coefficients $\varepsilon_\lambda(\boldsymbol{r}, \lambda)$ in the plasma:

$$L_\lambda(\lambda) = \int_0^{-d} \varepsilon(\boldsymbol{r}, \lambda) d\boldsymbol{r}$$

i. e. Integral along the line of sight !

Theoretical solution:
measurement of *L of the whole plasma cross-section* along many chords and from many directions !

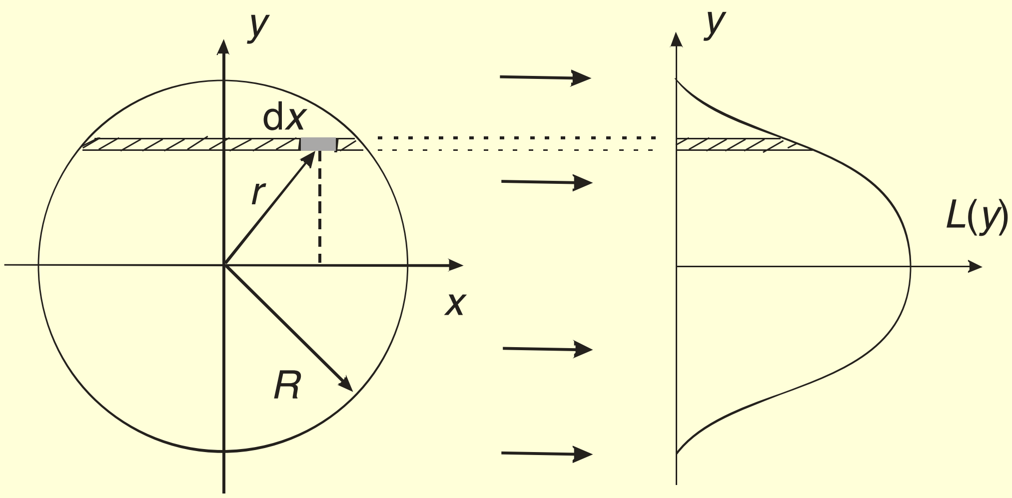
→ Computer tomography to arrive at $\varepsilon_\lambda(r,\lambda)$ $\left[\frac{\mathrm{W}}{\mathrm{m^3\,nm\,sr}}\right]$

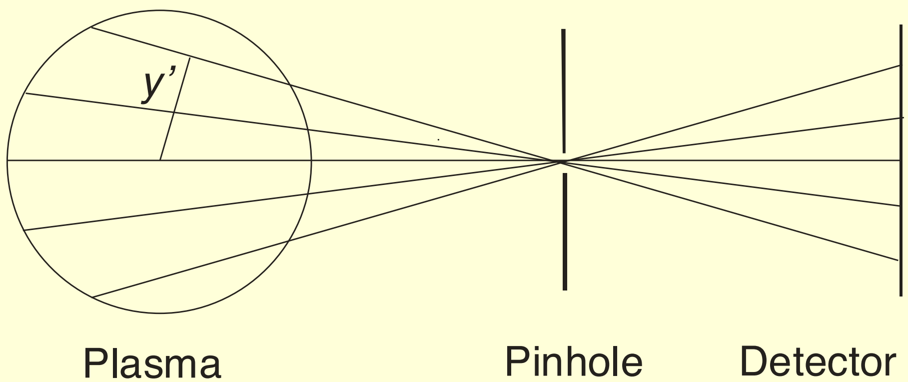
On most plasma devices not possible !

Exception: Radially symmetric cross-section of the plasma

Abel inversion gives

➡ $\varepsilon_\lambda(r,\lambda)$

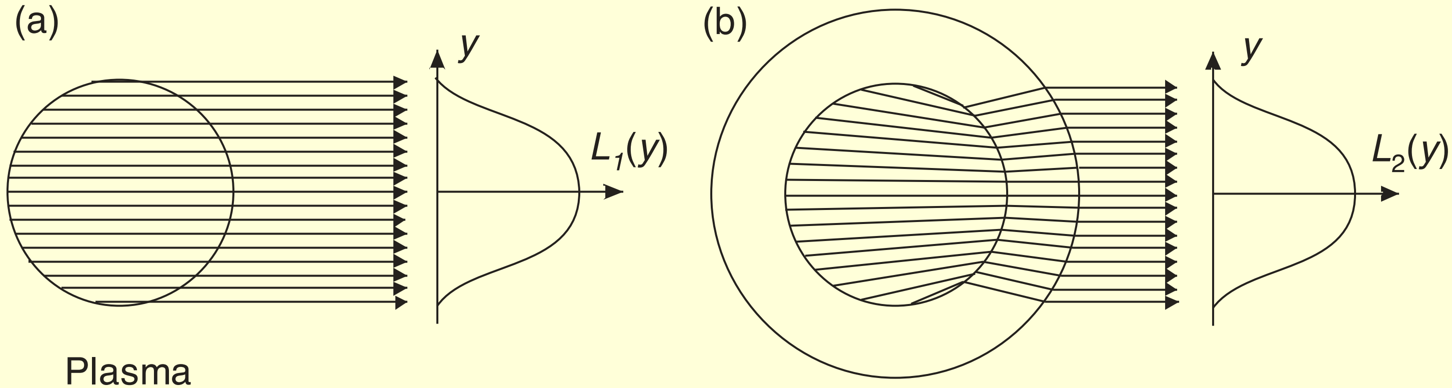




This configuration with a single hole is equivalent

Transformation to radial symmetry is also possible for limiter tokamaks with nested eccentric circles (Shafranov shift) and and for elliptic cross-sections

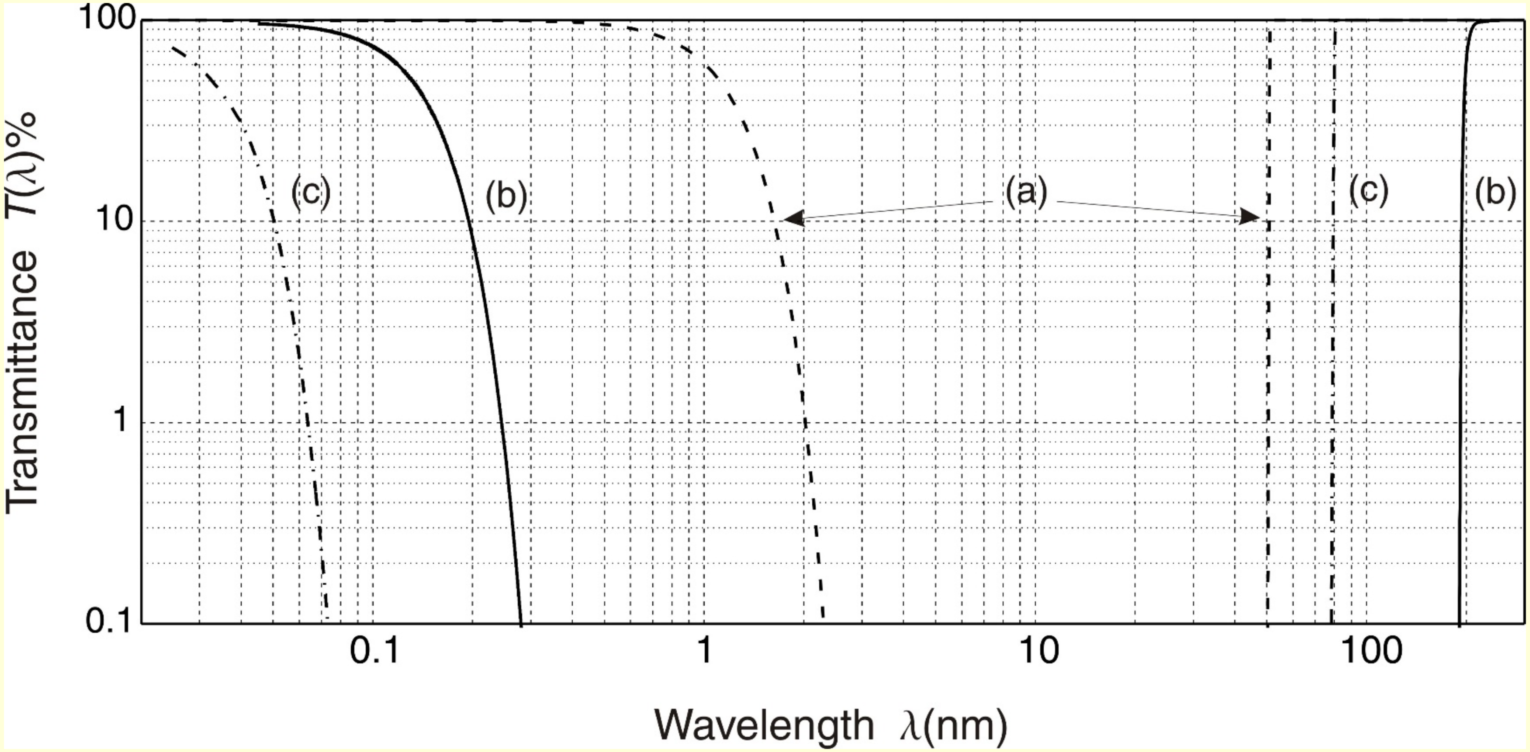
Distortion by a thick wall ?



Correct result only for radially symmetric plasmas

Wavelength dependent reflection from inner walls
can cause errors ??

Transmission of the radiation through air and optical
components like windows, filters, fibers,
and reflection on mirrors

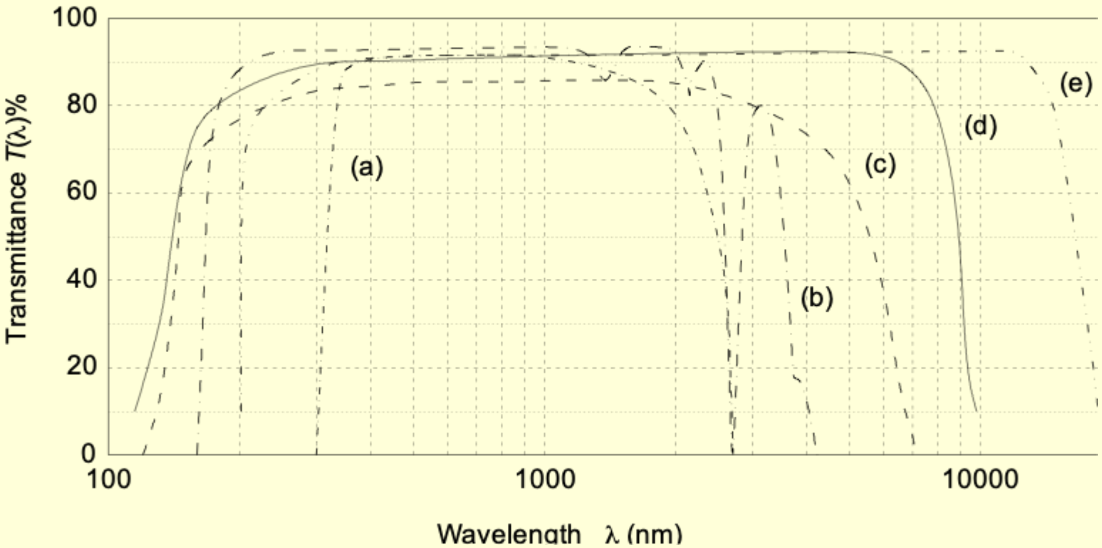


Transmission through 100 cm of gas at 101.325 kPa and 295 K:

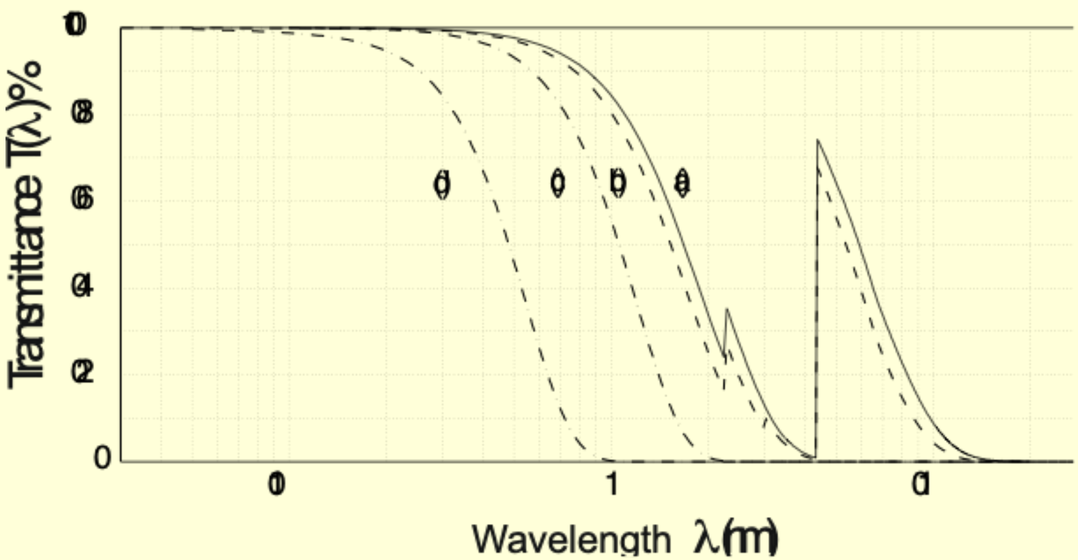
(a)He, (b) air, and (c) Ar.

Filling the spectrograph and pipes to the plasma chamber with He (or even with N_2) may relieve the experimentator from working in vacuum

Transmission of window materials



(a) BK7 (d=10 mm)
(b) Suprasil (d = 10 mm)
(c) Sapphire (d = 1 mm)
(d) CaF_2 (d = 10 mm)
(e) NaCl (d = 10 mm)



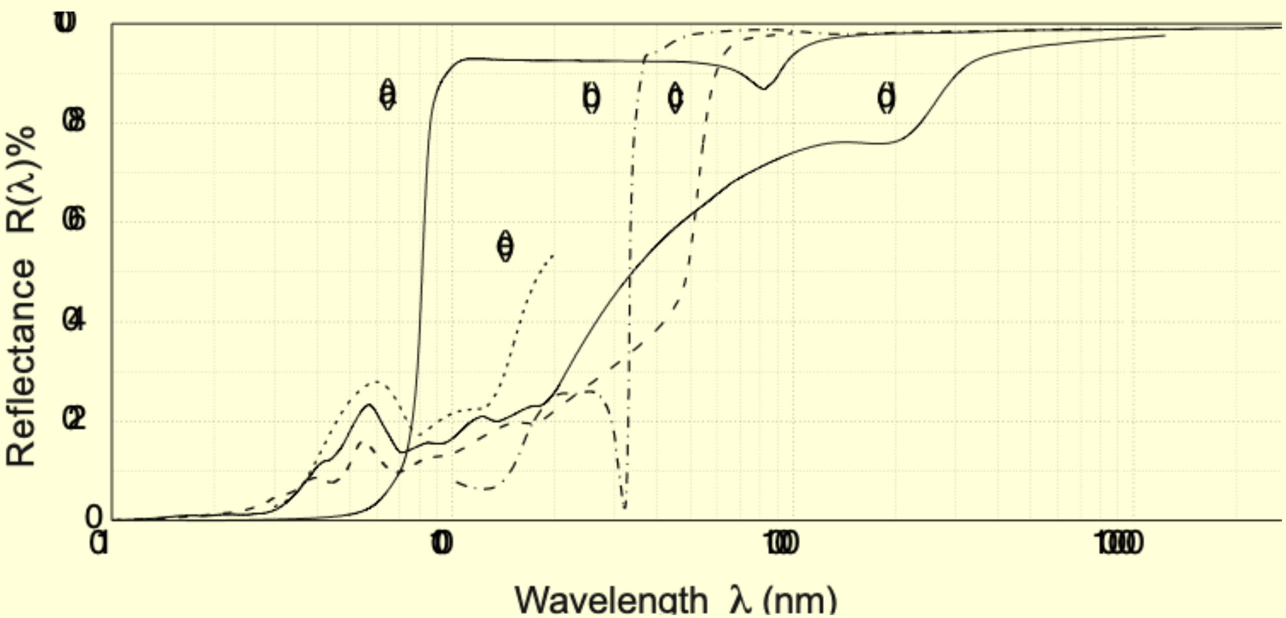
(a) Lexan (1 mm thick)
(b) Kapton (1mm thick)
(c) Be (10 mm thick)
(d) Be (100 mm thick)

Narrowband filters above 200 nm are based on single or multiple

Fabry-Perot etalons of thicknes nd=l/2, with the higher orders blocked

Mirrors

Thin metal coatings on plane, spherical, cylindrical or toroidal substrates are the standard mirrors over a wide range of wavelength because of the high reflectance!



(a) Al
(b) Silver
(c) Gold
(d) Platinum
(e) Osmium

Normal incidence reflectance drops at short wavelength

Reflectance is high for large angles of incidence α → **grazing incidence**

(Grazing incidence angle $\emptyset = 90° - \alpha$)

Selection of spectrographic equipment

Considerations

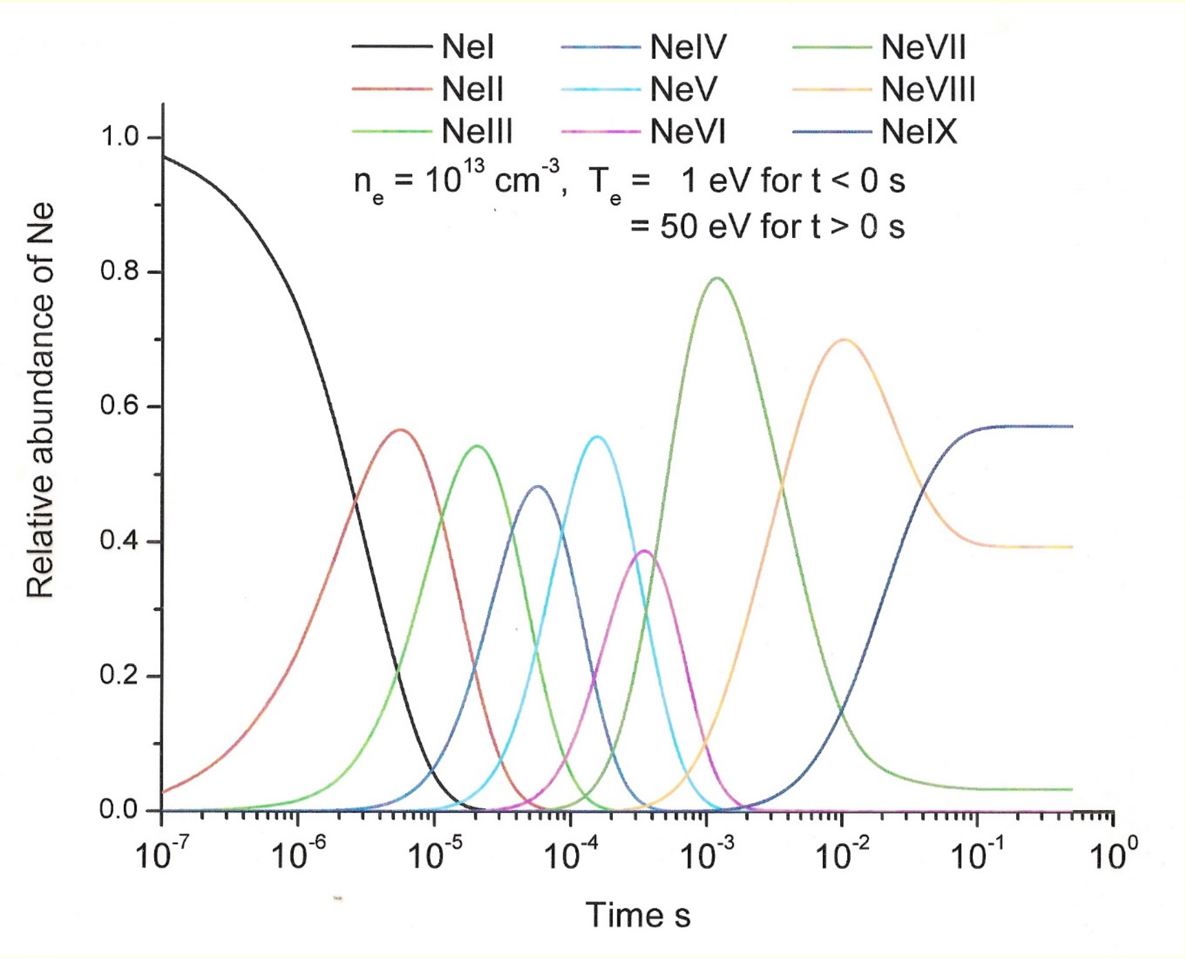
Survey spectra → low spectral resolution
Total line intensities → medium spectral resolution
Line profiles → high spectral resolution

Largest possible radiant flux → it is determined by the throughput or étendue (area of entrance slit times maximum solid angle)

important in cases of weak emission

Spectral region

(a rough estimate of the electron temperature is helpful here)



Atoms in a plasma go successfully through the ionization stages till ionization equilibrium is reached (ionization equals recombination)

Low densities

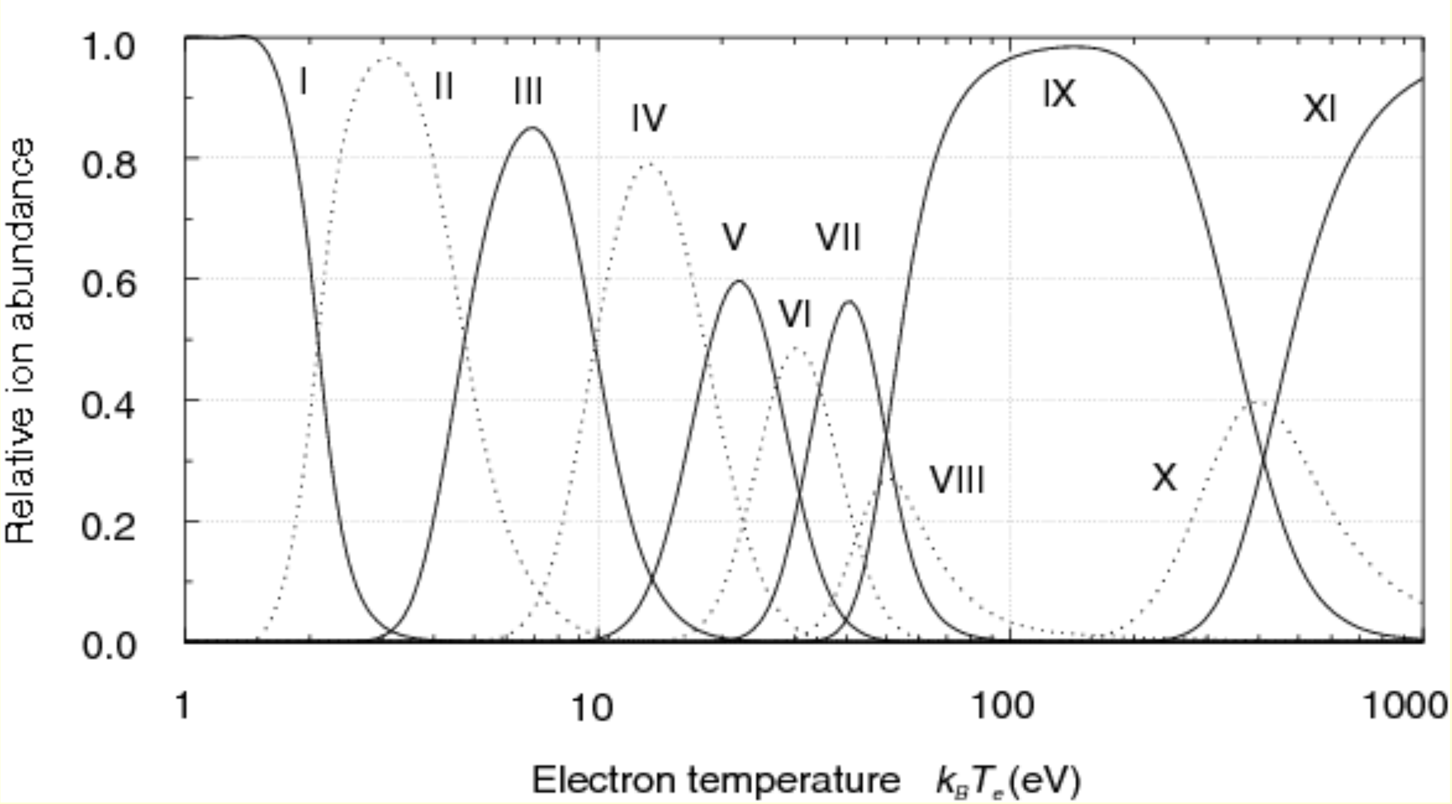
Corona equilibrium

$f(T_e)$

High densities

Saha equilibrium

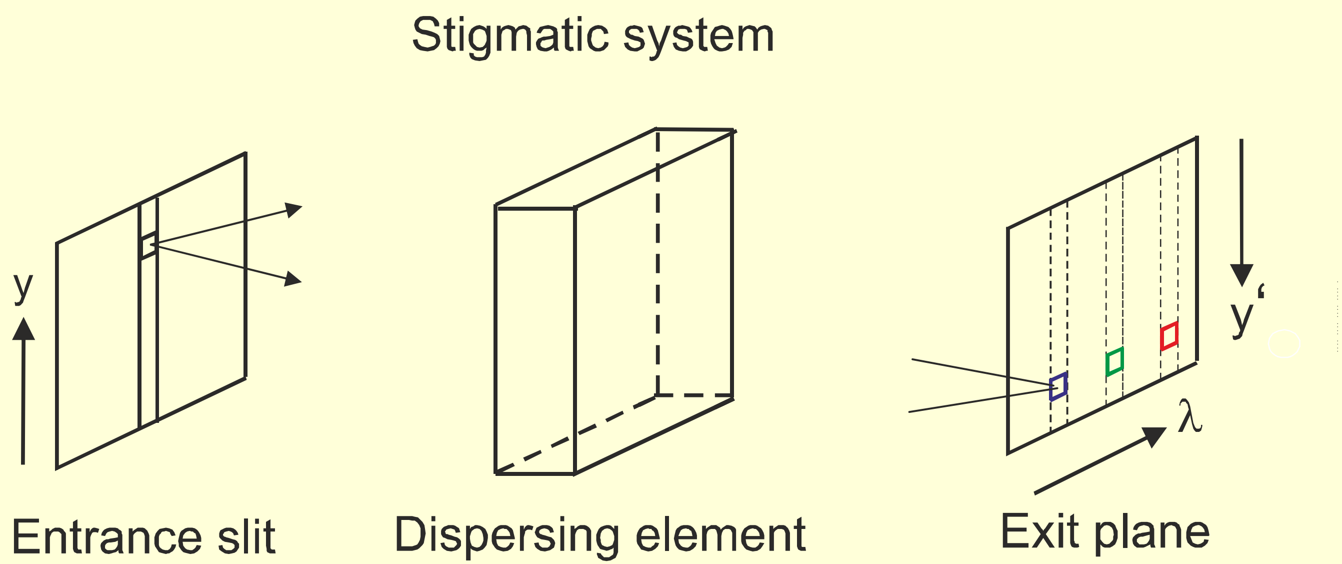
$f(T_e, n_e)$



Distribution of neon ions in corona equilibrium
With increasing electron density three-body recombination becomes important and pushes the maxima to lower temperatures

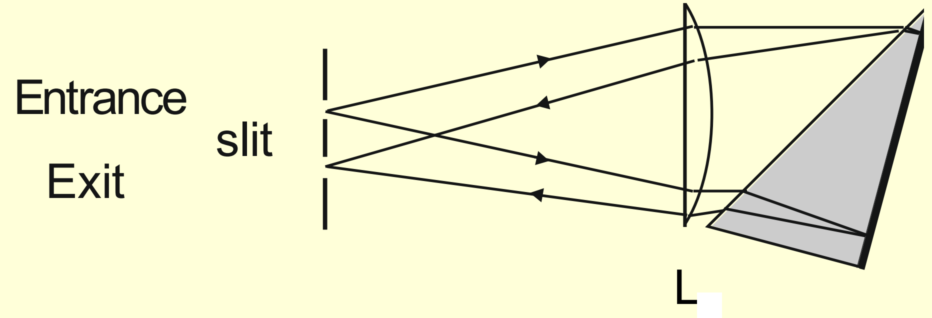
Once the dominant ions are known, one knows the spectral region of the major line emission

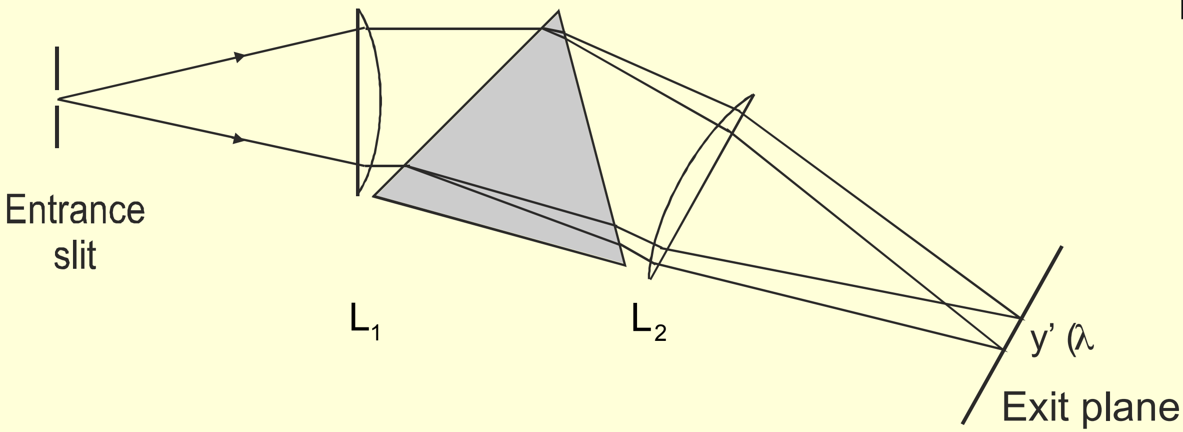
Stigmatic or astigmatic system ?



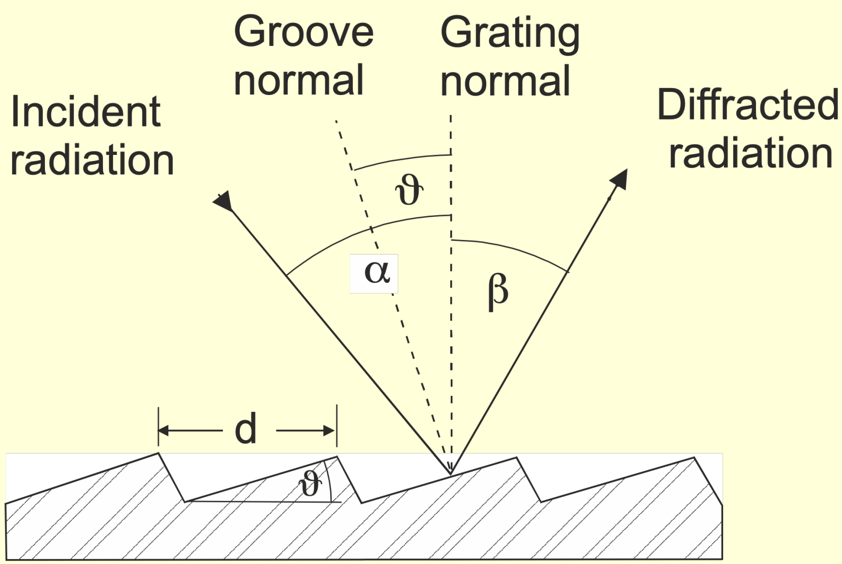
Dispersing elements and the main spectrographic systems

Prism instruments are cheap, simple to built and to align, have no overlapping orders, are practically everlasting and are easily cleaned





The majority of spectroscopic instruments employs gratings

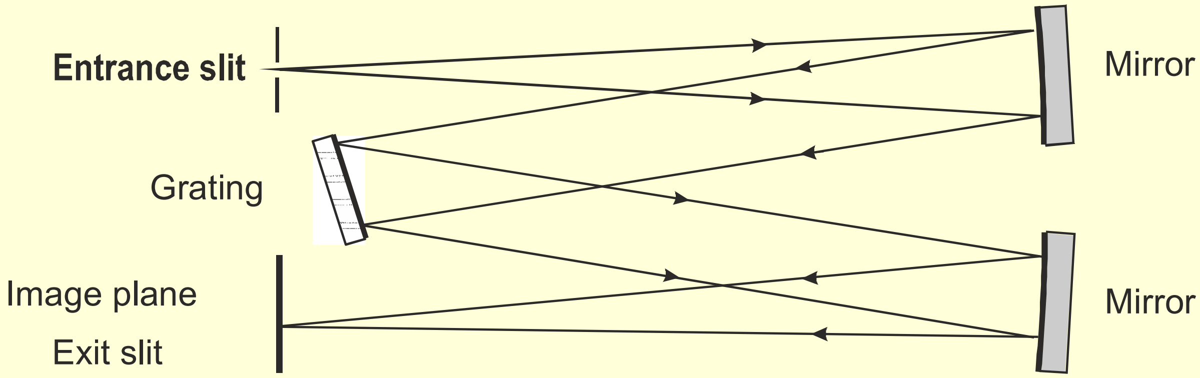


Ruled diffraction grating because of its shape diffracted power is concentrated into one direction

ϑ = blaze angle

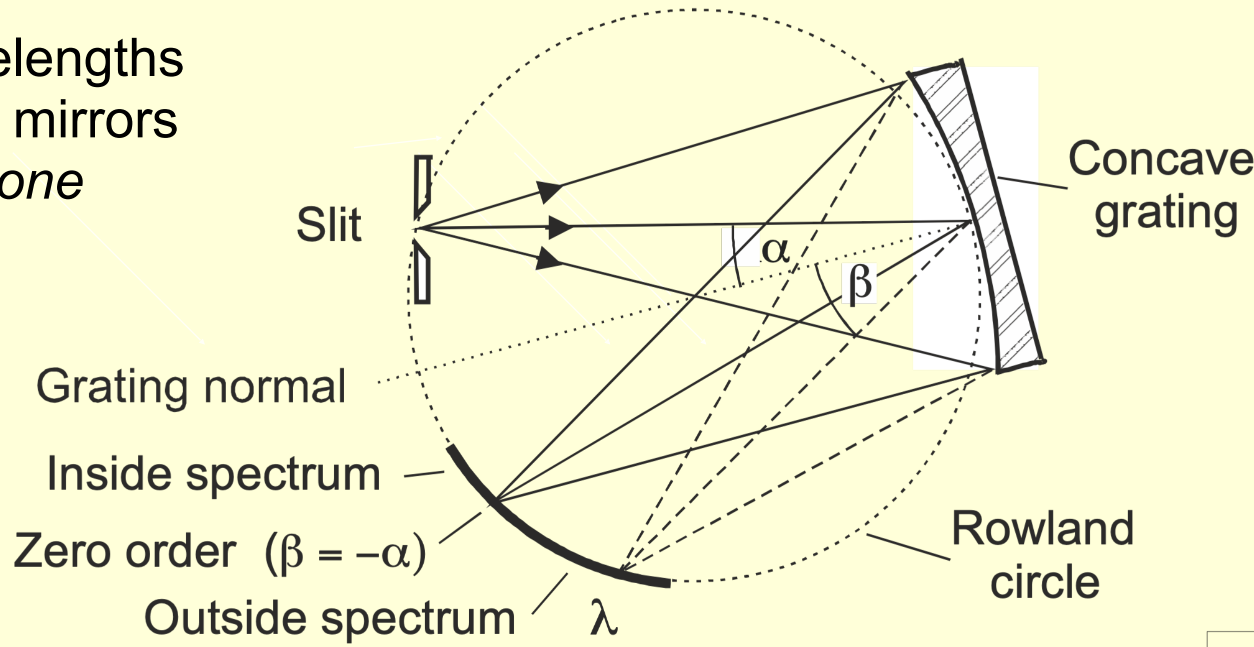
blaze wavelength 1. order
and a = 0
l_{B1} = d sin2J

The Czerny-Turner mount is probably the most commonly employed mount



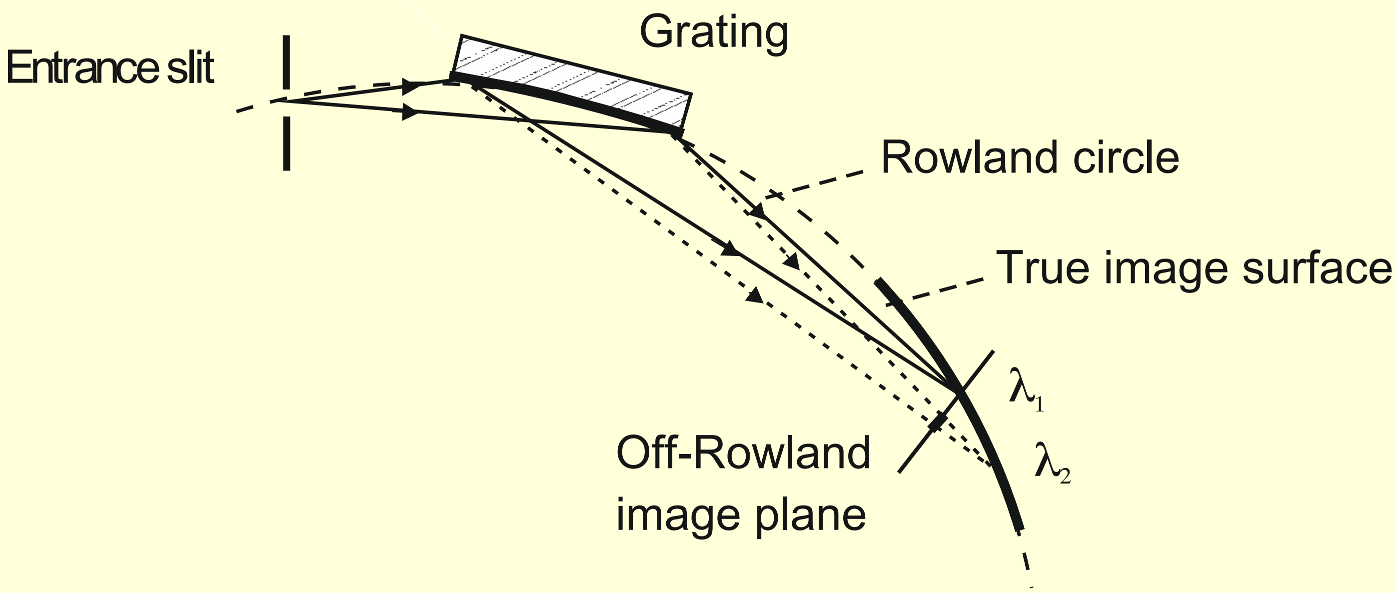
Three reflecting surfaces → high losses ?

For shorter wavelengths grating *and* both mirrors are replaced by *one* concace grating



Normal incidence instruments not usable below 30 nm because of negligible reflectance

→ grazing incidence instruments



Lowest reflected wavelength for a gold coated grating is 0.54 nm for a grazing incidence angle of 2°.

The alignment of these instruments requires great care.

The true image surface is curved !
Some low-resolution instruments use an off-Rowland image plane

Grazing incidence employing gratings with *varied line spacing*

are now also increasingly used

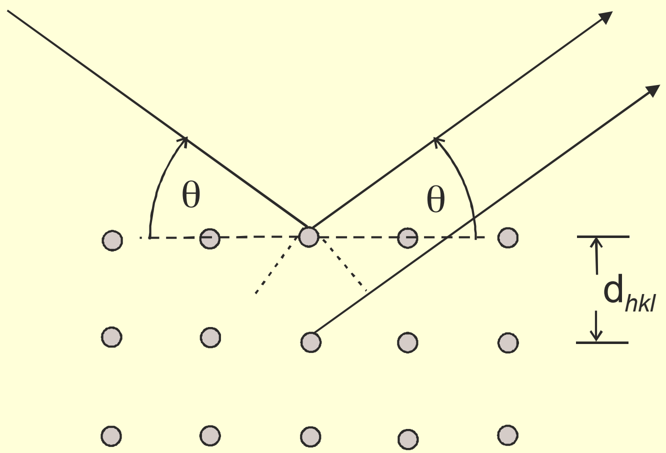
focal surface is flat over a large spectral region,

→ easier alignment !

Instruments are astigmatic !
This can be reduced in a combination with mirrors

Finally, high-efficiency instruments have been designed with toroidal gratings, varied line-spacing and curved lines to minimize abberations and to have a flat image plane

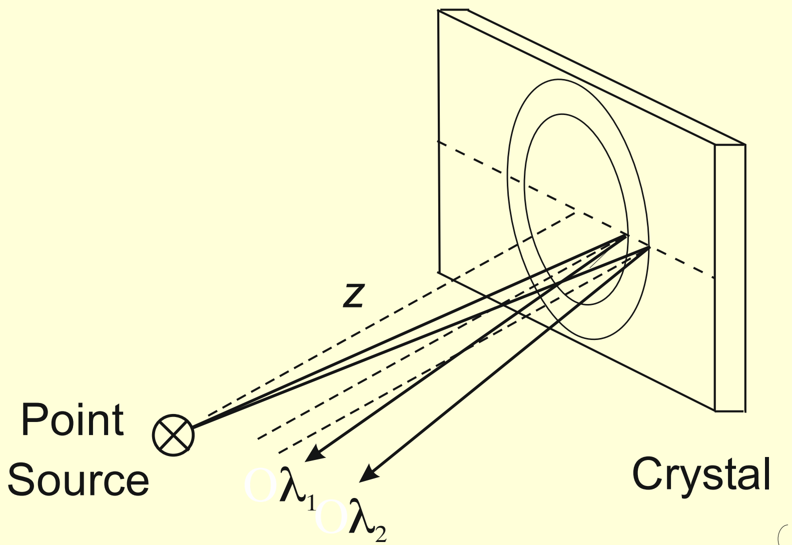
For wavelengths shorter than ≈10 nm crystals can be used as dispersing element



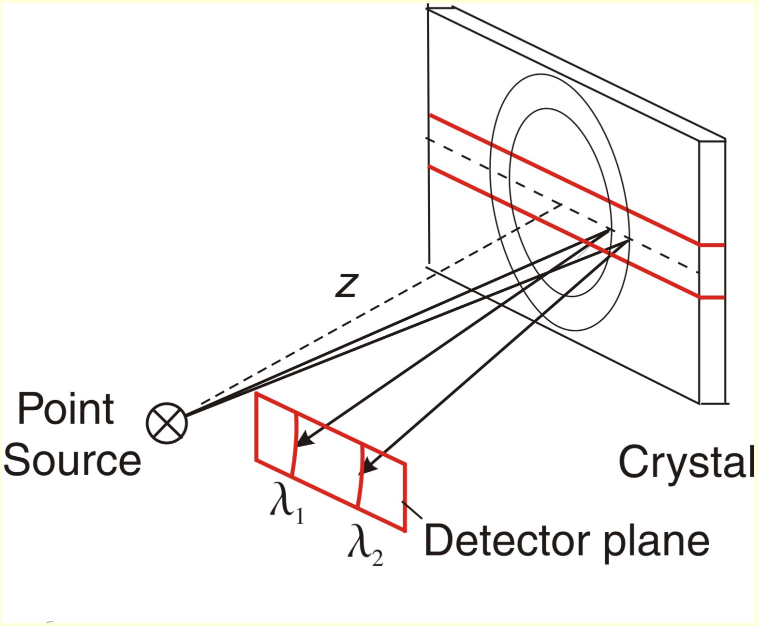
Waves reflected obey the famous Bragg condition for the wavelength

$$m\lambda = 2d_{hkl}\sin\Theta$$

d_{hkl} is the net spacing of the crystal planes



The radiation from a point source forms cones after reflection

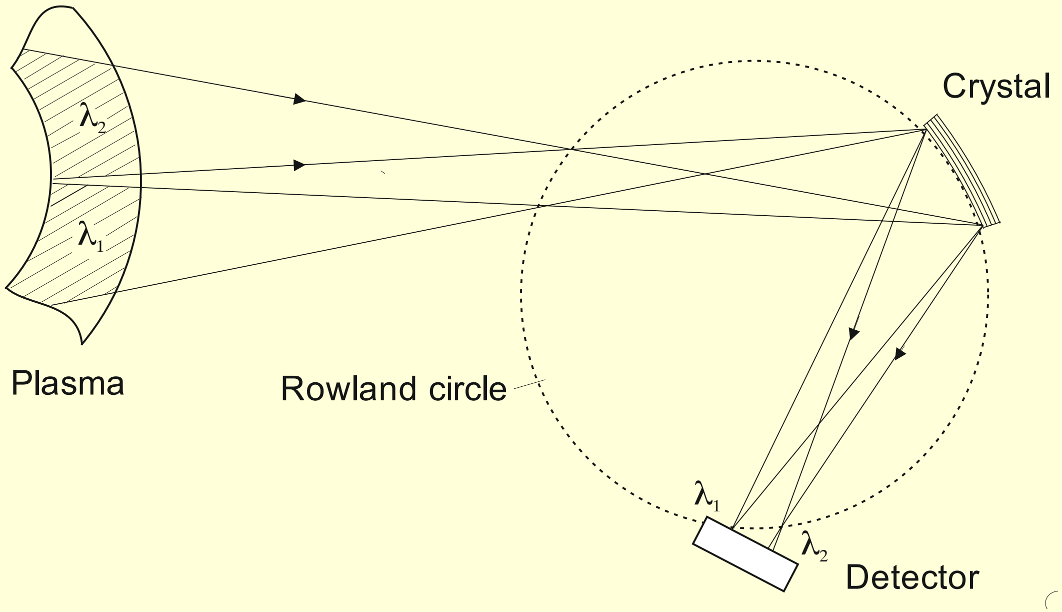


Depending on the position of the detector plane relative to the crystal the “spectral lines“ are sections of a circle, an ellipse, a parabola or a hyperbola

Keep in mind: each wavelength is reflected from a different part of the crystal !

A number of different useful crystals with different 2d spacing and different reflectivity are available,
supplemented by multilayer systems for the longer wavelengths

Bending the crystal introduces focussing properties analogous to those of concave gratings but imposing the additional condition of equal angles of incidence and reflection



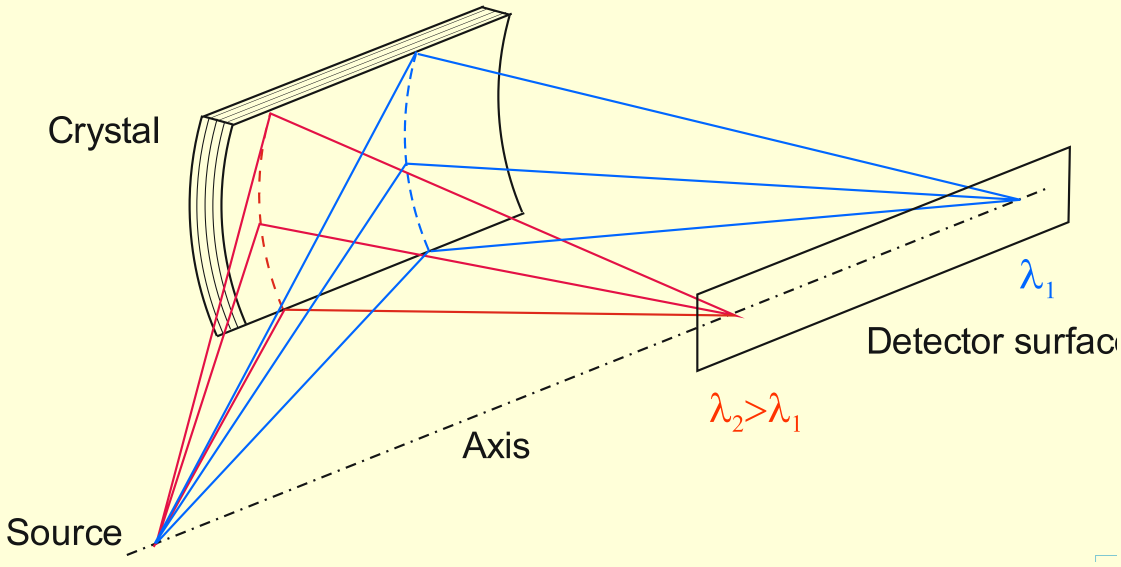
Johann mount
with a cylindrically
bent crystall

The plasma is placed
off the Rowland circle

Each wavelength is recorded from a different plasma region

With spherically or toroidally bent crystals nowadays also *spatially resolved* studies are possible.

Investigations of the polarization are possible, if the Bragg angle is equal to the Brewster angle of 45°. $2d_{hkl}$ of the crystal must be selected accordingly!



Van Hamos mount: cylindrically bent crystal, source and detector are on the cylindrical axis.

Detectors

They are selected in regard to the application

(a) A detector converts radiant flux F(l) into a current signal I

Spectral sensitivity
or responsivity

$$S(\lambda) = \frac{I}{\Phi(\lambda)} \quad \text{with} \quad [\mathrm{S}] = \frac{A}{W}$$

Time reponse is important
depending on the plasma ? steady state
slowly varying
extremely fast varying
plasmas

Characterized by either bandwith f_{bw}
or rise time T_r

$$f_{bw}\,T_r = 0.35$$

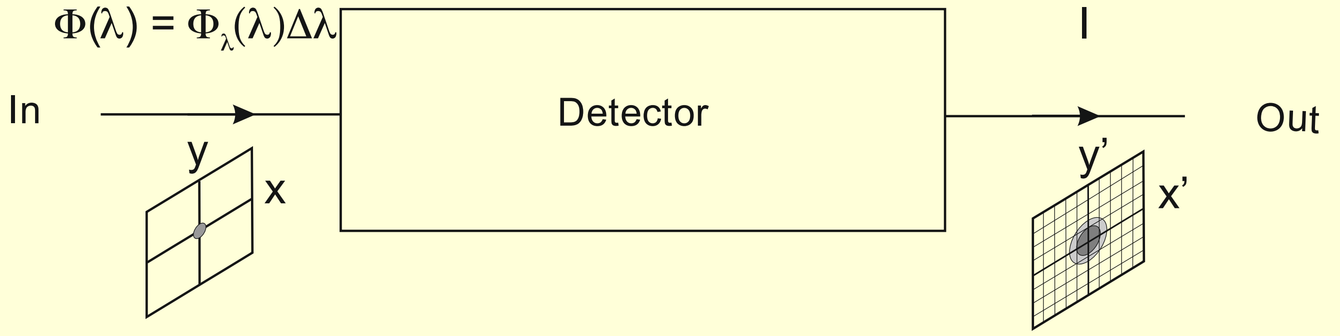
Dark current: output current without incident flux,
limits measurements at low flux levels,
in most cases of thermal origin →
cooling of detector

Internal delay time: important when correlating signals

Linearity of the system (dynamic range):

Long-time stability (aging?)

(b) Array detectors



Charge coupled devices (CCDs),
now most widely used,
produce a digitized image

Pixel size determines
spatial resolution

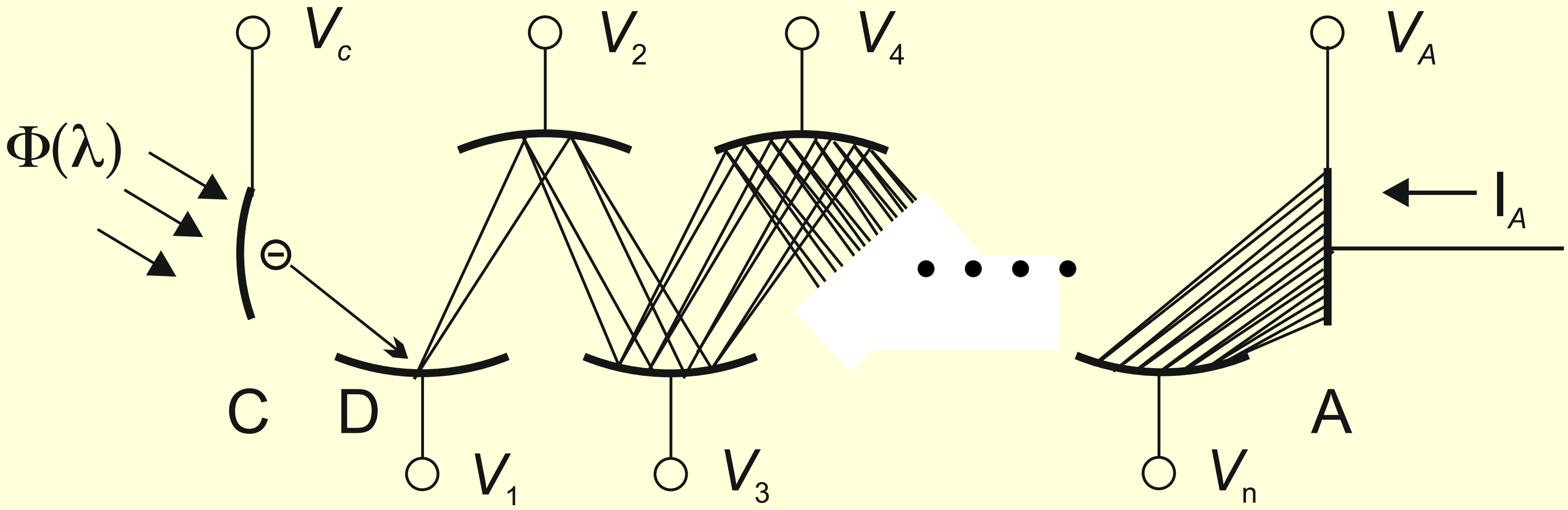
Image quality is desribed by a point spread function F(x‘,y‘)

Point object $f(x_0,y_0) \rightarrow F(x'-x_0', y' - y_0')$

Hence: A spectrograph with an entrance slit produces for monochromatic incident radiation an image called instrument function in its exit plane, and this has to be convoluted with the point spread function to obtain the image in the detector exit plane

For rapidly changing plasmas *gate times* are important as well as *frame rate* and *total number of frames.*

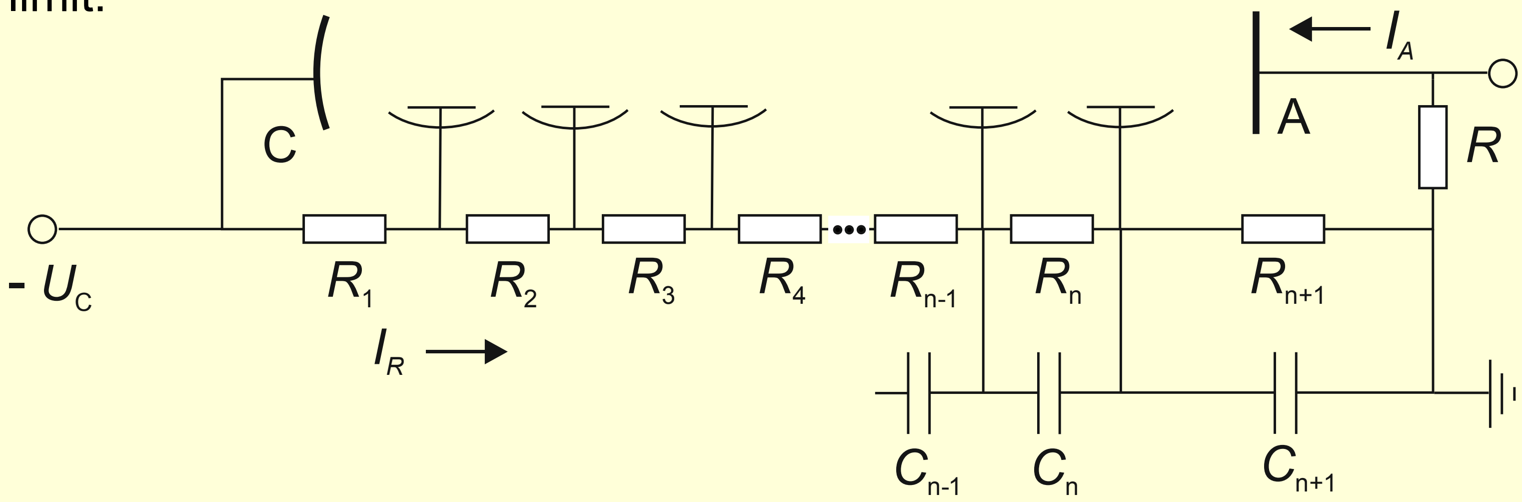
Photomultiplier Tube (PMT)



Radiant flux incident on the photocathode releases electrons; these are accelerated towards the first dynode, where they release secondary electrons, etc., till an electron avalanche arrives at the anode. This arrangemnet thus gives built-in internal amplification

Attention: If the electron current from the cathode becomes too large, space charge develops between cathode and first dynode, system does not more work anymore

Next limit:



Voltage to the cathode and dynodes is supplied by a voltage divider. For high currents especially between last dynode and anode, the voltage will drop!
Solution: Capacitors between the electrodes, which have to be properly selected!   This has too be watched.
Also entrance window and cathode materials determine the spectral sensitivity!

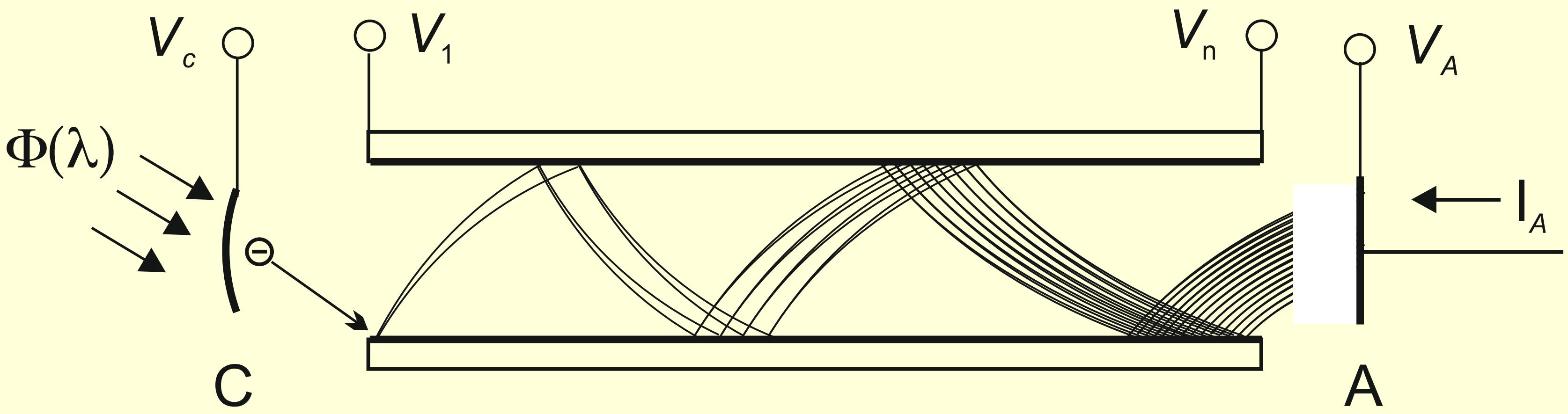
Vacuum-UV and x-ray spectral region

Properly selected *scintillator materials* are placed in front of the PMT

Quantum efficiency,
decay time of the fluorescent radiation,
matching the spectrum of the fluorescent radiation to the spectral sensitivity of the cathode of the PMT

Channel photomultiplier

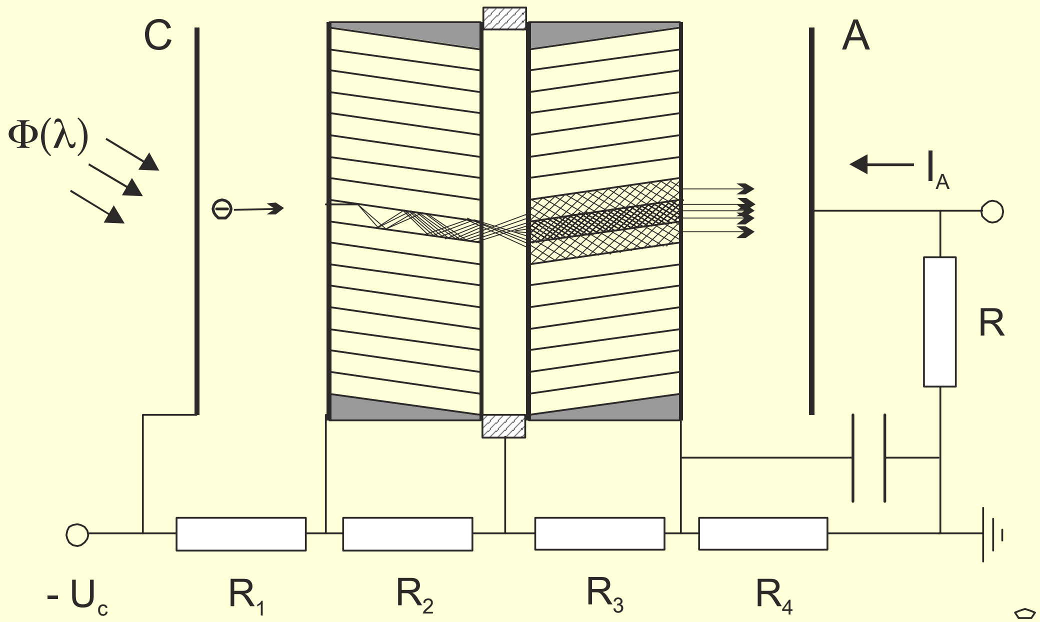
Discrete dynode structure is replaced by a channel electron multiplier



Separate photocathode can be redundant if inner wall has photo-emissive properties

Many channels in parallel → *microchannel plates* MCPs

Example of a two-stage MCP photomultiplier



Replacing the anode by a phosphor → image converter and image intensifier

Phospor can be coupled by fiberoptic to a CCD camera,
multiframe systems are available,
gating is easy by pulsing the voltage

A variety photodiodes are avaiable for the spectral region from 0.4 to 15 μm, and for the VUV and soft x-ray region

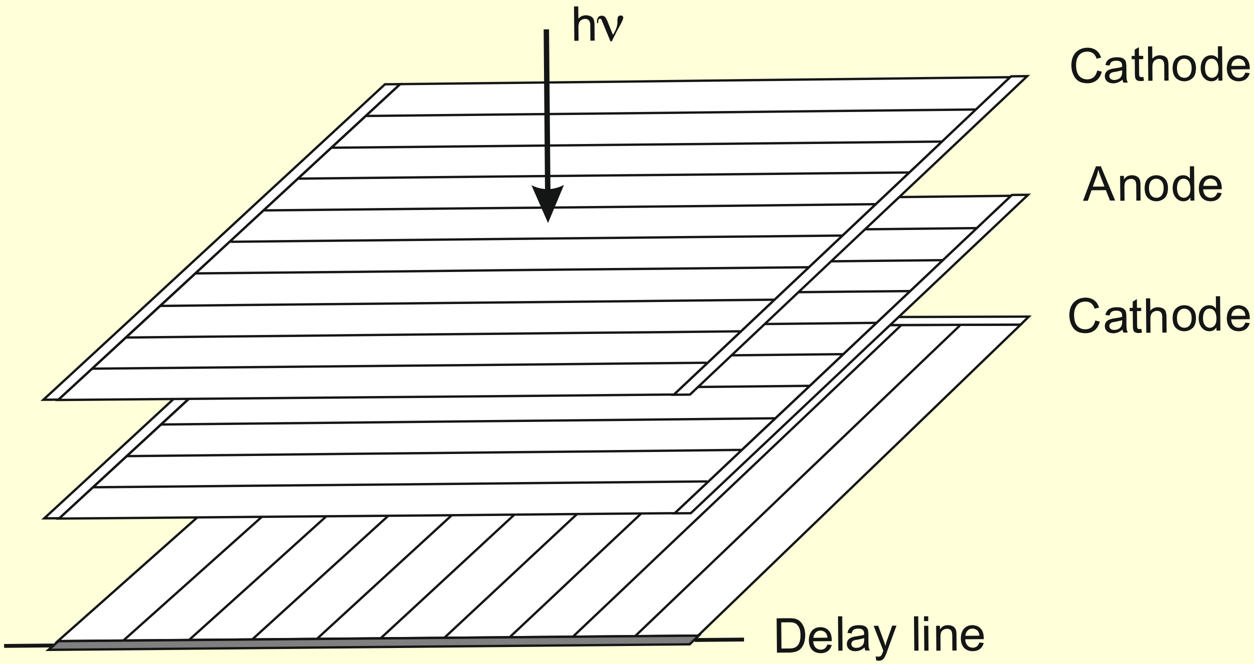
For photons above 1keV p-i-n diodes are excellent energy-resolving detectors for single photons by pulse-height analysis, no spectrograph necessary

Two-dimensional arrays made up of metal–oxide semiconductor capacitors (pixels) are known as CCD‘s. Charge is collected on each pixel and is read out.

Ionization chambers and proportional counters use the ionization of fill gases and are thus well suited for the x.ray region.

Multiwire proportional chambers (MWPCs) are widely employed in the exit plane of X-ray spectrographs on magnetic fusion devices

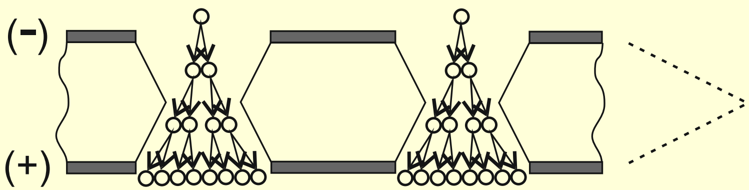
They consist of many single wire units closely spaced in parallel

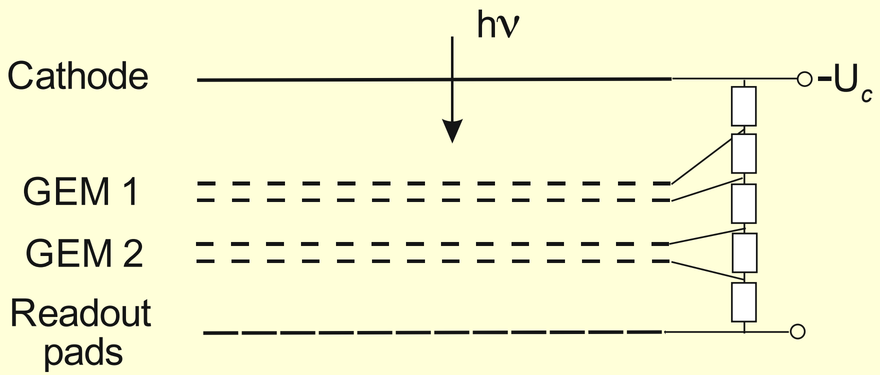


A photon produces an electron avalanche arriving on the anode, that induces an electron pulse on the cathode wires, and the difference of the arrival times at both ends yields the position

Two cathode planes as shown above allow two-dimensional encoding

Last but not least gas amplification multipliers.
Their concept was introduced by Sauli in 1997,
The basic element is known as gas electron multiplier (GEM)





A high electric field in the bi-conical holes leads to a multiplication of the primary photoelectrons by collisional ionization

Advantages: Amplification by 10^3
relatively cheap
robust against radiation damage
two-dimensional arrangement
two-stage systems possible

Calibration

Wavelength calibrations

For reliable measurements always do your own calibration of the spectrograpic system
even if suppliers claim to deliver to a calibrated system
(shipment may have caused misalignment)

UV to infrared region: commercial spectral lamps are available
VUV : high-current hollow-cathode discharges
X-ray region: seeding a hydrogen plasma with a proper impurity is the most simple approach, wavelengths of lines are well documented

Sensitivity calibration

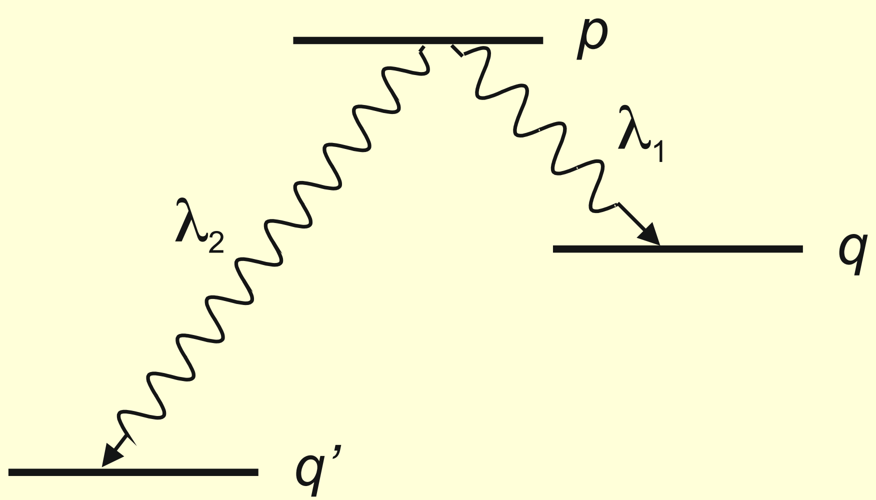
The absolute sensitivity calibration of a spectrographic system is best done for the complete system and not for the individual components *and,* with respect to the illumination, at conditions similar to those of the later application

Primary and secondary radiance standards

The **blackbody radiator** is a primary standard for the infrared to the visible region.
Its spectral radiance is determined by Planck‘s radiation law,
it is a function of the temperature only,
It is independent of the angle between the direction of emission and the normal of the surface (Lambert law).
A blackbody is realized by a hohlraum with a small hole as emitting surface

Electron storage rings are the radiometric standard sources for short wavelengths
Drawback: emission is into a small cone,
it is polarized
System has to be moved to the location of the synchrotron !

The sensitivity calibration of a system installed on a plasma device is easily transferred from one spectral region to another by *the branching ratio* method



One takes two lines from the *same* upper level p

The ratio of their radiances is simply

$$\frac{L(\lambda_2)}{L(\lambda 1)} = \frac{\lambda_1}{\lambda_2}\frac{A(p \to q')}{A(p \to q)}$$

Once you know the radiance of the line in one spectral region, you know the radiance of the second line, and you can derive the second spectral sensitivity.

Of course, the transition probabilities **A** must be known with sufficient accuracy

Two-dimensional recording in the exit plane of a spectrograph:
sensitivity variations along the Y-direction must be accounted for.

Causes can be vignetting of the optical path,
pixel to pixel changes of array detectors (corrections are
summarized as “flat fielding“

Fast-gated systems like image intensifiers can show
the “irising effect“:

Finite travel time of the gating pulse from the edge to the center
may lead to a delay in switching

A number of **secondary standard sources** have been developed and are available.

They are usually calibrated against a primary source.

UV to Near-Infrared

Tungsten-strip lamp,
it is the most commonly used secondary standard.
A tungsten strip in argon is heated by a highly stabilized arc to temperatures between 1600 to 2700 K.
Extensive tables are available to multiply the blackbody radiance with the spectral emissivity of tungsten

Low current carbon arc
it is a simple and easy to use secondary radiation standard,
its radiance has been well studied

Vacuum-Ultraviolet

Wall-Stabilized Arcs

Radiances are reported from from 95 to 330 nm

Deuterium lamps

They emit a line-free continuum from 165 to 350 nm

High-Current Hollow-Cathode Discharge

Between 13 and 125 nm, it emits a number of spectral lines with high reproducibility. The emission was calibrated against the synchrotron radiation of an electron storage ring

X-Ray Region

No standard sources are commercially available.
One group reported the development of a large-area X-ray source for the calibration of spectrometers.
It emits characteristic x-ray lines in the standard way by bombarding a cathode with fast electrons.
The radiance of the lines is obtained from the spectrum derived via pulse-height analysis of the photons.

The complete material of this lecture is from

Introduction to Plasma Spetroscopy

Springer 2009
Peking University Press 2013 (reprint)