Plasma Diagnostics of Ion Sources

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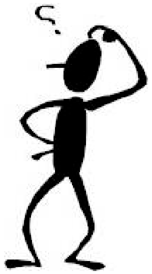
Diagnostics – The Window to the Knowledge

- **Langmuir probes:** ϕ_{pl}, n_e, T_e
- **Absorption techniques:** $n_s \rightarrow$ Cs, H^-
- **Emission spectroscopy:** n_s, $T_s \rightarrow$ e, H, H_2, H^-

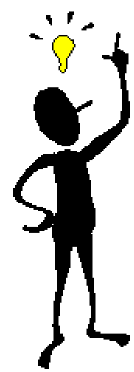
Monitoring and Quantification – Spatial and Temporal Resolution

Preliminary considerations



What do I want to know?

- identify the quantity (and the reason for it)
- define the required precision
- temporal behaviour and required time resolution
- necessity for spatial resolution
- ...



Adequate diagnostic technique?

- extensive or simple setup
- data acquisition and evaluation
- reliability
- costs and time (manpower) needed
- ...

Accessibility of the ion source?

- diagnostic ports
- test stand or continuous operation
- risks and feasibility
- reliability
- ...

General plasma diagnostics techniques

invasive – non-invasive ; active – passive ; basic – specific parameters

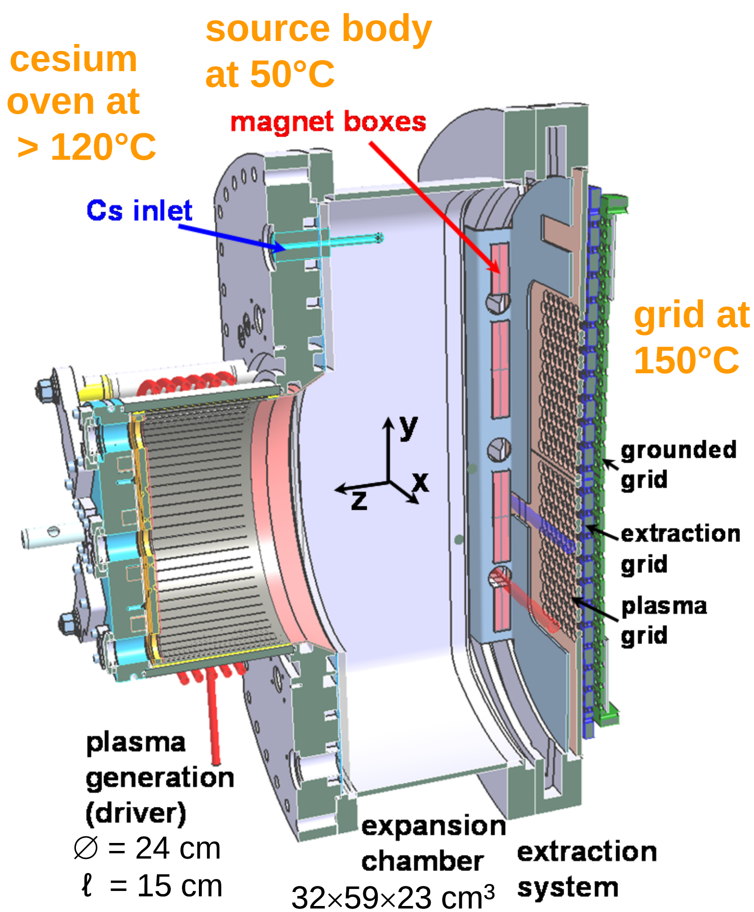
Method	Standard	Sophisticated	Extras
Langmuir probe	single probe (cylindrical or planar)	double or triple probe emissive probe	special method: Boyd-Twiddy
emission spectroscopy	optical wavelength range with fibre optics & survey spectrometer	extended wavelength range VUV, UV or IF	sophisticated system spectral resolution, type of detector
absorption spectroscopy	white light absorption technique	tuneable laser absorption	cavity-ringdown spectroscopy
Laser methods	laser induced fluorescence	TDLAS	
mass spectrometry	residual gas analyser	energy resolved mass spectrometry	

Introduction into techniques and applications for example in [1] – [7]

Example case: IPP ion source for negative hydrogen ions

ICP: f = 1 MHz, P = 70 kW, p = 0.3 Pa

6s plasma (4s beam), every 3 min: BATMAN
cw, up to 1 hour, every 3 min: MANITU



H^- formation and losses ...

volume process

$$H_2 + e^- \xrightarrow{H_2(B,C)} H_2(v) + e^- + h\nu$$

followed by

$$H_2(v) + e^- \xrightarrow[H_2^-]{} H^- + H$$

dissociative attachment

surface process

$$H, H_x^+ + \text{surface } e^- \rightarrow H^-$$

low work function
caesium layer

destruction processes

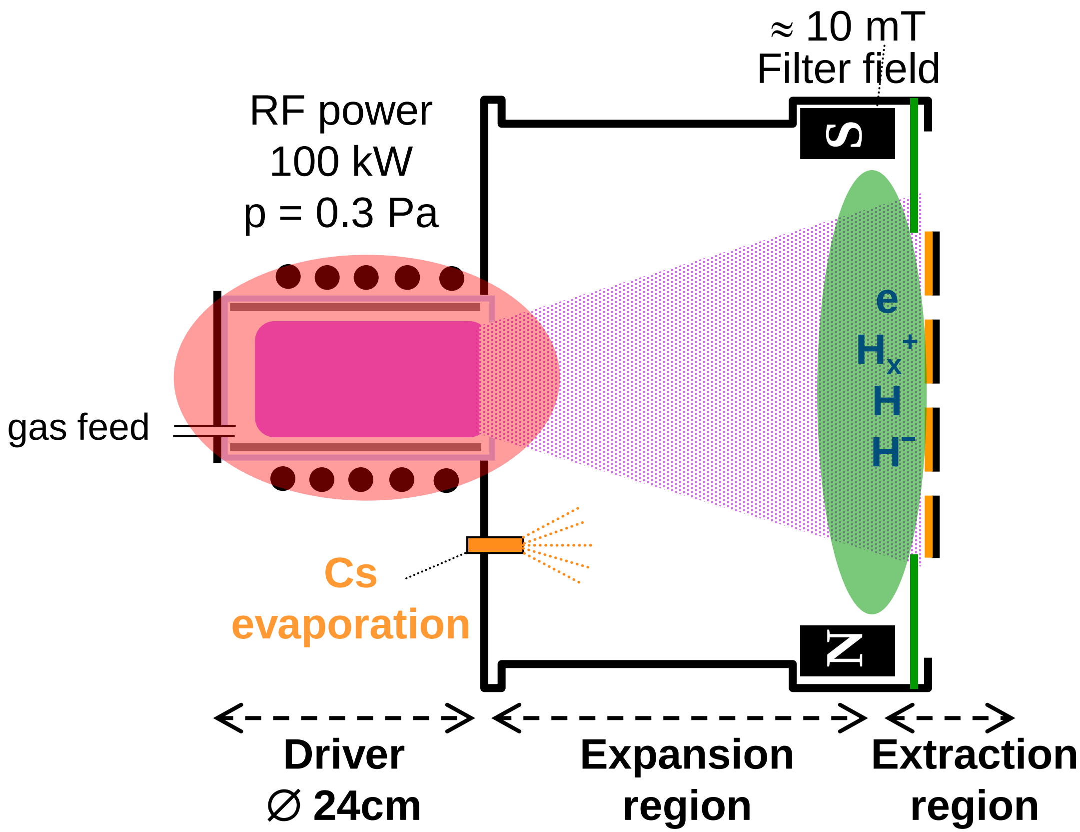
$$H^- + e^- \rightarrow H + 2e^-$$

$$H^- + H^+ \rightarrow H + H$$

$$H^- + H \rightarrow H + H + e^-$$

... determine source optimisation

Ion sources for negative hydrogen ions: ionising – recombining plasma



H, H_x^+ + surface e^- → **H^-**

Cs evaporation → low work function

Plasma generation
ionising plasma

- ionisation: $\alpha \approx 0.1$
- dissociation: $\delta \approx 0.3$
- $T_e \approx 10$ eV, $n_e \approx 5\times10^{18}$ m^{-3}

H^- generation
recombining plasma

- $T_e \approx 1$ eV, $n_e \approx 5\times10^{17}$ m^{-3}
- $H^-/n_e \approx 0.1 – 5$
- $Cs^+/n_e \approx 0.01 – 0.1$

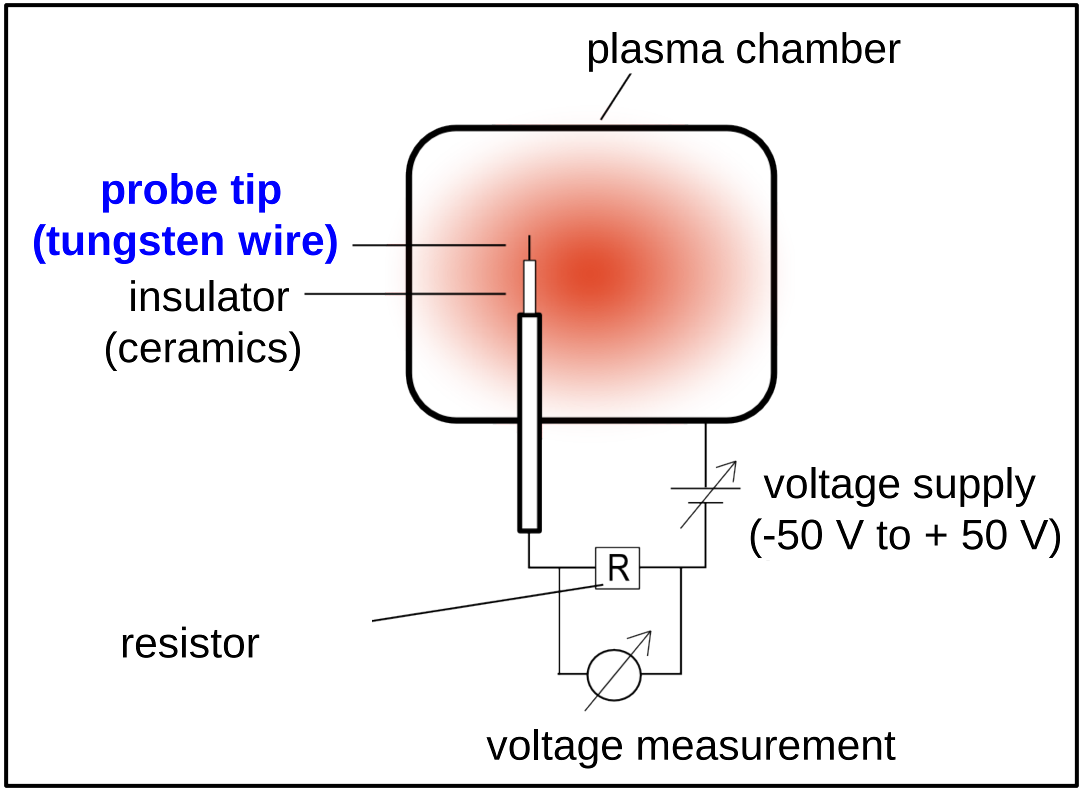
Main issues

- Production and destruction of negative ions
- Extraction of negative ions
- Reduction of co-extracted electrons

focus of diagnostics (and modelling) on plasma close to the grid

Langmuir probes: ϕ_{pl}, n_e, T_e, (EEDF)

Main principle



- stick a wire into the plasma
  tungsten, ∅≈ 100 µm, l = 1 cm
- choose a reference electrode
  potential of plasma chamber
- apply a variable voltage
  typ. from - 50 V to + 50 V

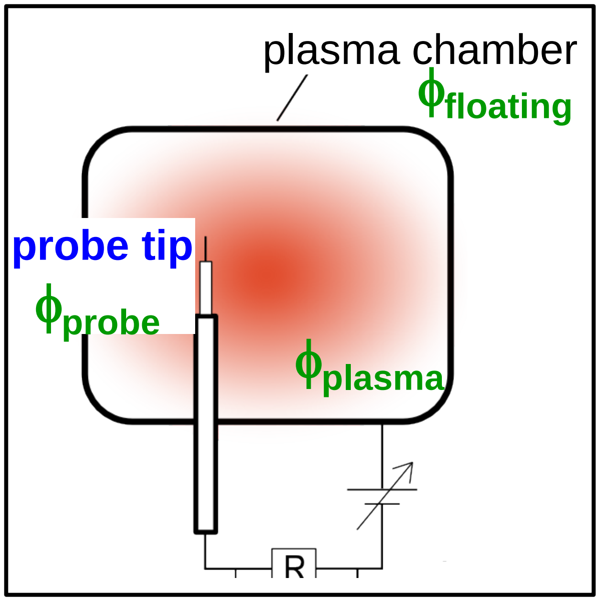
⬇

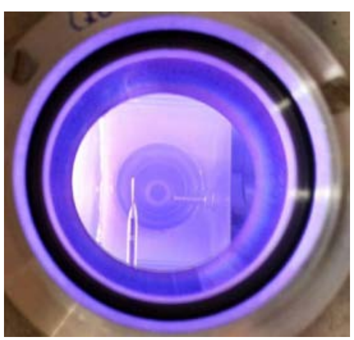
I – V characteristics

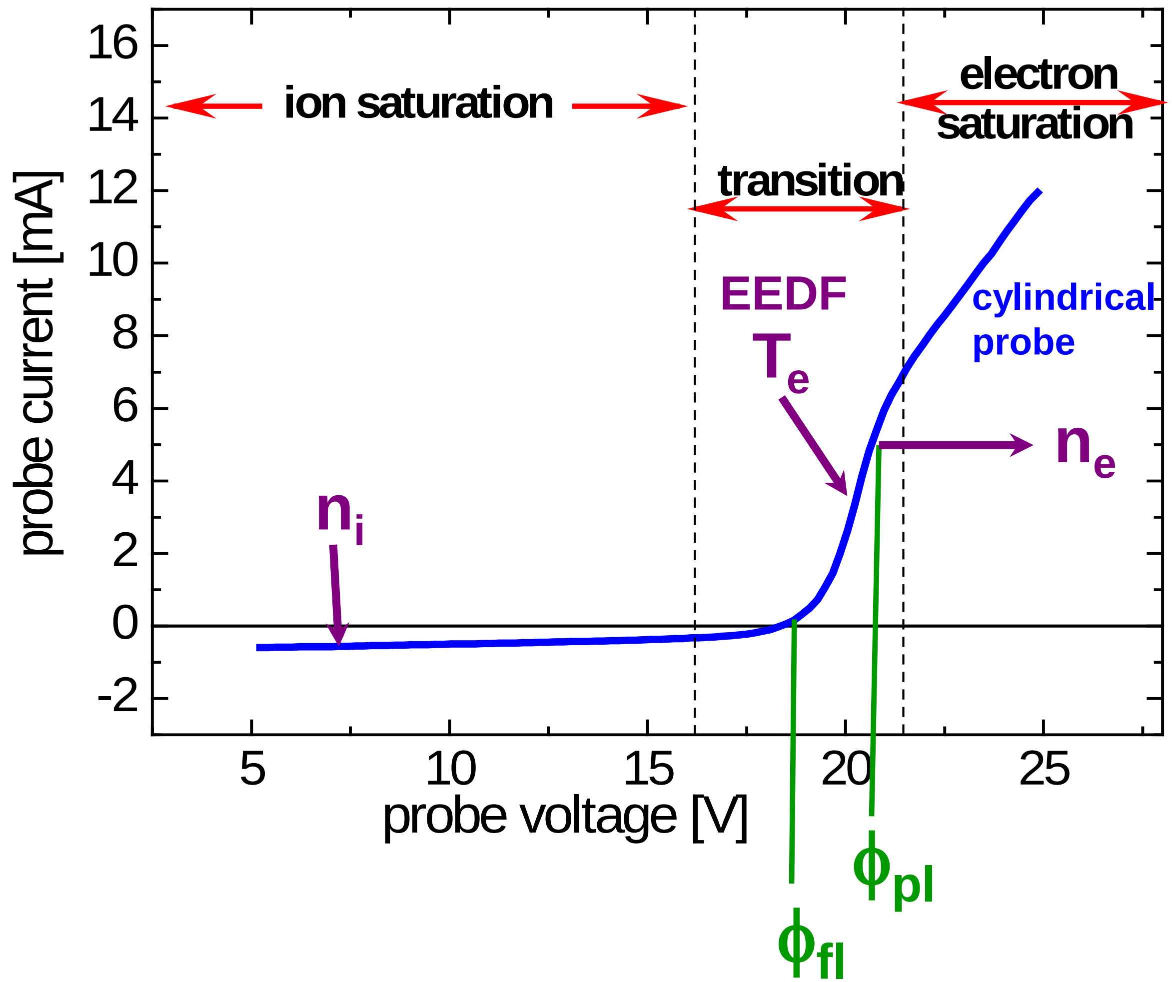
Recommended text books [1], [2], [5], [6] & publications and programs by F.F. Chen [8]

Langmuir probes: ϕ_{pl}, n_e, T_e, (EEDF)

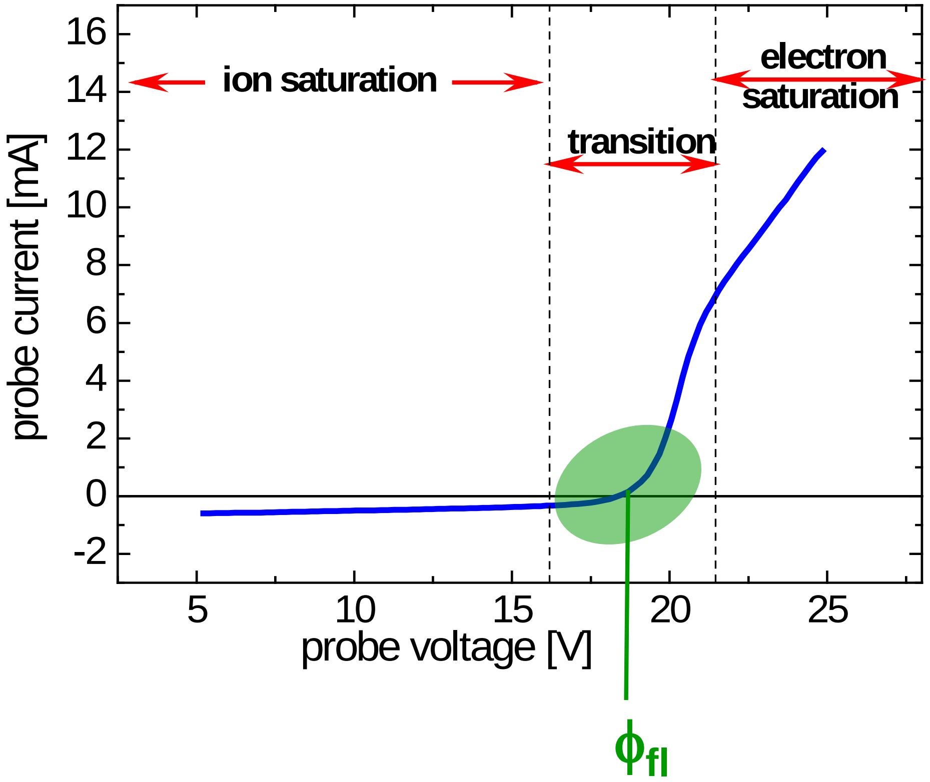
Main principle







Floating potential



- same fluxes for ions and electrons

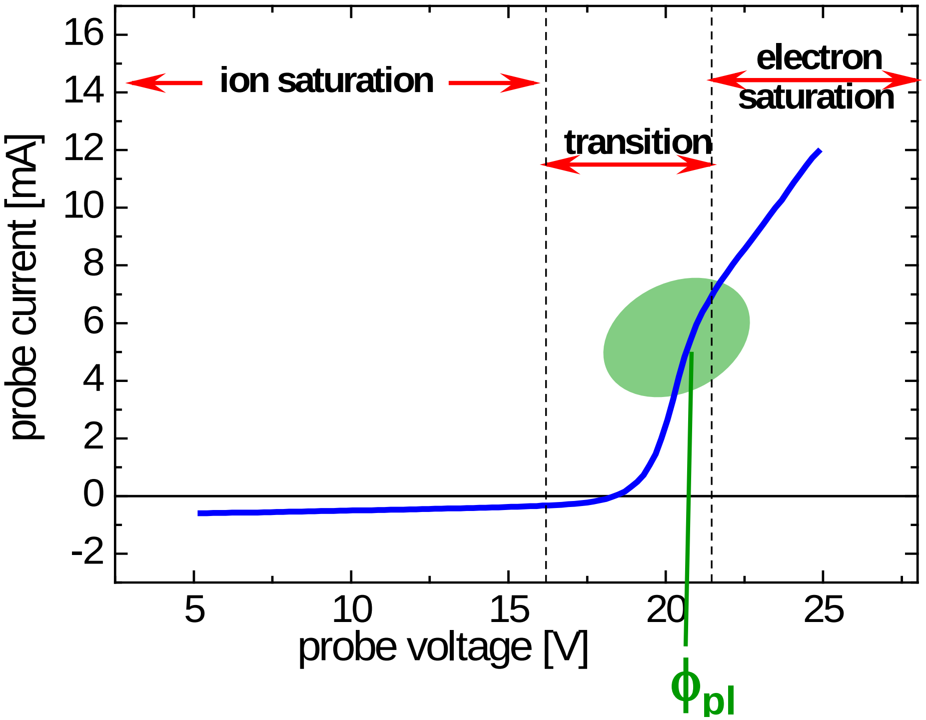
  $\Gamma_{ions} = \Gamma_{electrons}$

  same currents

- no probe current

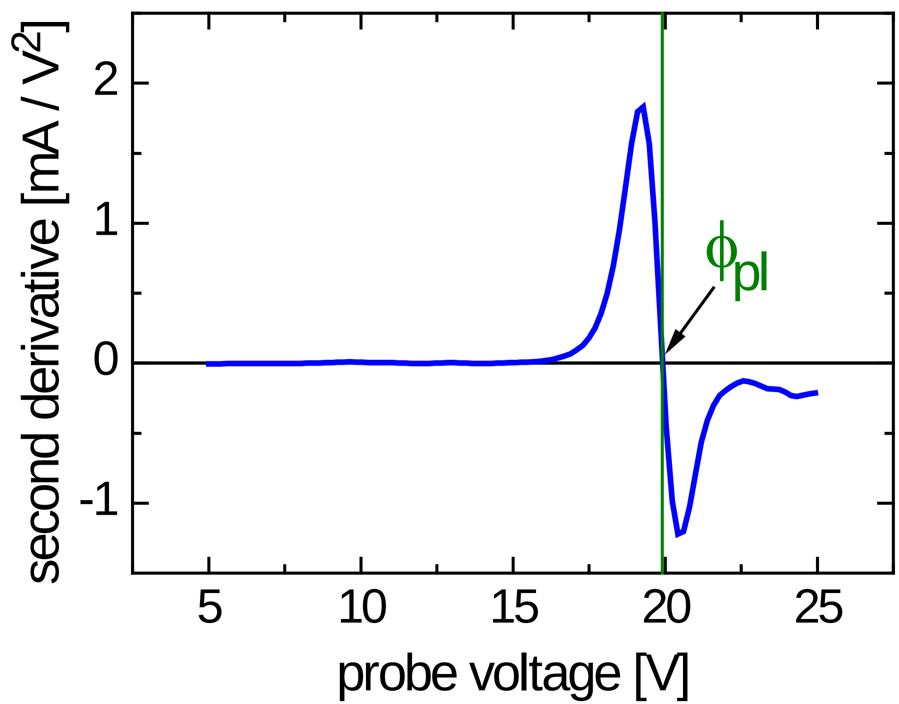
$$I_{probe} = 0 \rightarrow \phi_{fl}$$

Plasma potential



- determined by ambipolar diffusion
- turning point of I-V characteristics
- zero-crossing of second derivative

$d^2 I / d \phi_{pr}^2 \rightarrow \phi_{pl}$

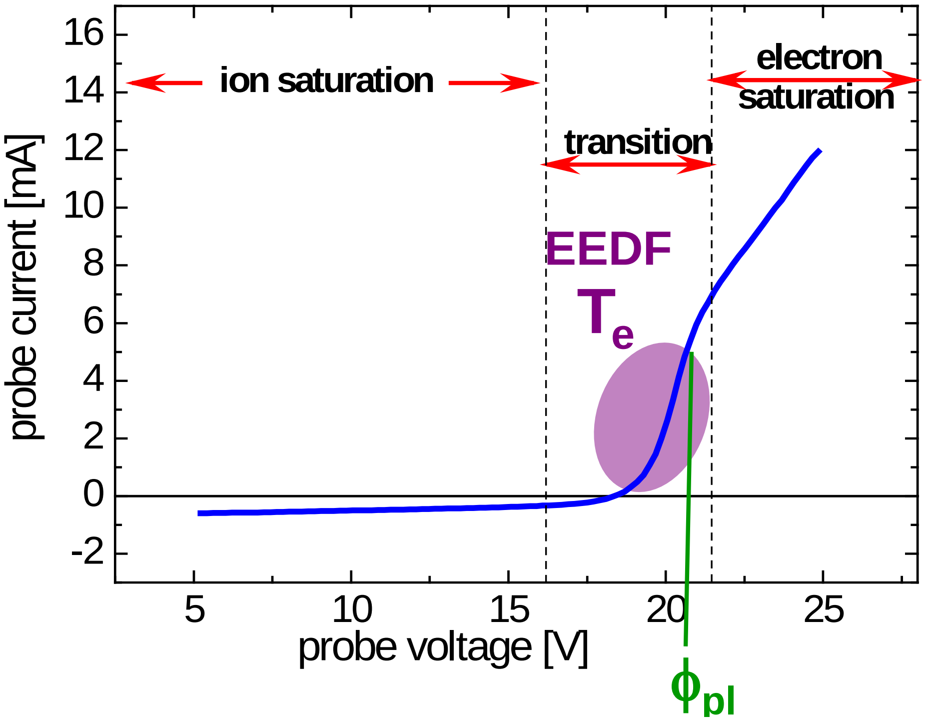


- for curves with high noise level

  crossing of linear fits to electrons saturation current and transition close to turning point

Langmuir probes: ϕ_{pl}, n_e, T_e, (EEDF)

Electron energy distribution function (EEDF) and electron temperature

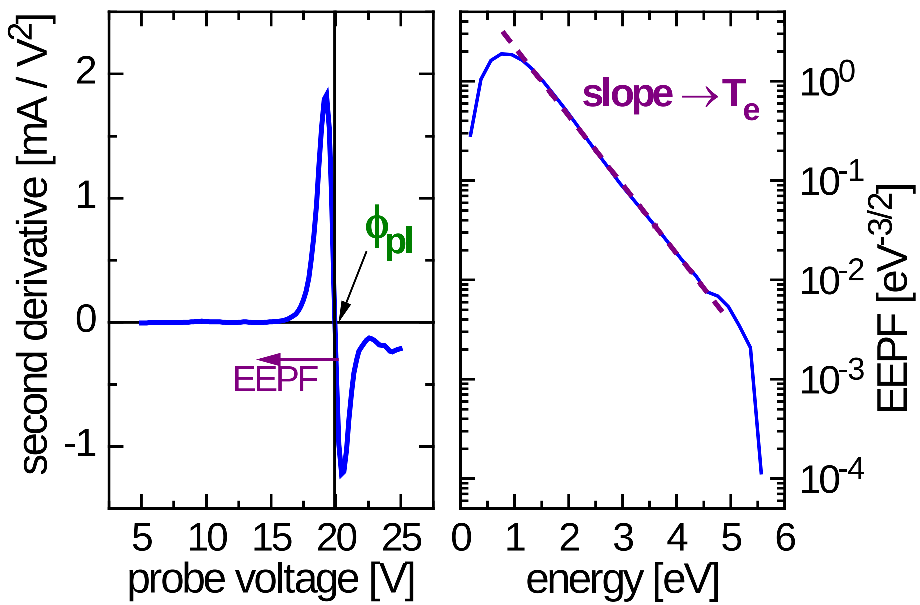


- distinguish: **EEDF = sqrt(E) × EEPF**

  e.g.: Maxwell function — probability function

  for both: normalisation
- plot $\log(I_{pr})$ versus $E = \phi_{pl} - \phi_{pr}$
- slope yields T_e for Maxwell EEDF

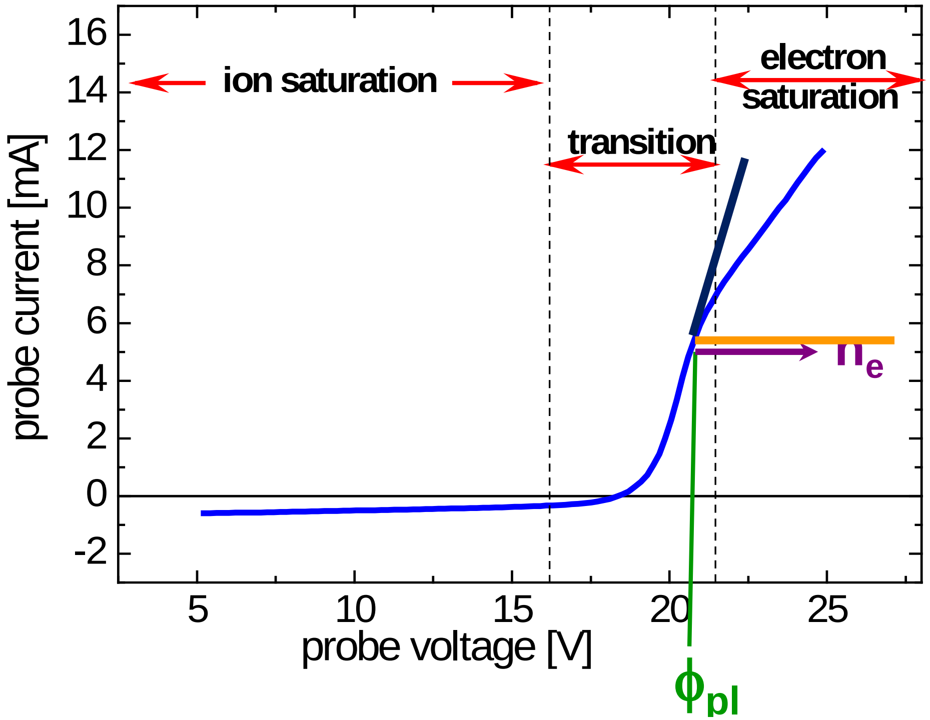
  $$d(\ln I) / dE = e / (k_b T_e)$$



- T_e also from potential difference

  $$\phi_{pl} - \phi_{fl} = k_b T_e \times \ln(\mathrm{sqrt}(m_i/(2\pi m_e)))$$
  $$\approx 2\text{-}3 \times T_e$$

The electron density



- electron saturation current

$$I_{e,sat} = \frac{1}{4} n_e e v_e A_{eff}$$

- problem: effective probe area
  due to increase of plasma sheath

- take current at plasma potential
  $\rightarrow$ $A_{eff} = A_{probe}$

$$n_e = \frac{I(\phi_{pl})}{r_{pr} l_{pr} e} \sqrt{\frac{m_e}{2\pi k_B T_e}}$$

needs T_e

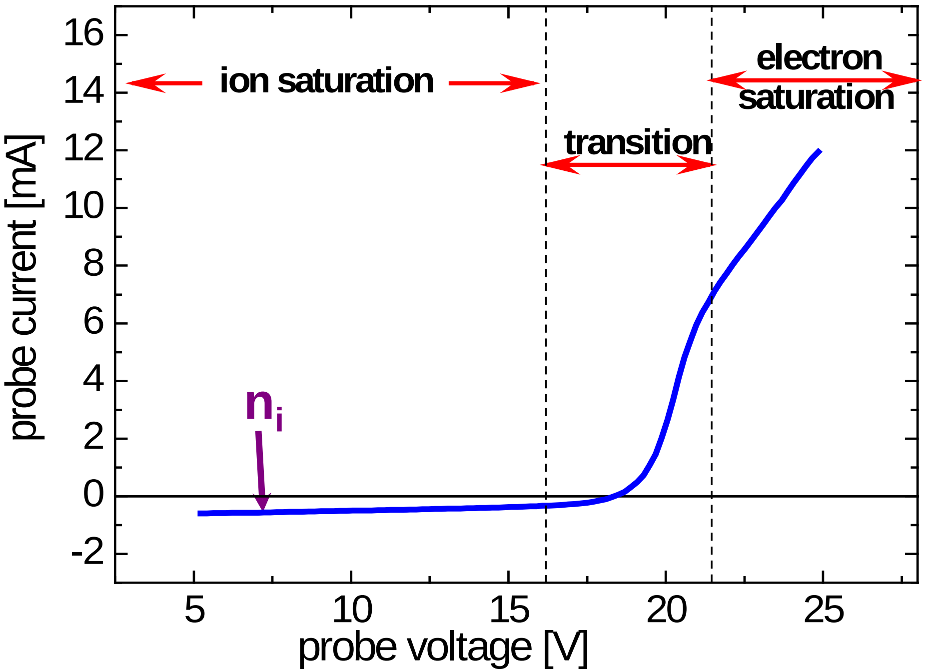
Probe geometry

influences shape of electron saturation current

- cylindrical probe (standard case)
- planar probe $\rightarrow A_{pr}$ >> sheath
- spherical probe

Langmuir probes: ϕ_{pl}, n_e, T_e, (EEDF)

Ion density (positive ions)



- ion saturation current
- basically three theories available

  OML: Orbital-Motion-Limited

  ABR: Allen-Boyds-Reynolds

  BRL: Bernstein-Rabinowitz-Langmuir

  all of them assuming collision-less plasma sheath, i.e. λ(ions) > r(sheath)

- simplest case: OML (r_{pr} /r_{sheath} < 3)

$$I_i = n_i e A_{pr} \sqrt{\frac{k_B T_e}{m_i}}$$

needs T_e

needs m_i

often unclear, e.g. hydrogen

$\rightarrow H^+, H_2^+, H_3^+$

- choose proper ϕ_{pr}

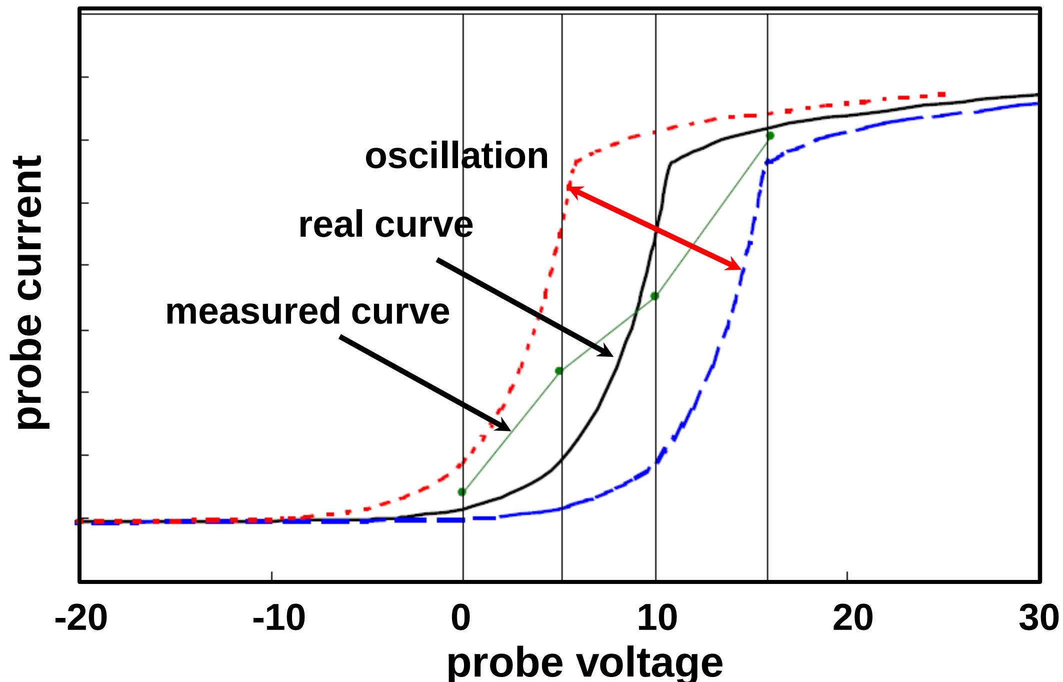
  guide line: $\phi = \phi_{pl} - 10 \times kT_e$

- check if $n_e = n_i$ is fulfilled
- **$I_{sat, i}$ at fixed ϕ_{pr}:** useful as monitor signal

Specific features – to keep in mind

- invasive method → probe size versus plasma volume
- level of noise → EEPF for typically three orders of magnitude
  average, smoothing, filtering
- RF field → oscillating ϕ_{pl}
  measured curve ≠ real curve

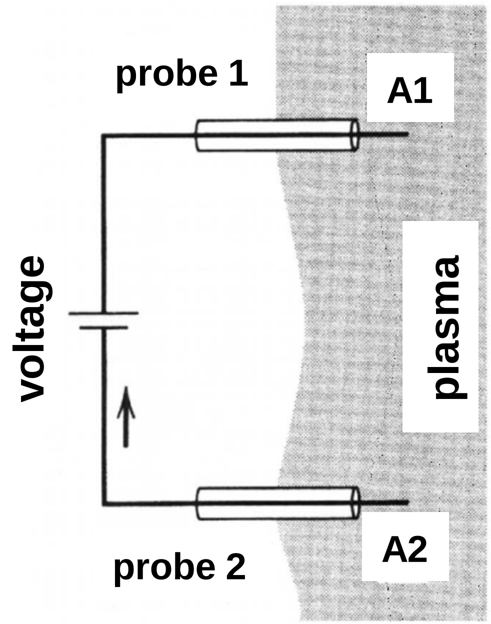
  RF compensation
  active or passive



- magnetic field → gyro motion
  use I_{ion} instead of I_e
- negative ions → $I_{neg.ion}$ instead of I_e
  for same mass $I_{sat,ion} = I_{sat,neg.\,ion}$ → symmetric curves

For monitoring or quantification with spatial and temporal resolution !

Double probe



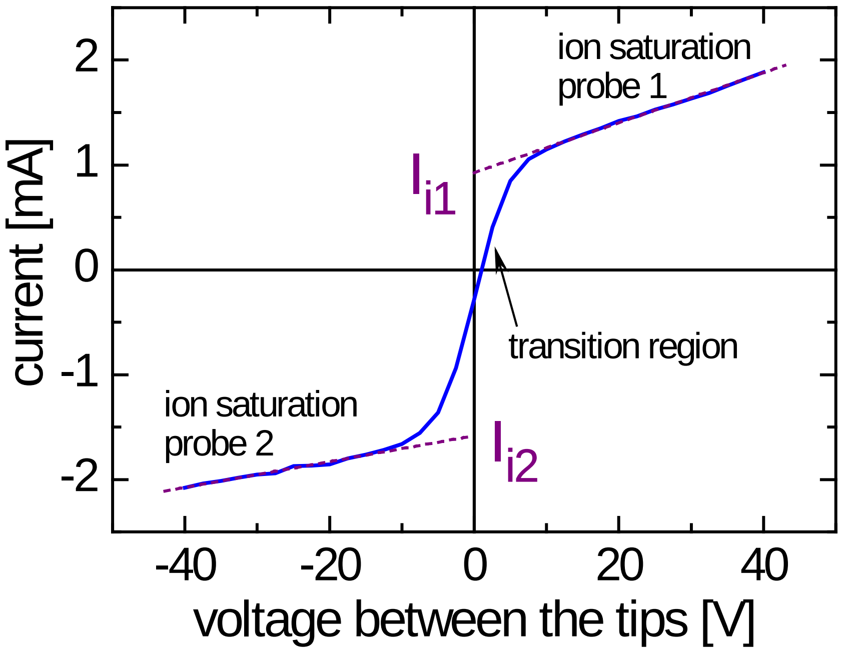
- two probe tips of same size
  distance > 2 Debye length
- voltage between the probes
  both probes are floating
  no reference potential needed

→ compatible with quartz or ceramic chamber and RF field

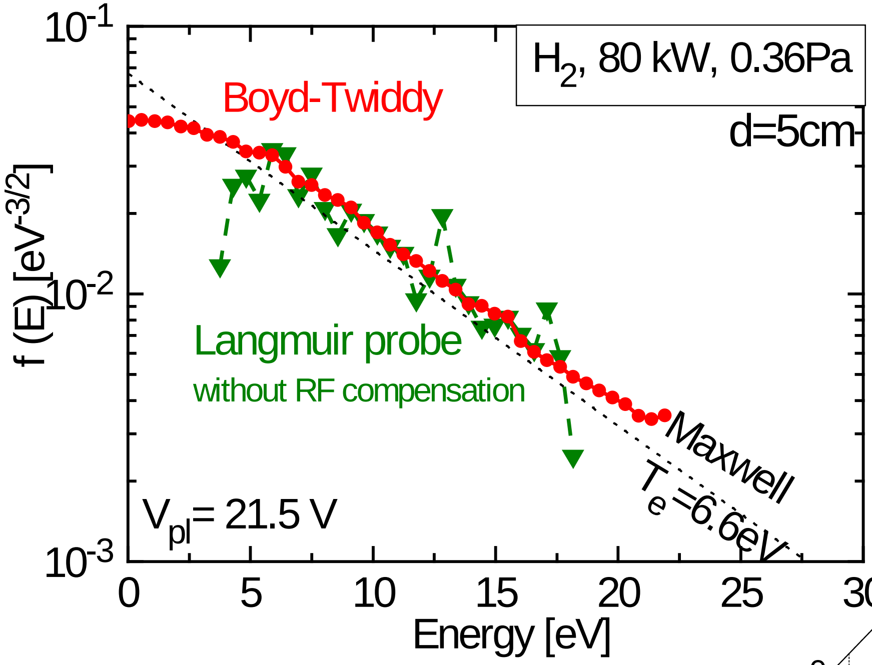
- symmetric curve: ion saturation current

$$I_{i,sat} = \frac{I_{isat,+} + I_{isat,-}}{2} \qquad n_i = \frac{I_{i,sat}}{eA\sqrt{\frac{k_B T_e}{m_i}}}$$

- T_e from transition region



Comparison of EEDF



Boyd-Twiddy method: direct measurement of EEDF

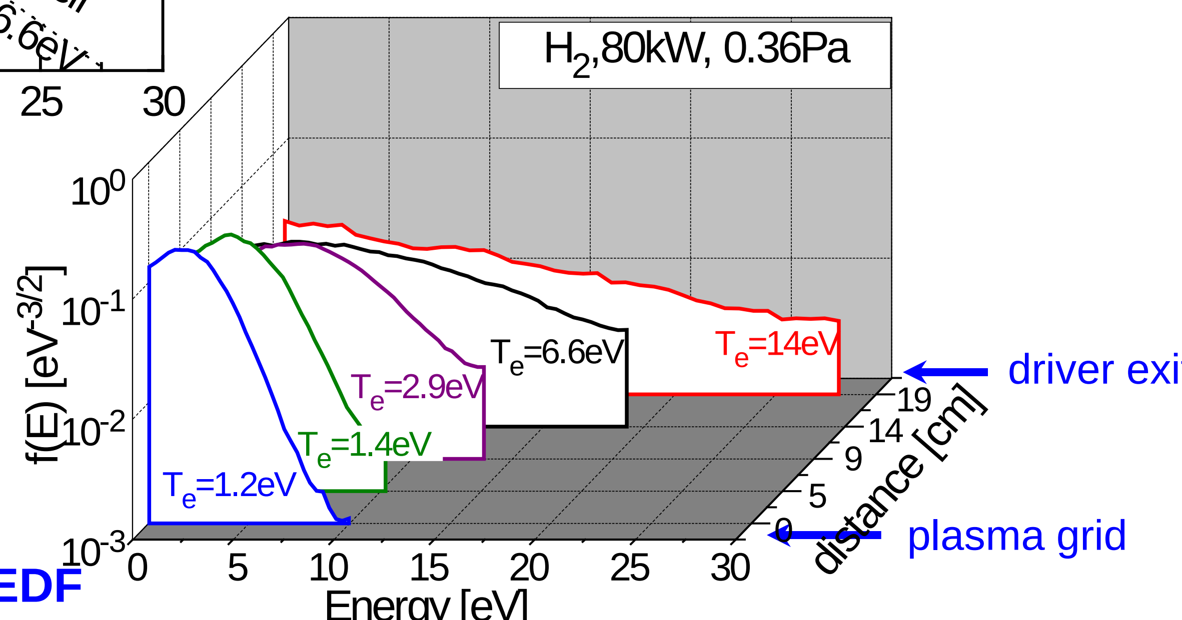
- voltage ramp is superimposed by AC modulated signal
- measure frequency spectrum of probe current

B. Crowley, S. Dietrich PSST 18 (2009) 014010

Sophisticated Langmuir probe system

for RF ion sources

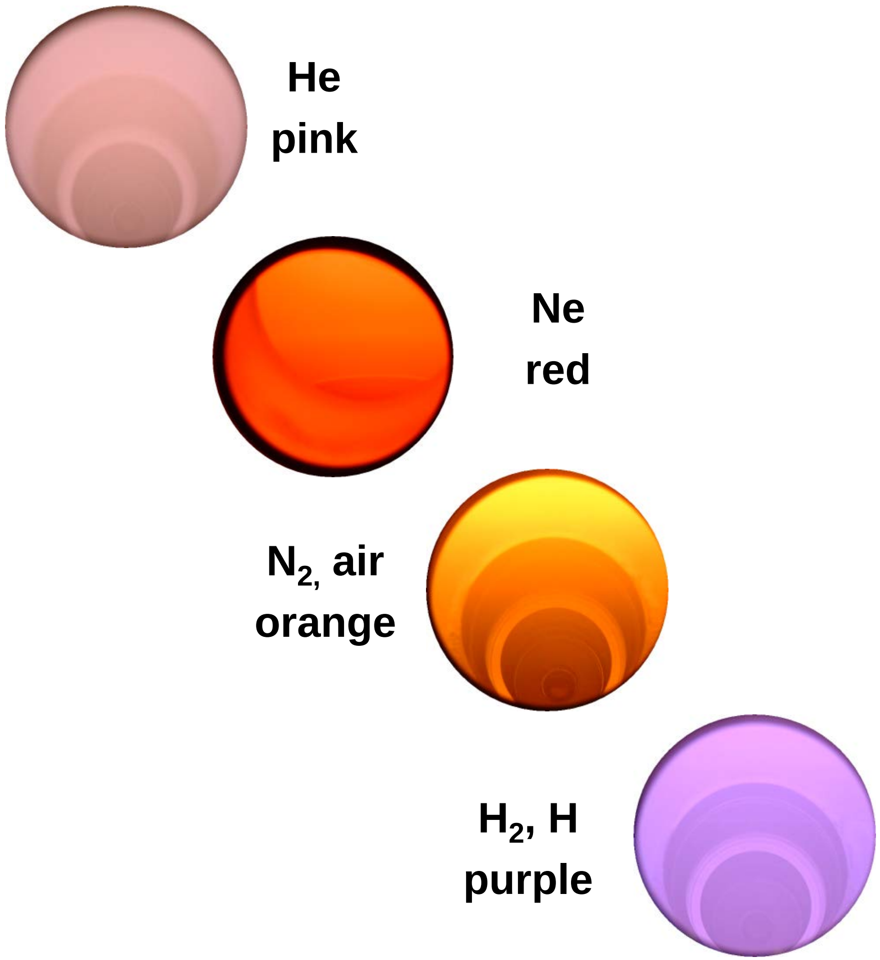
McNeely et al.
PSST 18 (2009) 014011



Maxwellian EEDF

Radiation of low temperature plasmas

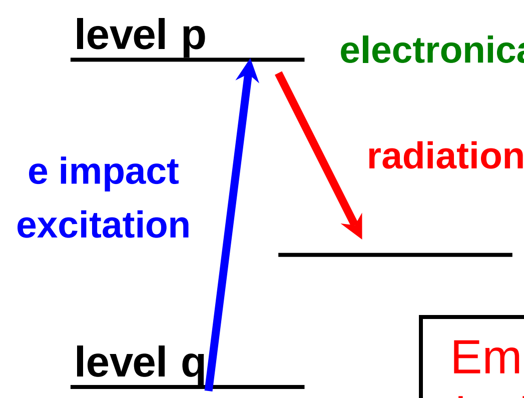
Colourful plasmas !



- **Neutrals** atoms and molecules
- **Ions** single charged
- **Electrons** $n_e \ll n_n$

collisions and spontaneous emission

$$a + e_f \rightarrow a^* + e_s \rightarrow a + h\nu + e_s$$



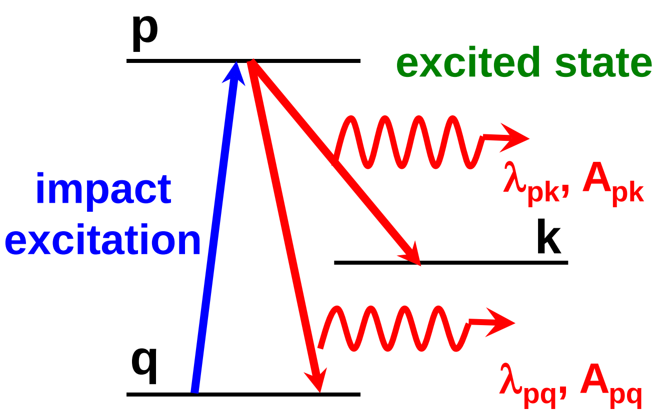
Emission of light in the UV-VIS-IR

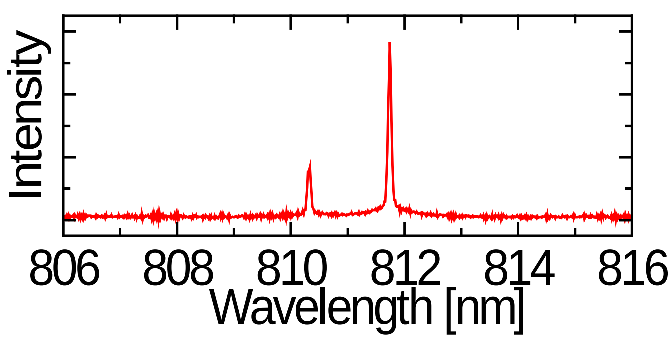
Emission versus absorption spectroscopy

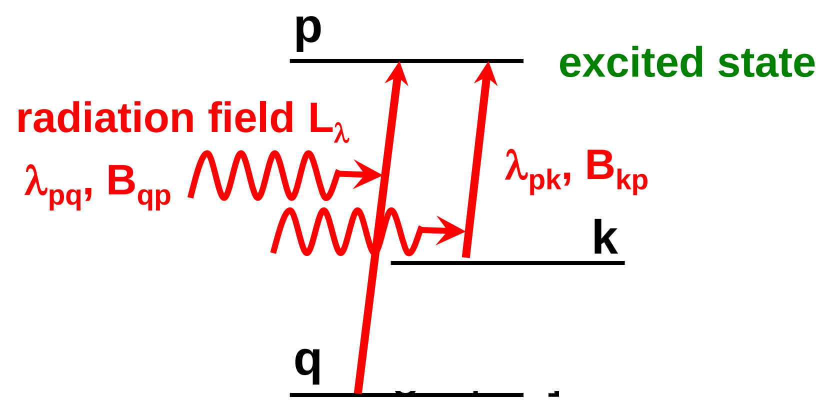
Emission
passive

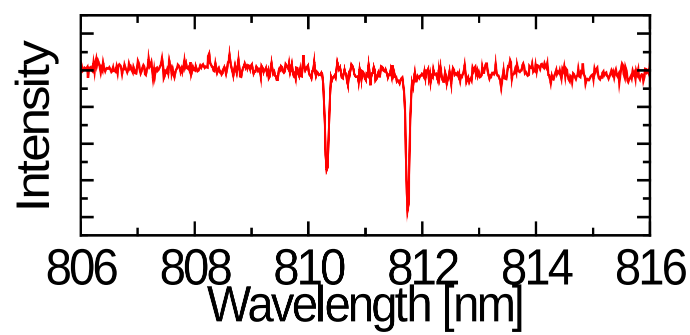
- photon energy $E = h\nu$
- wavelength $\lambda = (E_p - E_k)/hc$
- Einstein coefficients A_{pk}, B_{kp}

Absorption
active





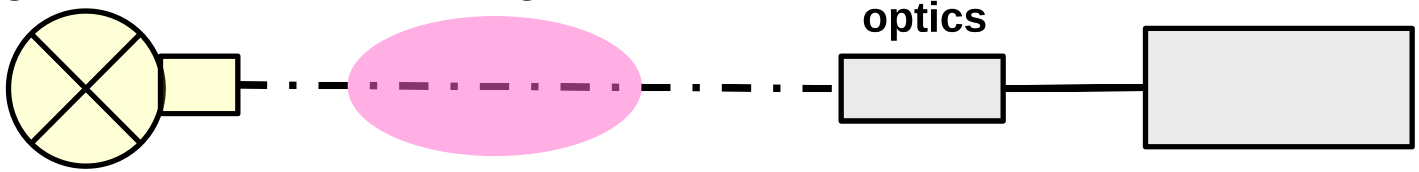




- VIS: simple equipment
- information of upper level p

- expensive equipment
- information of lower level q

Main principle of line absorption



Non-invasive and line of sight integrated method !

Absorption in a medium with path length l

$$I(\lambda,l) = I(\lambda,0)\exp\left[-\kappa(\lambda)l\right]$$

absorption coefficient $\kappa(\lambda)$
statistical weights g_i, g_k

$$k(\lambda) = \frac{1}{l}\ln\left(\frac{I(\lambda,0)}{I(\lambda,l)}\right)$$

with Ladenburg relation $\int_{line} \kappa_{ki}(\lambda)\, d\lambda = n_k \frac{g_i}{g_k} \frac{\lambda_0^{\,4}}{c} \frac{A_{ik}}{8\pi}$

Density of lower state
ground state, metastables

$$n_k = \frac{8\pi c}{\lambda_0^4} \frac{g_k}{g_i} \frac{1}{A_{ik} l} \int_{line} \ln\left(\frac{I(\lambda,0)}{I(\lambda,l)}\right) d\lambda$$

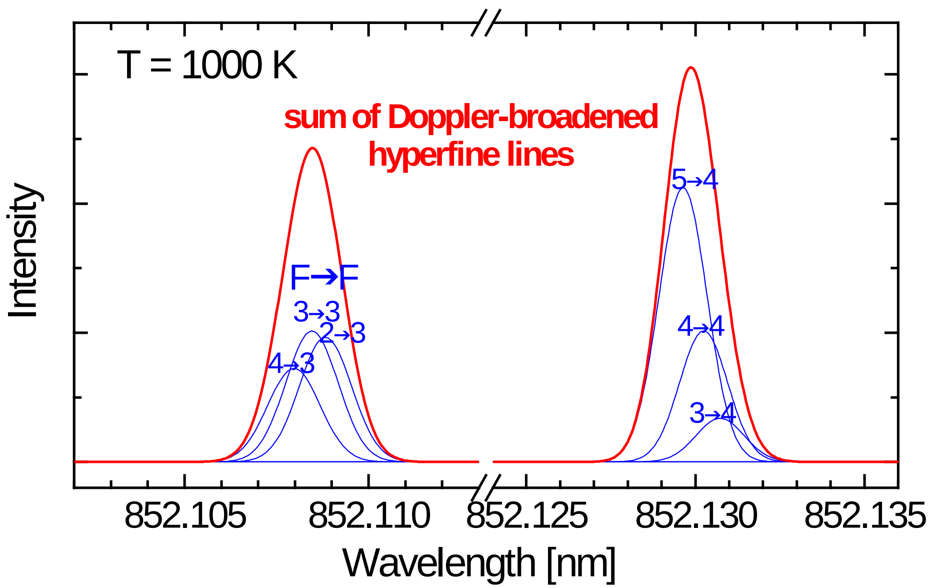
Example: Cs line at 852.1 nm

resonance line 6 $^2S_{1/2}$ – 6 $^2P_{3/2}$ with hyperfine structure

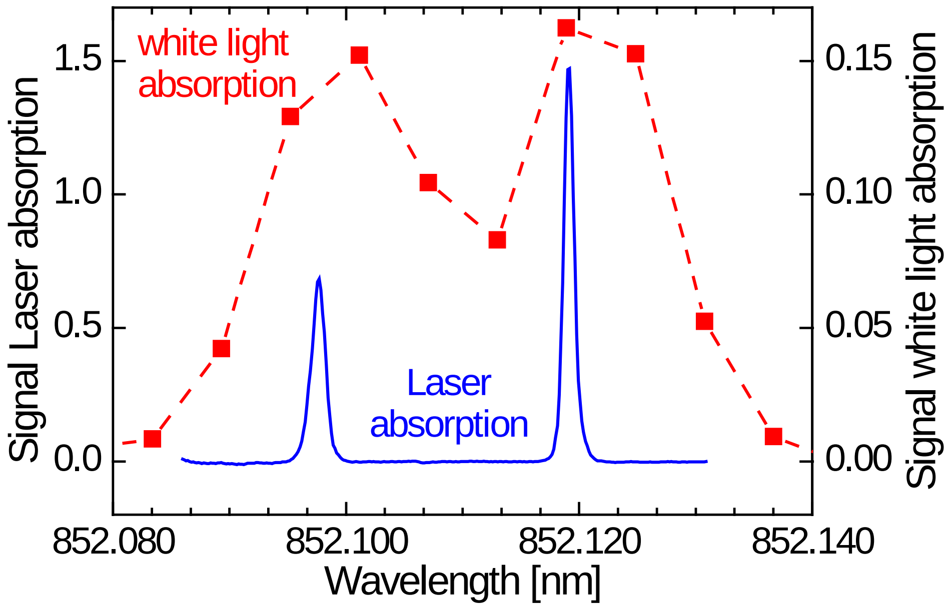
take line broadening into account

Doppler profile

$$\Delta\lambda_{D,FWHM} = \frac{\lambda}{c}\sqrt{\frac{8k_B T \ln 2}{m}}$$



appearance depends on technique



white light absorption ↔ laser absorption

apparatus profile (spectrometer) Doppler profile

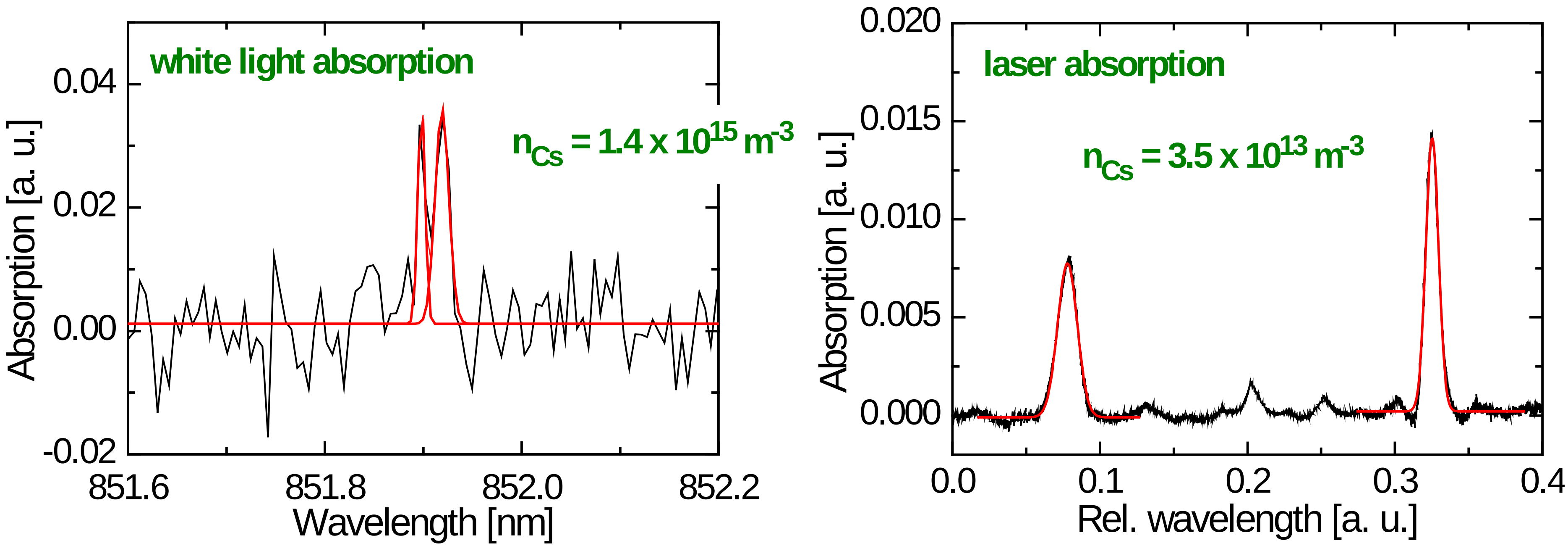
six hyperfine lines overlap to two peaks: Δλ ≈ 21 pm

Absorption techniques: $n_{species}$ → Cs, Ar, He, ...

U. Fantz, C. Wimmer
J. Phys. D **44** (2011) 335202

Example: Cs line at 852.1 nm

white light absorption versus laser absorption



Improved detection limit for laser absorption: factor > 40 !

sensitivity range: 3×10^{13} m^{-3} – 10^{17} m^{-3} (path length = 15 cm)
being perfectly in the range required for the ion sources

Straightforward analysis

- in vacuum
- with plasma → subtract emission

$$n_k = \frac{8\pi c}{\lambda_0^4} \frac{g_k}{g_i} \frac{1}{A_{ik} l} \int_{line} \ln\left(\frac{I(\lambda,0)}{I(\lambda,l)}\right) d\lambda$$

... but ....

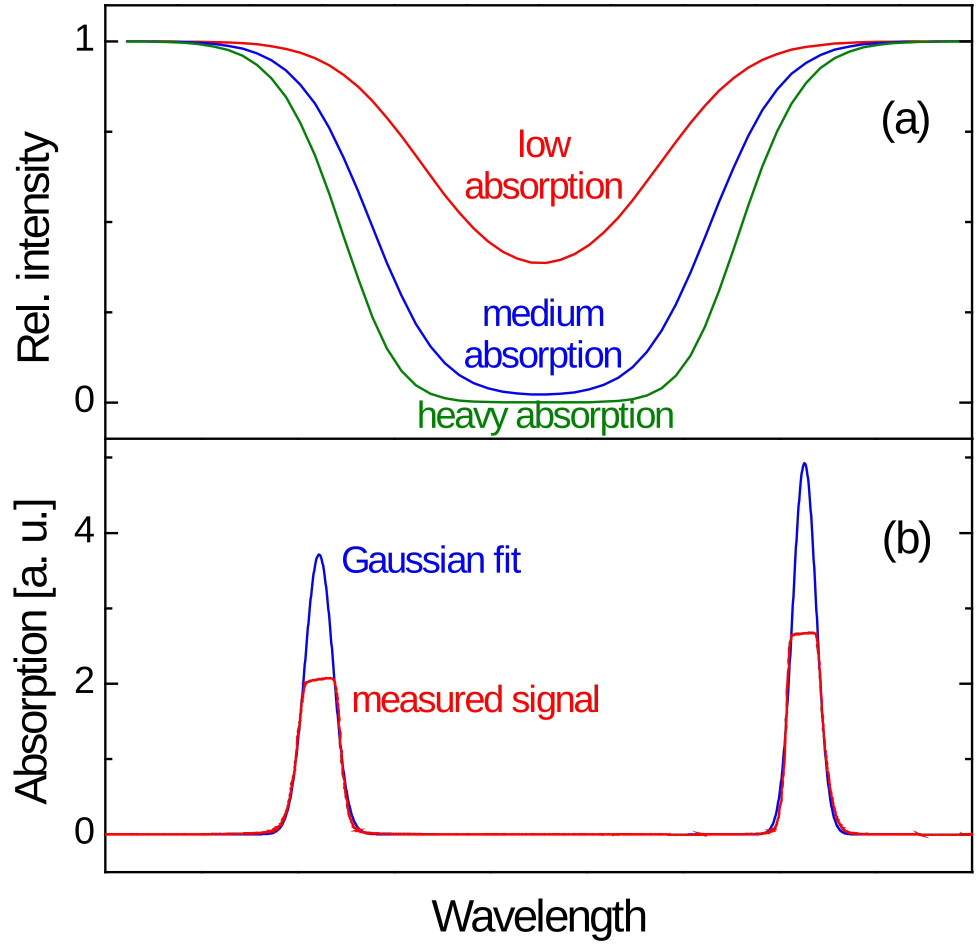
Line saturation

- strong absorption: $n_k \times l$
- correction factors by profile fitting

... and ....

Depopulation effect

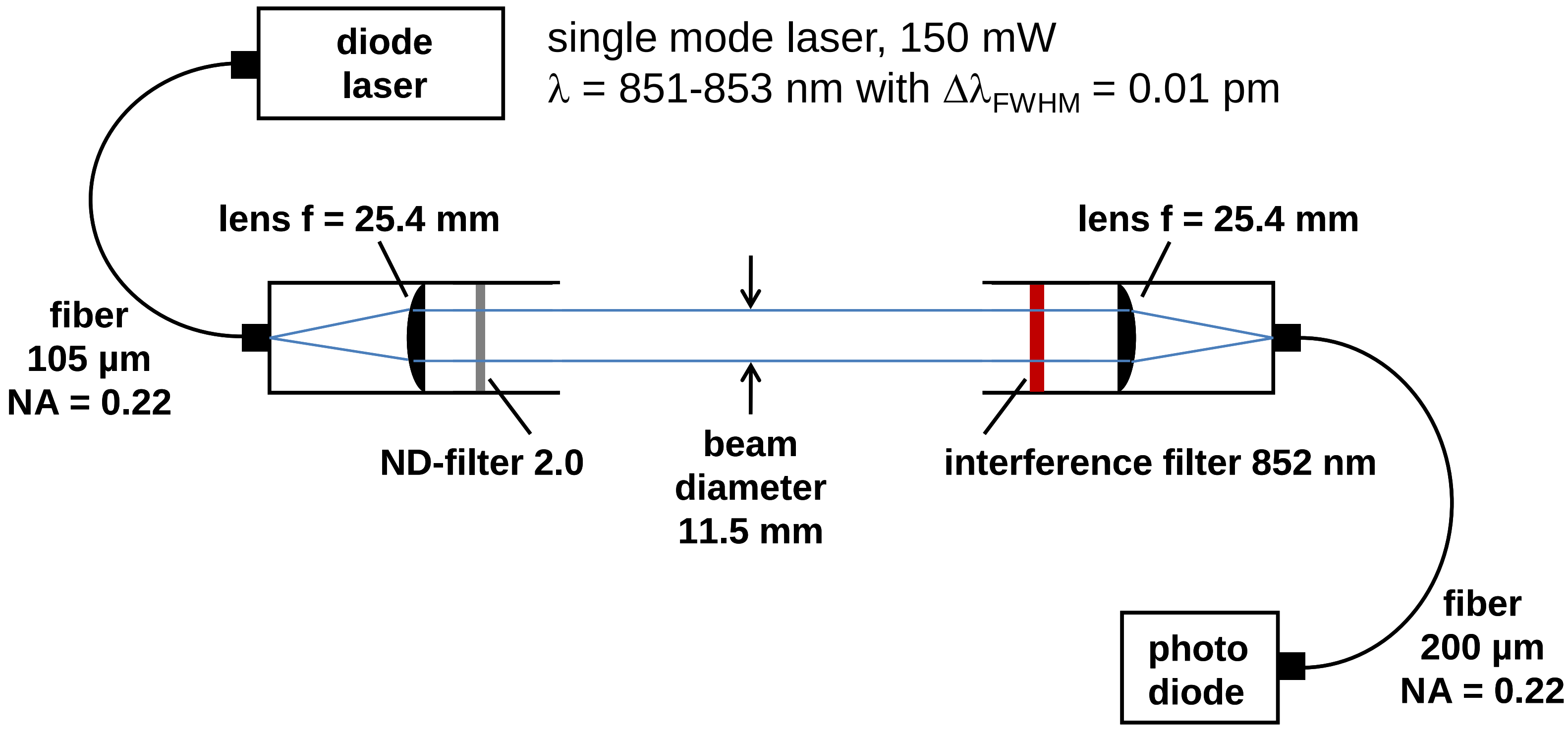
- strong intensity
- attenuation of laser to ≈1% → trade-off with temporal resolution



Tuneable diode laser – Fibre optics – Photo diode with interference filter

single mode laser, 150 mW

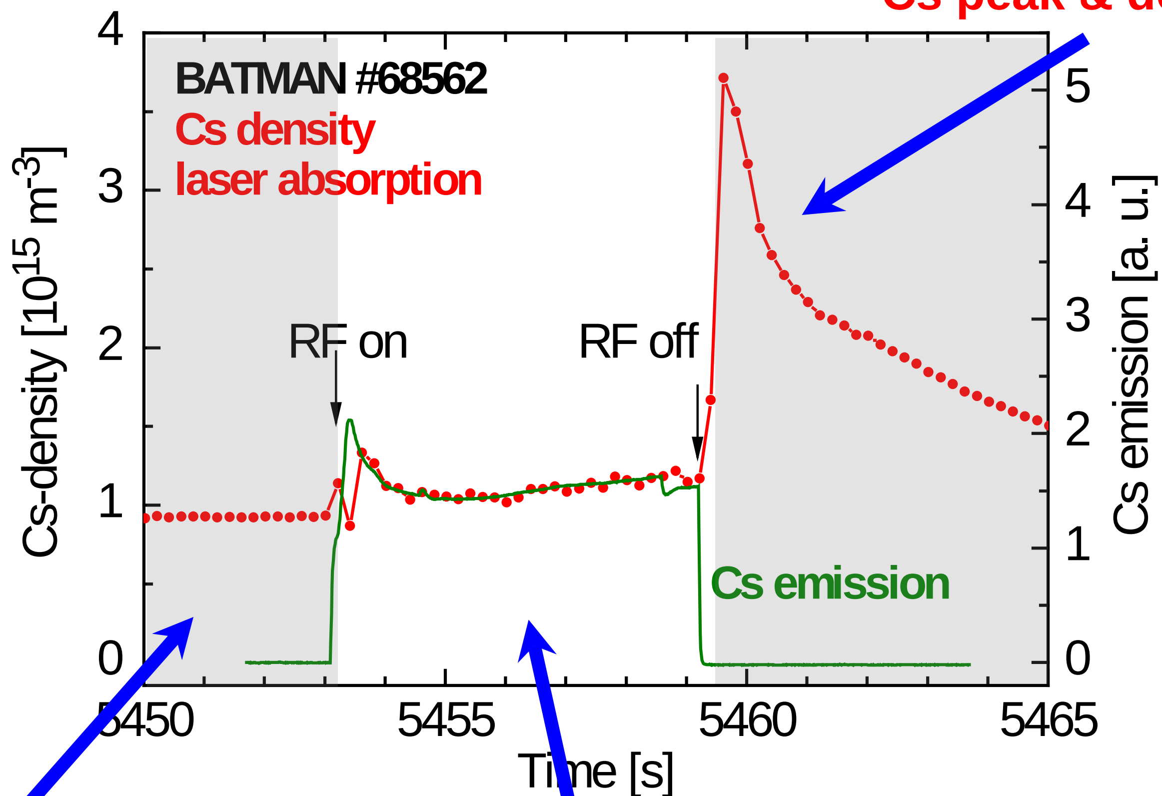
λ = 851-853 nm with $\Delta\lambda_{FWHM}$ = 0.01 pm



Simple and robust setup for application to ion sources !

On-line monitoring: vacuum – plasma (6s with 4s beam) - vacuum

③ **30 s after pulse:**
Cs peak & decay time

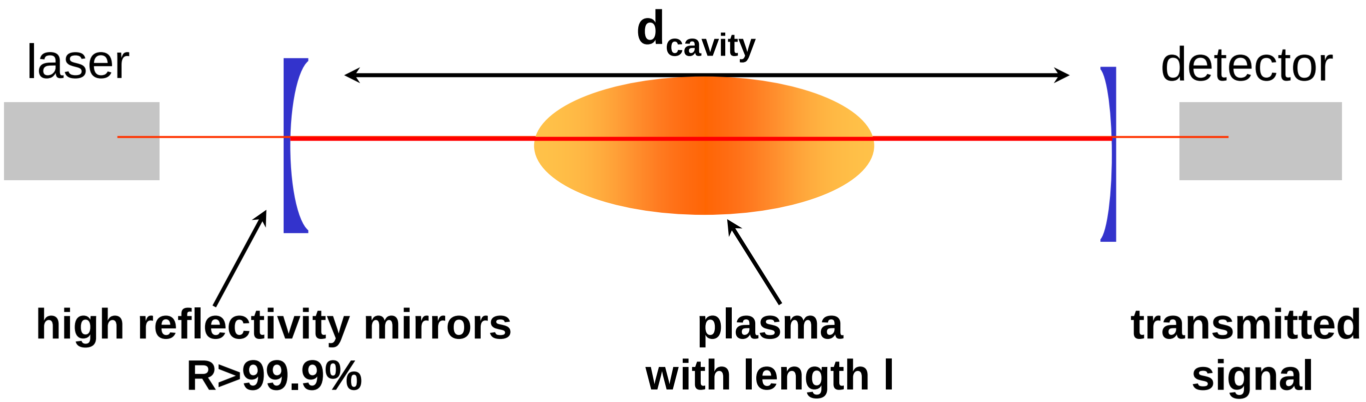


① **3 s before pulse: vacuum**

② **6 s plasma with 4 s beam: plasma**
90% of Cs is ionized

Cavity – Ringdown – Absorption – Spectroscopy → CRDS

pumping of an optical cavity by a (tunable) laser source
measurement of signal decay after laser source is switched off



Measurement of laser light attenuation trapped in a high-finesse optical cavity

transfers absorption signal from wavelength into time dependence

empty cavity with decay time τ_0

$$I(t) = I_0 \cdot e^{-t/\tau_0} \; ; \quad \tau_0 = \frac{d}{c(1-R)}$$

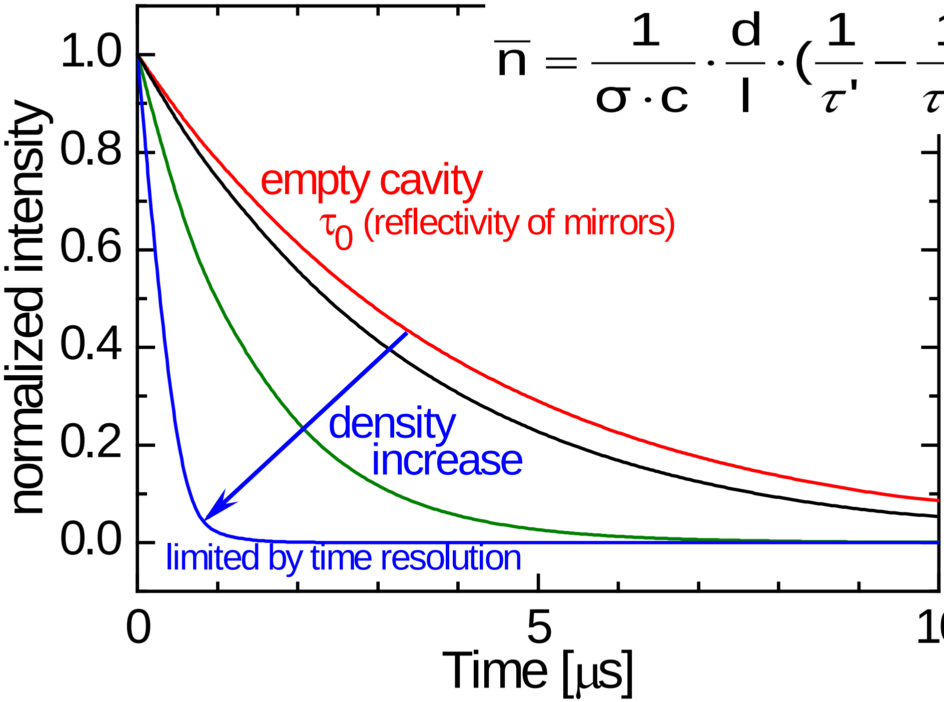
additional absorption $\tau_0 \rightarrow \tau'$

$$\overline{n} = \frac{1}{\sigma \cdot c} \cdot \frac{d}{l} \cdot \left(\frac{1}{\tau'} - \frac{1}{\tau_0}\right)$$

Absorption techniques: $n_{species} \rightarrow H^-, Cs, Ar, H_3^+ ...$

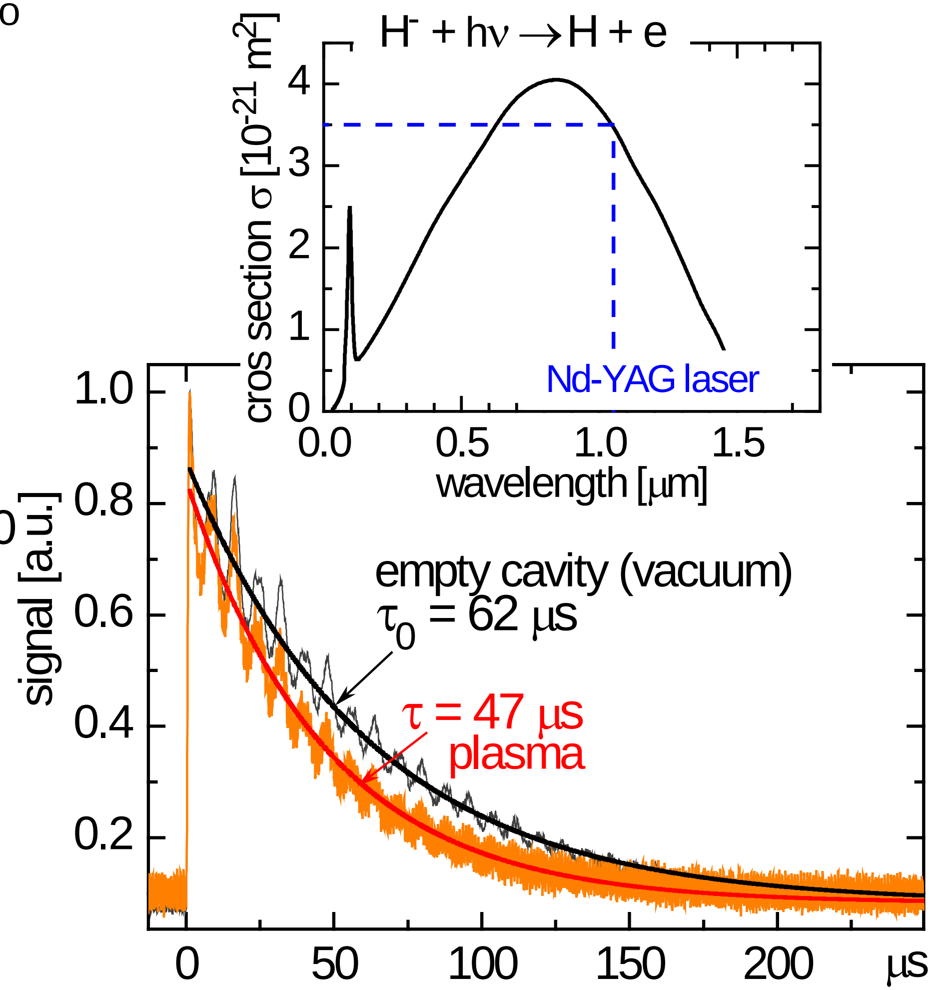
Cavity – Ringdown – Absorption – Spectroscopy → CRDS

$$\bar{n} = \frac{1}{\sigma \cdot c} \cdot \frac{d}{l} \cdot \left(\frac{1}{\tau'} - \frac{1}{\tau_0}\right)$$



Example H⁻

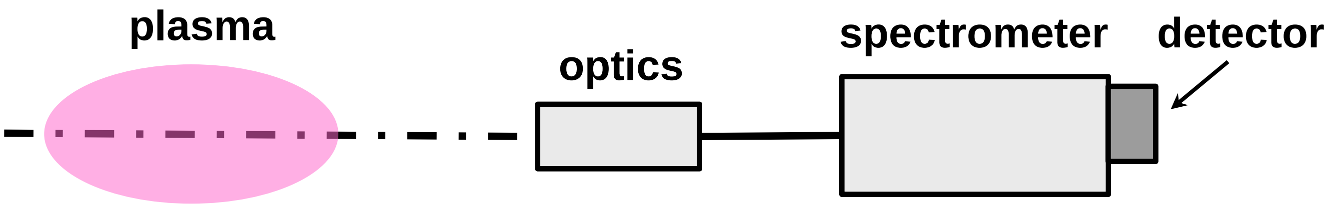
cross section: photodetachment



H^- density: line of sight averaged

- detection limit ≈ 10^{15} m^{-3}
- $H^- = 5 \times 10^{17}$ m^{-3} → t = 8 µs

The main principle



UV and VUV: vacuum system
IF: detector

Non-invasive and line of sight integrated method !

Measures density of excited state ...

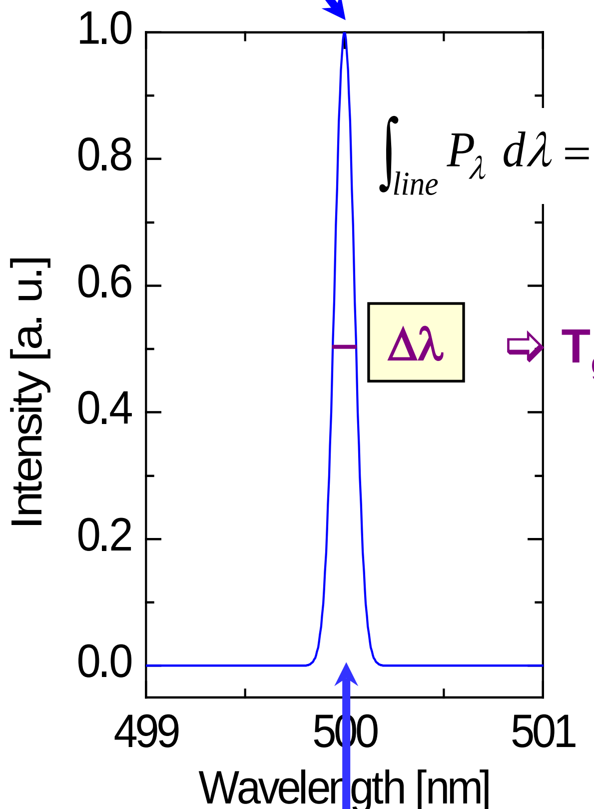
$$\varepsilon_{pk} = n(p) A_{pk} \frac{hc/\lambda}{4\pi}$$

... which depends on plasma parameters !

Recommended text books [1], [4], [7], [9], [10]

What information can be obtained from the line emission ?

I_{max} ⇨ n(p) A_{pk}



$$\int_{line} P_\lambda \, d\lambda = 1 \quad \Rightarrow \quad \varepsilon_\lambda = \varepsilon_{pk} \, P_\lambda$$

$\Delta\lambda$ ⇨ T_{gas}

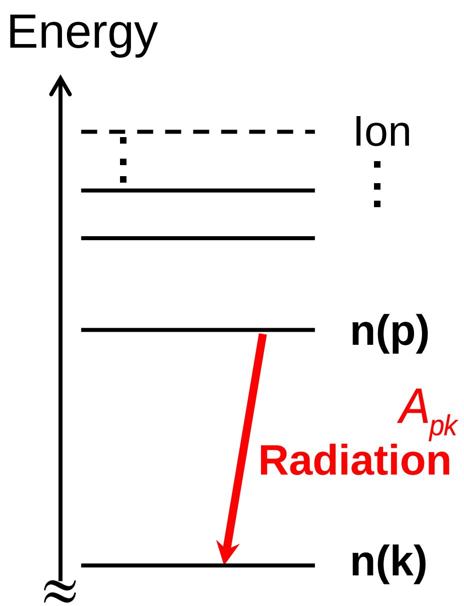
λ_0 ⇨ Element

- **Intensity:** plasma parameters

  density and temperature of neutrals, ions, electrons

  insight in plasma processes

- **Line profile:** broadening mechanism
- **Doppler broadening:** particle temperature
- **Wavelength:** species
- **Wavelength shift:** particle velocity

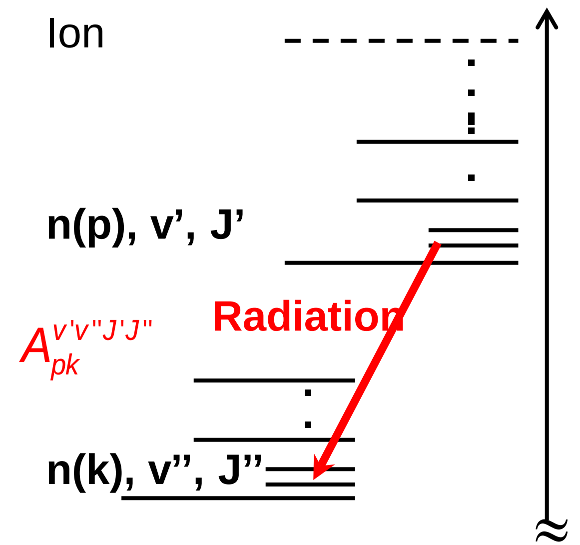


Atoms

$n\ell \;\; {}^{2S+1}L_{L+S}$

Molecules

${}^{2S+1}\Lambda^{+,-}_{\Lambda+\Sigma \; g,u}$



selection rules

Atoms:

$\Delta L = 0, \pm 1$

$\Delta J = 0, \pm 1$

$\Delta S = 0$

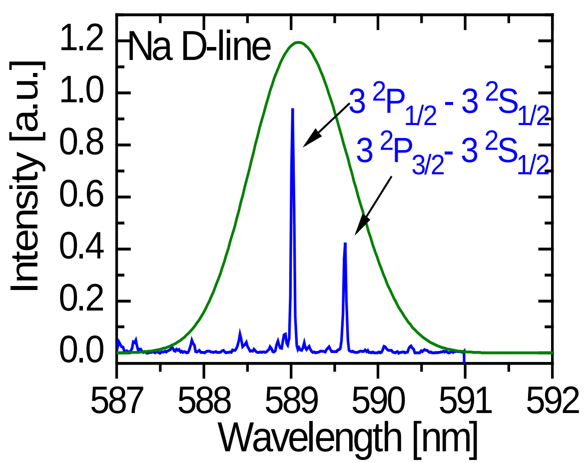
Molecules:

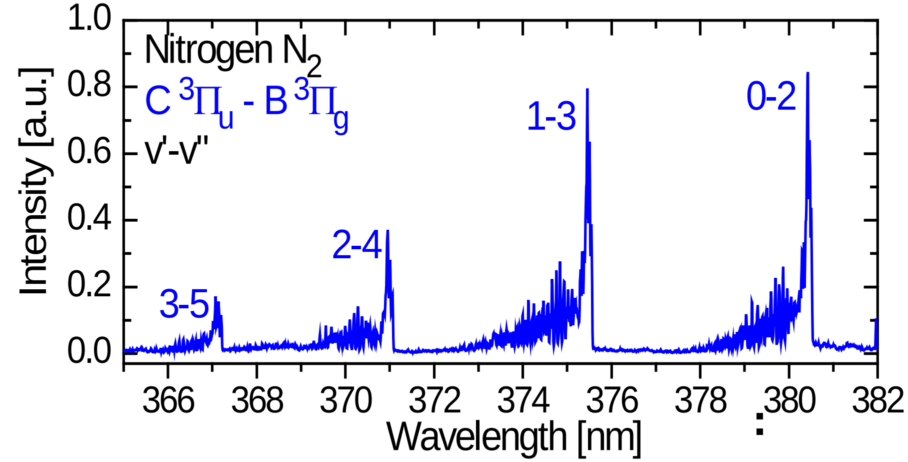
$\Delta \Sigma = 0$

$u \leftrightarrow g$

$J'' - J' = \Delta J = 0, \pm 1$

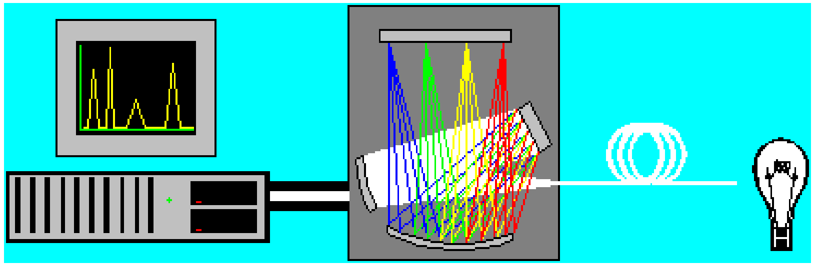
P, Q, R branch





Appearance depends on spectral resolution !

Spectroscopic system



Detector **Spectrometer** **Optics**

Detector

- photomultiplier
  λ scan
  Δλ, Δt
- diode array
  λ range
- CCD, ICCD
  pixel size - Δλ
  intensity

Spectrometer

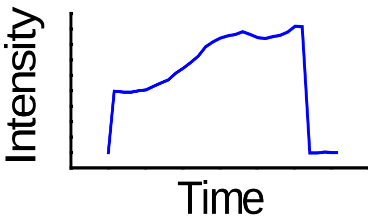
- focus length
  spectral resolution Δλ
- grating
  spectral resolution
  Blaze - intensity
- slits
  entrance slit Δλ
  exit slit - detector

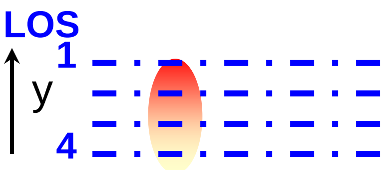
Optics

- fibre
  very flexible
  VIS: glass, quartz,
  UV enhanced
- lens and aperture
  Imaging optics
  solid angle

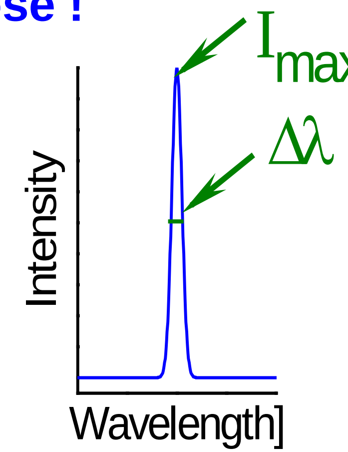
Emission spectroscopy: n_s, $T_s \rightarrow$ e, H, H_2, H^-

The spectroscopic system is determined by the purpose !





- time resolution — detector
- spatial resolution — detector, lines of sight
- intensity — detector, spec., optics
- spectral resolution — detector, spec., optics



survey spectrometer	pocket size	$\Delta\lambda \approx$ 1-2 nm
1m spectrometer	good optics	$\Delta\lambda \approx$ 20 pm
Echelle spectrometer	high resolution	$\Delta\lambda \approx$ 1-2 pm

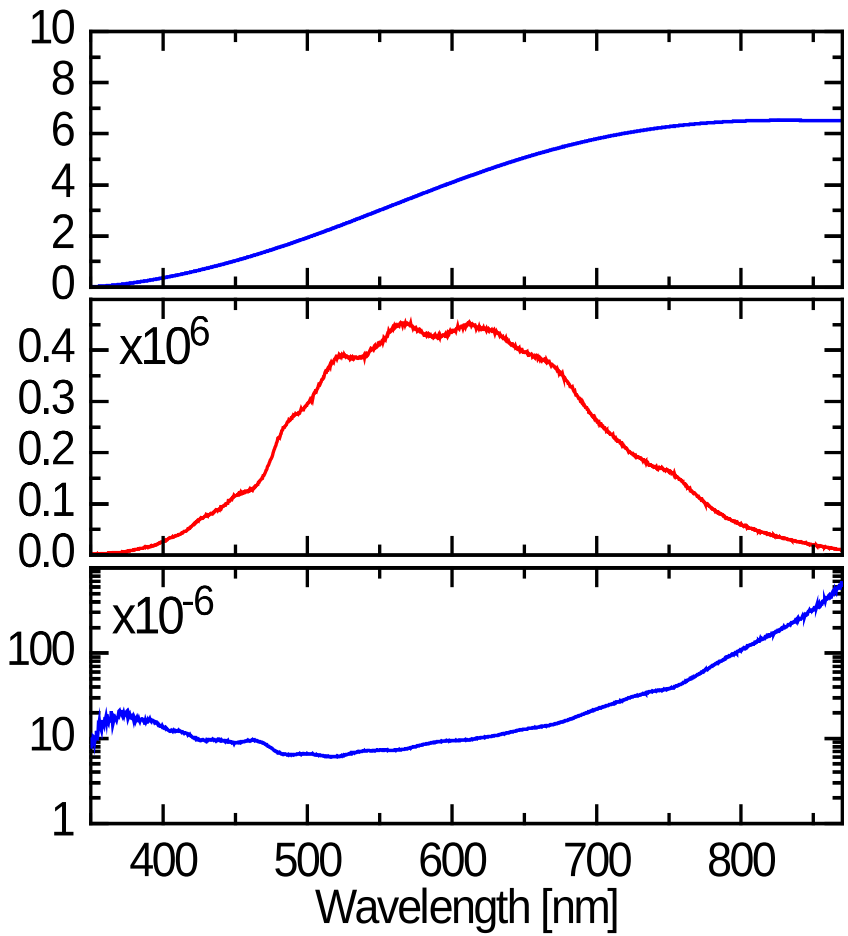
line profile
line shift

line monitoring	relative intensities	absolute intensities
very simple	common technique	expensive technique
Δt, poor $\Delta\lambda$	poor Δt, $\Delta\lambda$, Δx, flexible	poor Δt, $\Delta\lambda$, Δx, flexible
less information	moderate information	powerful tool

Calibration of the spectroscopic system

Wavelength: pixel → nm

spectral lamps, plasma, λ tables



Radiance - Intensity

counts → W/m²/sr, ph/m²/s

Ulbricht sphere

Calibrated spectrum
spectral radiance
[W/m²/sr/nm]

Measurement
intensity [counts/s]

Conversion factor
spectral sensitivity

$$\left[\frac{\mathrm{W}}{\mathrm{m^2\,sr\,nm\,(counts/s)}}\right] \times \frac{4\pi\lambda}{hc} = \left[\frac{\mathrm{photons}}{\mathrm{m^2\,s\,nm\,(counts/s)}}\right]$$

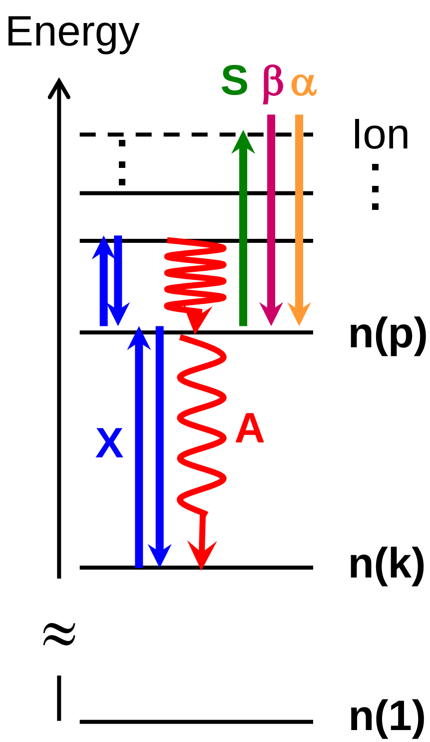
exposure time

Emission spectroscopy: n_s, $T_s \rightarrow$ e, H, H_2, H^-

From intensity $I_{pk} = n(p)\,A_{pk}$ **to plasma parameter**

Population models

high n_e	Boltzmann distribution (TE, LTE)	relevance of photons ↑
↓	Collisional radiative model	
low n_e	Corona equilibrium	



Rate equations for excitation and de-excitation processes

- electron impact excitation and de-excitation
- absorption and emission, heavy particle collisions, ...

Corona model

$$\frac{\mathrm{d}\,n(p)}{\mathrm{d}\,t} = n_1\,n_e X_{1p}(T_e) - n(p)\sum_k A_{pk} = 0$$

$n_1 \cong n_0$ (↓)

$X_{1p}(T_e)$: rate coefficient

X_{pk}: emission rate coefficient

$$I_{pk} = n_0\,n_e\,X_{pk}(T_e) \quad \textit{with} \quad X_{pk} = X_{1p}(T_e)A_{pk} / \sum_k A_{pk}$$

CR model

$$I_{pk} = n_0\,n_e\,X_{pk}^{eff}(T_e, n_e, \ldots)$$

Electron temperature from absolute line emission

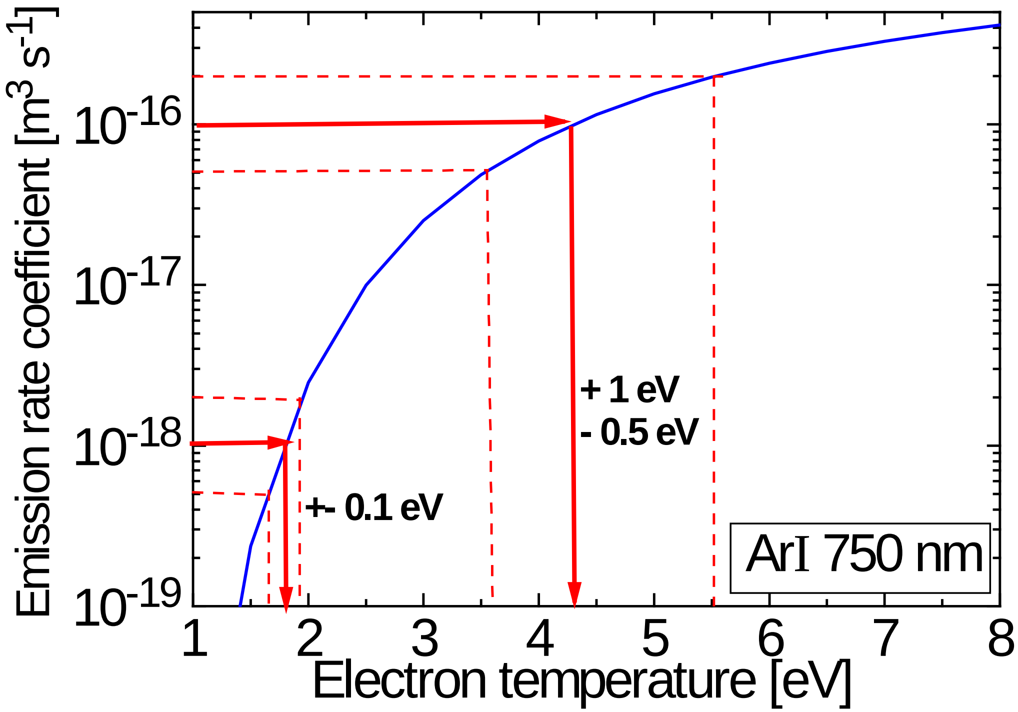
$$I_{pk} = n_0 \; n_e \; X_{pk}^{eff}(T_e, n_e, \ldots)$$

n_0, n_e known ⇨ $$X_{pk}^{eff}(T_e, n_e, \ldots) = \frac{I_{pk}}{n_0 \; n_e}$$

Find suitable gases and diagnostic lines

- admixture of small amount of diagnostic gas
- prominent example: Ar

Very sensitive for low T_e !



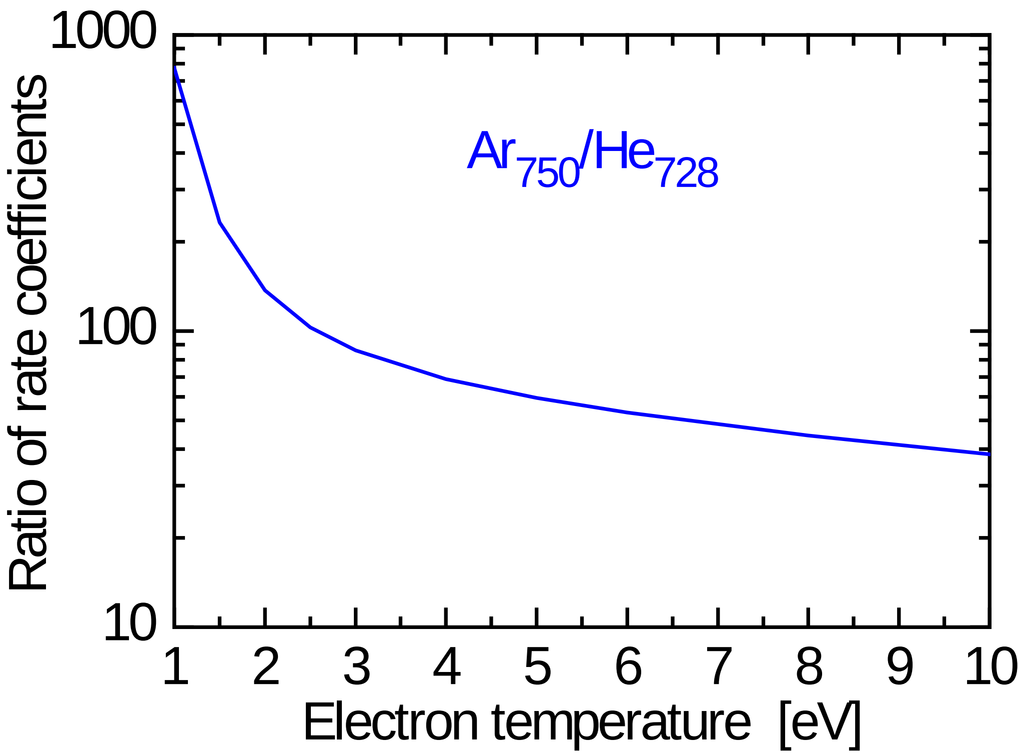
Electron temperature from line ratio (relative calibration)

$$\frac{I_{pk}^{1}}{I_{pk}^{2}} = \frac{n_1\, \cancel{n_e}\, X_{pk}^{1}(T_e)}{n_2\, \cancel{n_e}\, X_{pk}^{2}(T_e)}$$

$\rightarrow$ ratio of rate coefficients for known densities

Find suitable gases and diagnostic lines

- n_1, n_2 inert gases or $n_1 = n_2$
- I_{pk} undisturbed lines
- ground state excitation
- X_{pk} ratio depends on T_e



Emission spectroscopy: n_s, $T_s \rightarrow$ e, H, H_2, H^-

U. Fantz et al., Nucl. Fusion 49 (2009) 125007

Actinometry: density ratio from line ratio (relative calibration)

$$\frac{I_{pk}^{1}}{I_{pk}^{2}} = \frac{n_1 \, \not{n}_e \, X_{pk}^{1}(T_e)}{n_2 \, \not{n}_e \, X_{pk}^{2}(T_e)}$$

$\rightarrow$ ratio of densities for known rate coefficients

- density ratio (n_H/n_{H2})

$$\frac{I_{434}^{H}}{I_{Ful}^{H_2}} = \frac{n_H \, \not{n}_e \, X_{434}^{H}(T_e)}{n_{H_2} \, \not{n}_e \, X_{Ful}^{H_2}(T_e)}$$

independent on n_e

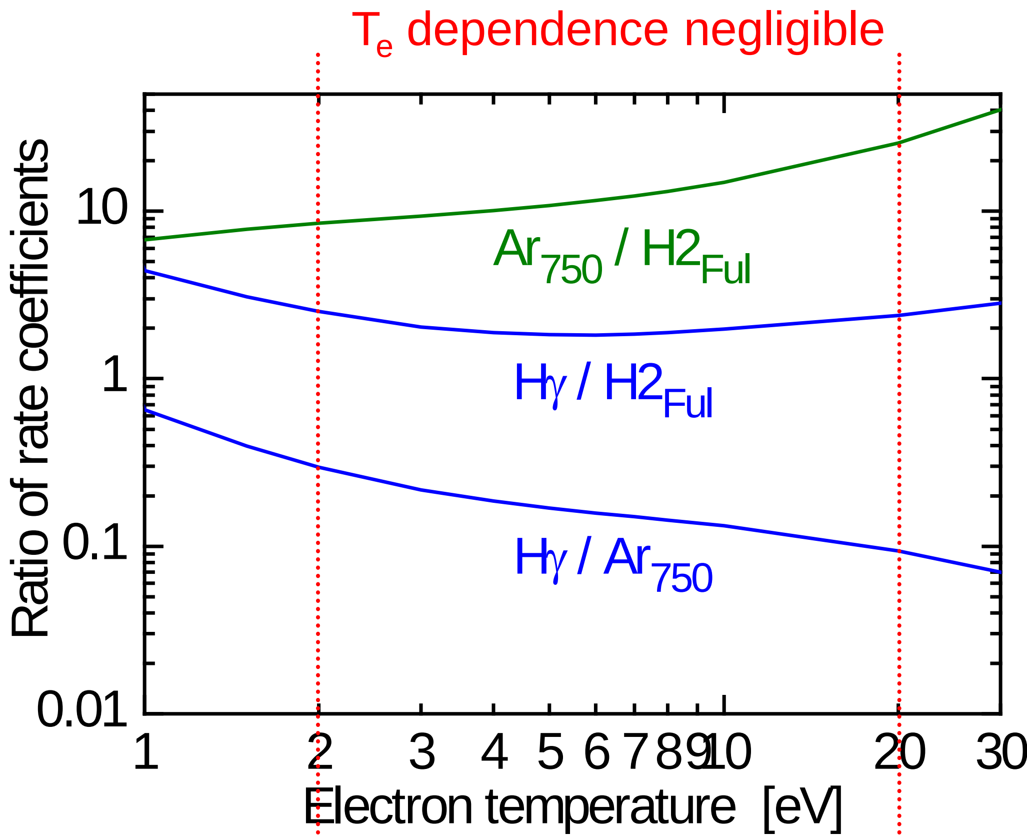
- density ratio (n_{Ar}/n_{H2})

$$\frac{I_{750}^{Ar}}{I_{Ful}^{H_2}} = \frac{n_{Ar} \, \not{n}_e \, X_{750}^{Ar}(T_e)}{n_{H_2} \, \not{n}_e \, X_{Ful}^{H_2}(T_e)}$$

- density ratio (n_{He}/n_{H2})

  dependence on T_e (factor of 10)

  $\rightarrow$needs iteration



Emission spectroscopy: n_s, $T_s \rightarrow$ e, H, H_2, H^-

Particle density from absolute line emission

$$I_{pk} = n_0 \, n_e \, X_{pk}^{eff}(T_e, n_e, ...)$$

n_e, T_e known ⇨ $$n_0 = \frac{I_{pk}}{n_e \, X_{pk}^{eff}(T_e, n_e, ...)}$$

Knowledge of dominant excitation mechanism is essential !

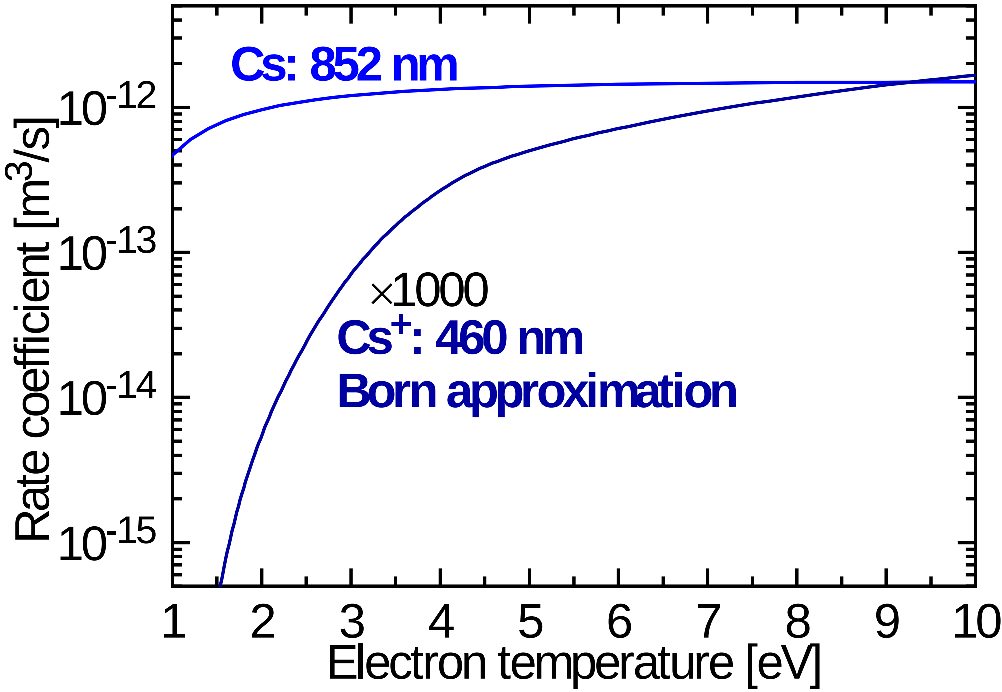
Example: Cs and Cs^+ lines

Cs: $I_{852}^{Cs} = n_{Cs} \, n_e \, X_{852}^{Cs}(T_e)$

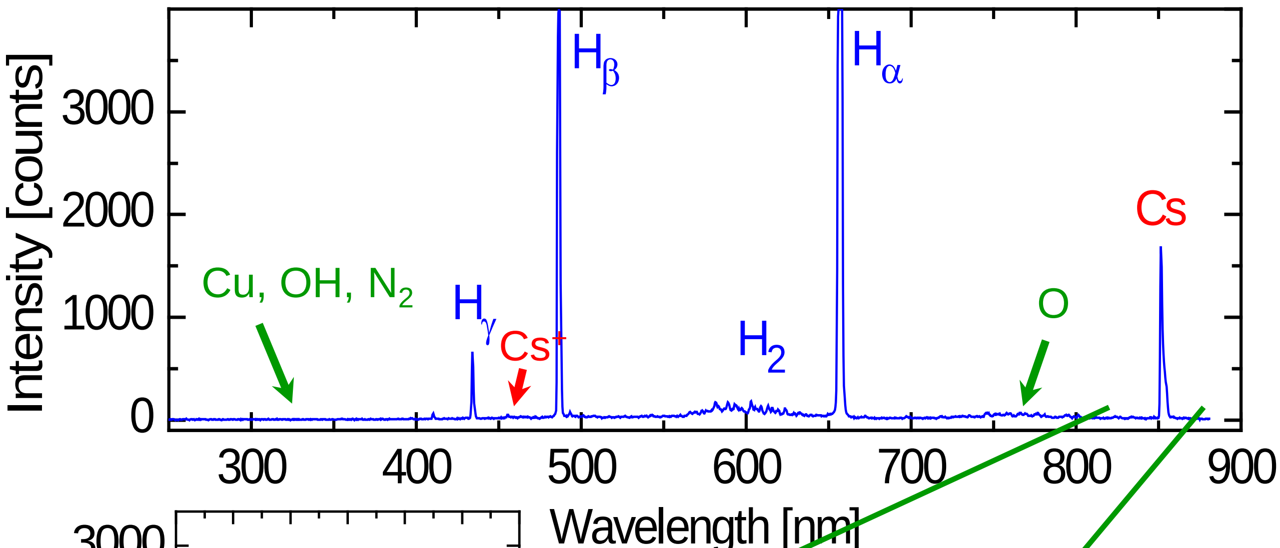
needs n_e, almost independent of T_e

Cs^+: $I_{460}^{Cs^+} = n_{Cs^+} \, n_e \, X_{460}^{Cs^+}(T_e)$

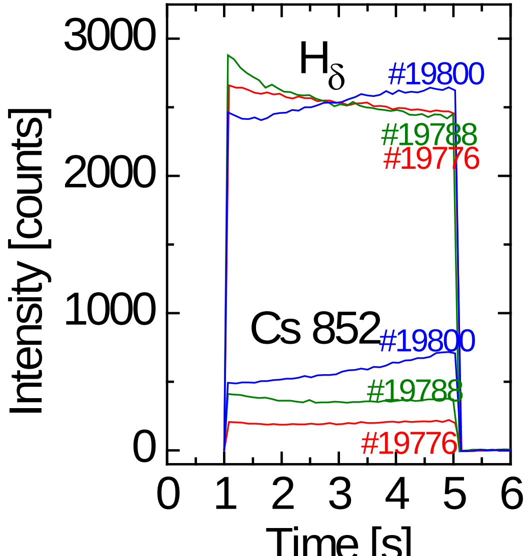
needs n_e, strong dependence on T_e

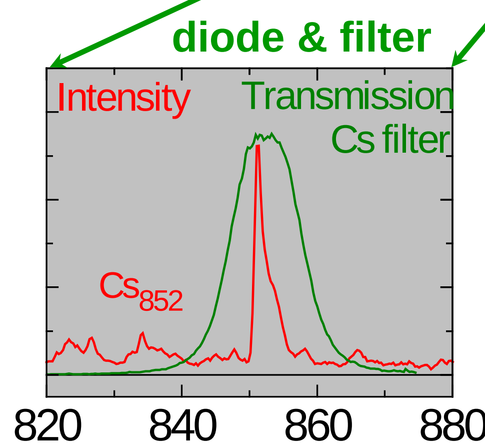


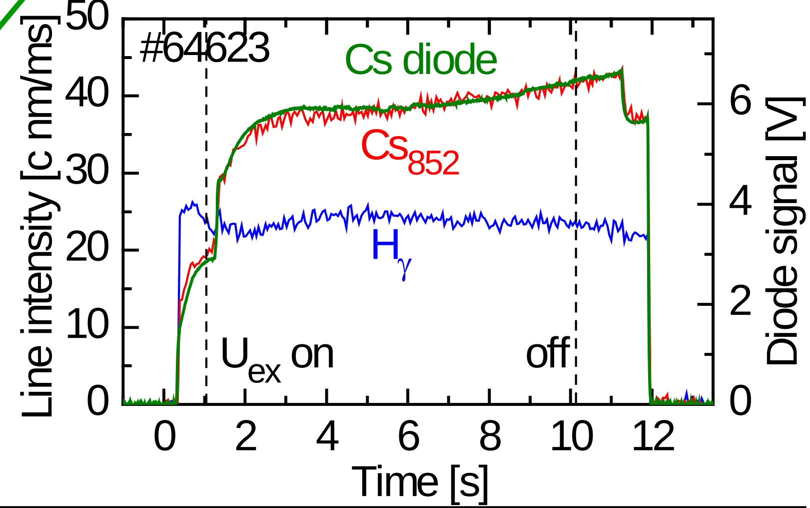
Survey spectrometer and on-line monitoring



- impurities
- Cs, Cs^+
- H from H_γ
- n_e from H_β/H_γ
- n_e, T_e diagnostic gas Ar
- H^- from H_α/H_β





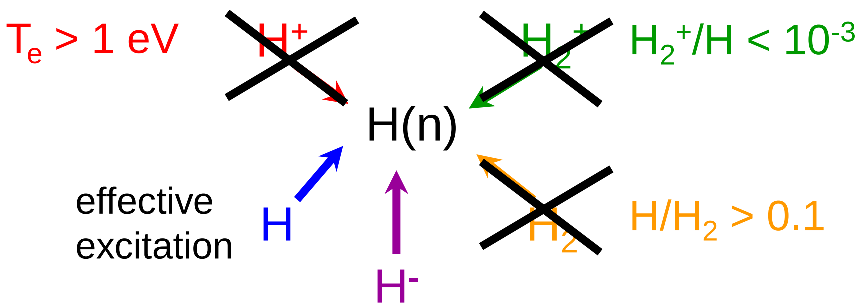


Example: emission spectroscopy: $n_s \rightarrow H^-$

U. Fantz, D. Wünderlich
NJP 8 (2006) 301

A novel diagnostic technique for H^- volume density

Population mechanisms for H



mutual neutralisation

$$H^+ + H^- \rightarrow H(n=3) + H$$

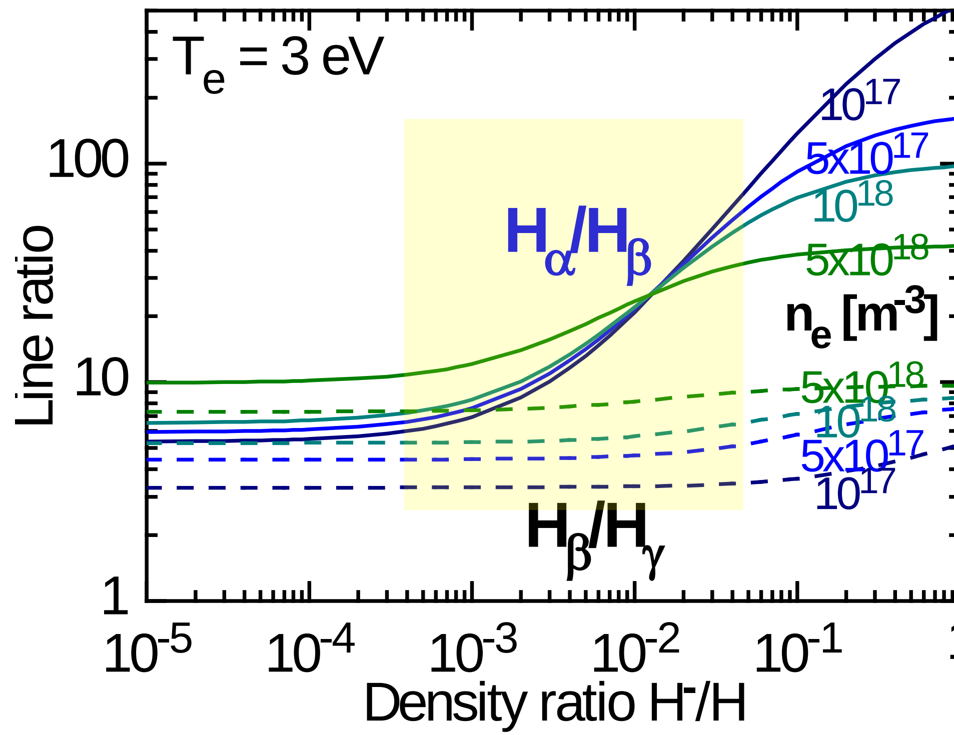
$\downarrow H_\alpha$

Collisional radiative model

Measurement of Balmer line ratios

- H_α/H_β depends on H^-/H
- H_β/H_γ reflects n_e and T_e

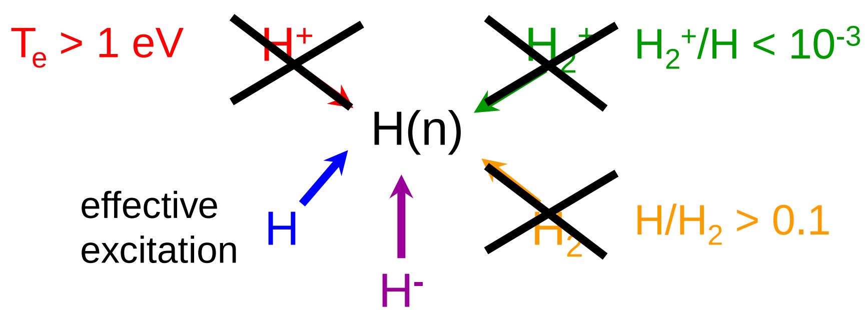
Line ratios depend on n_e, T_e and H^-/H



U. Fantz, D. Wünderlich

A novel diagnostic technique for H^- volume density *NJP 8 (2006) 301*

Population mechanisms for H

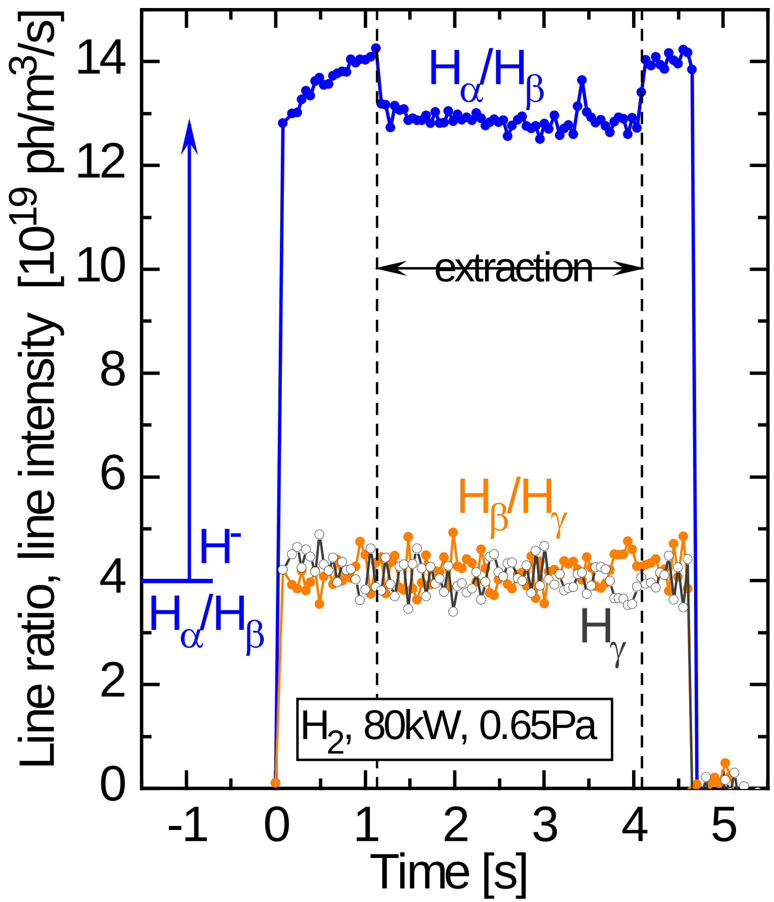


mutual neutralisation

$$H^+ + H^- \rightarrow H(n=3) + H$$

$H(n=3) \downarrow H_\alpha$

Collisional radiative model



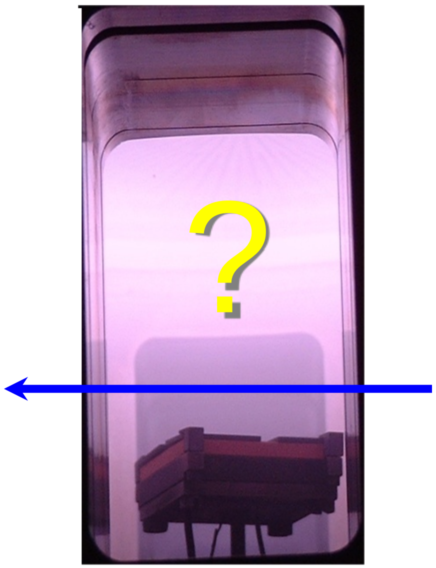
Measurement of Balmer line ratios

- H_α/H_β depends on H^-/H
- H_β/H_γ reflects n_e and T_e

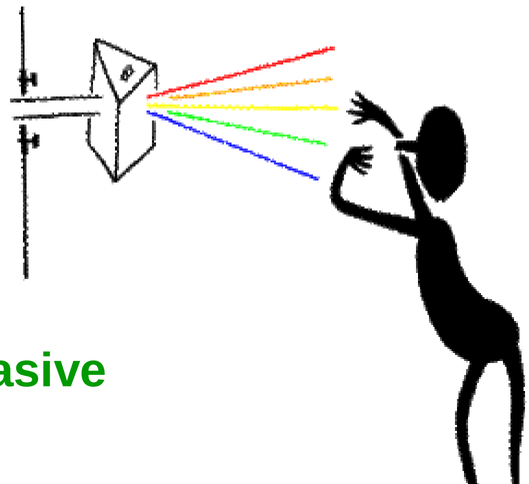
- high H_α/H_β ratio: $H^- = 1 \times 10^{17}$ m^{-3}
- stable H_β/H_γ ratio, i.e. stable n_e and T_e

Emission spectroscopy: n_s, $T_s \rightarrow$ e, H, H_2, H^-

Powerful diagnostic tool



simple equipment



in-situ, non-invasive

line of sight averaged results

- identification of species
- particle densities
- particle temperatures
- on-line monitoring
- insight in plasma processes
- spatial resolution by several lines of sight

Analysis — based on atomic and molecular physics

simple → **quite complex**

supported by collisional radiative models

Summary

Plasma Diagnostics of Ion Sources

The three W's

- What do I want to know ? → and why?
- What is the adequate technique ? → effort versus gain!
- What is the accessibility of the source ? → feasibility !

The three examples

- Langmuir probes → ϕ_{pl}, n_e, T_e, (EEDF)
- Absorption techniques → $n_{species}$ → Cs, H^-
- Emission spectroscopy→ n_s, T_s→ e, H, H_2, H^-

The three "keep-in-mind's"

- Monitoring versus quantification → trends or full information
- Spatial resolution → averaged or x-resolved (step width!))
- Temporal resolution → averaged or t-resolved (time scale!)

Diagnostics – The Window to the Knowledge !

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