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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

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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	

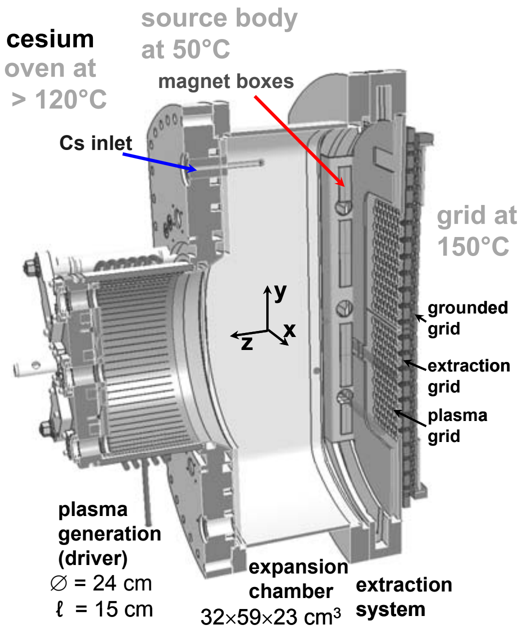
Introduction into techniques and applications for example in [1] – [7]

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

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

dissociative attachment

surface process

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

low work function

caesium layer

destruction processes

$$\mathbf{H^-} + e^- \rightarrow H + 2e^-$$

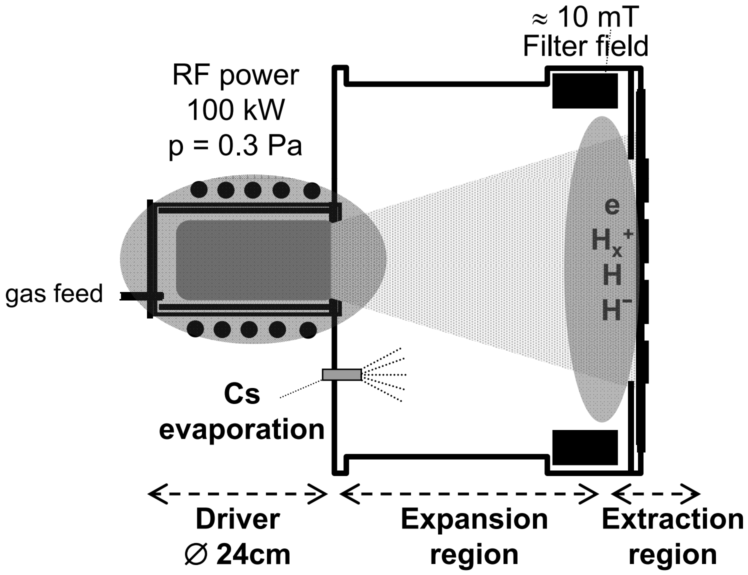
$$\mathbf{H^-} + H^+ \rightarrow H + H$$

$$\mathbf{H^-} + H \rightarrow H + H + e^-$$

... determine source optimisation

Example case: sources for negative hydrogen ions

Ion sources for negative hydrogen ions: ionising – recombining plasma



H, H_x^+ + surface e^- → $\mathbf{H^-}$

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

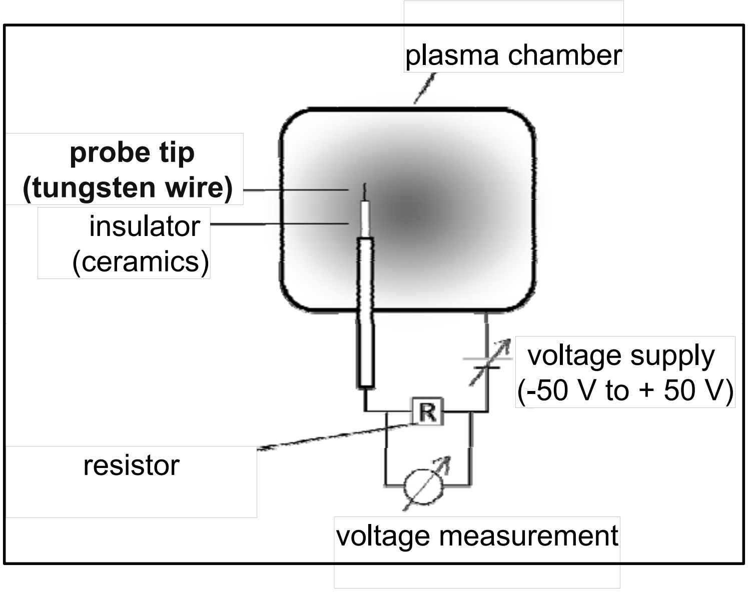
Main issues

- 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

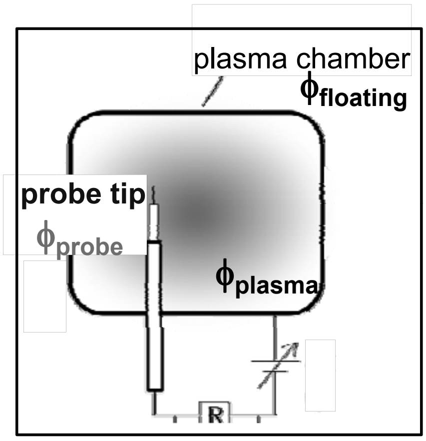
⬇

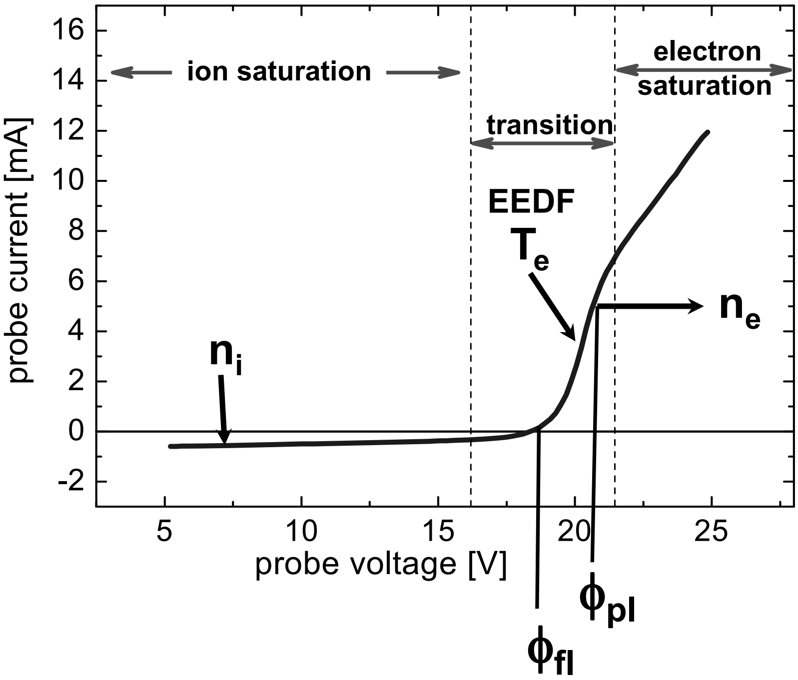
I – V
characteristics

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

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

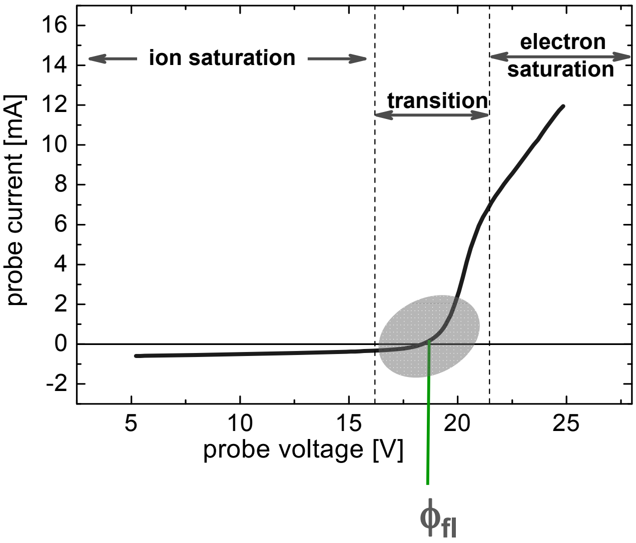
Main principle





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

Floating potential



- same fluxes for ions and electrons

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

  same currents

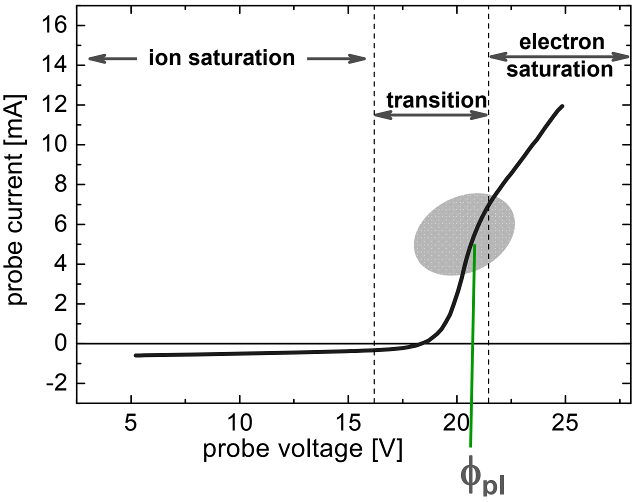
- no probe current

⬇

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

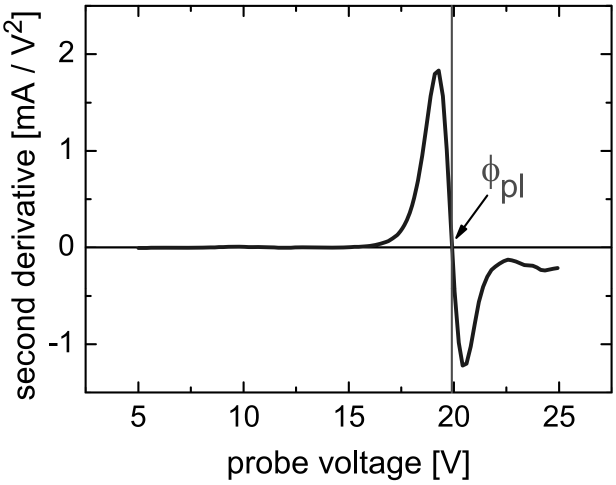
Langmuir probes: ϕ_{pl}, n_e, T_e, (EEDF)

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

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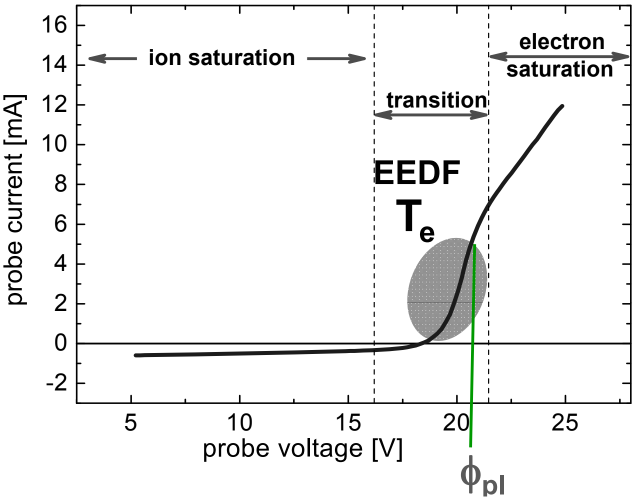
Langmuir probes: ϕ_{pl}, n_e, T_e, (EEDF)

Electron energy distribution function (EEDF) and electron temperature



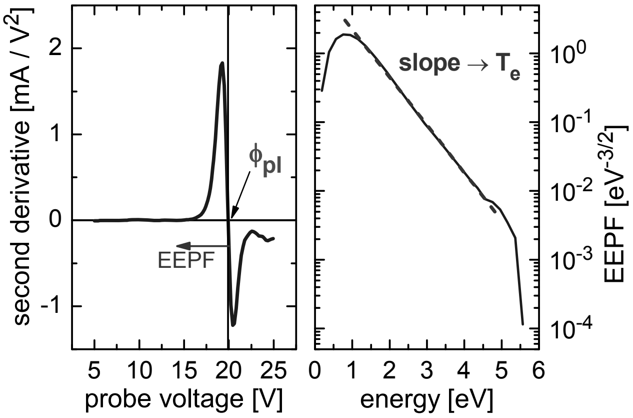
- distinguish: **EEDF = sqrt(E) × EEPF**

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

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

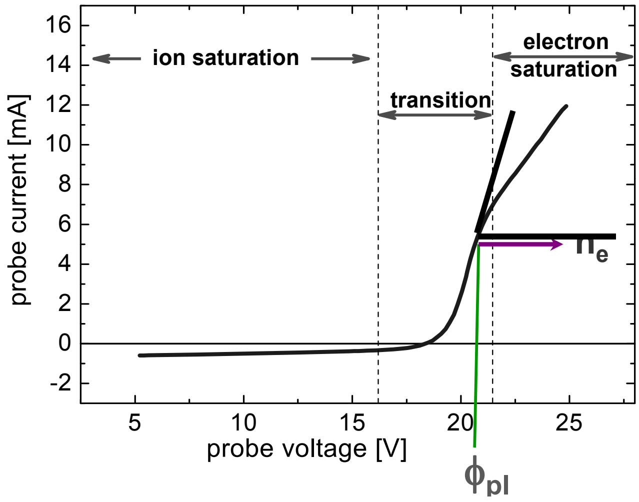


- T_e also from potential difference

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

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

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

  → $A_{eff} = A_{probe}$

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

needs $\mathbf{T_e}$

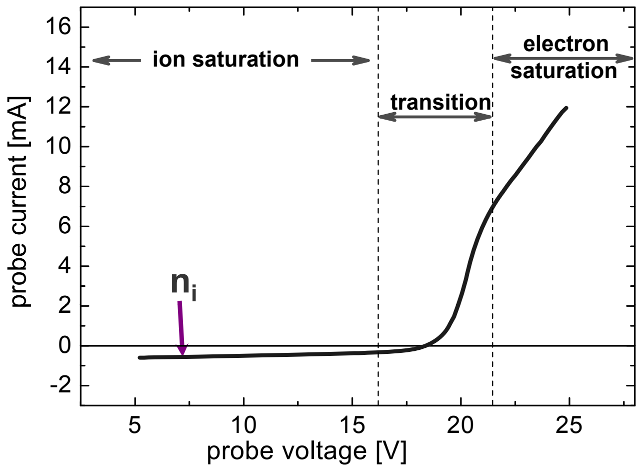
Probe geometry

influences shape of electron saturation current

- cylindrical probe (standard case)
- planar probe → A_{pr} >> sheath
- spherical probe

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

Ion density (positive ions)



- 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

- 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 $\mathbf{T_e}$

needs $\mathbf{m_i}$

often unclear, e.g. hydrogen

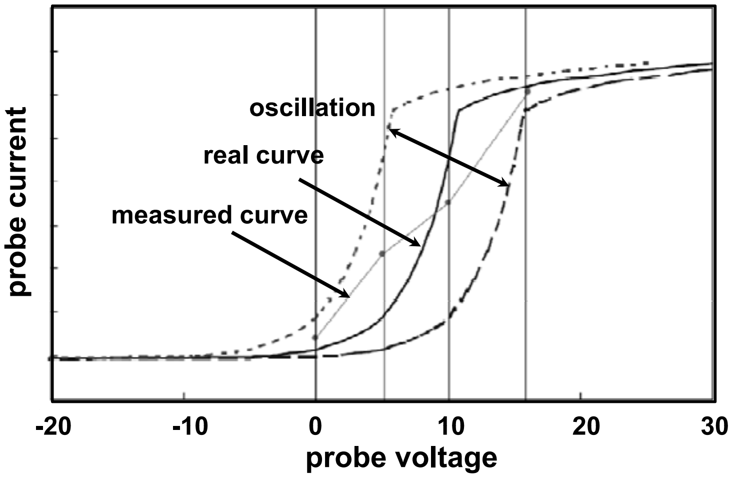
→ H^+, H_2^+, H_3^+

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

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

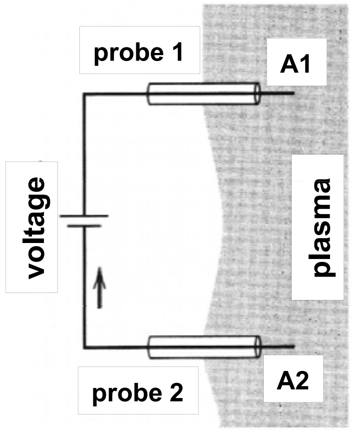


- magnetic field → gyro motion
  use I_{ion} instead of I_e
- negative ions → I_- instead of I_e
  for same mass $I_{sat,ion} = I_{sat,}$ symmetric curves

For monitoring or quantification with spatial and temporal resolution !

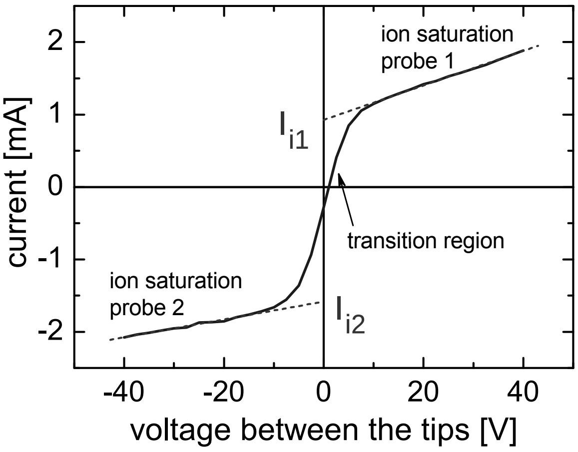
Langmuir probes: ϕ_{pl}, n_e, T_e, (EEDF)

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



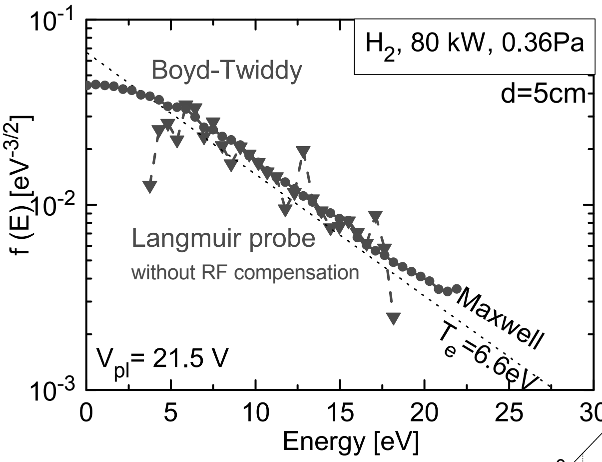
- symmetric curve: ion saturation current

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

- **T_e** from transition region

Example: Langmuir probes in ion source & Boyd-Twiddy setup

Comparison of EEDF



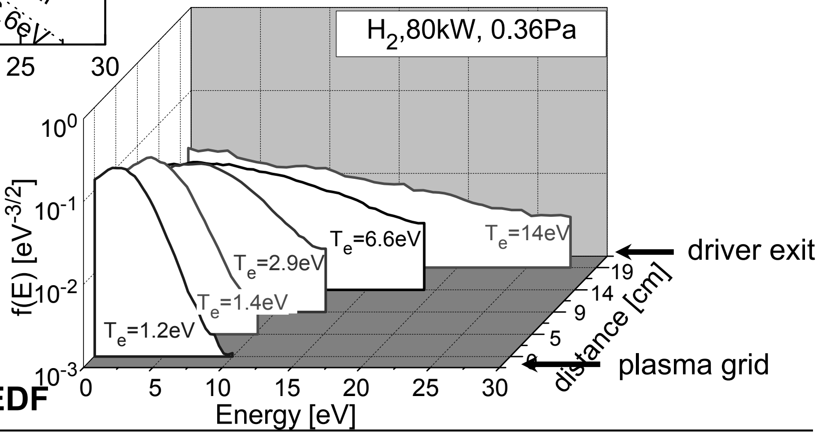
Boyd-Twiddy method: direct measurement of EEDF

- 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

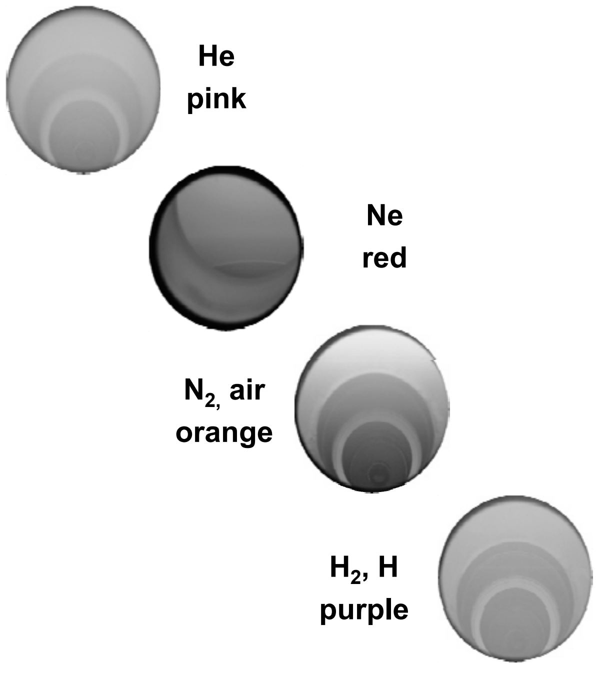


Maxwellian EEDF

All about photons: emission and absorption

Radiation of low temperature plasmas

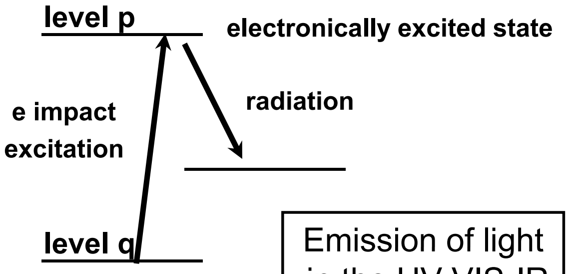
Colourful plasmas !



Neutrals	atoms and molecules
Ions	single charged
Electrons	$n_e << n_n$

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

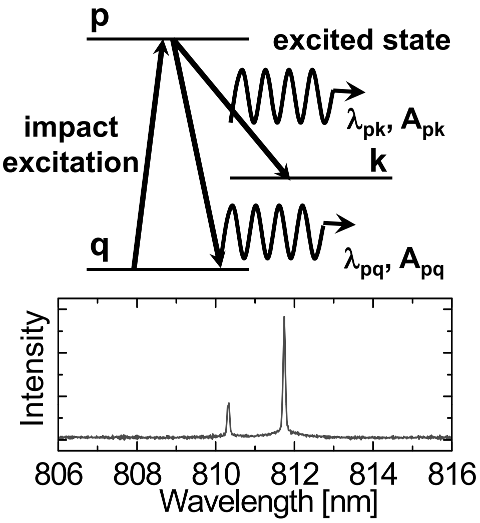
All about photons: emission and absorption

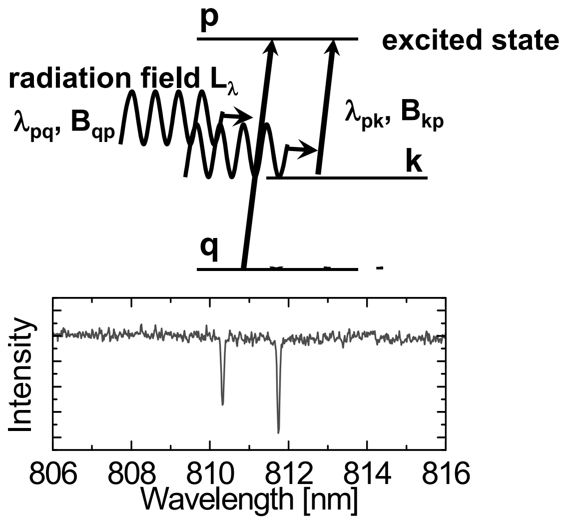
Emission versus absorption spectroscopy

Emission
passive

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

Absorption
active



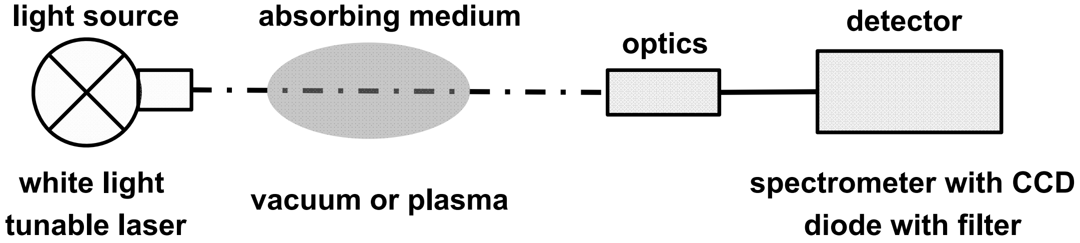


- VIS: simple equipment
- information of upper level p

- expensive equipment
- information of lower level q

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

Main principle of line absorption



light source **absorbing medium** **optics** **detector**

white light
tunable laser

vacuum or plasma

spectrometer with CCD
diode with filter

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

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

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

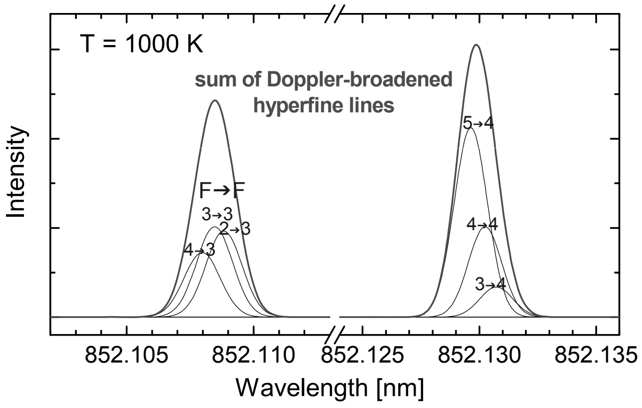
Example: Cs line at 852.1 nm

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

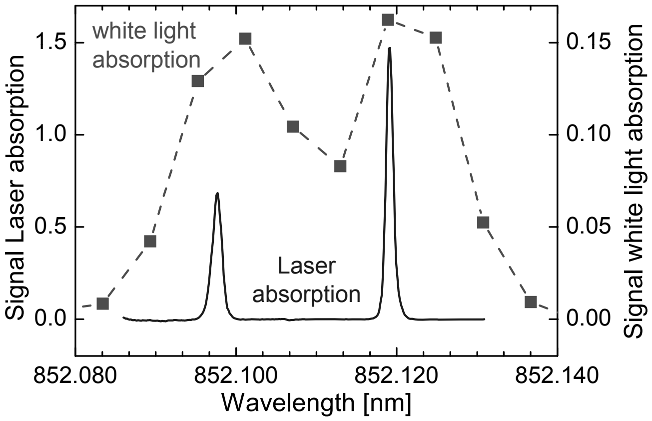
take line broadening into account

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: $\Delta\lambda \approx 21$ pm

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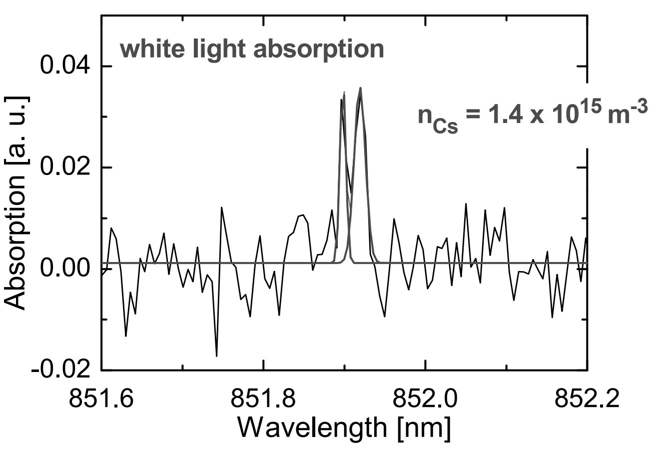
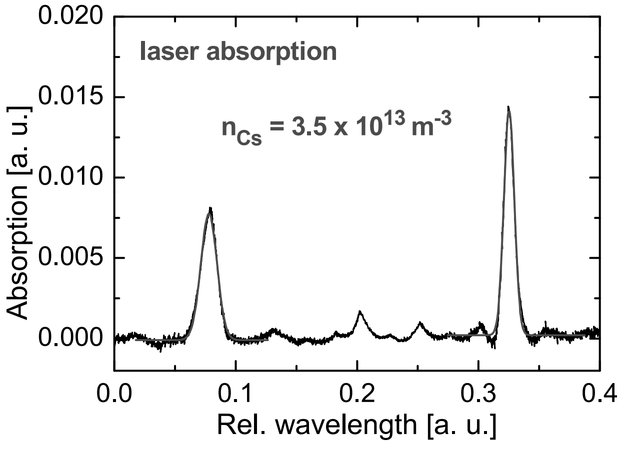
Absorption techniques: $n_{species} \rightarrow$ Cs, Ar, He, ...

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 !

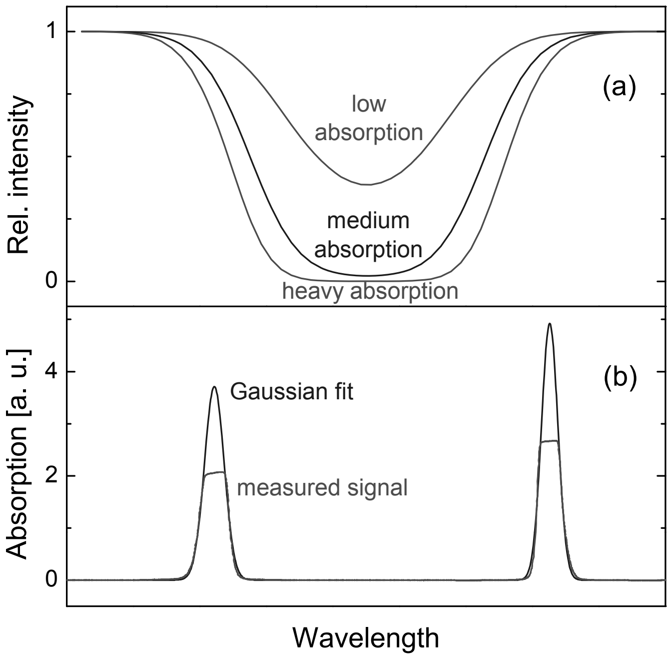
sensitivity range: 3×10^{13} m^{-3} - 10^{17} m^{-3} (path length = 15 cm)
being perfectly in the range required for the ion sources

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

Straightforward analysis

- in vacuum
- with plasma → subtract emission

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



... 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

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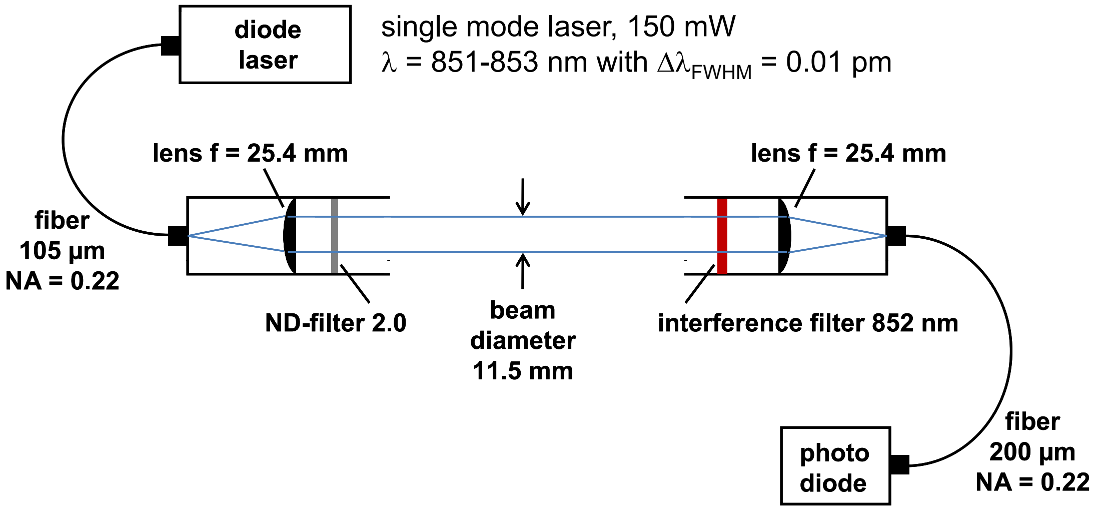
Laser absorption for Cs in ion sources

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



diode laser

single mode laser, 150 mW
λ = 851-853 nm with $\Delta\lambda_{FWHM}$ = 0.01 pm

lens f = 25.4 mm

lens f = 25.4 mm

fiber
105 µm
NA = 0.22

ND-filter 2.0

beam
diameter
11.5 mm

interference filter 852 nm

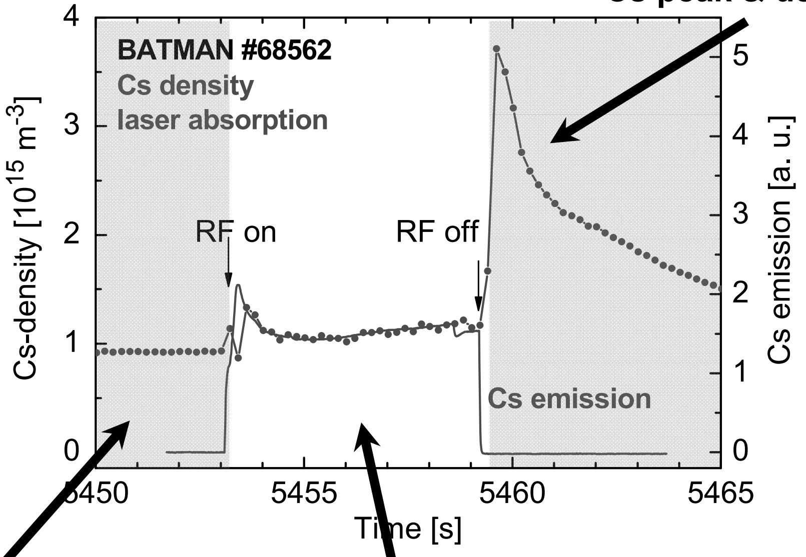
fiber
200 µm
NA = 0.22

photo diode

Simple and robust setup for application to ion sources !

Example: laser absorption for on-line monitoring of Cs dynamics

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



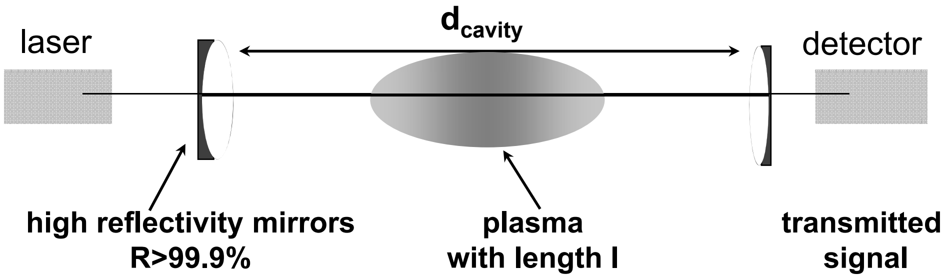
③ **30 s after pulse: Cs peak & decay time**

① **3 s before pulse: vacuum**

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

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

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

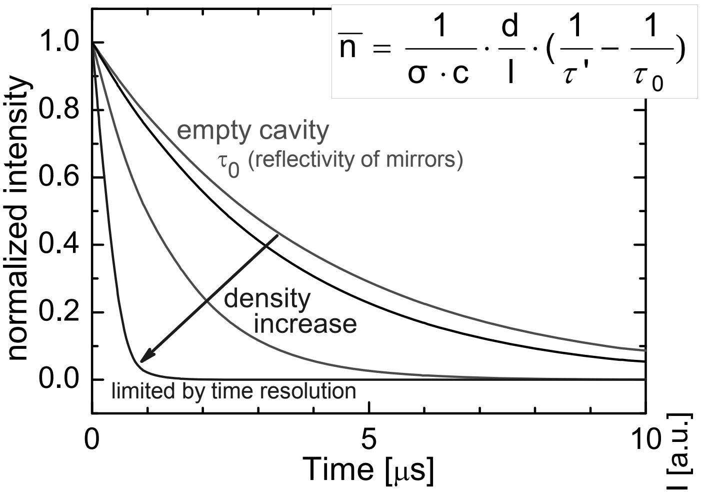
empty cavity with decay time τ_0

additional absorption $\tau_0 \rightarrow \tau'$

$$I(t) = I_0 \cdot e^{-t/\tau_0} \; ; \; \tau_0 = \frac{d}{c(1-R)} \longrightarrow \boxed{\bar{n} = \frac{1}{\sigma \cdot c} \cdot \frac{d}{l} \cdot \left(\frac{1}{\tau'} - \frac{1}{\tau_0}\right)}$$

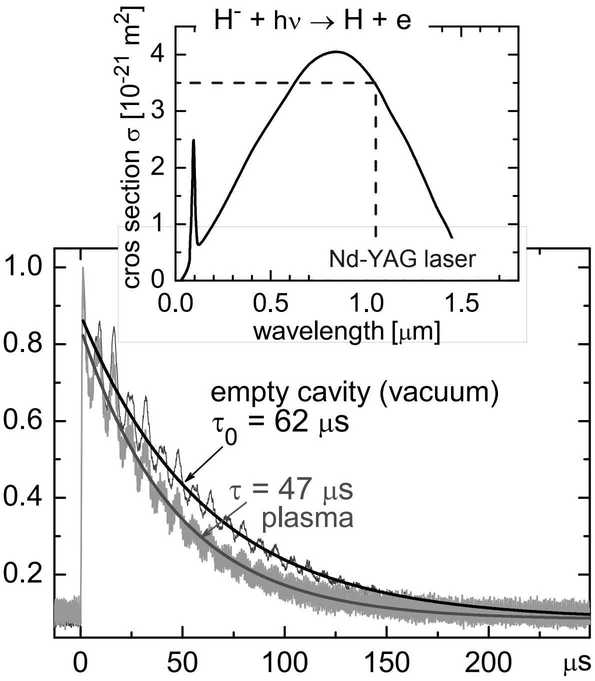
Absorption techniques: $n_{species}$ → H^-, Cs, Ar, H_3^+...

Cavity – Ringdown – Absorption – Spectroscopy → CRDS



Example H^-

cross section: photodetachment

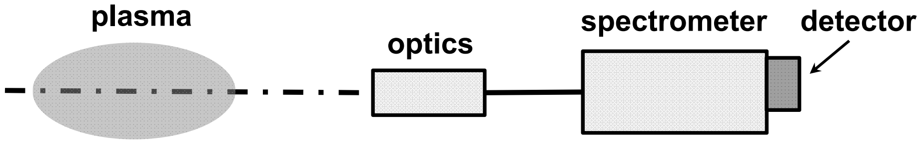


H^- density: line of sight averaged

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

Emission spectroscopy: n_s, T_s→ e, H, H_2, H^-

The main principle



UV and VUV: vacuum system
IF: detector

Non-invasive and line of sight integrated method !

Measures density of excited state ...

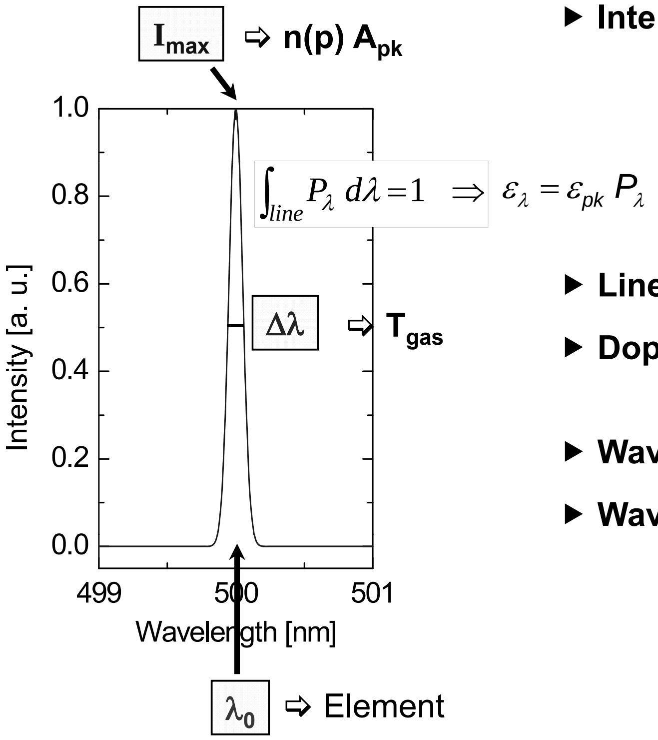
$$\boxed{\varepsilon_{pk} = n(p) A_{pk} \frac{hc/\lambda}{4\pi}}$$

... which depends on plasma parameters !

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

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

What information can be obtained from the line emission ?



$\boxed{I_{max}}$ ⇨ **n(p) A_{pk}**

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

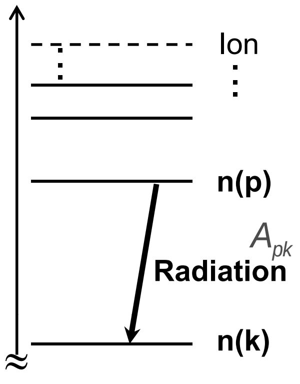
$\boxed{\Delta\lambda}$ ⇨ **T_{gas}**

$\boxed{\lambda_0}$ ⇨ 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

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

Energy



Atoms

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

Molecules

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

selection rules

Atoms:

$\Delta L = 0, \pm 1$

$\Delta J = 0, \pm 1$

$\Delta S = 0$

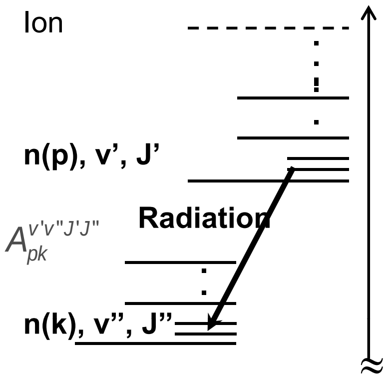
Molecules:

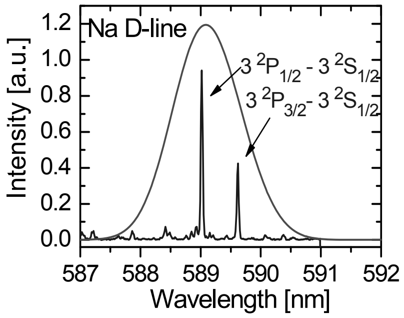
$\Delta\Sigma = 0$

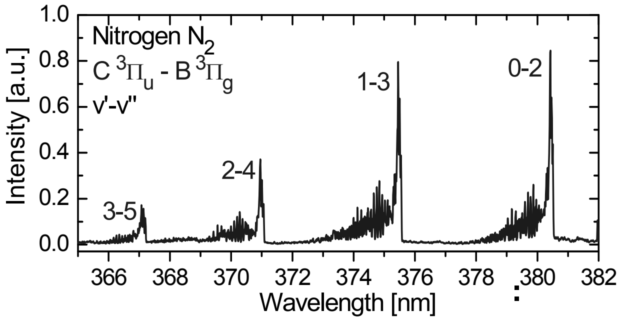
$u \leftrightarrow g$

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

P, Q, R branch



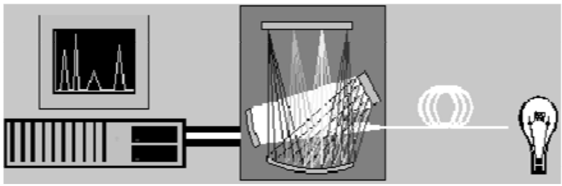




Appearance depends on spectral resolution !

Emission spectroscopy: n_s, T_s → e, H, H_2, H^-

Spectroscopic system



Detector **Spectrometer** **Optics**

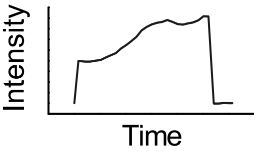
- photomultiplier
  λ scan
  Δλ, Δt
- diode array
  λ range
- CCD, ICCD
  pixel size - Δλ
  intensity

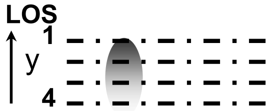
- focus length
  spectral resolution Δλ
- grating
  spectral resolution
  Blaze - intensity
- slits
  entrance slit Δλ
  exit slit - detector

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

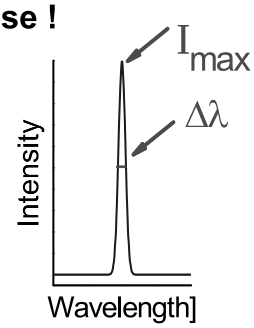
Emission spectroscopy: n_s, T_s → e, H, H_2, H^-

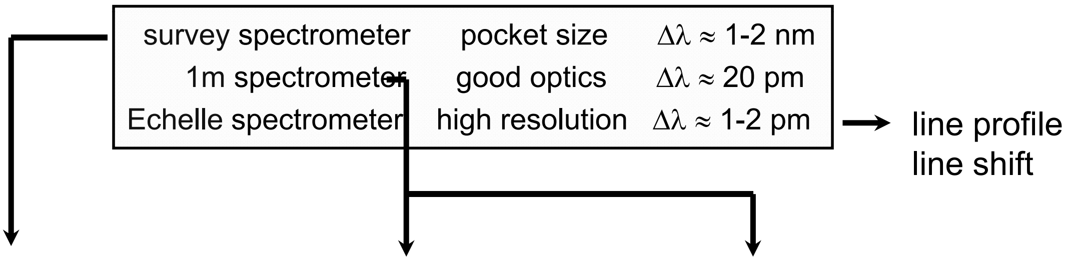
The spectroscopic system is determined by the purpose !





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





survey spectrometer	pocket size	Δλ ≈ 1-2 nm
1m spectrometer	good optics	Δλ ≈ 20 pm
Echelle spectrometer	high resolution	Δλ ≈ 1-2 pm

→ line profile
line shift

line monitoring
very simple
Δt, poor Δλ
less information

relative intensities
common technique
poor Δt, Δλ, Δx, flexible
moderate information

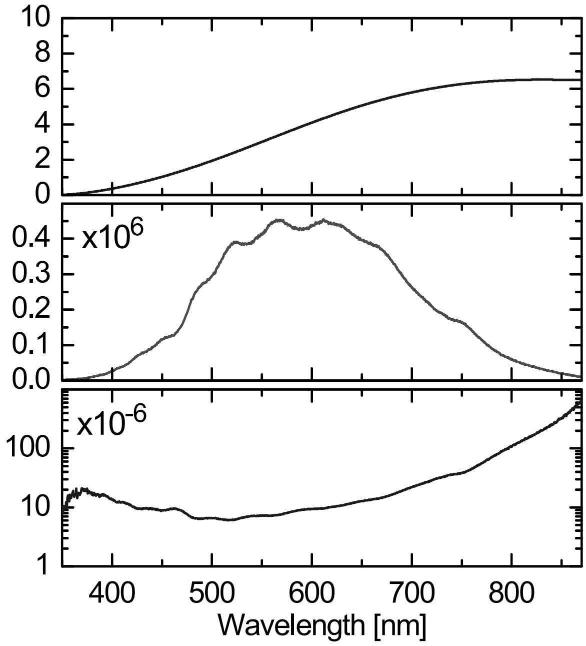
absolute intensities
expensive technique
poor Δt, Δλ, Δx, flexible
powerful tool

Emission spectroscopy: n_s, T_s → e, H, H_2, H^-

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 → e, H, H_2, H^-

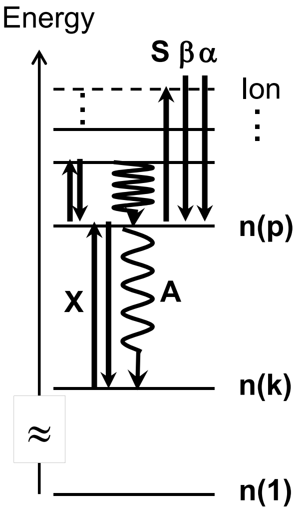
From intensity $I_{pk} = n(p)\,A_{pk}$ to plasma parameter

Population models

high n_e ↓ low n_e

Boltzmann distribution (TE, LTE)
Collisional radiative model
Corona equilibrium

↑ relevance of photons



Rate equations for excitation and de-excitation processes

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

Corona model

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

rate coefficient

$n_1 \cong n_0$

emission rate coefficient

$$\boxed{I_{pk} = n_0\; n_e\; X_{pk}(T_e)} \quad with \quad X_{pk} = X_{1p}(T_e) A_{pk} / \sum\nolimits_k A_{pk}$$

CR model

$$\boxed{I_{pk} = n_0\; n_e\; X^{eff}_{pk}(T_e, n_e, ...)}$$

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

Electron temperature from absolute line emission

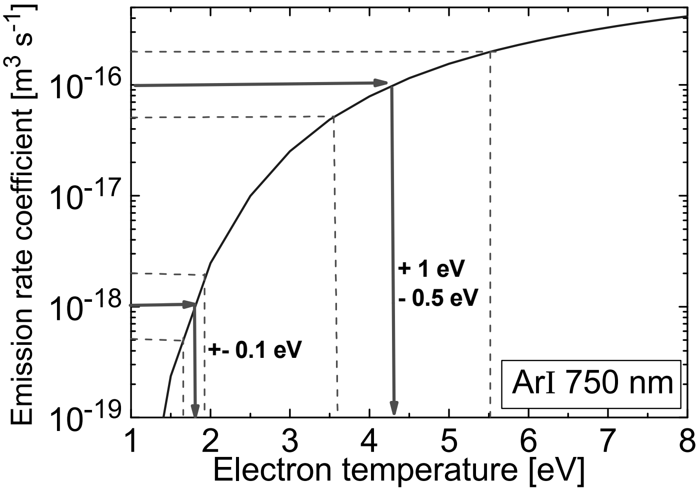
$$\boxed{I_{pk} = n_0\, n_e\, X_{pk}^{eff}(T_e, n_e, ...)}$$

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

Find suitable gases and diagnostic lines

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

Very sensitive for low T_e !



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

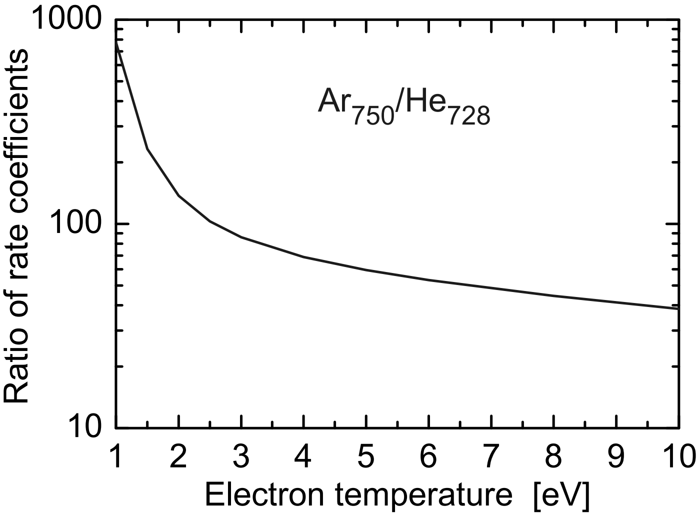
Electron temperature from line ratio (relative calibration)

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

→ 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)

$$\frac{I^1_{pk}}{I^2_{pk}} = \frac{n_1 \cancel{n_e} X^1_{pk}(T_e)}{n_2 \cancel{n_e} X^2_{pk}(T_e)}$$

→ ratio of densities for known rate coefficients

- density ratio (n_H/n_{H2})

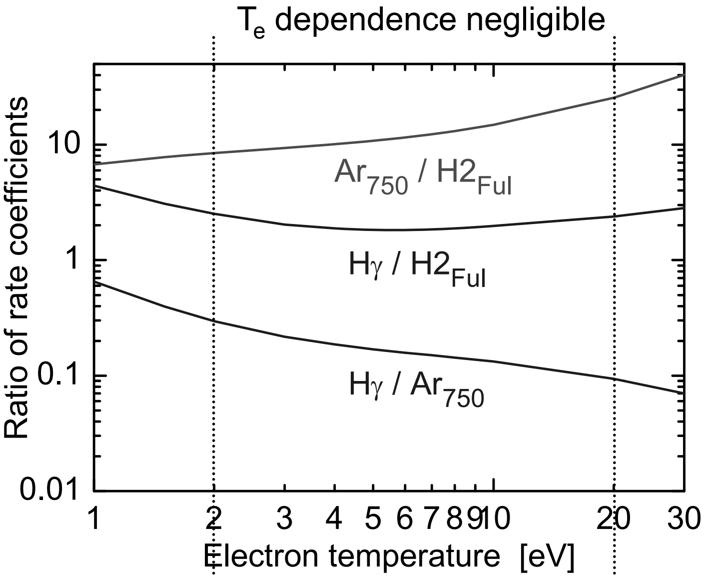
$$\frac{I^H_{434}}{I^{H_2}_{Ful}} = \frac{n_H \cancel{n_e} X^H_{434}(T_e)}{n_{H_2} \cancel{n_e} X^{H_2}_{Ful}(T_e)}$$

independent on n_e

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

$$\frac{I^{Ar}_{750}}{I^{H_2}_{Ful}} = \frac{n_{Ar} \cancel{n_e} X^{Ar}_{750}(T_e)}{n_{H_2} \cancel{n_e} X^{H_2}_{Ful}(T_e)}$$

- density ratio (n_{He}/n_{H2})
  dependence on T_e (factor of 10)
  →needs iteration



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

Particle density from absolute line emission

$$\boxed{I_{pk} = n_0 \; n_e \; X^{eff}_{pk}(T_e, n_e, ...)}$$

n_e, T_e known ⇨ $n_0 = \dfrac{I_{pk}}{n_e \, X^{eff}_{pk}(T_e, n_e, ...)}$

Knowledge of dominant excitation mechanism is essential !

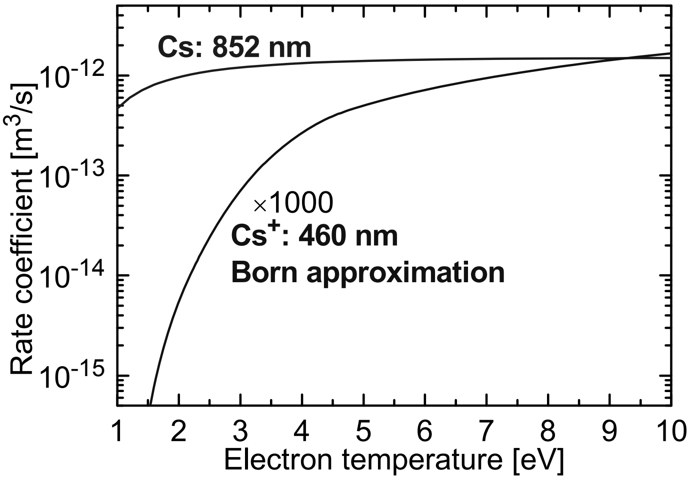
Example: Cs and Cs^+ lines

Cs: $I^{Cs}_{852} = n_{Cs} \; n_e \; X^{Cs}_{852}(T_e)$

needs n_e, almost independent of T_e

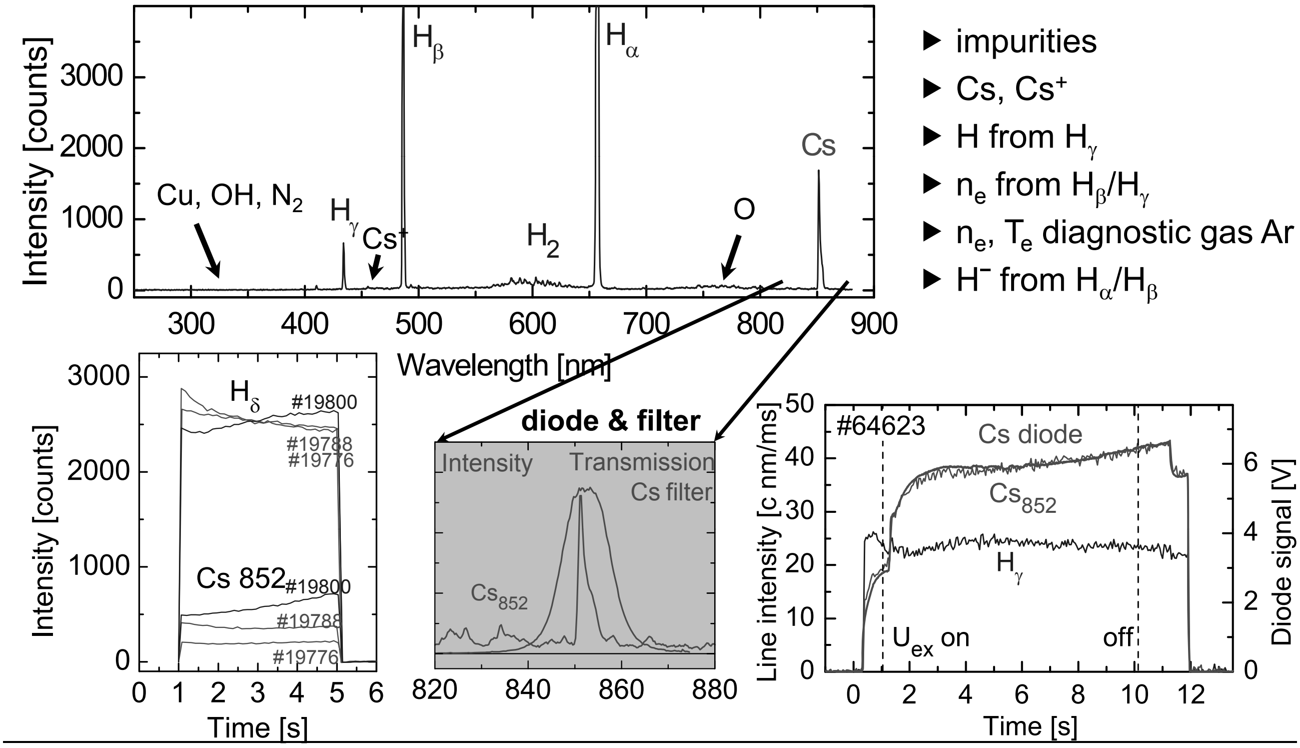
Cs^+: $I^{Cs^+}_{460} = n_{Cs^+} \; n_e \; X^{Cs^+}_{460}(T_e)$

needs n_e, strong dependence on T_e



Example: emission spectroscopy at the ion source

Survey spectrometer and on-line monitoring



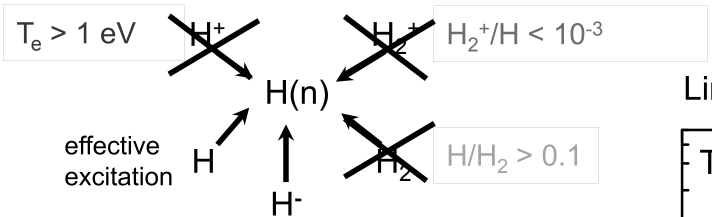
- impurities
- Cs, Cs^+
- H from H_γ
- n_e from H_β/H_γ
- n_e, T_e diagnostic gas Ar
- H^- from H_α/H_β

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

U. Fantz, D. Wünderlich

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

Population mechanisms for H



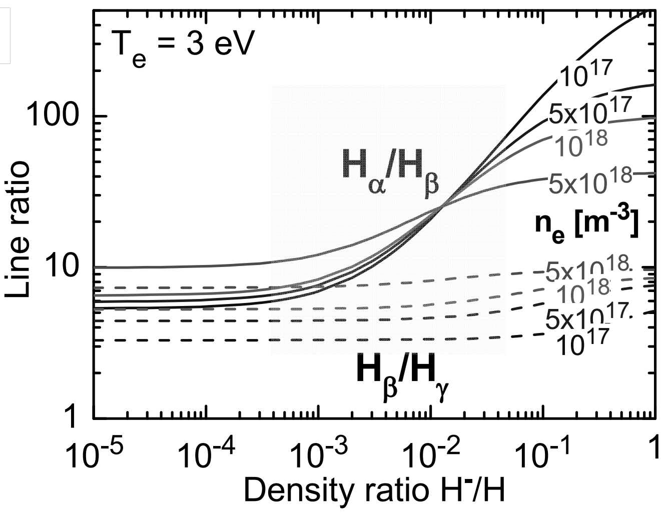
mutual neutralisation

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

$$\downarrow H_\alpha$$

Collisional radiative model

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



Measurement of Balmer line ratios

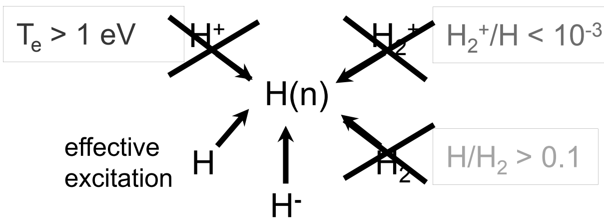
- H_α/H_β depends on H^-/H
- H_β/H_γ reflects n_e and T_e

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

U. Fantz, D. Wünderlich

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

Population mechanisms for H



T_e > 1 eV ~~H^+~~

~~H_2^+~~ $H_2^+/H < 10^{-3}$

H(n)

effective excitation H

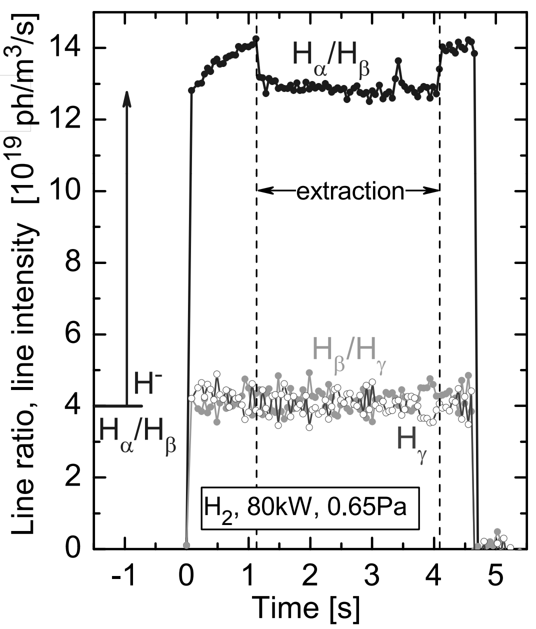
~~H_2~~ $H/H_2 > 0.1$

H^-

mutual neutralisation

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

Collisional radiative model



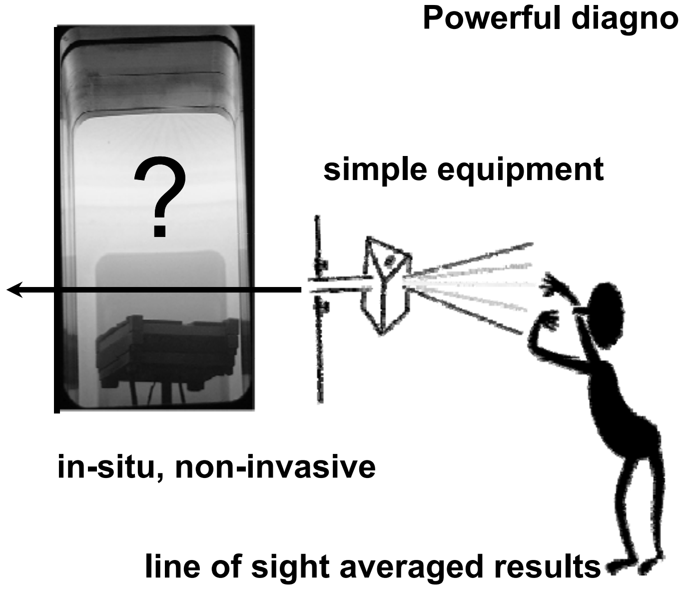
Measurement of Balmer line ratios

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

- high H_α/H_β ratio: $H^- = 1\times10^{17}$ 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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