EPFL

Plasma II
L12: Plasma diagnostics 1

H. Reimerdes

May 23, 2025

Swiss Plasma Center

Outline

- Introduction
- Passive measurements
  - EM emission
    - Bremsstrahlung
    - Line emission
    - Synchrotron radiation
    - Cyclotron emission
  - Magnetic fields
- Active measurements
  - Langmuir probes
  - Interferometry
  - Thomson scattering
- Appendix

Plasma diagnostics 1

Plasma diagnostics 2

- I.H. Hutchinson, "*Principles of plasma diagnostics*", Second edition, Cambridge University Press

Motivations

- Progress in physics usually through quantitative confrontation between theory and experiment
  - Requires theory predictions in realistic settings
  - Requires accurate and extensive measurements of the (plasma) properties → **Diagnostics**

Plasma properties

- Ions (various species and charge states), electrons and neutrals

  $f_s(\bar{x}, \bar{v}, t)$ - *Distribution function for particle species s*

  - Moments of the distribution function (see L2)
    - *N*=0: Density
    - *N*=1: Flow velocity
    - *N*=2: Pressure/Temperature
  - Deviations from a Maxwell-Boltzmann distribution (e.g. fusion alphas!)
  - Impurity concentrations
- Magnetic and electric fields
  - Their sources: electric currents and electric charges/potential
- Time-averaged values or fluctuations

Approaches to diagnostics

- What do we have to measure to deduce a particular quantity?
- What can we conclude from a specific measurement?

Aspects of diagnostics

- Physics
- Detection
  - Scheme
  - Technology
  - Perturbation of the plasma
- Signal-treatment/transfer
- Signal acquisition
- Post processing
- Data storage

} Address only these aspects in this course

Types of measurements

Passive measurements

- Radiation diagnostics
  - Spectroscopy
  - Bolometry
  - Radiation in magnetised plasmas
- Magnetic measurements
- Ion loss detectors
- …

Active measurements

- Langmuir probes
- Interferometry
- Scattering diagnostics
- Neutral beam (e.g. CXRS)
- Heavy beam probes
- …

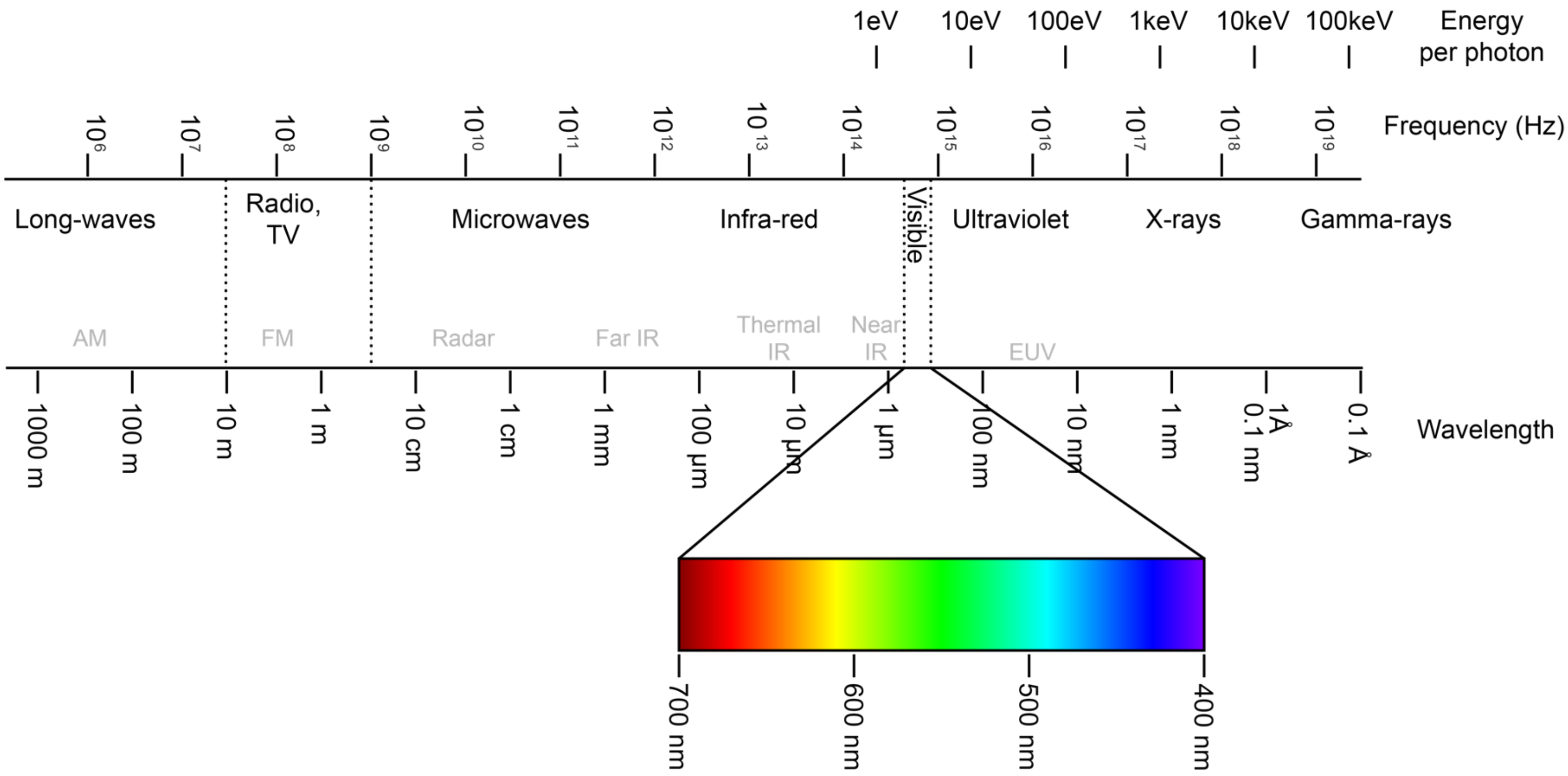
Outline

- Introduction
- **Passive measurements**
  - EM emission
    - Bremsstrahlung
    - Line emission
    - Synchrotron radiation
    - Cyclotron emission
  - Magnetic fields
- Active measurements
  - Langmuir probes
  - Interferometry
  - Thomson scattering
- Appendix

Plasma diagnostics 1

Plasma diagnostics 2

EM spectrum



Adopted from https://commons.wikimedia.org/wiki/File:Electromagnetic-Spectrum.svg

H. Reimerdes

Plasma radiation

- Plasmas can emit electro-magnetic radiation over a wide range of frequencies/wavelengths
  - From hard X-rays to cm waves
  - Emission dominated by characteristic lines on top of a lower continuum
  - (Laboratory) Plasmas often/for most υ optically thin → Measure $S_\upsilon = \int \varepsilon_\upsilon(\mathbf{r})\, d\mathbf{r}$

- Electrons
  - Free-free collisions with ions & electrons → Bremsstrahlung (continuum)
  - Free-bound → Recombination (continuum)
  - Bound-bound transitions → Line radiation
  - Free in B-field → Synchrotron & cyclotron radiation

Bremsstrahlung

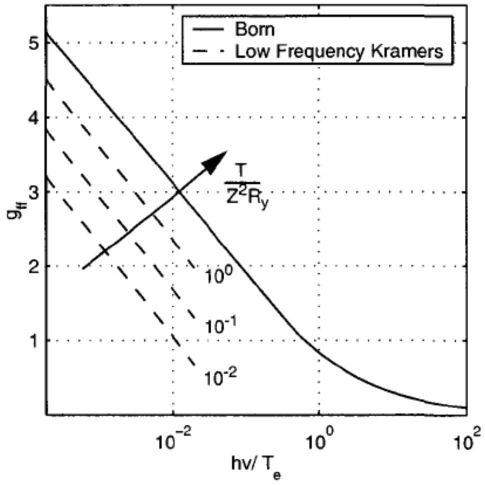
- Coulomb collisions deflect, i.e. accelerate charges → e-m emission

Bremsstrahlung

- Coulomb collisions deflect, i.e. accelerate charges → e-m emission

$$j(\nu) = \frac{n_e n_i Z^2}{4\pi}\left(\frac{e^2}{4\pi\varepsilon_0}\right)^3 \frac{32\pi^2}{3\sqrt{3}m_e^2c^3}\left(\frac{2m_e}{\pi T_e}\right)^{1/2} e^{-h\nu/T_e}\,\bar{g}$$

  - With Maxwell-averaged Gaunt factor $\bar{g}$
  - For $0.1 \le h\nu/T_e \le 10$, $\bar{g}$ of order unity → temperature dependence of $j(\nu)$ well described by $\propto T_e^{-1/2} e^{-h\nu/T_e}$



Total emissivity

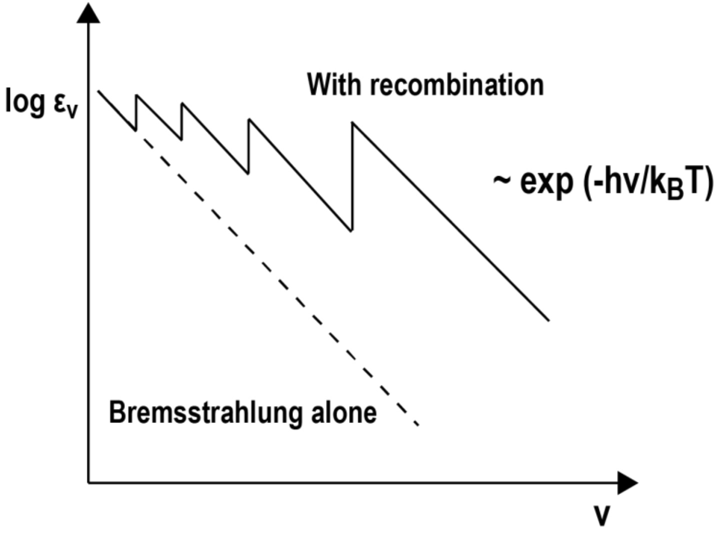
➢ Intensity and spectrum of bremsstrahlung yields information on plasma density, charge state and temperature

Recombination radiation

- Energy balance (hydrogen)

$$h\nu = \frac{1}{2}mv^2 + \frac{R_y}{n^2}$$

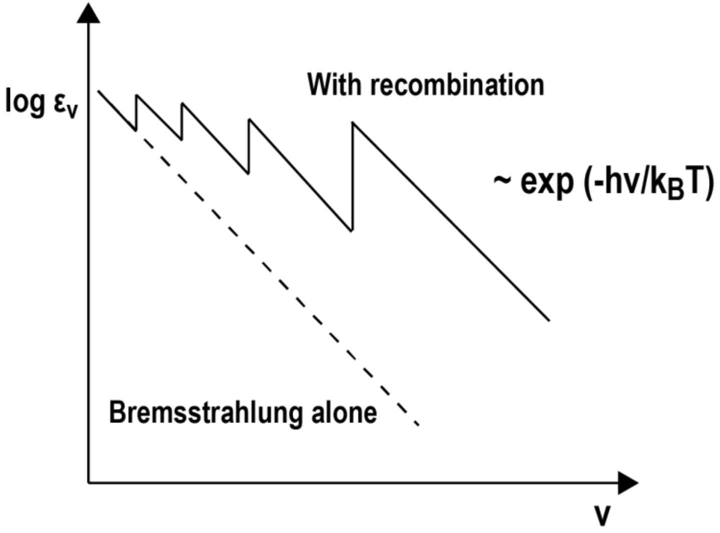
- Introduces 'edges' in the continuum as final states with lower n increase photon energy in discrete steps
  - For $h\nu \ll R_y$ the contribution of recombination is negligible



Use Bremsstrahlung to determine electron temperature

H. Reimerdes

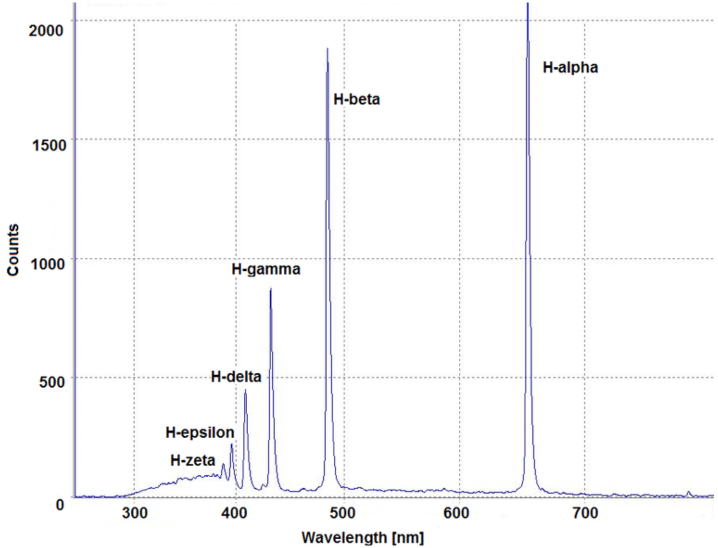
- Compare signal intensity with different filters → "Filter temperature"
  - Detect in the soft-x-ray regime
  - Use Be filters to suppress 'low' frequencies



Line radiation

- Pattern for hydrogen recognised by J. Rydberg in 1888
  - Express emission through wavenumber λ^{-1} was key for discovery

Visible emission of a hydrogen plasma in a theta pinch



[G. Loisch, et al., DOI:10.1109/PLASMA.2013.6633294]

For hydrogen

$$\frac{1}{\lambda} = R_{\mathrm{H}}\left(\frac{1}{n_1^2} - \frac{1}{n_2^2}\right)$$

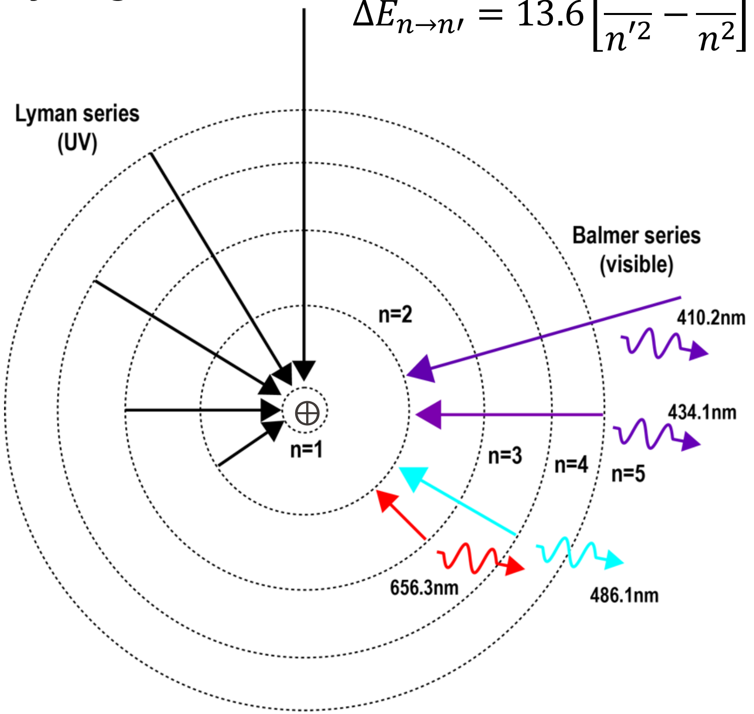
Line-radiation: Frequency selection

- Transitions between bound electron states lead to discrete photon energies

$$\Delta E_{n\rightarrow n'} = h\nu = \frac{hc}{\lambda} = E_n - E_{n'}$$

Ex.: Hydrogen

$$\Delta E_{n\rightarrow n'} = 13.6\left[\frac{1}{n'^2} - \frac{1}{n^2}\right]\,\mathrm{eV}$$



H. Reimerdes

Line-radiation: Line intensity

- Emission depends on density n_n of bound electrons in state n and transition probability $A_{n\to n'}$

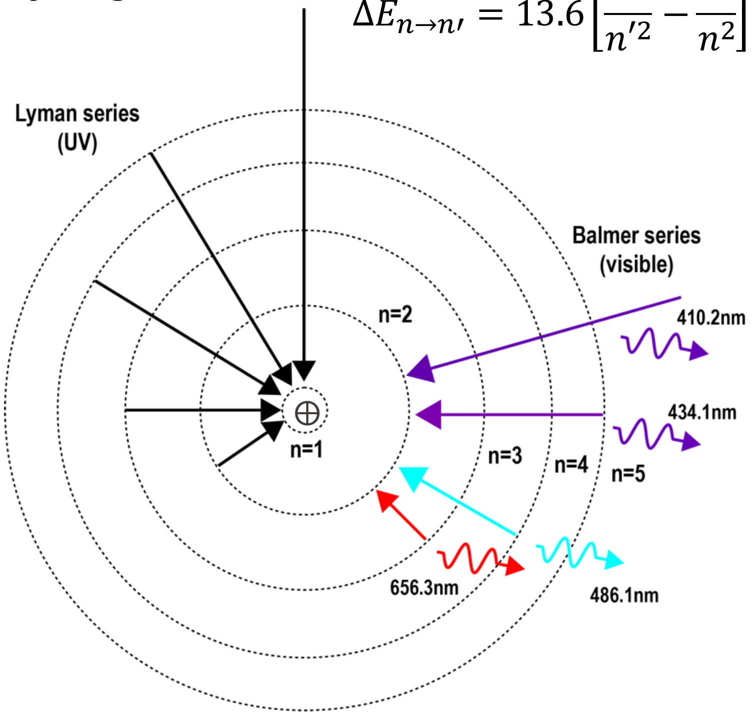
$$\varepsilon_L = \Delta E_{n\to n'} A_{n\to n'} n_n$$

- Measured line intensity (radiance)

$$I_L = \frac{1}{4\pi}\int \varepsilon_L \, dl$$

Ex.: Hydrogen

$$\Delta E_{n\to n'} = 13.6\left[\frac{1}{n'^2} - \frac{1}{n^2}\right]\text{eV}$$

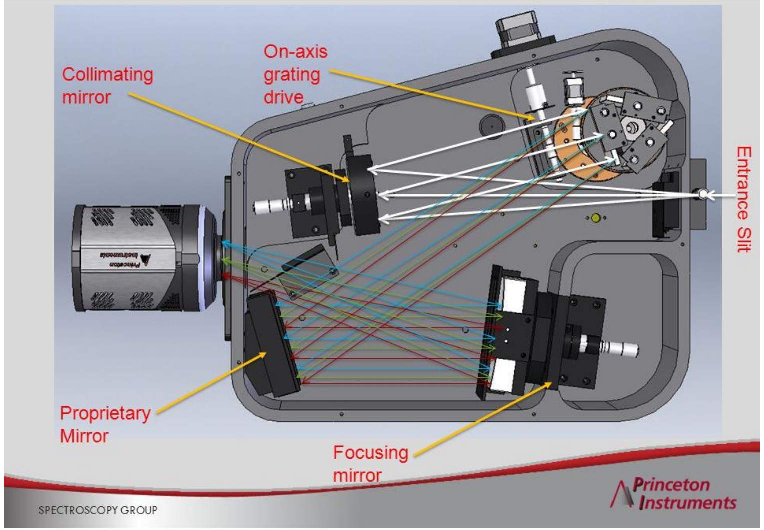


Spectrometry

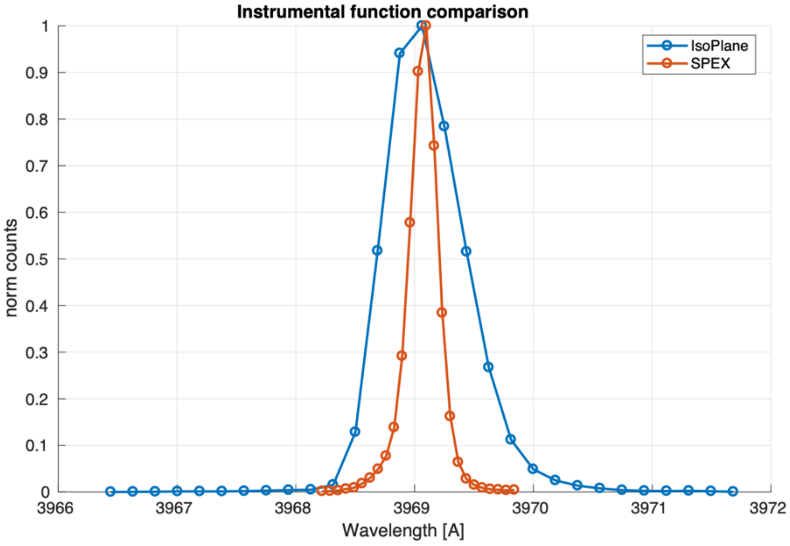
- Use a grating to 'Fourier transform' the emitted light

Spectrometer

- Schmidt-Czerny-Turner Spectrograph



- Ex.: Instrumental function of TCV's divertor spectrometers

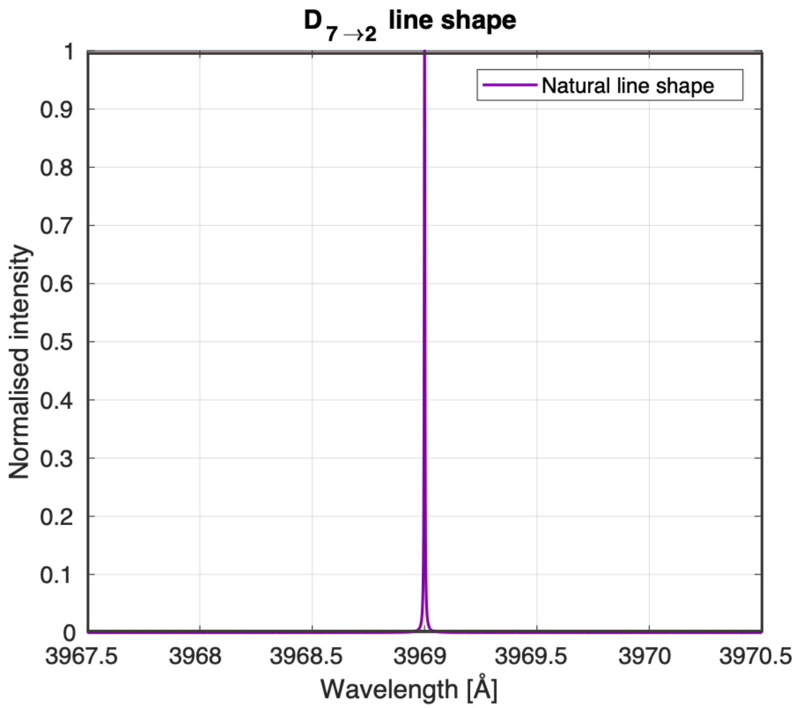


[Courtesy of L. Martinelli]

Spectral line shape

- Natural broadening causes a *Lorentzian distribution* of the emission intensity
  - Width inversely proportional to transition probability (Einstein coefficients)
- **Ex.**: D-ε

$$\mathrm{FWHM}(D_{7\to2}) \simeq 4 \cdot 10^{-3}\text{Å}$$

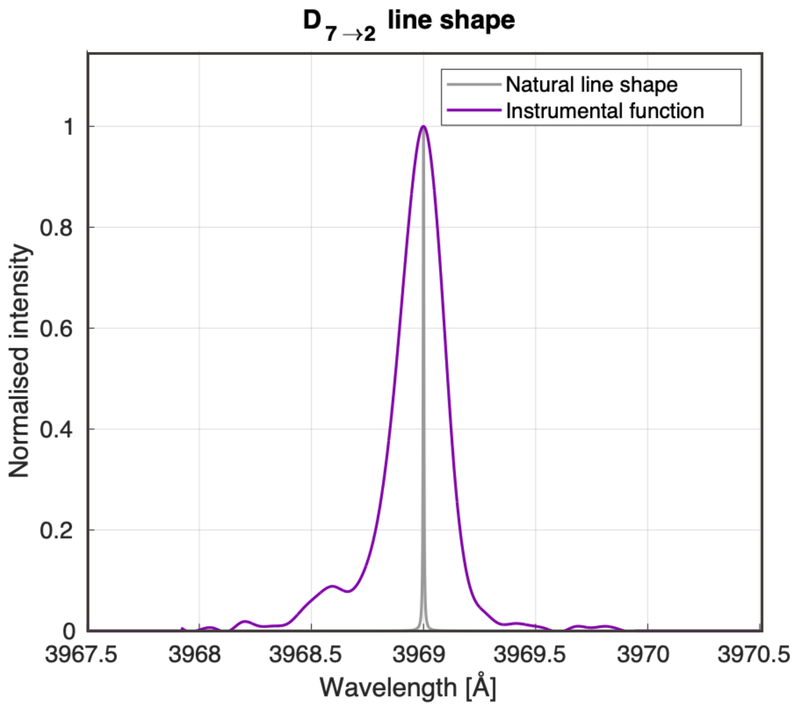


[Courtesy of L. Martinelli]

Spectral line shape

- Diagnostic setup broadens the line (*instrumental boadening*)
- **Ex.**: TCV high resolution divertor spectrometer (SPEX)

$$\text{FWHM}(\mathrm{SPEX}) \simeq 0.20\text{Å}$$

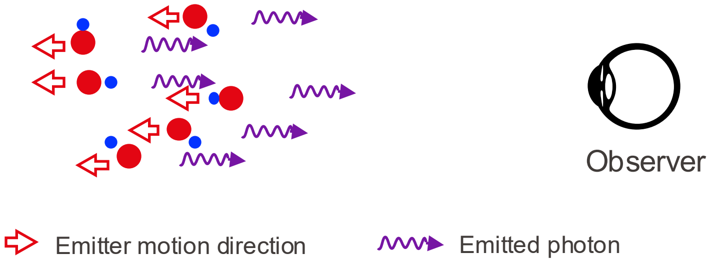


[Courtesy of L. Martinelli]

Spectral line shape
… can reveal the bulk motion

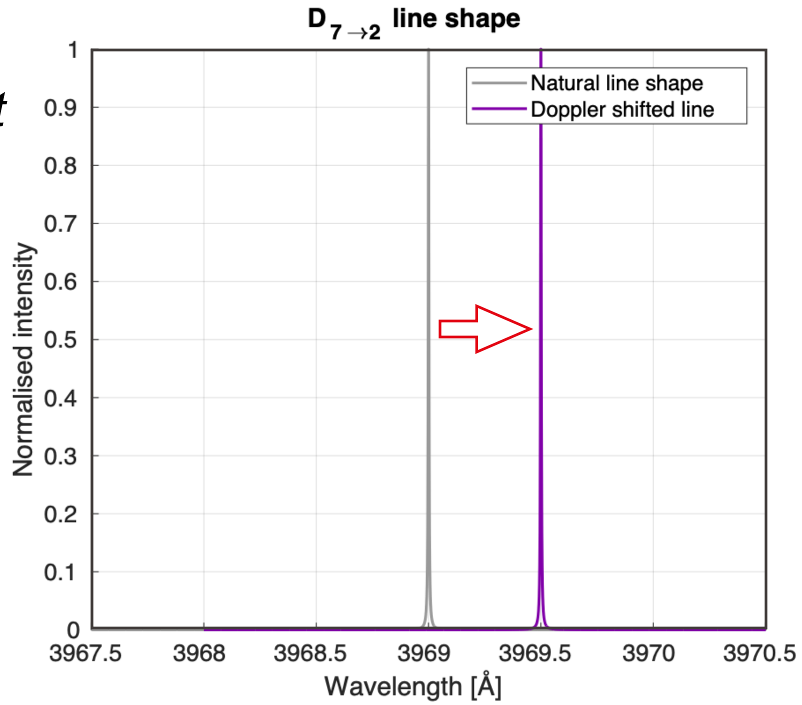
- Bulk motion of emitting species along the line of sight causes a *Doppler shift*

$$\Delta\lambda = \lambda_0 \frac{v}{c}$$



- **Ex.**: TCV plasma moving with ~35km/s with respect to spectrometer

$$\Delta\lambda_{D-\varepsilon} \simeq 0.5\text{Å}$$

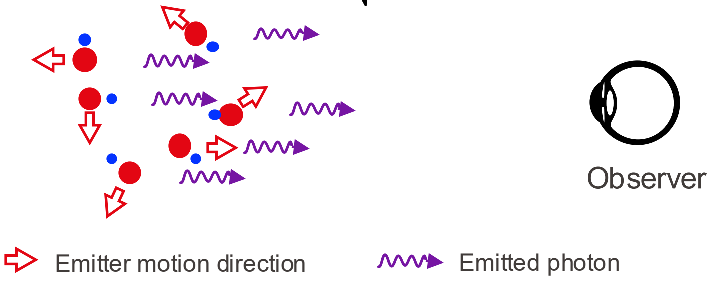


[Courtesy of L. Martinelli]

Spectral line shape
… can reveal the atom temperature

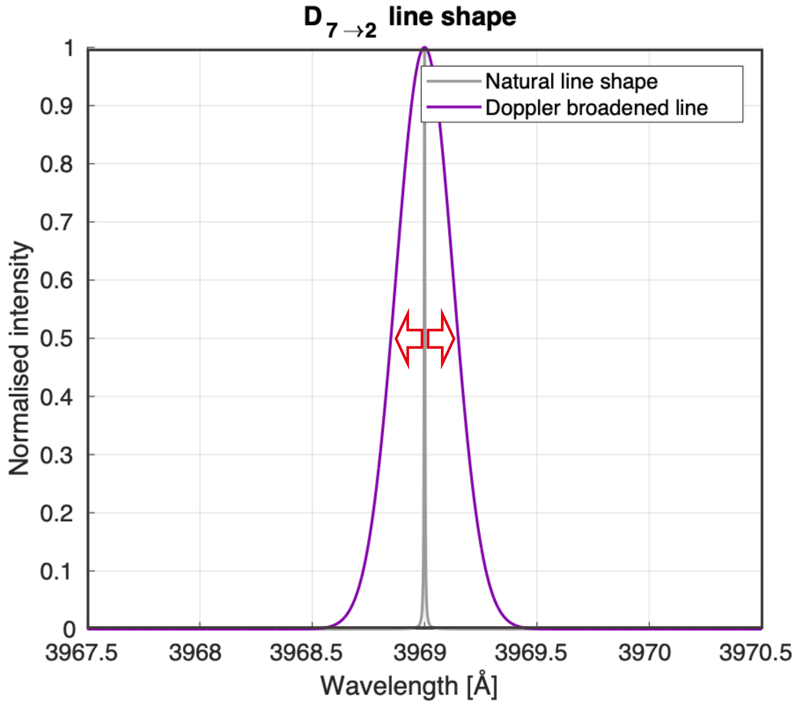
- Thermal motion of emitting particles leads to *Doppler* broadening

$$\Delta\lambda = \lambda_0 \sqrt{\frac{8 k_B T \ln 2}{m c^2}}$$



- **Ex.**: 1eV deuterium plasma

$$\Delta\lambda_{FWHM} \simeq 0.25\text{Å}$$

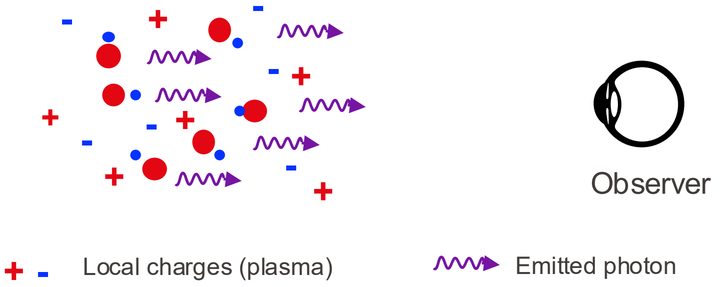


[Courtesy of L. Martinelli]

Spectral line shape
… can reveal the plasma density

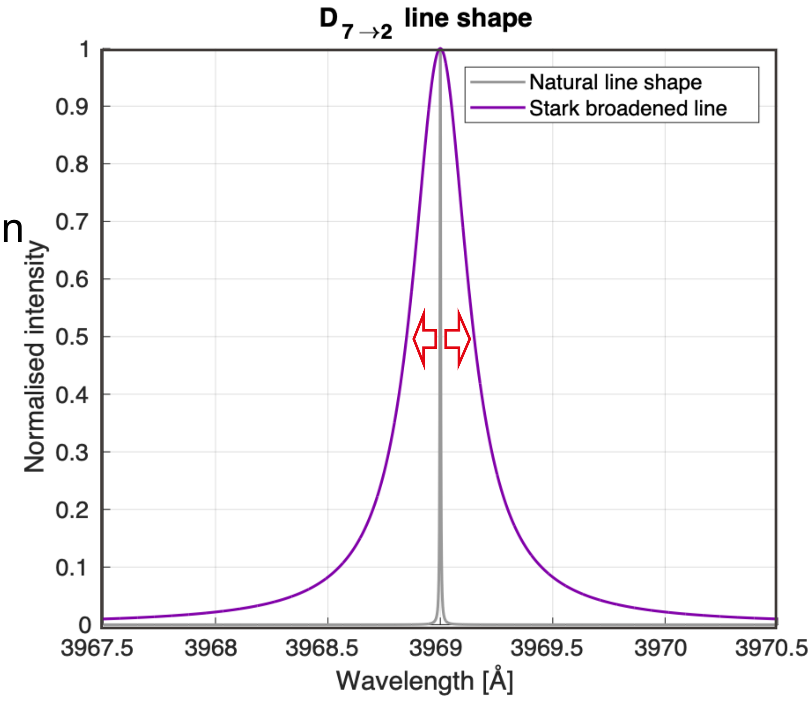
H. Reimerdes

- Random electric microfields induced by surrounding plasma lead to *Stark broadening*
  - Approximated by *Lorentzian* distribution



- **Ex.**: D-ε

$$\mathrm{FWHM}_{\mathrm{Stark}}(D_{7\to2}) \approx 0.21 \cdot \left(\frac{n_e[m^{-3}]}{10^{19}}\right)^{2/3} \text{Å}$$



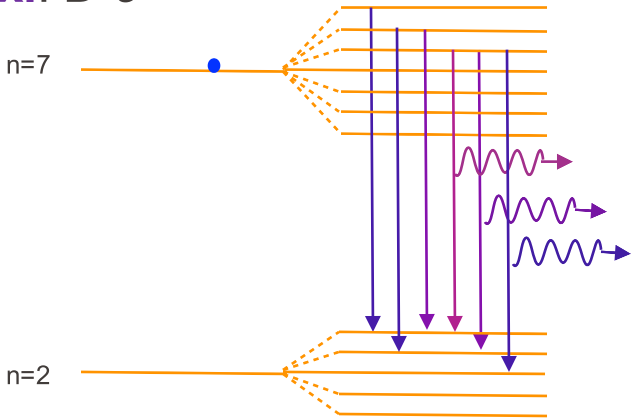
[Courtesy of L. Martinelli]

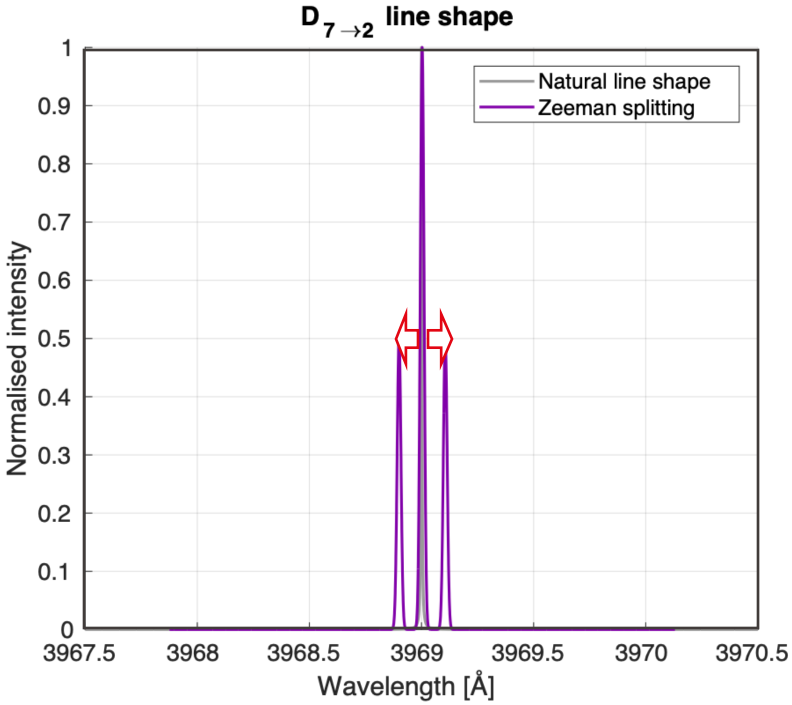
Spectral line shape
… can reveal the magnetic field

- Magnetic field perpendicular to the LOS splits upper and lower energy levels (Zeeman splitting)

$$\Delta E = \mu_B (L_Z + S_z) \cdot B \ , \quad \mu_B = \frac{\hbar e}{2 m_e}$$

- **Ex.**: D-ε

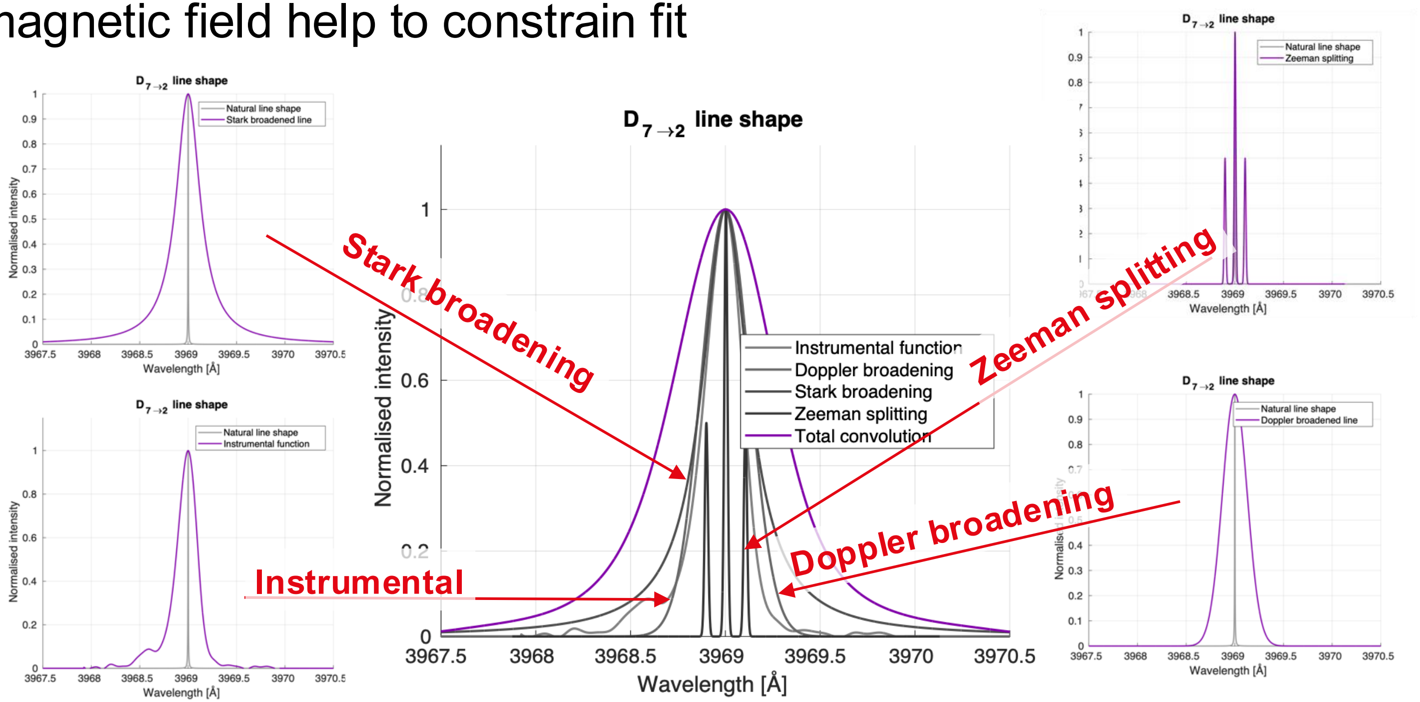




[Courtesy of L. Martinelli]

Measured spectral line shape is a convolution of all effects

- Knowledge of instrumental function, density, temperature and/or magnetic field help to constrain fit



[Courtesy of L. Martinelli]

Spectroscopy
Hydrogenic lines of interest

- Balmer lines ($n' = 2$) optically thin
- Lyman lines ($n' = 1$) radiate more power, but are all in the UV
  - Many lens and window materials do not transmit in the UV

Balmer lines	Wavelength [nm]	Energy difference [eV]	Colour
Alpha (3→2)	656.3	1.89	red
Beta (4→2)	486.1	2.55	aqua
Gamma (5→2)	434.0	2.86	blue
Delta (6→2)	410.2	3.03	violet
Epsilon (7→2)	397.0	3.13	(ultraviolet)
Zeta (8→2)	388.9	3.19	
Eta (9→2)	383.5	3.23	
Balmer break (Inf→2)	364.6	3.40	

Line intensities can be used to infer densities and temperatures

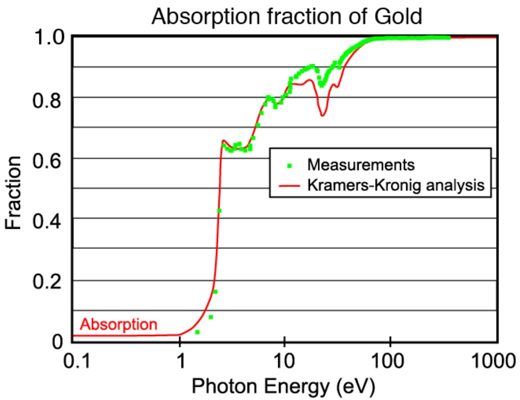
- Collisional-radiative modelling
  - Excited states *n* creates by collisions of electrons with lower states or through recombination of ions and electrons
  - Example: Balmer lines

$$\varepsilon_{n\to 2} = n_e n_{H^0} PEC^{\mathrm{EX}}_{n\to 2}(n_e, T_e) + n_e n_{H^+} PEC^{\mathrm{RC}}_{n\to 2}(n_e, T_e)$$

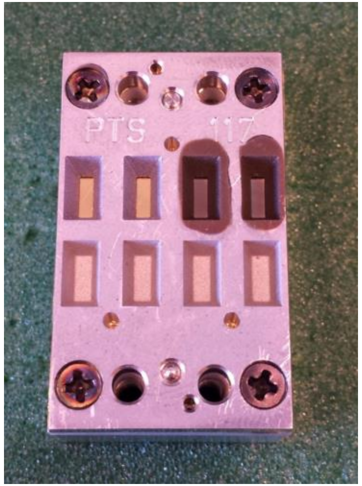
- ➢ Photo emission coefficients (PEC) depend on cross-sections and transition probabilities → tabulated in databases (e.g. ADAS)
- ➢ Use 3 Balmer line measurements to solve for the unknowns $n_e \sim n_{H^+}$, T_e, n_{H^0}

Total radiation

- Measurement of radiated power, regardless of wavelength, referred to as ***bolometry***
  - Eg. for power balance
- Requires a detector that is sensitive to a broad spectrum (in MCF typically from soft X-ray to the visible)
  - Metal foil (can be 'blackened')



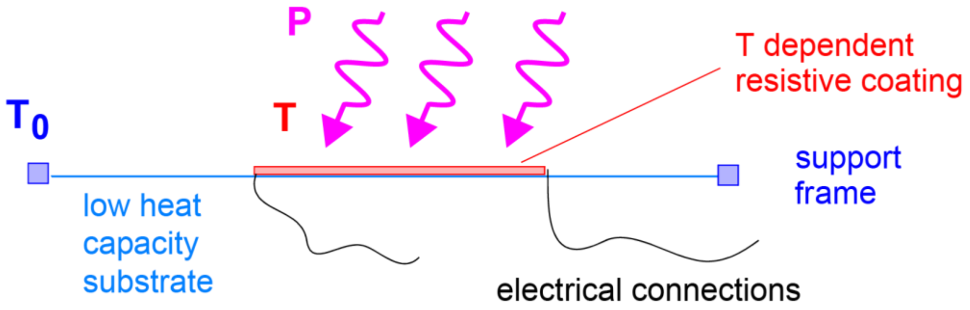
[Adapted from Huber, et al., FED (2007)]



[Sheikh, et al., RSI (2016)]

Metal foil detectors

- Temperature increase of metal foil yields radiance

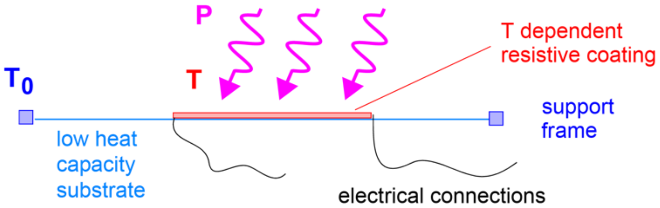


[Adapted from H. Weisen]

- Use temperature dependence of electrical resistivity
  - Heat capacity and thermal contact to heat sink limits time response

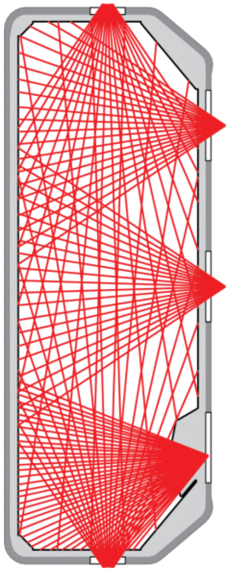
Metal foil detectors

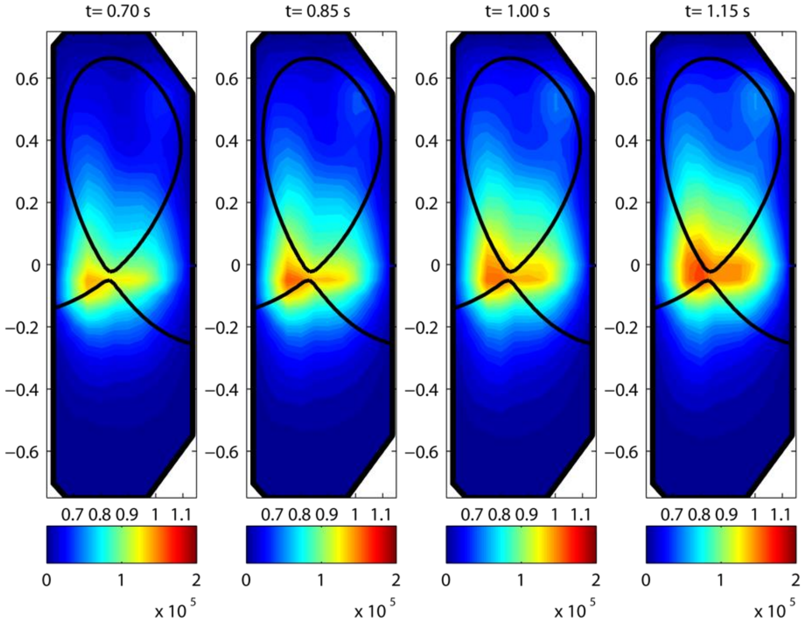
- Sensitivity and time response



Inversion of line integrated measurements

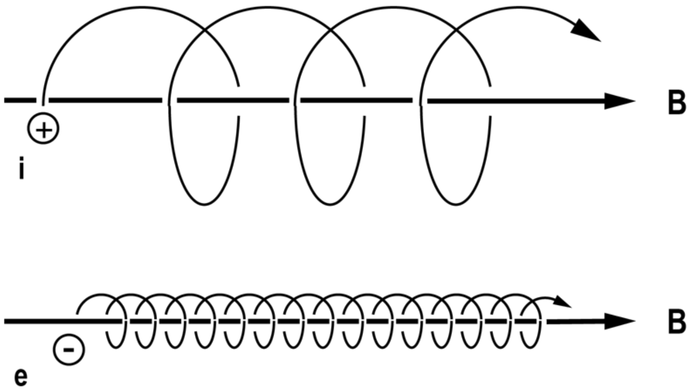
- Emission in an optical thin medium leads to line-integrated measurements → need an inversion (tomography) for spatial resolution
  - Use intersecting lines-of-sight (LoS) and/or constrain geometry of solution
- **Ex.**: TCV bolometer
  - 120 LoS





Additional radiation in magnetised plasmas

- Charged particles that move perpendicular to a magnetic field are subject to the Lorentz force and, hence, an acceleration and emit even without collisions (*magneto-bremsstrahlung*) → ***Cyclotron radiation***
  - When particles move with relativistic speeds *cyclotron radiation* is also referred to a *synchrotron radiation*



- Main contribution from electrons

$$\omega_{c,e} = l \cdot \frac{eB}{m_e} \quad \text{with} \quad l = 1,2,3,\ldots$$

Cyclotron radiation

- Cyclotron radiation is optically thick → Black-body radiation → Intensity depends only on electron temperature!
- With $\hbar\omega_{c,e} \ll k_{\mathrm{B}}T_e$ the 'black-body radiation' is described by Rayleigh-Jeans law

$$I_\nu^{\mathrm{bb}} = \frac{\omega_{c,e}^2 k_{\mathrm{B}} T_e}{8\pi^3 c^2}$$

Electron-cyclotron emission spectrum

- $\omega_{c,e}$ depends on magnetic field strength and, hence in tokamaks on the major radius
  - Emission at $\omega_{c,e}$ characteristic for a location → measurements at several frequencies yield T_e-profile

Outline

- Introduction
- **Passive measurements**
  - EM emission
    - Bremsstrahlung
    - Line emission
    - Synchrotron radiation
    - Cyclotron emission
  - **Magnetic fields**
- Active measurements
  - Langmuir probes
  - Interferometry
  - Thomson scattering
- Appendix

Plasma diagnostics 1

Plasma diagnostics 2

H. Reimerdes

Magnetic fields

- Magnitude of magnetic fields first measured by Carl Friedrich Gauss in 1833

Examples of B-field diagnostics

- Pick-up coils & flux loops (magnetic induction)
- Hall probe
- Fluxgate-magnetometer
- Spectroscopy → see Zeeman splitting

Measure B-field using magnetic induction

- Faraday's law $\nabla \times \mathbf{E} = -\frac{d\mathbf{B}}{dt}$
  - Integral form $\oint_{\partial S} \mathbf{E} \cdot \mathbf{dl} = -\int_S \frac{d\mathbf{B}}{dt} \cdot \mathbf{ds} = -\frac{d\phi_S}{dt}$

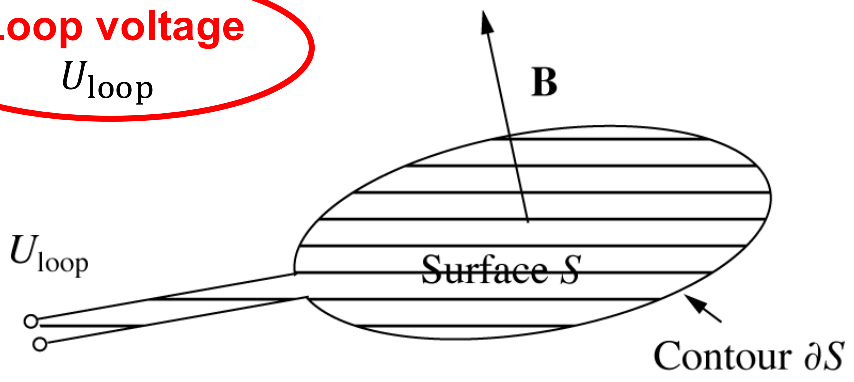
Magnetic flux $\phi_S = \int_S \mathbf{B} \cdot \mathbf{ds}$

Loop voltage U_{loop}

- Voltage induced in a loop (contouring the surface)

$$U_{\text{loop}} = -\frac{d\phi_s}{dt}$$

measures the component of $d\mathrm{B}/dt$ normal to (and integrated over) the plane of the loop



H. Reimerdes

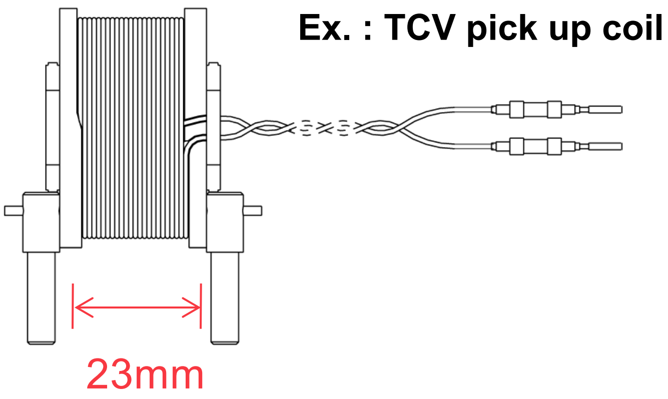
H. Reimerdes

Various geometries exist

- For a small rigid probe ($|\mathbf{B}|/(\nabla\mathbf{B})_\perp \gg L_{\text{probe}}$) with a cross-sectional area A and N turns

$$U_{\text{probe}} = -NA\frac{dB_\perp}{dt}$$

  - Probe measures the magnetic field component perpendicular to the probe surface $B_\perp$



- Other geometries
  - **Flux loops**: single loops that span a large area

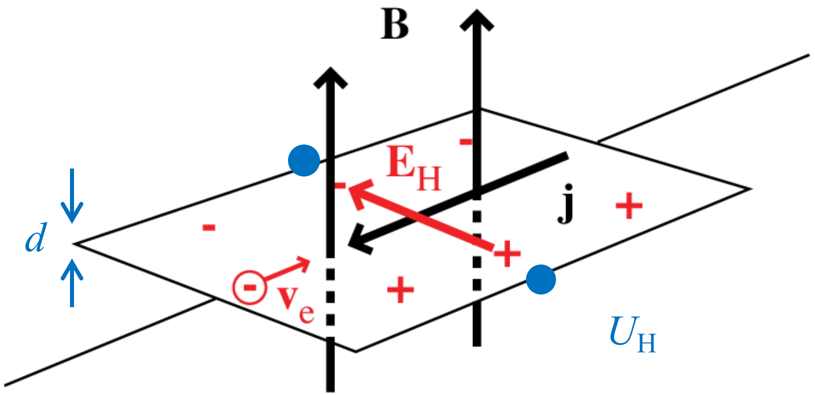
Measure B-field using the Hall effect

- Magnetic field leads to charge separation in a current carrying conductor

$$\mathbf{E}_\mathrm{H} = -\mathbf{v} \times \mathbf{B} = -\frac{\mathbf{j} \times \mathbf{B}}{nq}$$

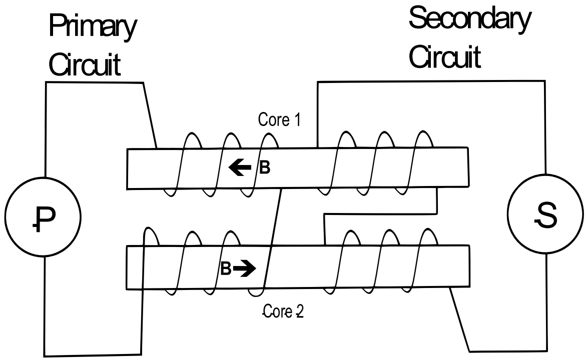
  - Hall field depends on the the charge carrier density *n* and their sign *q*

- Advantages
  - Compact – miniaturization through IC technology



Measure B-field using Fluxgate-magnetometer

- Detect asymmetries in the saturation of a ferromagnetic coil core
- Constraints
  - Field of coil must be larger than measured field (not applicable to MCF)

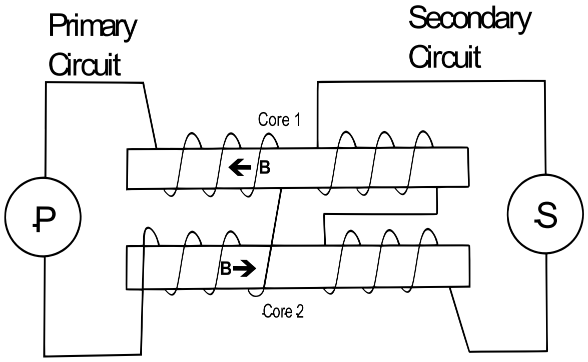


Source: Von Pdornel - Eigenes Werk, CC BY-SA 4.0, https://commons.wikimedia.org/w/index.php?curid=40110734

- Without a magnetic field the voltages induced in the secondary loop (S) cancel

Measure B-field using Fluxgate-magnetometer

- Detect asymmetries in the saturation of a ferromagnetic coil core
- Constraints
  - Field of coil must be larger than measured field (not applicable to MCF)
- Advantages
  - Low power consumption
  - Rugged
  - Compact & light
    - Miniaturization recently advancing to the point of complete sensor solutions as IC



Source: Von Pdornel - Eigenes Werk, CC BY-SA 4.0, https://commons.wikimedia.org/w/index.php?curid=40110734

- Without a magnetic field the voltages induced in the secondary loop (S) cancel

Measure B-field using Fluxgate-magnetometer

- Detect asymmetries in the saturation of a ferromagnetic coil core
- Constraints
  - Field of coil must be larger than measured field (not applicable to MCF)
- Advantages
  - Low power consumption
  - Rugged
  - Compact & light
    - Miniaturization recently advancing to the point of complete sensor solutions as IC

Source: ESA

FGM diagnostic of Cluster satellites (see L2)

Literature

Textbooks

- J. Wesson, “Tokamaks”, Third edition, Oxford Science Publications – Chapter 10 ← *Good overview*
- I.H. Hutchinson, “Principles of plasma diagnostics”, Second edition, Cambridge University Press ← *Very detailed description based on first principles, goes well beyond course content*