Experimental spectroscopy for (magnetic) fusion

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Joint IAEA-ICTP School on molecular and atomic processes – 4-8 May 2026

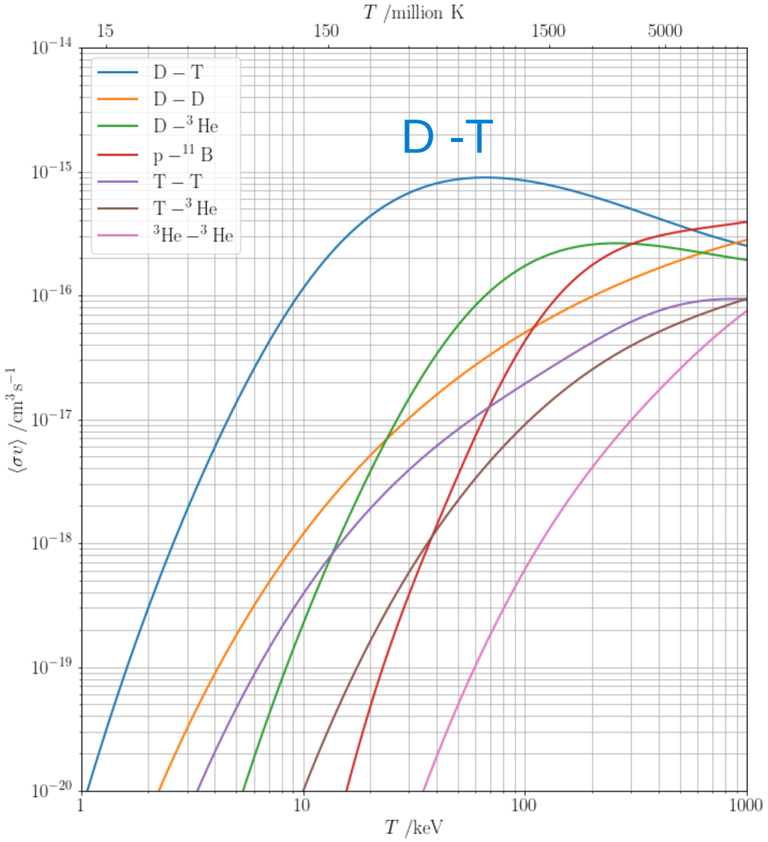
Nuclear fusion reactions

- Sun: p-p, very inefficient (slow & releases little energy)

- $D^+ + T^+ \rightarrow \alpha + n$ the most attractive:
  - highest reactivity,
  - highest energy gain (17.5 MeV),
  - max. reactivity at lowest T (80 keV)
- Produces 14 MeV neutrons (not so good ☹)
- 3.5 MeV α particles heat the fuel (D^+ and T^+ ions)
- Temperature ~ keV ⇒ plasma!

- $P_{fus} = n_D \times n_T \times \langle\sigma v\rangle_{DT} \times E_{DT} \times V_{Pl} = \frac{n^2}{4}\langle\sigma v\rangle_{DT} \times E_{DT} \times V_{Pl}$

W m^{-3} m^{-3} m^3/s J (MeV) m^3



Self-sustained fusion conditions

- The plasma must be:

→ stationary - Power balance: $P_{in} = P_{out}$

Total plasma energy

$$\Rightarrow P_{ext} + P_{\alpha} - P_{cond,conv} = P_{ext} + P_{\alpha} - \frac{W}{\tau_E} > 0$$

Engineering

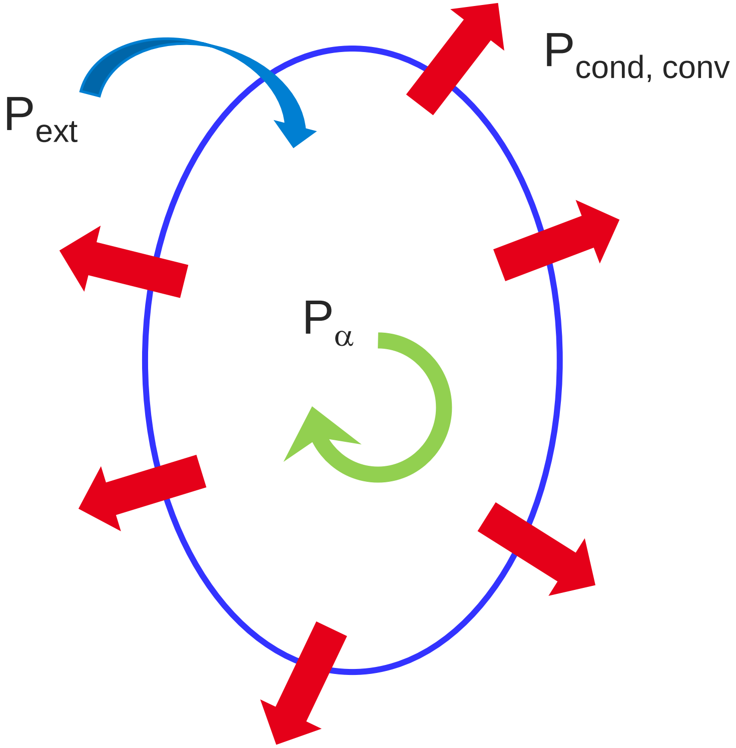
Fusion reactions

'Energy confinement time'

→ at 'ignition' i.e. self-sustained: $P_{ext} = 0$

$$\Rightarrow \frac{n^2}{4}\langle\sigma v\rangle_{DT} \times E_{DT} \geq \frac{3nT}{\tau_E}$$

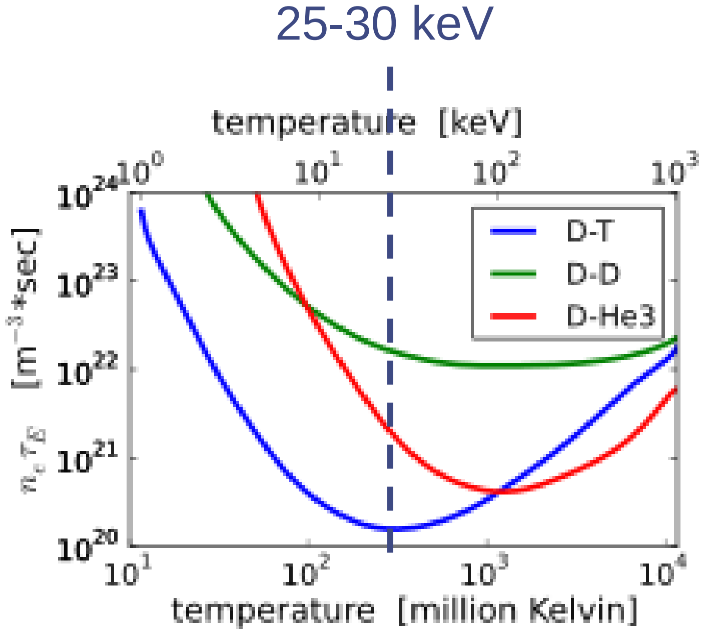
$\Rightarrow n\tau_E \geq \frac{12T}{\langle\sigma v\rangle_{DT} \times E_{DT}}$ (Lawson criterion)



Self-sustained fusion conditions

Temperature range:

$n\tau_E \geq \frac{12T}{\langle\sigma v\rangle_{DT} \times E_{DT}}$ (Lawson criterion)



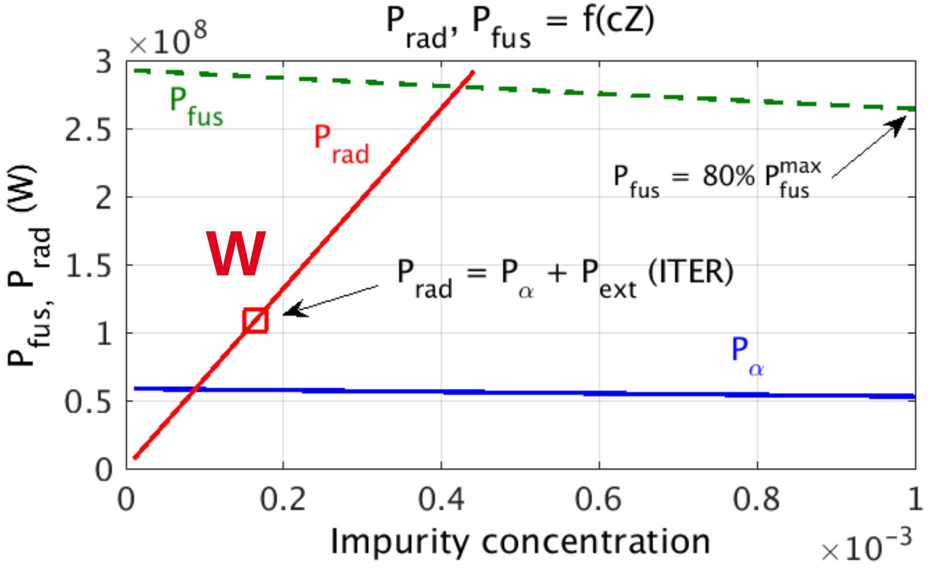
- Lawson criterion threshold: $n\tau_E = \frac{12T}{\langle\sigma v\rangle_{DT} \times E_{DT}}$ depends only on T
- Easiest to fulfill at T ~ 25-30 keV
- Energy stability considerations lower this optimum to **T ~ 15-20 keV**

Density range:

- Density must be maximised but electron density limited to $\boldsymbol{n_{max} \sim 10^{20} m^{-3}}$ (empirical limit)
- 50-50 mix of fuel ions ⇒ $\boldsymbol{n_D = n_T = n_{max}/2}$

Fusion power and radiative losses

- $P_{fus} = \frac{n_{max}^2}{4} \langle \sigma v \rangle_{DT} \times E_{DT} \times V_{Pl}$: only if plasma is pure D+T
- With impurities (Z, n_Z): $n_{max} = n_D + n_T + \sum_Z Z n_Z$
- $P_{fus} = \frac{(n_{max} - \sum Z n_Z)^2}{4} \langle \sigma v \rangle_{DT} \times E_{DT} \times V_{Pl}$
- Power radiated by an impurity: $P_{rad} = n_e n_Z L_Z(T_e)$
- Power balance: $P_{in} = P_{out} \Rightarrow (P_{ext}+)\, P_\alpha - \frac{W}{\tau_E} - P_{rad} = 0$
- In ITER $(P_{ext} \neq 0)$, the absolute limit is: $P_{rad} = P_{ext} + P_\alpha$
- In a fusion plant at ignition $(P_{ext} = 0)$, the absolute limit is: $P_{rad} = P_\alpha$



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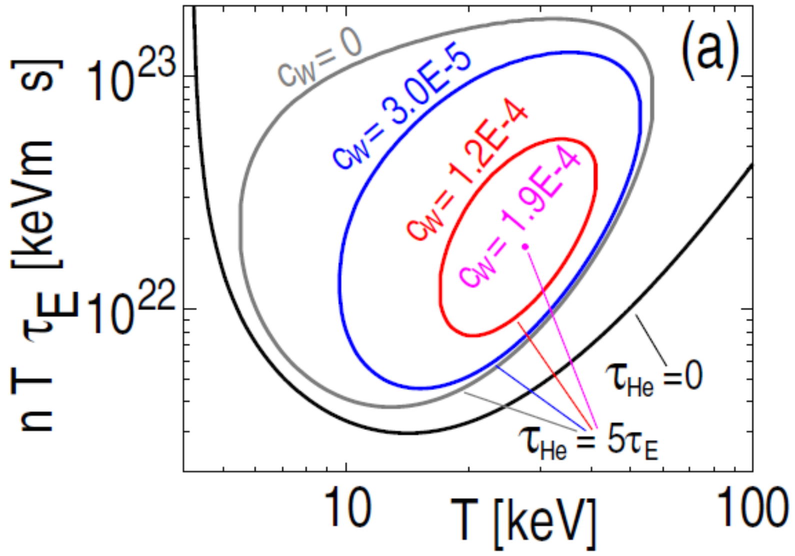


Puetterich, Nucl. Fusion 2010

Radiative power losses are only one of the reasons why impurities are studied in fusion....

... and why radiation measts are so important...

... and why it is useful to know (some) atomic physics ☺

Outlook

Introduction

1. Atomic & radiative processes

2. Visible spectroscopy – impurity sources and recycling

3. (V)UV for impurity densities and transport

4. Soft-X ray for ion temperature and velocity

Summary and conclusions

1. Atomic & radiative processes

1.1 Charge-changing processes (1)

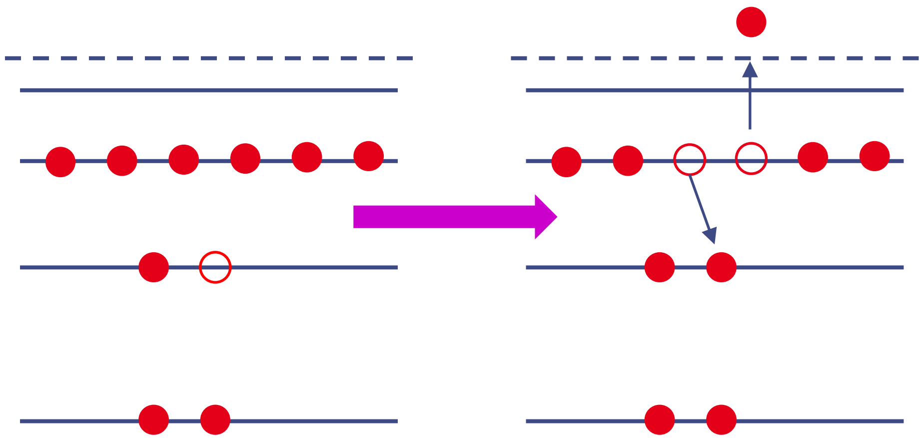
Ultra-dominant processes:

- Ionisation: e- collisions $X^{z+} + e^- \rightarrow X^{(z+1)+} + 2e^-$
- Recombination: radiative $X^{z+} + e^- \rightarrow X^{(z-1)+*} \rightarrow X^{(z-1)+} + h\nu$

  di-electronic $X^{z+} + e^- \rightarrow X^{(z-1)+**} \rightarrow X^{(z-1)+} + h\nu + h\nu$

In addition:

- Auto-ionisation:
- Charge exchange: $X^{z+} + Y^{q+} \rightarrow X^{(z-1)+*} + Y^{(q+1)+}$



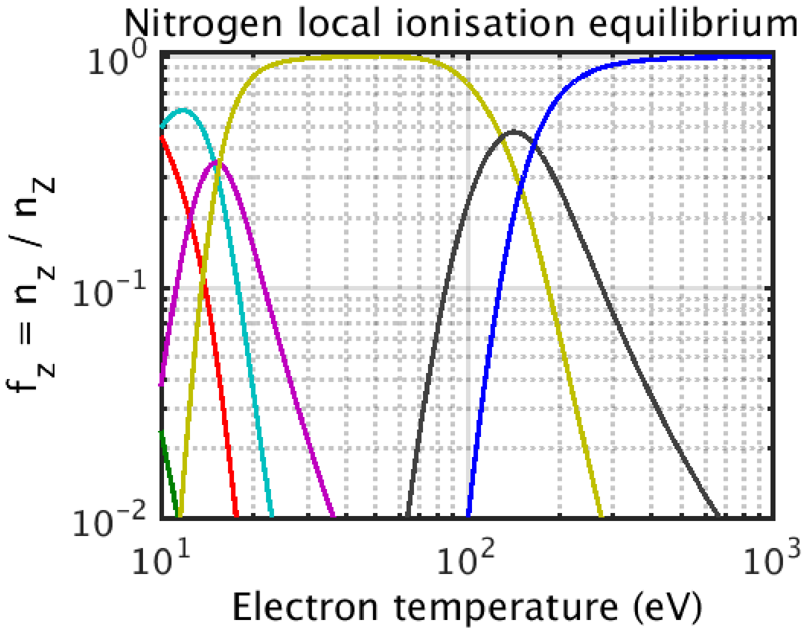
1. Atomic & radiative processes

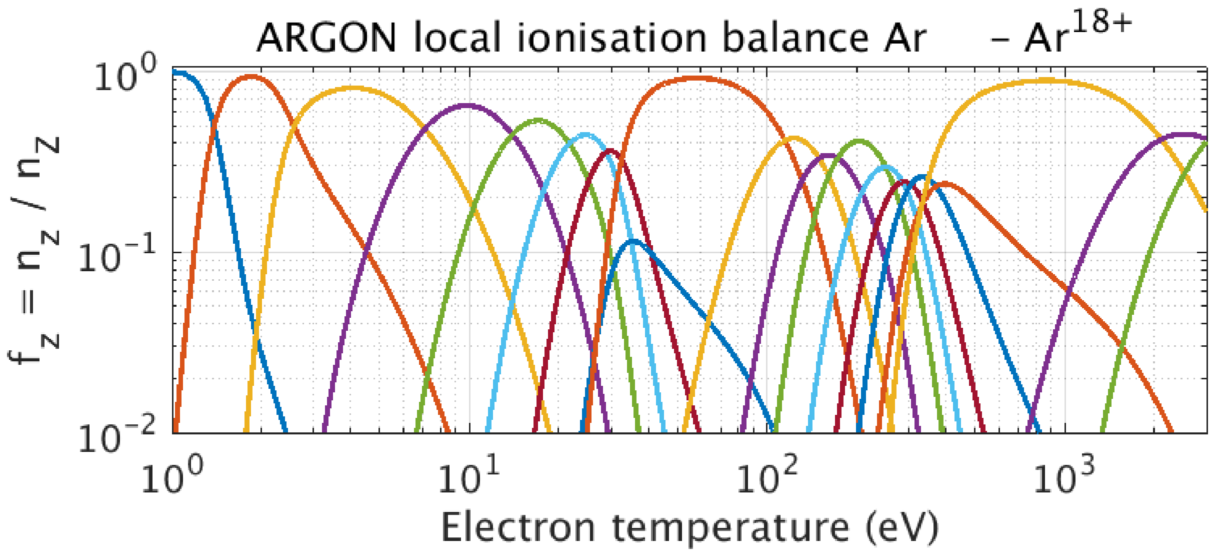
1.1 Charge-changing processes (2)

Ionisation and recombination are 'fast' processes (ms) with respect to most plasma phenomena

$\Rightarrow$ we assume local ionisation balance: $\left(\frac{dn}{dt}\right)_{\text{ionis}} = \left(\frac{dn}{dt}\right)_{\text{recomb}}$ for each ion X^{z+}

$$\Rightarrow \frac{n_z}{n_{z+1}} = \frac{\langle\sigma v\rangle_{z+1}^{rec}}{\langle\sigma v\rangle_{z}^{ionis}} \Rightarrow f_z = \frac{n_z}{n_{tot}} \text{ = fractional abundances}$$





1. Atomic & radiative processes

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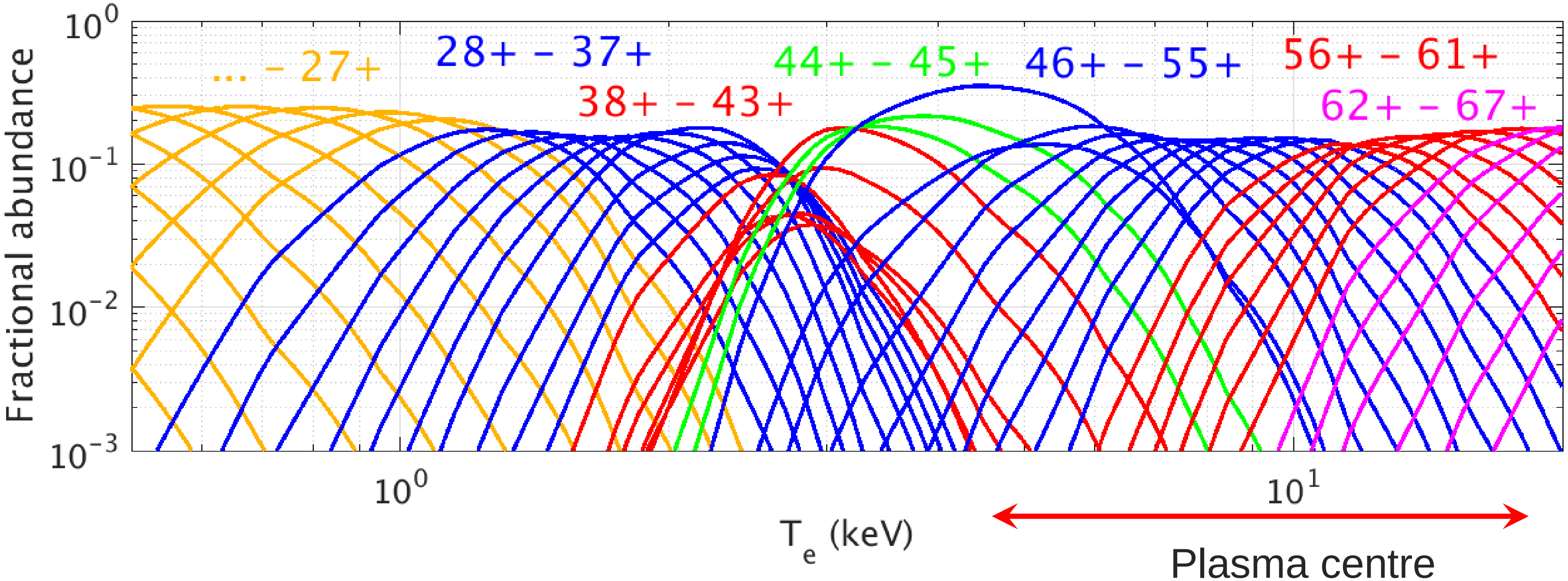


Plasma edge

Plasma centre

1. Atomic & radiative processes

1.2 Level-changing processes

Ultra-dominant processes:

- Excitation: e- collisions $X^{z+} + e^- \rightarrow X^{z+*} + e^-$
- De-excitation: spontaneous decay $X^{z+*} \rightarrow X^{z+} + h\nu$ (including cascades)

Collisional excitation & spontaneous decay are fast (< ms) with respect to plasma phenomena
⇒ we assume population equilibrium

Coronal equilibrium << $n \sim 10^{20}\ m^{-3}$ << LTE

↓

Collisional-radiative model

1. Atomic & radiative processes

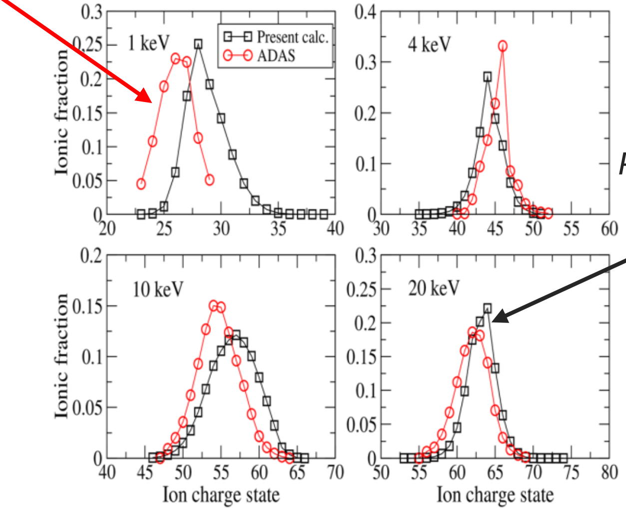
1.1 (back to) Charge-changing processes

- The detailed calculation is performed by a collisional-radiative model which solves:

$$\frac{dN_c}{dt} = 0 = \sum_{c'} N_{c'} T(c' \to c) - N_c \sum_{c'} T(c \to c')$$

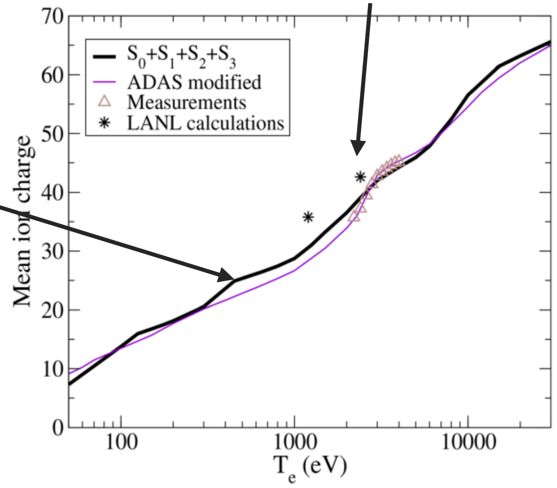
- The results depend strongly on the number and the nature of the configurations in the model

Puetterich, Nucl. Fusion 2010



Peyrusse, Phys. Plasmas 2026

Colgan, Atoms 2015



Ionisation equilibrium is still an issue

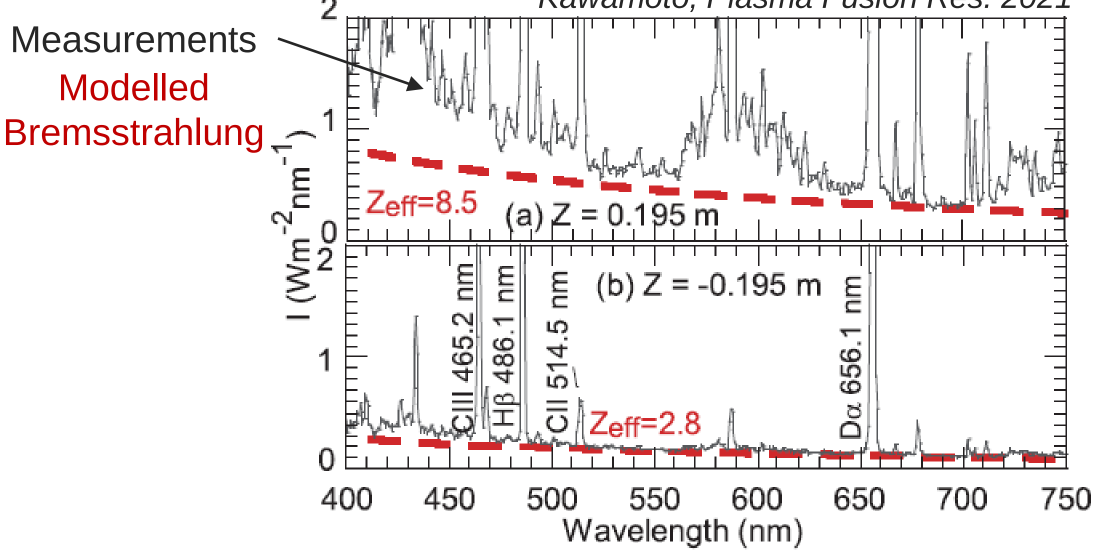
1. Atomic & radiative processes

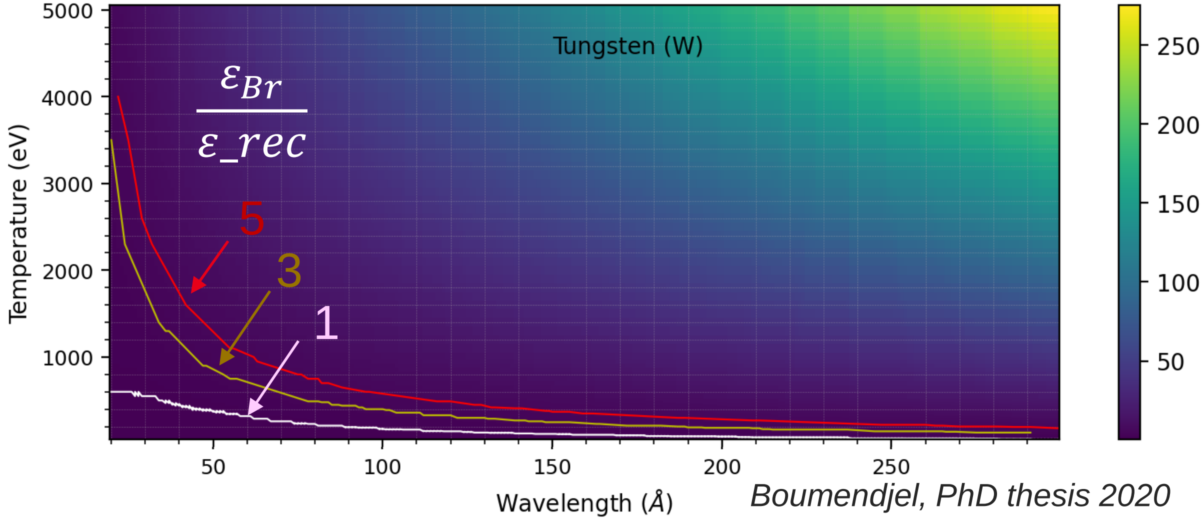
1.3 Radiative processes

Continuum

- Bremsstrahlung: $\varepsilon_{br} \propto Z_{eff} \frac{n_e^2}{\sqrt{T_e}}, \quad Z_{eff} = \sum_Z n_Z Z^2$
- Recombination radiation: much weaker

Kawamoto, Plasma Fusion Res. 2021





Boumendjel, PhD thesis 2020

1. Atomic & radiative processes

1.3 Radiative processes

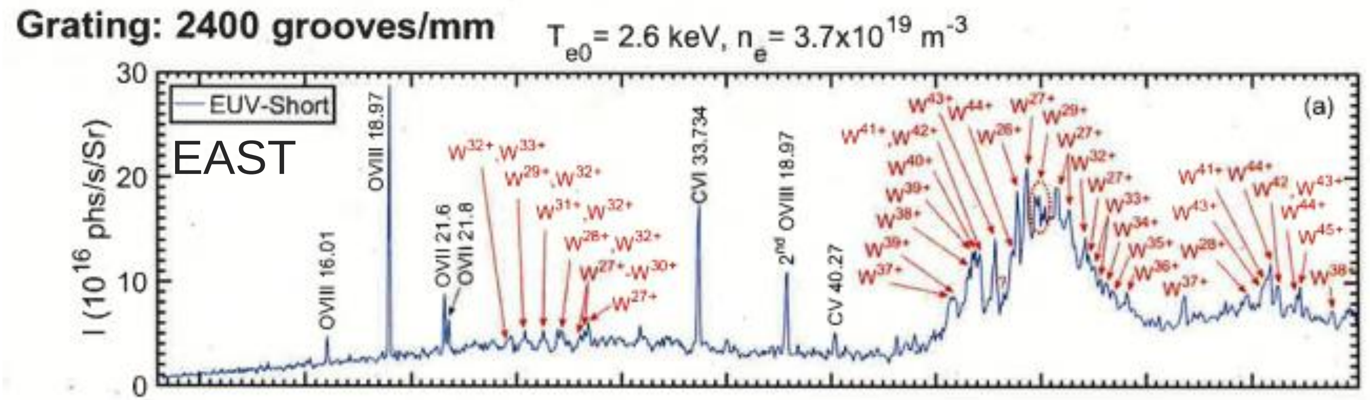
Continuum

- Bremsstrahlung: $\varepsilon_{br} \propto Z_{eff}\frac{n_e^2}{\sqrt{T_e}}, \quad Z_{eff} = \sum_Z n_Z Z^2$
- Recombination radiation: much weaker

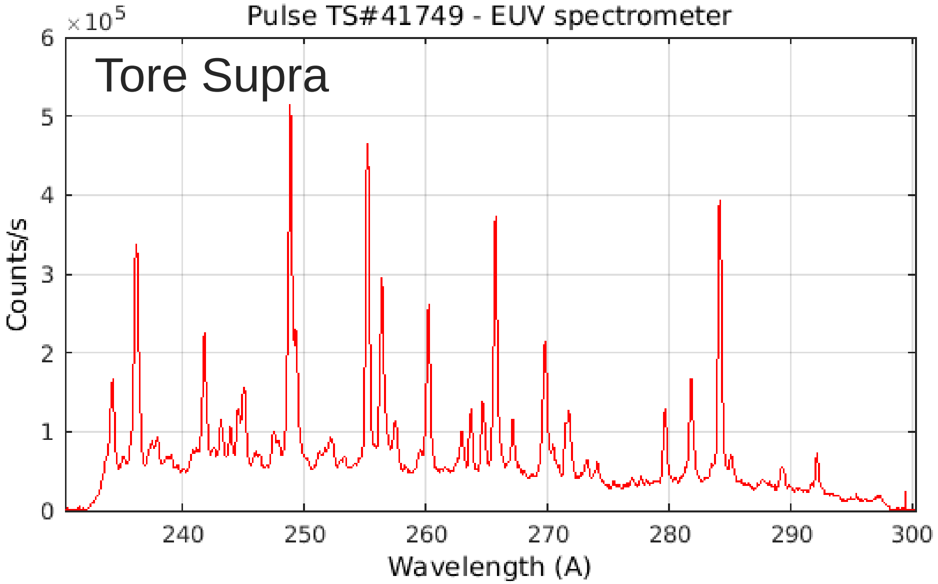
Discrete

- Spontaneous decay:

- most prominent in measured spectra
- takes away most of the radiated power
- contains useful information



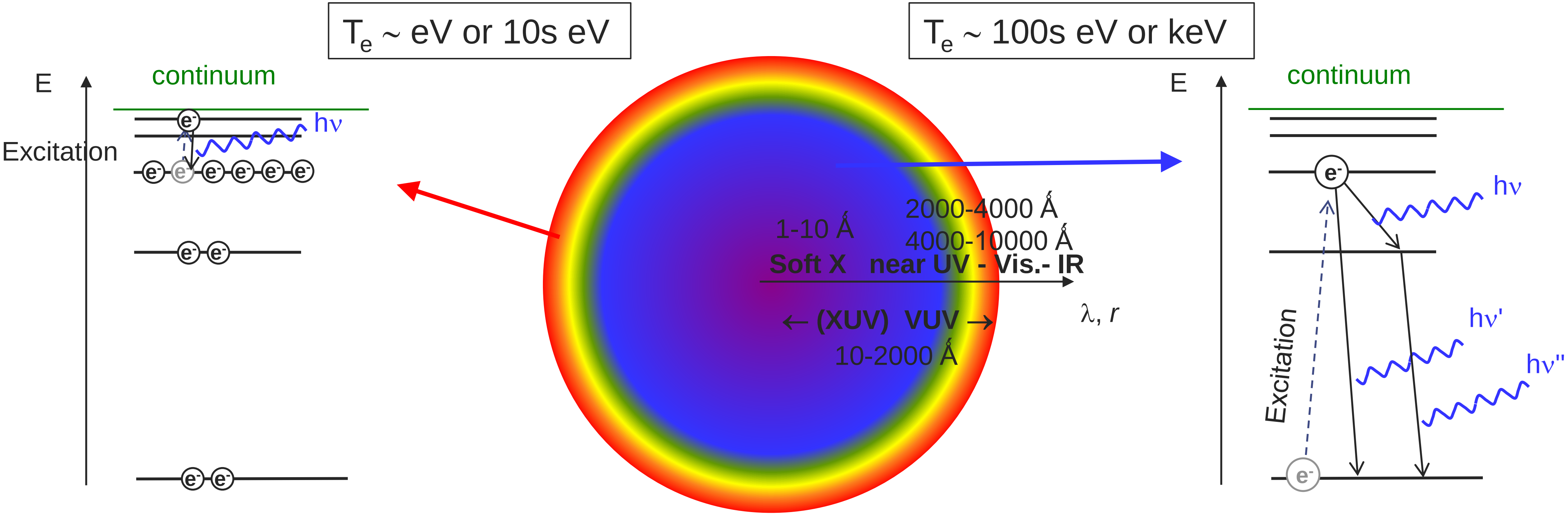
Z Xu et al. Nucl. Instrum. Meth. A , 1010 165545 (2021)



1. Atomic & radiative processes

1.4 Wavelength range

Photon energy depends on energy level



T_e ~ eV or 10s eV

T_e ~ 100s eV or keV

Outlook

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2. Visible spectroscopy – impurity sources and recycling

2b. Visible spectroscopy – with beams

3. (V)UV for impurity densities and transport

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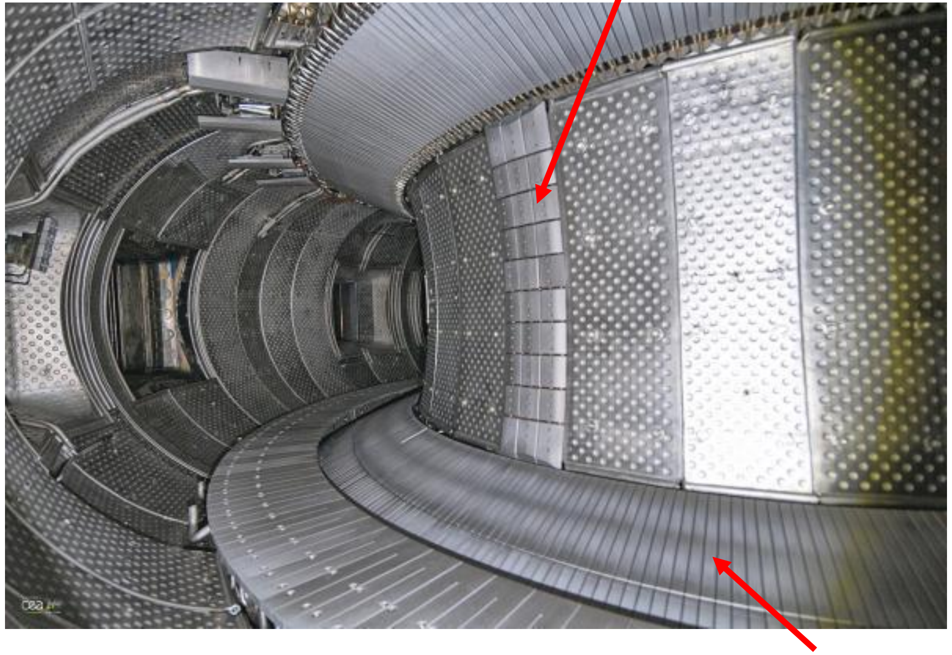
Summary and conclusions

2. Visible spectroscopy – sources & recycling

2.1 Source observation

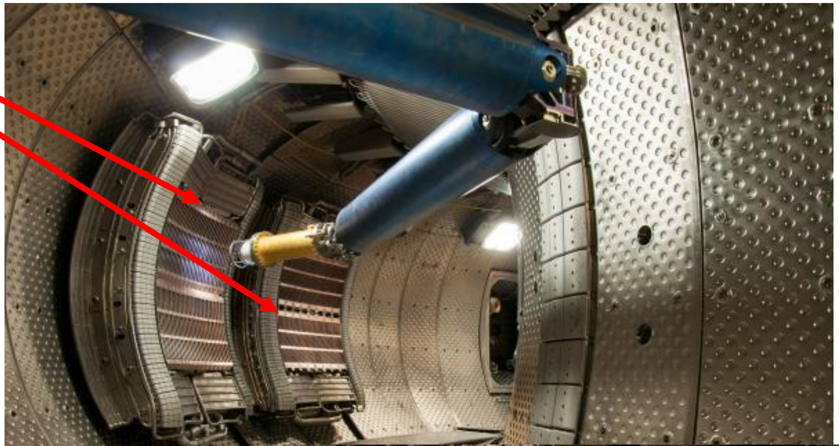
What is to be observed? Everything in contact with the plasma

This (limiter)

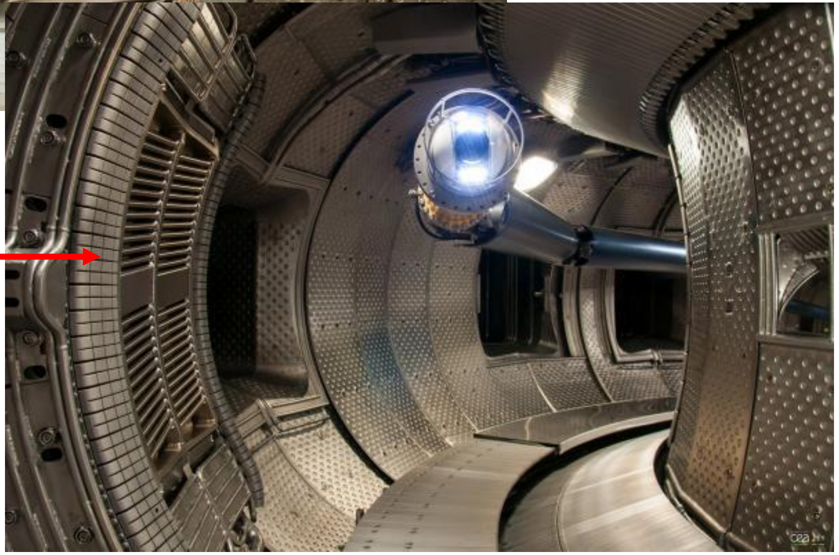


...that (divertor plate)

... and those two (LH antennae)

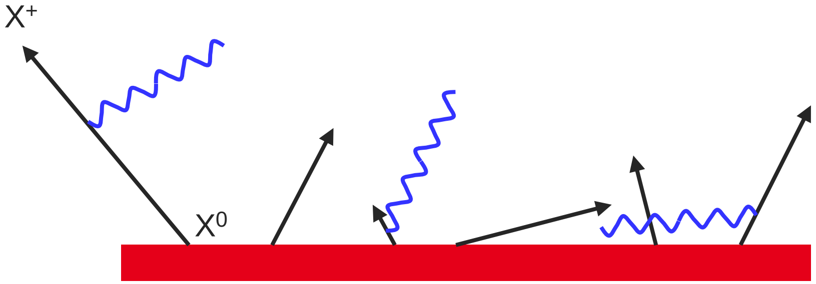


... and that one too (ICRH antenna)



2. Visible spectroscopy – sources & recycling

2.2 Flux measurements



- Ionisation flux:

$$\Gamma_i = n_0 n_e S$$

(S: ionisation rate coeff.)

- Excitation (GS→j) flux:

$$\Gamma_j^{exc} = n_0 n_e X_j$$

(X_j: excitation rate coeff.)

- Ionisation to excitation ratio:

$$\frac{\Gamma_i}{\Gamma_j^{exc}} = \frac{S}{X_j}$$

- Population equilibrium:

$$\Gamma_j^{exc} = \Gamma_j^{decay} = \sum_k n_j A_{jk} = n_j \sum_k A_{jk}$$

- Observation of one spectral line:

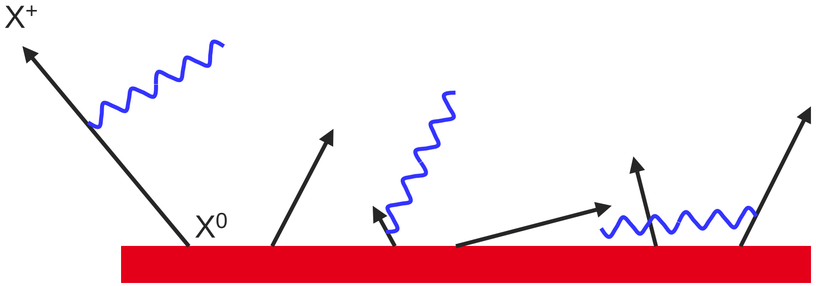
$$I_{jp} = n_j A_{jp} \Rightarrow \frac{\Gamma_j^{decay}}{I_{jp}} = \frac{\sum_k A_{jk} A_{jp}}{A_{jp}} = \frac{1}{B_{jp}}$$

- Ionisation flux as a function of measured line intensity

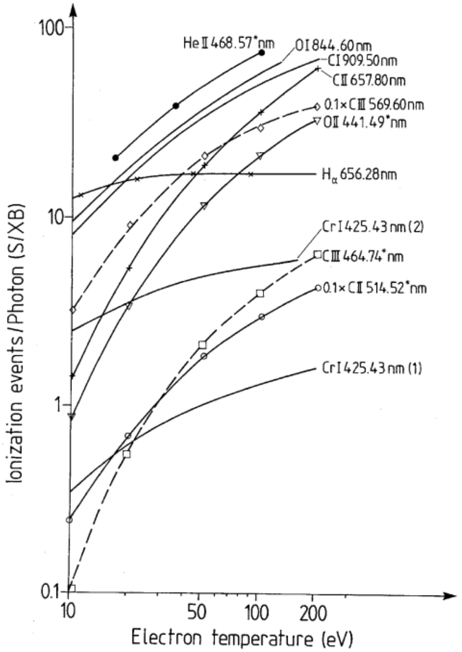
$$\Gamma_i = I_{jp} \times \frac{S}{X_j B_{jp}} = I_{jp} \times \left(\frac{S}{XB}\right)_{jp}$$

2. Visible spectroscopy – sources & recycling

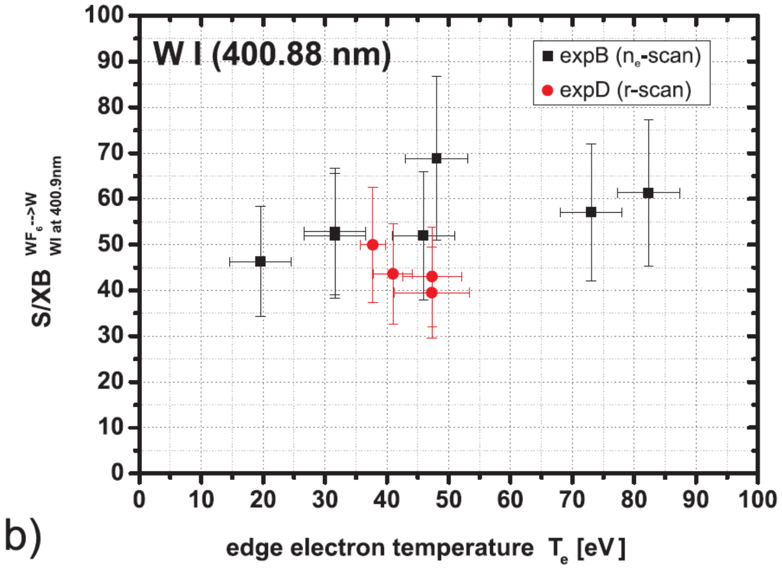
2.2 Flux measurements



'SXB' coefficients can be calculated... and sometimes (rarely) determined experimentally



Pospieszczyk, Fusion Sci. Techn. 2006



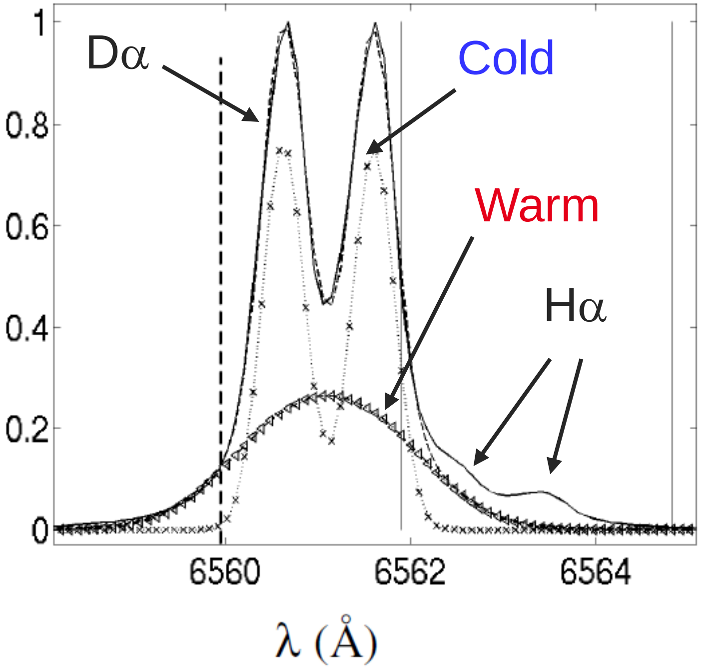
Brezinsek, Phys. Scr.. 2017

2. Visible spectroscopy – sources & recycling

2.3 Spectral lineshape for recycling

- In magnetic fusion, all lines are Zeeman-split
- Populations with different temperatures: 1.5-2.5 eV → D_2 dissociation
  20-25 eV → D+ backscattering, CX (D^+ D)

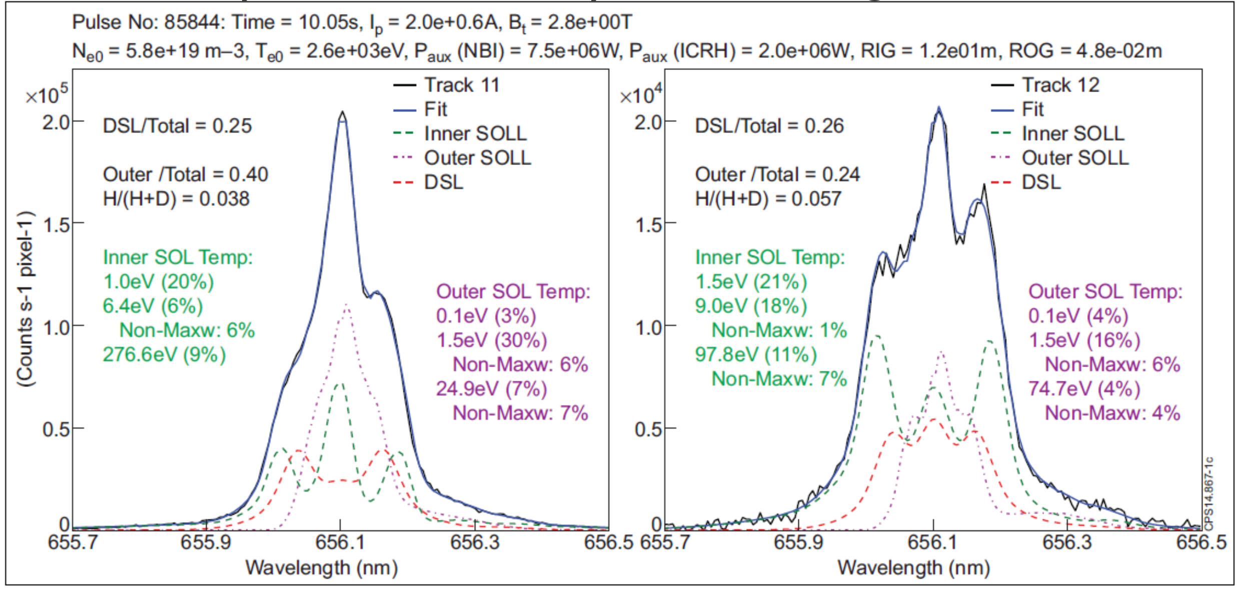
Escarguel, Contrib. Plasma Phys. 2002

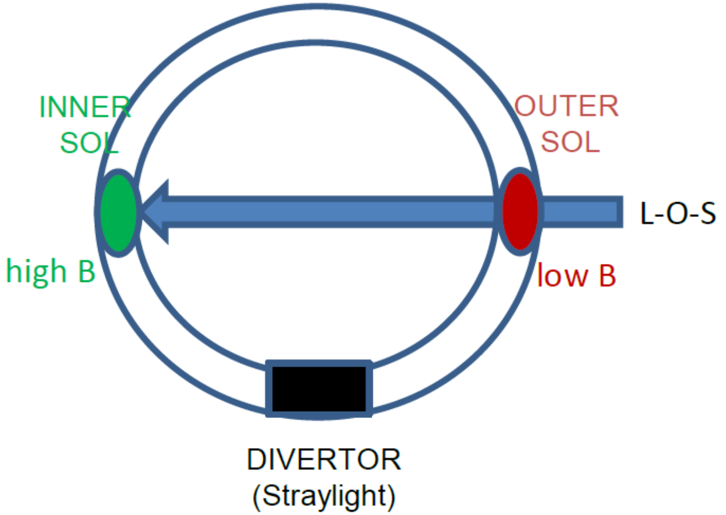


2. Visible spectroscopy – sources & recycling

2.3 Spectral lineshape for recycling

- In magnetic fusion, all lines are Zeeman-split
- Populations with different temperatures: 1.5-2.5 eV → D_2 dissociation
  20-25 eV → D+ backscattering, CX (D^+ D)
- Lineshape can be complicated: angle wrt $\vec{B}$, line of sight, D source processes, fuel mix, reflections,...





- Atomic and molecular fluxes
- H/(H+D)
- n_e if high enough (Stark broadening)

2b. Visible spectroscopy – with beams

2.4 Charge exchange recombination spectroscopy (CXRS)

$$X^{z+} + Y^{q+} \rightarrow X^{(z-1)+*} + Y^{(q+1)+}$$

- Interesting properties in case of atomic D beam: Y^{q+} = D

$$X^{z+} + D \rightarrow \boxed{X^{(z-1)+*}} + D^{+}$$

→ High-l excited state populated only by CX

- Examples:

$He^{2+} + D \rightarrow He^{+*} + D^{+}$	n = 4-3	468.52 nm
$C^{6+} + D \rightarrow C^{5+*} + D^{+}$	n = 8-7	529.06 nm
$Ne^{10+} + D \rightarrow Ne^{9+*} + D^{+}$	n = 11-10	524.49 nm

- Photons in the visible range: technically (relatively) simple and flexible
  Reliable intensity calibration
  spectral resolution suitable for Doppler analysis

→ Impurity density, velocity and temperature in the core

2b. Visible spectroscopy – with beams

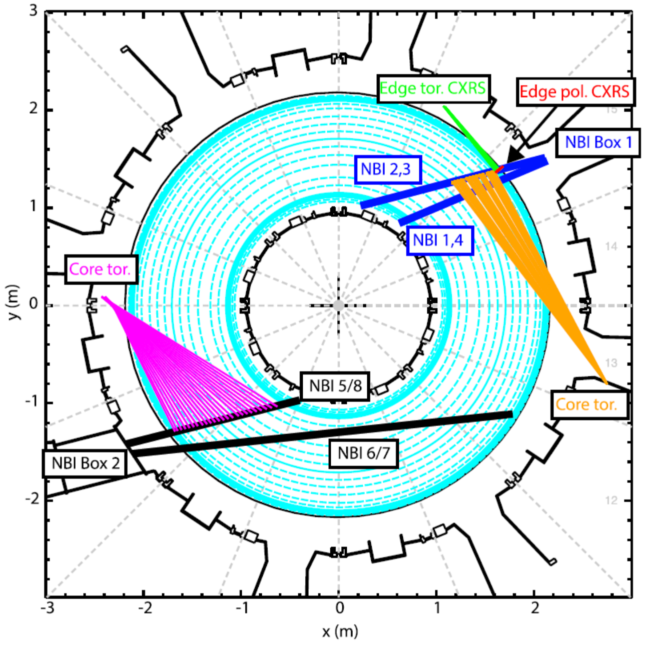
2.4 Charge exchange recombination spectroscopy (CXRS)

$$X^{z+} + Y^{q+} \rightarrow X^{(z-1)+*} + Y^{(q+1)+}$$

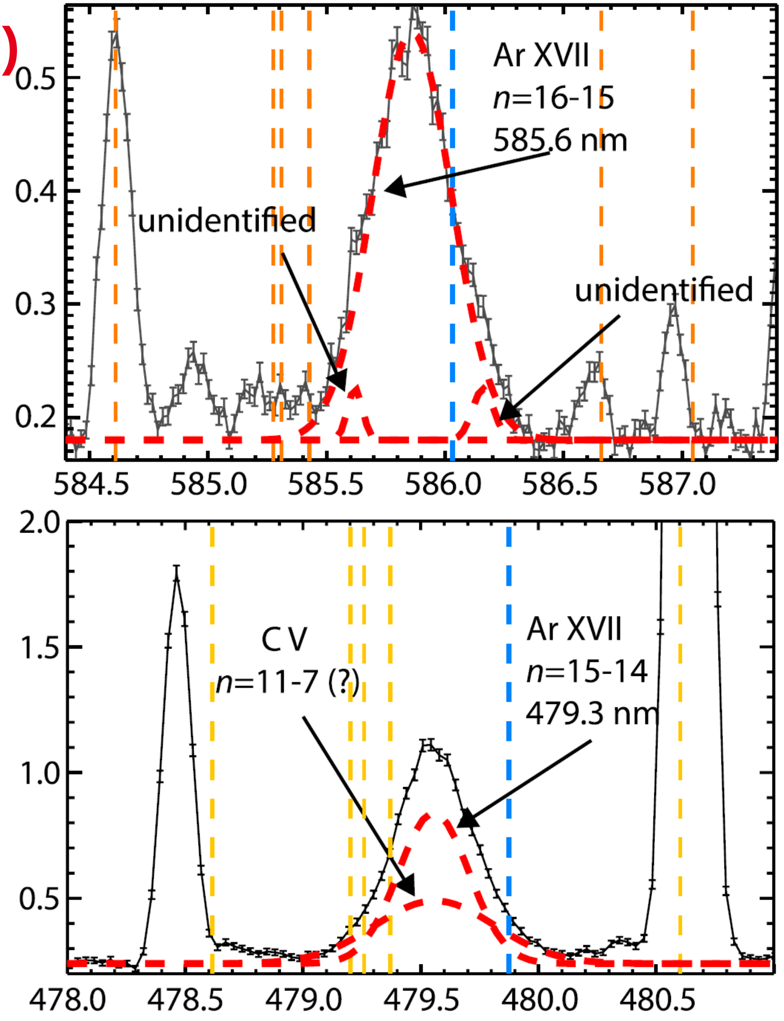
- Case X^{z+} = Ar^{17+}, Y^{q+} = D: $Ar^{17+} + D \rightarrow Ar^{16+*} + D^{+}$

Neutral beam

Spectroscopy lines of sight



McDermott, Plasma Phys. Control. Fusion 2018



McDermott, Nucl. Fusion 2021

2b. Visible spectroscopy – with beams

2.4 Charge exchange recombination spectroscopy (CXRS)

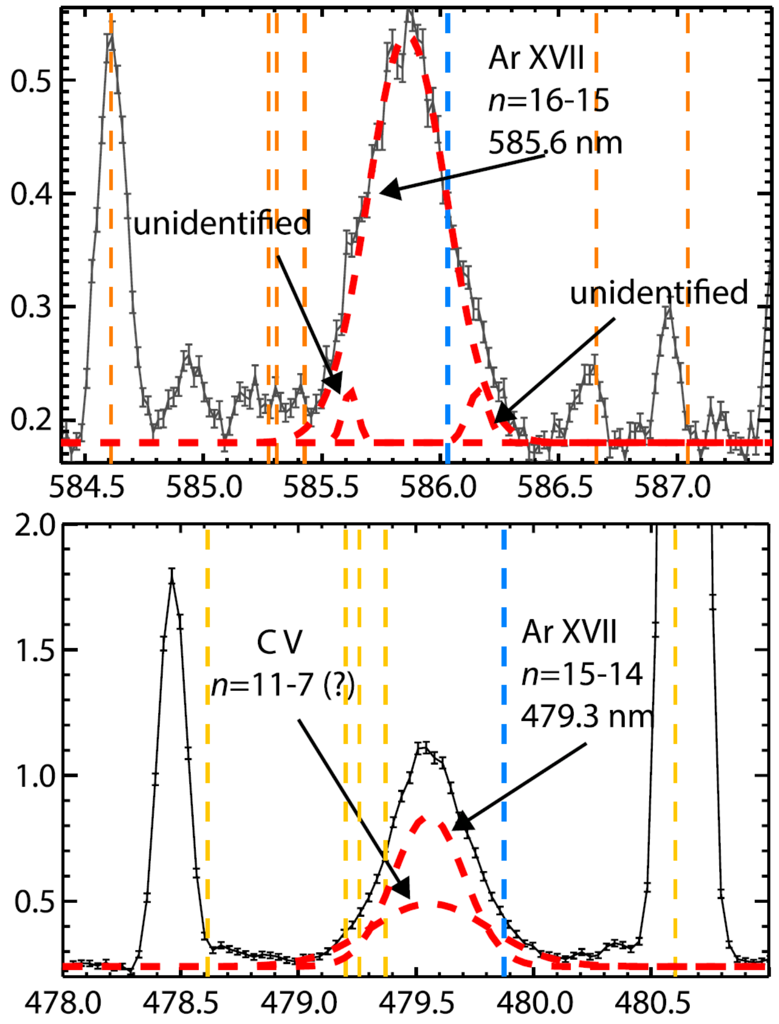
$$X^{z+} + Y^{q+} \rightarrow X^{(z-1)+*} + Y^{(q+1)+}$$

- Ex: X^{z+} = Ar^{17+}, Y^{q+} = D: $Ar^{17+} + D \rightarrow Ar^{16+*} + D^{+}$

- (Doppler) line width → Ion temperature
- Line intensity → emitter density, provided beam attenuation precisely known

(but this is yet another chapter of the atomic processes...)

- n_Z and T_i exp. values up to the centre
- Impurities up to Ar (Z=18)
- CX cross sections must be well known
- Line fitting can be difficult (passive component)

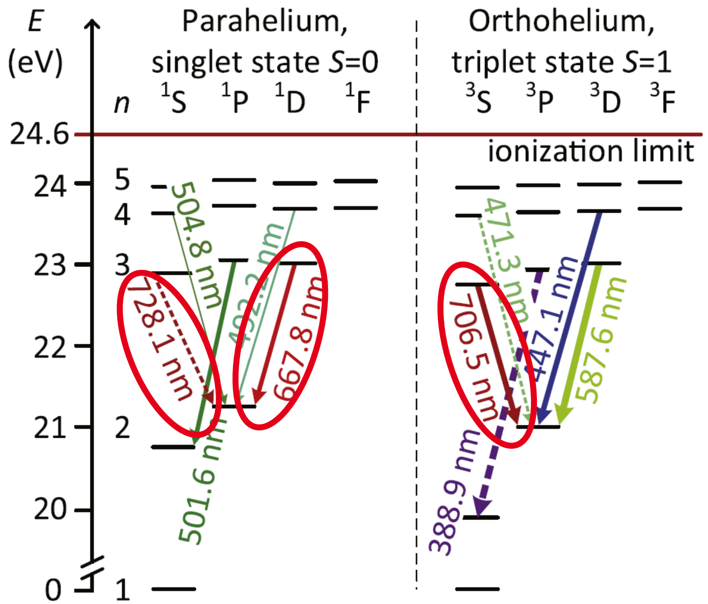


McDermott, Nucl. Fusion 2021

2b. Visible spectroscopy – with beams

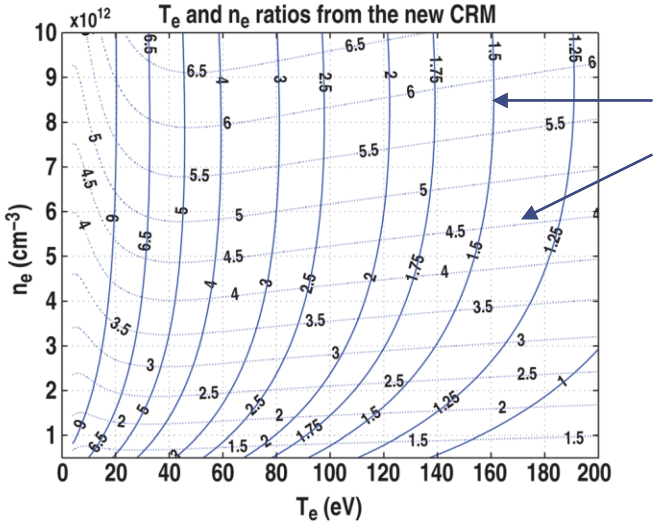
2.4 He beam for edge n_e and T_e

- Neutral He: singlet and triplet



Griener, Phys. Plasma Phys. Control. Fusion 2018

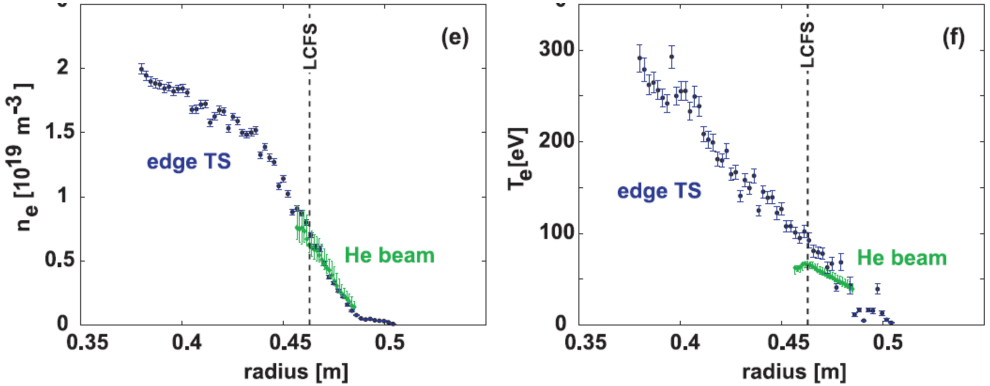
Muñoz Burgos, Phys. Plasmas 2019



706.5 nm / 728.1 nm: T_e

667.8 nm / 728.1 nm: n_e

Schmitz, Phys. Plasma Phys. Control. Fusion 2008



Very useful at low T_e and n_e – exact calculations not so easy

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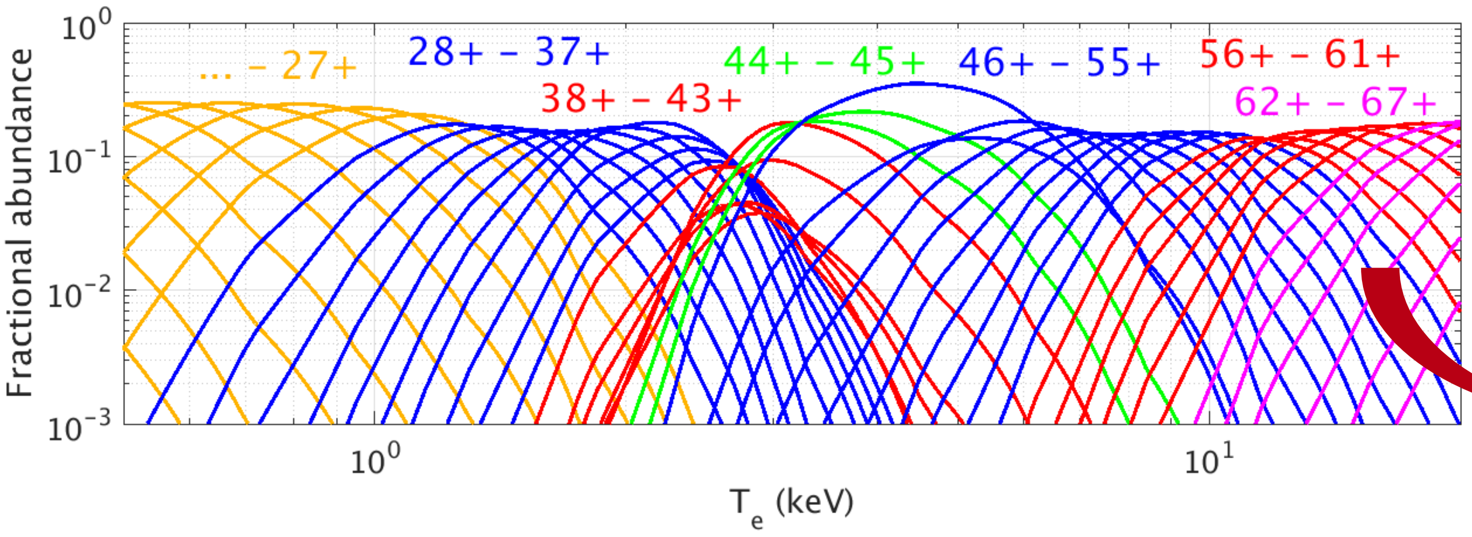
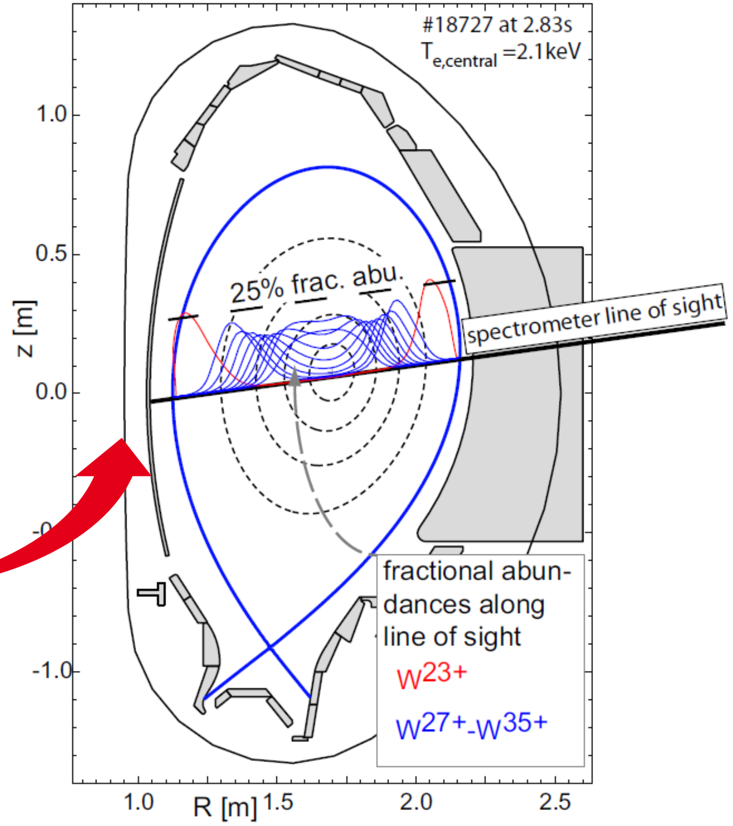
Summary and conclusions

3. (V)UV – Impurity density & transport

3.1 Local ionisation equilibrium and impurity density

- Electron temperature determines location of ionisation stages





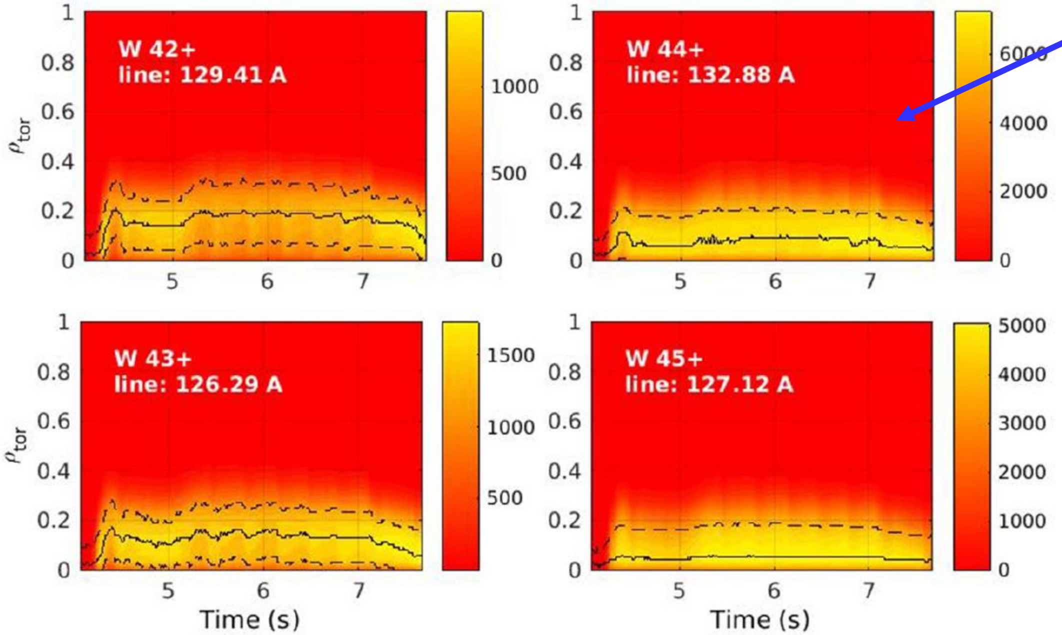
Puetterich, APIP Conf. 2013

3. (V)UV – Impurity density & transport

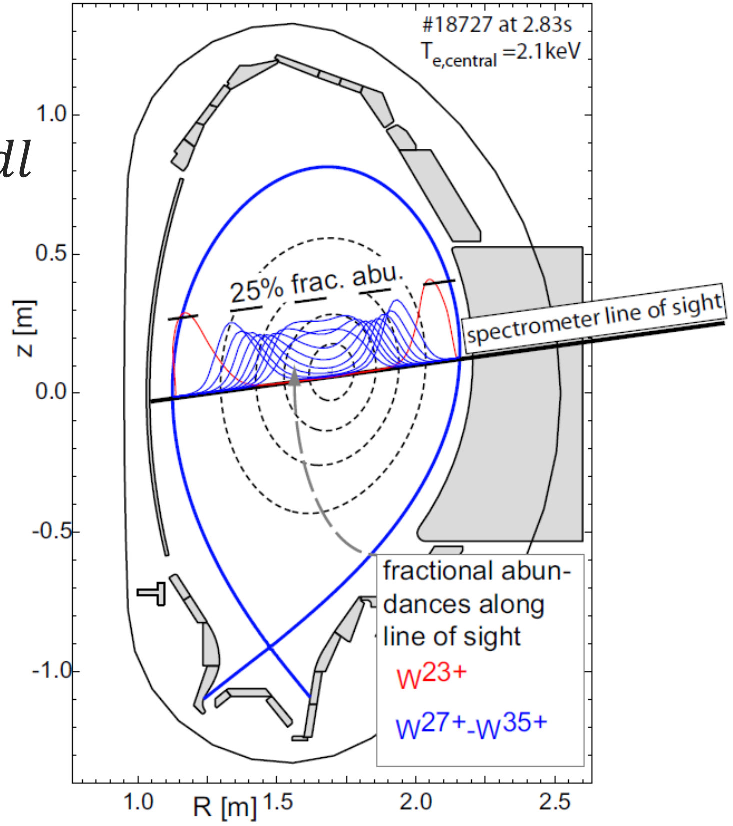
3.1 Local ionisation equilibrium and impurity density

- Electron temperature determines location of ionisation stages
- Even with a single line of sight, localised measurement (sort of...)

$$B_{ij} = \frac{1}{4\pi}\int n_e n_{Z,z} PEC_{Zz}^{ij} dl = \frac{1}{4\pi}\int n_e n_Z f_{Z,z} PEC_{Zz}^{ij} dl \sim \frac{\bar{n}_Z}{4\pi}\int \boxed{n_e f_{Z,z} PEC_{Z,z}{}^{ij}} dl$$



Guirlet, Plasma Phys. Control. Fusion 2022



Puetterich, APIP Conf. 2013

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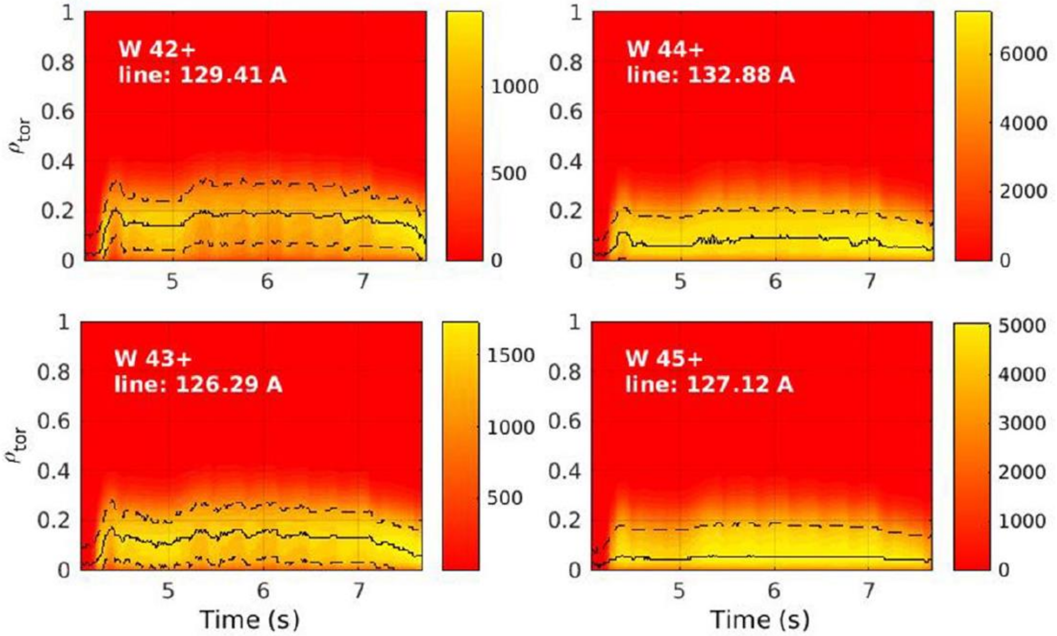
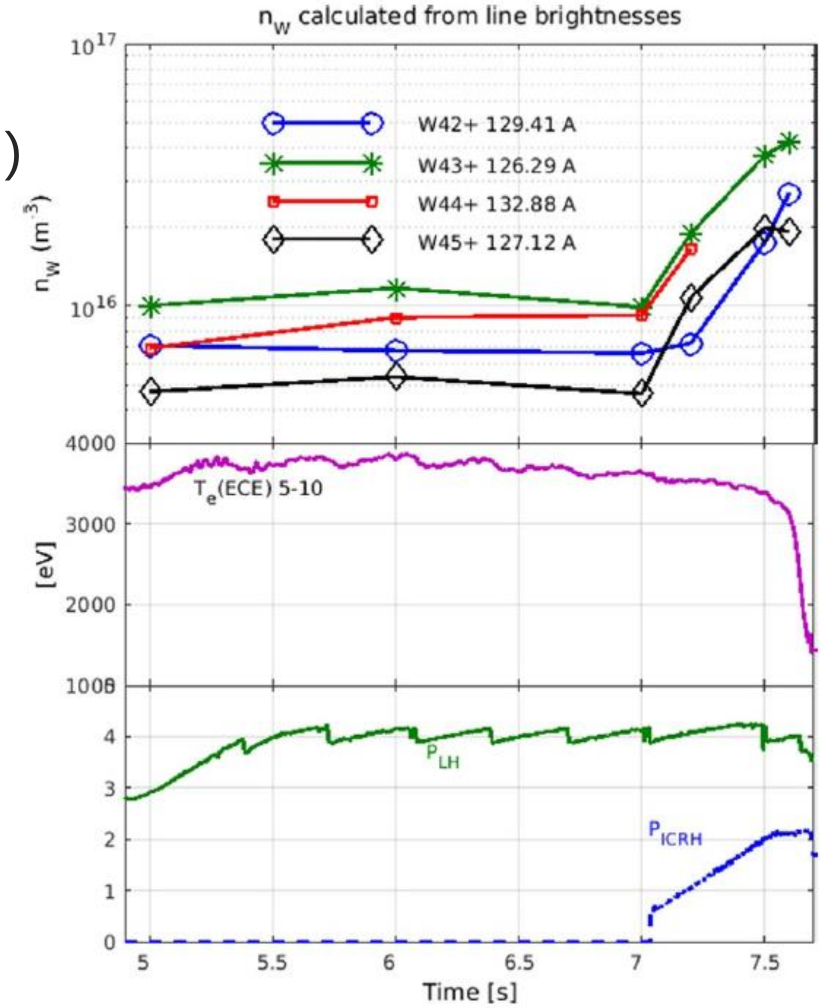
- Electron temperature determines location of ionisation stages
- Even with a single line of sight, localised measurement (sort of...)

$$B_{ij} \sim \frac{\bar{n}_Z}{4\pi}\int n_e f_{Z,z} PEC_{Z,z}{}^{ij}\, dl \Rightarrow \boldsymbol{\bar{n}_Z \sim \frac{4\pi B_{ij}}{\int \ldots}}$$



Guirlet, *Plasma Phys. Control. Fusion 2022*



3. (V)UV – Impurity density & transport

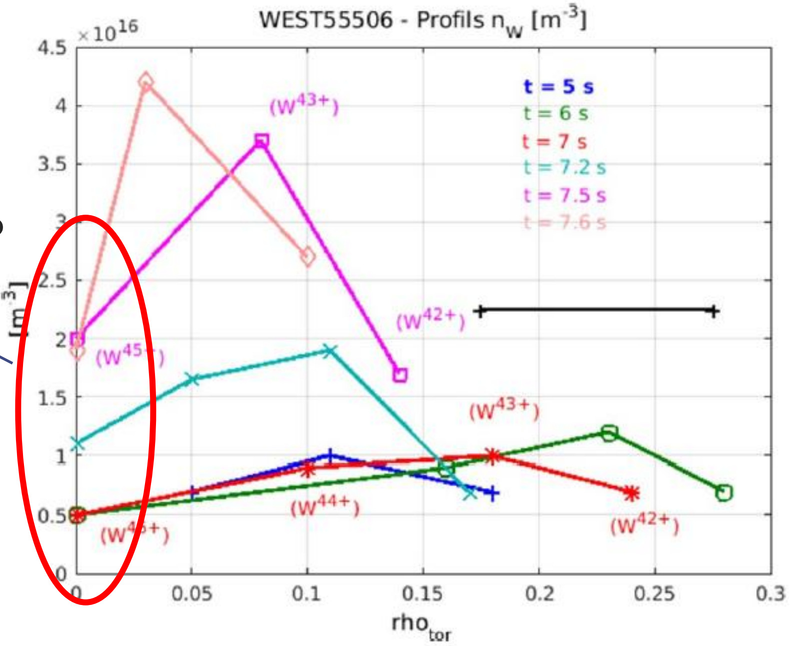
3.1 Local ionisation equilibrium and impurity density

- Electron temperature determines location of ionisation stages
- Even with a single line of sight, localised measurement (sort of...)

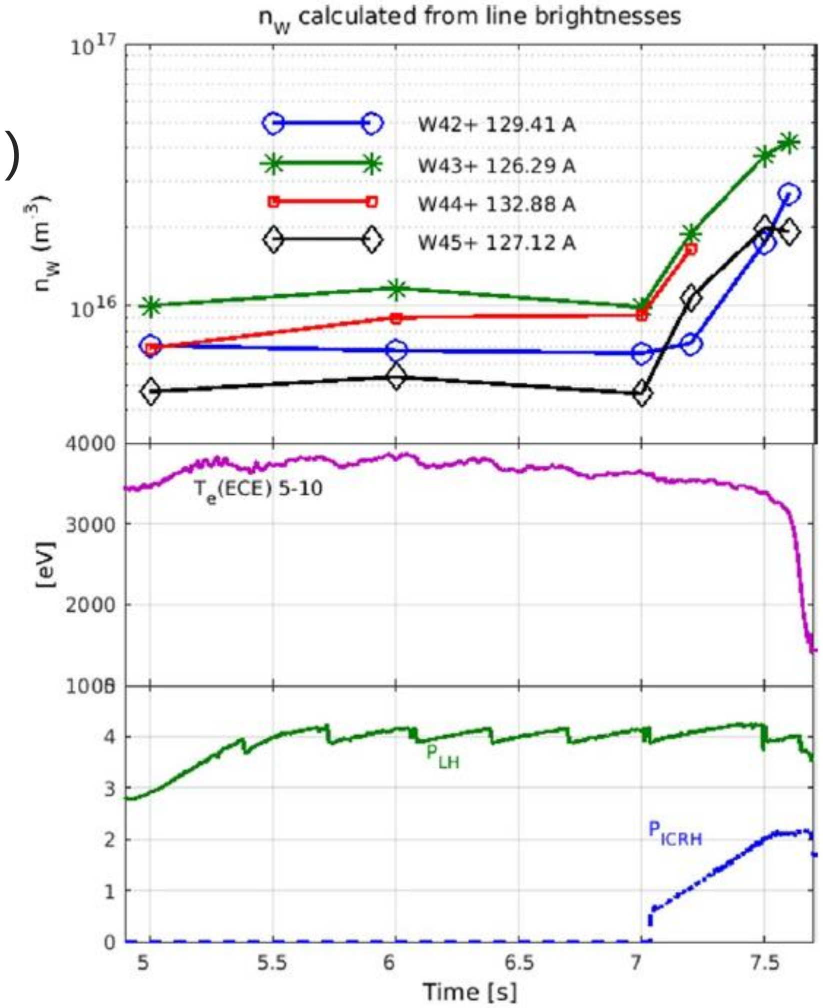
$$B_{ij} \sim \frac{\bar{n}_Z}{4\pi} \int n_e f_{Z,z} PEC_{Z,z}{}^{ij} \, dl \Rightarrow \boldsymbol{\bar{n}_Z \sim \frac{4\pi B_{ij}}{\int \ldots}}$$

PEC wrong?

$\bar{n}_Z$ assump. wrong?



Guirlet, Plasma Phys. Control. Fusion 2022



3. (V)UV – Impurity density & transport

3.1 Transport

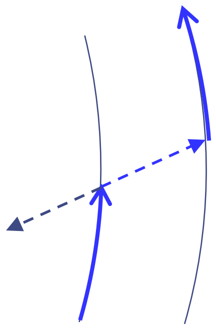
- Transport determines the history of impurity ions from source to sink (edge)
- Magnetised plasmas: governed by charged particle collisions + turbulence
- Relevant quantity: flux $\Gamma_Z = -D_Z \nabla n_Z + V_Z n_Z$
- Weak transport means good confinement (bad for impurities!)
- Transport coefficients are not measured $\Rightarrow$ empirical

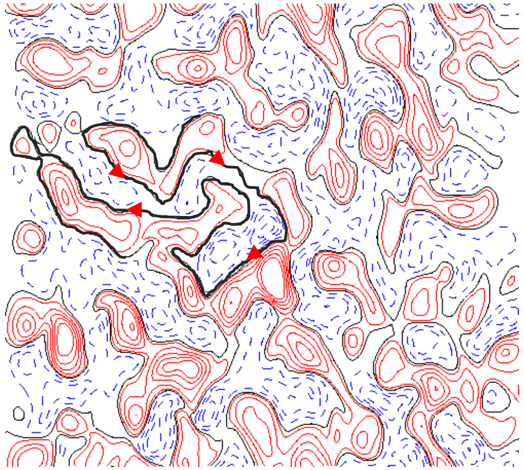
3. (V)UV – Impurity density & transport

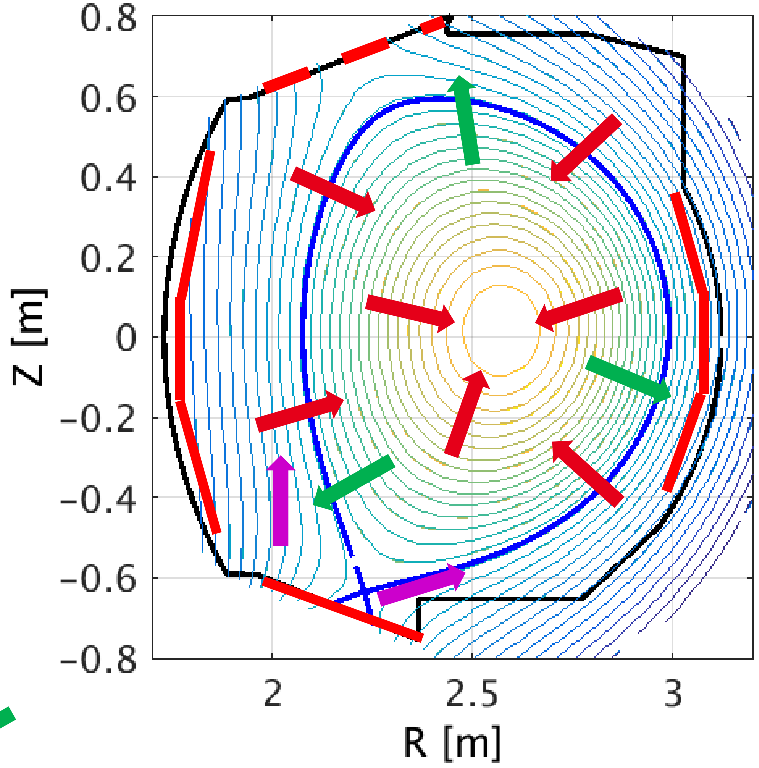
3.1 Transport

- Transport determines the history of impurity ions from source to sink (edge)

- Impurities are produced at the edge
- Once ionised, they move along the field lines
- Due to collisions... and turbulence,
  they are transported across the field lines







- Eventually, they are transported back to the edge

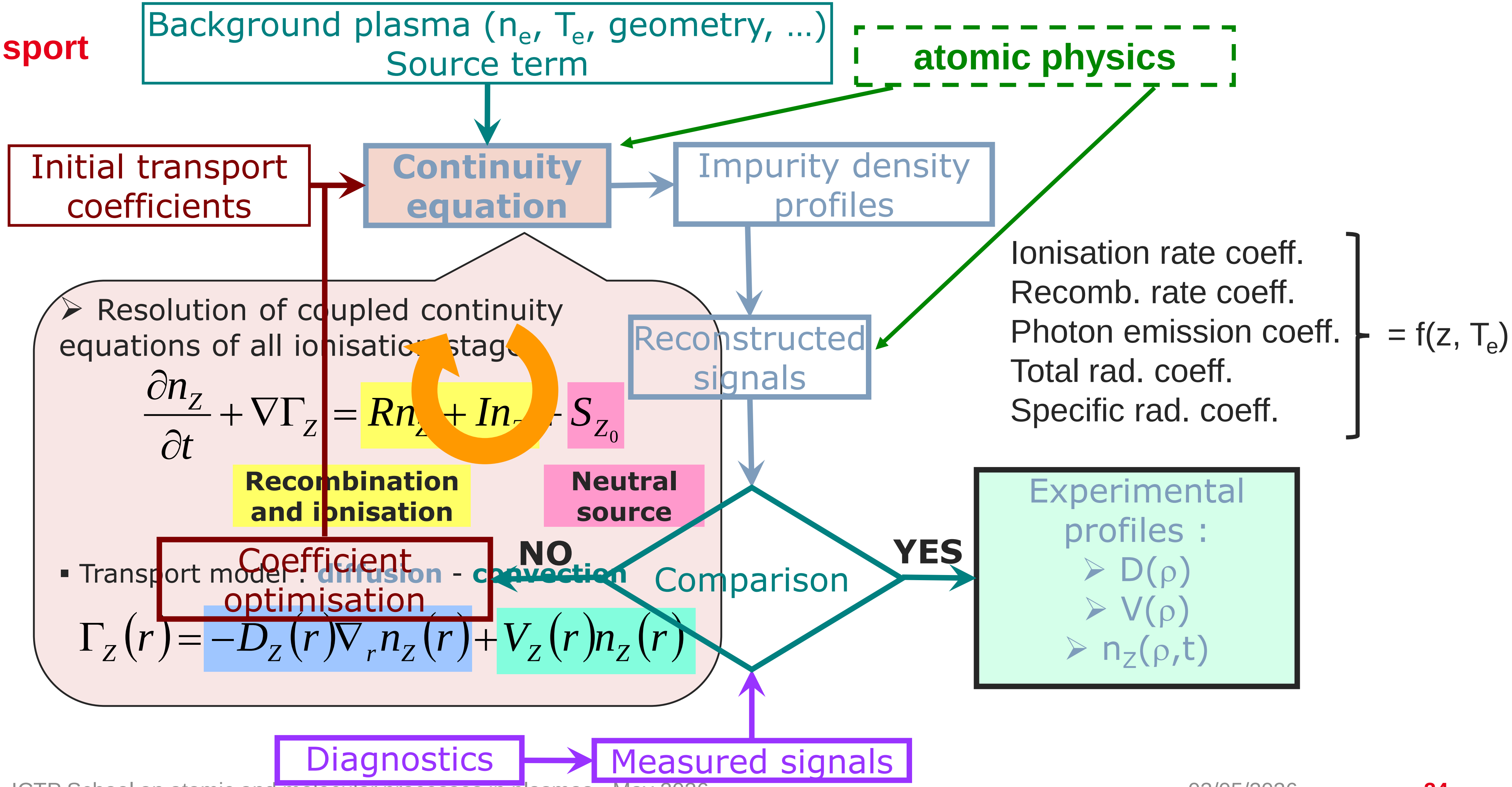
3. (V)UV – Impurity density & transport

3.1 Transport

- Relevant quantity: flux $\Gamma_Z = -\boldsymbol{D_Z}\nabla n_Z + \boldsymbol{V_Z} n_Z$
- **Transport coefficients** are not measured ⇒ empirical method

3. (V)UV – Impurity density & transport

3.1 Transport



Background plasma (n_e, T_e, geometry, …)
Source term

atomic physics

Initial transport coefficients

Continuity equation

Impurity density profiles

- Resolution of coupled continuity equations of all ionisation stages

$$\frac{\partial n_Z}{\partial t} + \nabla\Gamma_Z = Rn_Z + In_Z + S_{Z_0}$$

Recombination and ionisation

Neutral source

- Transport model : **diffusion** - **convection**

$$\Gamma_Z(r) = -D_Z(r)\nabla_r n_Z(r) + V_Z(r)n_Z(r)$$

Coefficient optimisation

Reconstructed signals

Ionisation rate coeff.
Recomb. rate coeff.
Photon emission coeff.
Total rad. coeff.
Specific rad. coeff.

= f(z, T_e)

NO

Comparison

YES

Experimental profiles :

- D(ρ)
- V(ρ)
- n_Z(ρ,t)

Diagnostics

Measured signals

Outlook

Introduction

1. Atomic & radiative processes

2. Visible spectroscopy – impurity sources and recycling

3. (V)UV for impurity densities and transport

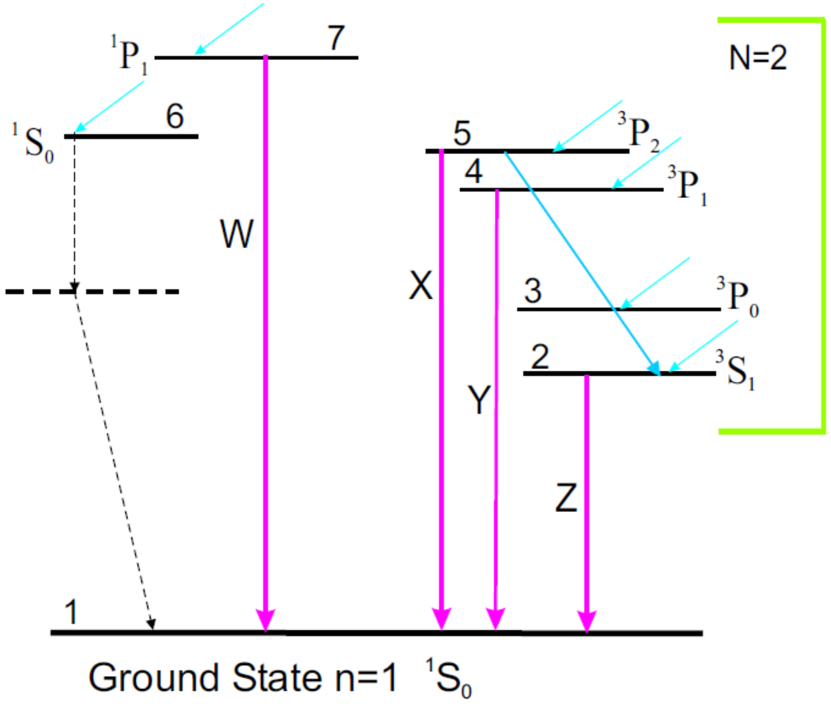
4. Soft-X ray for ion temperature and velocity

Summary and conclusions

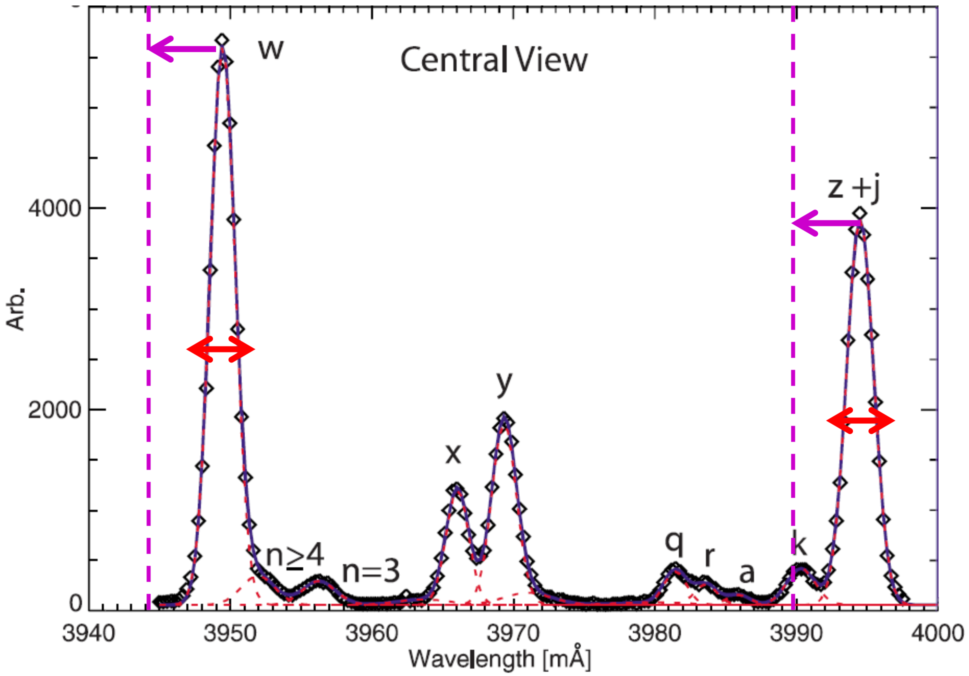
4. Soft-X ray for ion temperature and velocity

4.1 He-like spectrum

- Small number of low excited states, close to each other
- Forbidden lines generally strong
- Lines easily identified



Ince-Cushman, Rev. Sci. Instr. 2008



- Doppler broadening dominates

→ Ion temperature from Doppler width ↔

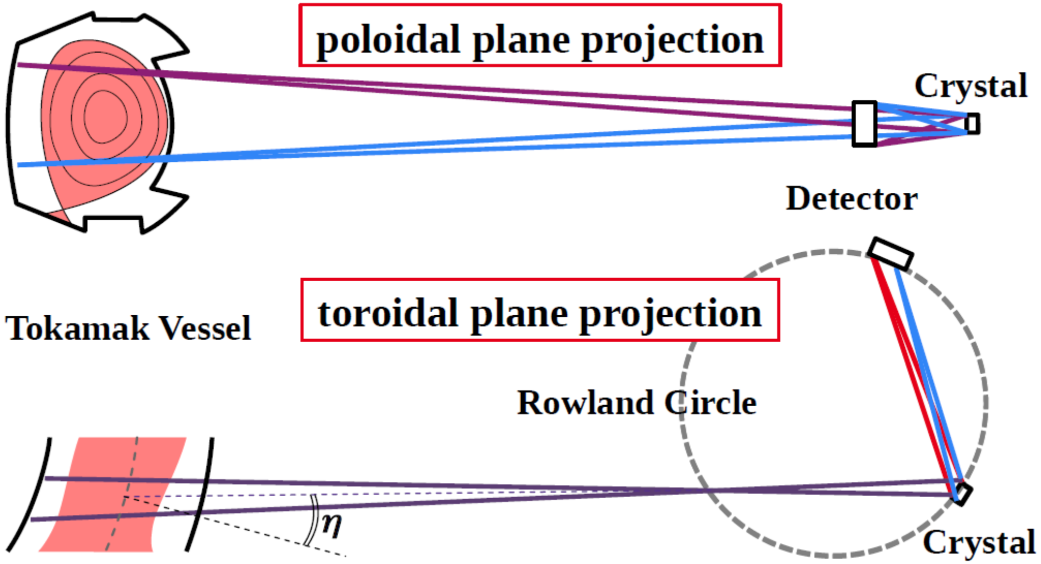
- If absolute λ calibration

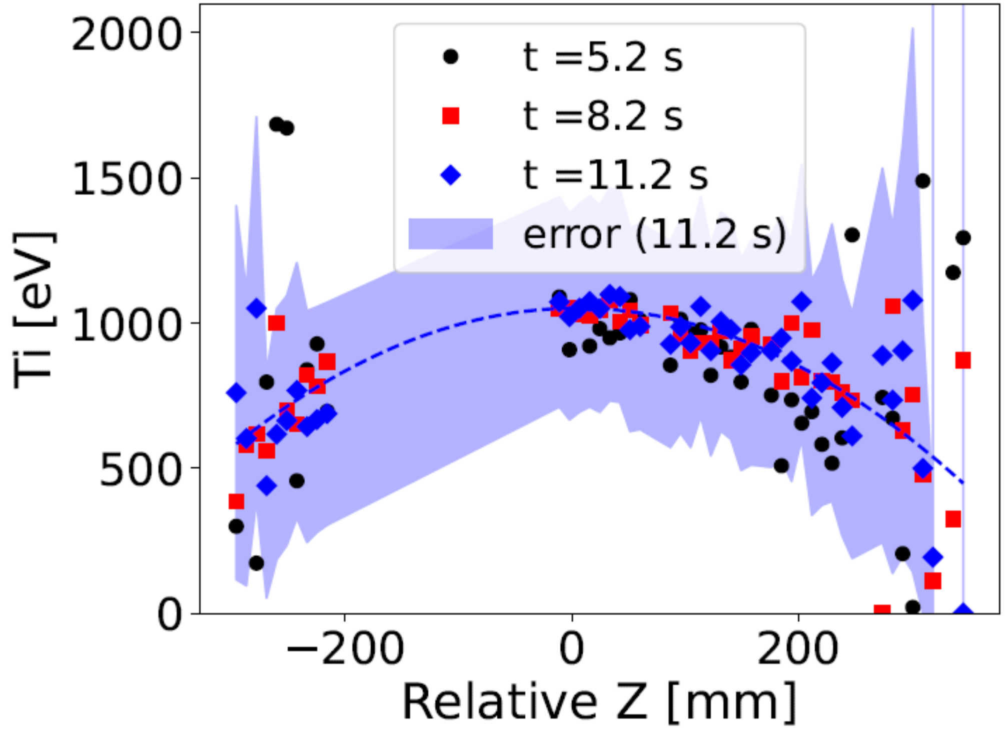
→ Ion velocity from Doppler shift ←

4. Soft-X ray for ion temperature and velocity

4.2 'Imaging' spectrometers

- Concave crystal
- Wavelength in one direction, line of sight in the other
- Can provide ion temperature and velocity profiles





See Pierre Forestier-Colléoni!

Outlook

Introduction

1. Atomic & radiative processes

2. Visible spectroscopy – impurity sources and recycling

3. (V)UV for impurity densities and transport

4. Soft-X ray for ion temperature and velocity

Summary and conclusions

Summary - Conclusions

- In MCF plasmas, emission from visible to X-ray can provide information
- Mostly on impurities but not only (electron and ion temperature)
- Visible-UV → plasma edge, VUV-SXR → confined plasma
- Whole variety of atomic physics data necessary:
  - Ionisation rate coeff.
  - Recombination rate coeff.
  - Photon emission coeff. (spectral lines)
  - Beam attenuation coefficients
  - Cooling functions (total and SXR)
- Beam spectroscopy broadens possibilities but uses different coeff.
- W brings a lot of concerns from the operational point of view...
- ... and a lot challenges from the atomic physics point of view

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