Line shape models in magnetic fusion research and astrophysics

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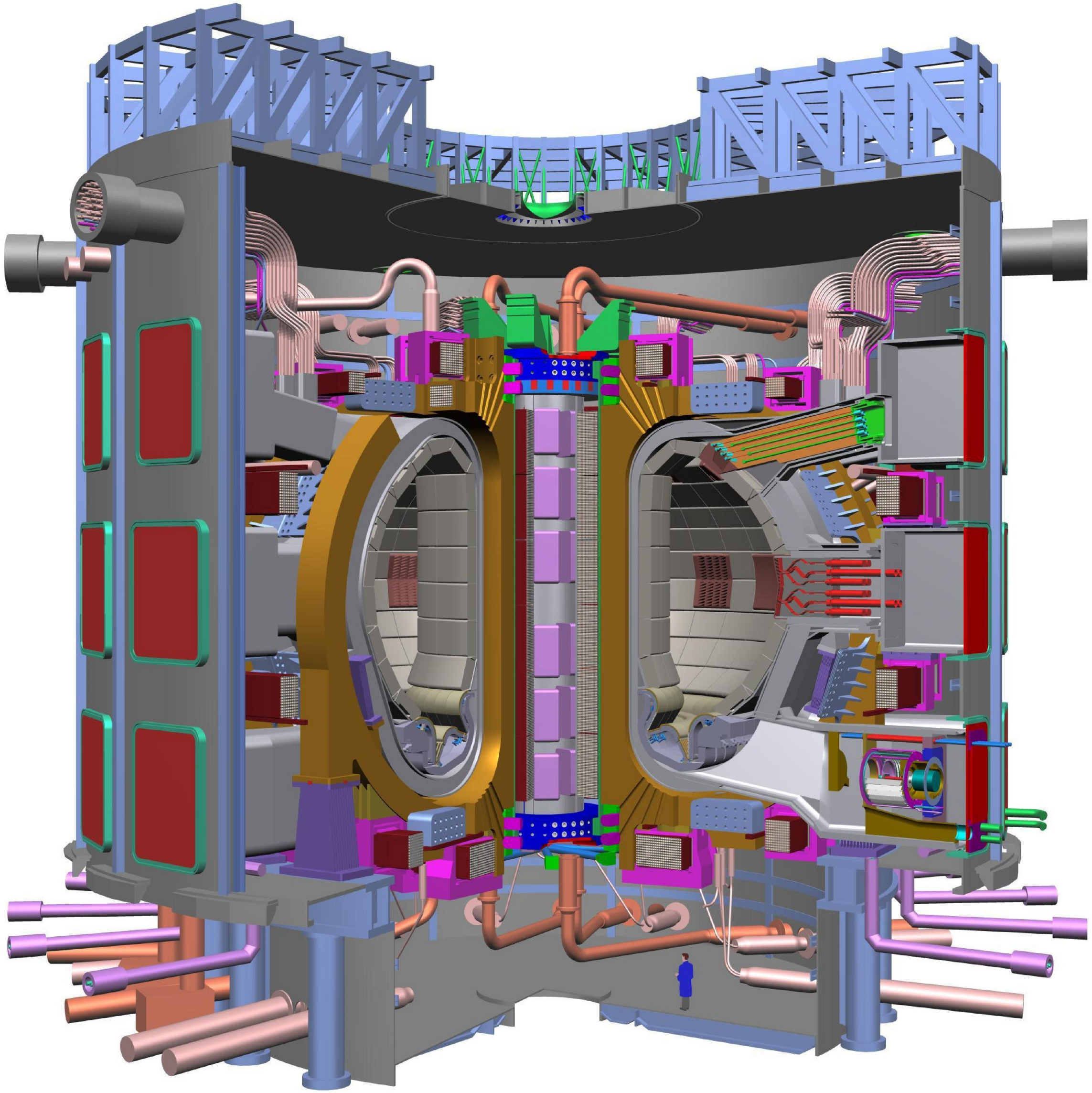
Outline

1) The ITER project: an overview

2) Passive spectroscopy of current tokamak plasmas: line shapes, Stark broadening and Zeeman effect

3) Applying line shape models to stellar atmosphere spectra analysis

The ITER project (www.iter.org)



iter
china eu india japan korea russia usa

Aim: demonstrate the feasibility of the fusion power

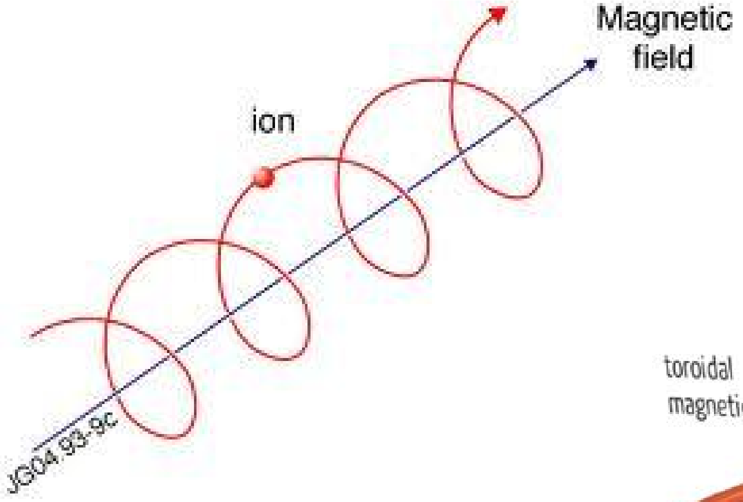
An international collaboration
- 1st controlled fusion burning plasma
- Presently under construction (France)
- First plasma in 2025

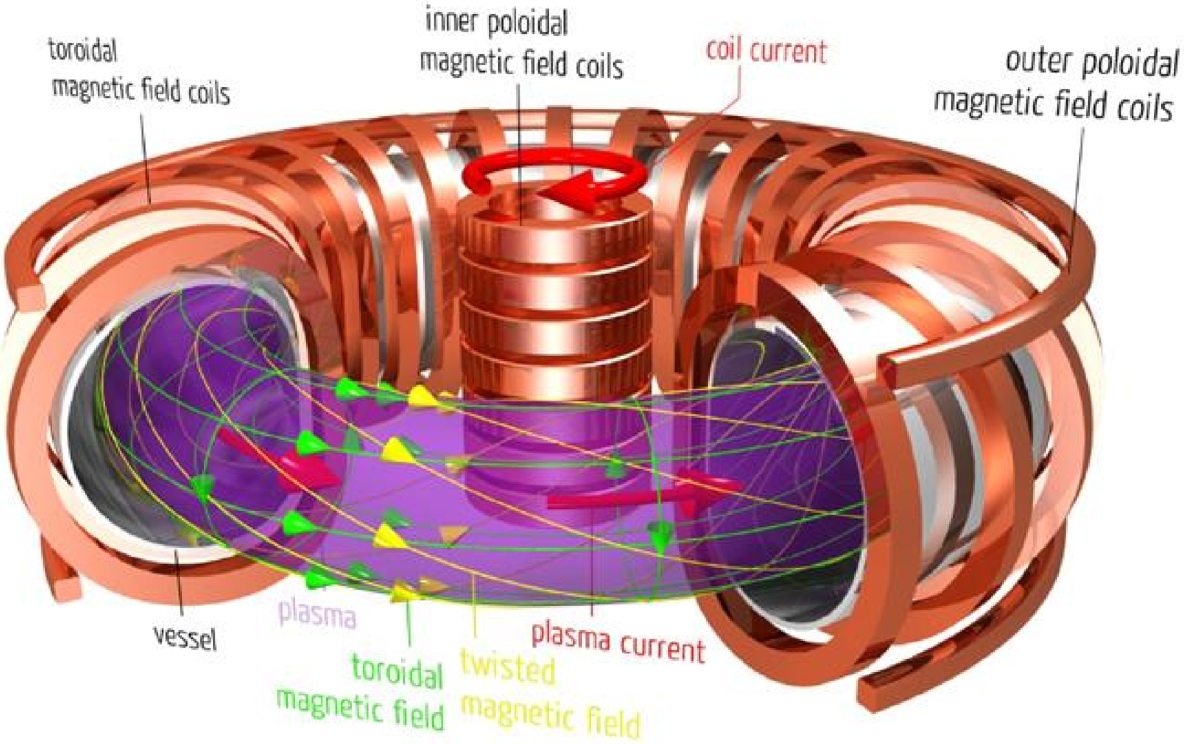
The ITER project (www.iter.org)

Research activities in France and in Europe

From www.euro-fusion.org:
“EUROfusion funds fusion research activities in accordance with the *Roadmap to the realisation of fusion energy*. The Roadmap outlines the most efficient way to realise fusion electricity by 2050.”

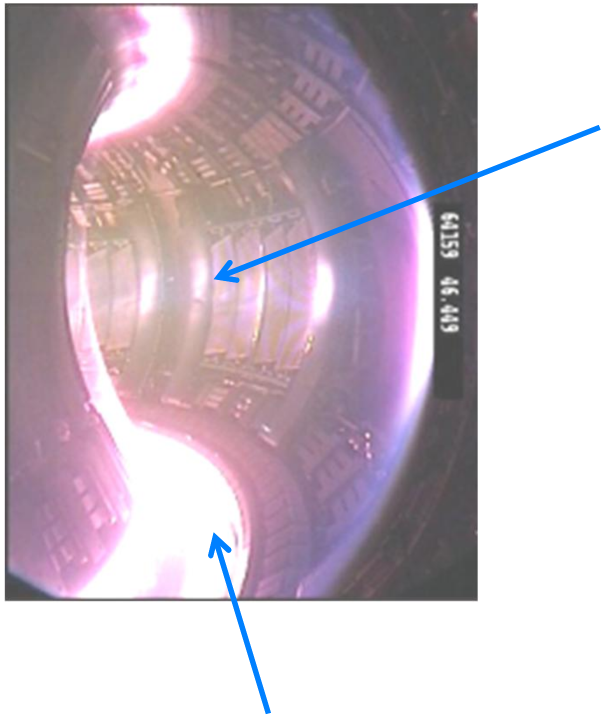
ITER is a tokamak





$$D^{+} + T^{+} \rightarrow He^{2+} + n$$

Presentation of tokamak plasmas



Center:
- T_e, T_i up to 10 keV
- fully ionized H plasma
- presence of multicharged impurity ions

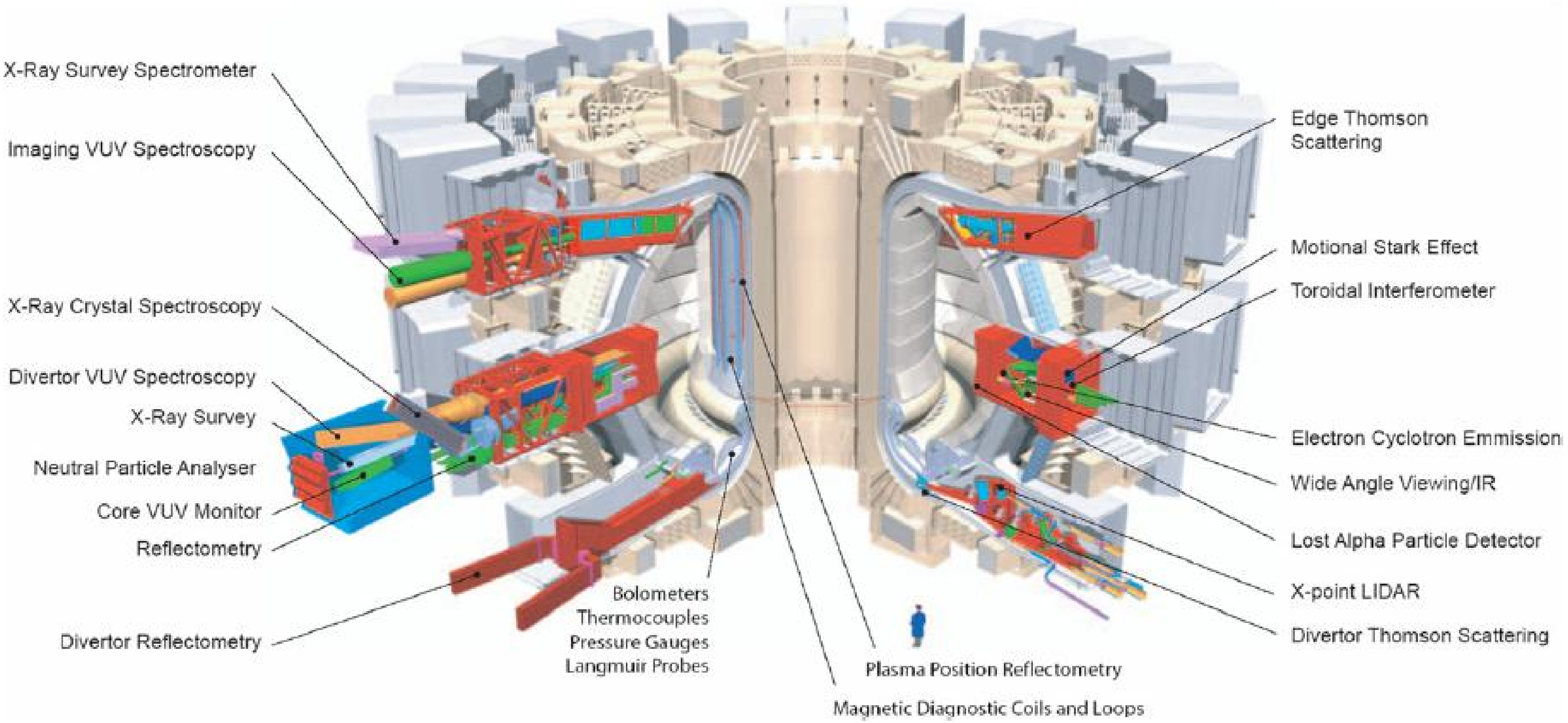
Electron densities range in ~ $10^{12} – 10^{15}$ cm^{-3}

B-field: several teslas

Edge & divertor :
- temperatures down to 1 eV, and less
- a large amount of neutrals can be present (“detached regime”)
- strong atomic line radiation

An extensive set of diagnostics for ITER

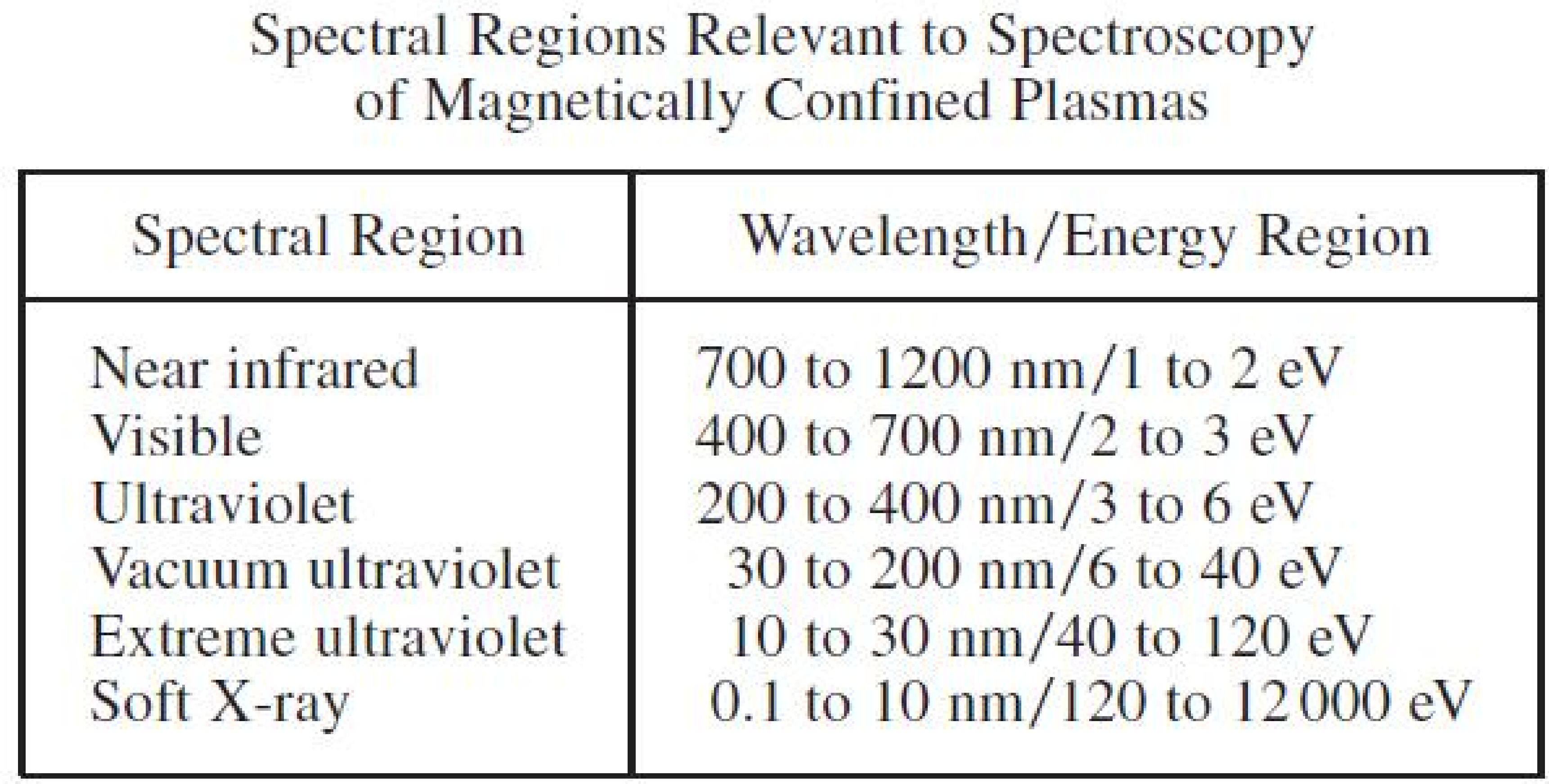
See Progress in the ITER Physics Basis, Nucl. Fusion special issue (2007)



Spectroscopic observations are done in a wide wavelength range: IR, visible, X…

Passive and active methods are used

An extensive set of diagnostics for ITER



Spectral Regions Relevant to Spectroscopy
of Magnetically Confined Plasmas

Spectral Region	Wavelength/Energy Region
Near infrared	700 to 1200 nm/1 to 2 eV
Visible	400 to 700 nm/2 to 3 eV
Ultraviolet	200 to 400 nm/3 to 6 eV
Vacuum ultraviolet	30 to 200 nm/6 to 40 eV
Extreme ultraviolet	10 to 30 nm/40 to 120 eV
Soft X-ray	0.1 to 10 nm/120 to 12 000 eV

Fus. Sci. Technol. 53, Special Issue on Plasma Diagnostics for Fusion Research (2008)

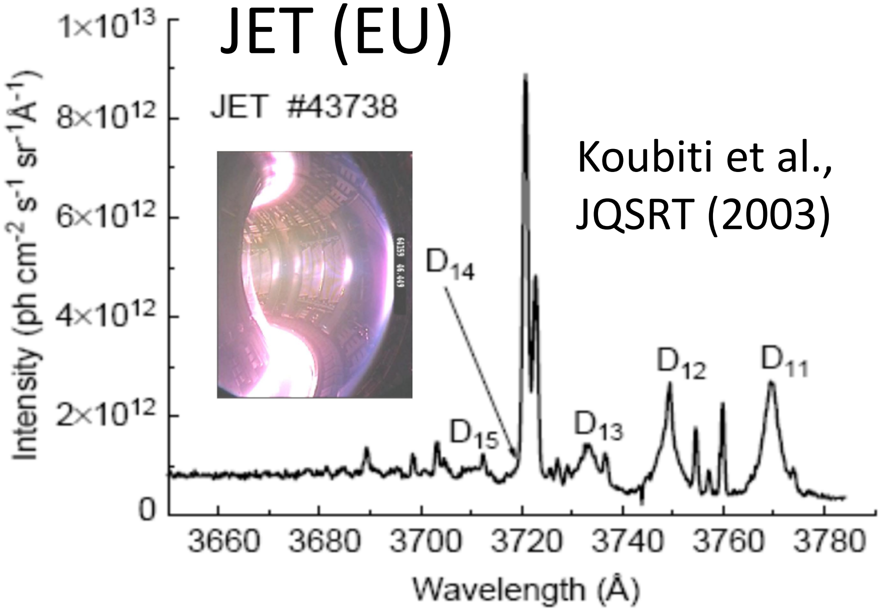
Passive spectroscopy in current tokamaks

An analysis of line shapes, line widths, line intensities provides information on the plasma parameters

All elements are considered:
- neutral atoms and molecules (edge region, divertor)
- multicharged impurity ions (core region)

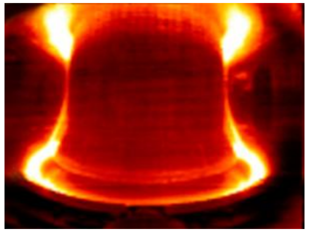
Hydrogen line spectra in tokamak edge and divertor plasmas

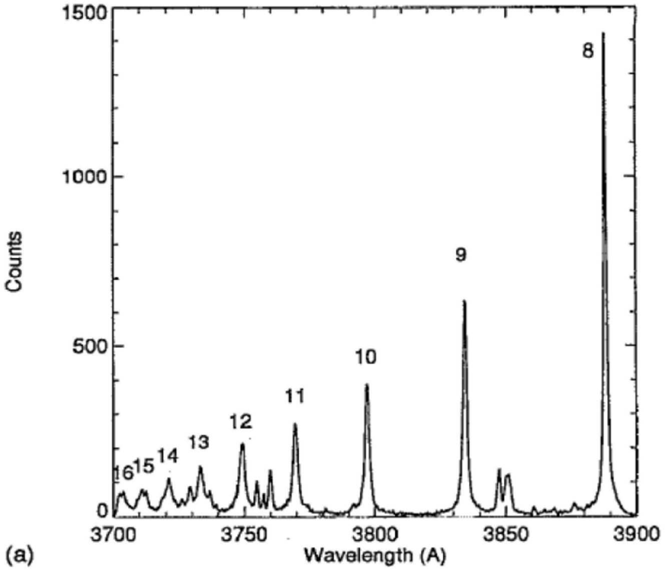
JET (EU)



Koubiti et al., JQSRT (2003)

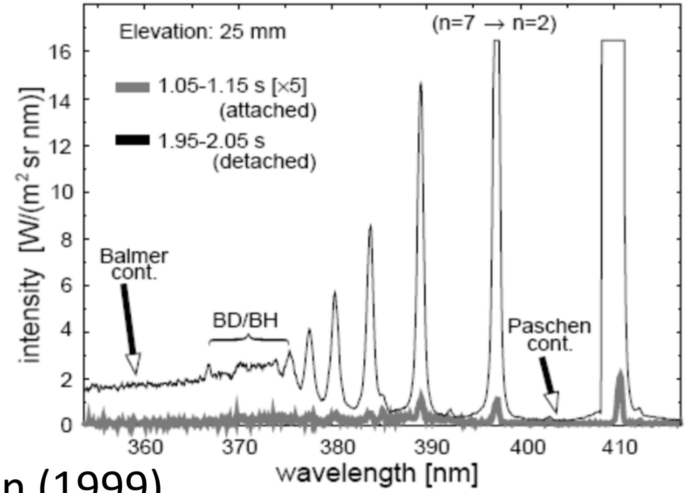
Alcator C-Mod (US)





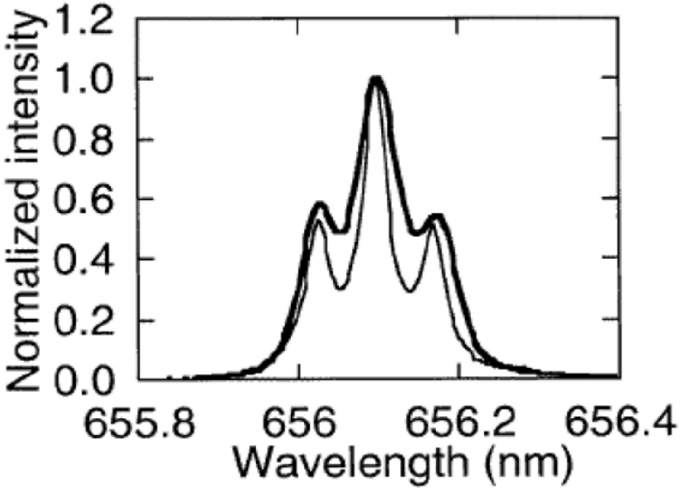
Welch et al., PoP (1995)

ASDEX Upgrade (Germany)



Wenzel et al., Nucl. Fusion (1999)

JT-60U (Japan)



Kubo et al., PPCF (1998)

Hydrogen line spectra in tokamak edge and divertor plasmas

Lines with a high principal quantum number have been observed in recombining (“detached”) divertor plasma conditions
Their width provides information on the electron density from Stark broadening analysis

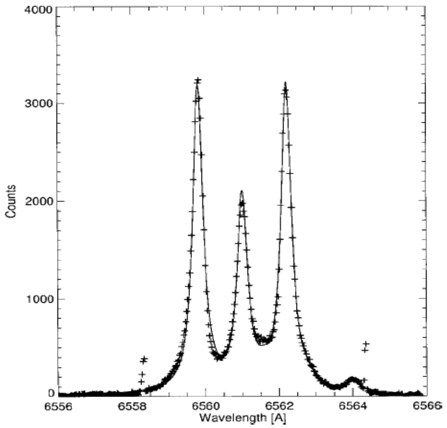
The profile of lines with a low principal quantum number (especially Balmer α) is usually dominated by Doppler broadening and Zeeman splitting
An analysis of the shape provides information on the neutral velocity distribution function f(v) in the edge region

Problematic issues for ITER

The divertor will be of large size
Can one obtain local information on the plasma parameters?

The density will be sufficiently high so that low-n lines
will be affected by both Doppler and Stark effects
Can one extract reliable information on the neutrals’ VDF f(v)
from Doppler analysis?

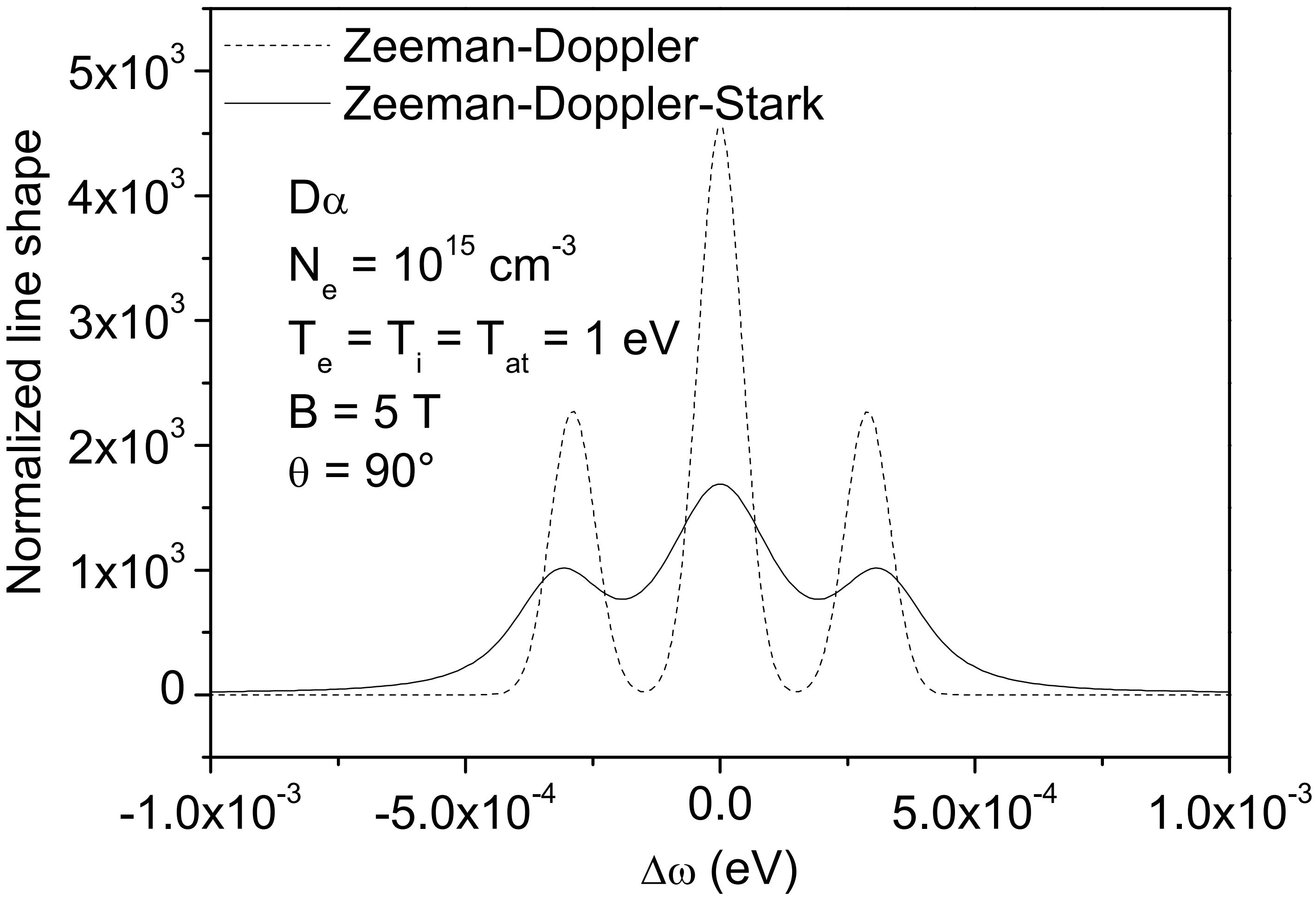
Already problematic
in Alcator C-Mod



Dα Zeeman-Lorentz triplet:
both Doppler & Stark effects
contribute to the broadeing

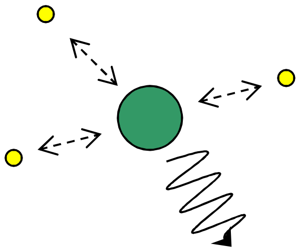
Welch et al., PoP (2001)

Problematic issues for ITER



Stark broadening modeling

Stark broadening: when emitting a photon,
an atom feels the presence of the charged particles
located at vicinity

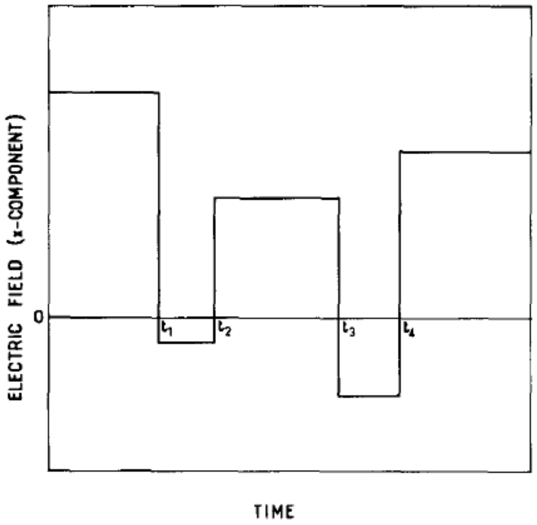


According to classical textbooks and articles (Baranger, Griem),
the Stark-broadening problem amounts to solve the time-dependent
Schrödinger equation for the evolution operator U(t)

$$i\hbar\frac{dU}{dt}(t) = (H_0 - \vec{d}\cdot\vec{E}(t))U(t)$$

A formal solution can be written using the Dyson series,
but there is no explicit form applicable in a general case

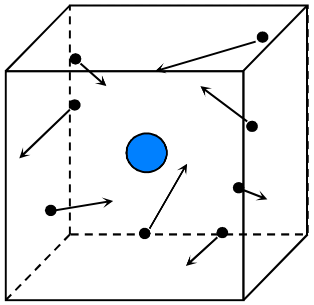
Models and methods for ion dynamics



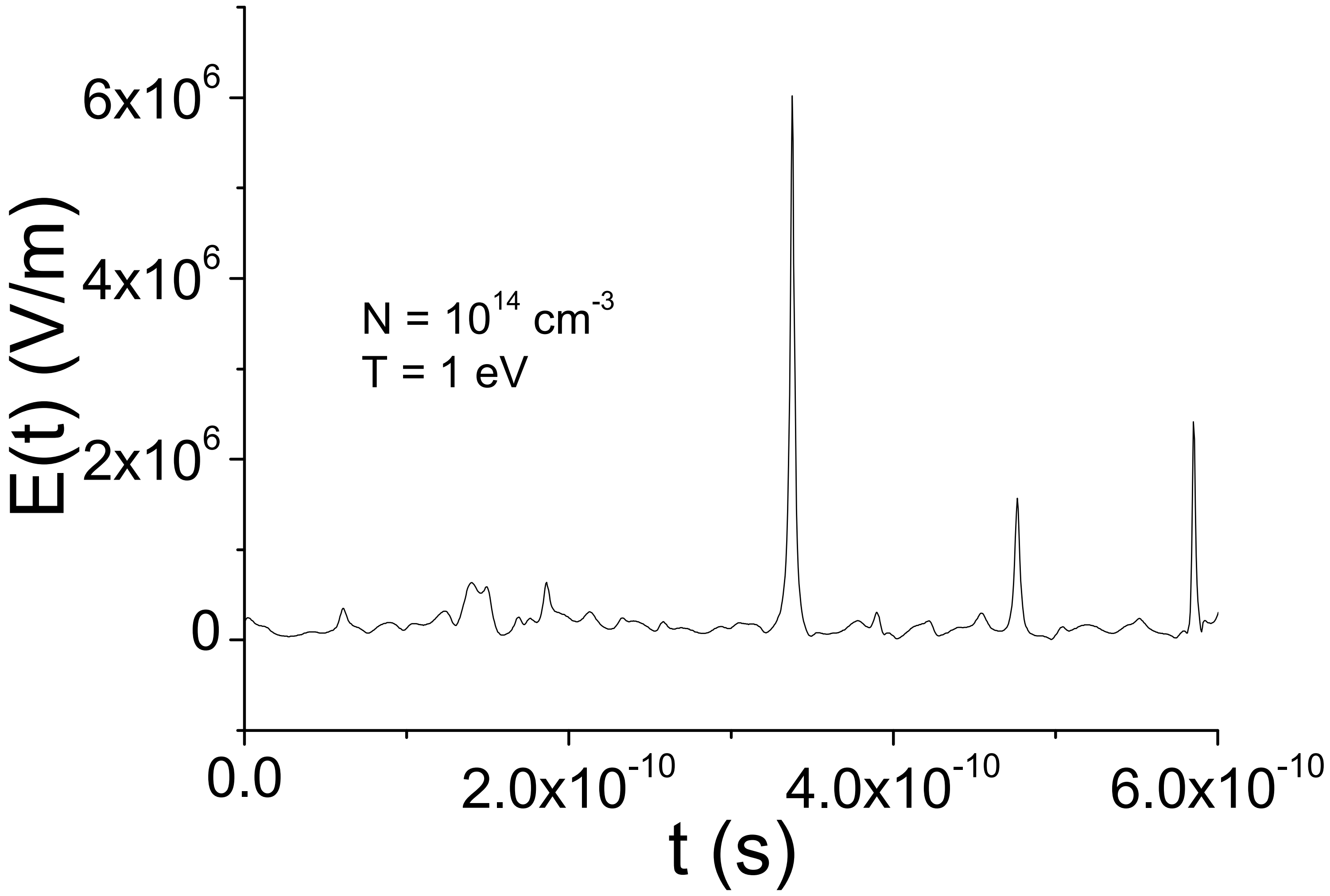
MMM (Model Microfield Method, 1970s):
- the E-field is described using a stochastic process
- the Schrödinger equation has an exact solution but this is not the true field

FFM (Frequency Fluctuation Model, 1990s)

Numerical simulation (1970s):
- particle motion is simulated and the Schrödinger Eq. is solved numerically
- this method is more accurate (benchmark)
- it is time consuming

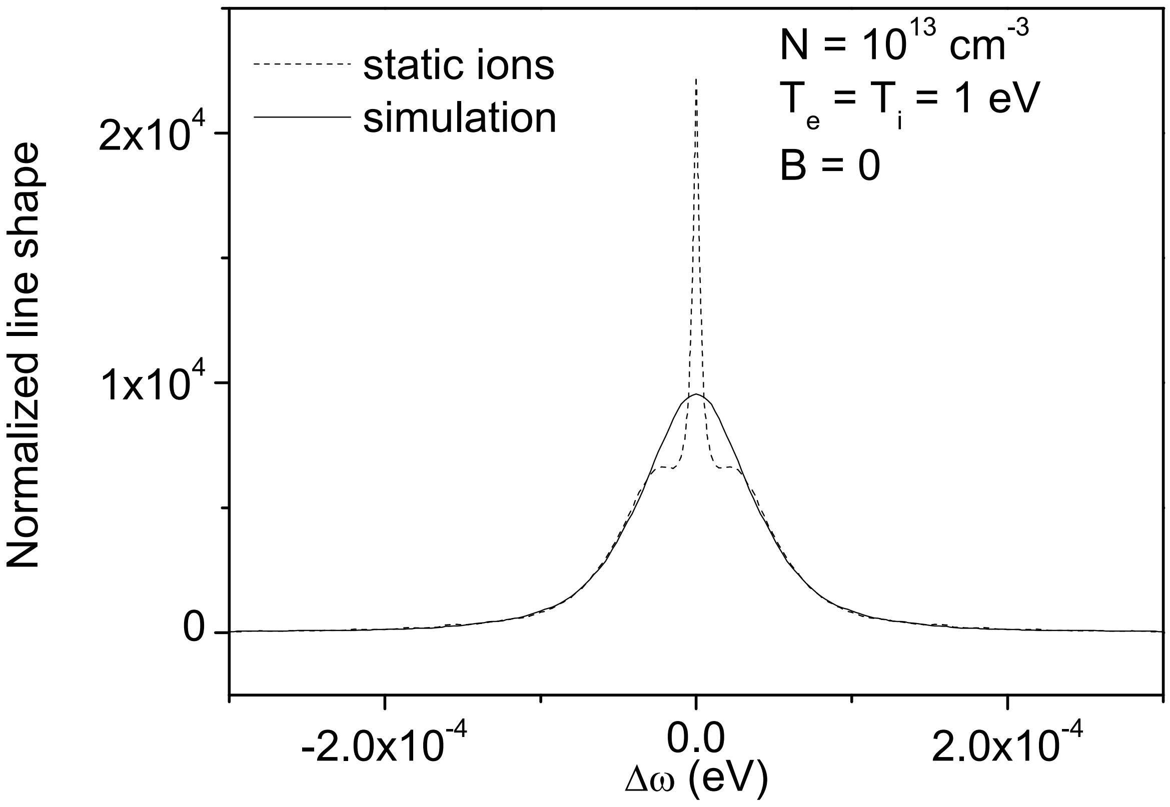


Models and methods for ion dynamics



Models and methods for ion dynamics

Dγ line (deuterium Balmer γ)



The ion dynamics yields additional broadening

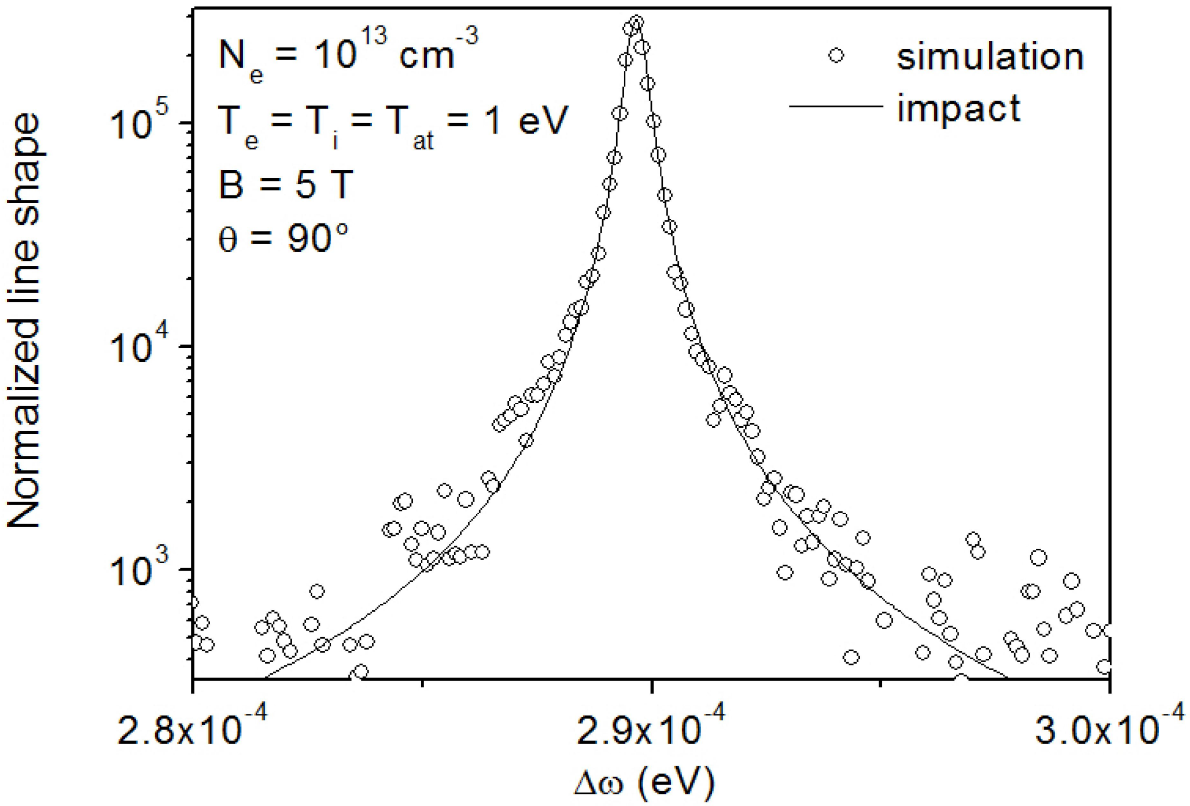
Models and methods for ion dynamics

Under high dynamics conditions (low n / low N_e / high T), numerical simulations are time consuming

The use of an impact collision operator for ions can be relevant

See talk by R. Stamm tomorrow for a discussion

Ly α lateral (Doppler free) Zeeman component

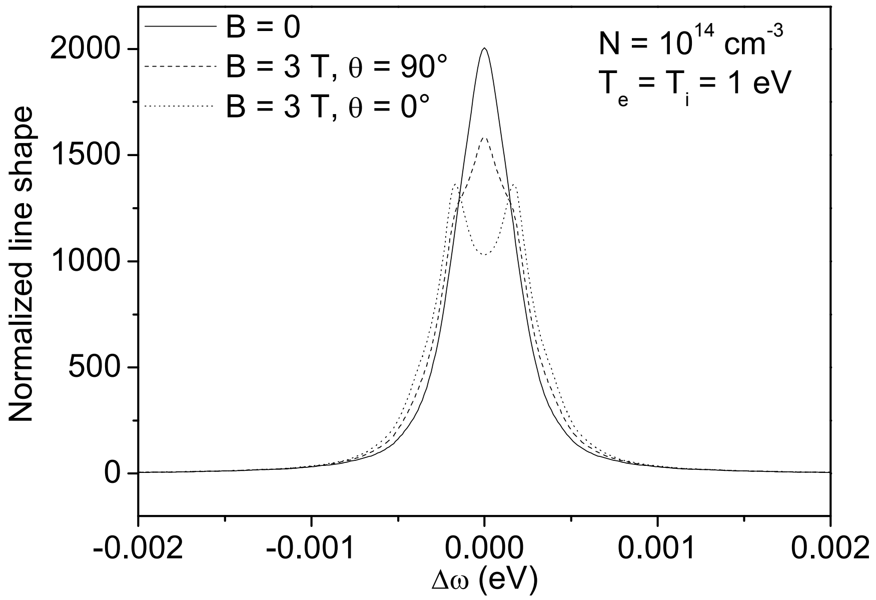


In general, all methods are complementary to each other; they can be tested by performing calculations under suitably chosen plasma conditions (e.g. SLSP code workshop, E. Stambulchik)

A database for ITER and current tokamaks

Tables for the first Balmer lines have been constructed using the numerical simulation method: from Dα to Dε

- $T_e = T_i = 0.316,\ 1,\ 3.16,\ 10,\ \text{and } 31.6\ \text{eV};$
- $N = (1,\ 2.15,\ 4.64) \times (10^{13},\ 10^{14},\ 10^{15}),\ \text{and } 10^{16}\ \text{cm}^{-3};$
- $B = 0,\ 1,\ 2,\ 2.5,\ 3,\ \text{and } 5\ \text{T}.$



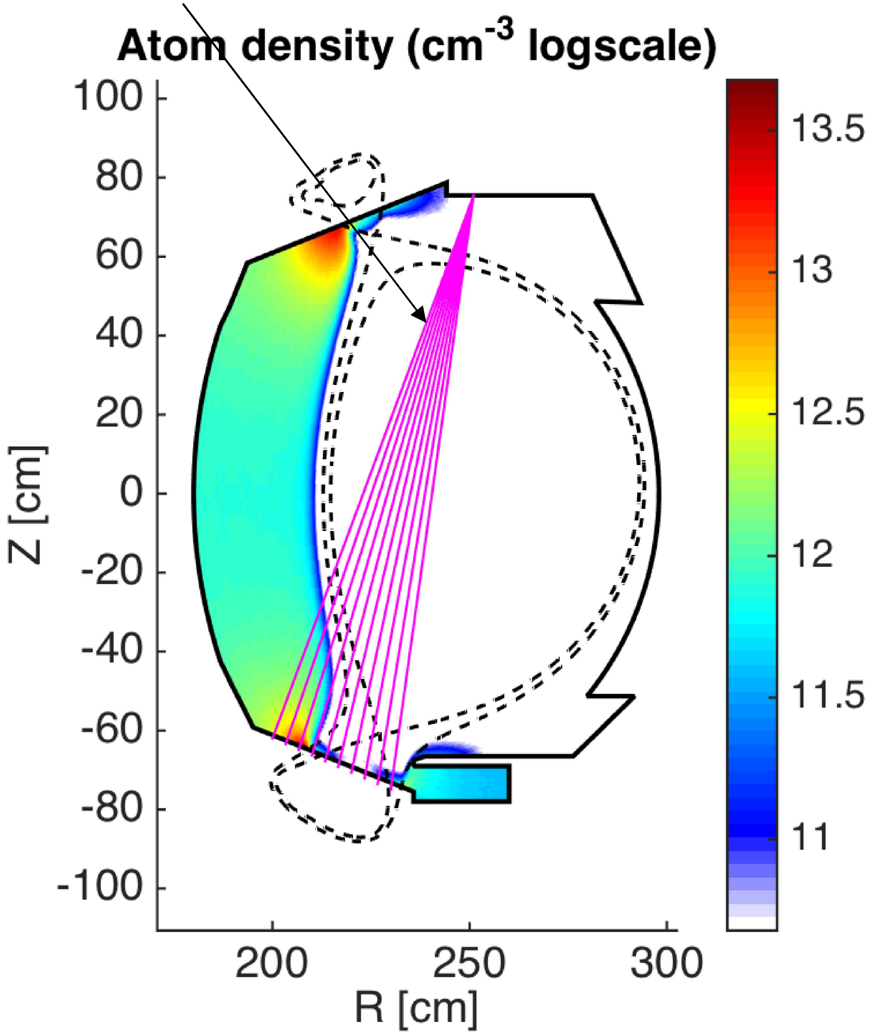
J. Rosato et al., JQSRT 187, 333 (2017)

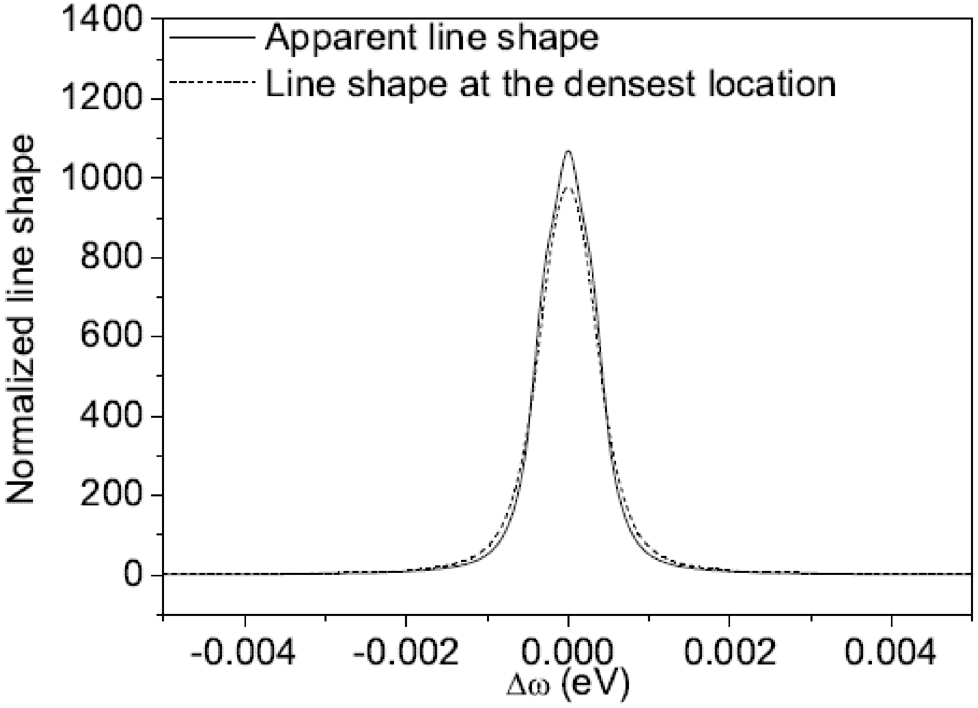
A FORTRAN program that reads the database is ready for use

Simulations of observable spectra

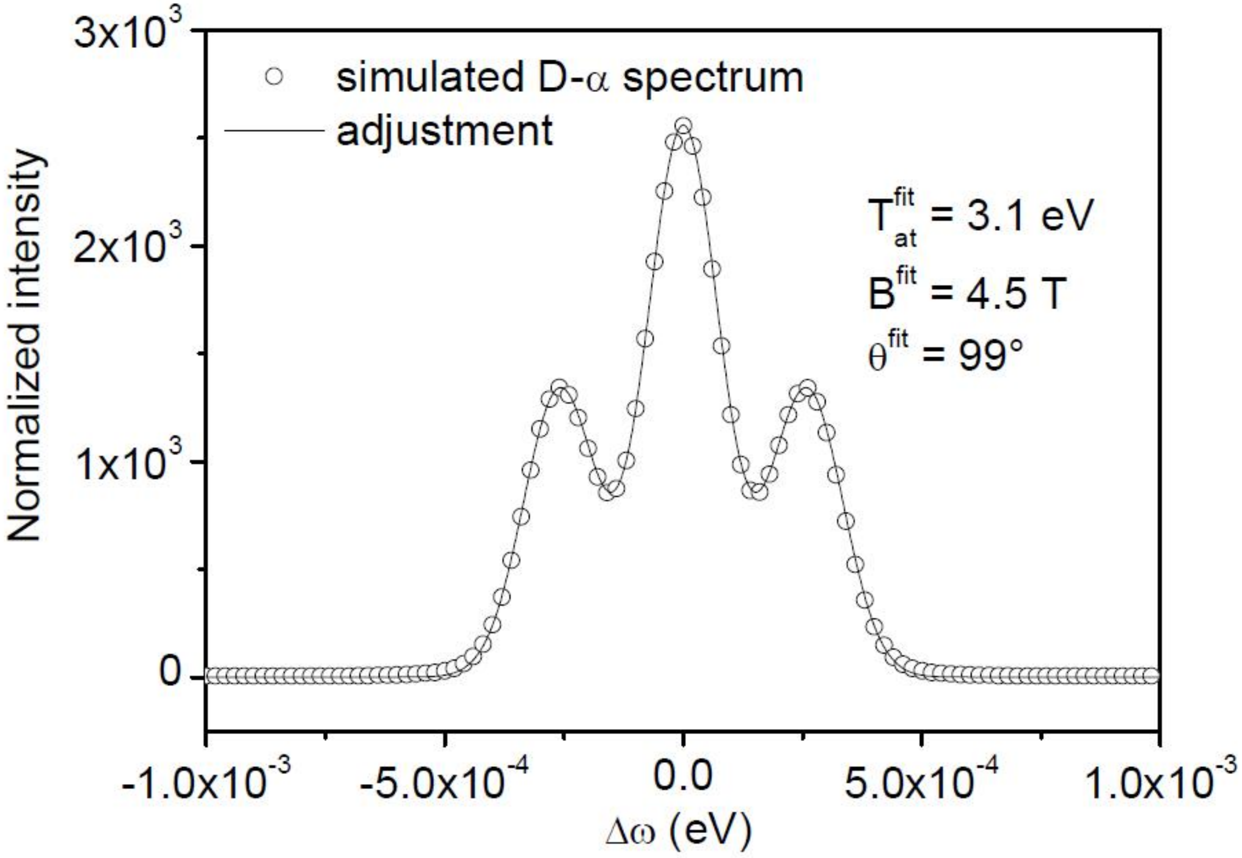
WEST tokamak (France)

Lines of sight





An analysis of Dα observed in a simulated tokamak edge plasma

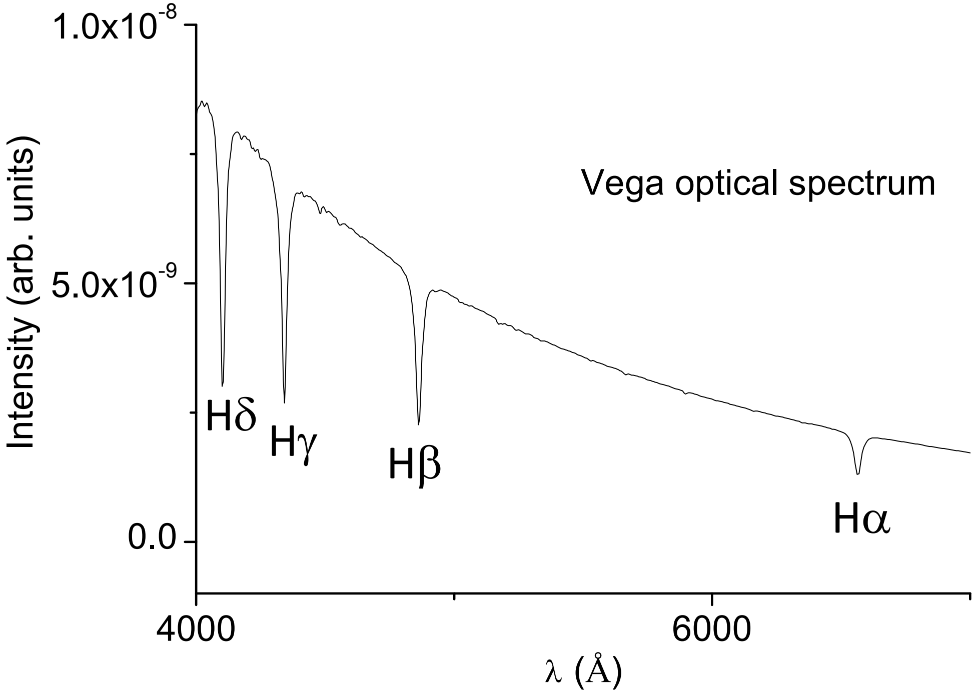


Information on the densest location has been obtained
Here, the adjustment assumes a Zeeman-Doppler model

Adapting the line shape models to stellar atmospheres

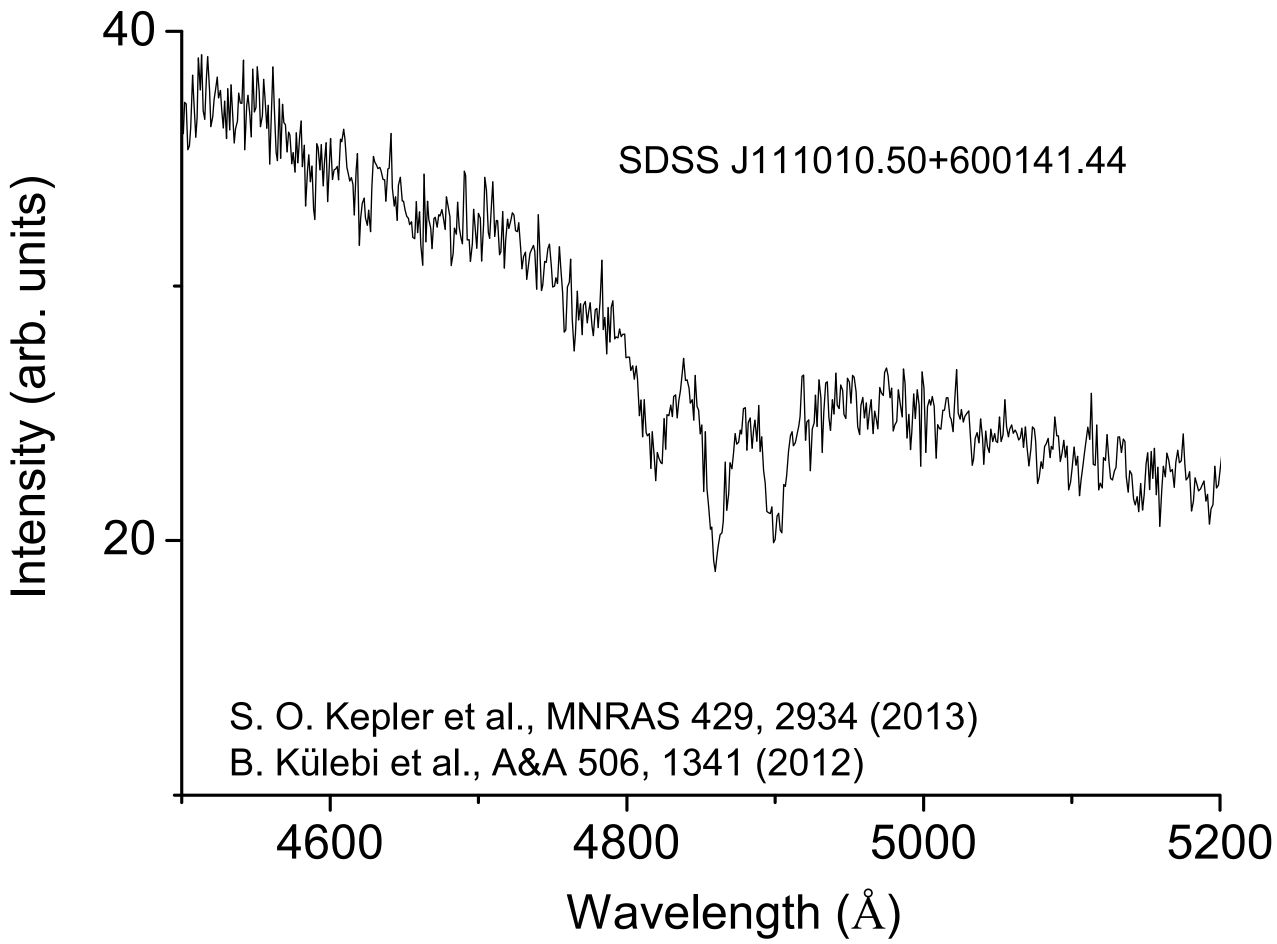
In stellar atmospheres, the temperature is low enough so that there is a significant amount of neutrals

The spectrum of A type stars presents hydrogen absorption lines which can be analyzed using the same tools as in magnetic fusion



http://vizier.u-strasbg.fr/viz-bin/VizieR

Zeeman splitting in magnetic white dwarfs
(N. Kieu et al., poster 13)

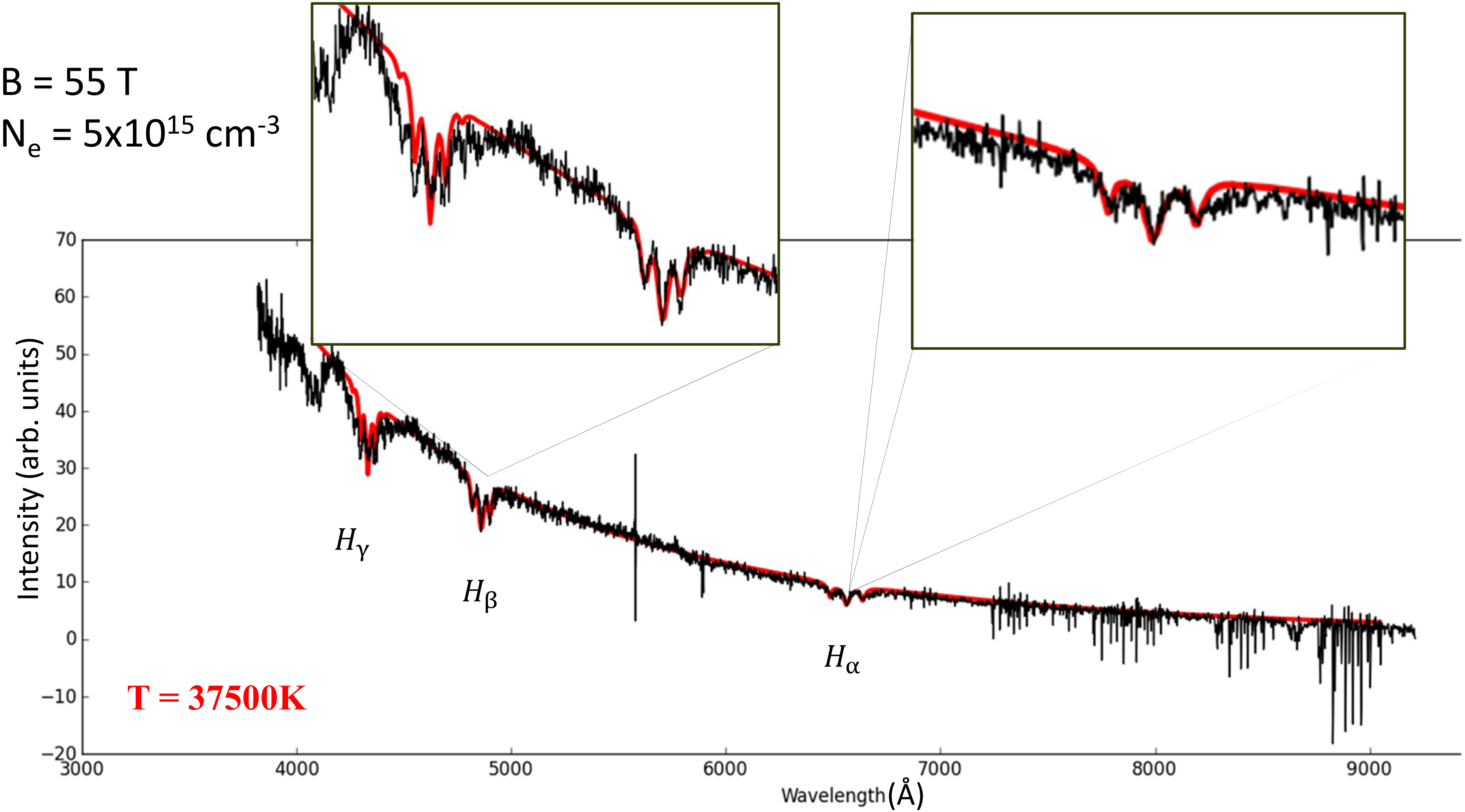


S. O. Kepler et al., MNRAS 429, 2934 (2013)
B. Külebi et al., A&A 506, 1341 (2012)

Line shape fitting

B = 55 T
$N_e = 5\text{x}10^{15}$ cm^{-3}

B = 100 T
$N_e = 5\text{x}10^{16}$ cm^{-3}



T = 37500K

Summary

1) Atomic spectroscopy can be used as a diagnostic
for tokamak edge and divertor plasmas
Models involve both atomic and plasma physics

2) A problem inherent to hydrogen line shape modeling concerns the description of Stark broadening

3) Models can be applied both to magnetic fusion and astrophysics