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ENEA
Agenzia nazionale per le nuove tecnologie,
l'energia e lo sviluppo economico sostenibile

Plasma Diagnostics:

Spectroscopy

Onofrio Tudisco

Ricercatore ENEA

May 2020

Lay-out

- Part I
  - Emission spectral range
  - Spectrometers
  - Line monitoring : D_α and particle balance
  - UV spectroscopy
  - X-ray spectroscopy
- Part II
  - bremsstrahlung
  - Active diagnostic : CXS
  - Active diagnostic : MSE
  - X ray tomography
  - Laser induced florescence

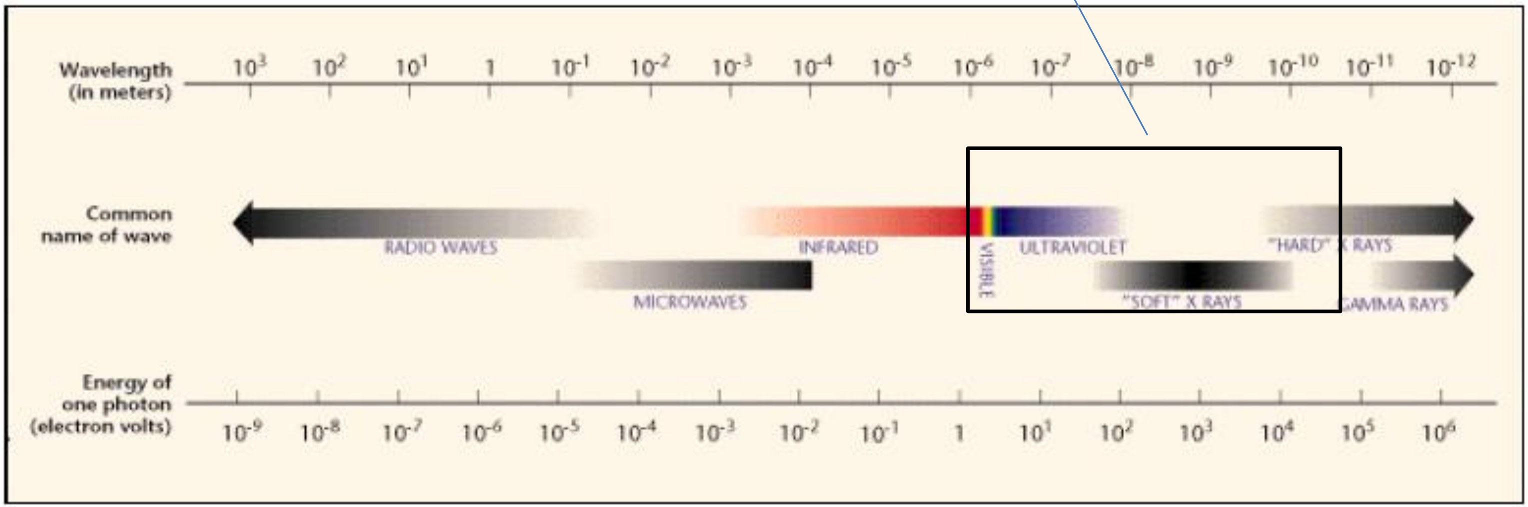
Tokamak spectroscopy

- For “spectroscopy” is intended those diagnostics that measure the line emission of partially ionized ions.
- It can provide relevant information on
  - Amount of impurity present in the plasma
  - Plasma velocity
  - Plasma temperature
- Other spectroscopy are used in plasma physics as :
  - Far infrared spectroscopy
  - RF spectroscopy
  - γ- spectroscopy
  - Neutron spectroscopy

but are referred with different name.

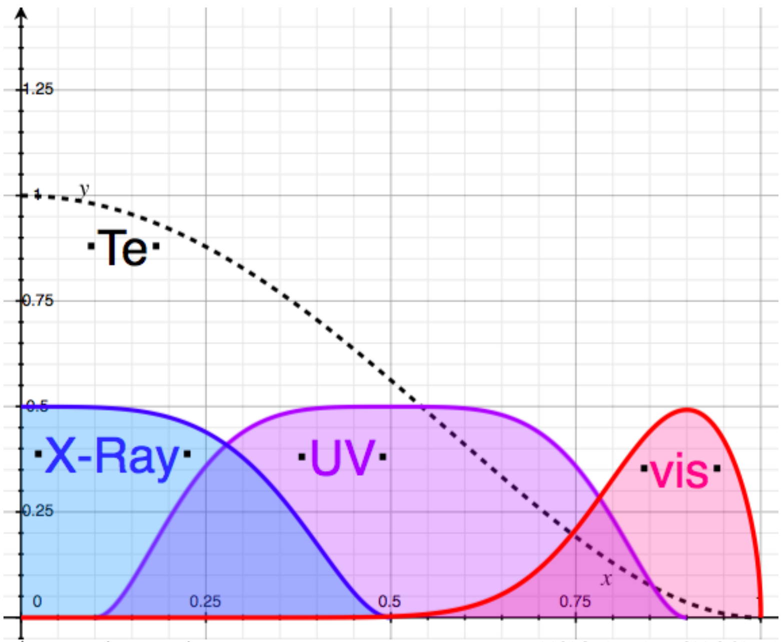
Spectral range

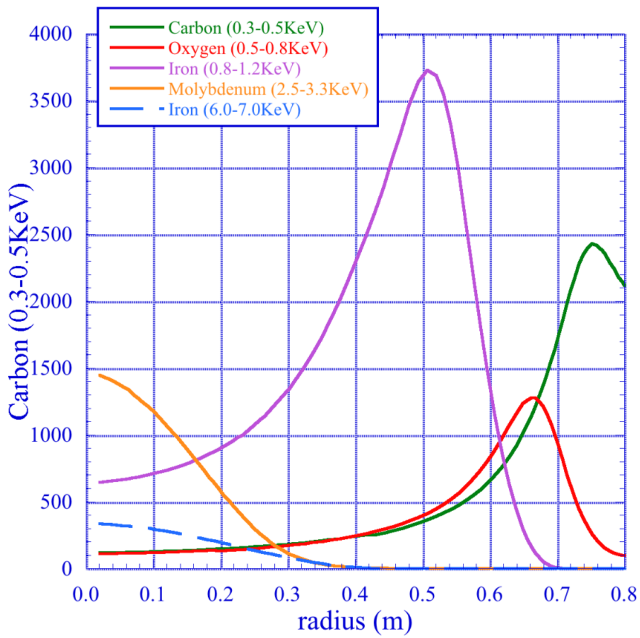
Impurity emission range in tokamak



Radiation Regions

- T_e in tokamaks varies from few eV to keV
- Both line and continuum radiation are emitted over a large range of frequency
- Visible light is emitted at edge, UV at half radius, and soft X-ray in plasma core.





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Information from spectral line

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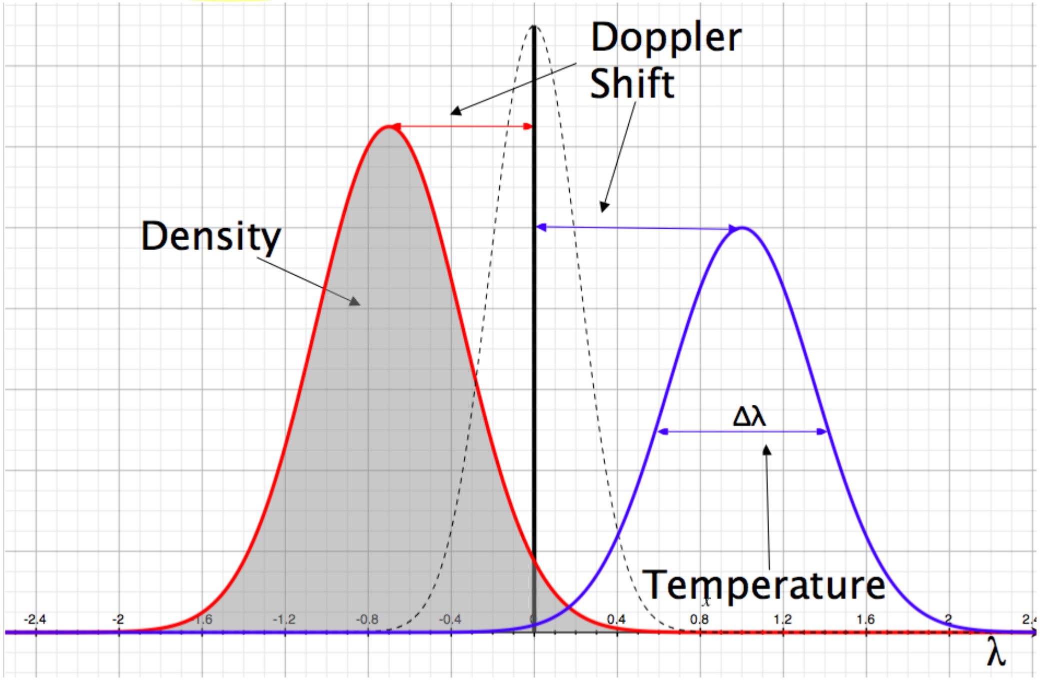
From line emission we can get :

- Density of impurity (area below the line)
- Temperature (line width)
- Average velocity along the line sight (Doppler Shift)



Spectra measurements

- Different kind of spectrometers are employed in plasma diagnostic: it depends on spectral range, resolution and measurements scope.
  - Grating spectrometer in visible range
  - Interferential filters (visible/NIR)
  - UV spectrometer
  - Soft X ray spectrometer

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Plasma image in visible light

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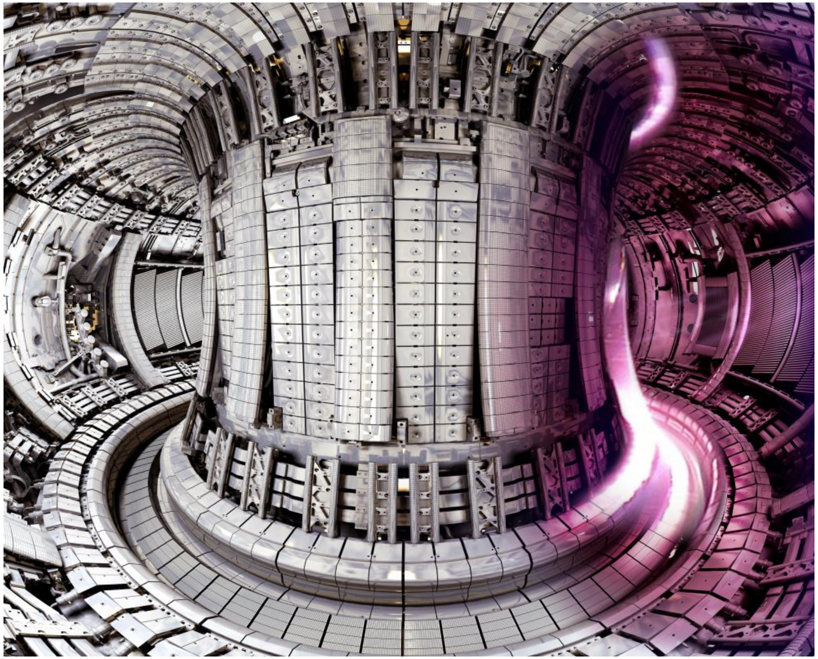
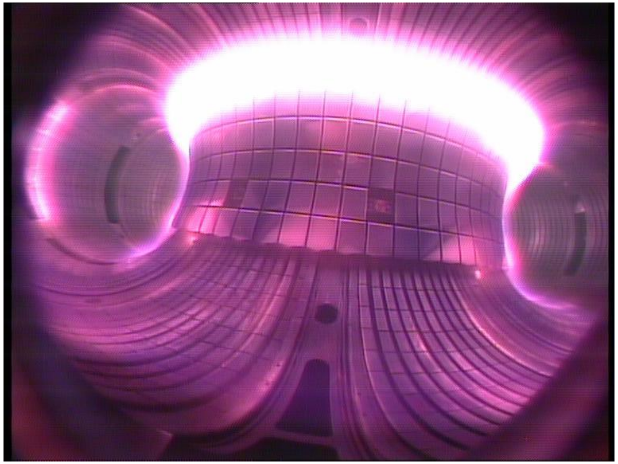
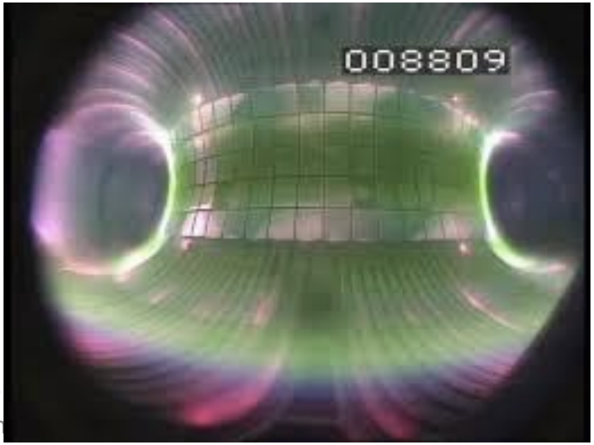
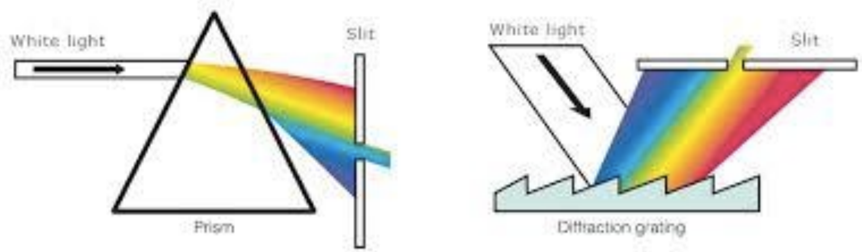




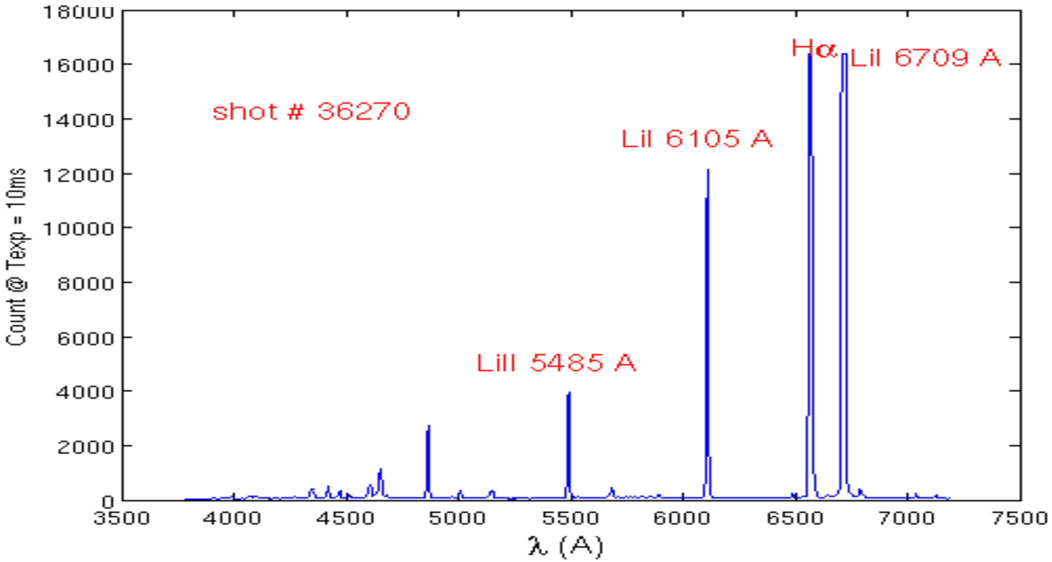


Example of spectrum in visible range

Sketch of Spectrometer layout

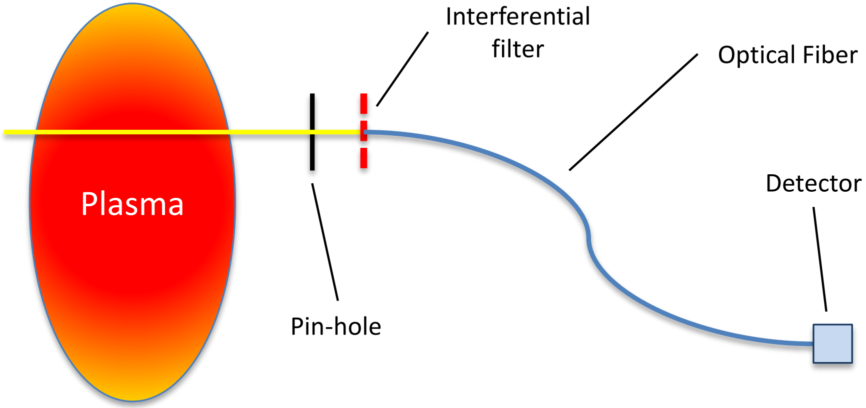


Visible spectrum in FTU



Line monitoring

- Using interferential filters it is possible monitoring the evolution of a thin slice of spectrum.
  - examples: D_α, Li, bremsstrahlung,



D_α Diagnostic Layout

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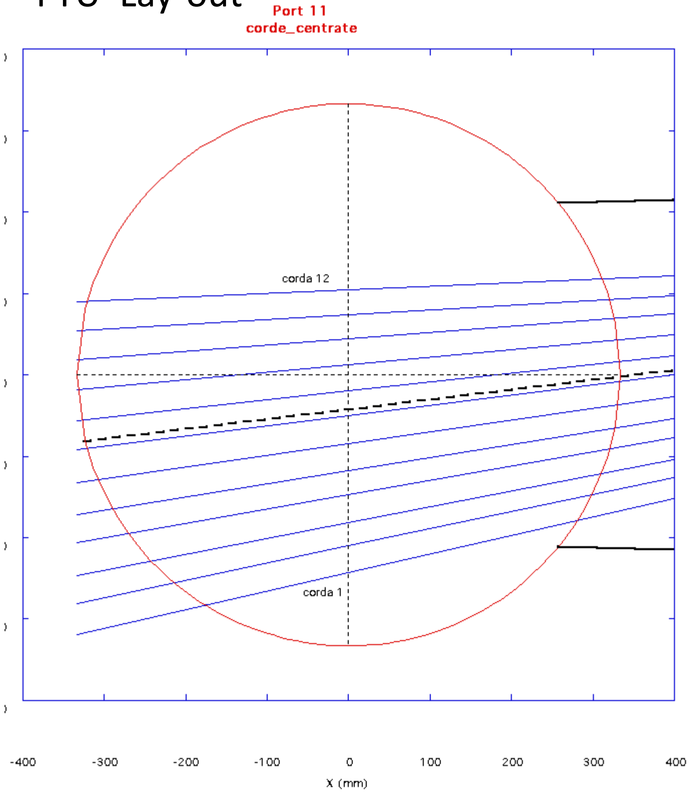
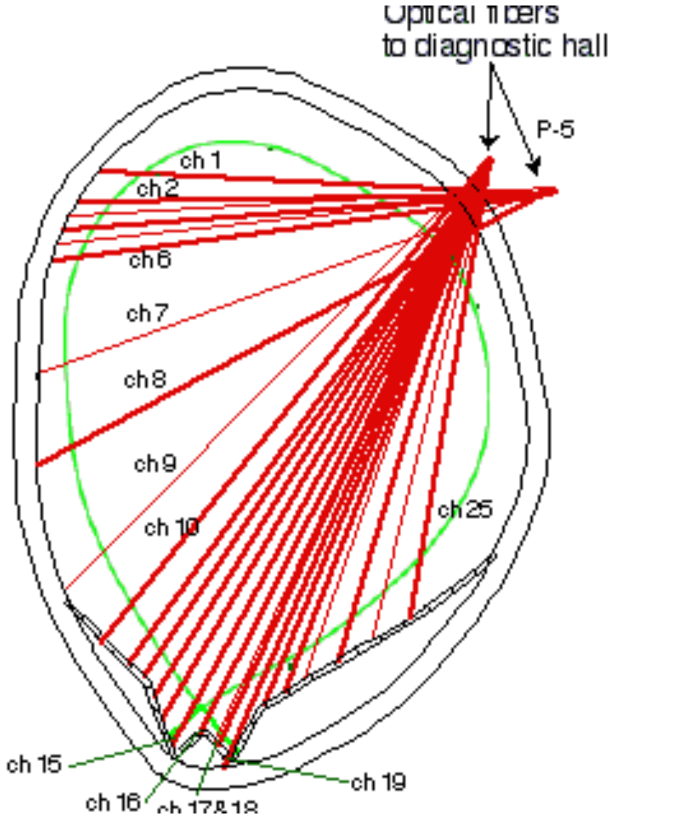
FTU Lay-out

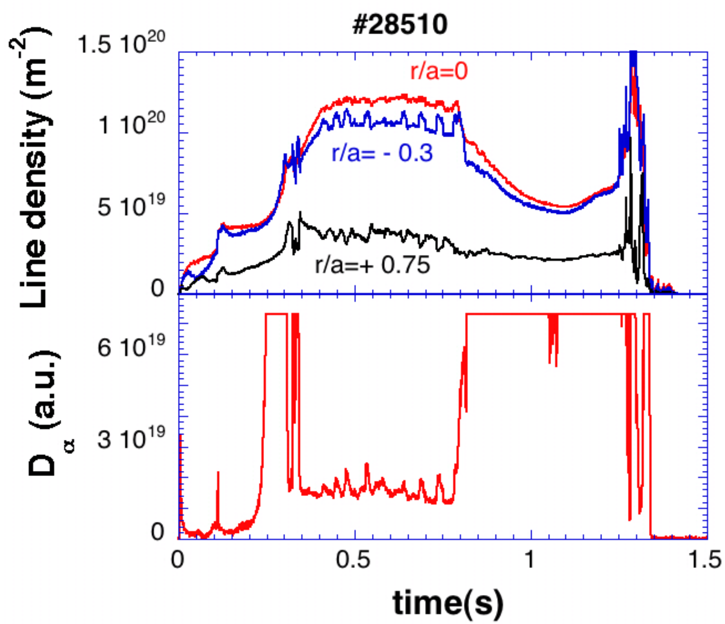


JT60 Lay-out

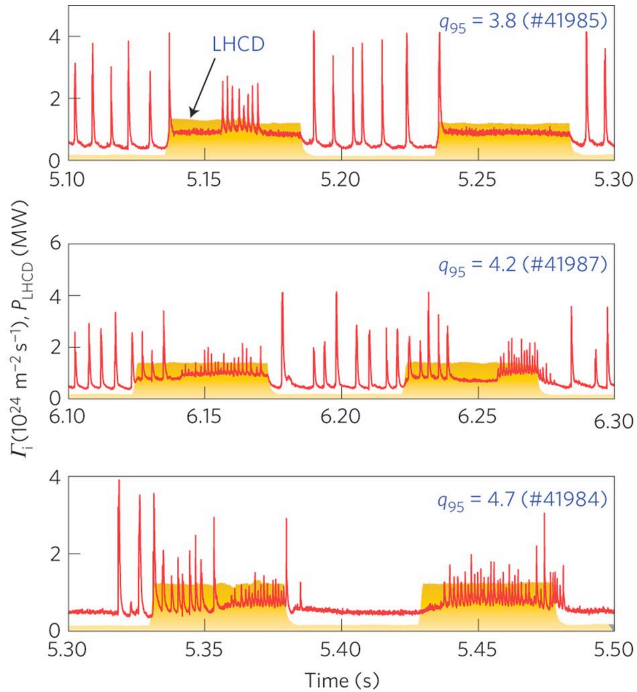


D_α monitor

D_α is used as a monitor for fast edge phenomena as MARFE and ELMS



D_α emission during MARFE in FTU



ELM control study at EAST tokamak

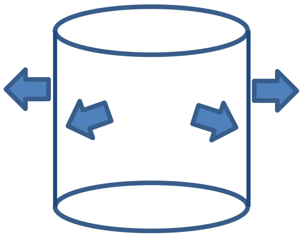
Particle Balance from D_α

From D_α it is possible to obtain the flux of neutral particle entering the plasma and the particle confinement time.

Consider a plasma cylinder of radius a. Ion balance eq., in steady state condition, is

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\Gamma_i\right) = n_O n_e S_O - n_i n_e \alpha$$

$$a\Gamma_i = \int_o^a n_O n_e S_O r\, dr$$



Neglecting recombination, and integrating over the plasma radius:

D_α emission along a line is give by:

$$I_\alpha = \int_{-a}^{a} n_O n_e X B\, dr$$

neutral density is appreciable only at edge and So/XB is only weakly dependent on temperature and density

Γ : particle flux
n_o : neutral particle density
n_e : electron density
n_i : ion density
S_o : ionization rate
α : recombination rate
X : D_α excitation rate
B : D_α branching ratio for de-excitation
I_α : D_α mission

Particle Balance from D_α

we can rewrite the integral

$$\int_o^a n_O n_e S_O r\,dr \cup a\frac{S_o}{XB}\int_o^a n_O n_e XB\,dr = \frac{1}{2}a\frac{S_o}{XB}I_\alpha$$

Hence the particle flux can be obtained as:

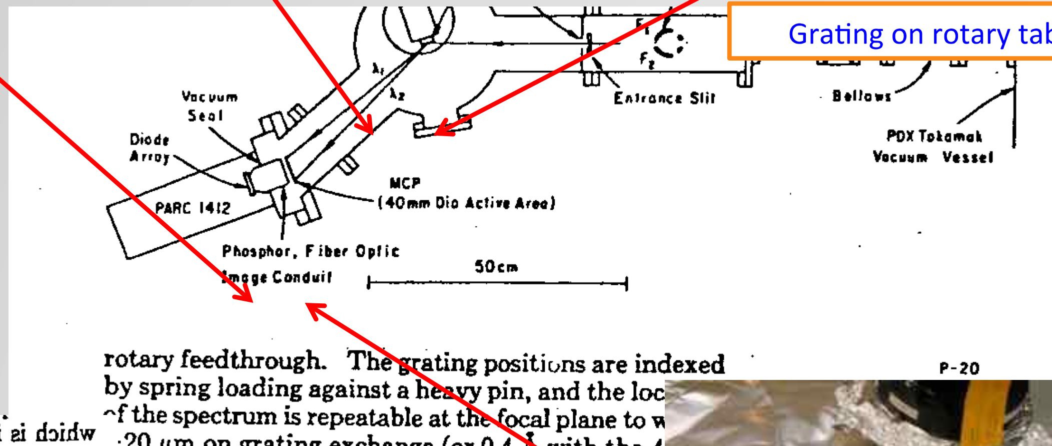
$$\Gamma_i = \frac{1}{a}\int_o^a n_o n_e S_o r\;\; dr \sim \frac{S_o}{XB}\int_o^a n_o n_e XB\;\; dr \;=\; \frac{1}{2}\,\frac{S_o}{XB} I_\alpha$$

Γ : particle flux
n_o : neutral particle density
n_e : electron density
n_i : ion density
S_o : ionization rate
α : recombination rate
X : Dα excitation rate
B : Dα branching ratio for de-excitation

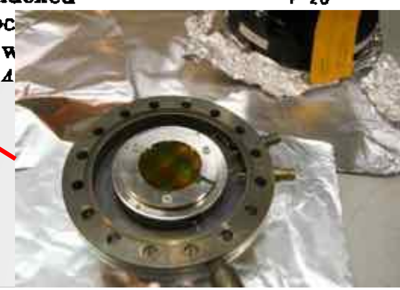
UV Spectrometer FTU

FTU UV spectrometer

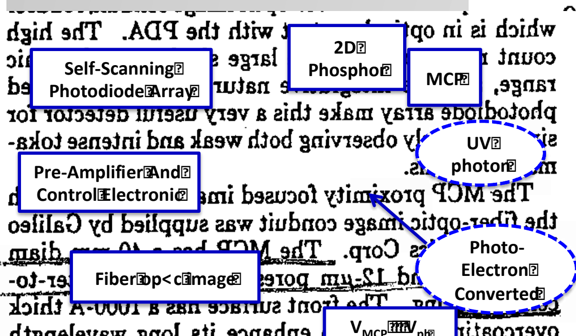
Photodiode array



Grating on rotary table



MCP



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UV spectra

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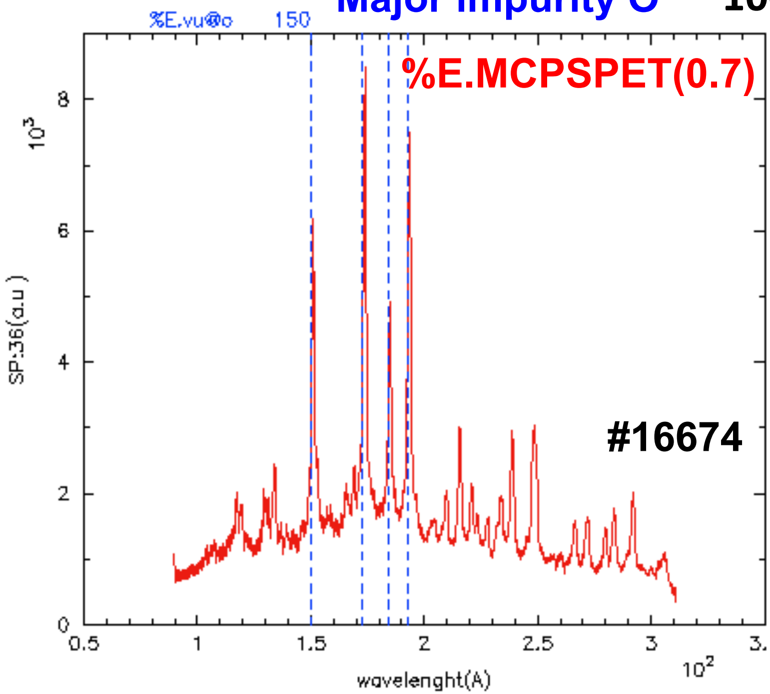
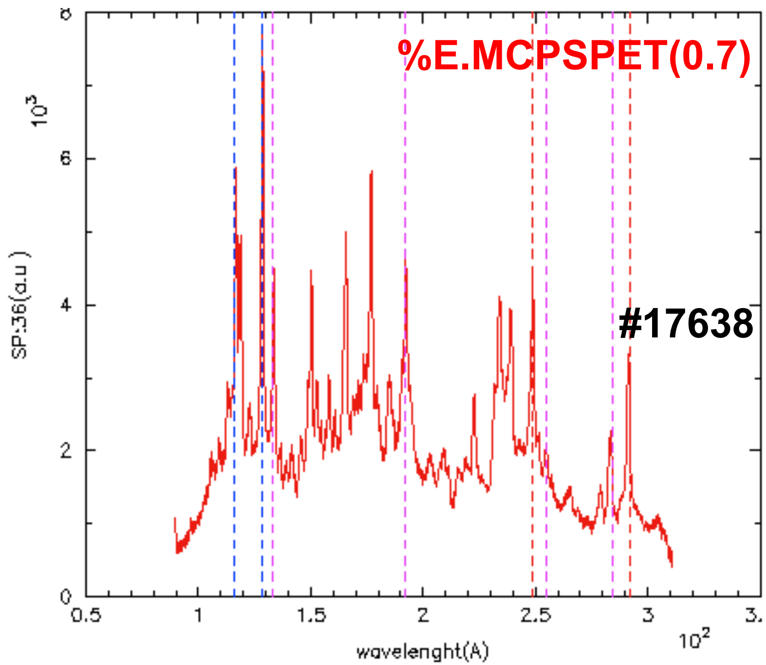
Major impurity O **100 – 300 Å** **Metal impurity plasma**

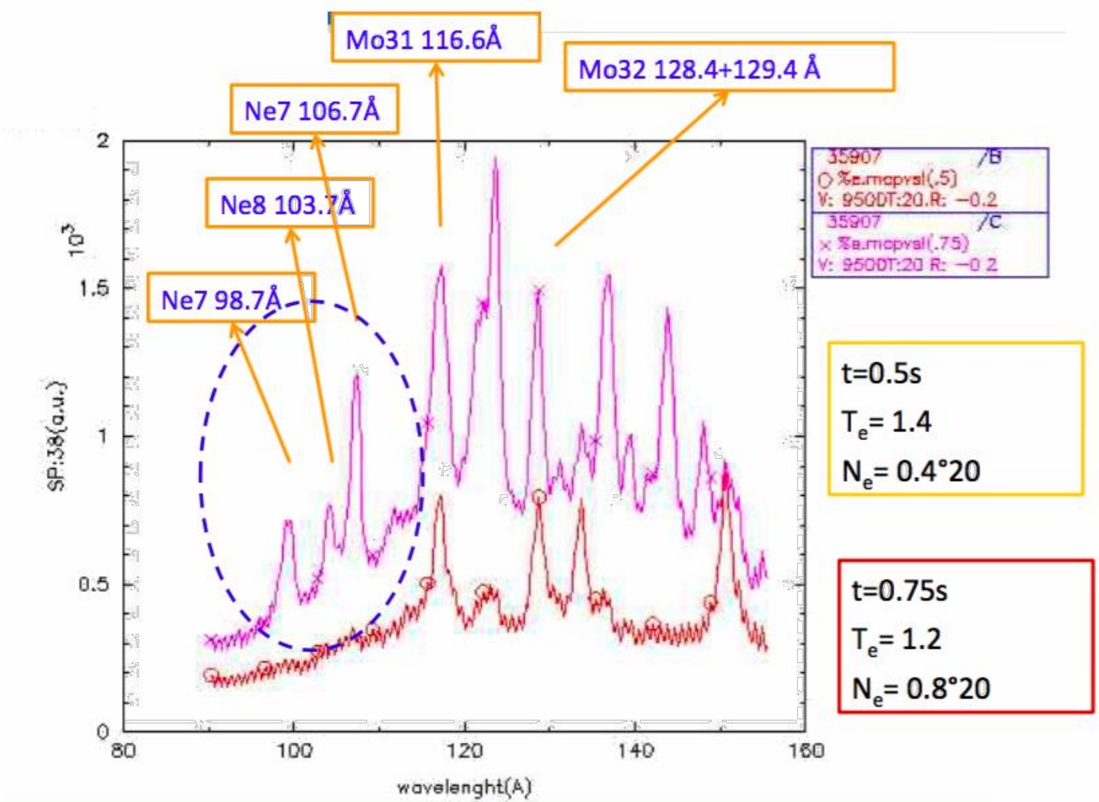




O VI ---> 150.08 Å
O VI ---> 173.084 Å
O VI ---> 184.05 Å

Mo XXXI ---> 116 Å
Mo XXXII ---> 128 Å
Ni XVII ---> 249 Å
Ni XVIII ---> 292 Å
Fe XXXIII --->133 Å

UV spectrum: Ne injection



Impurity transport

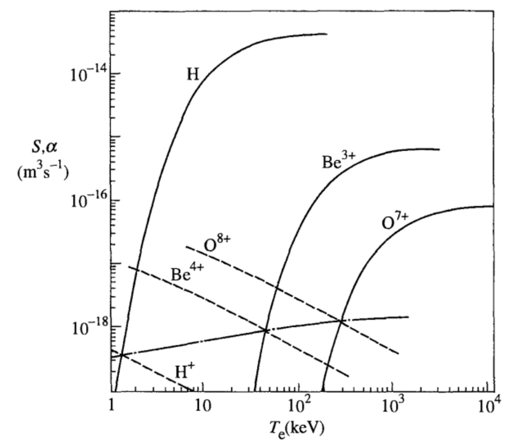
For each impurity species and ionization state we can write an equation for its diffusion in

$$\frac{\partial n_{Z_j}}{\partial t}+\frac{1}{r}\frac{\partial}{\partial r}\left(r\Gamma_{Z_j}\right)=-n_{Z_j}n_eS_{Z_j}+n_{Z_{j-1}}n_eS_{Z_{j-1}}+n_{Z_{j+1}}n_e\alpha_{Z_{j+1}}-n_{Z_j}n_e\alpha_{Z_j} \qquad j=0 \rightarrow Z$$

where S and α are the ionization and recombination rate, while:

$$\Gamma_Z=-D\frac{\partial n_Z}{\partial r}-Vn_Z$$

These are a set of Z coupled differential equations



Impurity transport

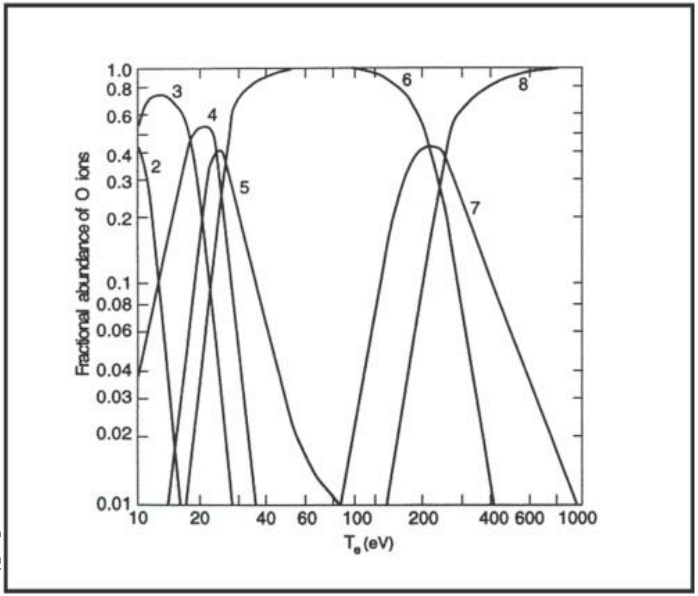
Solving this equations for all states is usually very complex, so that a series of assumptions are made:

Steady state $\left(d/dt = \partial/\partial t + \nabla \cdot = 0 \right)$

Neglect higher ionization state (Coronal equilibrium)

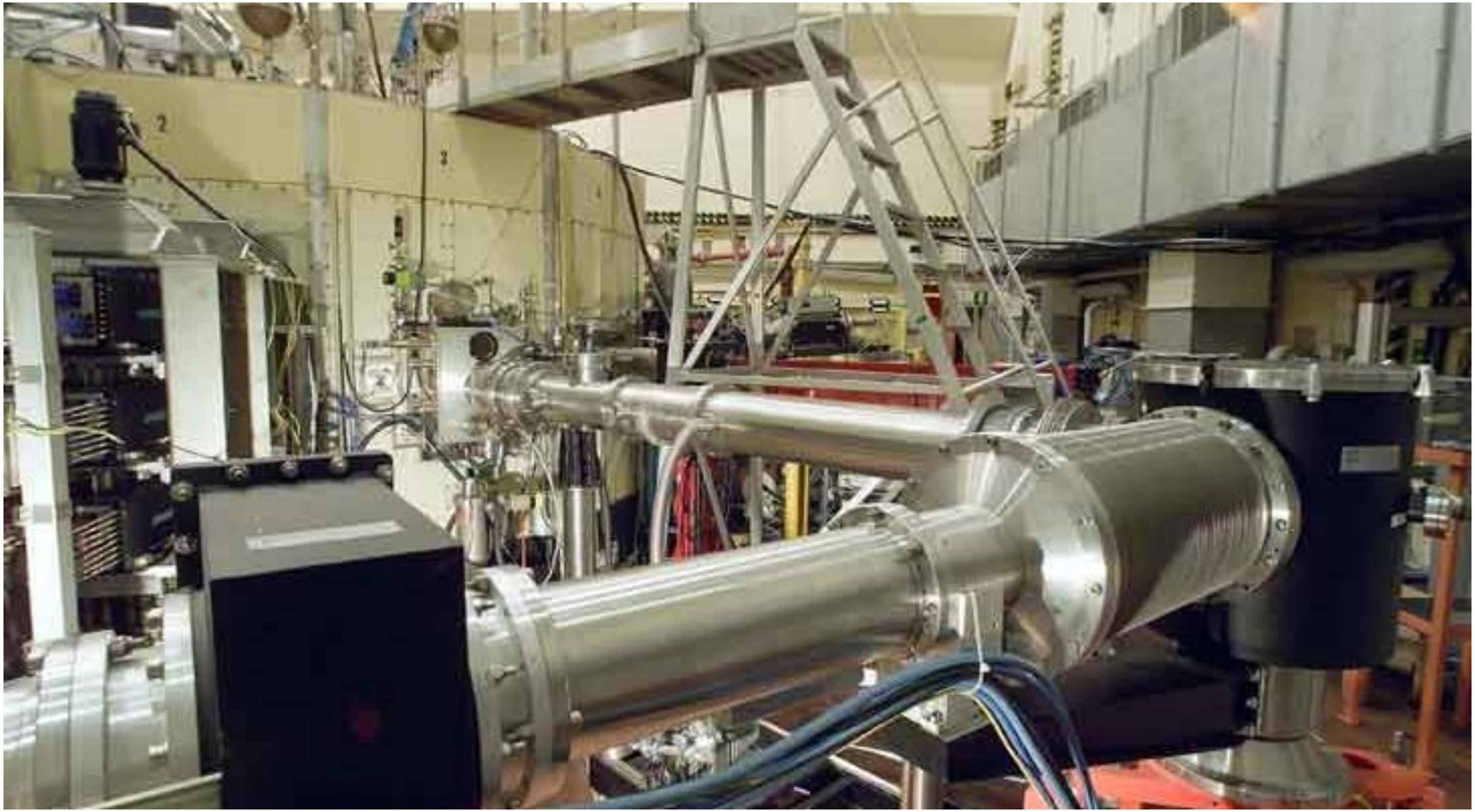
$$0 = n_{Z_{j-1}} n_e S_{Z_{j-1}} - n_{Z_j} n_e \alpha_{Z_j}$$

$$\frac{n_{Z_{j-1}}}{n_{Z_j}} = \frac{\alpha_{Z_j}}{S_{Z_{j-1}}}$$



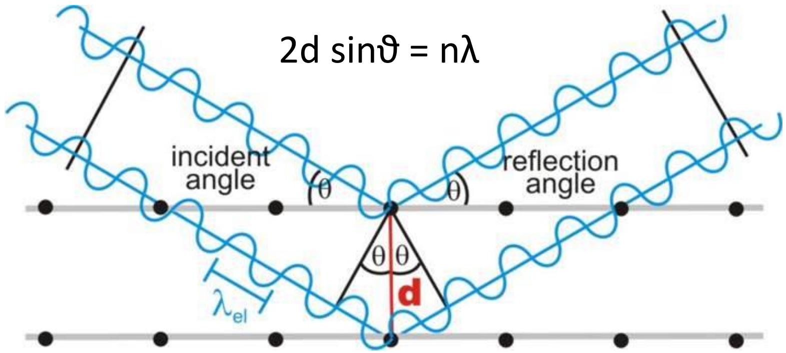
X-Ray spectrometer

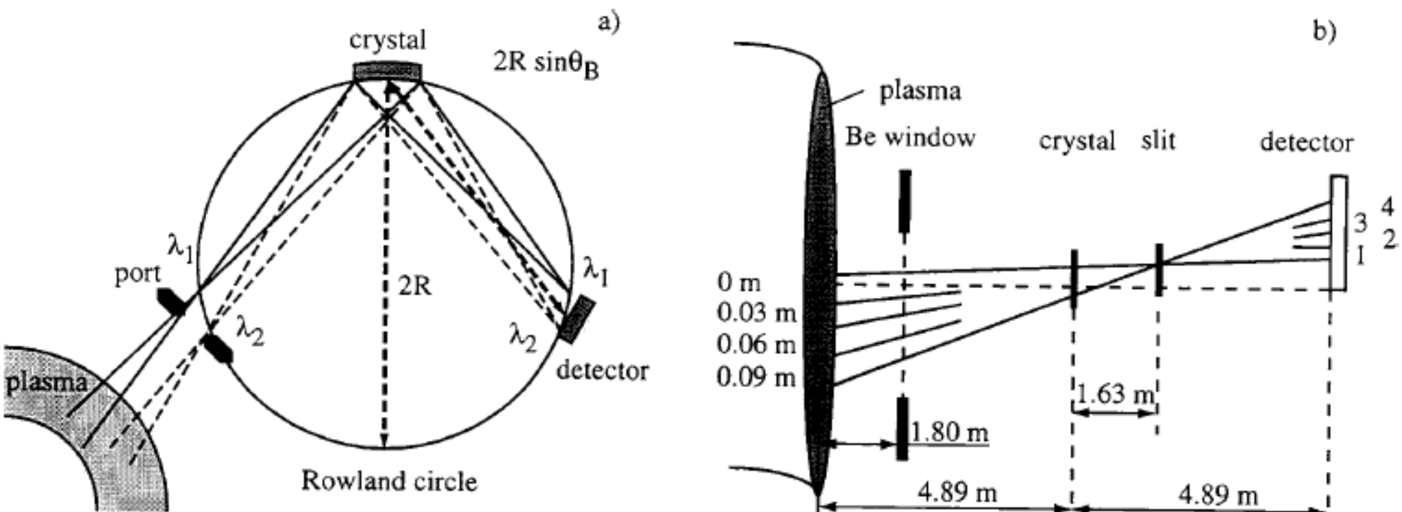
FTU SXR high resolution spectrometer (not installed anymore)



X-Ray bent crystal

Bragg diffraction





X-Ray spectroscopy

SXR high resolution spectrum in Alcator C. Spectrum fitted with T=1.2 keV

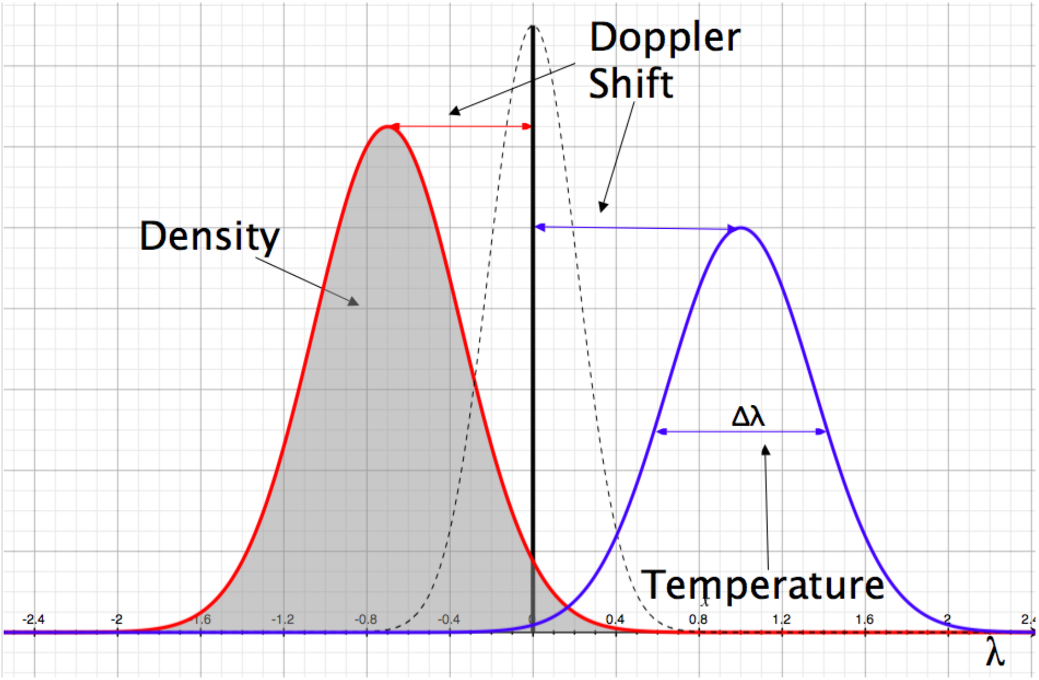
broadening.

ity of 3.7 Å (= 0.37 nm) wavelength, a
e lines are visible: two are from the L
argon A^{17+} and a third is from moly
ominantly excited in the center of thi
ybdenum line is noticeably narrower
e slowly owing to its greater mass. T
the line widths are consistent (~1200
rtainty.
nother possibility for Doppler broad

Information from spectral line

From line emission we can get :

- Density of impurity (area below the line)
- Temperature (line width)
- Average velocity along the line sight (Doppler Shift)



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Rotation from Doppler shift

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Plasma rotation speed from High resolution SXR spectroscopy on PLT during NBI injection

Fig. 6.10. Measurements of plasma flow velocity using
from different impurity species. The injection of energ
this tokamak plasma to rotate toroidally. Prior to inje
to measure [after Suckewer *et al.* (1979)].

nerally speaking, the presence of broadening
on will set a lower limit to the detectable line shi
iermal Doppler width, the fraction depending o
enter of the broadened line can be determined
ise levels (see Exercise 6.13).

cause the thermal velocity is inversely propo
of the mass of the species, heavier ions will ger
of line width to line shift (assuming their mea