



PIIM



**Preliminary Study on
a Resonance-Fluorescence Experiment
using the New Generation XUV Monochromatic Sources
for Hot and Dense Plasma Spectroscopy**

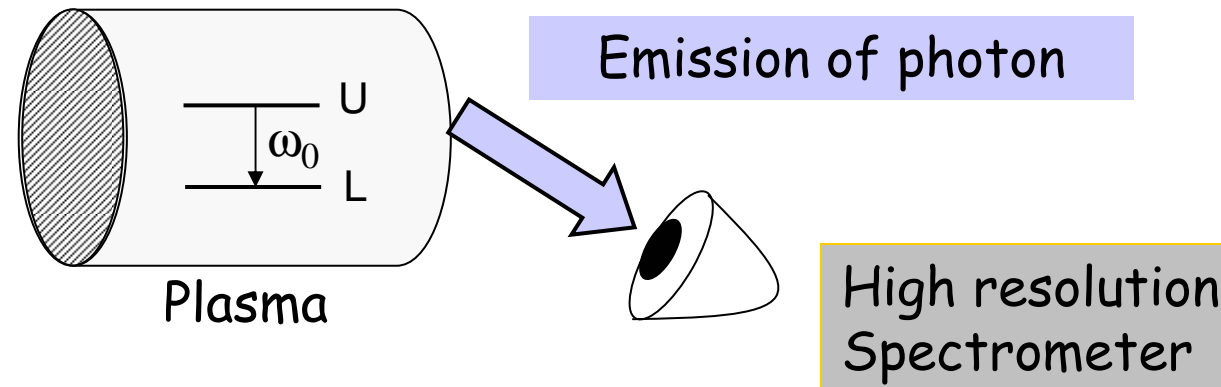
Caroline Mossé-Sabonnadiere

S. Ferri, A. Calisti, B. Talin

Laboratoire Physique des Interactions Ioniques et Moléculaires
UMR 6633 CNRS Université de Provence, Marseille, France

High resolution spectroscopy

Passive spectroscopy



Measure of the plasma emissivity:

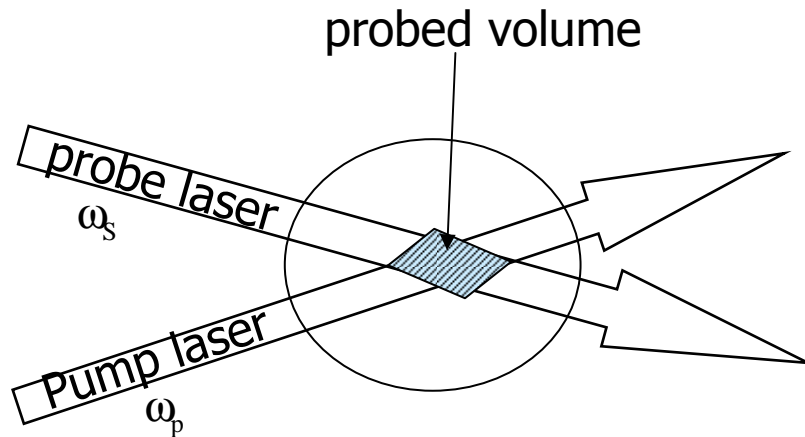
⇒ Spontaneous emission

Spectral line intensity : $I(\omega) = N_U A_{UL} \hbar \omega_0 \Phi(\omega)$

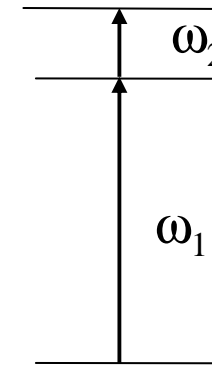
Line shape (FFM)

effect of the plasma environment on the emitter

The XUV sources should be employed in active spectroscopy experiments



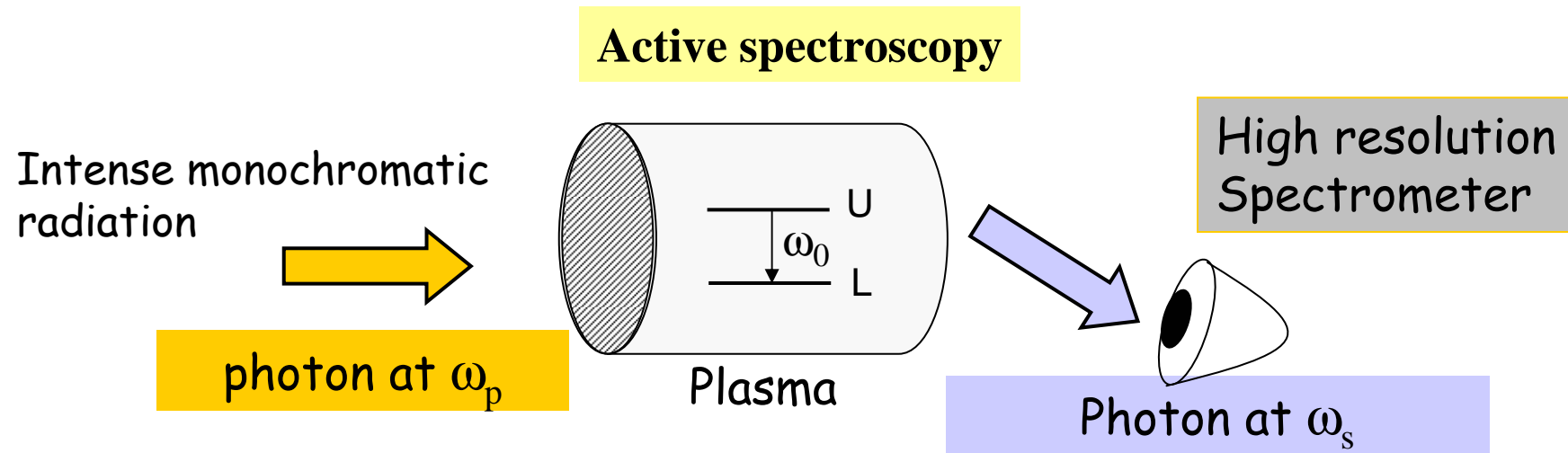
pump-probe experiment



two-photon spectroscopy

With the development of the XUV monochromatic sources,
is it possible to extend methods
of **Active Spectroscopy** to **hot dense plasmas** ?

Schematic Resonance - Fluorescence experiment



Measure of the plasma emissivity:

⇒ Scattering process

$$I(\omega_s) = N_L B_{LU} \hbar \omega_0 \int d\omega_p R(\omega_p, \omega_s) I(\omega_p)$$

|
Frequency redistribution function

PLAN

- ❑ Description of the redistribution functions model
 - based on the one-photon line shape, the Frequency Fluctuation Model (FFM)
- ❑ Experimental projects of Resonance Fluorescence
 - Study of feasibility of a former experimental project of photopumped resonance fluorescence (LLNL)
 - Preliminary study with X-ray lasers (LASERIX)
 - Examples of calculations with XFEL :
 - Transitions of Li-like Iron $1s^2 2p - 1s^2 4p$
 - Spectrum of Al K-shell
- ❑ Conclusions

The model for calculating redistribution functions permits to study scattered processes for complex emitters

Lines in plasmas are inhomogeneous :

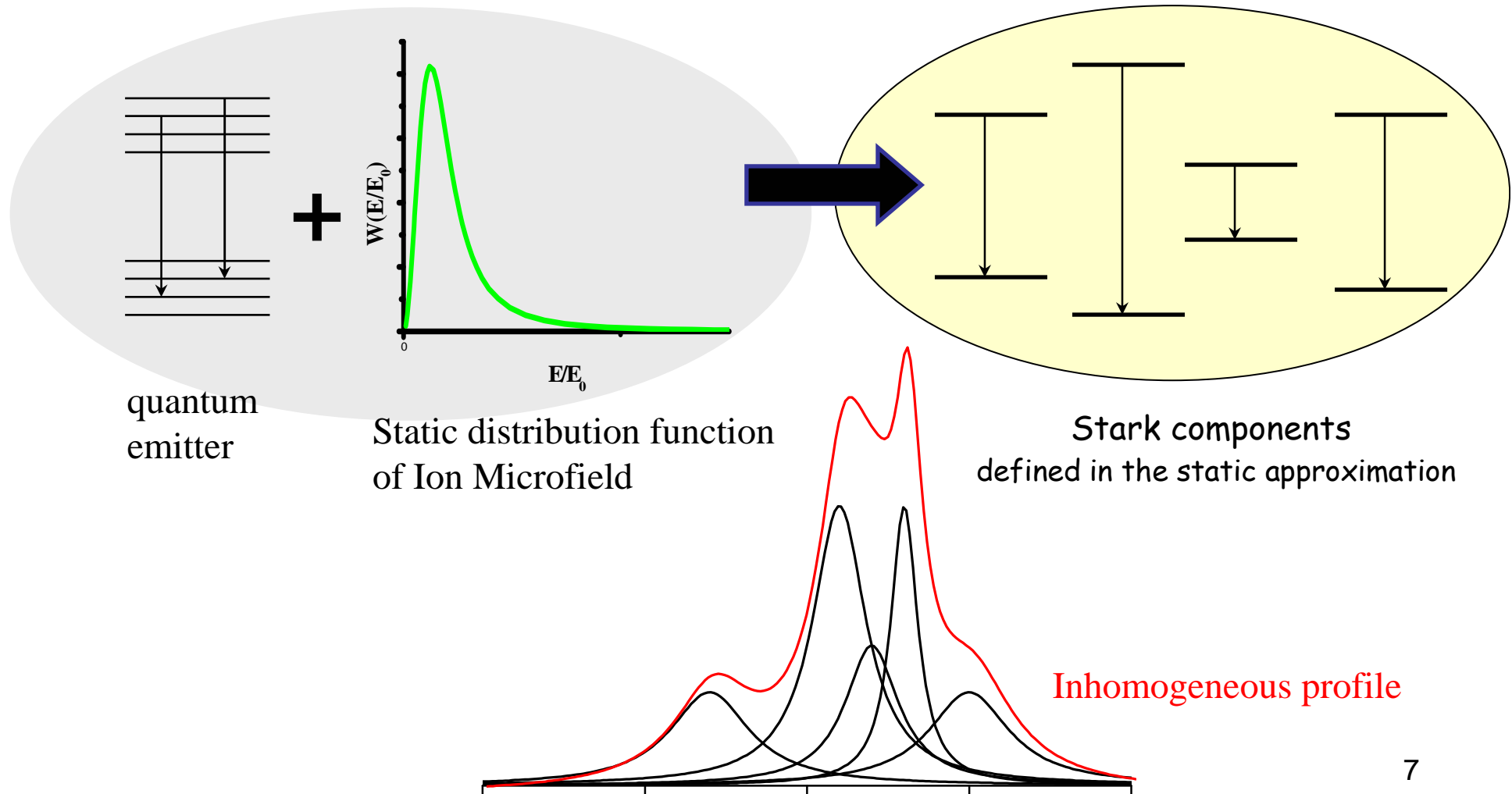
- the fine structure of multi-electron ions
- the Stark effect
- the Doppler effect

The homogeneity is altered by :

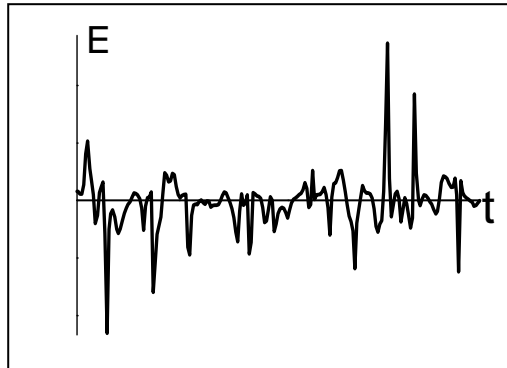
- inelastic collisions
- microfield fluctuations
- velocity changing collisions

Inhomogeneous Line shape

The plasma-emitter interaction leads to the Stark broadening of the spectral lines



Inhomogeneous to homogeneous profile due to field fluctuations

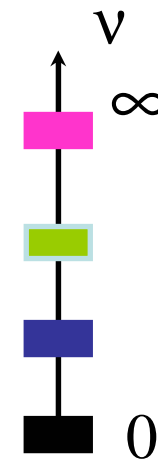
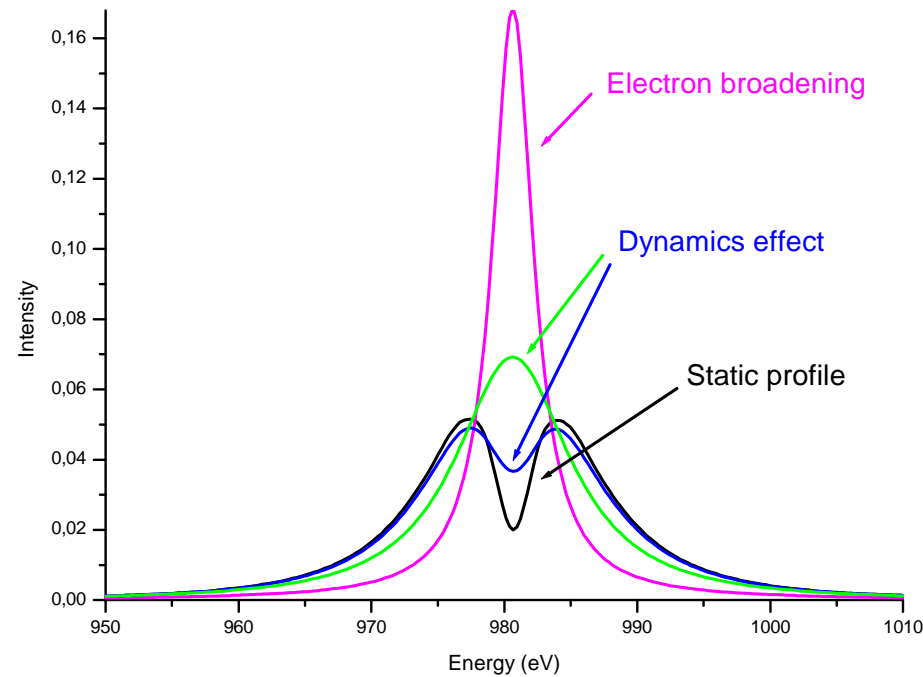
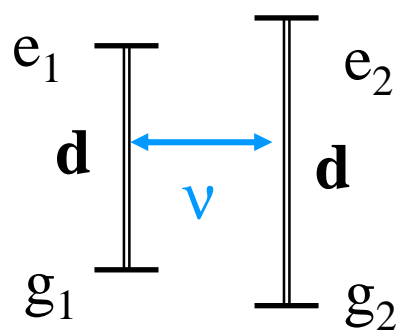


Field fluctuations alter the inhomogeneity of the profile

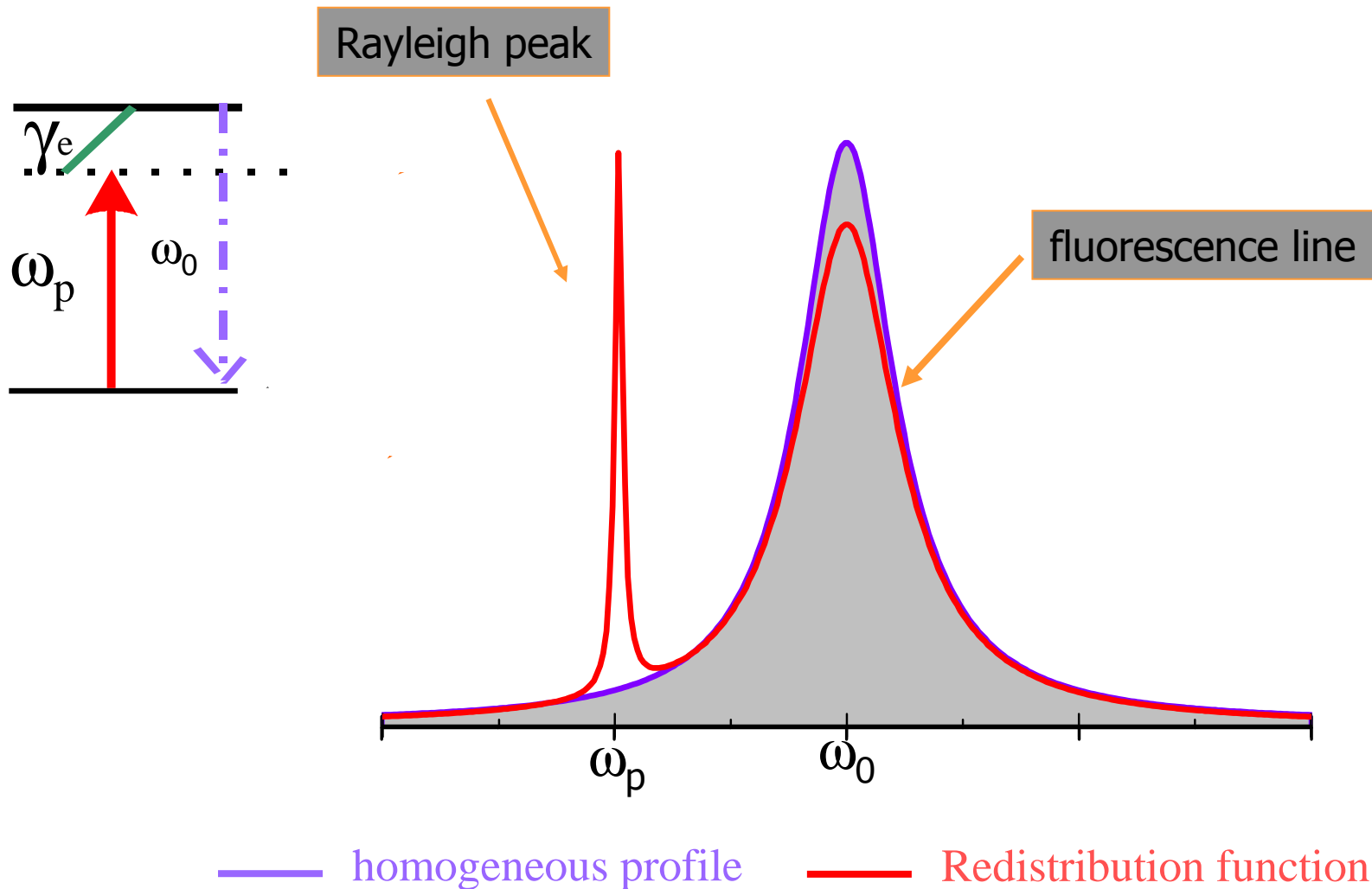
Frequency Fluctuation Model

Ion microfield fluctuation rate

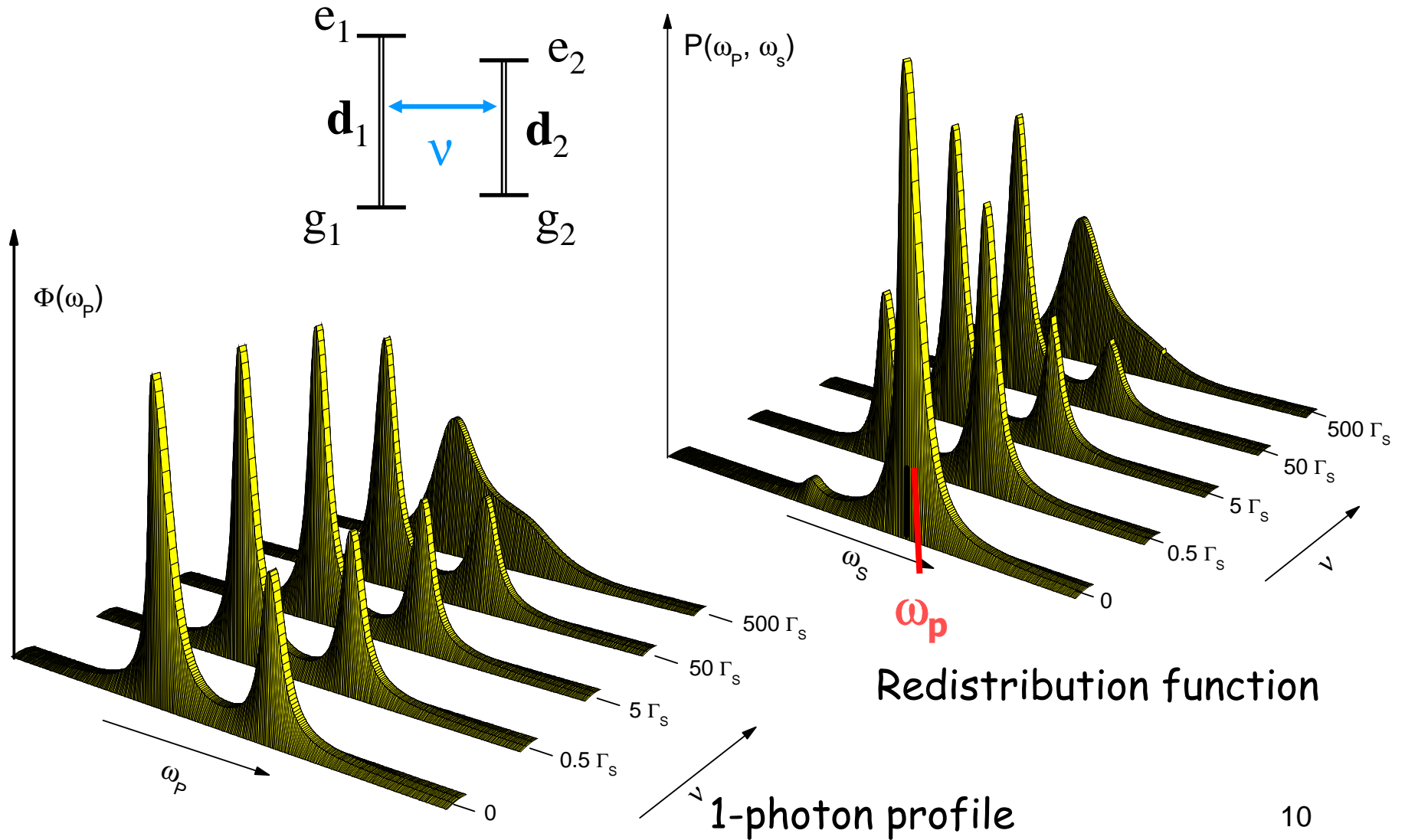
$$\nu = \frac{V}{r} \quad ; \quad \nu = (kT/m)^{1/2} \text{ and } r = (3/4\pi N)^{1/3}$$



Qualitative description of $R(\omega_p, \omega_s)$



Partial/complete redistribution



Experimental projects of Resonance Fluorescence

Active Spectroscopy in dense plasmas

The following tasks have to be resolved :

- finding a coincidence between an X-ray laser line and a resonance line of the plasma
- creating a compatible plasma to be pumped
- being able to pump significantly the plasma $\Rightarrow R_{LU}/A_{UL}$ (radiative pumping rate/spontaneous emission rate)
- modeling the emissivity accounting for the plasma complexity

Ideal experiment to study radiative redistribution

Bright, tunable, monochromatic pump: I_0, ω_p, D

- To move the population: $R_{LU} > A_{UL}$

$$\frac{R_{LU}}{A_{UL}} = 6.67 \times 10^{-22} \frac{g_U}{g_L} \lambda^5 (\text{\AA}) I_0 \left(\frac{W}{\text{cm}^2} \right) \frac{[]}{\delta_\lambda \Delta \lambda}$$

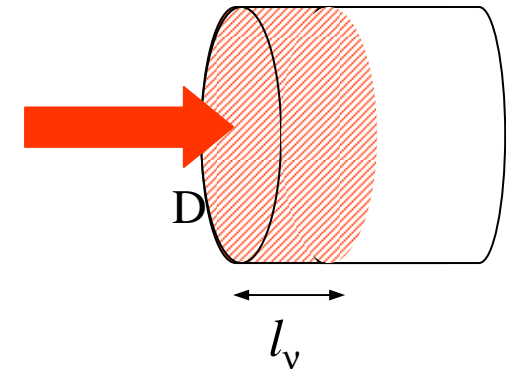
- For $I_0 = 10^{14} \text{ W.cm}^{-2}$
- And $\frac{[]}{\delta_\lambda \Delta \lambda} = 10^{-3}$

$$\frac{R_{LU}}{A_{UL}} \approx 10^{-4} \frac{g_U}{g_L} \lambda^4$$

$$\text{For } \frac{R_{LU}}{A_{UL}} \approx 1 \longrightarrow \lambda \sim 10 \text{\AA}$$

- Fluorescence yield: $Y \propto R(\omega_p, \omega_s)$

- Total number of photons emitted (in 4π sr): $P = \pi (D/2)^2 l_v N_L Y$

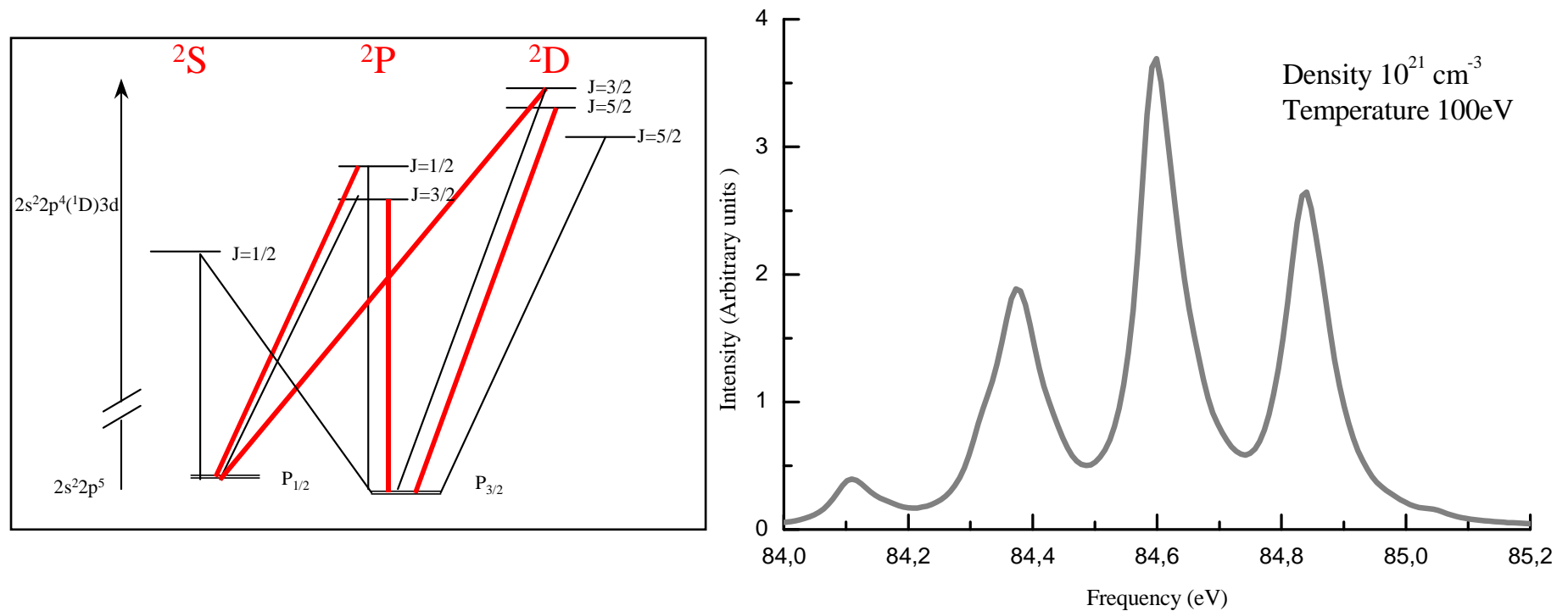


Pumped volume

Experimental project of photopumped resonance fluorescence (LLNL,1997)

Coincidence between :

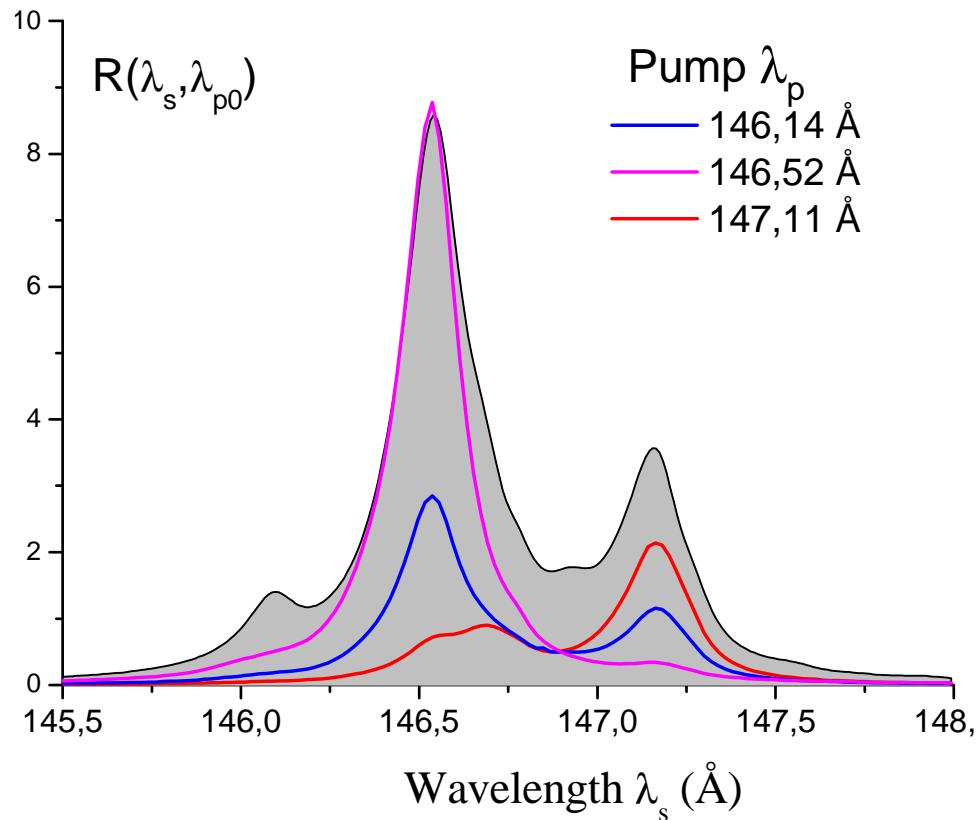
- Zirconium X-ray laser line $\lambda = 146.515 \text{ \AA}$
- 3d-2p line of magnesium F-like : $\lambda = 146.526 \text{ \AA}$



*C. Mossé, A. Calisti, R. Stamm, B. Talin, R.W. Lee, J. Koch, A. Asfaw, J. Seely, J. Wark and L. Klein
 J.Q.S.R.T. **58**, N°4-6, 803 (1997)

Experiment feasibility

Redistribution function
of $2p^43d-2p^5$ line of F-like Mg



$$N_e = 10^{21} \text{ cm}^{-3}$$

$$T_e = 100 \text{ eV}$$

Pumping efficiency R_{lu} / A_{ul}	20-80
fluorescence yield $Y \propto R(\omega_p, \omega_s)$	54%
emitted photon number $P = V N_1 Y$	5×10^{10}
density of Mg IV ground state : N_1	$3 \times 10^{20} \text{ cm}^{-3}$

➤ characteristics of Zr X-ray laser :

- $I_{\text{laser}}^0 = 9 \cdot 10^{10} \text{ W/cm}^2$

- gaussian profile of 15 mÅ width

➤ pumped volume $V = 2 \cdot 10^{-8} \text{ cm}^3$

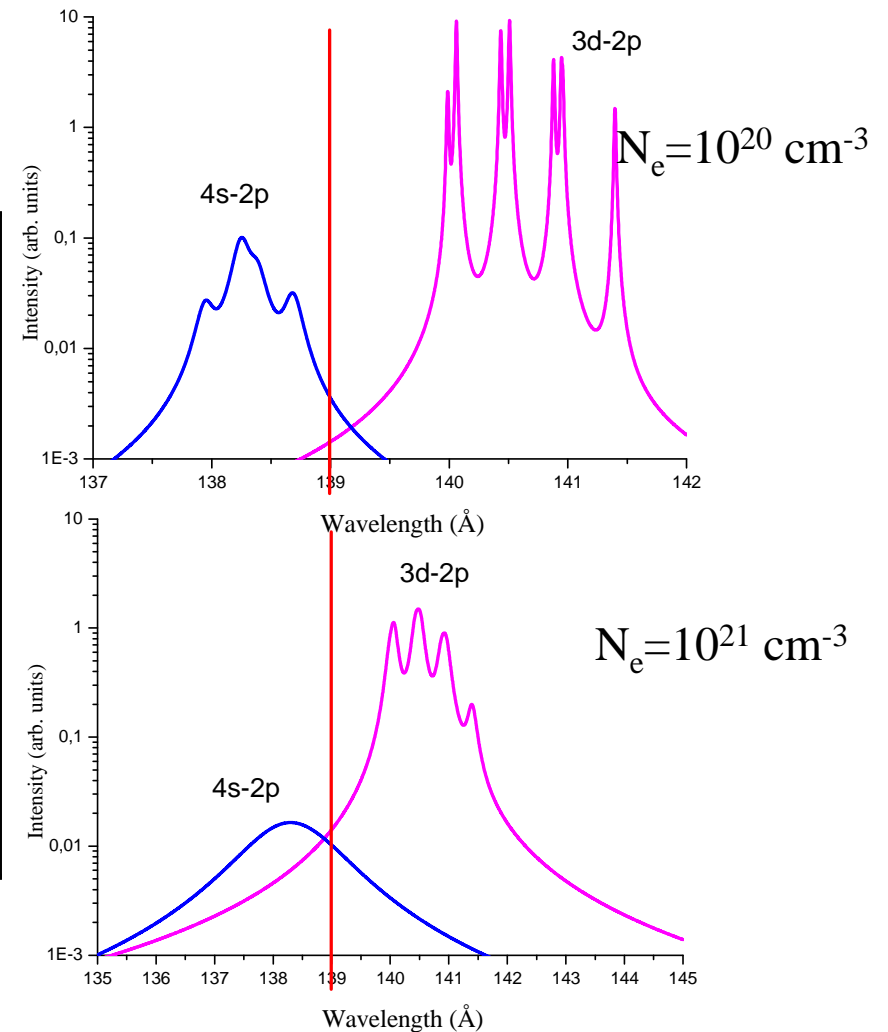
(cylinder diameter : 75 μm - length : 4 μm)

Preliminary study for an application with X-ray lasers at LASERIX

Potential resonances near 139 Å
with Ni-like Silver laser line

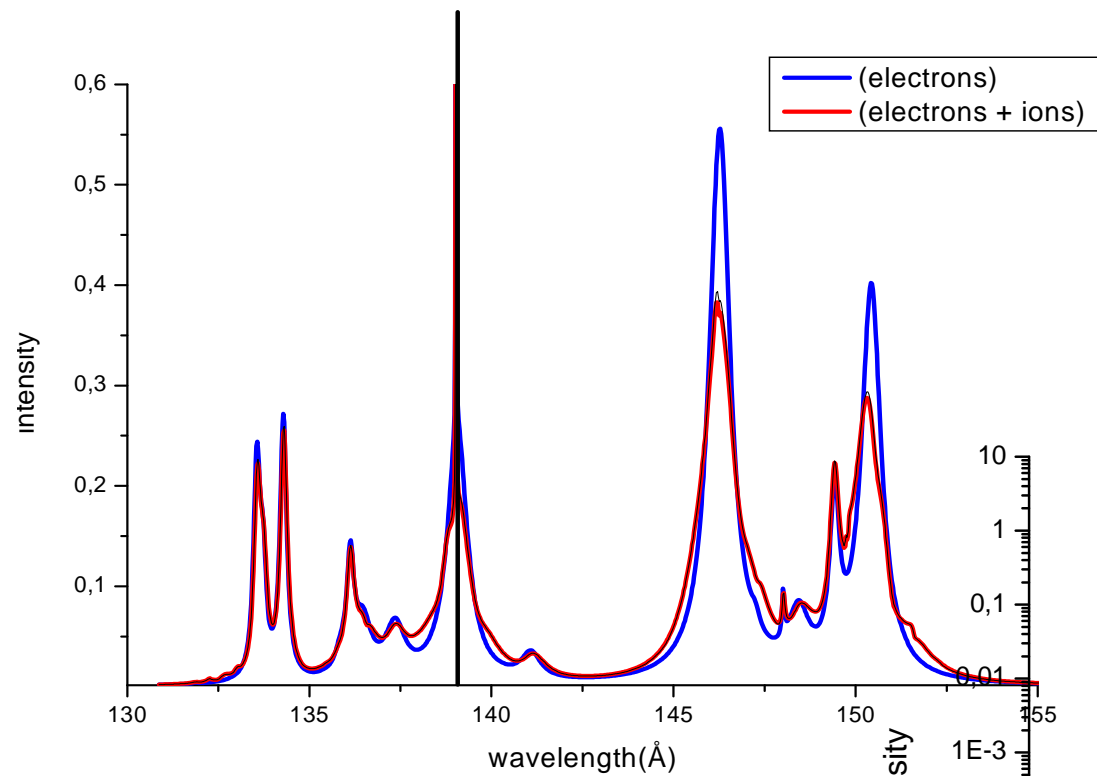
Ion	Observed Wavelength (Å)	Configurations
Mg IV	138.261 λ <math>< 139.117</math>	2s ² 2p ⁵ -2s ² 2p ⁴ 4s
Mg IV	139.989 λ <math>< 140.964</math>	2s ² 2p ⁵ -2s ² 2p ⁴ 3d
O V	139.029	1s ² 2s ² -1s ² 2p3d

Data from NIST Atomic Spectra Database Lines Data



Lines shapes of Mg IV

Line shape of OV $\sim 139 \text{ \AA}$

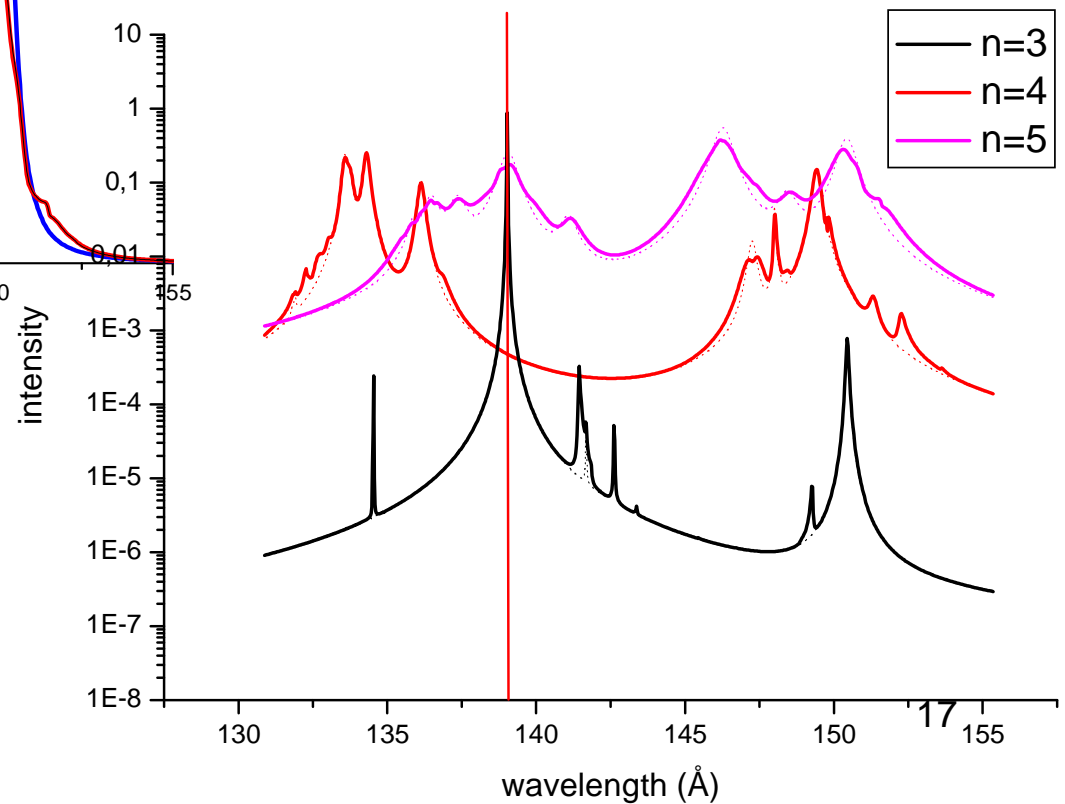


$1s^2 2s^2 - 1s^2 2p 3d$

$N_e = 10^{20} \text{ cm}^{-3}$

$T_e = 10 \text{ eV}$

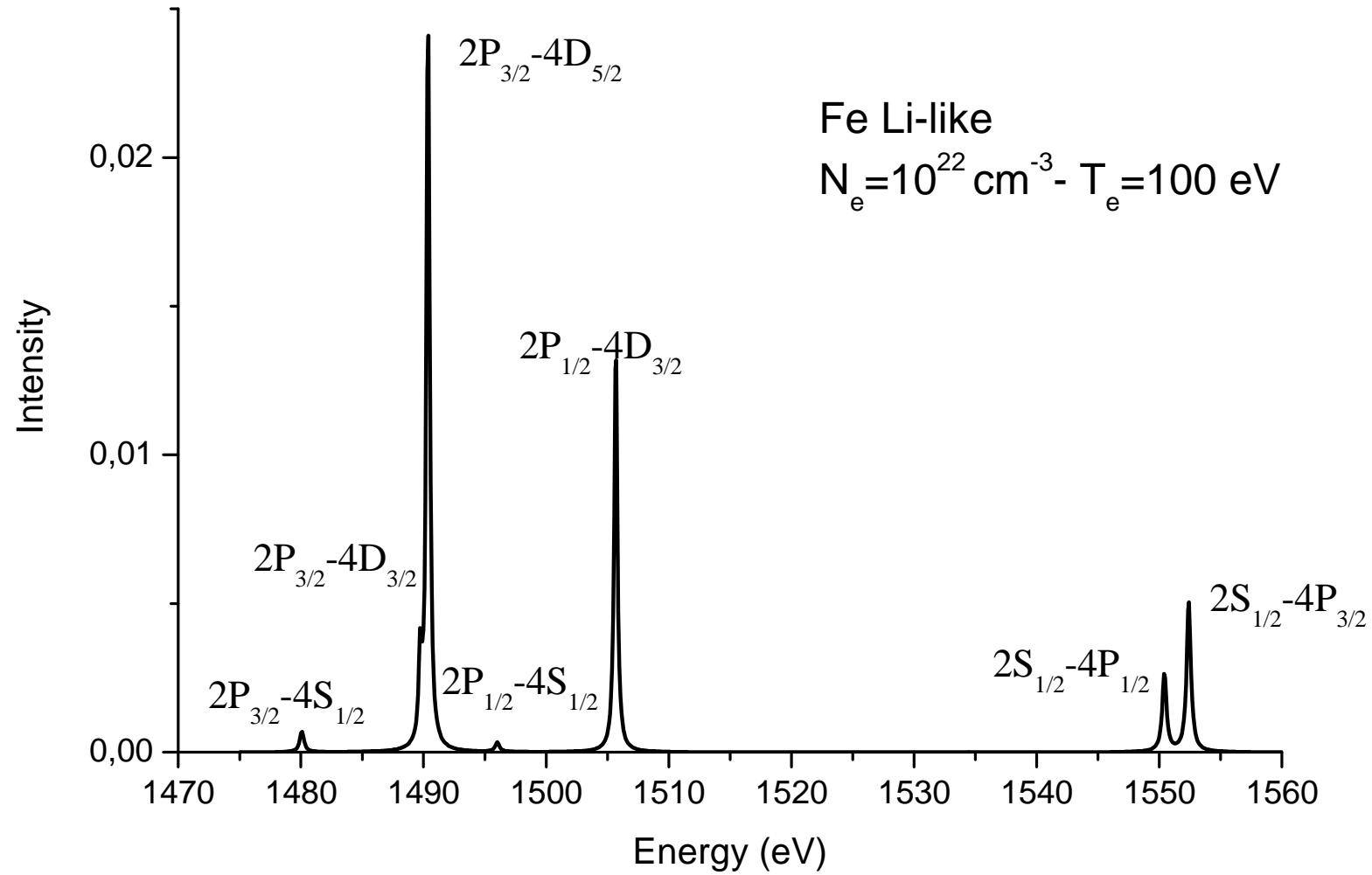
30 % of O V



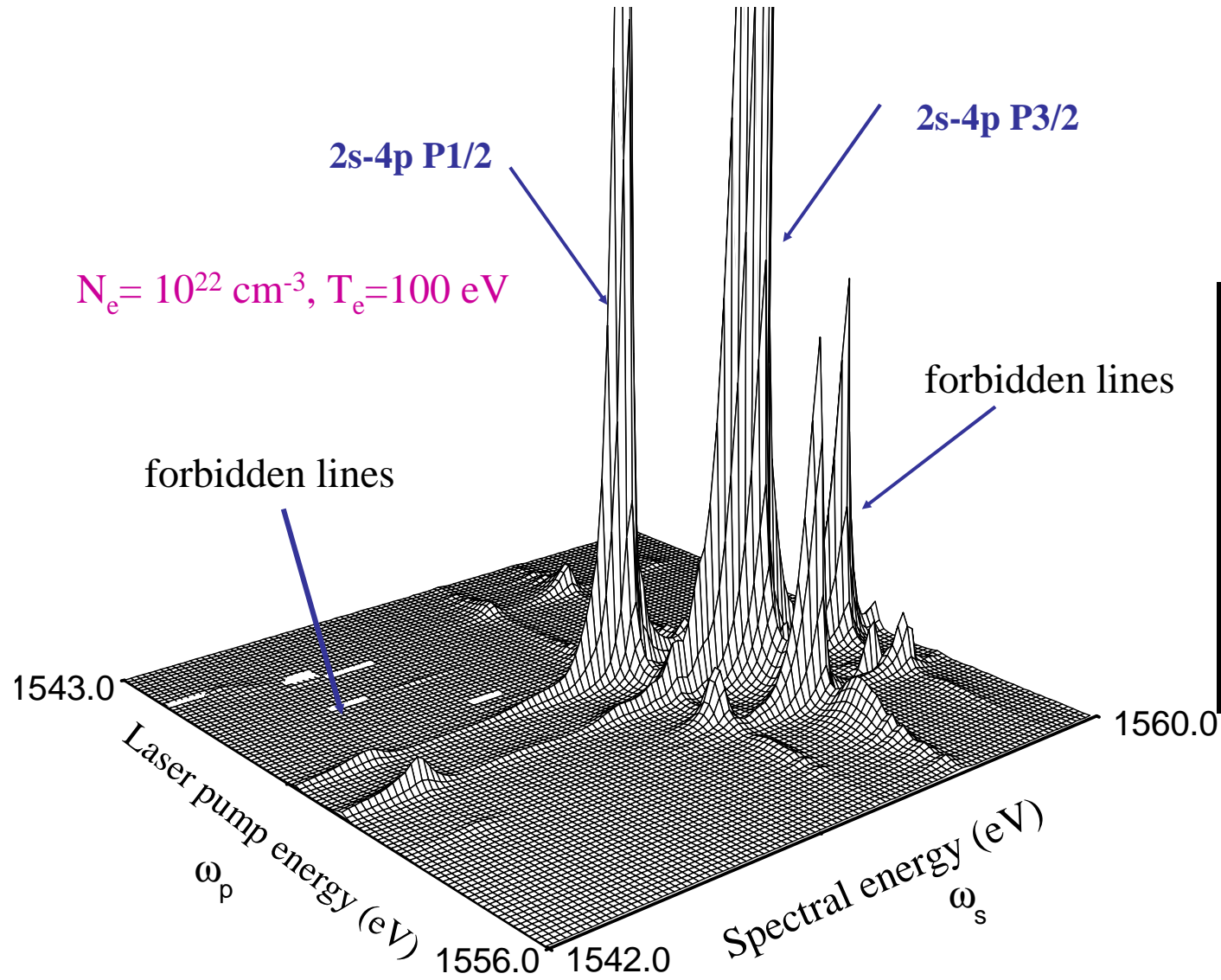
— $n=3$
— $n=4$
— $n=5$

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Pumping the 7.98 Å transitions $1s^22l-1s^24l$ of the lithium-like Iron (Fe XXIV)



Pumping the 7.98 Å transitions $1s^22l-1s^24l$ of the lithium-like Iron (Fe XXIV)



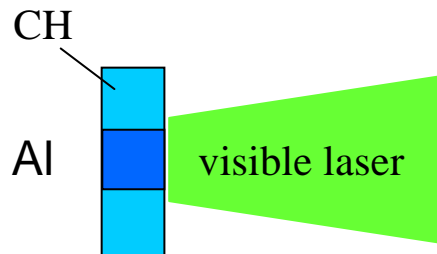
Estimation for
 $I_0^{\text{laser}} = 10^{14} \text{ W/cm}^2, D = 10 \mu\text{m}$

Pumping efficiency R_{lu} / A_{ul}	2
fluorescence yield Υ	44%
number of photons emitted P (in 4π sr)	$1.2 \cdot 10^{11}$

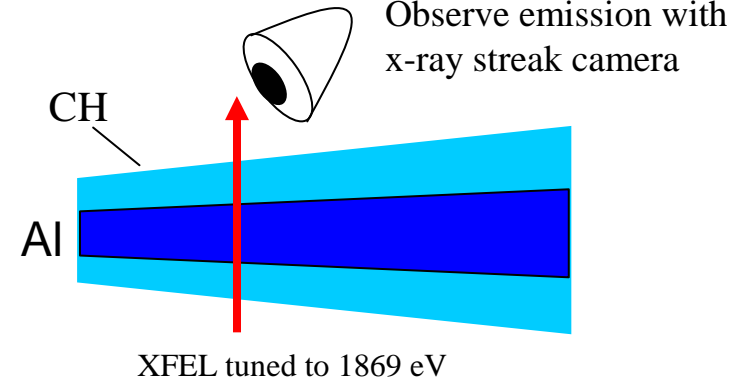
XFEL can photopump a transition the emission provides critical test of plasma processes

- **Schematic experiment**

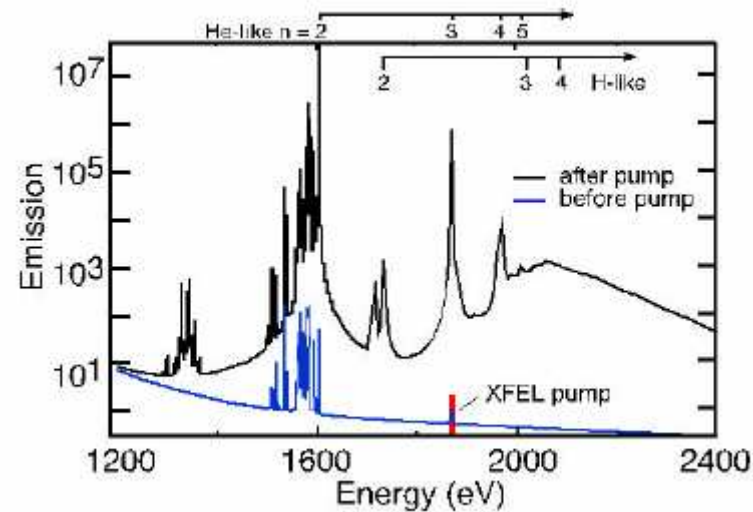
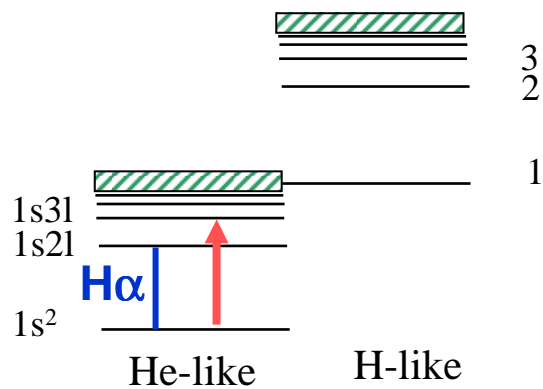
- $t=0$ laser irradiates an Al target



- $t=100$ ps XFEL irradiates Al plasma



- **Simulation**



Conclusion

- A resonance fluorescence experiment using XUV sources could be a step beyond in the study of hot dense plasmas
 - the understanding of the physical processes which occur in these plasmas
 - the implication in the radiative transfer problem
- Active spectroscopy might be a source of information
 - Plasma kinetic processes
 - Inelastic collision rates
 - Microfield fluctuation rates