Quantitative studies of laser-cluster interaction: Status and Prospects

via X-ray production (keV)

L. Adoui[4] , J.-C. Gauthier[3] , O. Gobert[2] , E. Lamour[1], P. Meynadier[2] , D. Normand[2] , M. Perdrix[2] , C. Prigent[1], J.-P. Rozet[1] , D. Vernhet[1]

[1] Groupe de Physique des Solides, Universités Paris 6 et 7
[2] LUCA/CEA-Saclay, Gif-sur-Yvette
[3] LULI, École Polytechnique, Palaiseau
[4] CIRIL, Caen

-GSI- 2002-

Context of laser-cluster interaction studies:

Relatively "new" field: 1994……...

Why Clusters?…….of 10^4-10^6 atoms/cluster

- local density ≈ 10^{22} cm^{-3} (solid density)
- all cluster atoms in the same "uniform" electric field (skin depth ≈ cluster size - 40 nm)

simplification allows a test of models

Which studies?

Production of • multicharged ions (up to MeV)

⇨ ***Connected to both plasma and cluster explosion dynamics***

Mechanisms identified ; Review paper: Ditmire *et al.*, Phys. Rev. A 53, 1996

Generation of • hot electrons (up to keV)

• keV x-rays

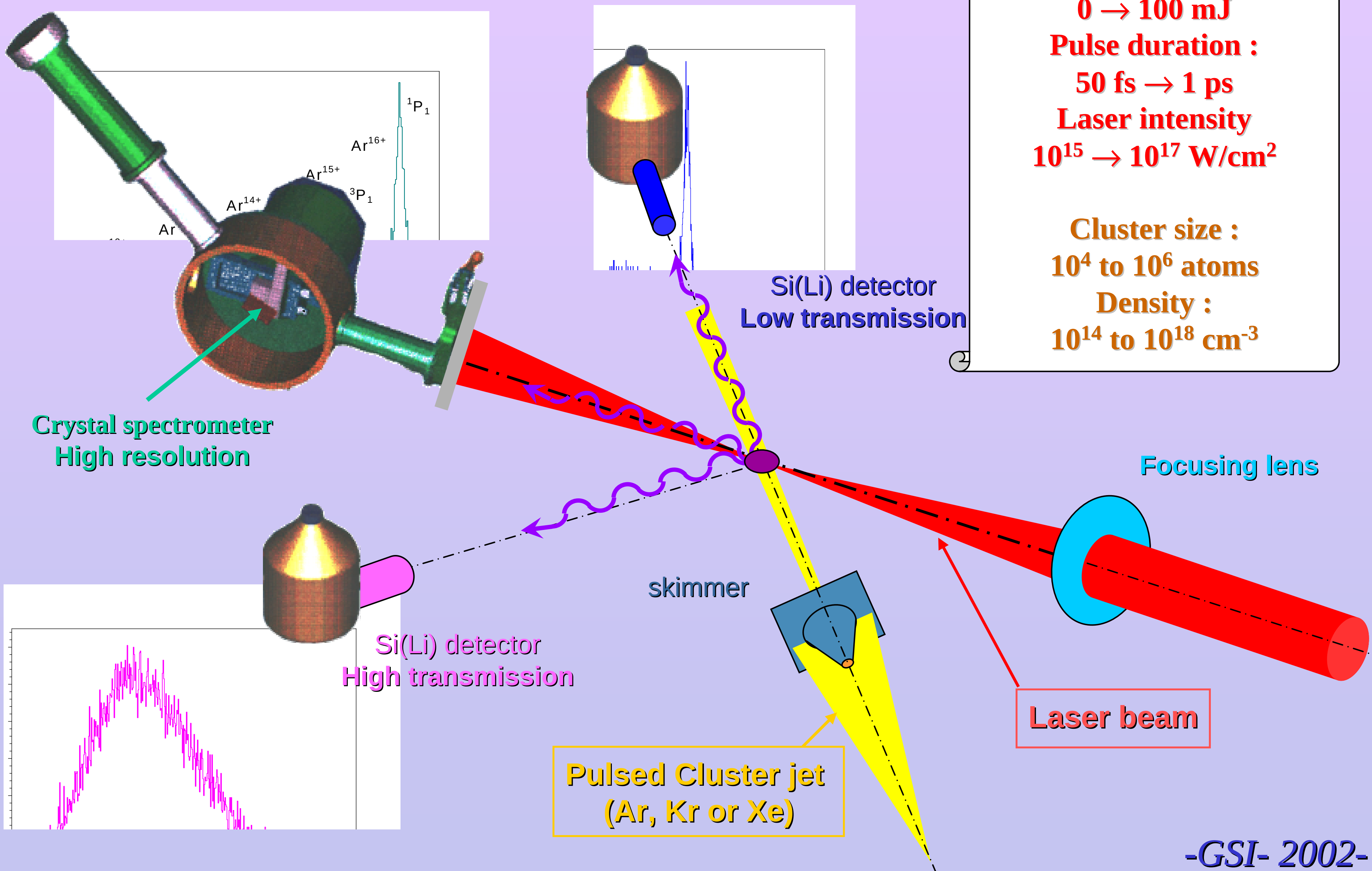
⇨ ***Direct insight into the early evolution of the nanoplasma***

Only qualitative measurements ,
Mechanisms of inner-shell vacancies? …2002 controversial interpretations

Experimental Set - up

Wavelength :
IR(800 nm) or UV(400 nm)
Energy / pulse :
0 → 100 mJ
Pulse duration :
50 fs → 1 ps
Laser intensity
$10^{15} \rightarrow 10^{17}$ W/cm^2

Cluster size :
10^4 to 10^6 atoms
Density :
10^{14} to 10^{18} cm^{-3}

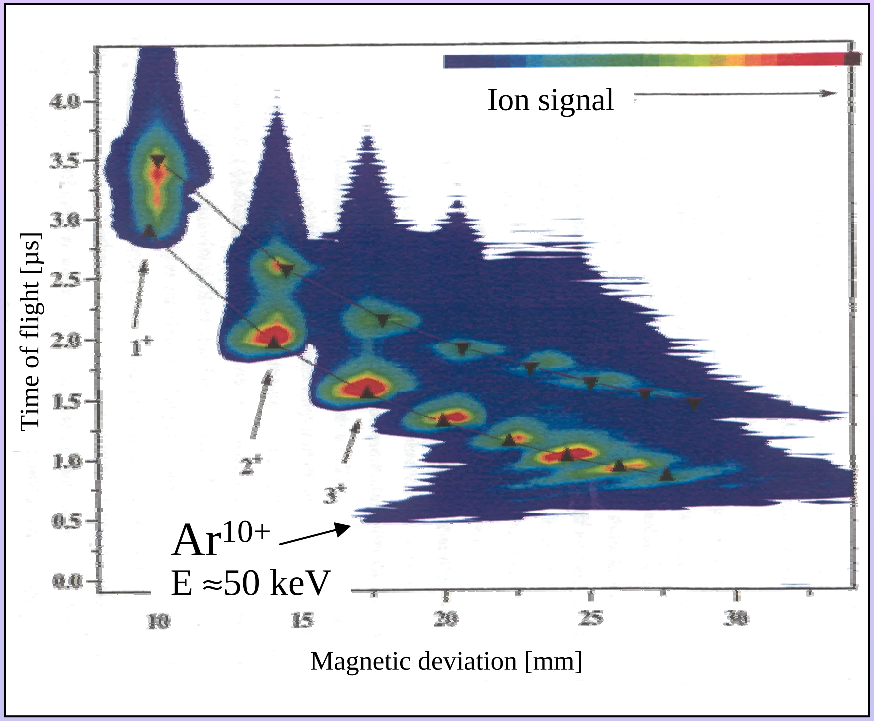


-GSI- 2002-

Advantage of the x-ray spectroscopy

Ion Spectroscopy

Ion charge state distribution in the plasma

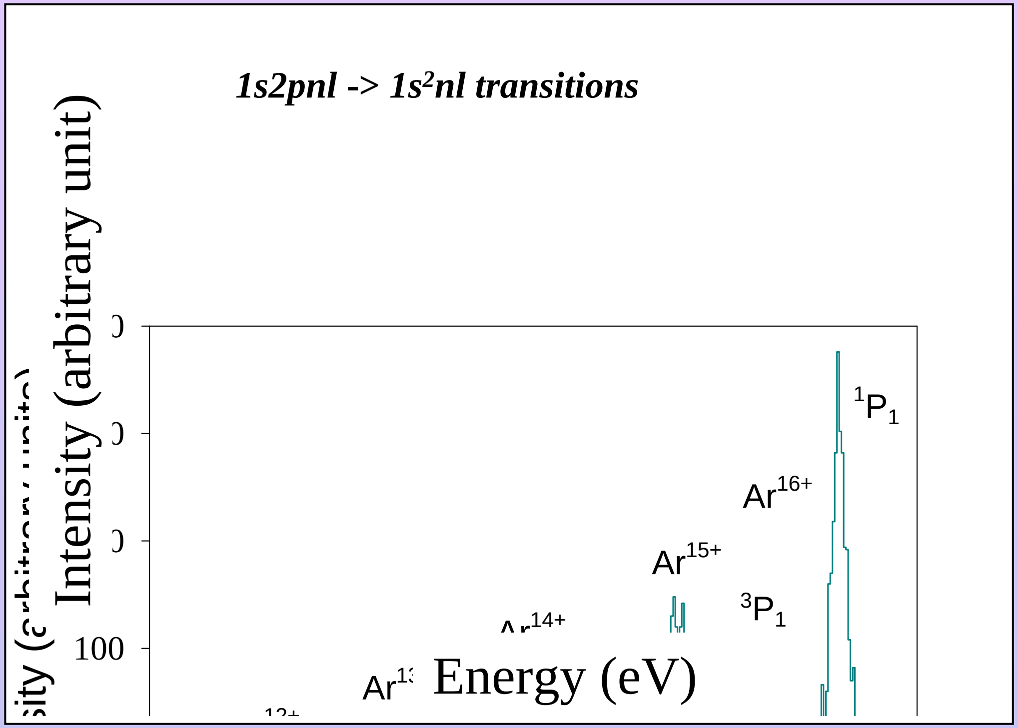


up to Ar^{10+}

MD-TOF ~ 0,5 μs

X-ray Spectroscopy

Charge state distribution of ions with a K vacancy

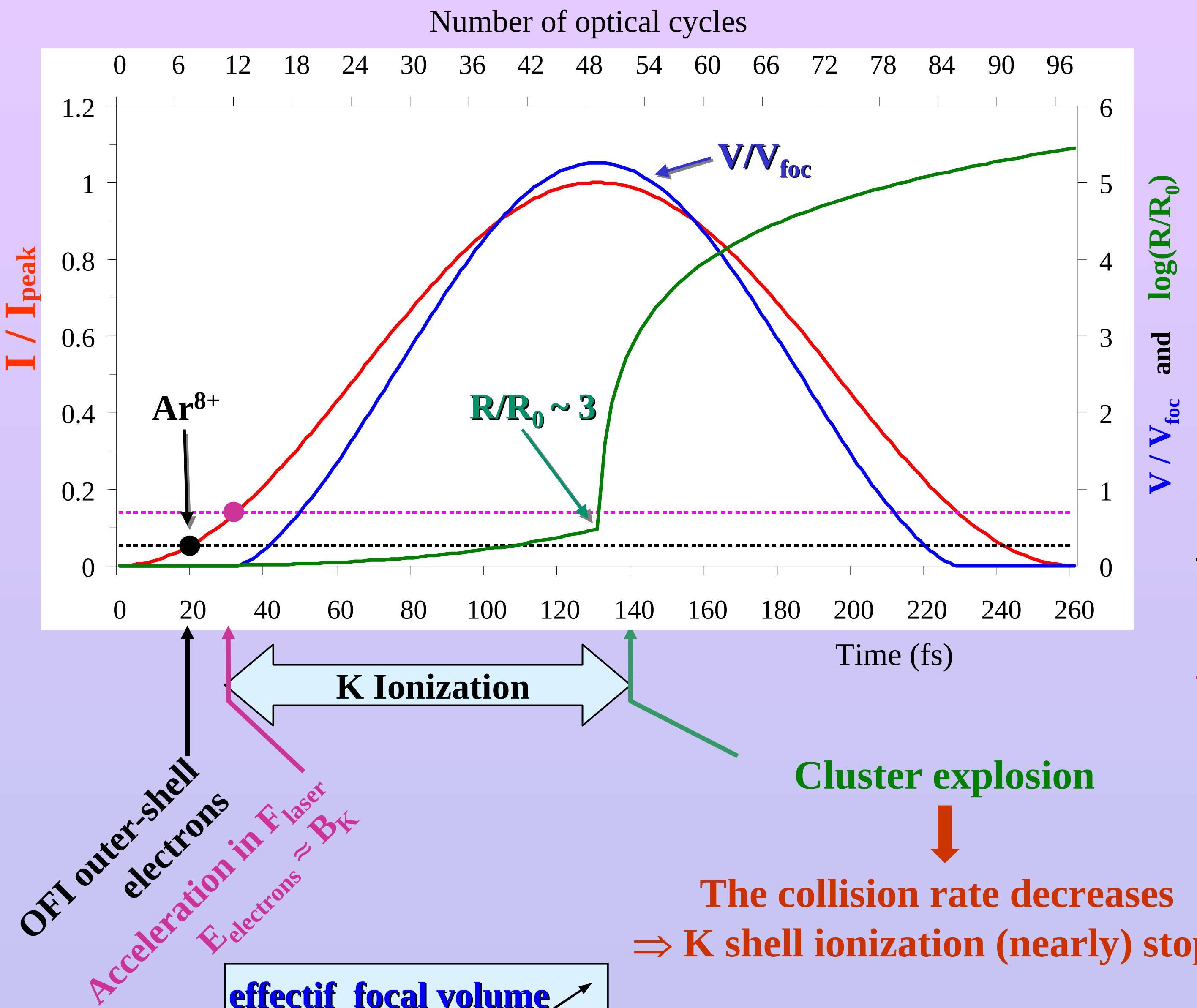


up to Ar^{16+}

$\tau\ (^1P_1) = 15$ fs

Inner-shell ionization model: the scenario

$(Ar)_n$ clusters
τ = 130 fs
(λ = 800 nm)
$I_{peak} = 5 \times 10^{17}$ W/cm^2
P_0 = 18 bar



Cluster explosion

⬇

The collision rate decreases
⇒ K shell ionization (nearly) stops

effectif focal volume ↗

1st step :
8 e^- : I_{Th1} = 2.6 10^{16} W/cm^2

2nd step :
E_{cin}(e-) = 4 keV
I_{Th2} = 3.5 10^{16} W/cm^2

Some predictions:

- **scaling laws:**

$$\overline{N}_{vacancies} = P_0^{5/3}\, n_{OFI}\, \sigma\, A_c^{1/3}\, d^{-2}\, V_f(I_{Th2})$$

$$= P_0^{5/3}\, n_{OFI}\, \sigma\, A_c^{1/3}\, d^{-2}\, I_{peak}^{3/2}$$

- **absolute photon yield:** $N_{h\nu} = \overline{\omega} \times \overline{N}_{vacancies}$

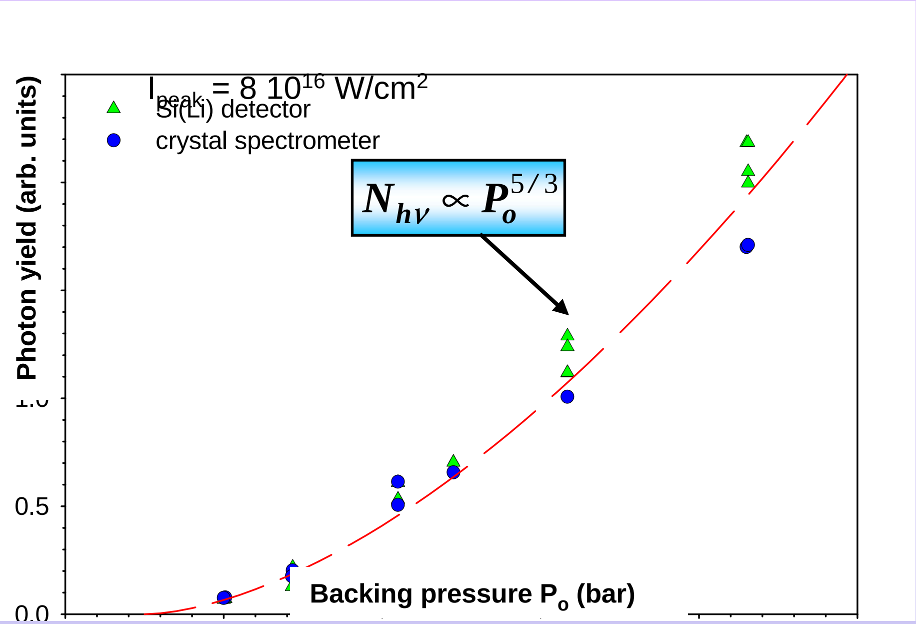
example:

	Argon
$E_{h\nu}$(eV)	3086
$N_{h\nu\,/\,pulse}$ (theo)	$6.\ 10^4$
$N_{h\nu\,/\,pulse}$ (exp)	7.10^4

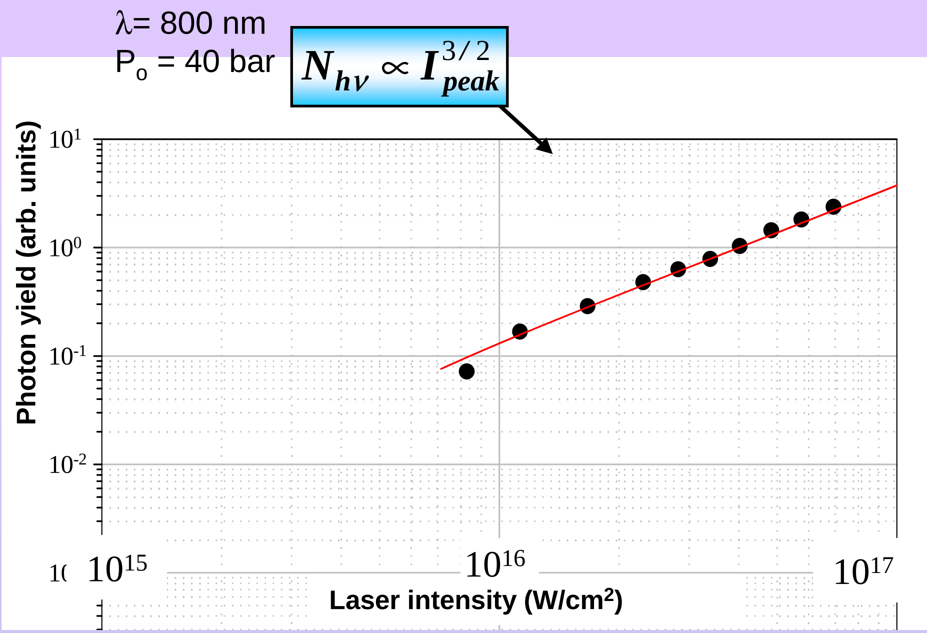
IR; λ = 800 nm; τ = 130 fs
I_{peak} = 5 10^{17} W/cm²
P_o = 18 bar

Results : what we understand … (Ar clusters: X_K)

evolution with cluster size



evolution with laser intensity



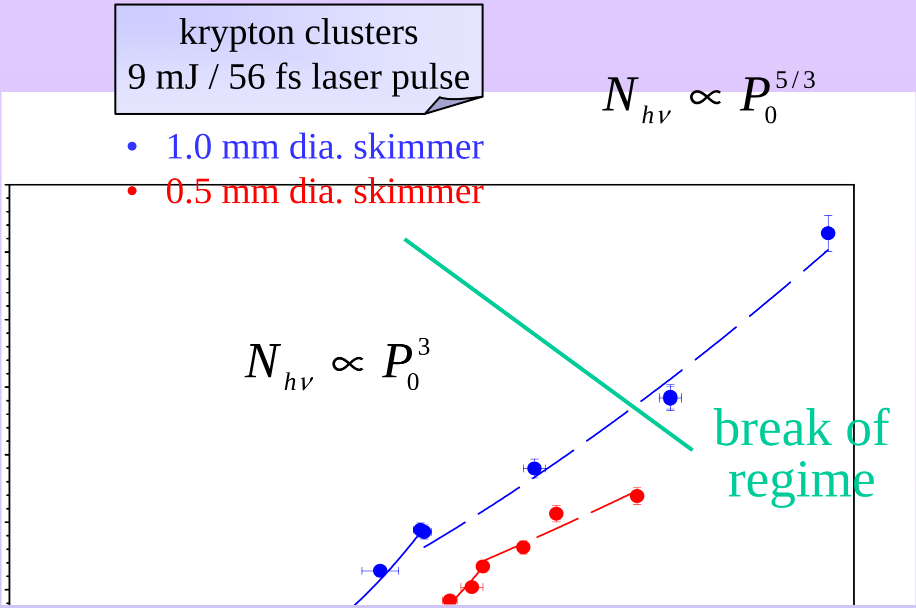
scaling law with pressure : $P_0^{5/3}$
and the mean charge state increases

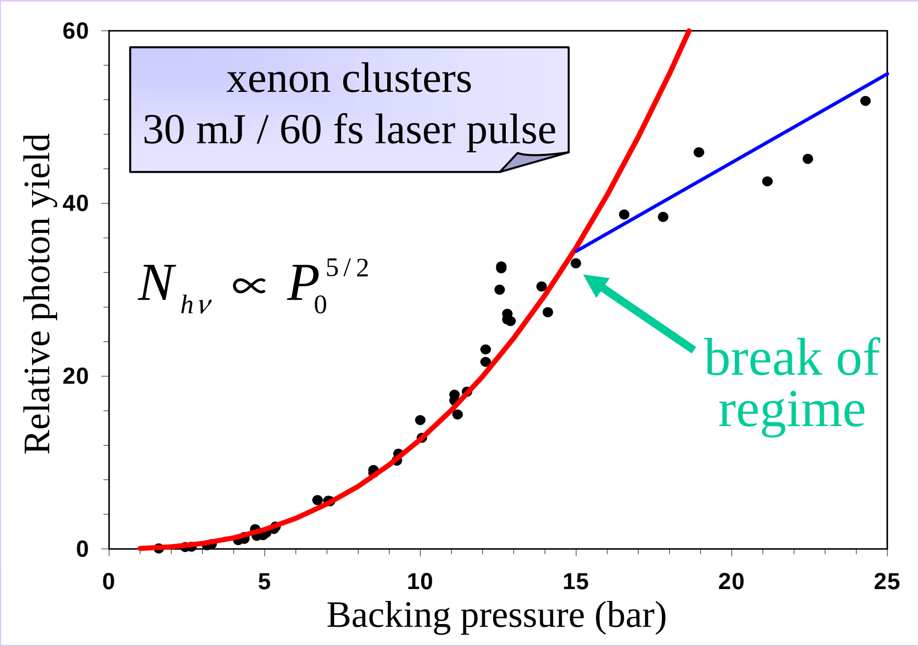
in agreement with a collisional picture (e^- / ions)

scaling law with peak intensity : $I_{peak}^{3/2}$
and constant mean charge state

increases like the effective focal volume
the saturation regime is reached

Results : what do we need to understand (1) … (X_L)





Not in agreement with argon results!

but $P_0^{5/3}$ law assumes:

- $\bar{N}_{cluster} \propto P_0^2$
- ω_L **constant!**
- **………..??**

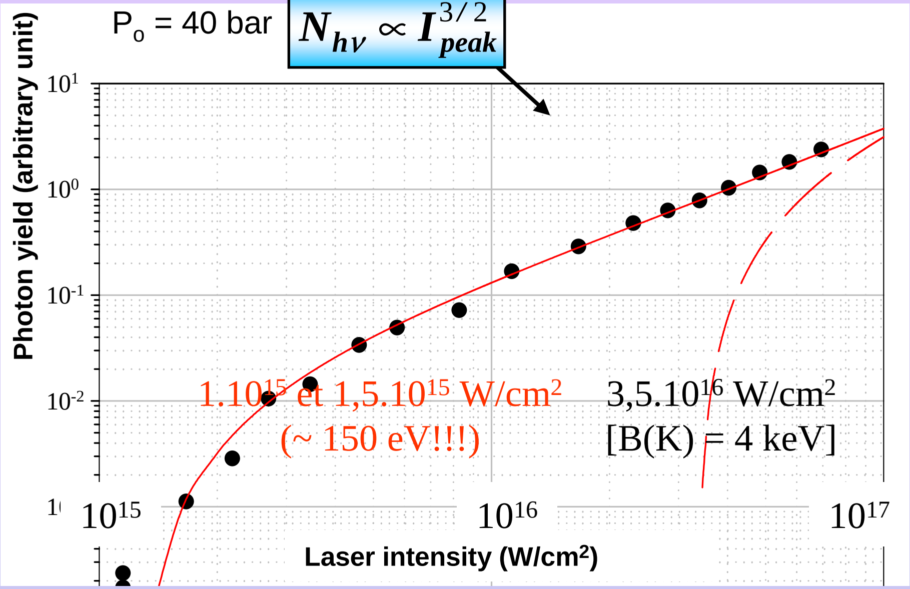
Results : what do we need to understand (2) …

The x-ray threshold !!

ARGON **X(K)**

λ= 800 nm
P_o = 40 bar

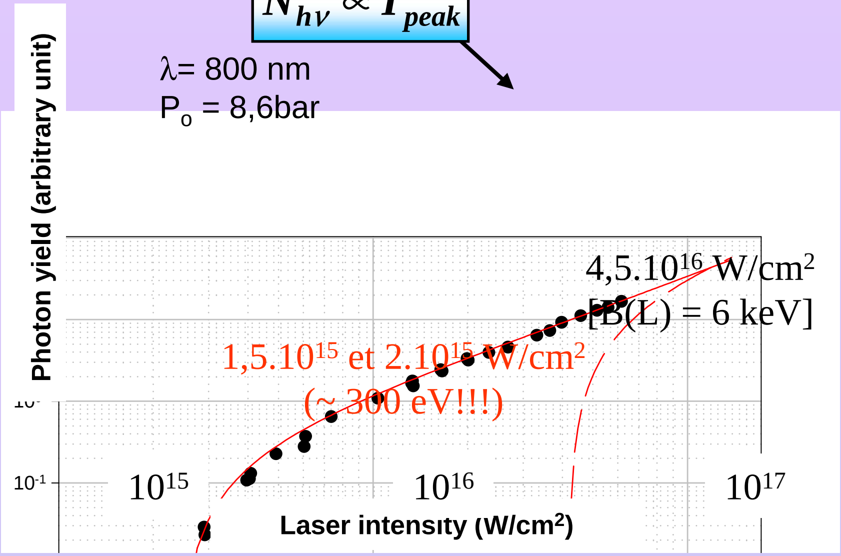
$N_{h\nu} \propto I_{peak}^{3/2}$



XENON **X(L)**

$N_{h\nu} \propto I_{peak}^{3/2}$

λ= 800 nm
P_o = 8,6bar



KRYPTON **X(L)**

Same result
Threshold ~ 1,3.10^{15} W/cm²
but B(L) ~ 2 keV

Very LOW ***whatever the binding energies !***

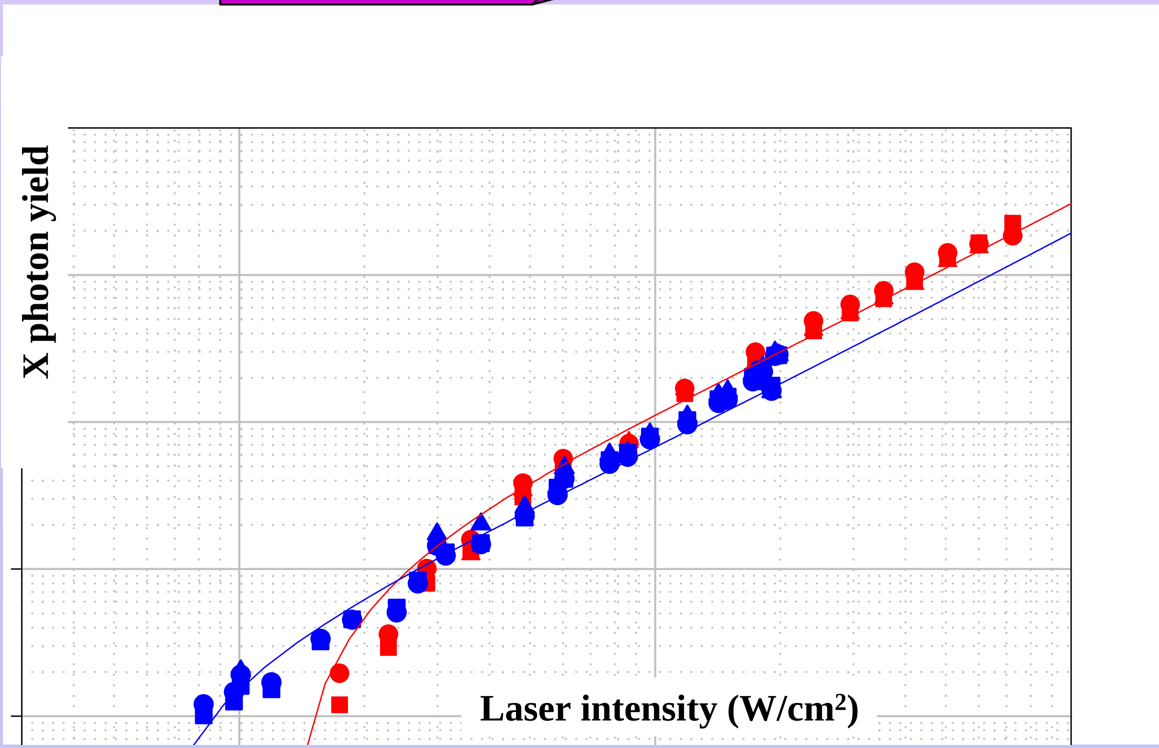
Results : what do we need to understand (3) …

Function of laser wavelength

Some differences?

- e- oscillation : U_p (UV) < U_p (IR) (/4)
- inverse Bremsstrahlung : E_{e-}(UV) > E_{e-}(IR)

ARGON



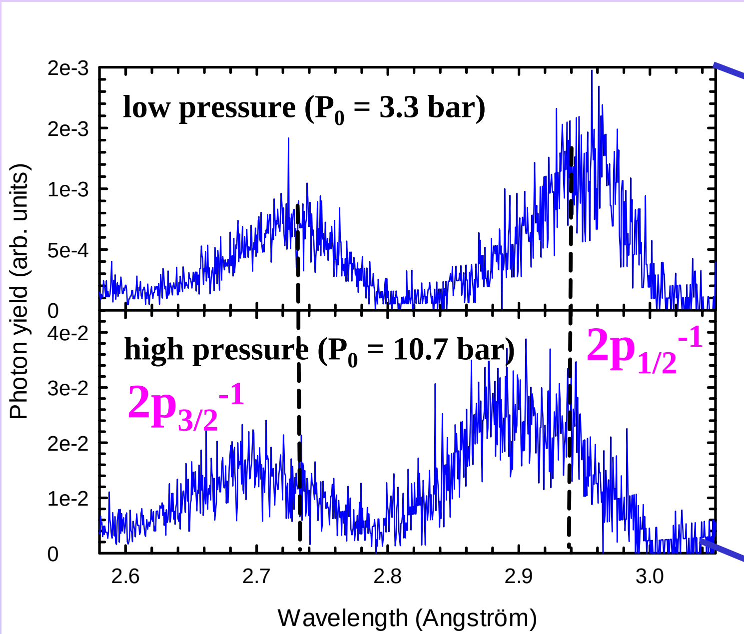
X threshold
UV < IR

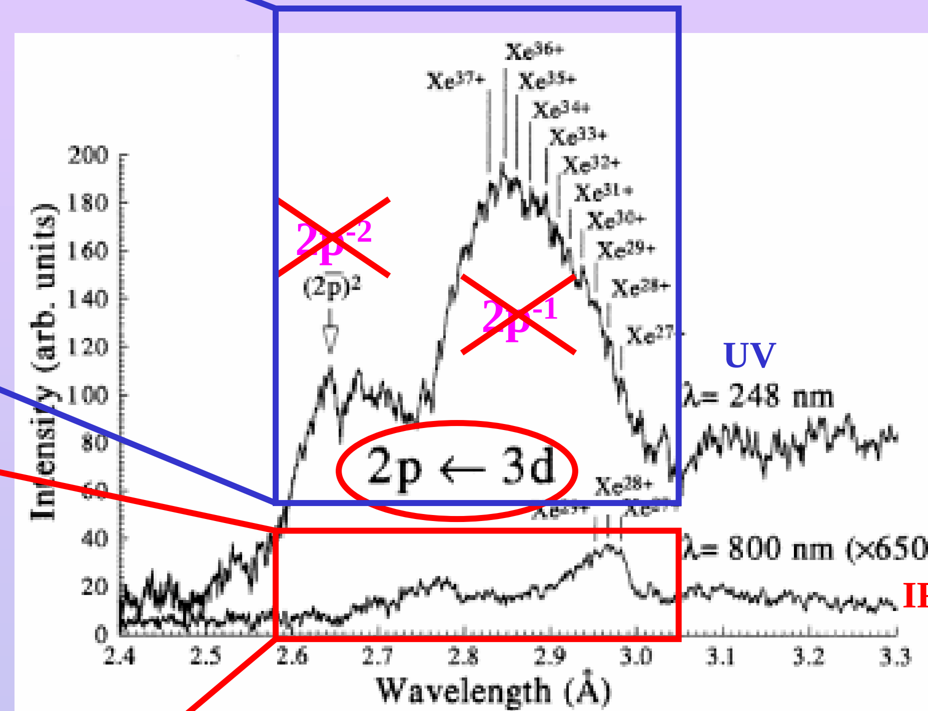
X photon yield
UV ~ IR

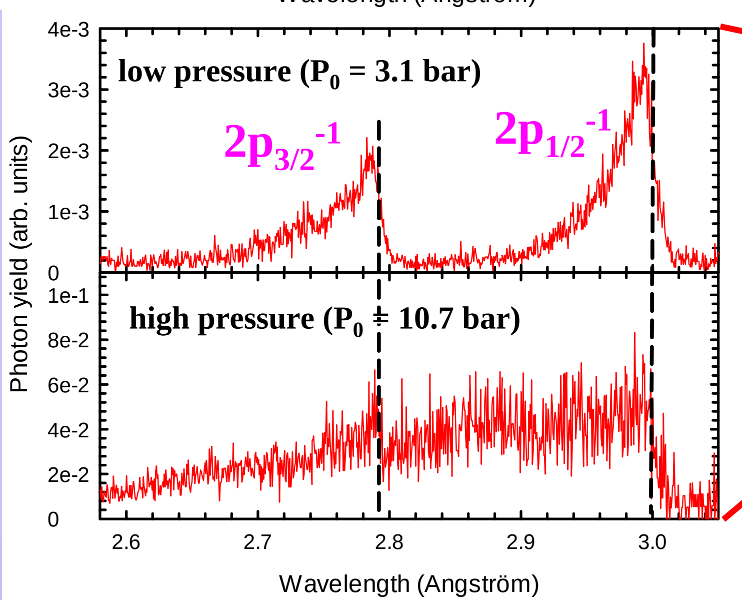
In agreement with
Ditmire *et al.* J. Phys. B (1998)
for the X_M photon yield
of Xe clusters

recent results on X_L photon yield…! with xenon clusters…

Kondo, Mc Pherson, Rhodes *et al.*
Exp: *J. Phys. B*, **30** (1997) 2707-2716
Theo : *J. Phys. B*, **34** (2001) 297-319
recently : *J. Phys. B*, **35** (2002) L461-L467







~~X_L Intensity $\propto \lambda^{-6}$~~

UV/IR only 3!!!

-GSI- 2002-

Summary and perspectives

X-ray yield measurements

- easily 10^{12} $h\nu$/pulse (4π); quasi mono-chromatic

  renewable X-ray source free of debris ➟ potential applications

- X-ray yield = f (I_{laser})

  for X-ray production: I_{Th} in a large focal volume

  not I_{peak} max in a small V_f ➟ X source optimization

- Parameter control on the X-ray yield

  present theoretical descriptions fail ➟ mechanisms?

  a strong effort is needed

…..other parameters

X-ray yield versus pulse duration

cluster size distribution versus P_0, etc……….

…..a challenge

reliable measurement of the X-ray duration…shorter than 100 fs?

➟ the issue at stake for applications