Generation of keV photons and electrons during laser-cluster interaction

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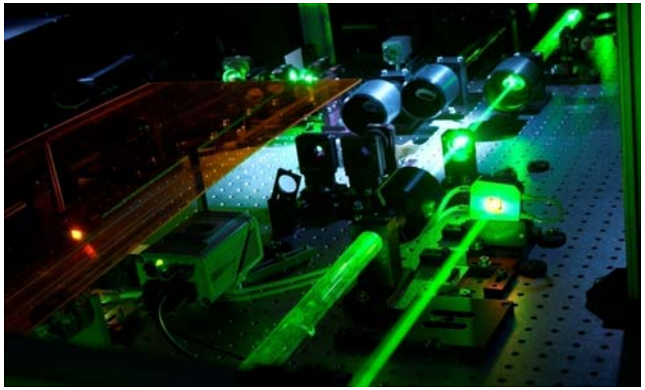

Collaborations:

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Outline

- some properties of intense laser - cluster interaction

  correlation between X-ray emission and energetic electrons?

- Interaction dynamics:

  mechanisms responsible for the X-ray production

- results focused on the last experiments performed:

  evidence of an ignition process

  correlation between X-ray yield and electron spectra

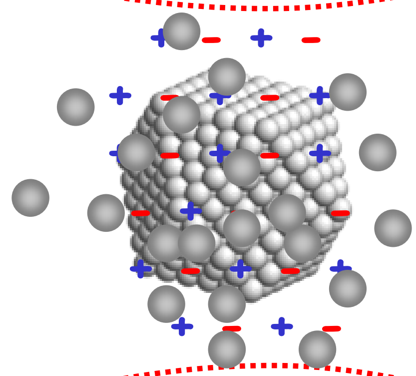
- conclusions & perspectives

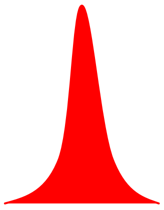
Clusters in intense laser fields

Strong optical fields

F > 10^9 V/cm

$E_{h\nu}$ ~ 1.6 eV / 3.2 eV





Creation of nanoplasmas

time scale ~ pulse duration

+

Expansion and explosion of heated clusters

Van der Waals clusters….why?

Finite systems with variable sizes : Ñ = 10^3 - 10^6 at/cl   (ϕ ~ 1 to 30 nm)

$\lambda_{laser} >>$ ***skin depth*** $\geq \phi_{cluster} \Rightarrow$ *uniform field inside each cluster*

Cluster jet

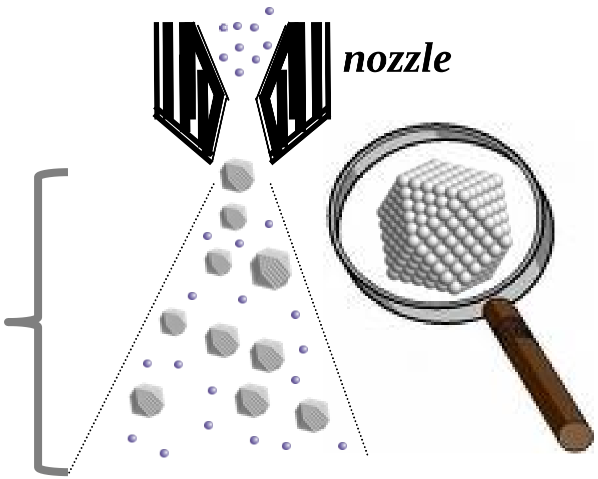
❑ ***low mean atomic density***

~ 10^{14-17} at/cm^3

well separated (~ 1-10 µm)

no problem of laser propagation

no x-ray absorption



❑ ***high local density***

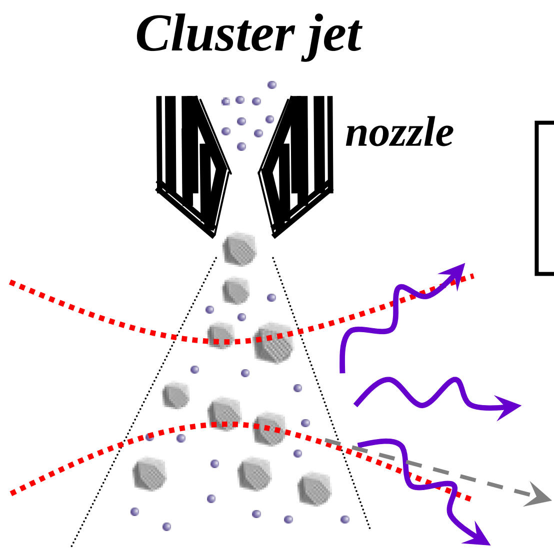
close to solid ~ 10^{22} at/cm^3

enhanced energy coupling

between light & matter

A cluster jet combines advantages of gaseous and solid targets

Van der Waals clusters in intense laser fields



Strong optical fields

F > 10^9 V/cm

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Emission of X-rays in the keV range

X_K(Ar) ~ 3.1 keV

ejection of hot electrons (E_{kin} ~ keV)

Direct insight into the early evolution of the nanoplasma (time-scale comparable to the laser pulse duration)

But never under the same experimental conditions!!!

An incomplete list of several studies:

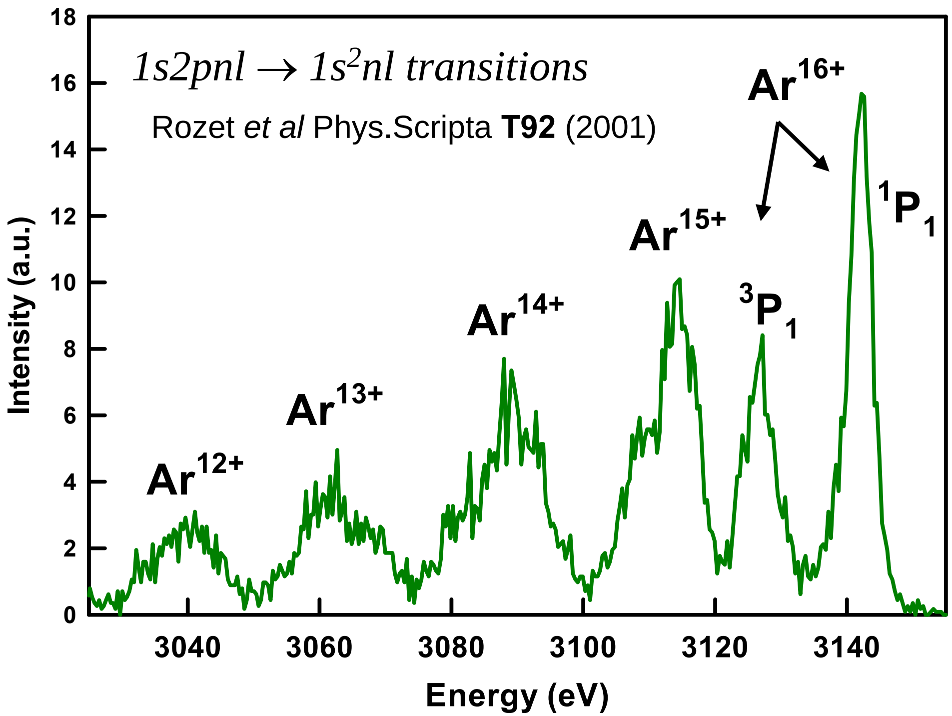
- H. M. Milchberg *et al* PRE **62** (2000)
- J.P. Rozet *et al* Phys.Scripta **T92** (2001)
- V. Kumarappan *et al* PRA **63** (2001)
- F. Dorchies et *al* PRE **71** (2005)
- L.M. Chen et *al.* PRL **104** (2010)
- Y.L.Shao et *al*. PRL **16** (1996)
- L.M. Chen et *al.* PRE **66** (2002)
- E.Springate PRA et *al*. **68** (2003)
- V.Kumarappan et *al*. PRA **67**(2003)
- Y.Liu et *al*. Phys. of Plasma **16** (2009)

Van der Waals clusters in intense laser fields

What we understand about the X-ray production

Emission of X-rays in the keV range ⇐ Inner shell vacancy production

⇒ **Deexcitation of HCl with inner shell vacancies**



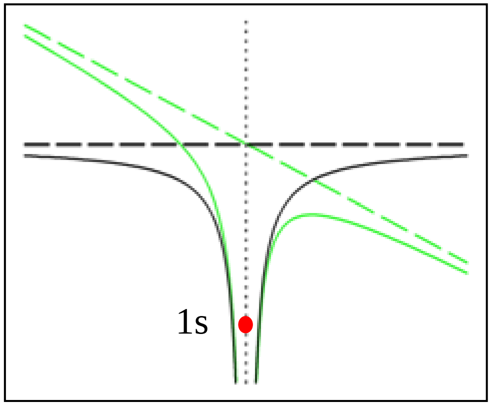
up to Ar^{16+} with $\tau(^1P_1)$ = 15 fs

time scale down to some fs

Van der Waals clusters in intense laser fields

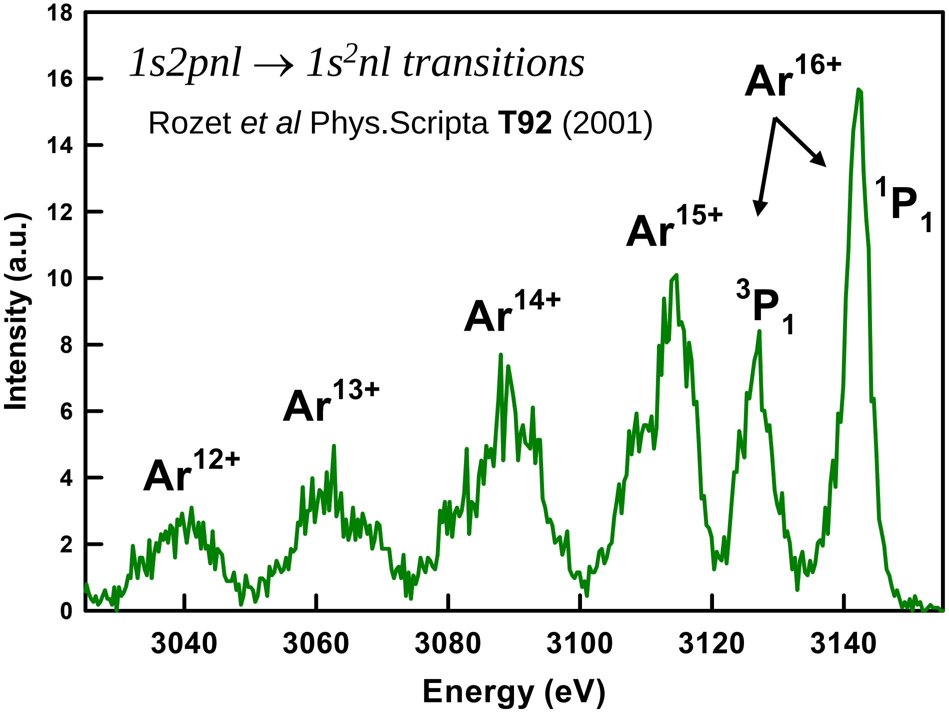
What we understand about the X-ray production

Emission of X-rays in the keV range ⇐ Inner shell vacancy production



Inner shell vacancy by OFI

Ar^{16+} (1s) → ~~4 10^{21} W/cm²~~



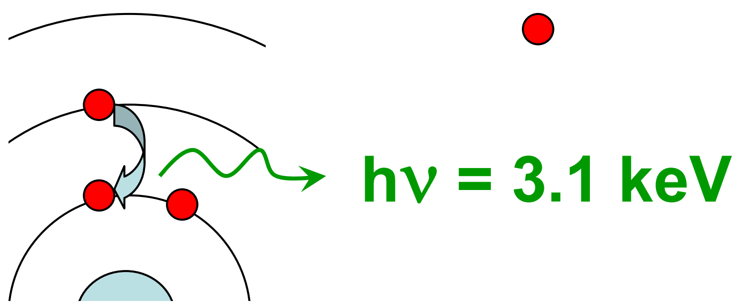
up to Ar^{16+} with $\tau(^1P_1)$ = 15 fs

time scale down to some fs

Van der Waals clusters in intense laser fields

What we understand about the X-ray production

Emission of X-rays in the keV range ⇐ Inner shell vacancy production ⇐ Electron impact ionization



Fast electrons
with $E = E_K \sim 3 - 4$ keV
for argon ions

Understanding of the electron heating mechanisms and the link between energetic electrons and X-ray

Outline

- some properties of intense laser - cluster interaction
  correlation between X-ray emission and energetic electrons?

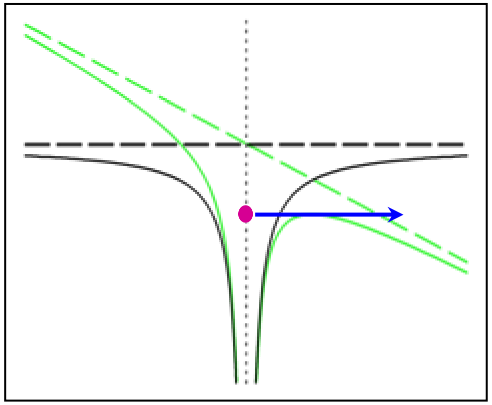
- Interaction dynamics:
  mechanisms responsible for the X-ray production

- results focused on the last experiments performed:
  evidence of an ignition process
  correlation between X-ray yield and electron spectra

- conclusions & perspectives

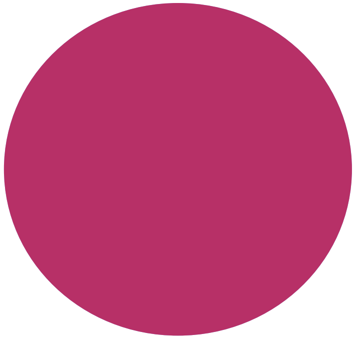
Scenario for electron heating mechanisms in the MF CTMC

Developed by the group of J.Burgodörfer



Optical field ionization

→ a cold nanoplasma

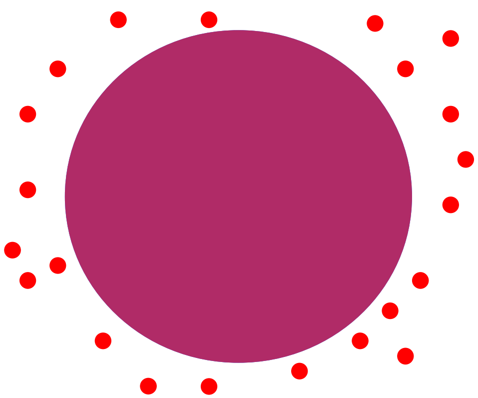


The electron cloud driven by the laser field

Polarizable sphere

→ screening of the laser field inside the cluster

→ but on the poles electric field enhanced



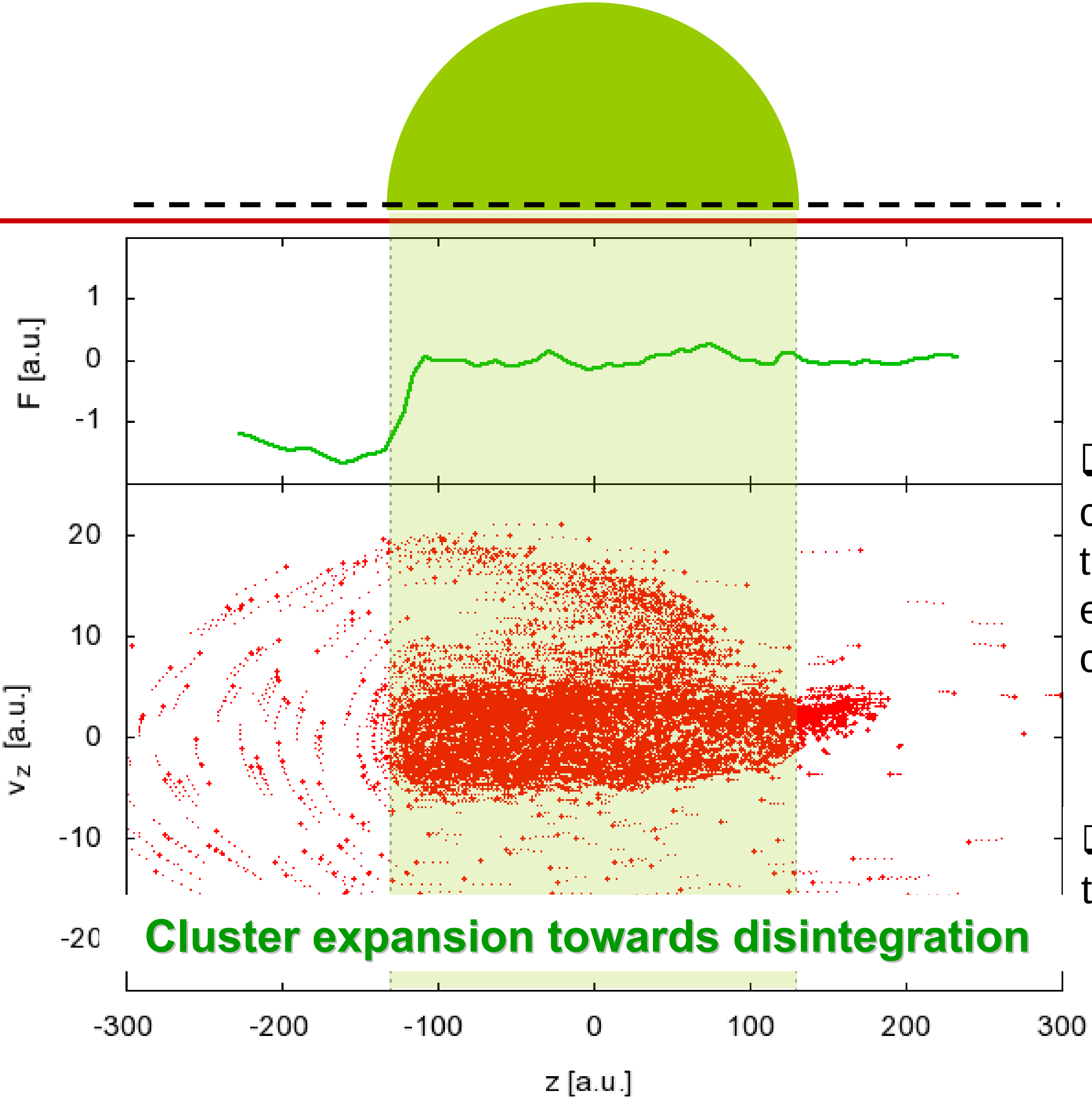
Outer ionization : electrons leave the cluster

Build-up of a positive charge on the cluster surface

Prigent, Deiss *et al* PRA **78** (2008)

Electron dynamics

C.Deiss et al *J.Phys.:Conf.Ser*. **88** (2007)

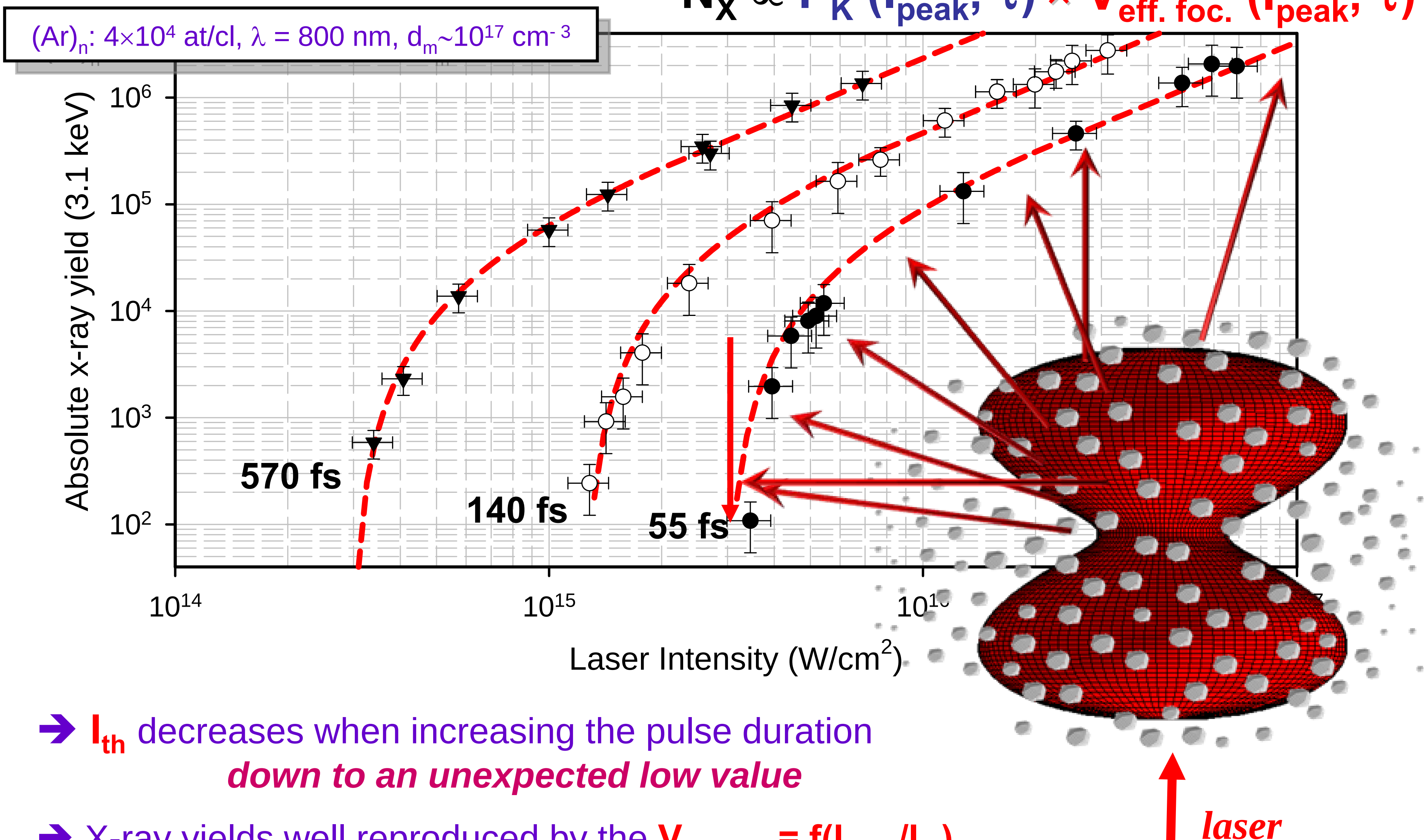


Cluster expansion towards disintegration

- ❑ a fraction of electrons can gain energy due to the presence of strong electric fields at the cluster poles
- ❑ electrons accelerated through back the cluster → K-shell ionization

Absolute X-ray yields *vs* laser intensity for different τ

$N_X \propto P_K (I_{peak}, \tau) \times V_{eff.\ foc.} (I_{peak}, \tau)$

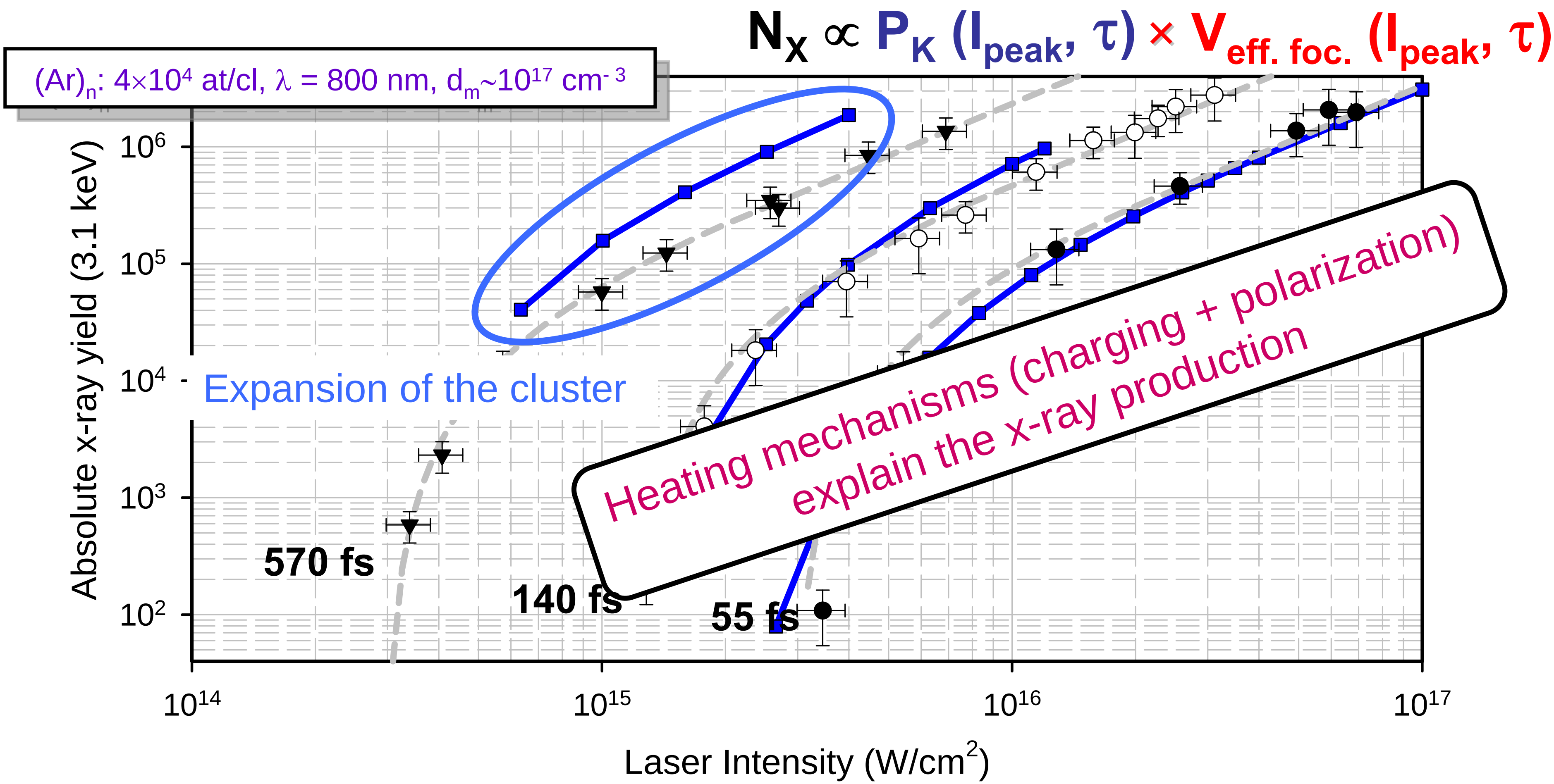


➔ I_{th} decreases when increasing the pulse duration
down to an unexpected low value

➔ X-ray yields well reproduced by the $V_{eff.\ Foc} = f(I_{peak}/I_{th})$.

C. Prigent, C. Deiss *et al* PRA **78** (2008)

Comparison with CTMC simulation



➔ Intensity & pulse duration dependences well reproduced

➔ Good prediction of the intensity threshold I_{th}

➔ Discrepancy for long pulse duration: *role of the ion dynamics i.e. cluster expansion*

C. Prigent, C. Deiss *et al* PRA **78** (2008)

Van der Waals clusters in intense laser fields

Emission of X-rays in the keV range	⇐	Inner shell vacancy production	⇐	Electron impact ionization

Scenario for the heating mechanisms in the MF CTMC

✓Charging-up of the cluster

✓Dynamic polarization of the cluster

➡ Electrons are heated to at least 3-4keV

***Our goal**:* improve the precision on I_{th}

Energy distribution of the electrons & link it to the X-ray emission

- ***Quantitative measurements of***
  - ✓ absolute photon emission yields
  - ✓ high energy electron distribution

as a function of different parameters

- ✓ I_{laser} , τ , polarization….

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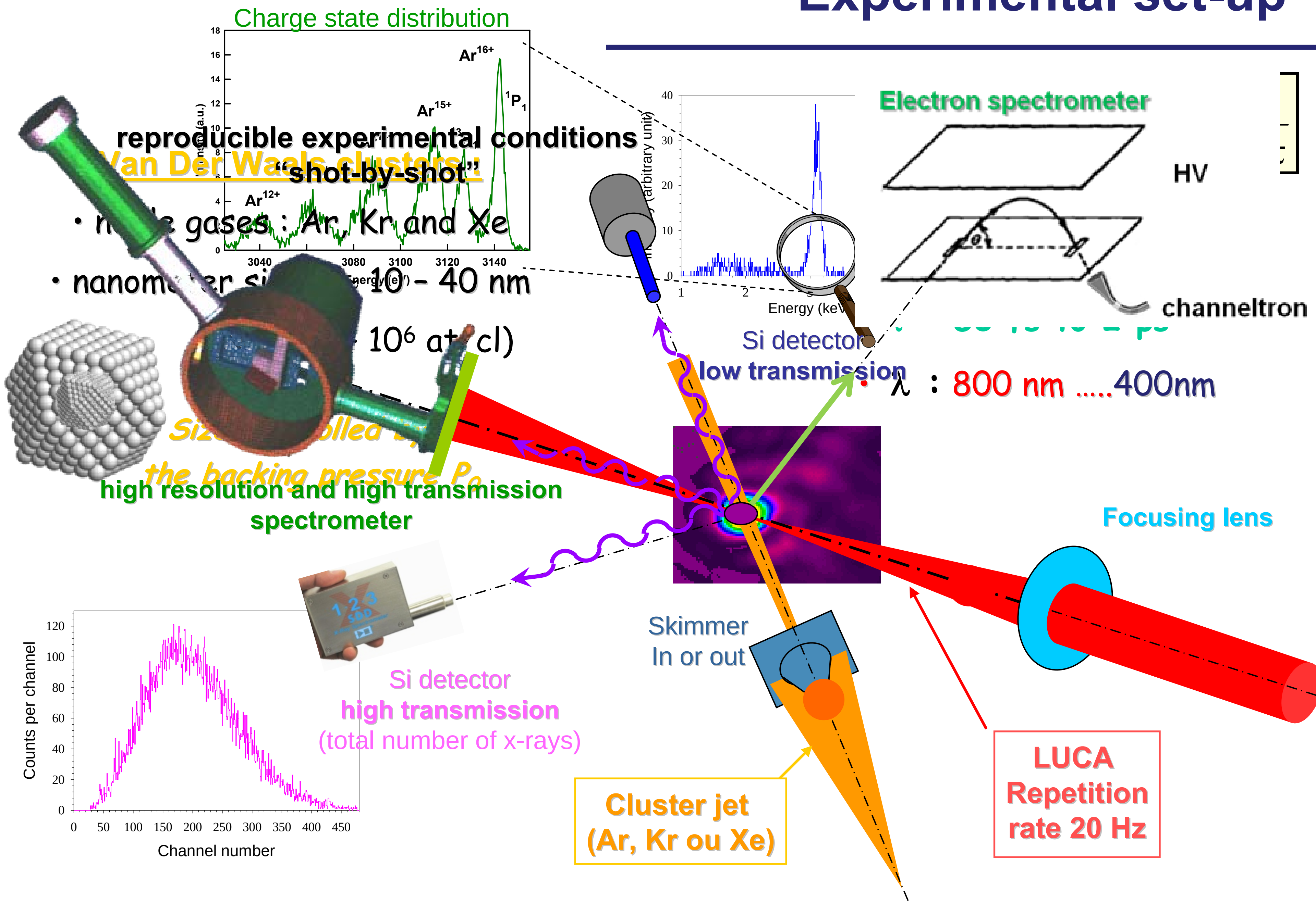
  correlation between X-ray yield and electron spectra

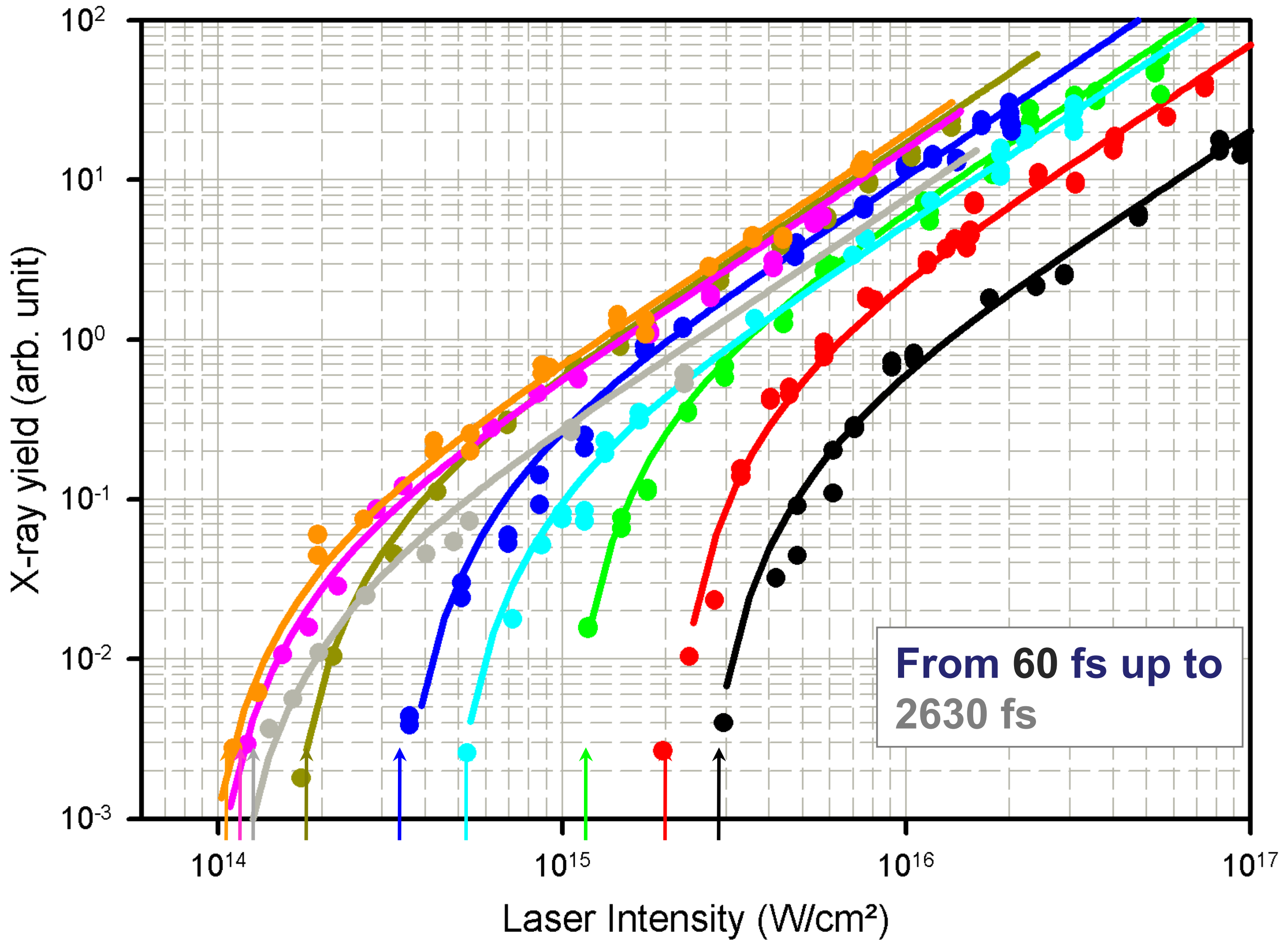
- conclusions & perspectives

Experimental set-up

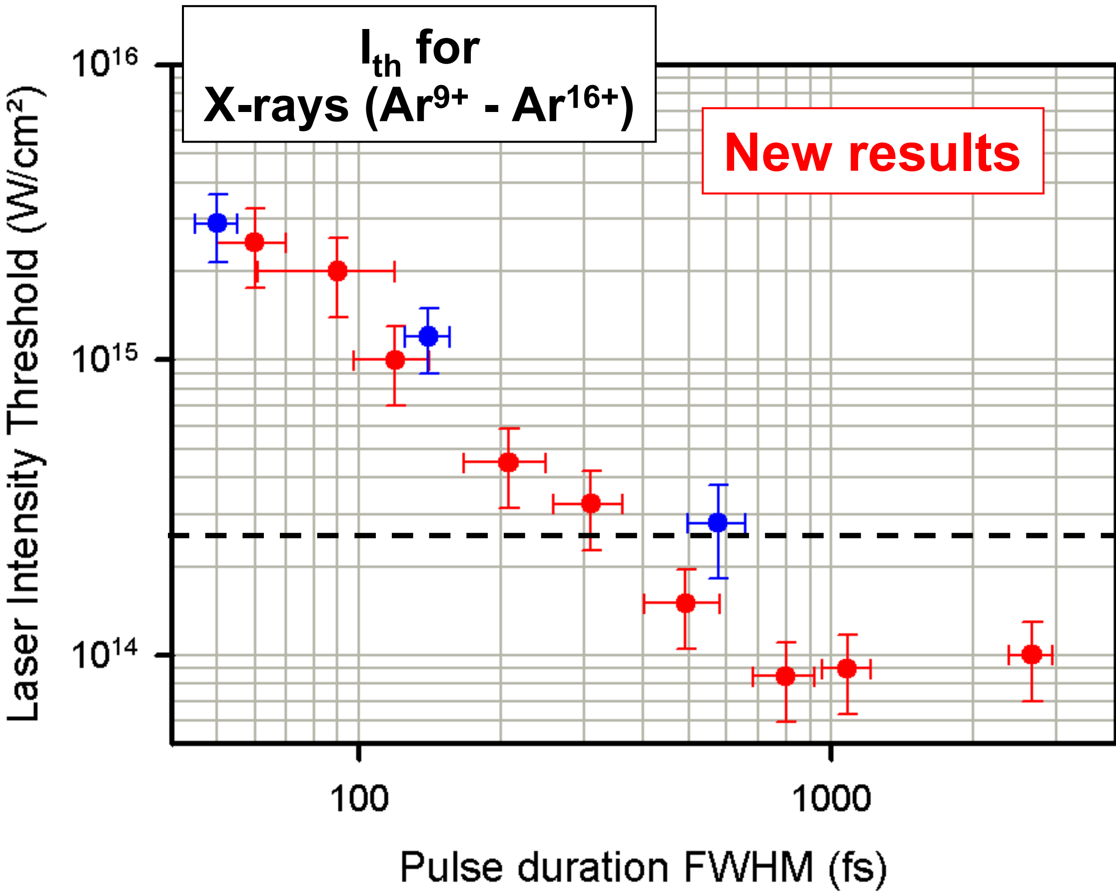


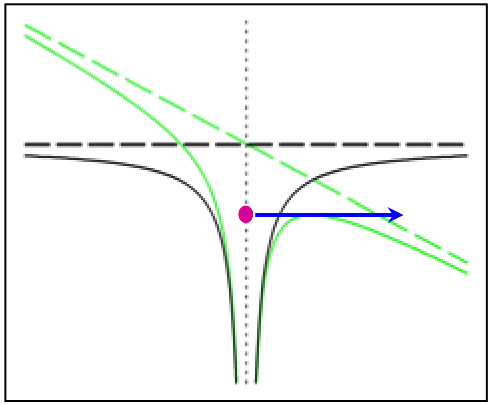
Absolute X-ray yields vs laser intensity for many pulse durations

$(Ar)_n$: 2×10^5 at/cl, λ = 800 nm, d_m~10^{14} cm^{-3}; **PRELIMINARY RESULTS**



Intensity threshold for X-ray production versus pulse duration, τ



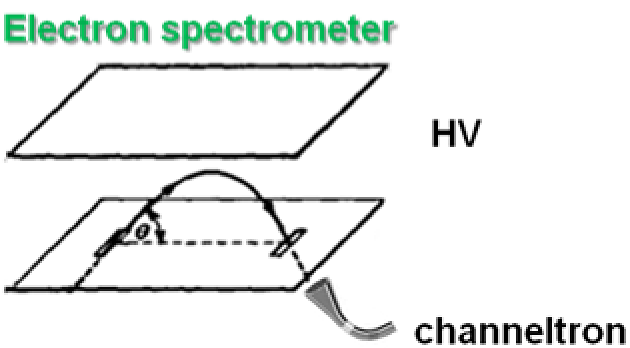


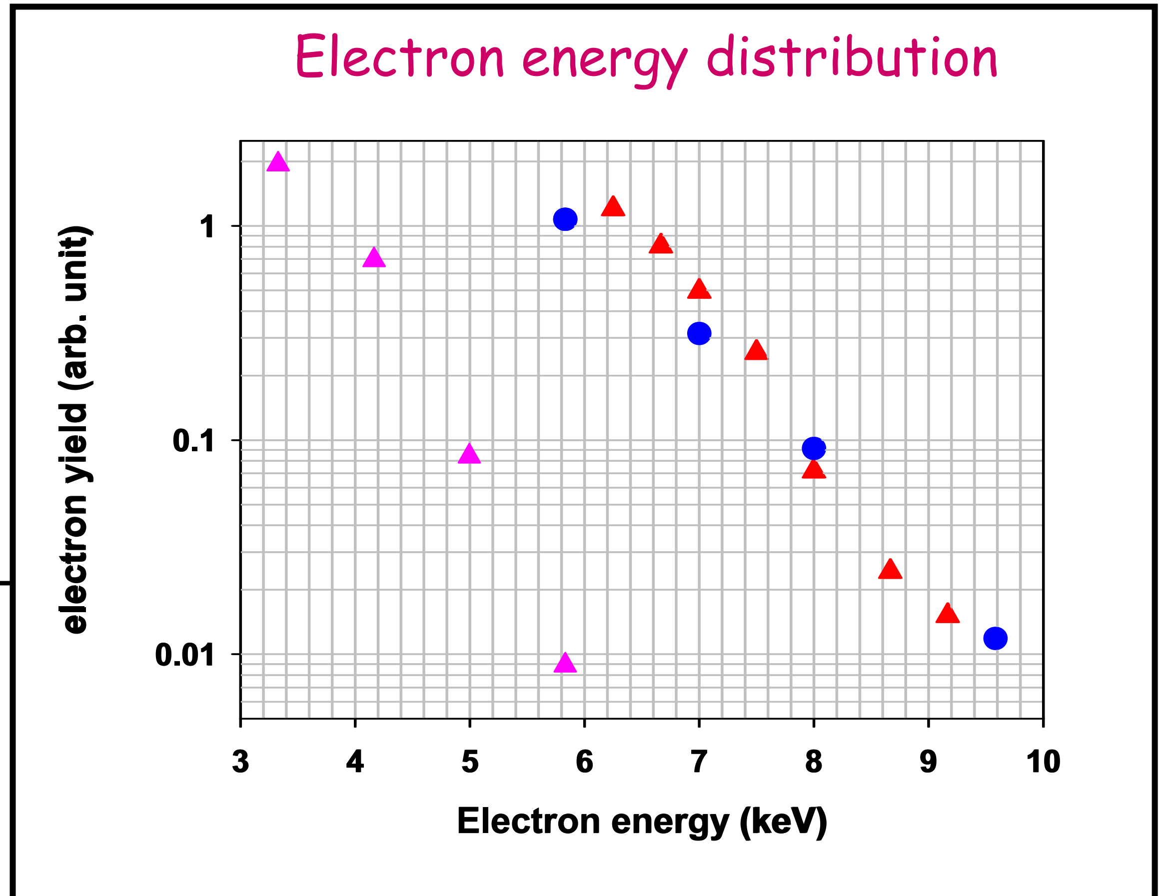
I (OBI) Ar → Ar^{1+} + e^-

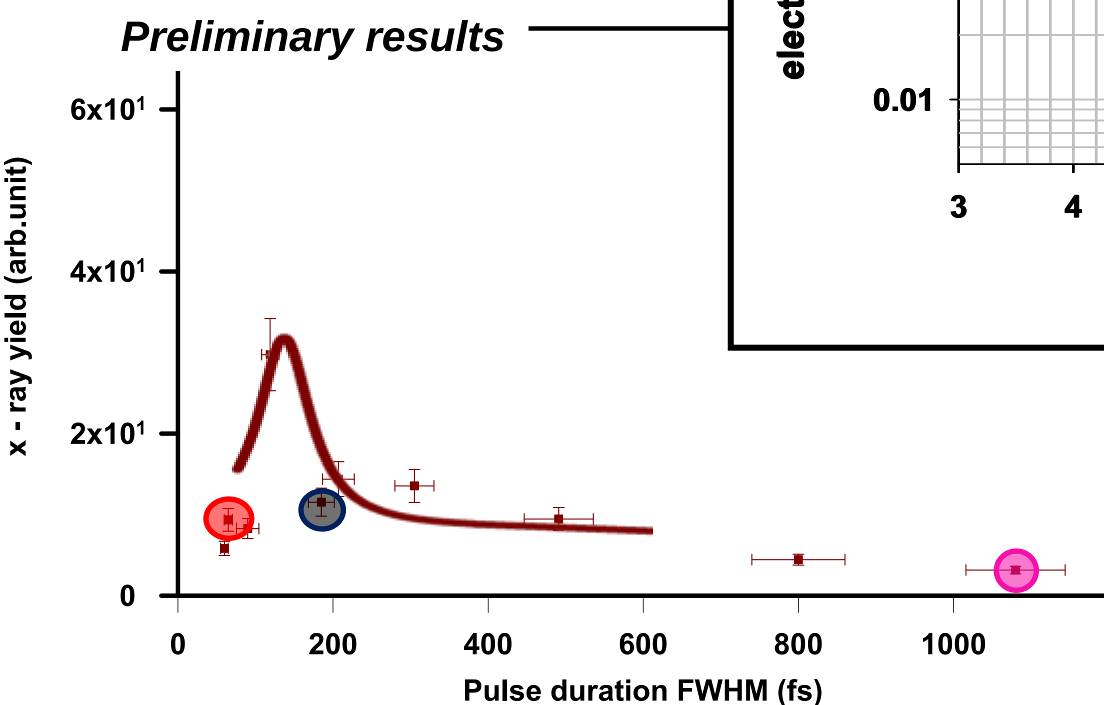
Contribution of tunnel and multiphoton ionization
similarly to Ar atom

Production of (Ar^{1+} + e^-) is the ignition process for X-ray production from HCI

Correlation between X-ray and electron yields







same X-ray yield ➔ same P_E(e-)

X-ray yield/3 ➔ lower P_E(e-)

Conclusions & perspectives

✓ Absolute X-ray yield measurements under well controlled conditions provide insight of the cluster dynamics on a very short time scale

✓ Production of Ar^{1+} is the ignition process for X-ray production emitted from Ar^{9+}-Ar^{16+}

✓ Strong correlation between X-ray and high energy electron yields

… data analysis and further theoretical developments under progress

✓Systematic studies have to be performed with a 400nm laser wavelength
better implementation of the expansion of the cluster in the theoretical model

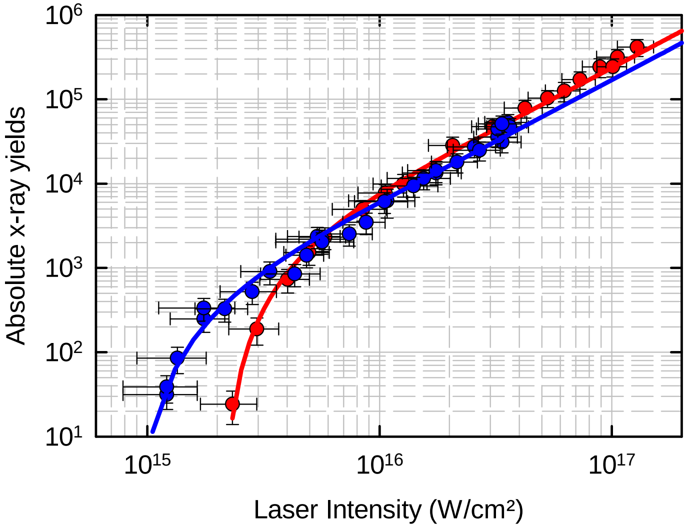
Thank you for your attention

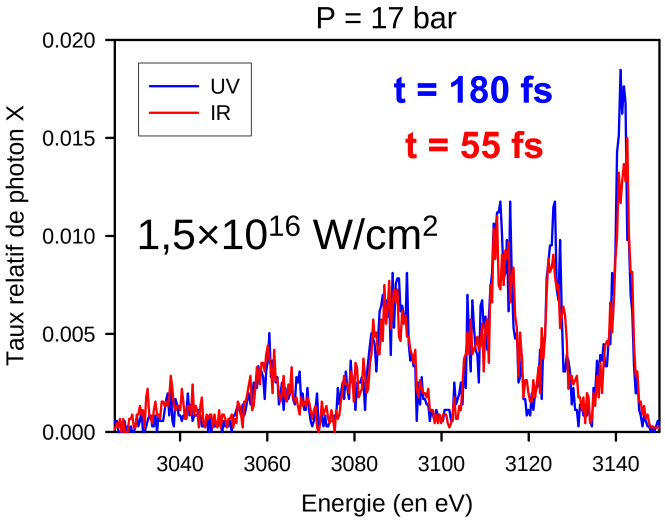
Experiments under progress at Saclay

Doubling-frequency has been realized to obtain laser pulses @400nm

✓Energy up to 15mJ

✓Pulse duration between 60fs and 1 ps.





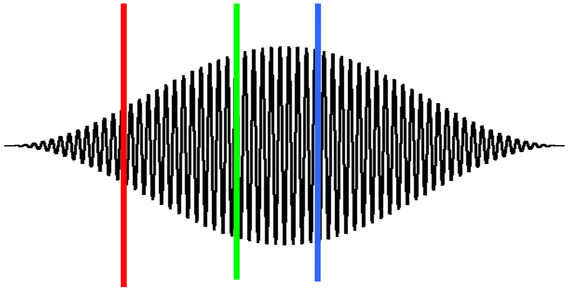
Influence of τ at 400 nm

Both X-ray and electron spectroscopy are performed

⟶ Understand the heating mechanisms @400nm

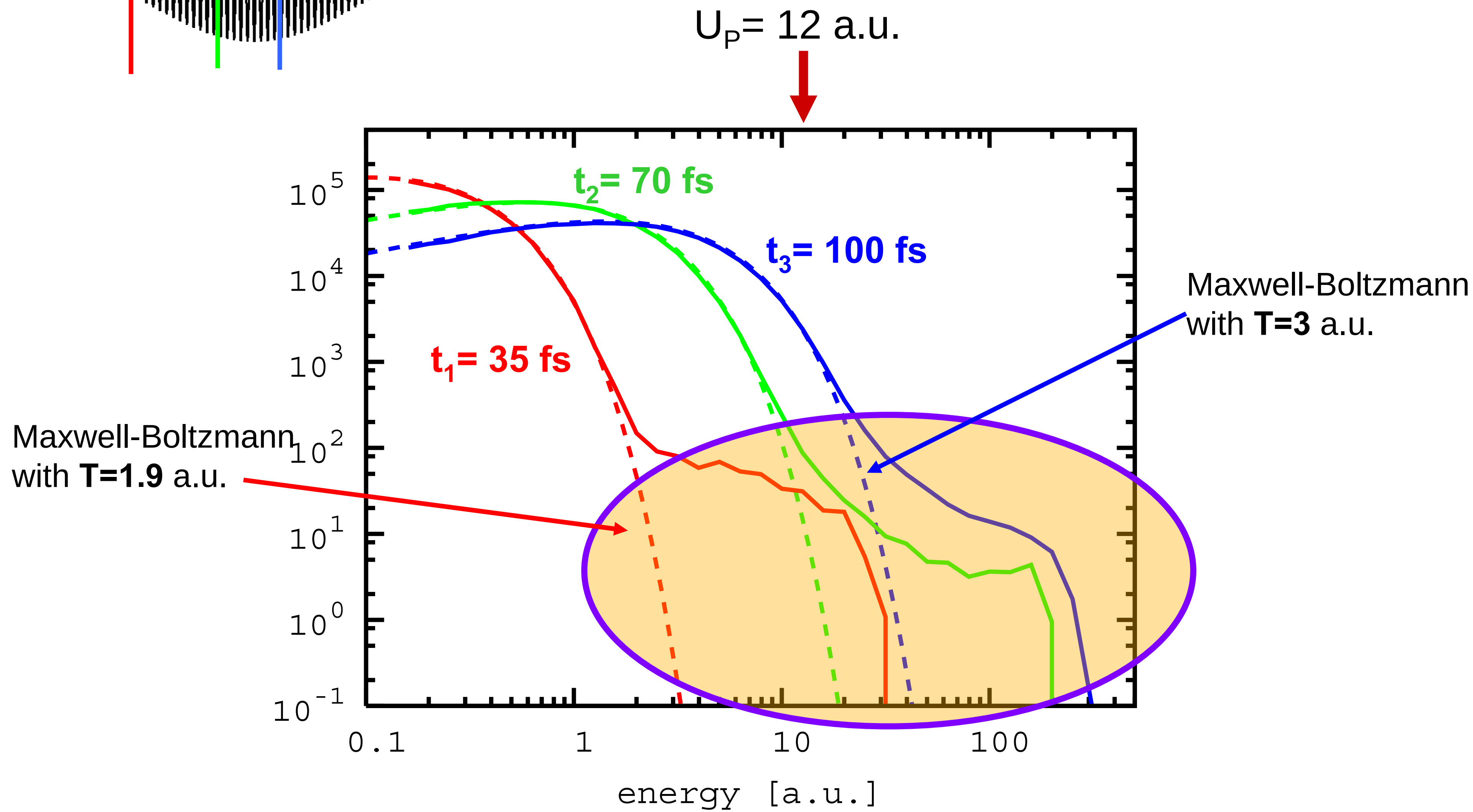
And gain insight in the cluster expansion dynamics

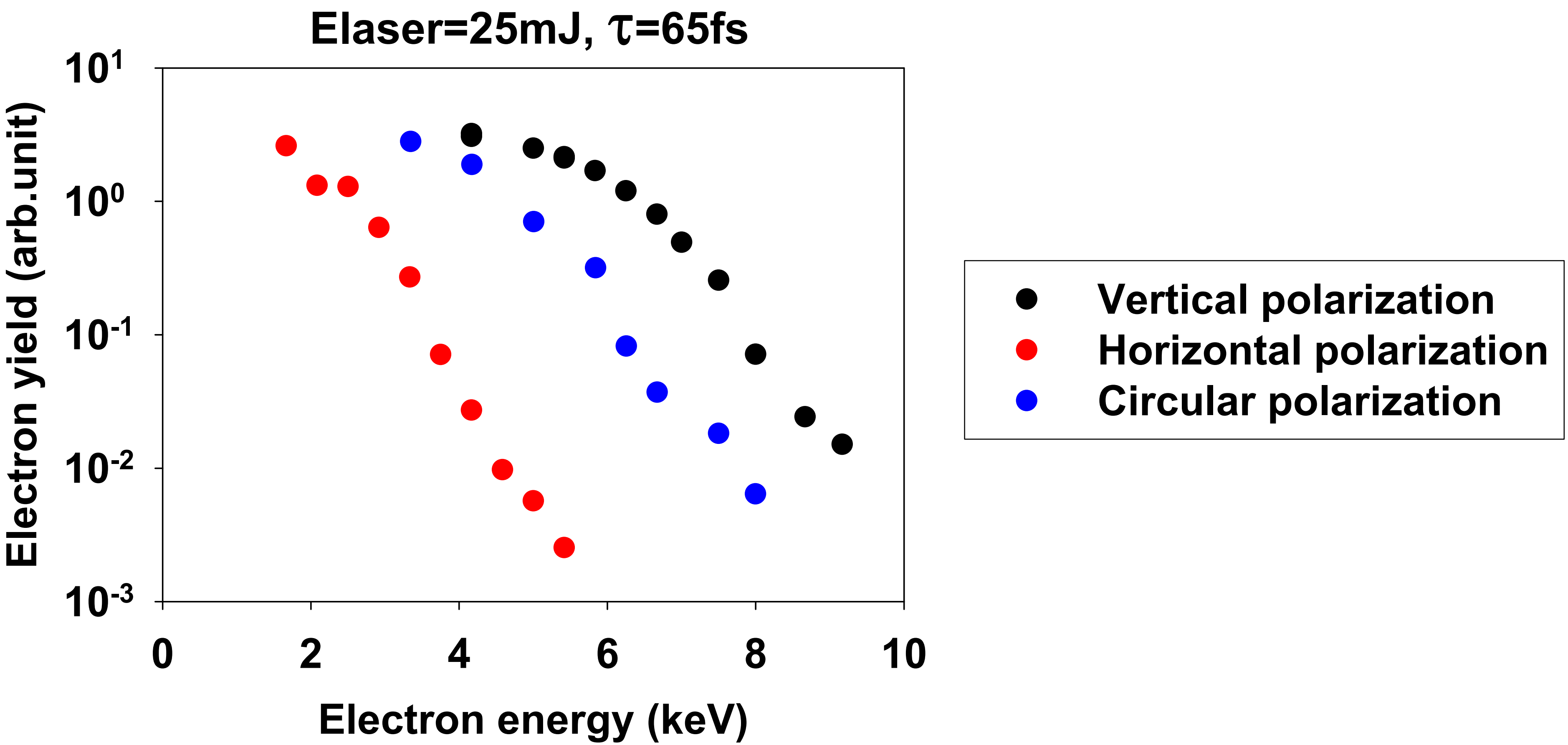
a mean field classical transport simulation



at a given τ=85 fs

N=$4 \cdot 10^4$ atoms
I=$5.3 \cdot 10^{15}$ Wcm^{-2}

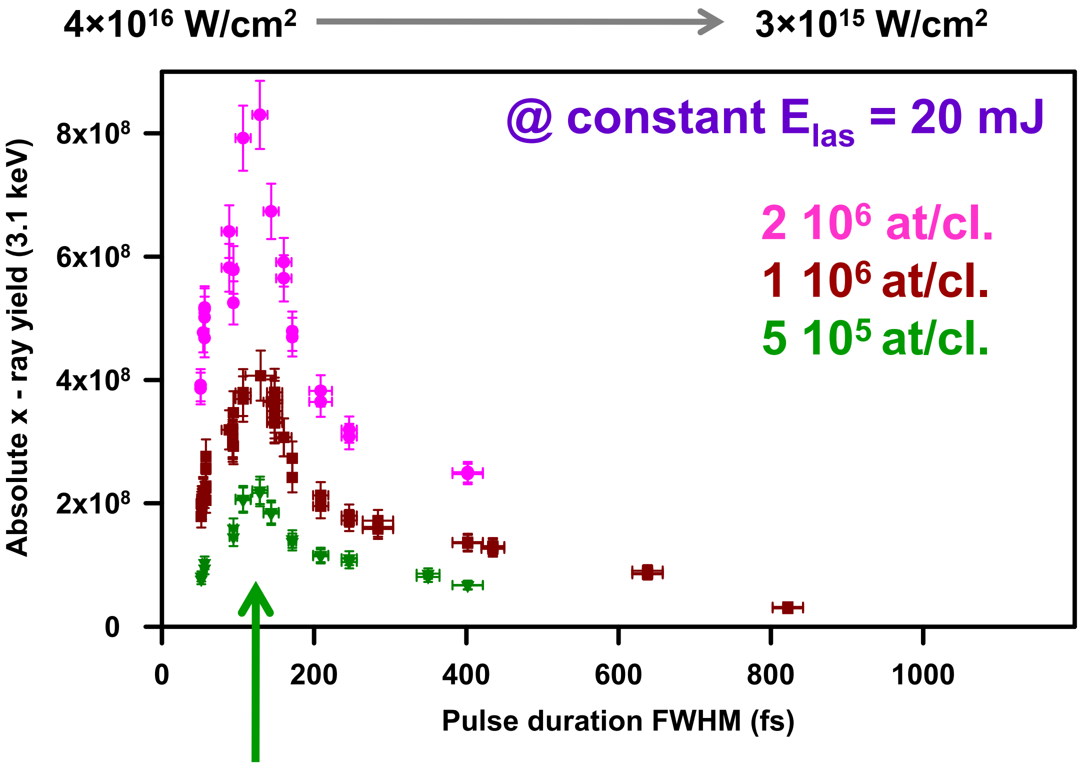


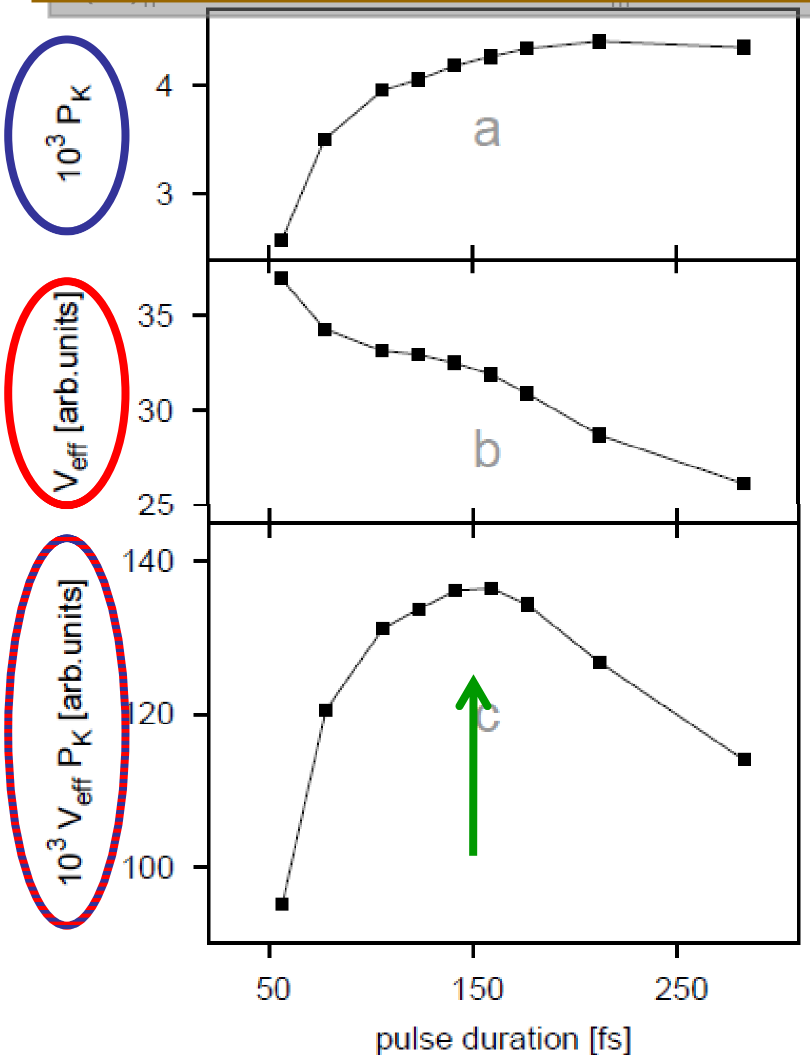


Vertical polarization: electrons are collected in the direction of the laser polarization
Horizontal polarization: electrons are collected in the direction perpendicular to the polarization of the laser

Absolute X-ray yields *vs* τ

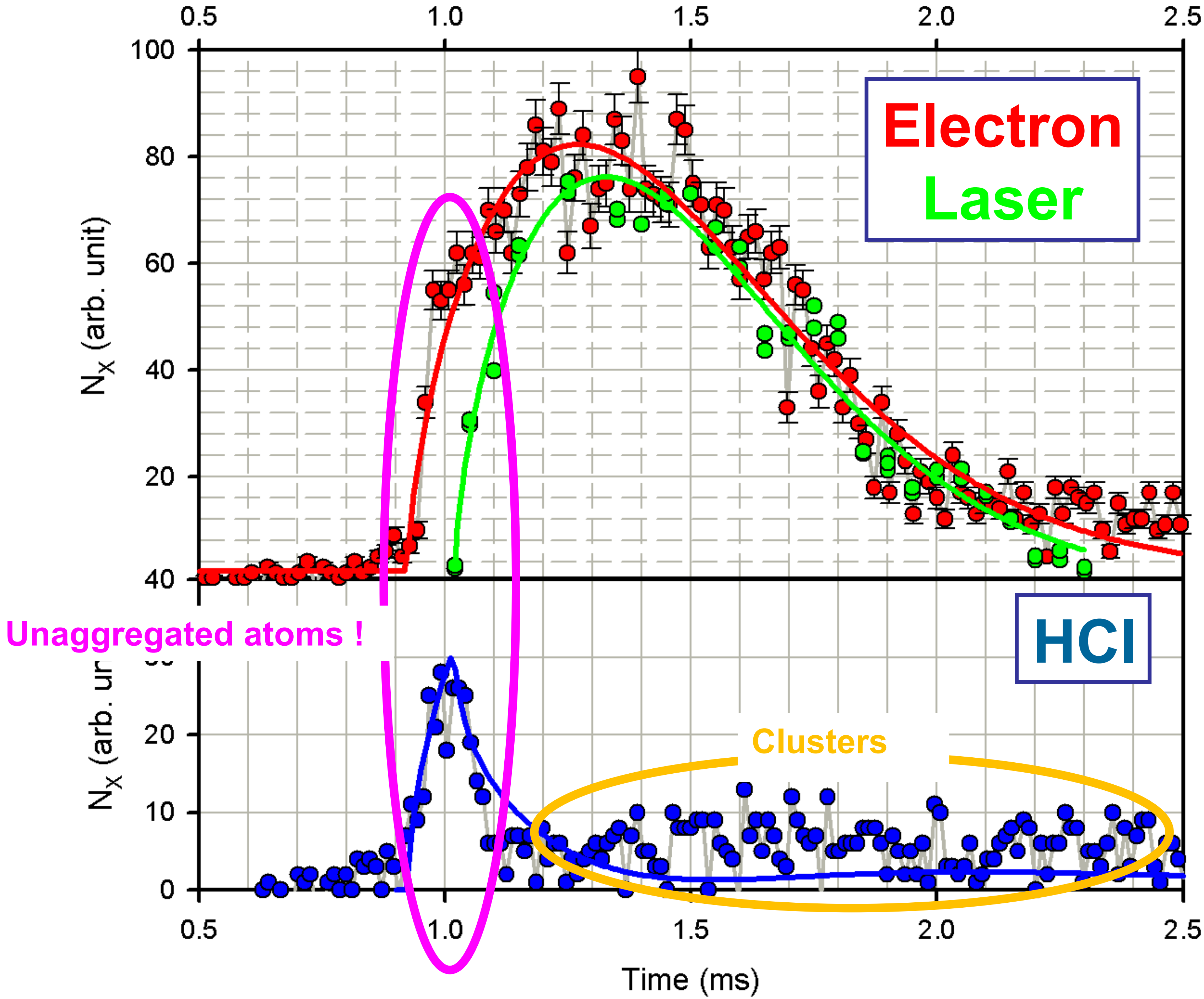
(Ar)$_n$: 4×10^4 at/cl, λ = 800 nm, d$_m$~10^{17} cm^{-3}





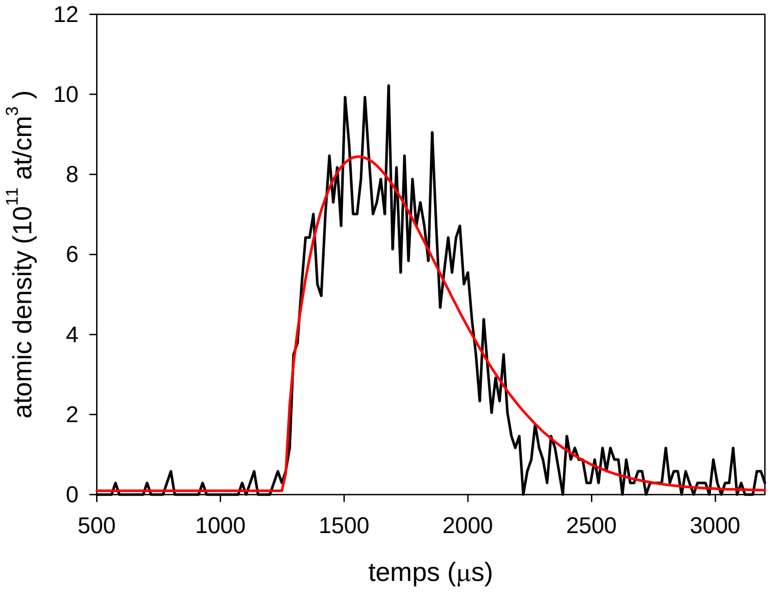
$N_X \propto P_K(I_{peak}, \tau) \times V_{eff.\,foc.}(I_{peak}, \tau)$

competition between $N_{X/cl.}$ (via P_K) and n_{cl} (via $V_{eff.\,foc.}$)



Electron
Laser
HCl
Unaggregated atoms !
Clusters
N_X (arb. unit)
Time (ms)

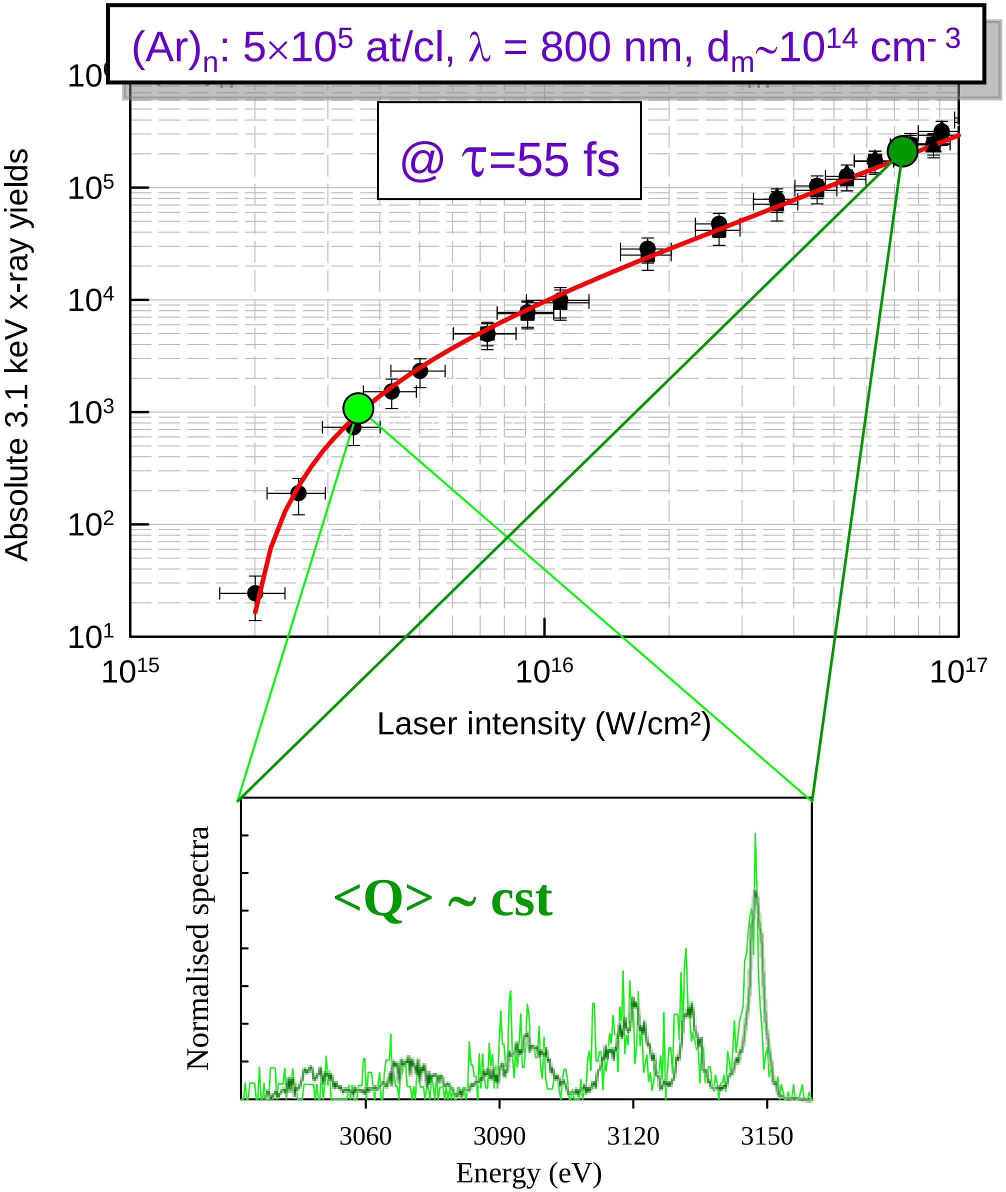
Better knowledge on the cluster jet as the atomic density, the clustering rate…



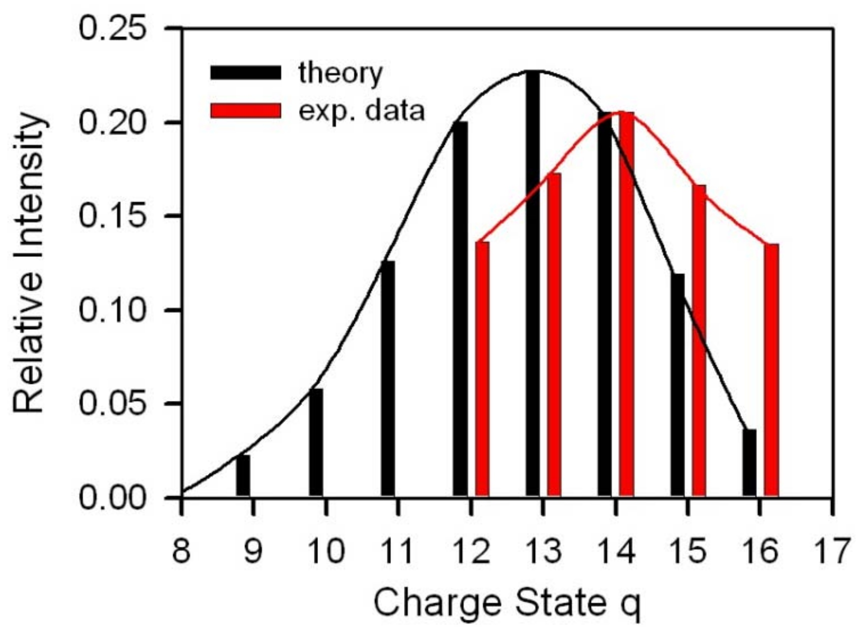
(under progress)

Time dependence of the cluster jet profile for P_0 = 20 bars, an opening time of the valve of 500 µs and at a distance of 396 mm.

Charge state distributions



C. Prigent, C. Deiss *et al* PRA **78** (2008)



rather good agreement
for I > 10^{16} W/cm^2

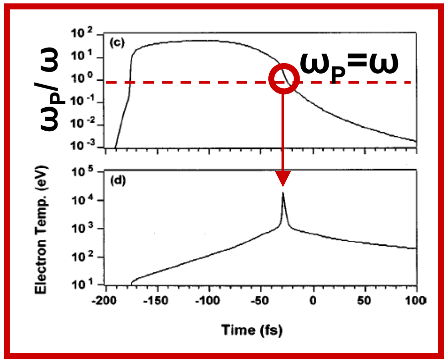
exp. & th. differ only by one q

short laser – cluster interaction

The main theoretical descriptions:

▶ **Nanoplasma model**

T. Ditmire et al., Phys. Rev. A 57, 369 (1999)
revisited by F.Megi et al., J. Phys. B, 36, 273 (2003)



- tunnel ionization (W_{tun}) + collisionnal ionization (W_{coll})
- electron oscillation due to E_{int} + Inverse Bremsstrahlung (*via* $\nu_{électronique}$)
- Cluster explosion *via* coulomb effect and hydrodynamic pressure

resonance: $n_e = 3.n_c \Rightarrow$ amplification of E_{int}

short laser – cluster interaction

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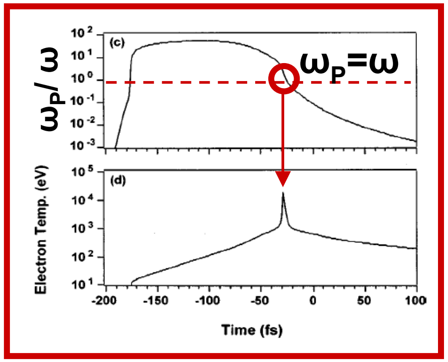
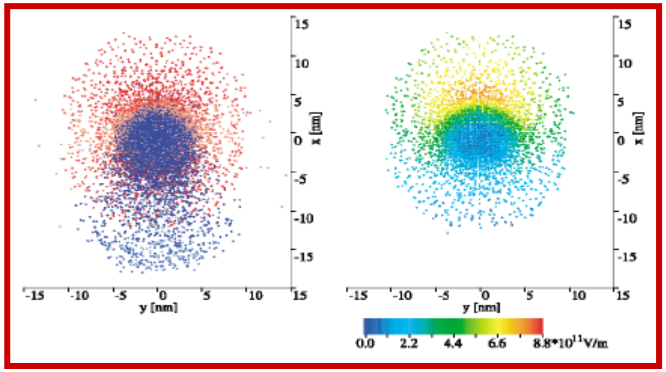




▶ Molecular dynamics simulations - MPIC

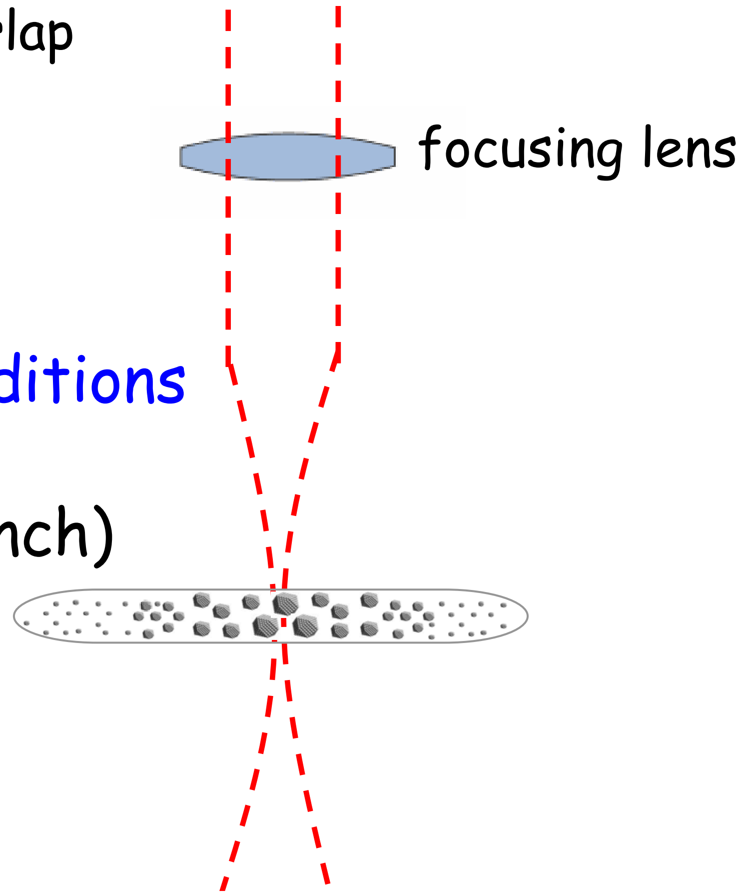
K. Ishikawa and Th. Blenski , PRA 62, 063204 (2000)
C. Jungreuthmayer et al., PRL 92, 133401 (2004)

- field ionization + electronic impact ionization
- Calculation of the electric field around each particle; electron and ion motions are followed

the role of cluster polarization
for the production of fast multicharged ions

Experimental method

Control of the spatial and temporal overlap
between
the laser pulse and the cluster bunch

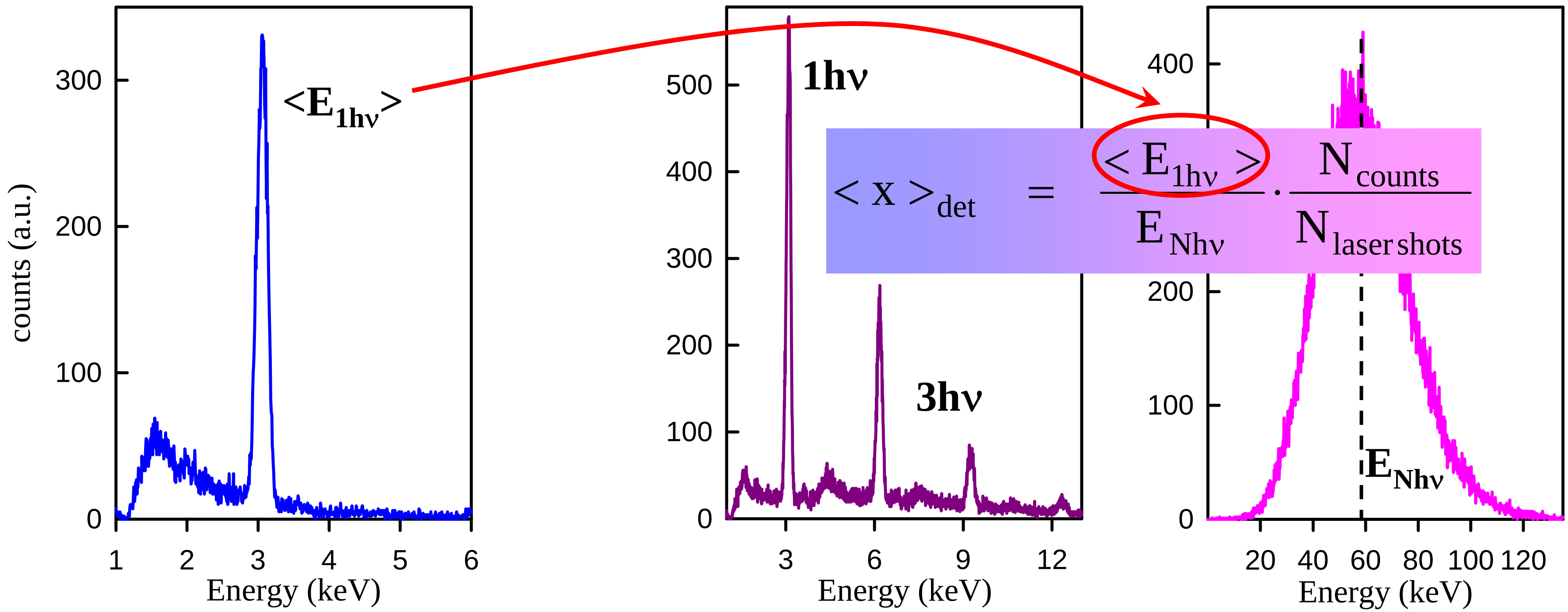


reproducible experimental conditions
shot by shot
(one laser shot for one cluster bunch)

Optimisation of the X-ray signal

Two semiconductor detectors : make use of pile-up process

Counting rate << 1 hν/shot ~ 1 hν/shot >> 1 hν/shot



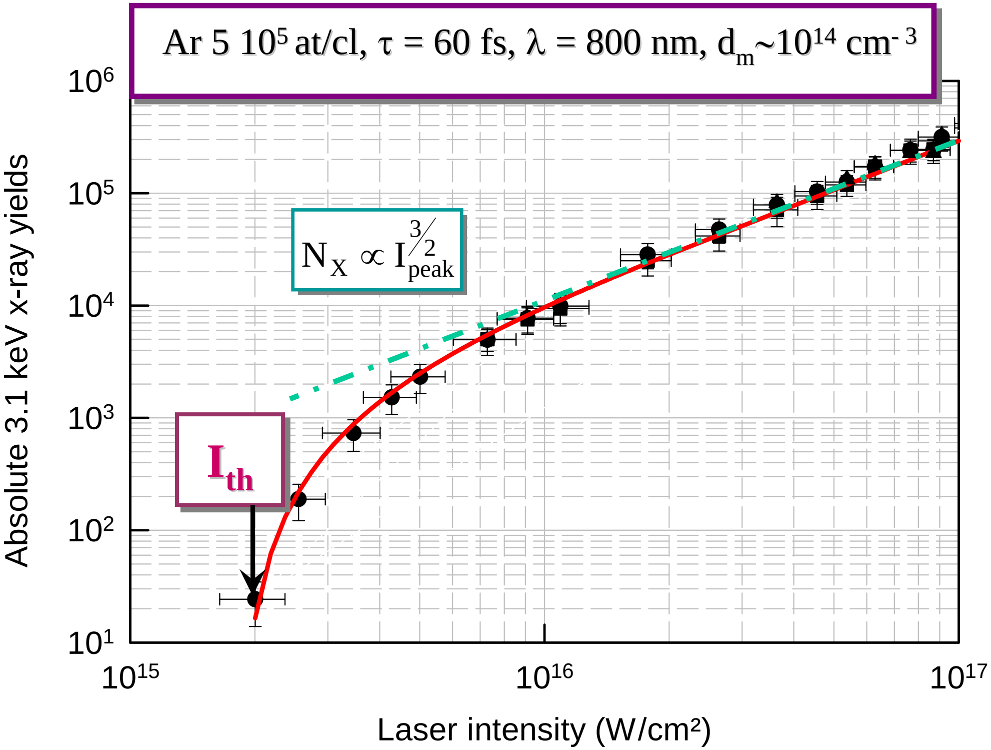
$$\langle x \rangle_{det} = \frac{\langle E_{1h\nu} \rangle}{E_{Nh\nu}} \cdot \frac{N_{counts}}{N_{laser\,shots}}$$

Single photon spectrum Poisson's distribution Gaussian distribution

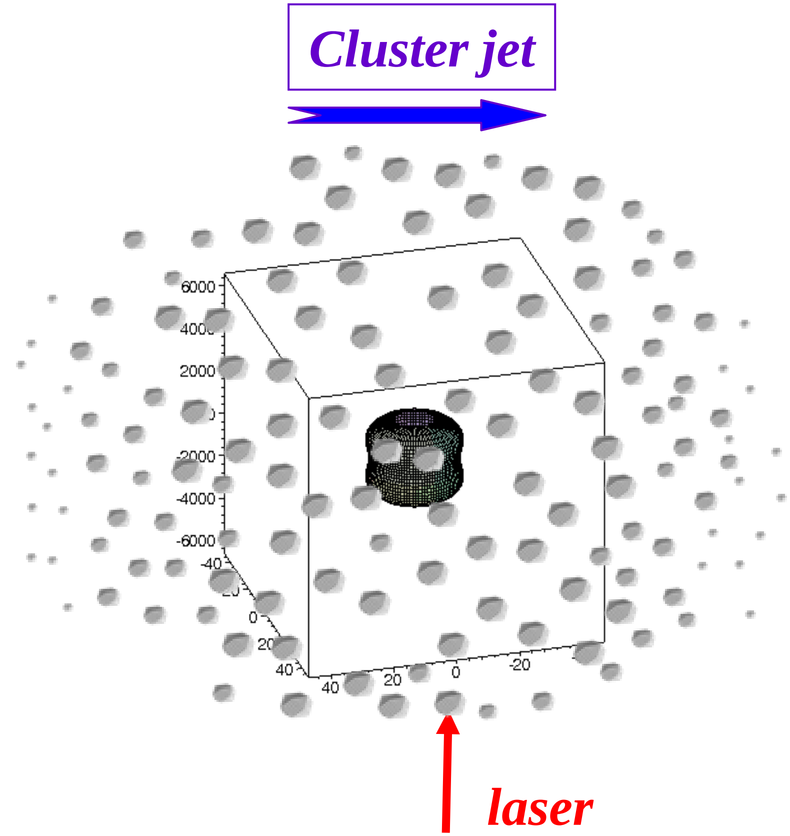
Absolute x-ray yields over 4 orders of magnitude

example: from 10^5 up to $2\ 10^9$ photons/laser shot in 4π (argon clusters)

Evolution with the laser intensity



Lamour, Prigent, Rozet, Vernhet NIMB **235** (2005)
Deiss, Burgdörfer *et al* PRL **96** (2006)



$V_{eff\ foc}(w_0, \lambda, I_{laser}, I_{th}) \neq V_{nom\ foc}(w_0, \lambda)$

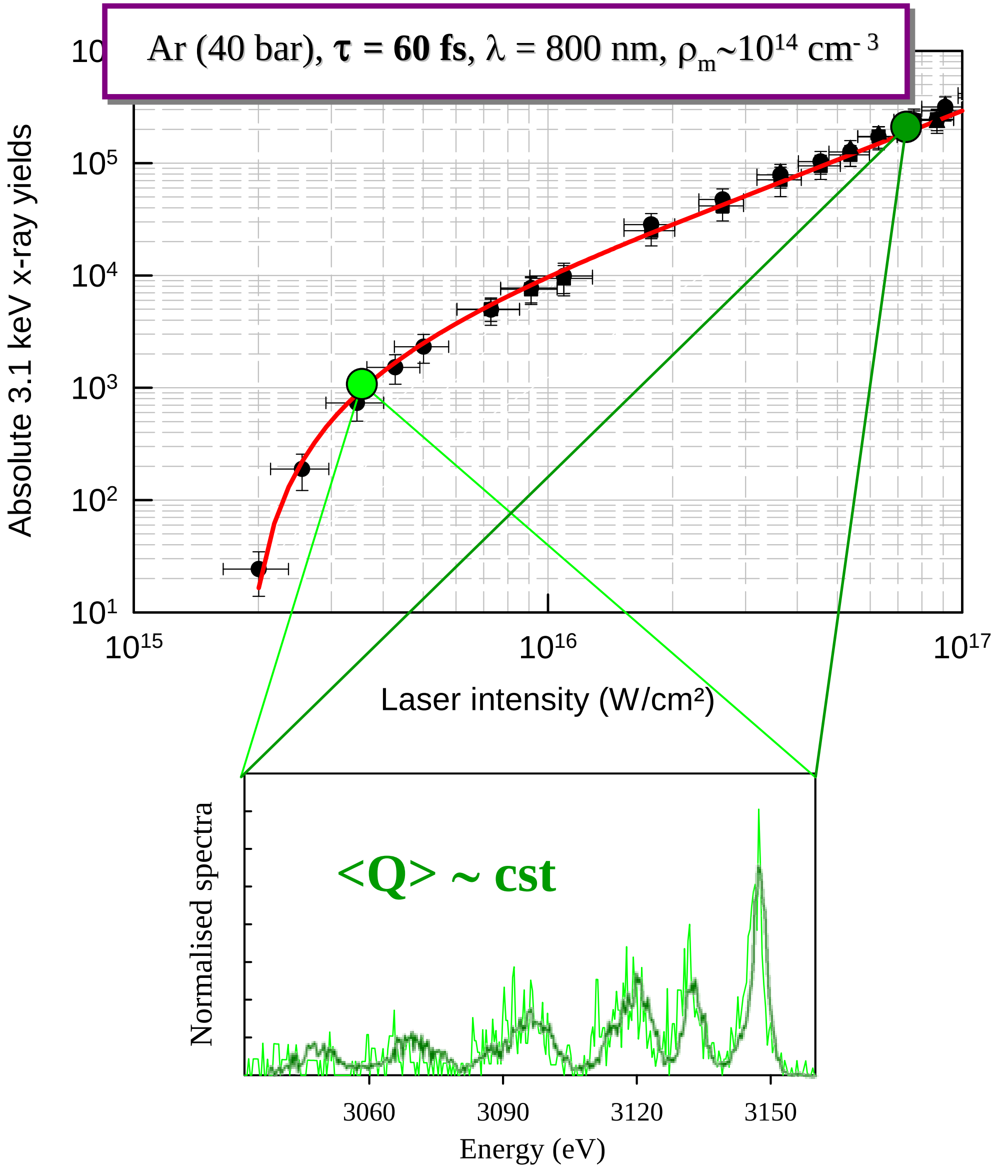
a direct outcome for $I_{laser} > I_{th}$ $P^{ionisation}_{inner\ shell} \approx cst$

$V_{eff.foc.} = \frac{(\ldots)}{\lambda}\left\{\frac{\ldots}{3}\cdot\left(\frac{I_{peak}}{I_{th}}-1\right)^{3/2}+\frac{\ldots}{9}\cdot\left(\frac{I_{peak}}{I_{th}}-1\right)^{\ldots} - \frac{4}{3}\cdot\mathrm{arctg}\left(\frac{I_{peak}}{I_{th}}-1\right)^{1/2}\right\}$

~ 10^{-5} for $(Ar)_n$

from 3 10^{-4} to 10^{-3} for $(Xe)_n$

Evolution with the laser intensity



$N_X \propto V_{eff\ foc}$

✓ a direct outcome

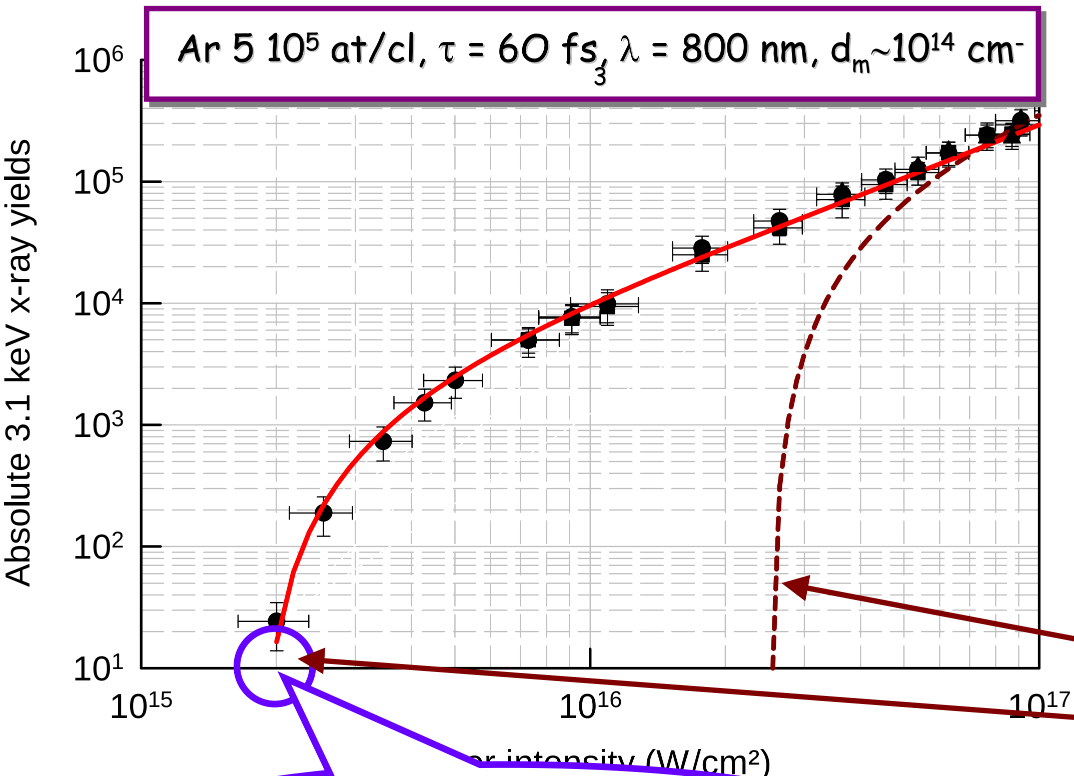
$$P_{x-ray/at} = \frac{N_x}{< n >_{eff}} \approx \text{constant}$$

with $< n_{eff} >= \rho \times V_{eff.foc}$

✓ In addition :

Saturation of the ionisation probabilities for L and K shells

Absolute X-ray yield versus laser intensity



Exp.: ~ 2 10^{15} W/cm²

I_{th}??

the "heating" processes?

"Optical Field Ionisation"

Ar^{16+} (1s) → 4.0 10^{21} W/cm²

Nanoplasma model

Ditmire *et al.*, Phys. Rev. A **53** (1996)

Megi *et al.*, J. Phys. B **36** (2003)

I< 10^{16} W/cm² → Te < 80eV

Ponderomotive energy

2Up = 3 to 4 keV → 2-3 10^{16} W/cm²

2Up = 260 eV ← 2 10^{15} W/cm²

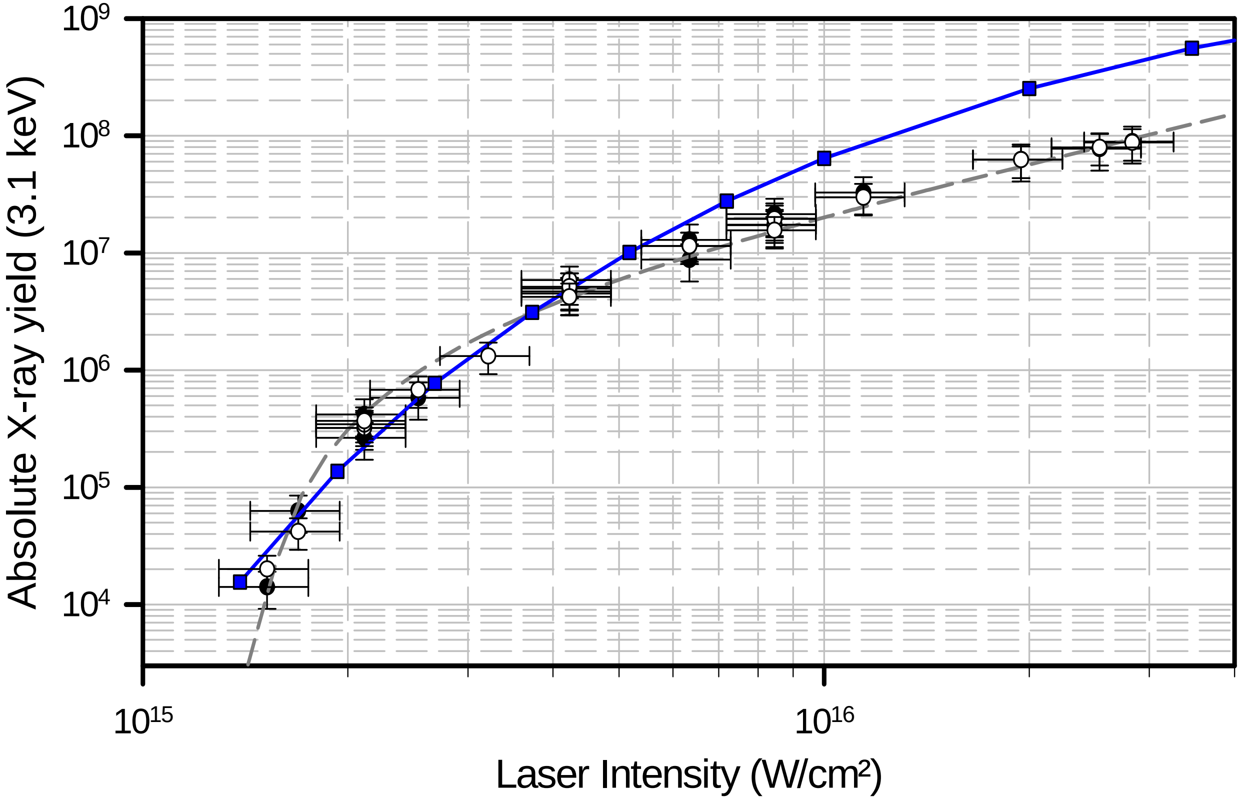
additional heating mechanisms for electrons in clusters?

Lamour et al, NIM B **235** (2005) 408

Prigent, PhD thesis (2004); http://tel.ccsd.cnrs.fr/tel-00008159

Comparison with experiment: N_X versus I

Ar (40bar): <N>= 5 10^5 at/cl, τ = 60 fs, λ = 800 nm, d_m~10^{14} cm^{-3}



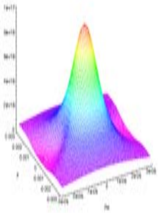
fluorescence yield

ω_f = 0.25

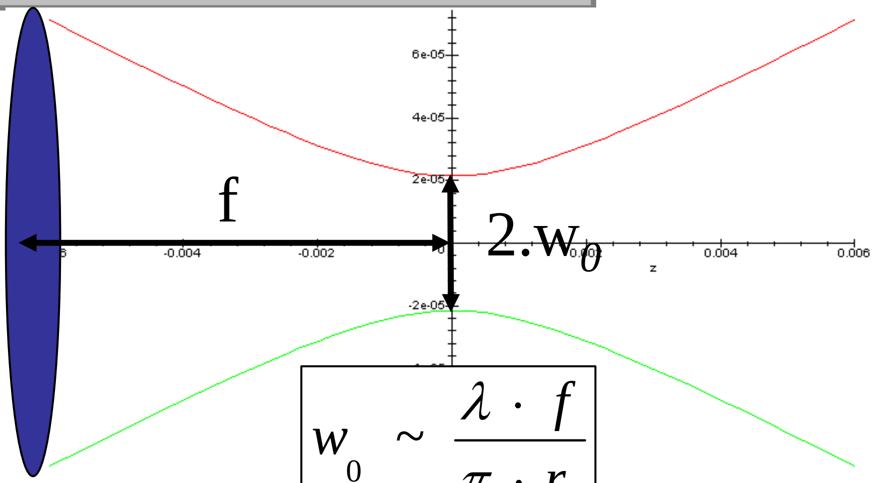
clustering rate

33%

Laser intensity: spatial distribution



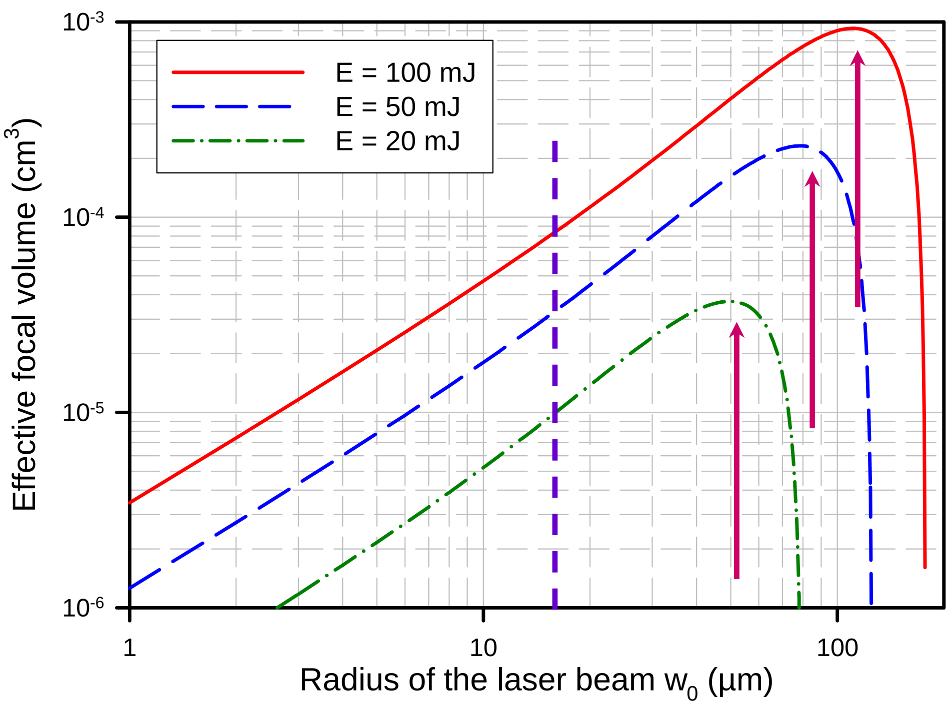
Consequence on the optimization of the x-ray yield …



$$w_0 \sim \frac{\lambda \cdot f}{\pi \cdot r_0}$$

$N_X \propto V_{eff\ foc}(I_{th})$

I_{th} = 1.4 10^{15} W/cm² for τ = 65 fs



Prigent, Deiss et al. Phys. Rev. A 2008

max. X-rays ⇒ optimum $V_{Eff.\ Foc.}$

defocusing up to a quite large w_0 !!

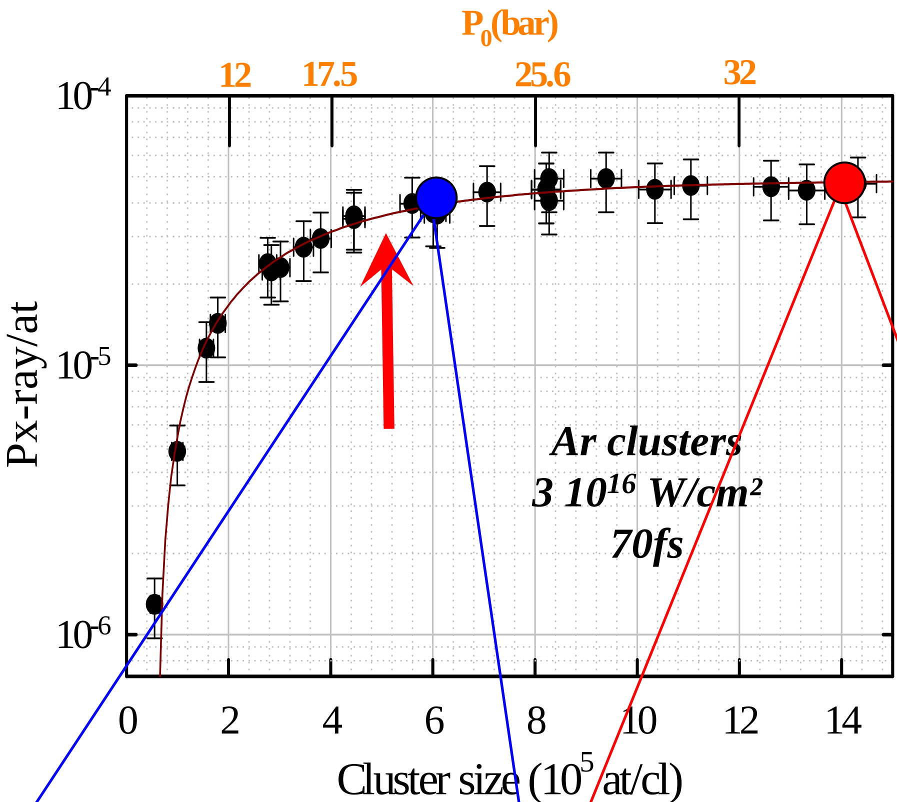
(in our experiment : w_0 ~ 16 µm)

up to 10^9 hν/ pulse in 4π for Ar_n

energy conversion ~ 10^{-2}%

Cluster size dependence on the x-ray emission probability

Experimentally $\mathbf{P_0} \Rightarrow \tilde{N} \propto \mathbf{P_0}^{1.8}$ and $\rho_{mean} \propto \mathbf{P_0}$



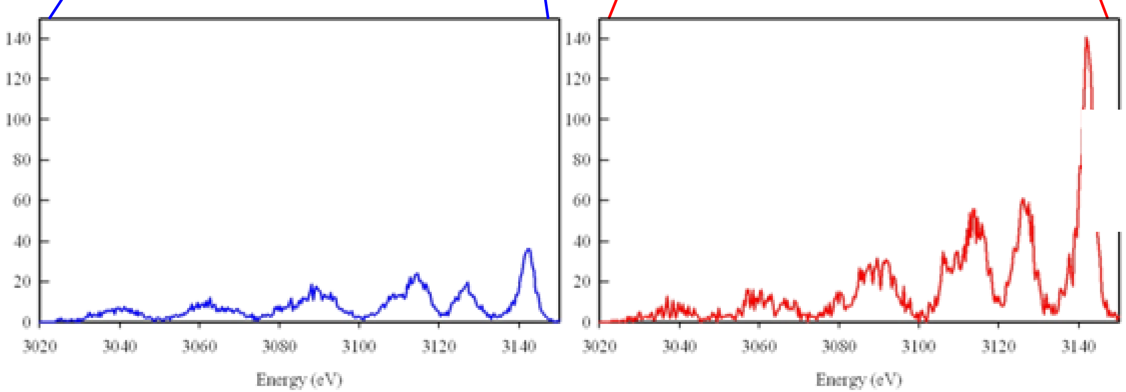
$$P_{x-ray/at} = \frac{N_x}{<n>_{eff}}$$

with $<n_{eff}> = \rho \times V_{eff.foc}$

***$V_{eff.foc}$ = cst** (whatever the size for a given τ)*

Saturation of the x-ray production above a given cluster size

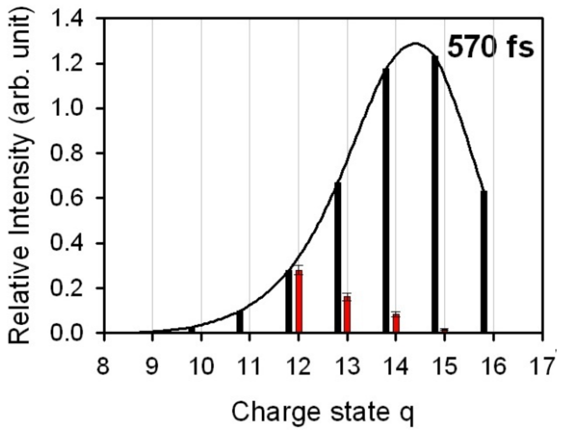
$N_x \propto P_0$ increase with the number of partners in $V_{eff.foc}$ in the saturation region

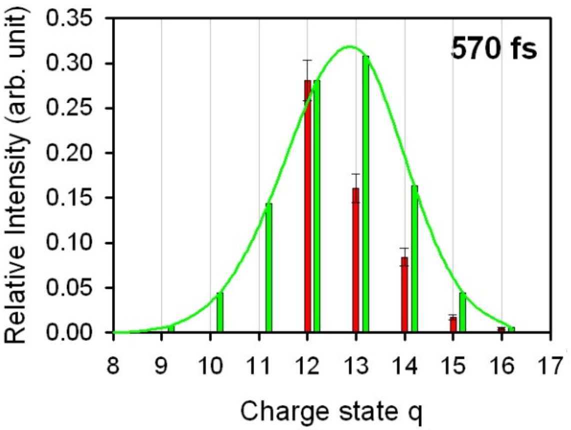


<Q> still increases somewhat
⇒ Increase of L shell ionisation

Comparison with the simulations: charge state distribution

Simulations with shielding	***Simulations without shielding***





Two limiting cases:

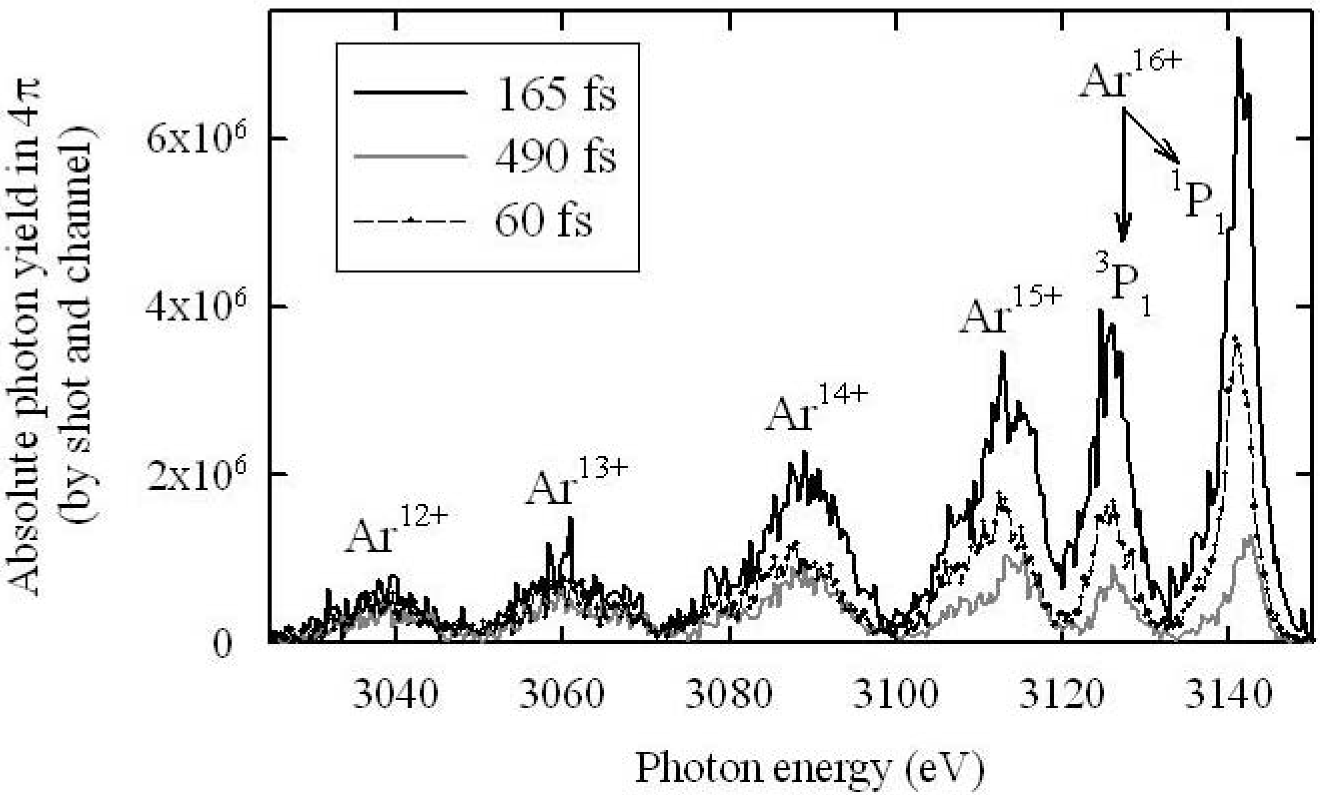
i) $q_i^{eff}(t)$ ionic charge reduced (shielded) by the surrounding free electrons. Particularly valid when electrons are slow (low laser intensities).

ii) $q_i(t)$ ionic charge without any shielding. Valid when electrons are too fast to be strongly influenced by ions (high laser intensities).

Influence on the description of the ion expansion

Evolution of the charge states with the pulse duration τ

Ar <N>= 1 10^6 at/cl, λ = 800 nm, E= 9mJ

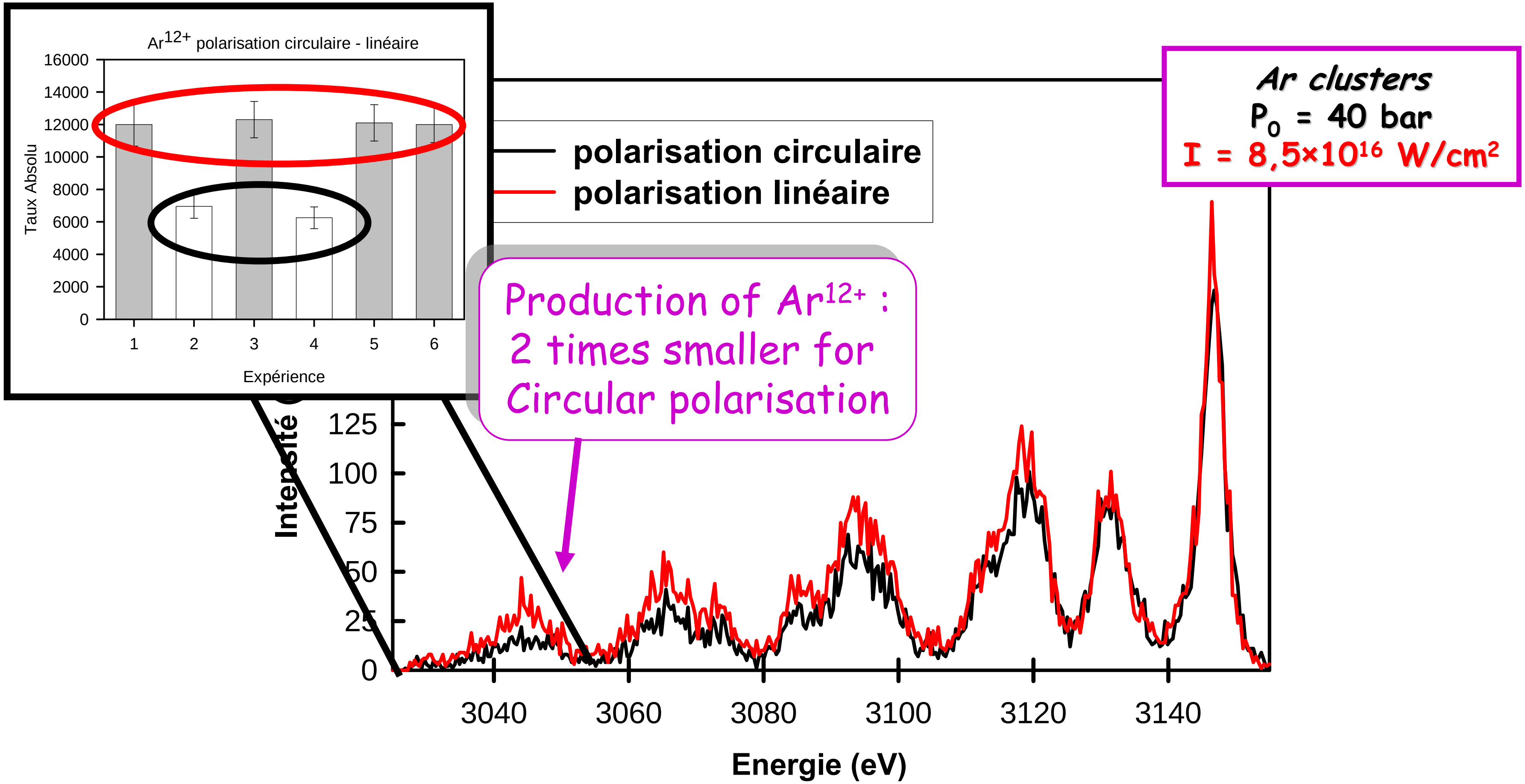


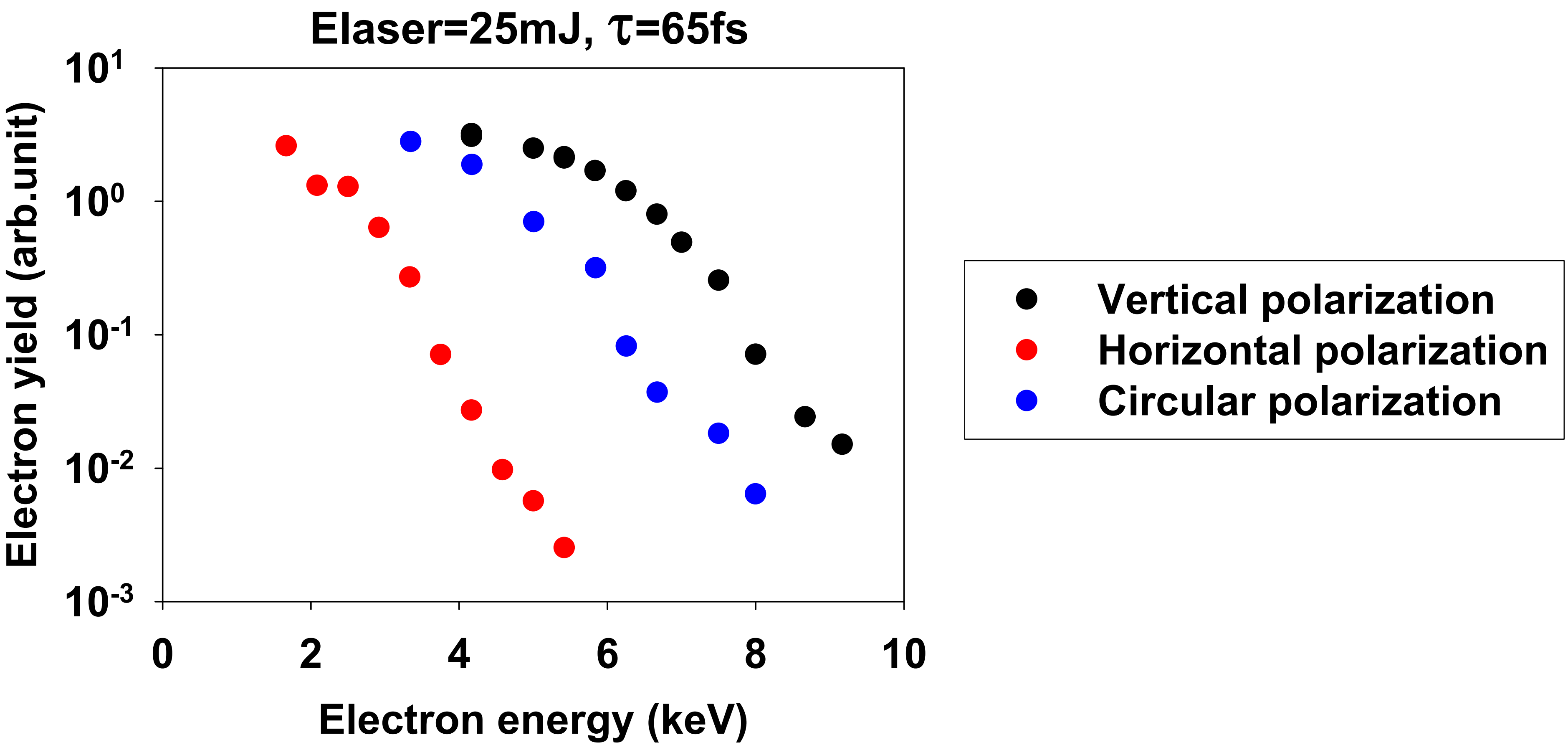
E. Lamour et al., J. Phys, 88, 012035 (2007)

Dependence with the laser polarization

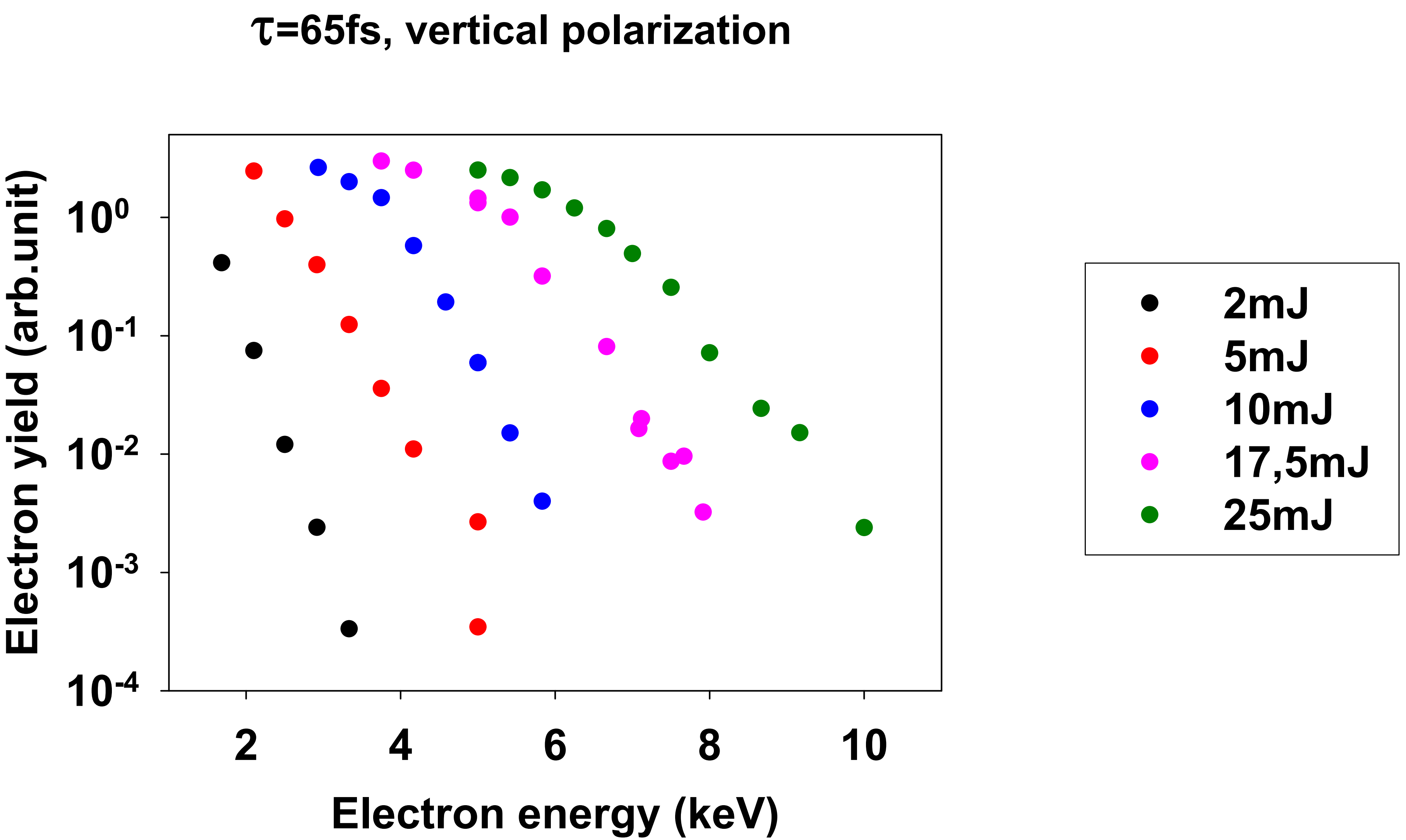
- very weak difference between linear and circular laser polarization

N_X (circular) = 80% × N_X (linear)



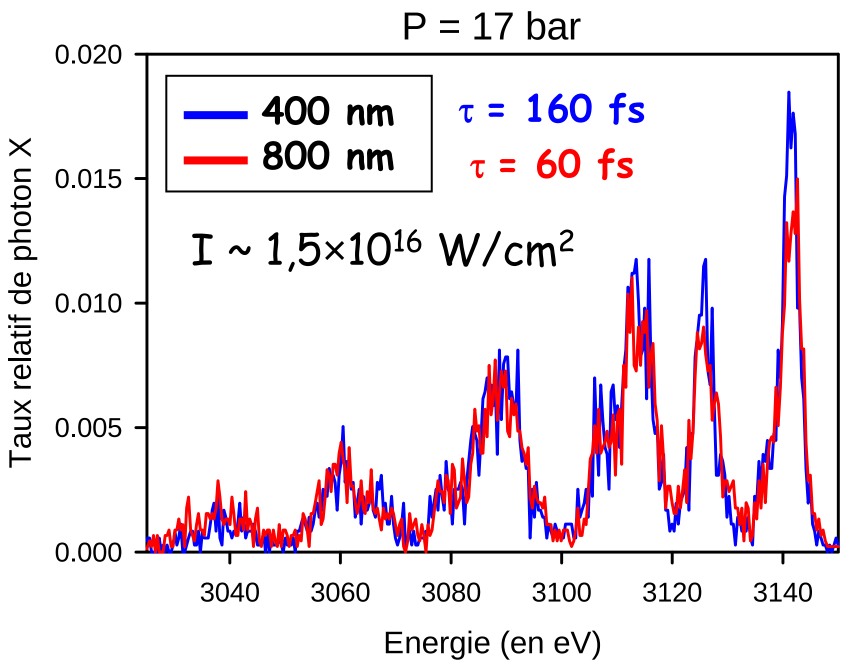


Vertical polarization: electrons are collected in the direction of the laser polarization
Horizontal polarization: electrons are collected in the direction perpendicular to the polarization of the laser


τ=65fs, vertical polarization
Electron yield (arb.unit)
10^0
10^-1
10^-2
10^-3
10^-4
2
4
6
8
10
Electron energy (keV)
2mJ
5mJ
10mJ
17,5mJ
25mJ

Evolution with the laser wavelength λ (800 versus 400 nm)

Argon cluster



Same charge state distribution

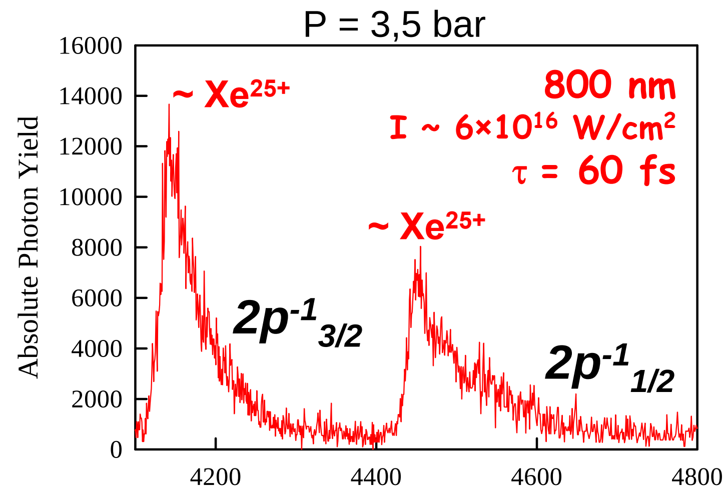
For Ar or Xe

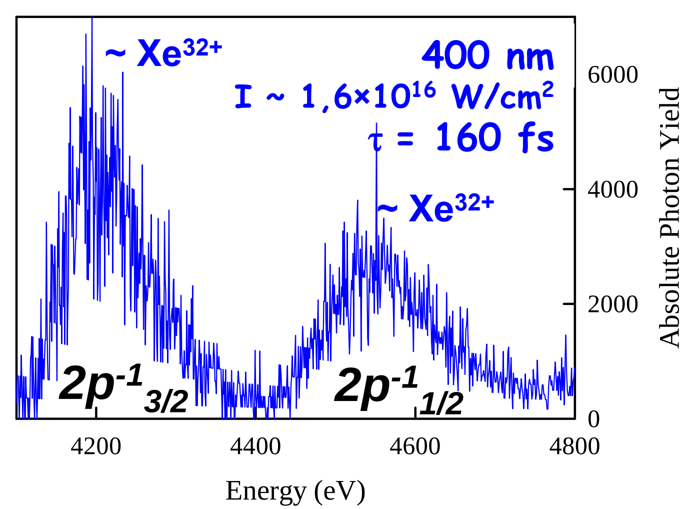
τ , I and N comparable:

N_X(800 nm) ~ 10 × N_X(400 nm)

~~N_X(800 nm) << N_X(400 nm)~~ (QP model)

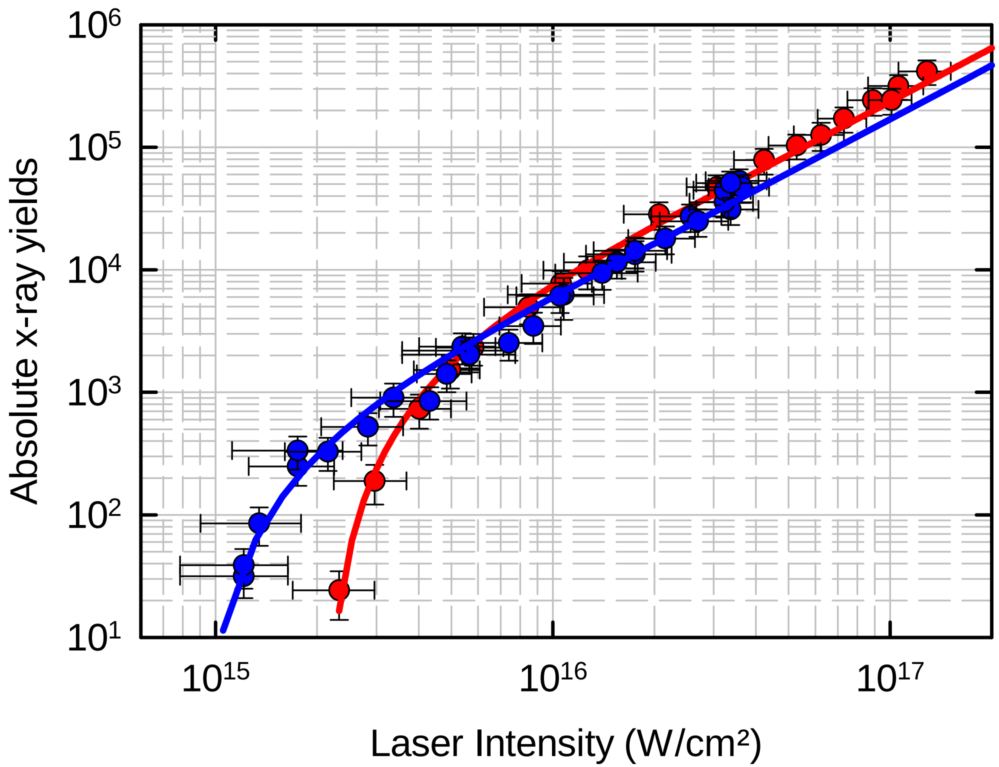
Xenon cluster

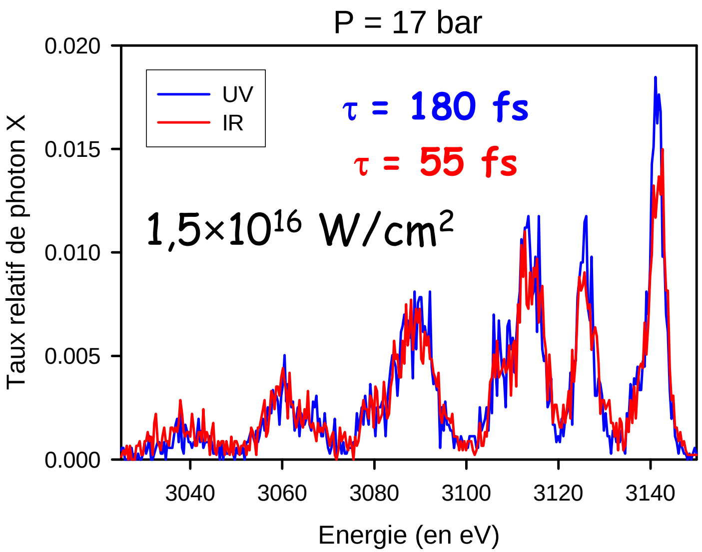




Different charge state distribution

Influence of the laser wavelength





λ (nm)	τ (fs)	I_{th} (W/cm²)
800	55	~ 2.2×10^{15}
400	180	~ 1×10^{15}

τ , I and size comparable:

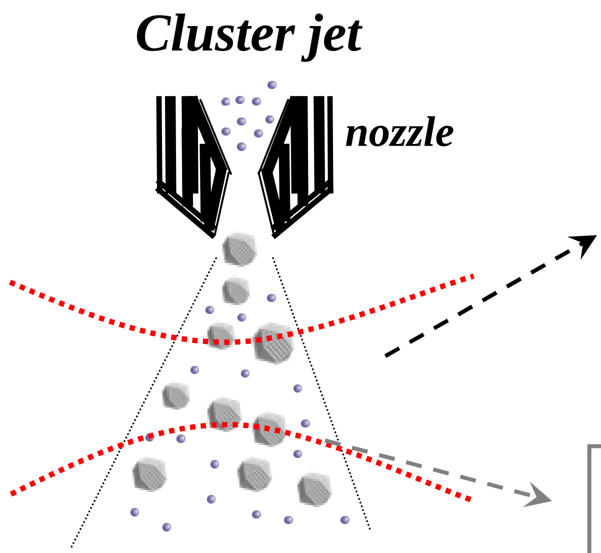
N_X(800 nm) ~ 10 × N_X(400 nm)

Van der Waals clusters in intense laser fields

Strong optical fields

F > 10^9 V/cm

$E_{h\nu}$ ~ 1.6 eV / 3.2 eV



production of HCI
with E_{kin} from keV to MeV
($Xe^{q<40+}$, $Ar^{q<14+}$)

ejection of hot electrons
(E_{kin} ~ keV)

connected to both plasma
and cluster explosion dynamics

Information on a µs time scale: after the laser pulse and the cluster disintegration

An incomplete list of several studies:

T. Ditmire, J. Marangos, J. Tisch *et al.*, Nature **386** (1997)
M. Vrakking *et al.,* Phys. Rev. A **68** (2003)
D. Mathur *et al.,* Phys. Rev. A **66** (2002), A **69** (2004) …
H. Ueda, Y. Kishimoto *et al.,* Phys.Rev. A **67** (2003)
E. Skopalová, J.Tisch, J.P. Marangos et *al*. PRL **104** (2010)

Scenario of the dynamics of a single cluster

charging up of the cluster & polarization of the cluster
➔ a strong asymmetry of the electric field, $F_z(z)$

Field enhanced by charging of the cluster and polarization of the cluster

Laser field screened by polarization of the cluster