KeV photons and electrons induced by laser pulses on clusters

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Outline

- some properties of intense laser - cluster interaction
  a short overview of the scientific context

- specificities of the experiments to test the dynamics
  & the mean field simulation based on CTMC

- results focused on:
  - x-ray yields versus laser intensity
    comparison for x-ray yield & charge state distributions
  - evolution with the pulse duration
    x-ray yields & electron energy distributions

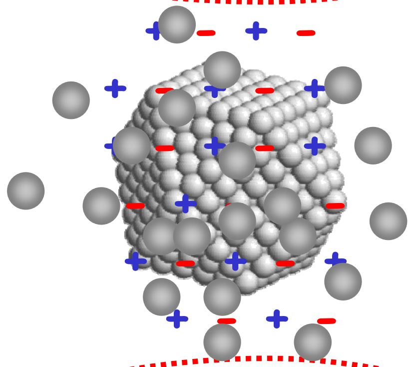
- conclusions

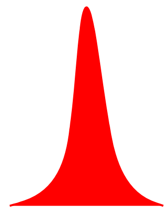
Clusters in intense laser fields

Strong optical fields

$F > 10^9$ V/cm

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





Creation of nanoplasmas

time scale ~ pulse duration

+

Expansion and explosion of heated clusters

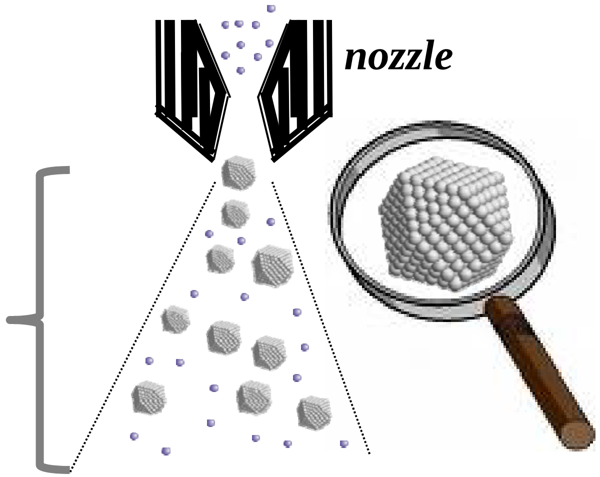
very efficient energy coupling

Van der Waals clusters….why?

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

λ_{laser} >> ***skin depth*** ≥ $\phi_{cluster}$ ⇒ *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

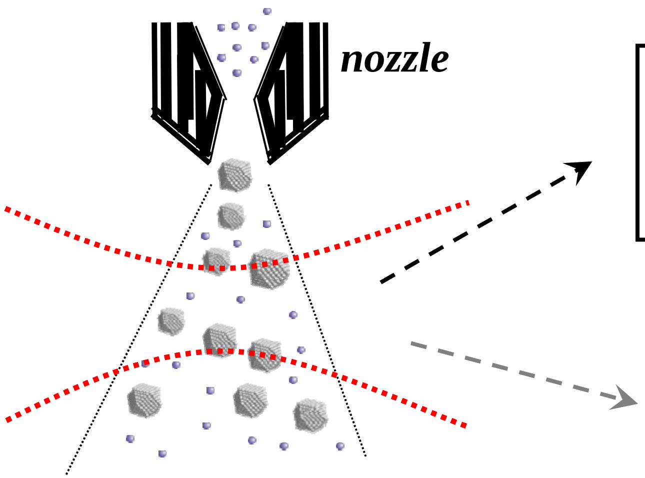
enhanced energy coupling

between light & matter

A cluster jet combines advantages of gaseous and solid targets

Van der Waals clusters in intense laser fields

Cluster jet



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)

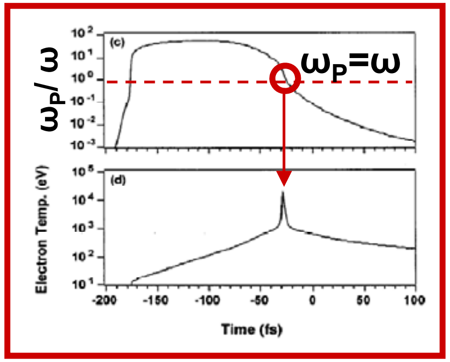
Clusters in intense laser fields

The main theoretical descriptions:

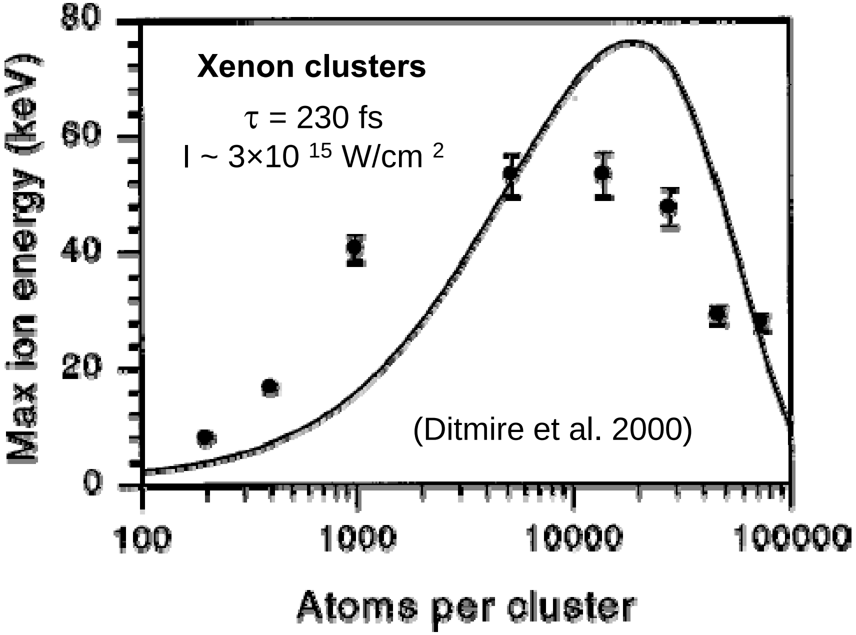
▶ Nanoplasma model

T. Ditmire et al., Phys. Rev. A 57, 369 (1999)

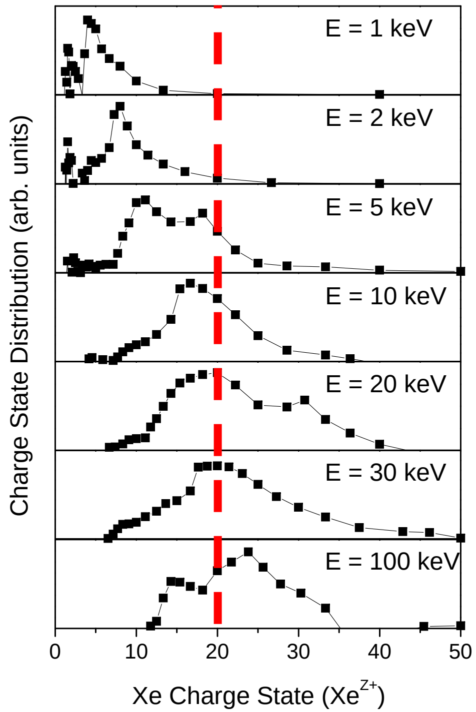
revisited by F.Megi et al., J. Phys. B, 36, 273 (2003)



Exp: **Ion energy distribution** but **not the high charge states**



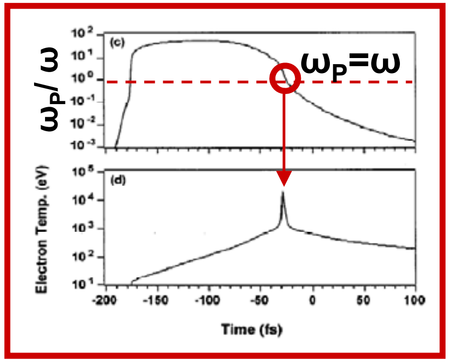
N ~ 2,3×10^3 atoms and I ~ 2×10^{16} W/cm^2



Ditmire et al 1997

Clusters in intense laser fields

The main theoretical descriptions:



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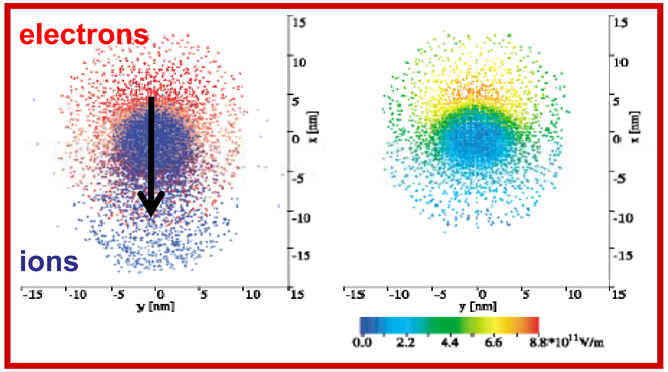


▶ **Molecular dynamics simulations - MPIC**

K. Ishikawa and Th. Blenski , PRA 62, 063204 (2000)

C. Jungreuthmayer et al., PRL 92, 133401 (2004)

Exp: **cluster polarization** but **small sizes**

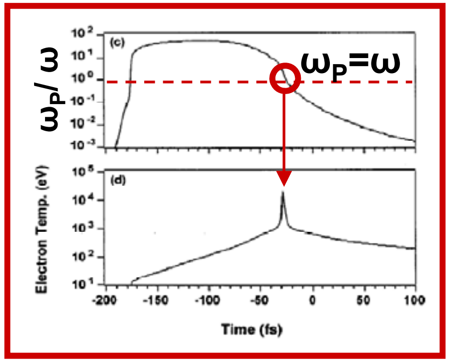
↓

Anisotropy in the ionic distribution

Production of fast multicharged ions

Clusters in intense laser fields

The main theoretical descriptions:



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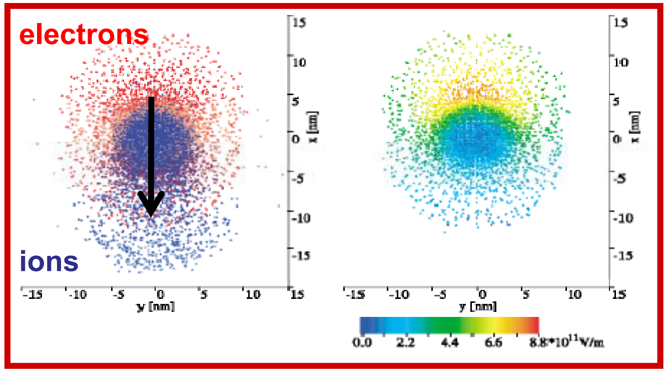

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C. Jungreuthmayer et al., PRL 92, 133401 (2004)

Exp: **cluster polarization** but **small sizes**

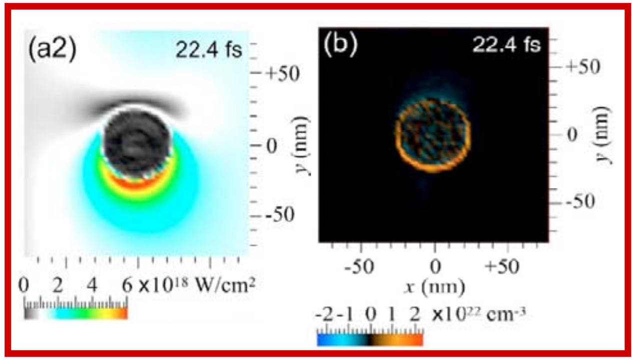
▶ Mean field approach - PIC

T. Taguchi, A. Gupta et al., PRL 92, 205003 (2004)

PRE 74, 046408 (2006)

Y. Fukuda et al., PRA 73, 205003 (2006)

Exp: **Energy absorption vs pulse duration for large clusters**



Reviews: VP. Krainov and MB. Smirnov, Phys. Rep. 370 (2002)

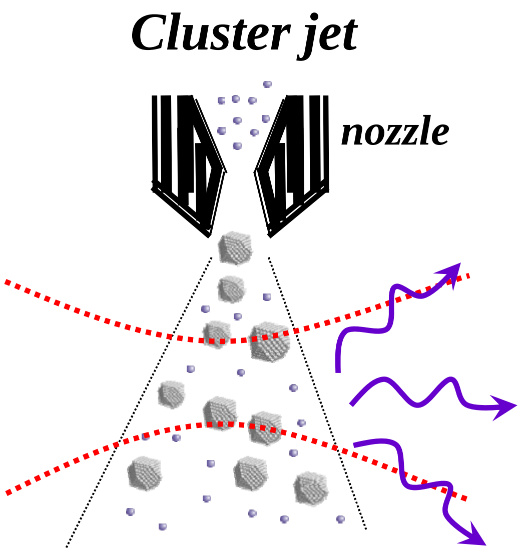
U. Saalmann et al., J. Phys. B 39, R39 (2006)

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



Emission of X-rays in the keV range

X_K(Ar) ~ 3.1 keV
X_L(Kr) ~ 1.7 keV
X_L(Xe) ~ 4.4 keV

efficient for converting photons from eV to keV even at moderate laser intensities

An incomplete list of several studies:

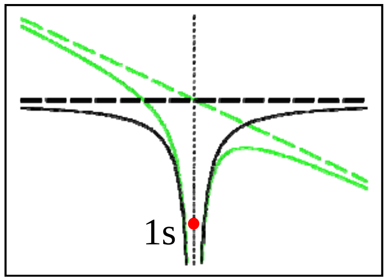
S. Dobosz *et al* PRA **56** (1997)
H. M. Milchberg *et al* PRE **62** (2000)
J.P. Rozet *et al* Phys.Scripta **T92** (2001)
V. Kumarappan *et al* PRA **63** (2001)
F. Dorchies et *al* PRE **71** (2005)
L.M. Chen et *al.* PRL **104** (2010)

Van der Waals clusters in intense laser fields

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

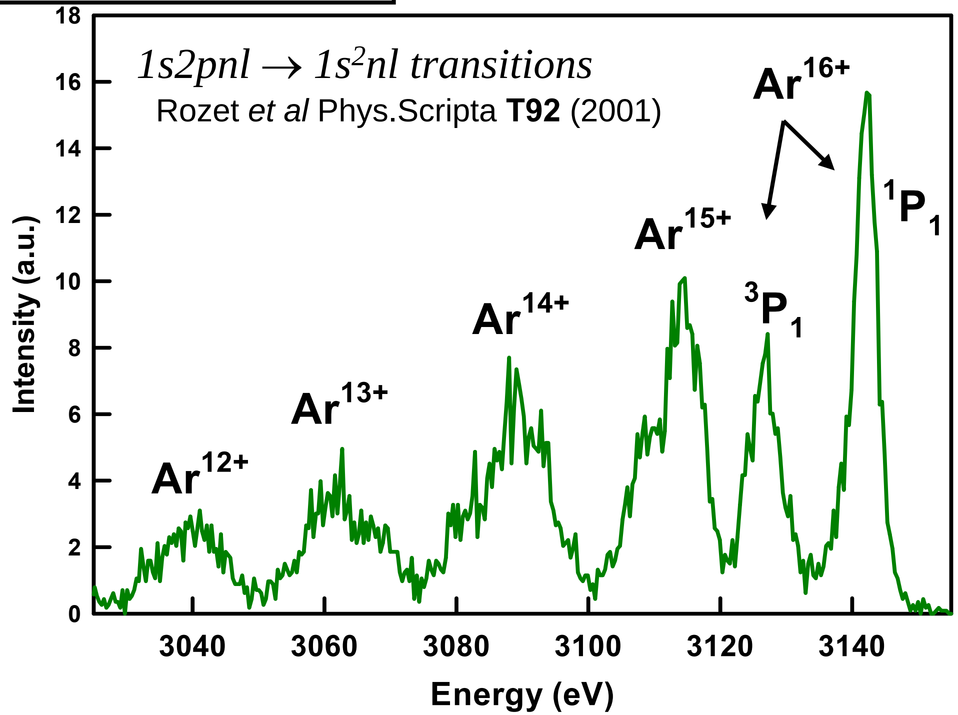
⇒ **Deexcitation of HCl with inner shell vacancies**

Direct insight into the early evolution of the nanoplasma



Inner shell vacancy by OFI

Ar^{16+} (1s) → ~~4 10^{21} W/cm²~~

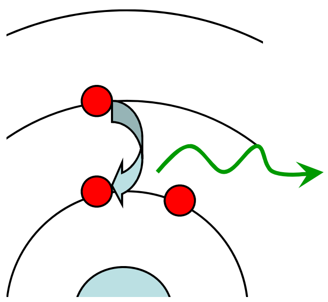


up to Ar^{16+} with $\tau(^1P_1)$ = 15 fs

time scale down to some fs

Van der Waals clusters in intense laser fields

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



$h\nu = 3.1$ keV

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

heating mechanisms are needed

Van der Waals clusters in intense laser fields

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

What are the heating mechanisms?

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

Our goal: **to test the nanoplasma dynamics**

❑ ***Quantitative measurements of***
- ✓ absolute photon emission yields
- ✓ charge state distributions
- ✓ high energy electron distribution

as a function of different parameters
- ✓ I_{peak} , τ , λ , polarization
- ✓ species, P_0 (size), ρ_m

❑ ***Development of the first model giving absolute photon yields***
- ✓ based on a mean field Monte – Carlo approach

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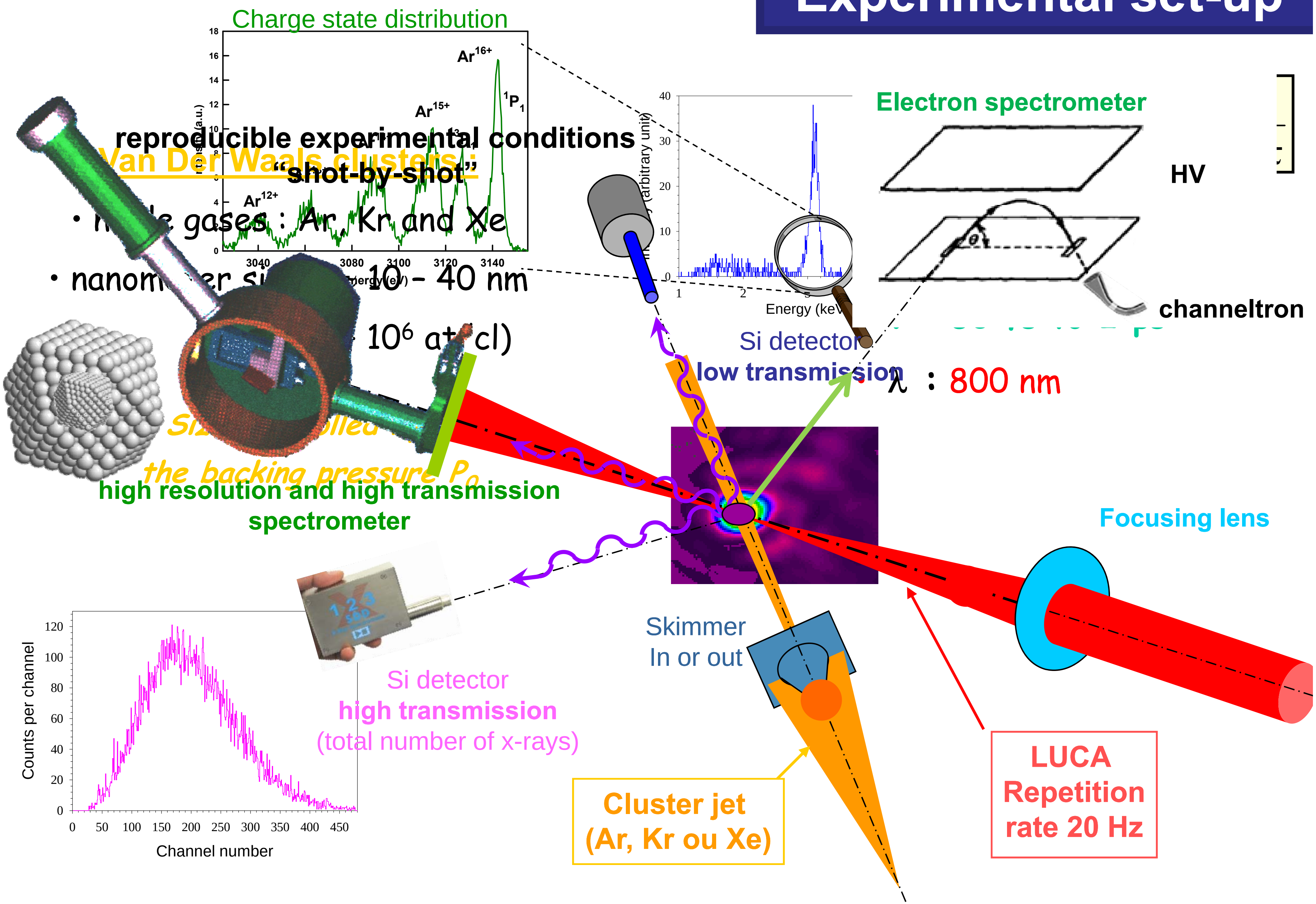
Experimental set-up



Mean field classical transport simulation

C. Deiss, J. Burgdörfer, J. Phys, 88, 012036 (2007)

- ❑ test particle discretization

~10^5 atoms → $N_{\text{test}} = 0.1 N_{\text{e}}$ ⇒ large clusters

- ❑ many-particle effects included via Monte Carlo events: *Langevin* equation

$$m_i \ddot{\vec{r}}_i = q_i(t)\left(\vec{F}_{\text{L}}(t) + \vec{F}_{\text{mean}}(\vec{r}_i, t)\right) + \vec{K}_{\text{stoc}}(\vec{r}_i, \dot{\vec{r}}_i, t)$$

Charge state is time-dependent for ions

Laser field

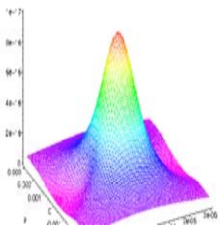
Mean field monopole & dipole

Stochastic forces:
- **elastic electron-ion scattering**
- **ionization mechanisms**
- **electron-electron scattering**

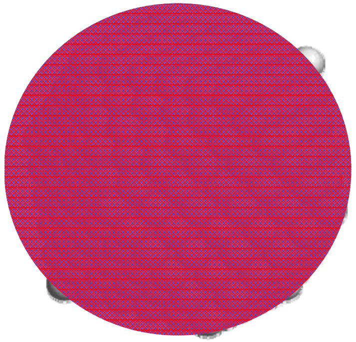
- ❑ probability for fast electrons to produce K-shell vacancy:

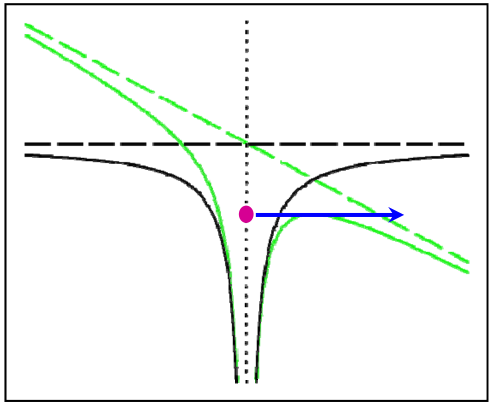
$$P_K = \sigma_K(E)\rho(t)v(t)\Delta t$$

- ❑ fluorescence yield: $N_X = \omega_K N_K$

absolute x-ray yields:  Gaussian spatial intensity profile + clustering rate η

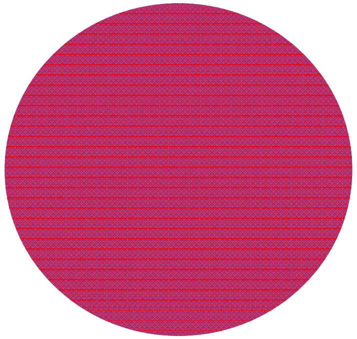
Scenario of the dynamics of a single cluster





Optical field ionization

→ a cold nanoplasma

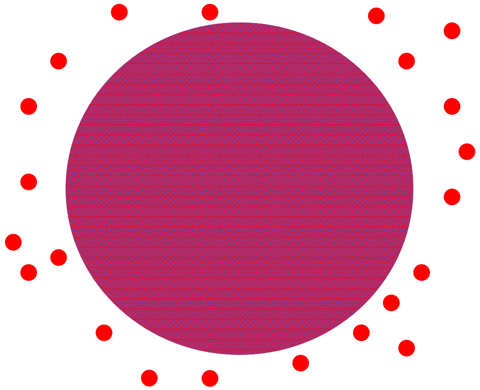


The electron cloud driven by the laser field

Polarizable sphere

→ screening of the laser field inside the cluster

→ but on the poles electric field enhanced



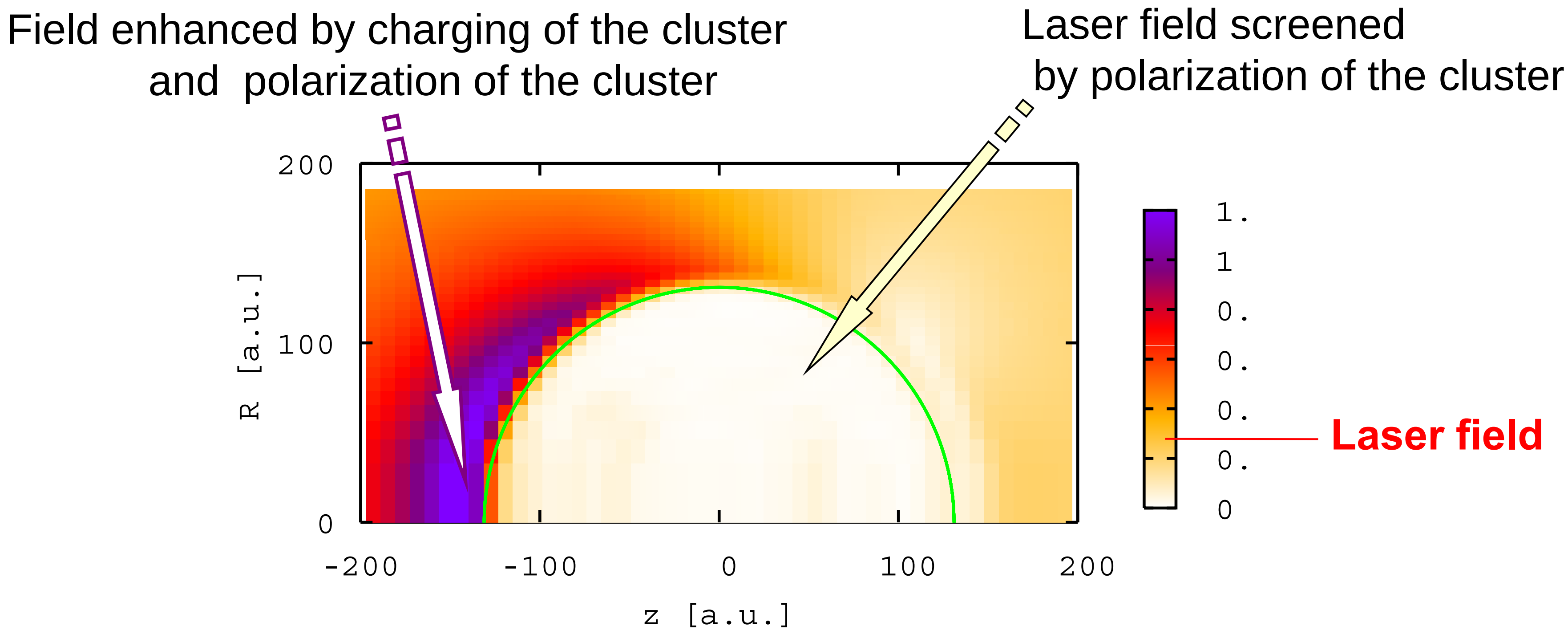
Outer ionization : electrons leave the cluster

Build-up of a positive charge on the cluster surface

Fukuda *et al.* PRA **73** (2006); Prigent, Deiss *et al* PRA **78** (2008)

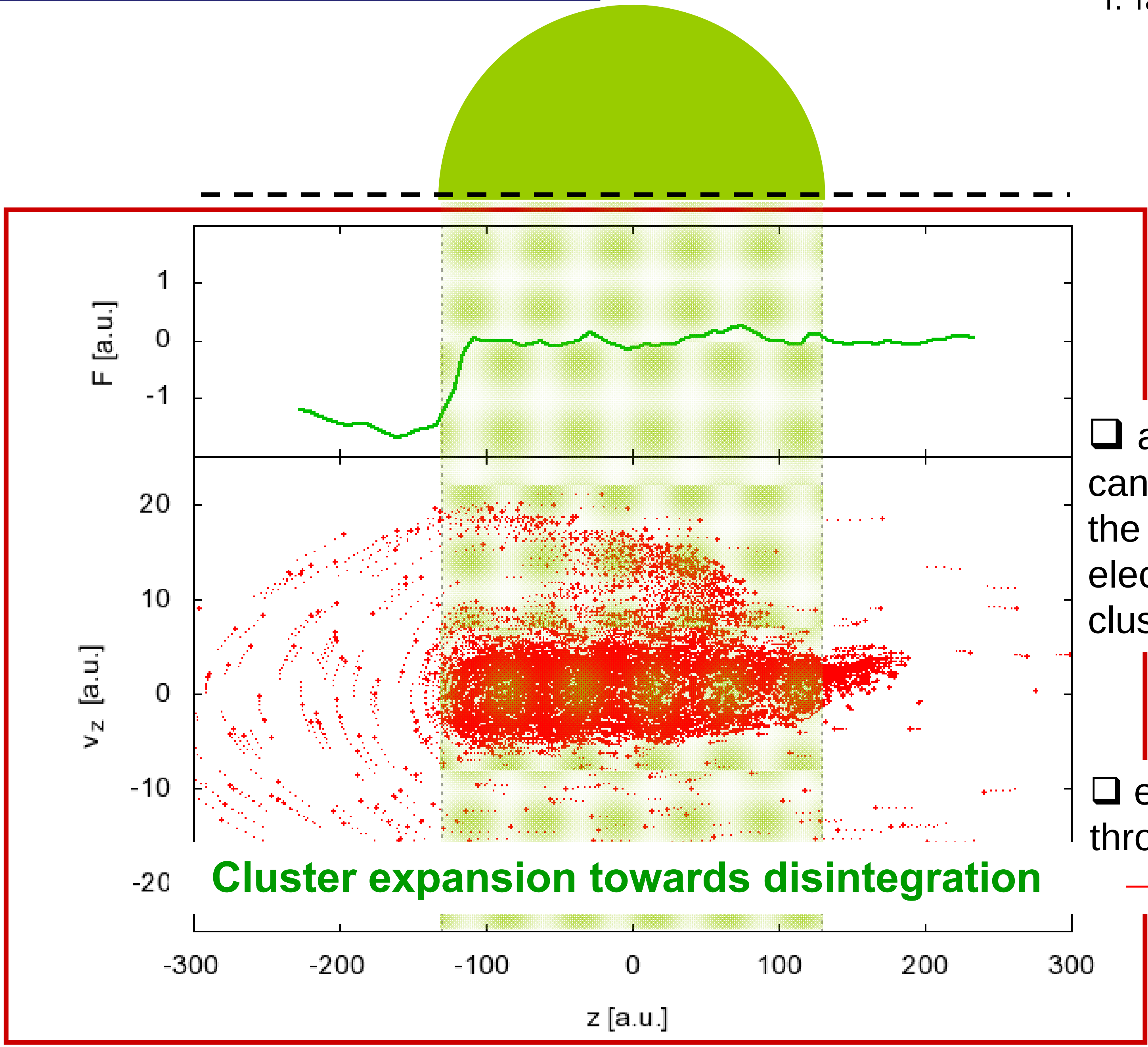
Scenario of the dynamics of a single cluster

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



Electron dynamics

see also PIC simulation:
T. Taguchi *et al.* PRL **92** (2004)



- 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

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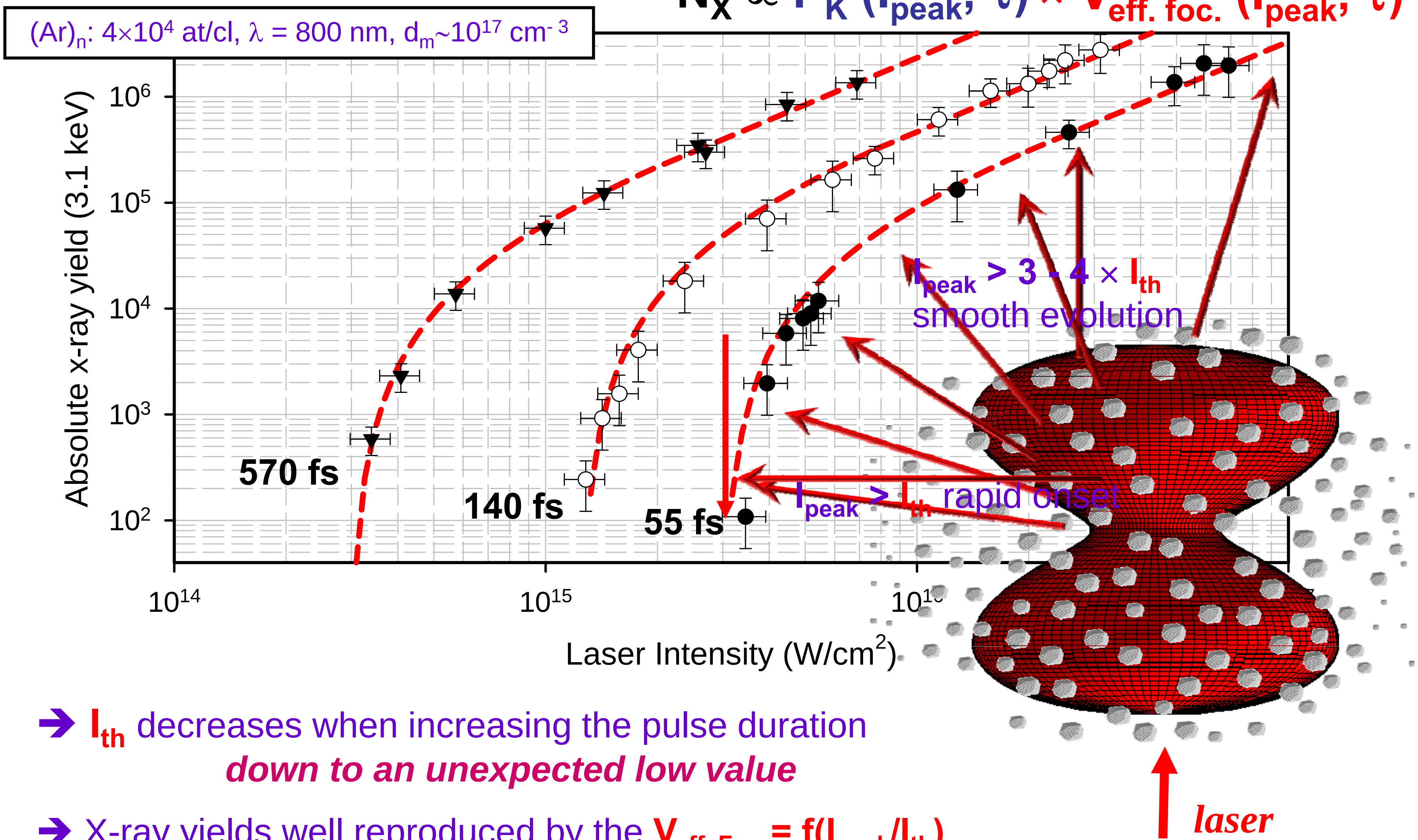
Absolute X-ray yields vs laser intensity for different τ

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



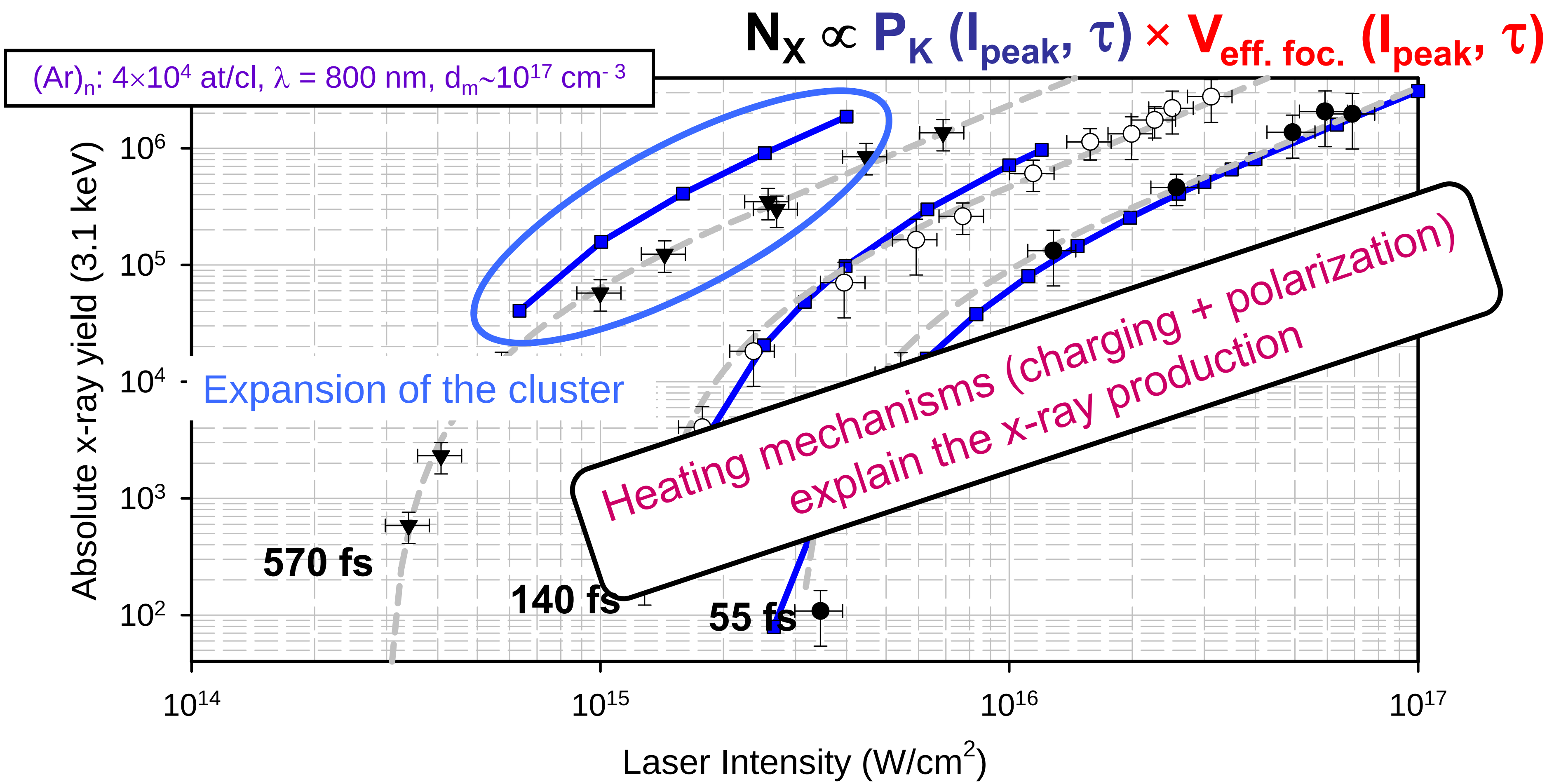
➔ I_{th} decreases when increasing the pulse duration

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

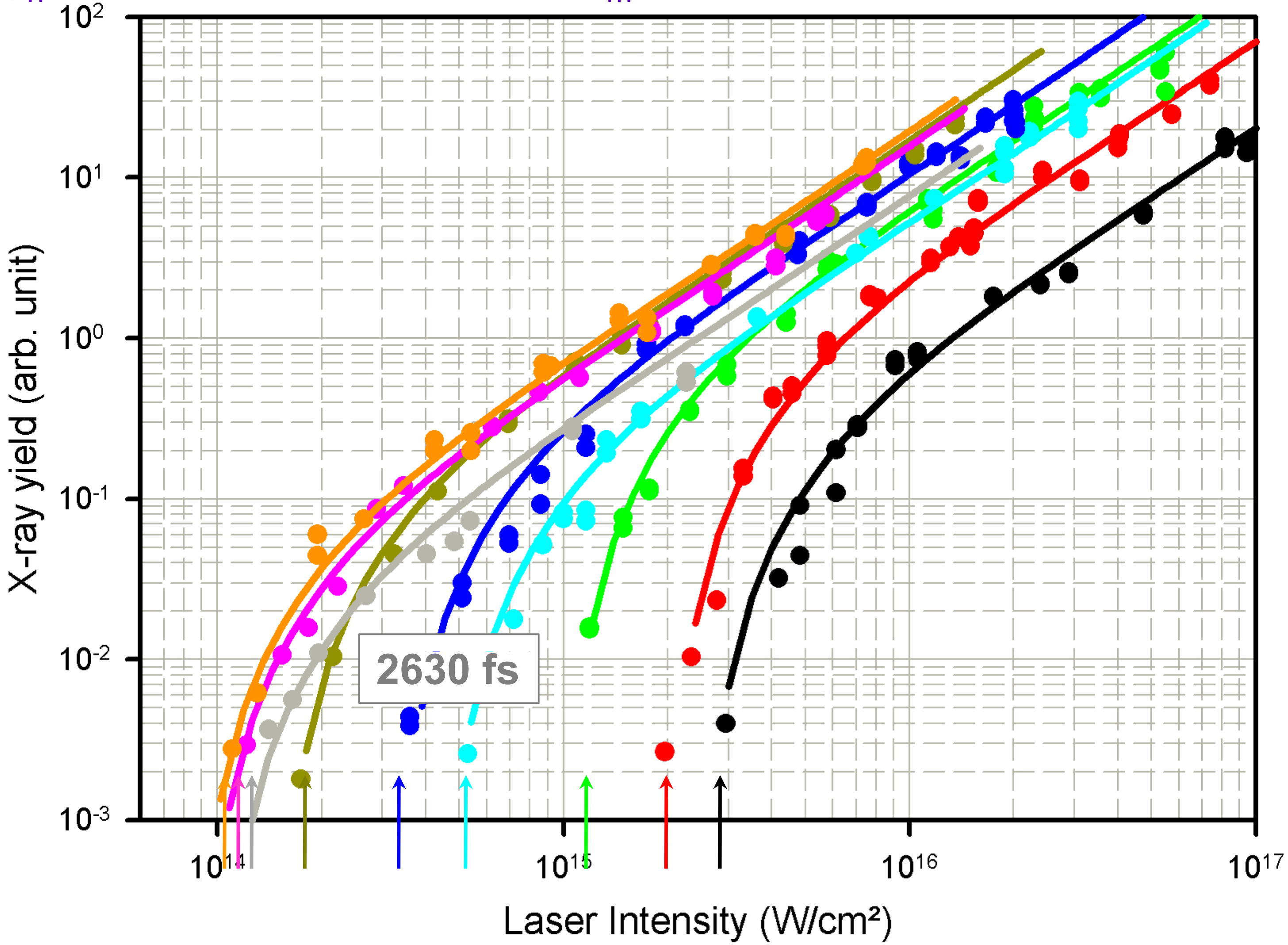
➔ Good prediction of the intensity threshold I_{th}

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

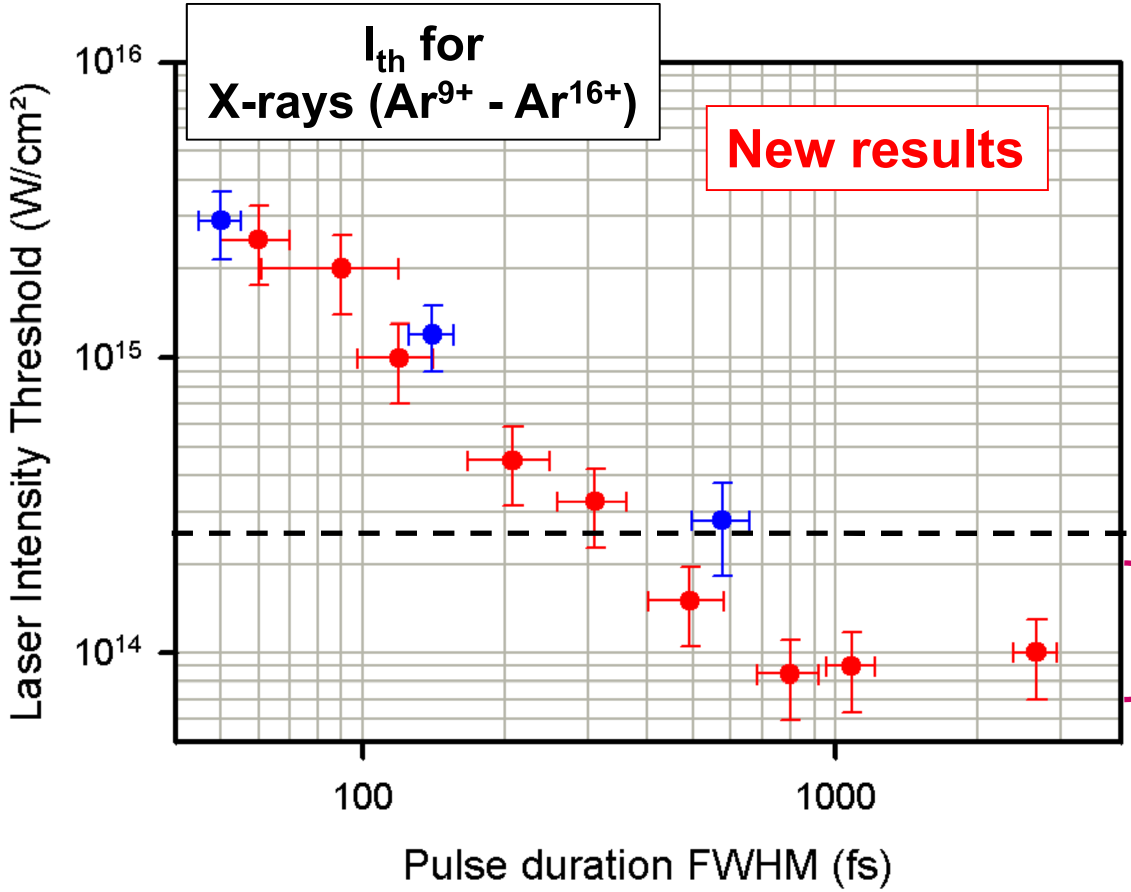
C. Prigent, C. Deiss *et al* PRA **78** (2008)

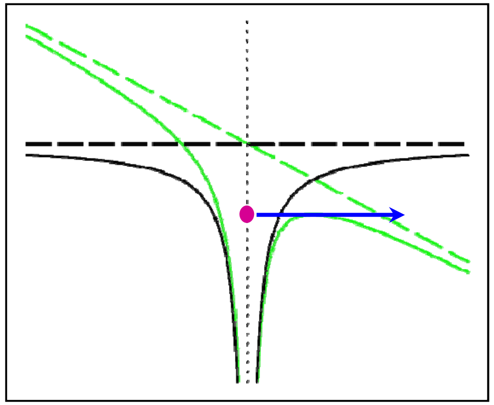
Absolute X-ray yields vs laser intensity for many pulse durations, τ

$(Ar)_n$: 2×10^5 at/cl, λ = 800 nm, $d_m\sim10^{14}$ cm^{-3}; **PRELIMINARY RESULTS**



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





I (OBI) $Ar \rightarrow Ar^{1+} + e^-$

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

Absolute X-ray yields *vs* τ

X-ray emission influenced by :

I_{peak} and τ

( )

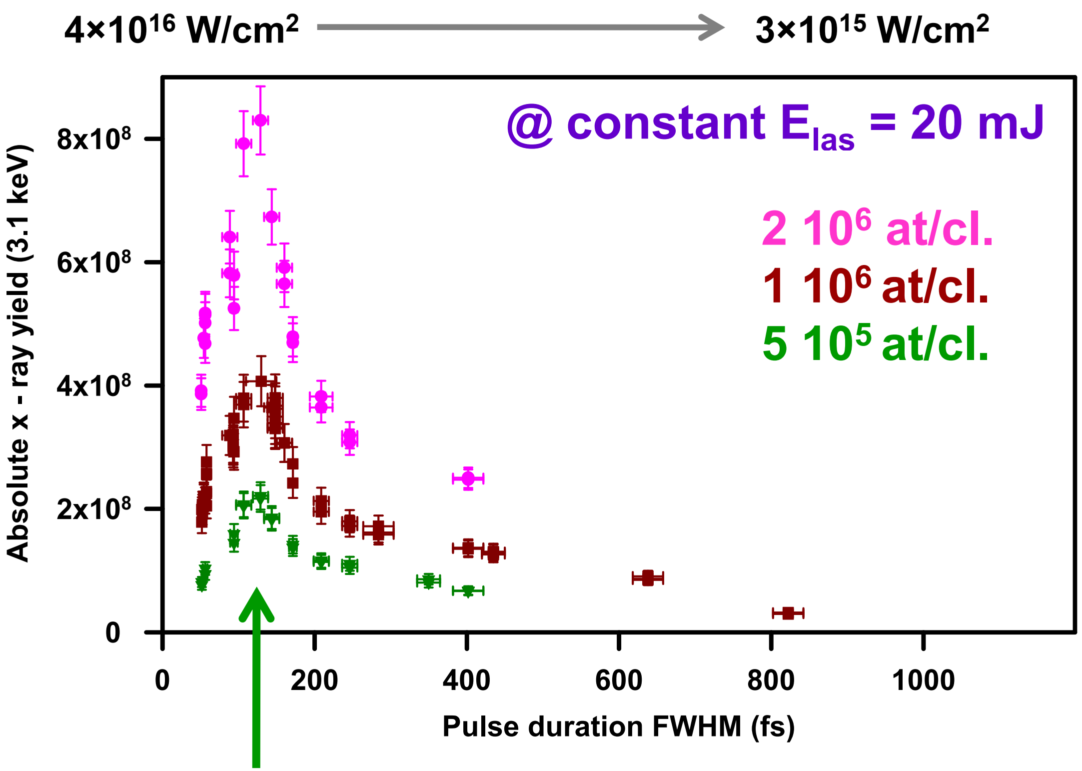
mapping the cluster dynamics by varying $\boldsymbol{\tau}$

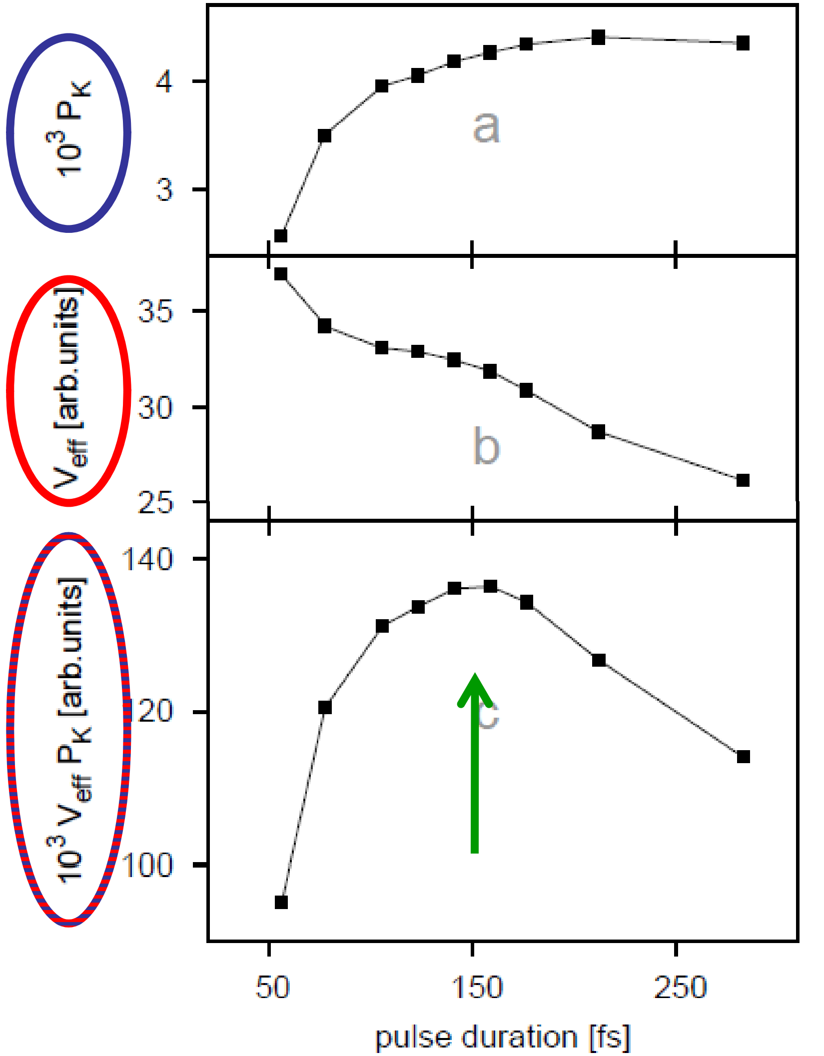
@ constant $E_{laser} \propto$ **($I_{peak} \times \tau$)**

at a value such that I_{th} is exceeded

Absolute X-ray yields *vs* τ

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



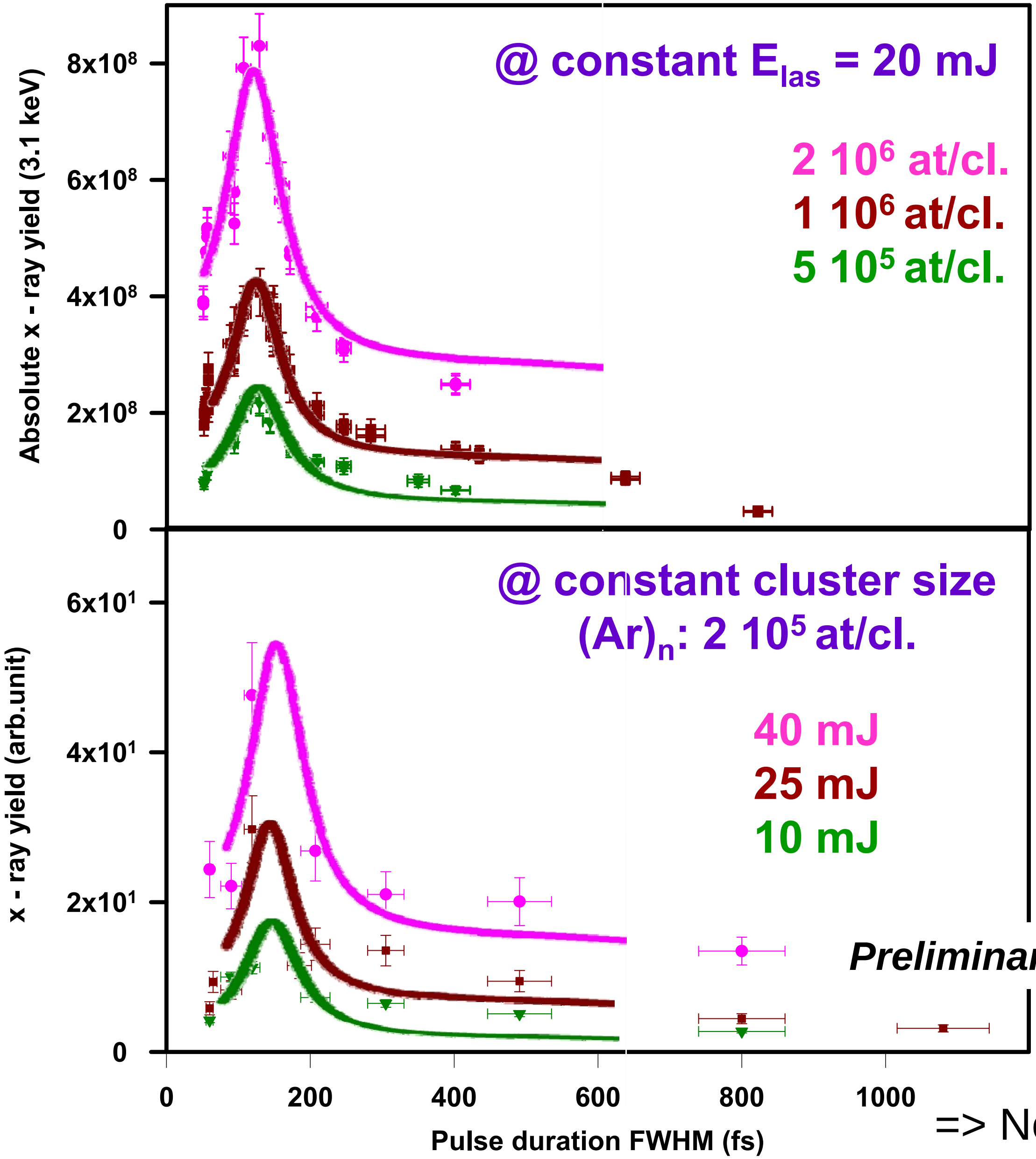


$$N_X \propto P_K (I_{peak}, \tau) \times V_{eff.\,foc.} (I_{peak}, \tau)$$

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

Absolute X-ray yields *vs* τ

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



whatever the cluster size

Same optimal pulse duration

&

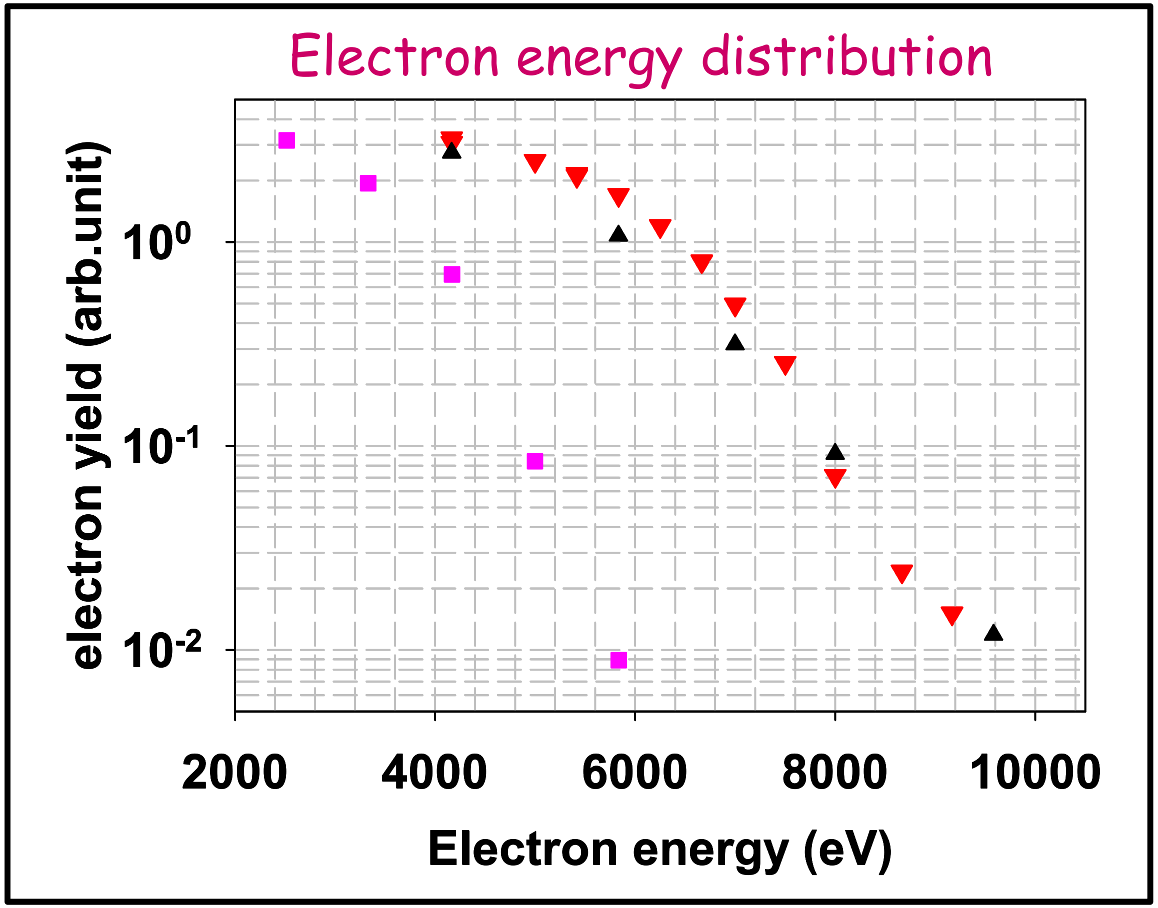
whatever the laser energy

Preliminary results

Optimal pulse duration

=> Not a signature of a plasma resonance

Correlation between X-ray and electron yields



same X-ray yield ➔ same P_E(e-)

X-ray yield/3 ➔ lower P_E(e-)

Conclusions

taking advantage of the very efficient energy coupling
between intense laser fields and clusters

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

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

Ÿ key for optimization of an X-ray source

Evidence of inner-shell ionization at low intensity threshold
Production of Ar^{1+} is the ignition process for X-ray production emitted from Ar^{9+}-Ar^{16+}

… quantitative benchmarks for theoretical models

- Mean field classical transport simulations for large clusters

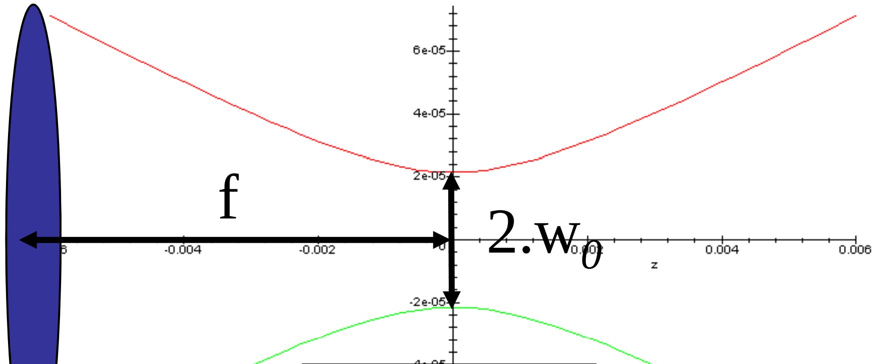
allows identifying effective heating mechanisms:
combined action of cluster charging and polarization at the cluster poles

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

… data analysis and further theoretical developments under progress

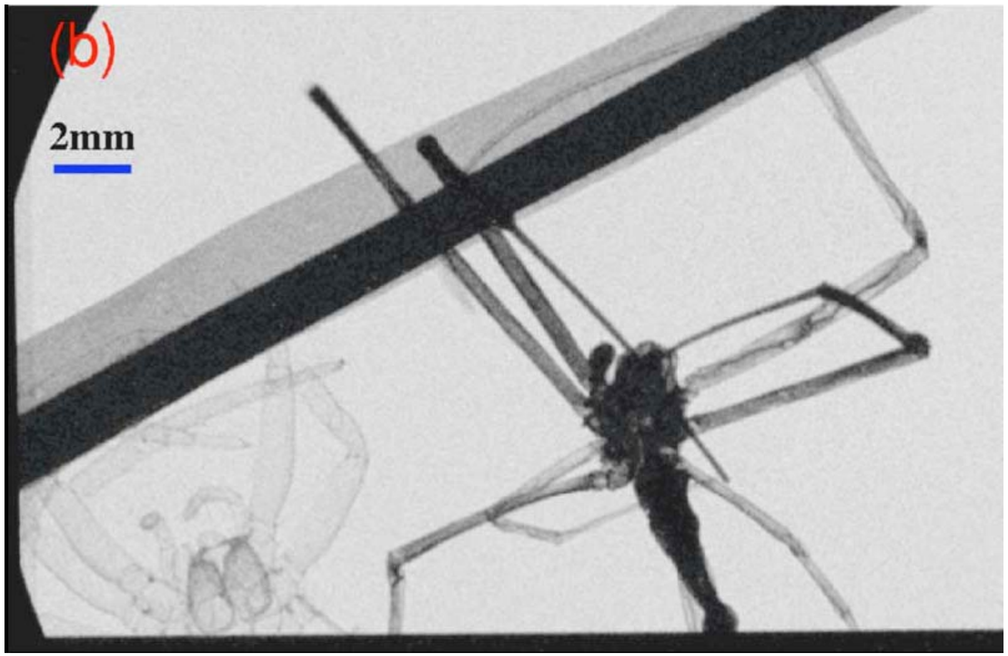
Consequence on the optimization of the x-ray yield

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



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

X-ray radiography of a spider with Ar_n
$I = 3\ 10^{15}$ W/cm^2, τ= 70 fs, 2w~170µm



max. X-rays ⇒ optimum $V_{Eff.\ Foc.}$
defocusing up to
a quite large w_0 !!

~1 10^8 photons/pulse/mm^2/mrad^2
L.M. Chen et al., Appl. Phys. Lett.**90** (2007)

THANK YOU
FOR YOUR ATTENTION