X-RAY SPECTROSCOPY TO INVESTIGATE THE LASER-CLUSTER INTERACTION

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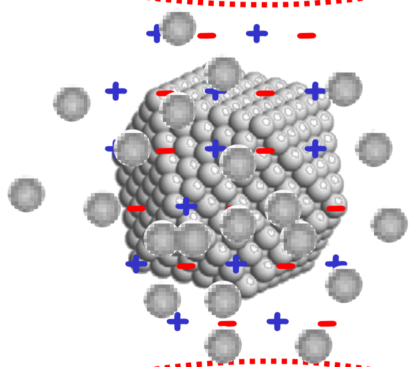
Intense laser – cluster interaction

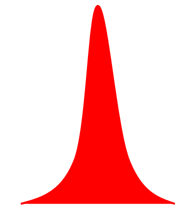
Strong optical fields

$F > 10^9$ V/cm

in the fs to ps scale

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





Creation of nanoplasmas

time scale ~ pulse duration

+

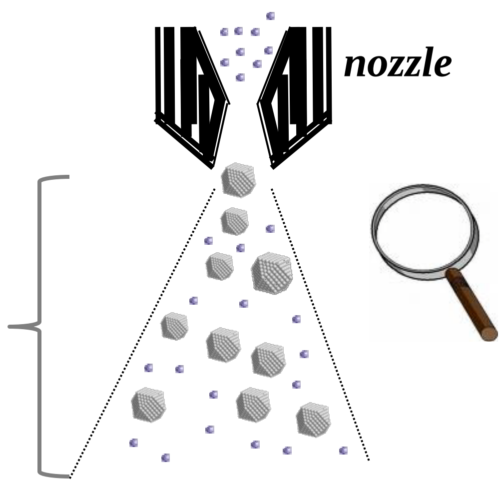
Expansion and explosion

of heated clusters

Characteristics of clusters

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

Cluster jet



❑ ***low mean atomic density***

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

clusters well separated (~ 1-10 µm)

no problem of laser propagation

no x-ray absorption

❑ ***high local density***

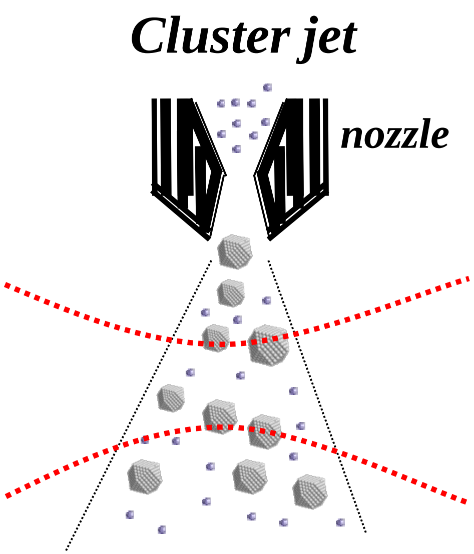
close to solid ~ 10^{22} at/cm^3

enhanced energy coupling

between light & matter

Clusters combine advantages of gaseous and solid targets

Observations with rare gas clusters



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

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

Observations that follow the cluster explosion:
Information a µs after the laser pulse and the cluster disintegration

X-ray emission in the keV range

X_K(Ar) ~ 3.1 keV

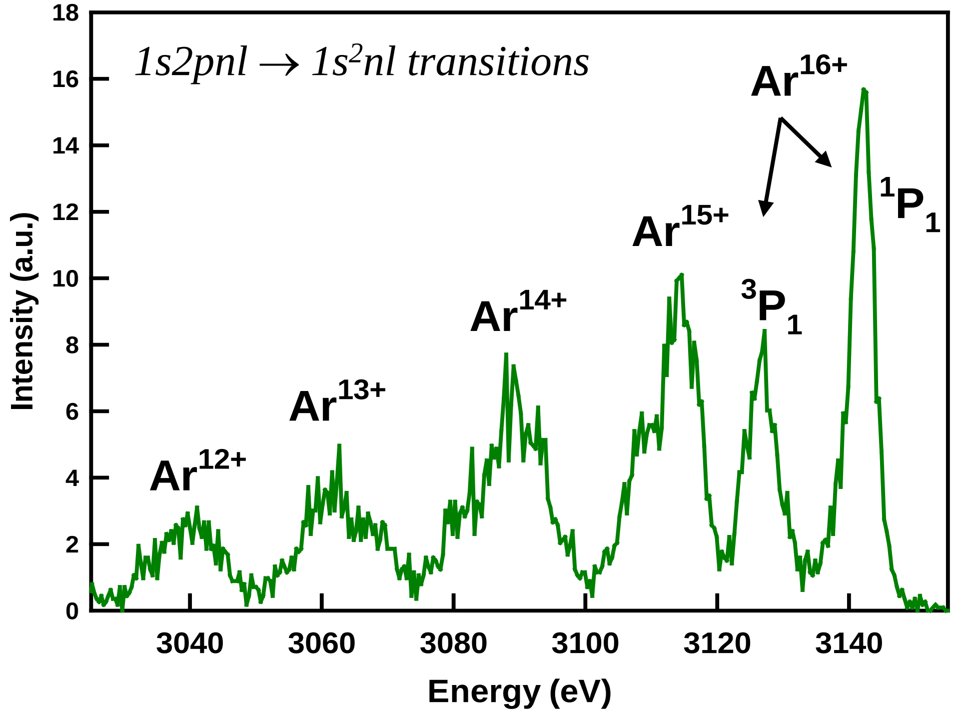
Direct insight into the early evolution of the nanoplasma

X-ray spectroscopy to test the dynamics

X-ray emission in the keV range ← Inner shell vacancy production ← Electron impact ionization

Fast electrons
with E = E_K ~ 3-4 keV for argon

Deexcitation of HCI with inner shell vacancies



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

time scale down to some fs

X-ray spectroscopy to test the dynamics

Production of fast electrons: what are the heating mechanisms?

Interplay between electronic & ionic dynamics

- ***Quantitative measurements of***
  - ✓ absolute photon emission yields
  - ✓ charge state distributions

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

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

Experimental set-up

Van Der Waals clusters :

• noble gases : Ar, Kr and Xe

• nanometer size $\phi \approx 10 - 40$ nm

($N \sim 10^3 - 10^6$ at/cl)

Size controlled by

the backing pressure P_0

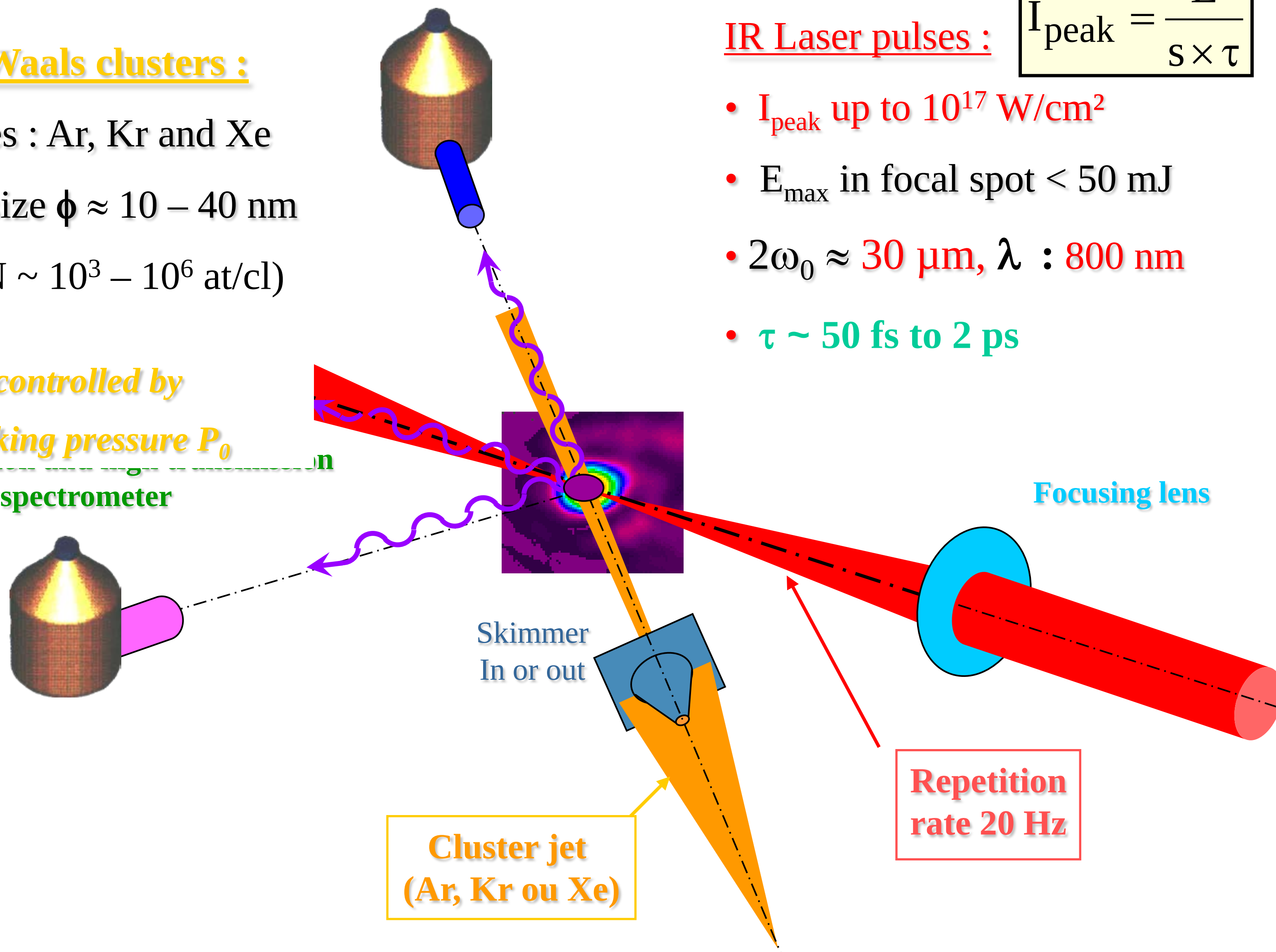
IR Laser pulses : $I_{peak} = \dfrac{E}{s \times \tau}$

• I_{peak} up to 10^{17} W/cm²

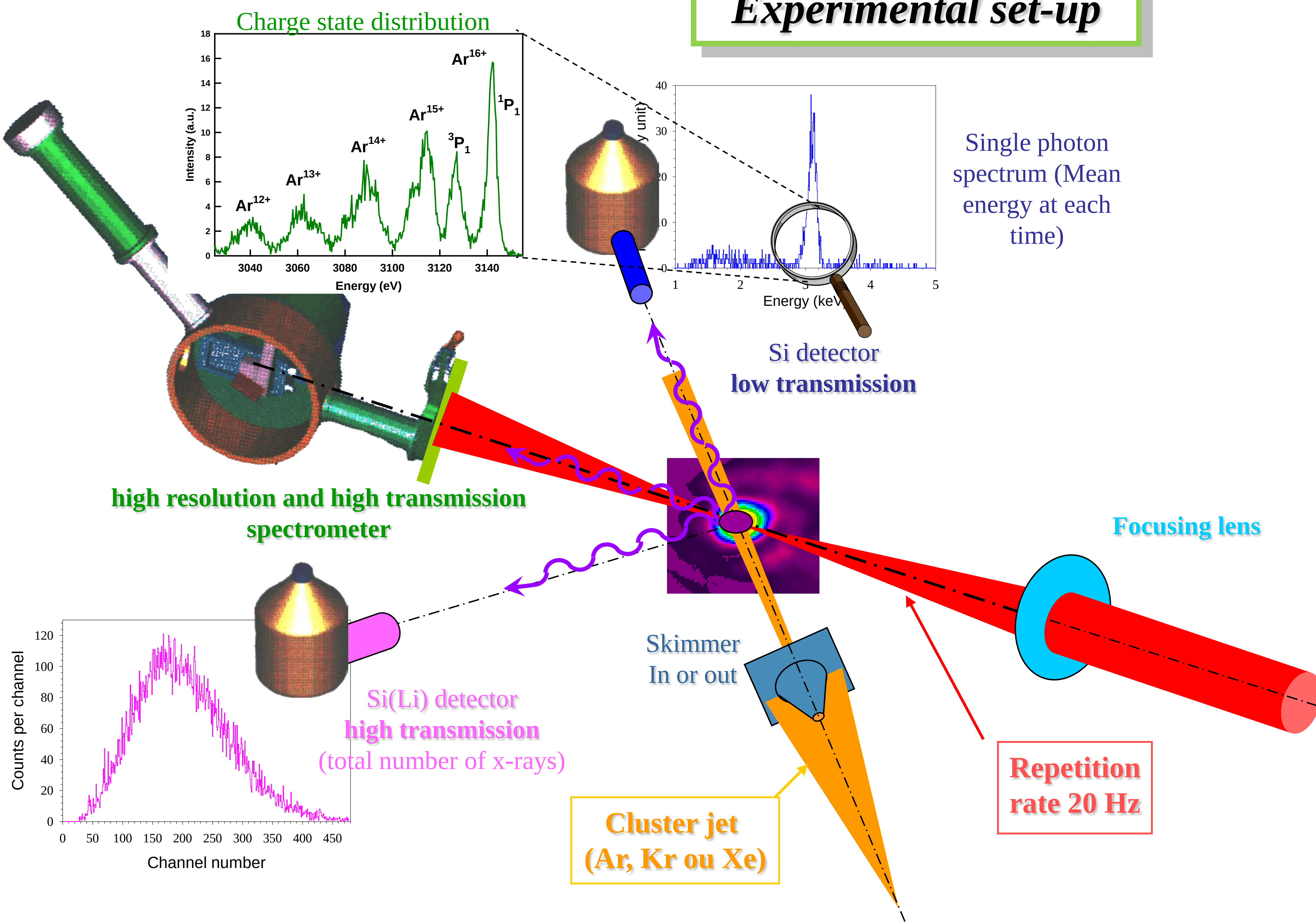
• E_{max} in focal spot < 50 mJ

• $2\omega_0 \approx 30$ µm, λ : 800 nm

• **$\tau \sim 50$ fs to 2 ps**



Experimental set-up

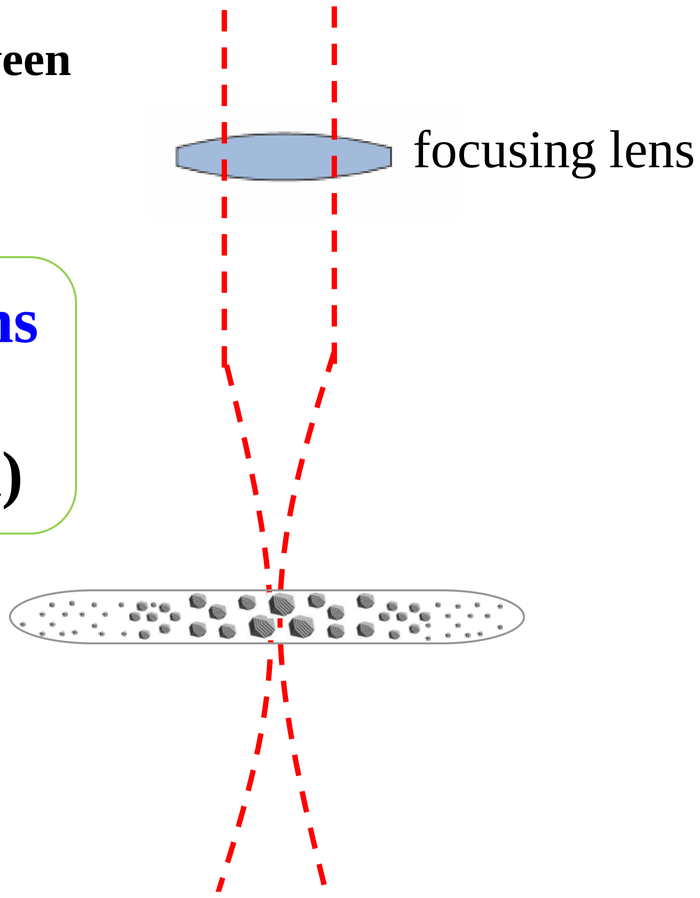


Experimental set-up

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

Simulations: a mean field classical approach

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

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

Charge state is time-dependent for ions

Laser field

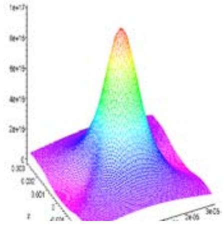
Mean field: charging of the cluster and polarization

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

- ***probability for fast electrons to produce K-shell vacancy:*** $P_K = \sigma_K(E)\rho(t)v(t)\Delta t$

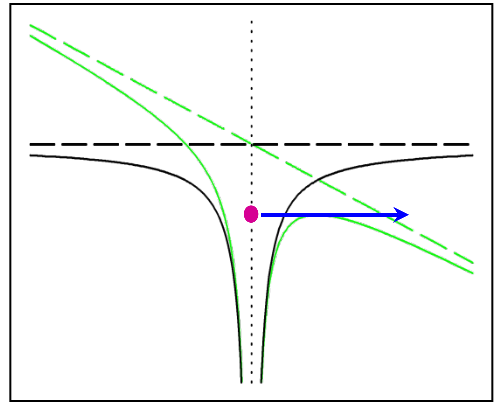
- ***fluorescence yield:*** $N_X = \omega_K N_K$

- ***absolute x-ray yields :***



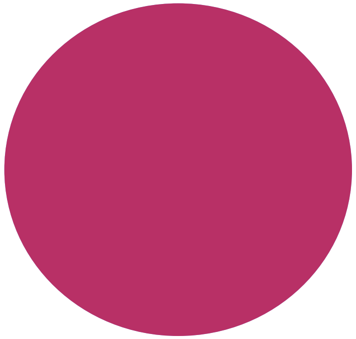
Gaussian spatial intensity profile + clustering rate η

Scenario of the dynamics of a single cluster



Optical field ionization

→ a cold nanoplasma

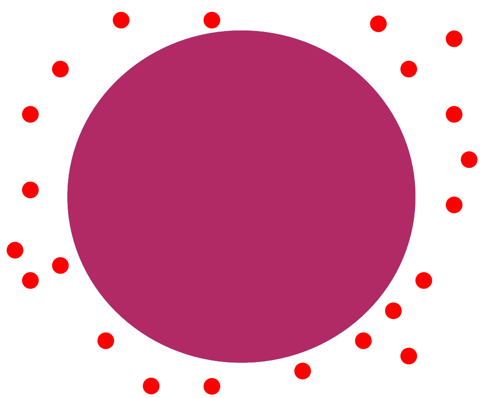


The electron cloud driven by the laser field

Polarizable sphere

→ screening of the laser field inside the cluster

→ electric field enhanced on the poles



Outer ionization : electrons leave the cluster

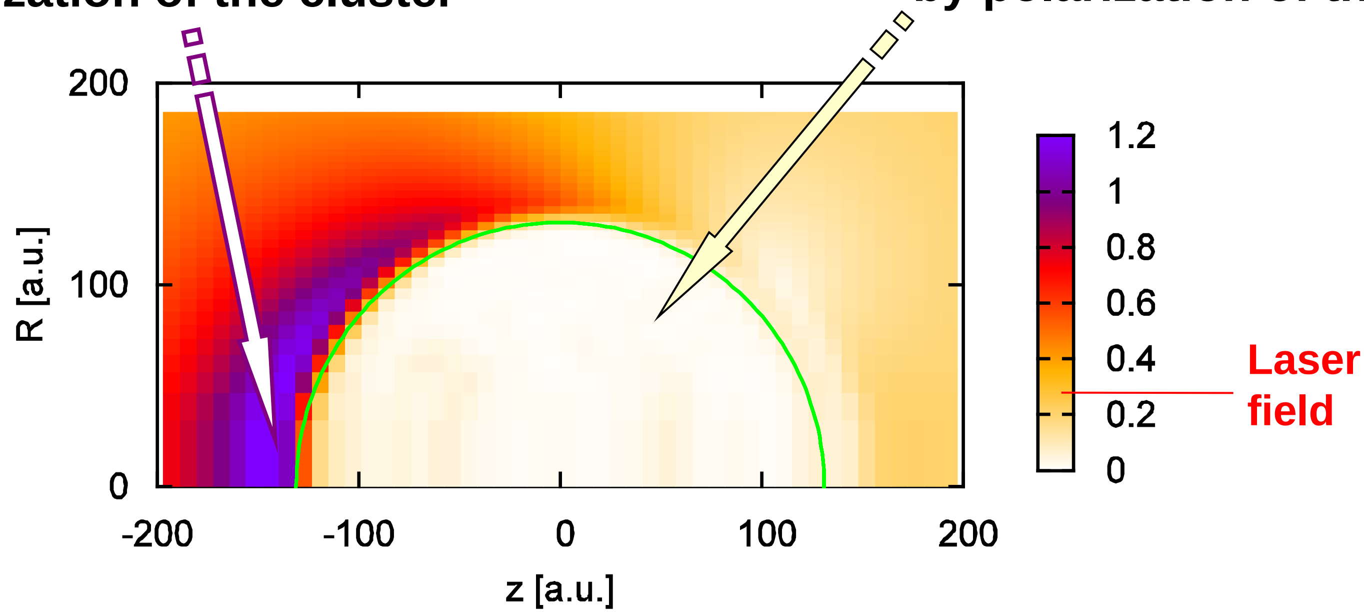
Build-up of a positive charge on the cluster surface

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

Scenario of the dynamics of a single cluster

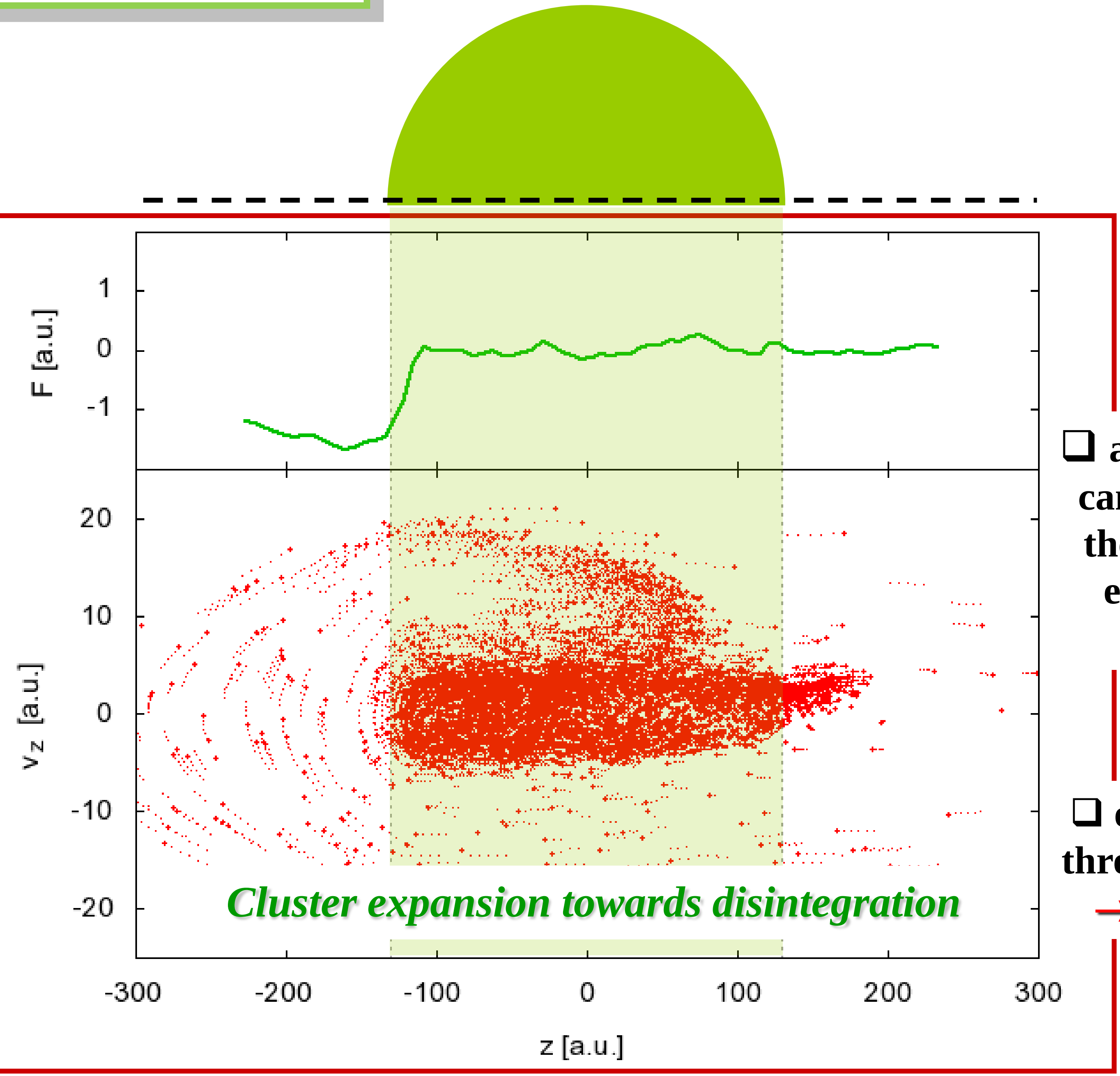
Field enhanced by charging of the cluster and polarization of the cluster

Laser screened by polarization of the cluster



Electron dynamics

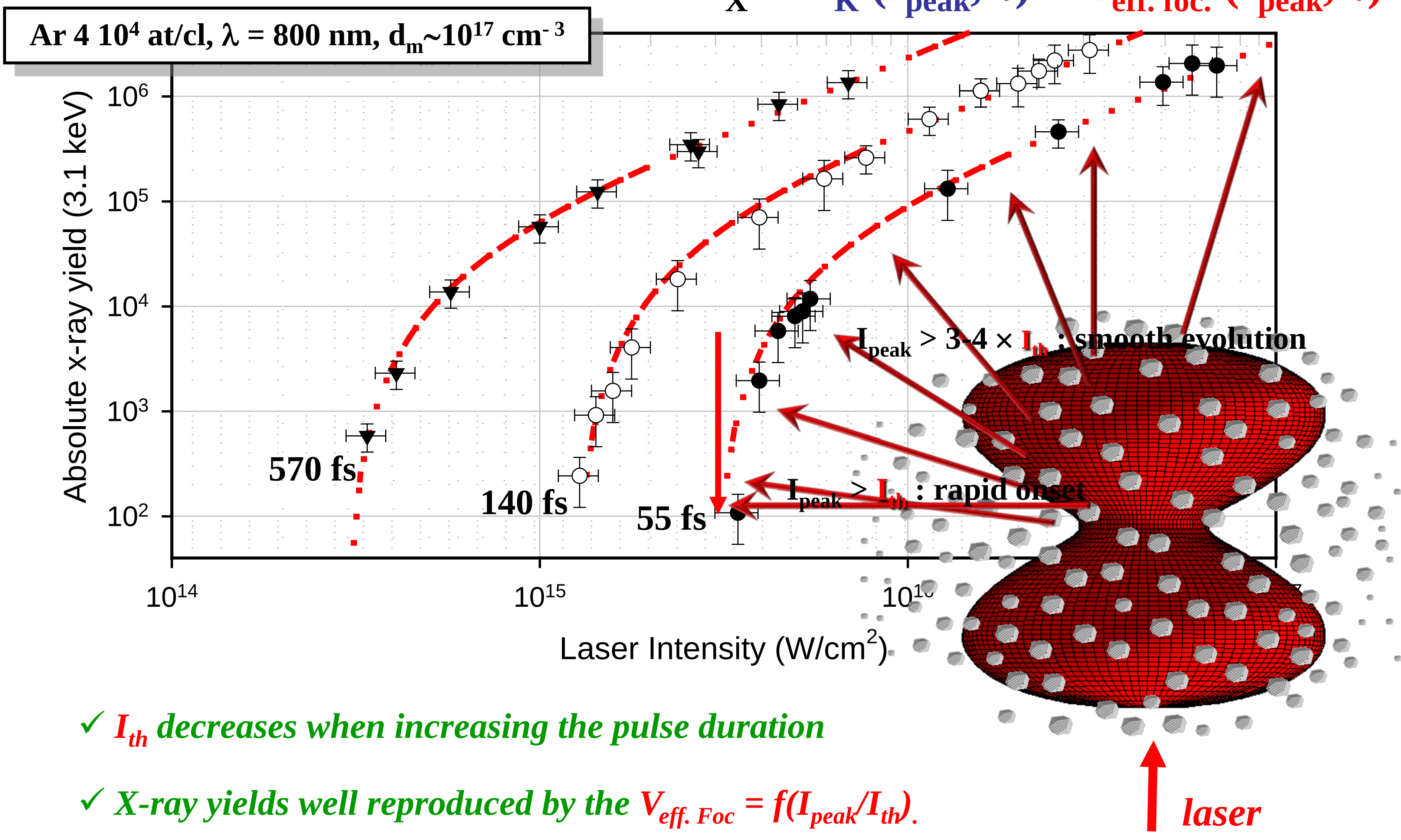
see also: T. Taguchi *et al*. PRL **92** (2004)



- **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**

Pulse duration effect on the absolute x-ray yield

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

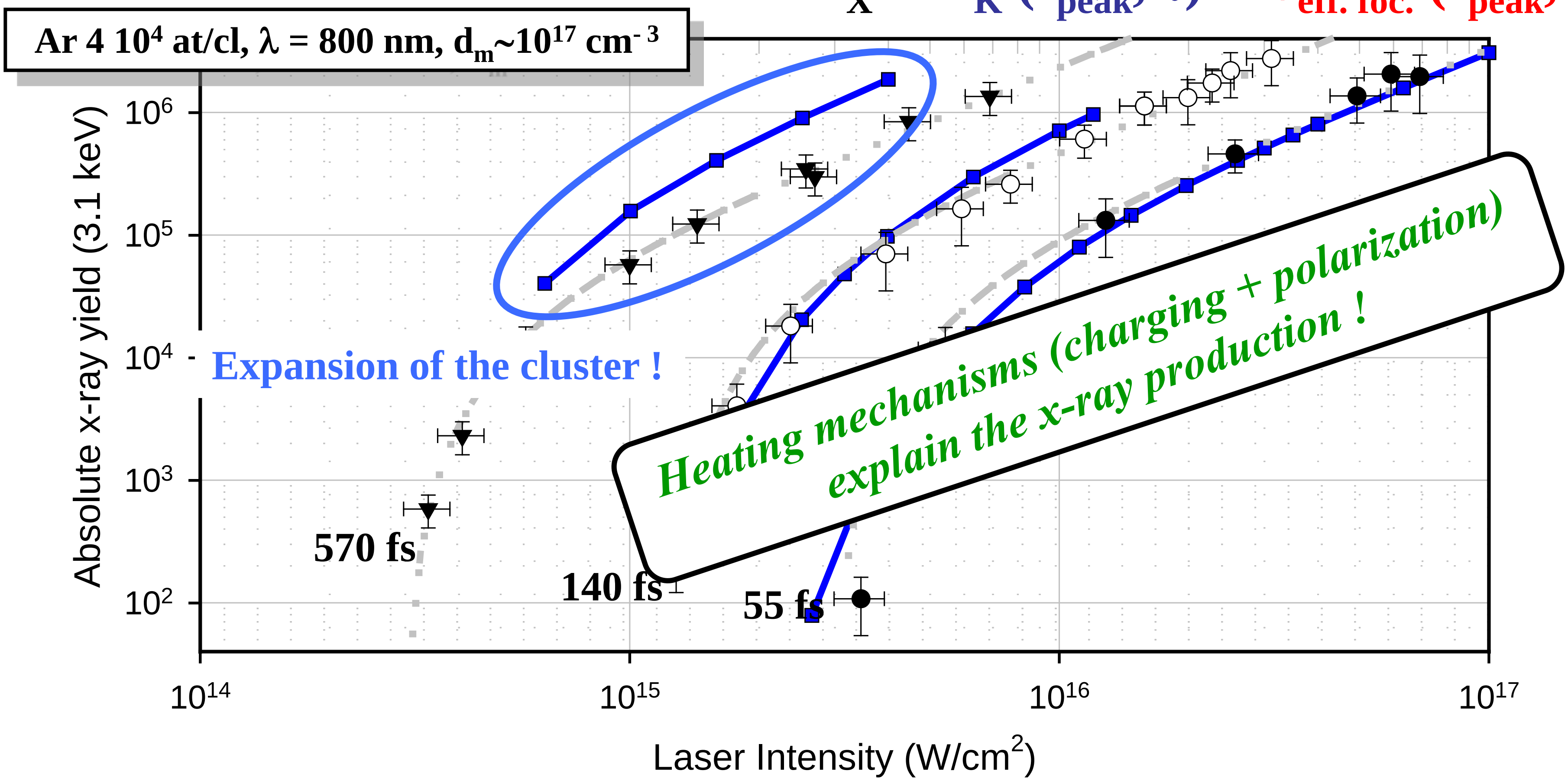


✓ *I_{th} decreases when increasing the pulse duration*

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

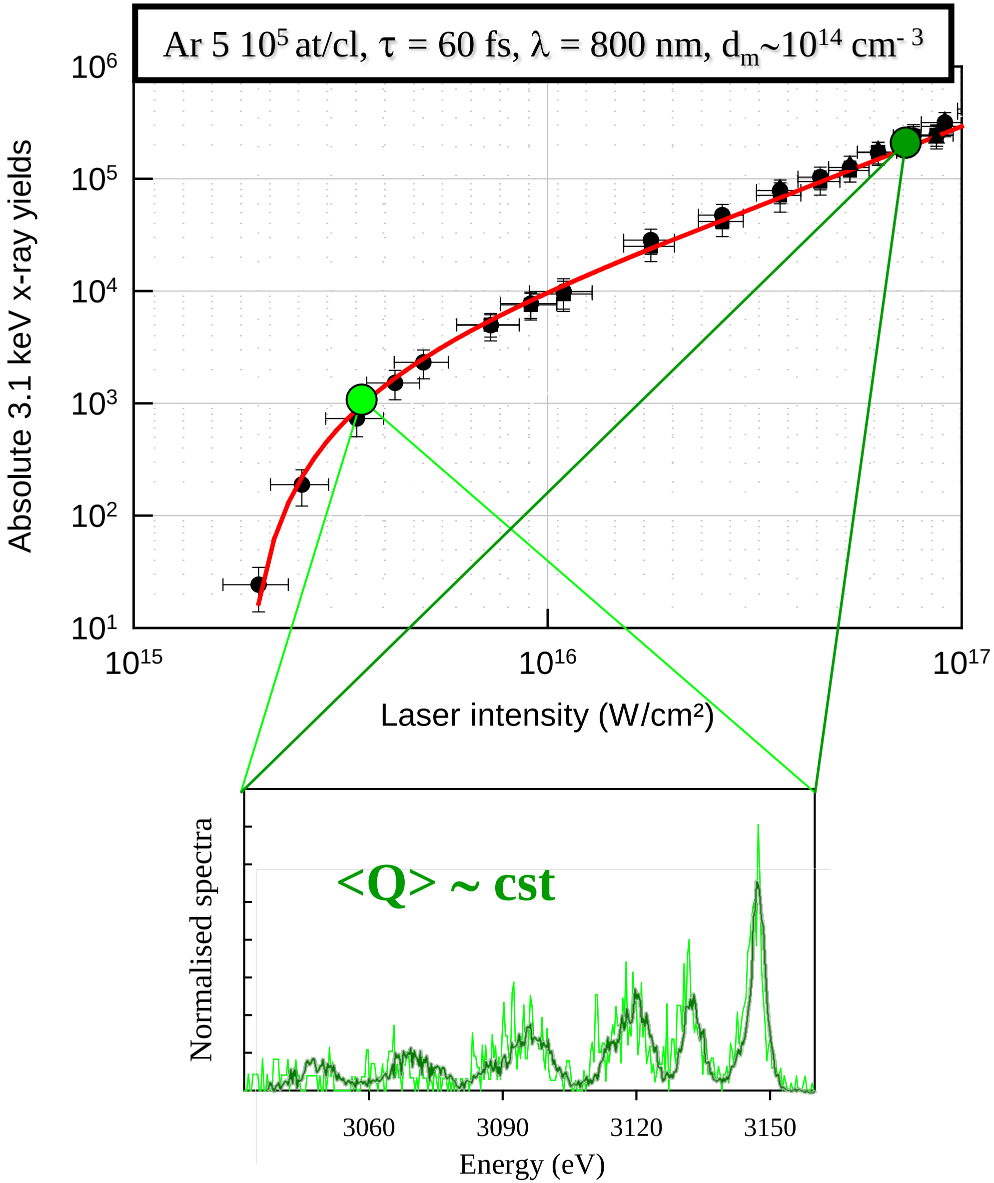
Comparison with the simulations: (1) absolute x-ray yield

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

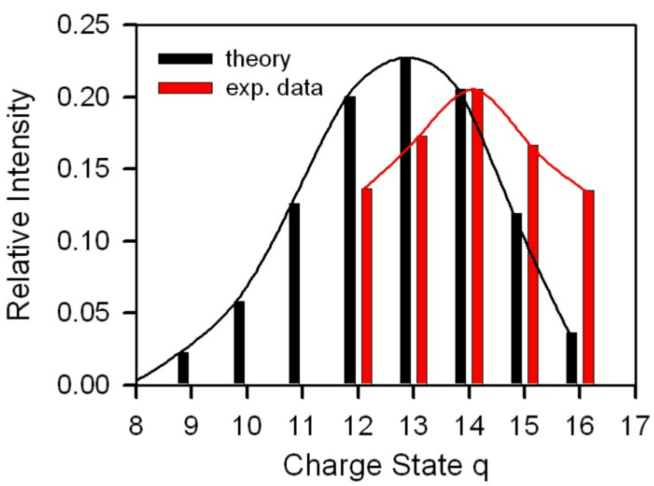


- ✓ **Intensity & pulse length dependence well reproduced**
- ✓ **Good prediction of the intensity threshold I_{th}**
- ✓ **Discrepancy for long pulse duration …** ***role of the ion dynamics i.e. cluster expansion***

Comparison with the simulations: (2) charge state distribution



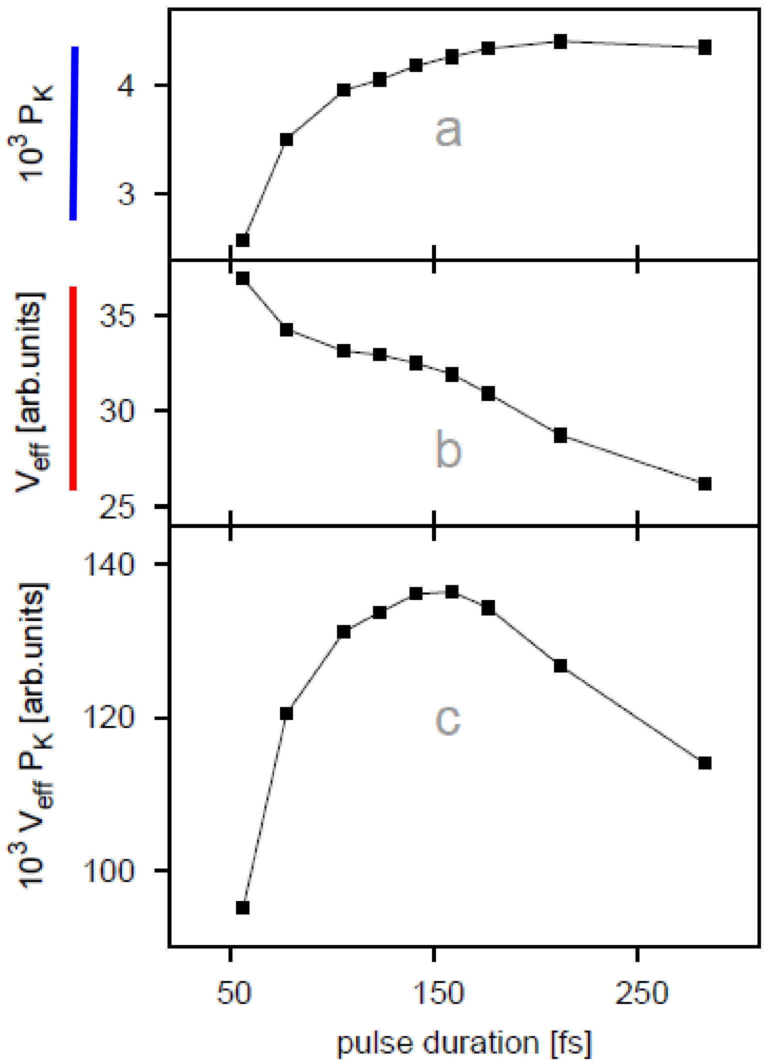
Comparison at high laser intensities
where <Q> ~ cst



rather good agreement !!

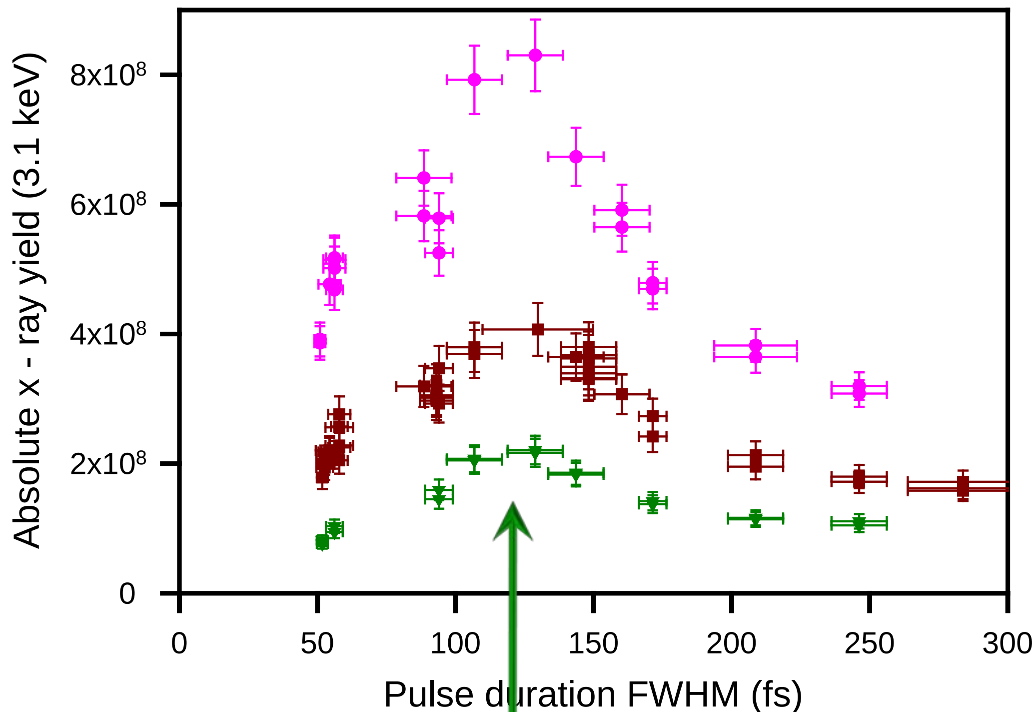
Exp. and th. results differ only by one charge state

Comparison with the simulations: (3) Optimal pulse duration



$E \propto I_{peak} \times \tau$ = 20 mJ

(from 5×10^5 to 2×10^6 atoms/cl...)



Optimal pulse duration

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

Competition between n_{cl} (via $V_{eff.\ foc.}$) and N_X/cl. (via P_k)

Conclusions on the laser-cluster interaction

- **Absolute x-ray measurements under well controlled conditions**

- **Efficient energy coupling for converting photons from eV to keV**

up to 10^9 hν/ pulse in 4π for Ar_n → energy conversion ~ 10^{-2}%

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

- **Mean field classical transport simulations**

Heating mechanisms of electrons up to energies in the keV range identified

Strong enhanced electric field at the cluster poles :
Combined action of cluster charging & polarization

First simulations giving absolute X-ray yield predictions

Intensity & pulse duration dependences well reproduced
Prediction of an optimal pulse duration due competition between single cluster dynamic & number of clusters in $V_{eff.\ foc.}$

To be done in a near future…

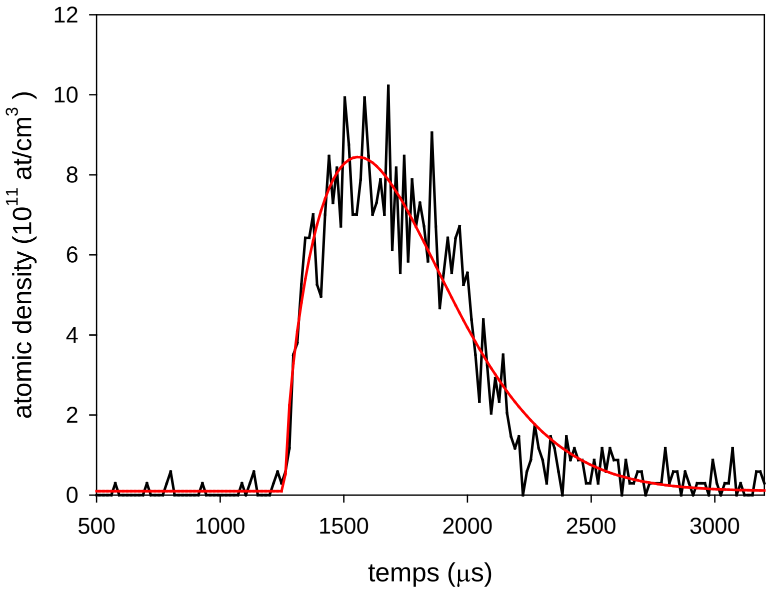
I_{th} strongly depends on τ : a more precision evolution is needed **(under progress)**

Its evolution allows to explain the optimum in the x-ray production

Access to a better definition of the competition between the heating mechanisms and the cluster expansion

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.

To be done in a near future…

I_{th} strongly depends on τ : a more precision evolution is needed **(under progress)**

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

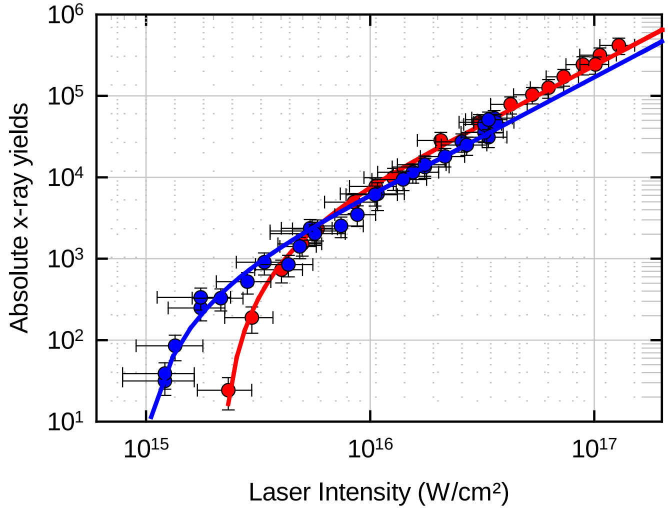
(under progress)

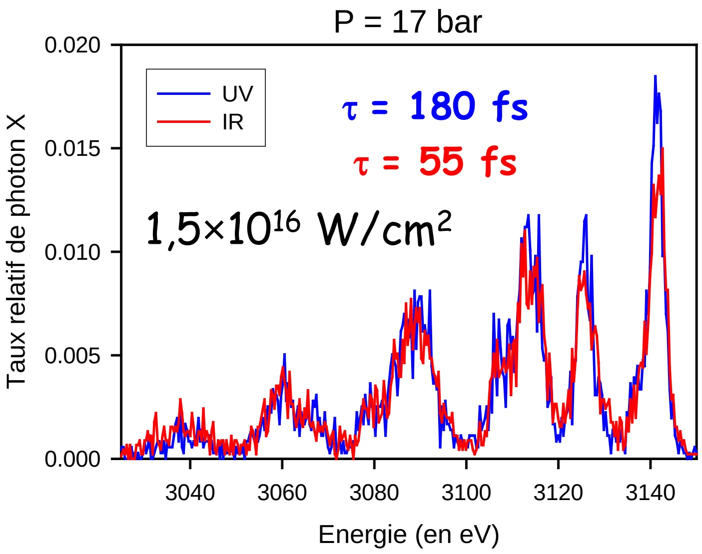
Further developments of the simulation for a better ion expansion description

For τ = 570 fs, X-ray yields overestimated

The simulation needs to be tested with other parameters as the cluster size, the laser wavelength

Influence of τ at 400 nm





THANKS