Coulomb Explosion of Rare Gas Clusters Irradiated by Intense VUV Pulses of a Free Electron Laser

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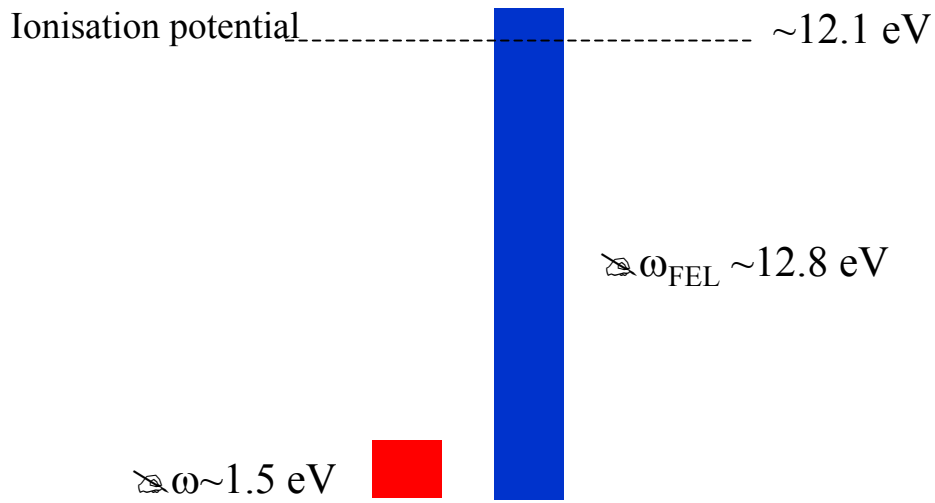
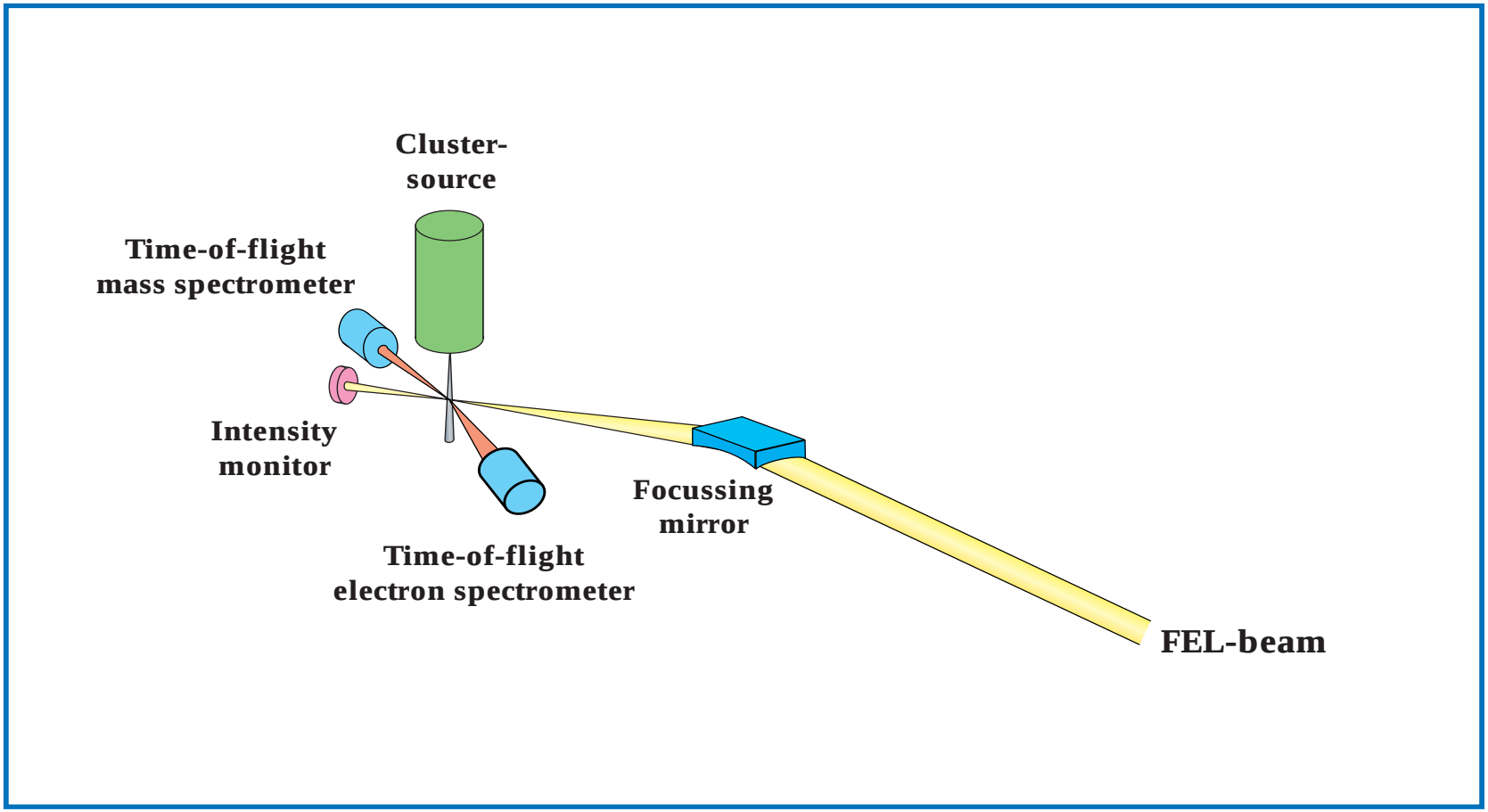
IR-Laser	FEL
λ= 800 nm	λ= 97 nm
$I_{FEL}=10^{16}W/cm^2$	$I_{FEL}=10^{14}W/cm^2$
U_p~ 600 eV	U_p~ 100 meV

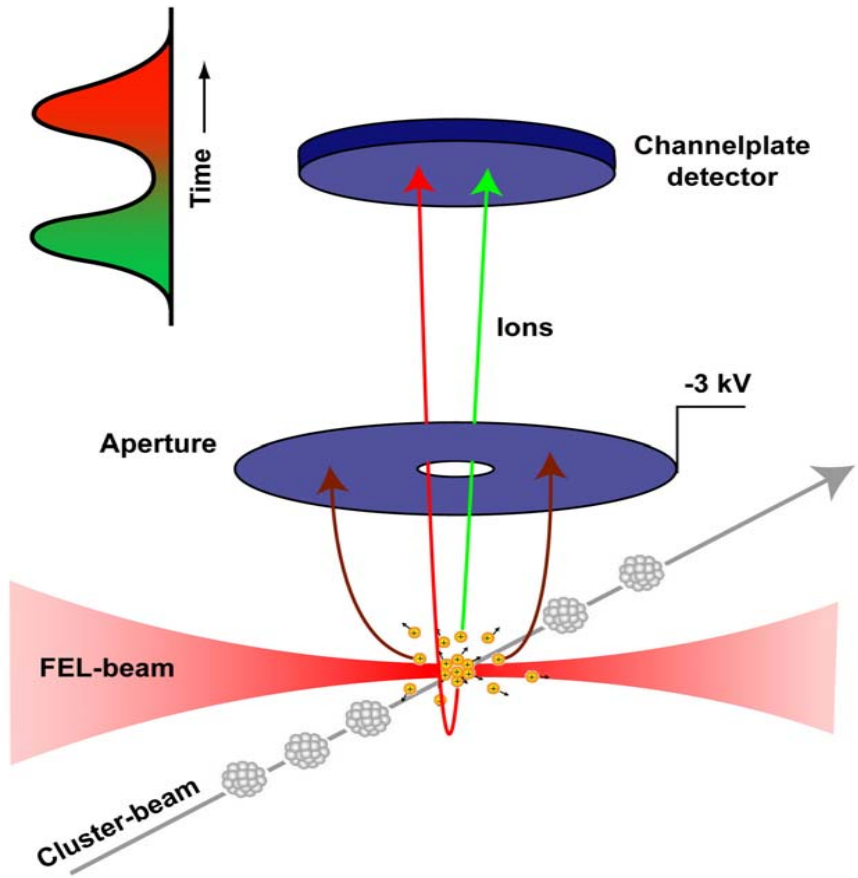
Questions:
field ionisation?
multiphoton processes?



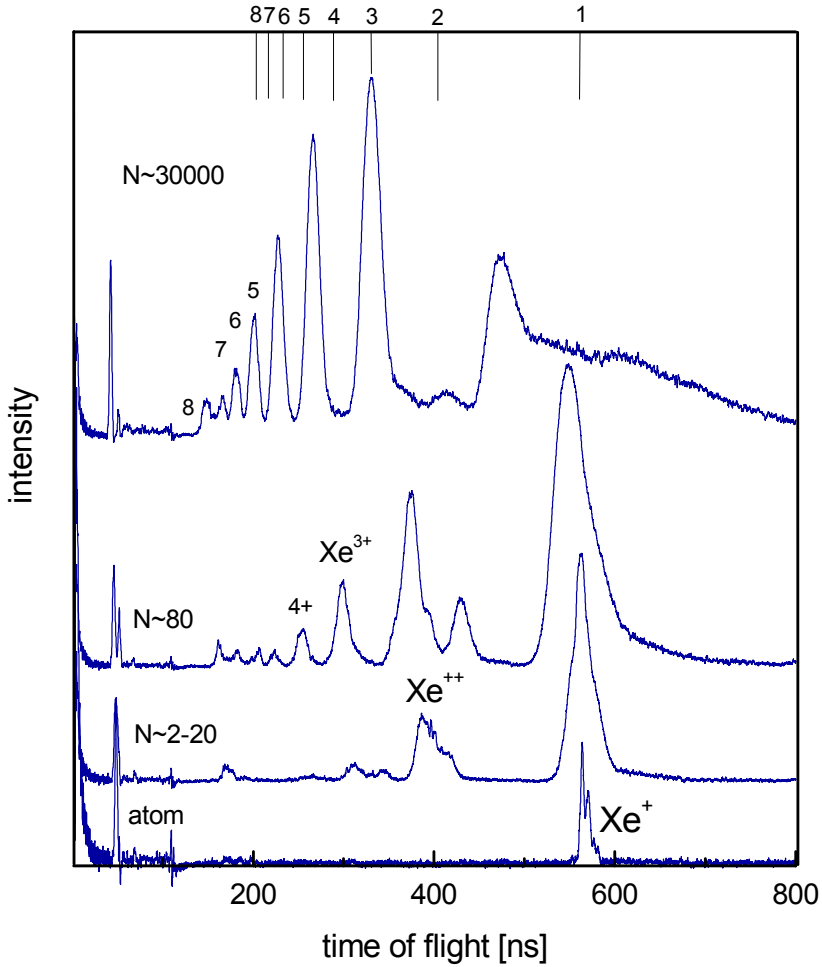
Experimental set-up



Cluster-Ion Detector



Time of flight mass spectra of xenon atoms and clusters

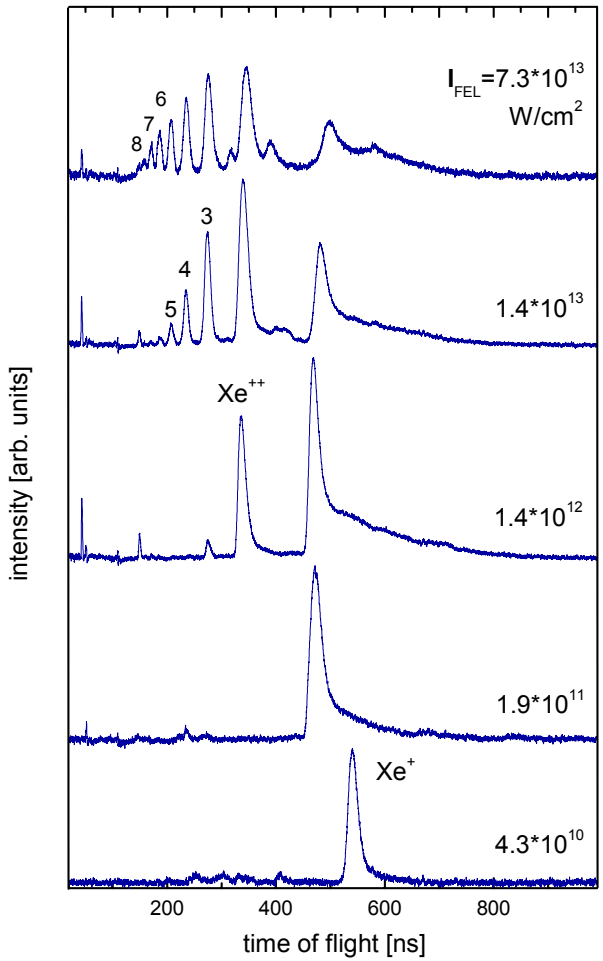


$2*10^{13}$ W/cm^2

3 messages:

- **multiply charged ions from clusters**
- **ions show kinetic energy**
- **no heavy fragments**

Dependence on the power density

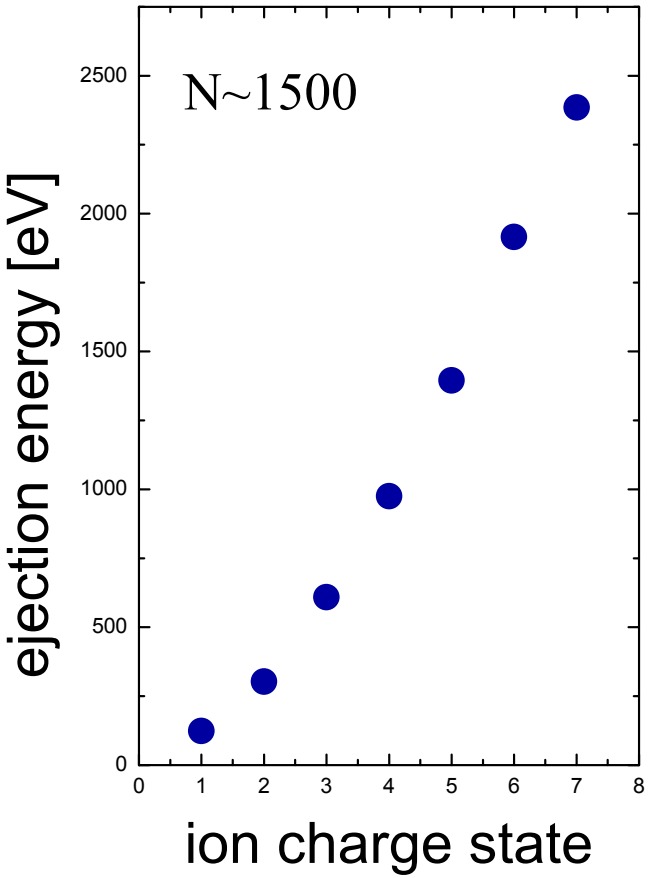


7*10^{13} Watt/cm^2

Xenon clusters, 1500 atoms

4*10^{10} Watt/cm^2

Kinetic energy of the ejected ions



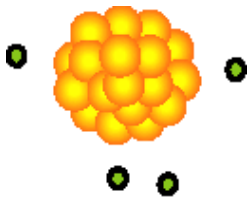
- Quadratic dependence on charge
- Coulomb explosion
- Up to 2.5 keV kinetic energy
- Each atom in the cluster absorbs 30 photons

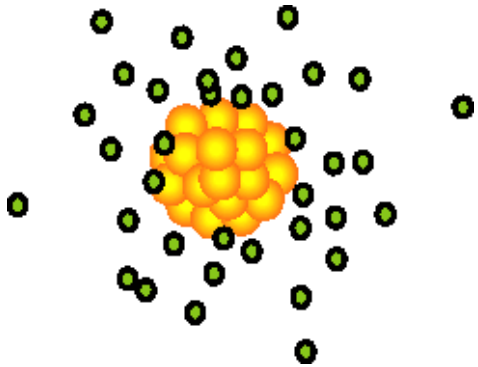
Coulomb explosion of clusters

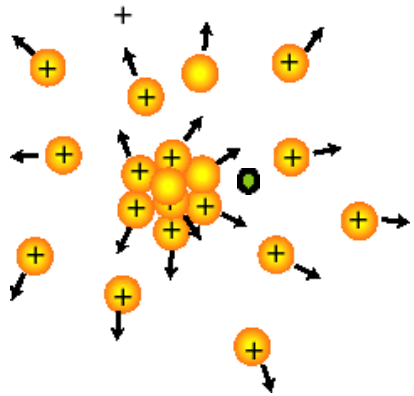
t_0 beginning of the pulse

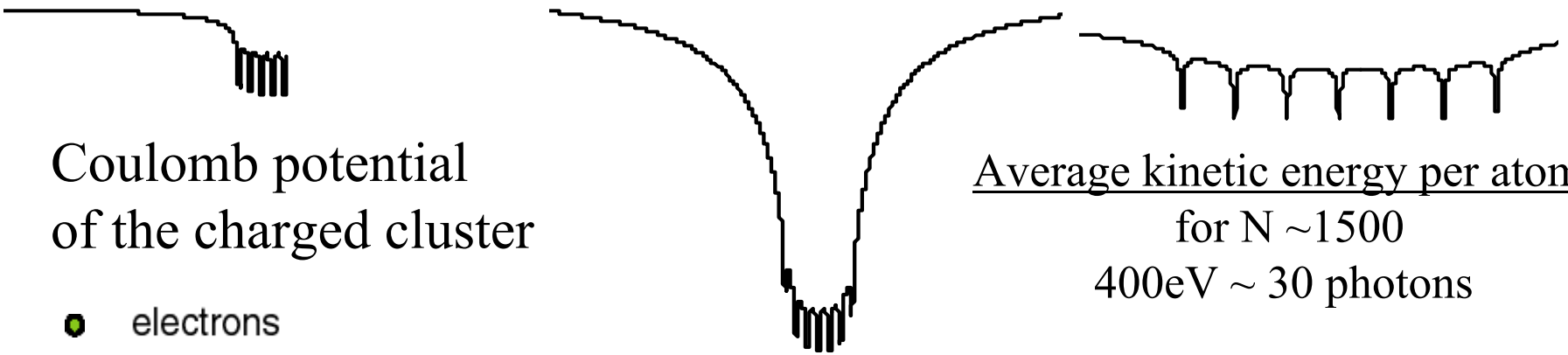
t_1 maximum

t_2 end of the pulse









Coulomb potential
of the charged cluster

electrons

Average kinetic energy per atom
for N ~1500
400eV ~ 30 photons

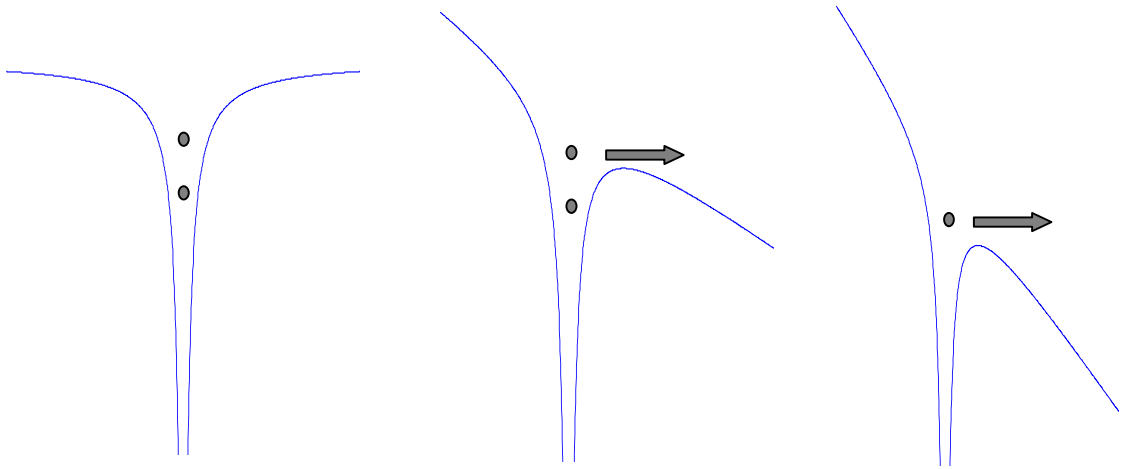
I ~$7.3*10^{13}$W/cm^2 ~ 10 Mbarn

Ionisation Model:

barrier suppression

Classical dynamics simulation
Xenon cluster; N=55-1063;
λ=780 nm;
I= 10^{16}W/cm^2 ; T_{puls}=100fs
J. Jortner, PRA 62 013201, 2000

Ionisation ignition model

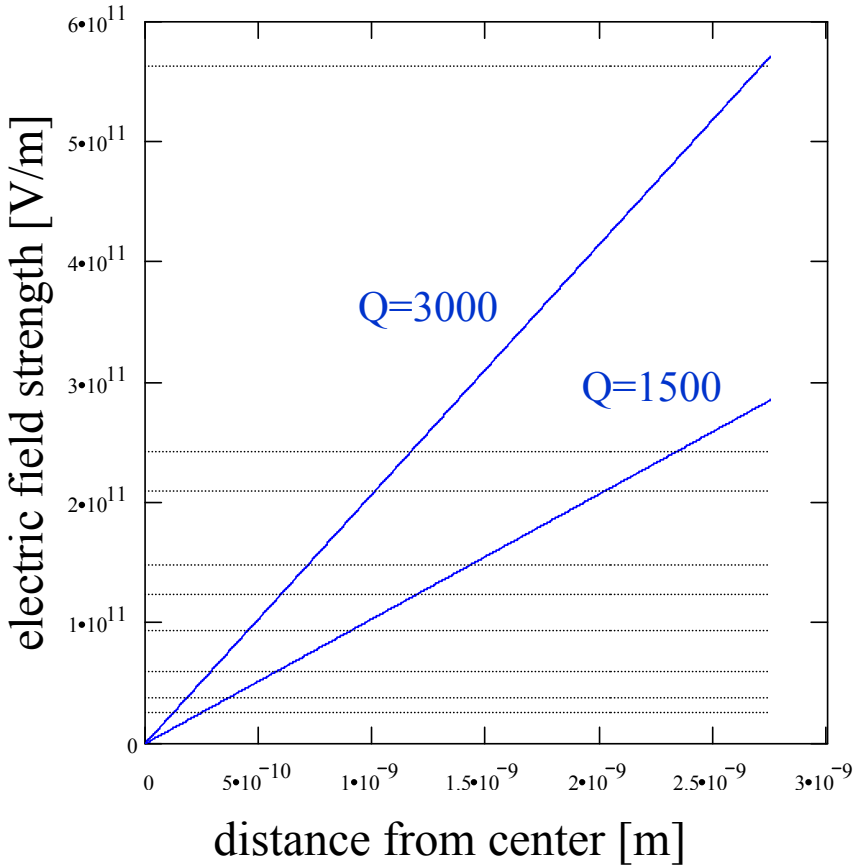


Coulomb potential + Laser + Cluster potential

- 5p electrons removed within 1.2 fs
- 5s electrons within 4 fs
- significant part of the electrons leave the cluster
- all ionisation events due to barrier suppression

Barrier suppression

Xenon cluster N=1500



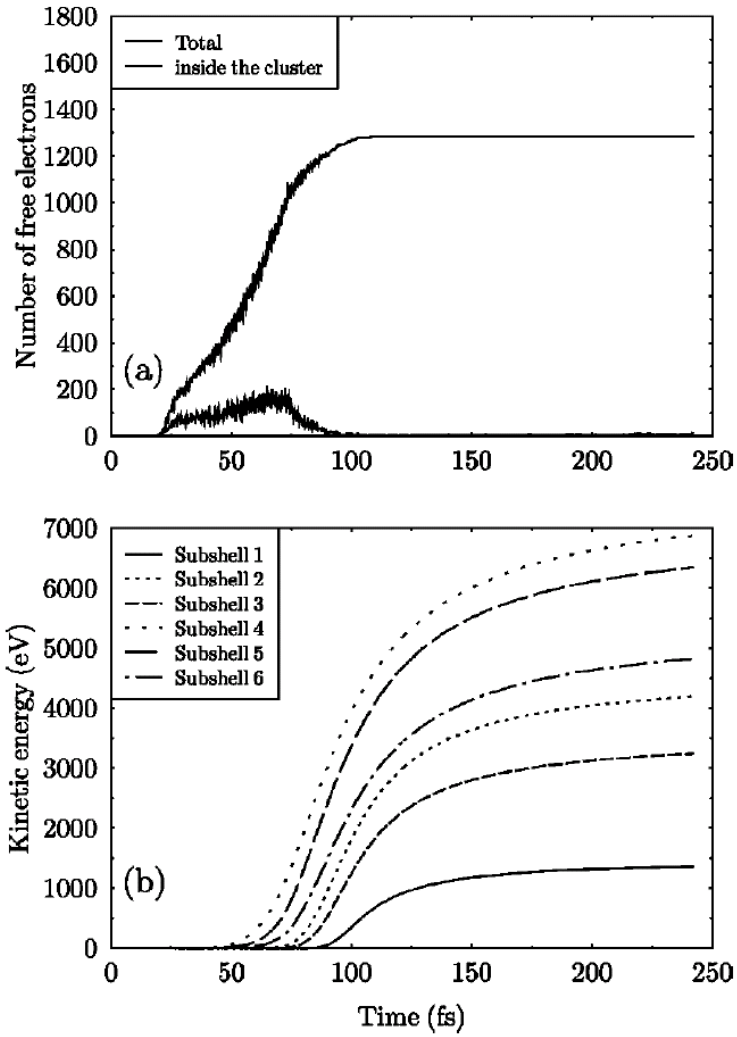
- uniformly charged sphere
  $E_{cluster}(r) = Qr/4\pi\varepsilon_0 a^3$
- Barrier suppression
  $E = I_p^2 \pi\varepsilon_0/Ze^3$
- Peak electric field of FEL
  $2.34*10^{10}$ V/m << $E_{cluster}$

Electric field of the cluster produces high charge states

Dashed lines: barrier suppression for Xe atomic ions with charge state z-1

Cluster Expansion

Classical particle simulation
Xenon cluster; N=147;
λ=780 nm;
I= $8.8*10^{15}$W/cm^2 ; T_{puls}=100fs
K. Ishikawa, PRA 62, 063204, 2000



Electrons quit cluster before
main stage of the ion acceleration

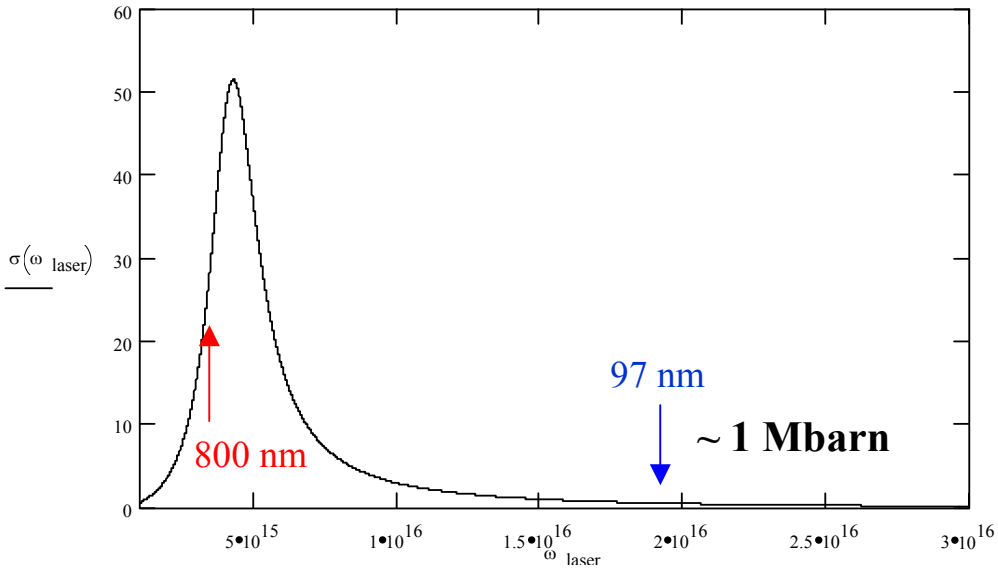
⇒ **No significant energy exchange with ions**

Coulomb explosion

- Stepwise character of cluster explosion,
- Ions in outer shells ionized earlier and accelerated more effective

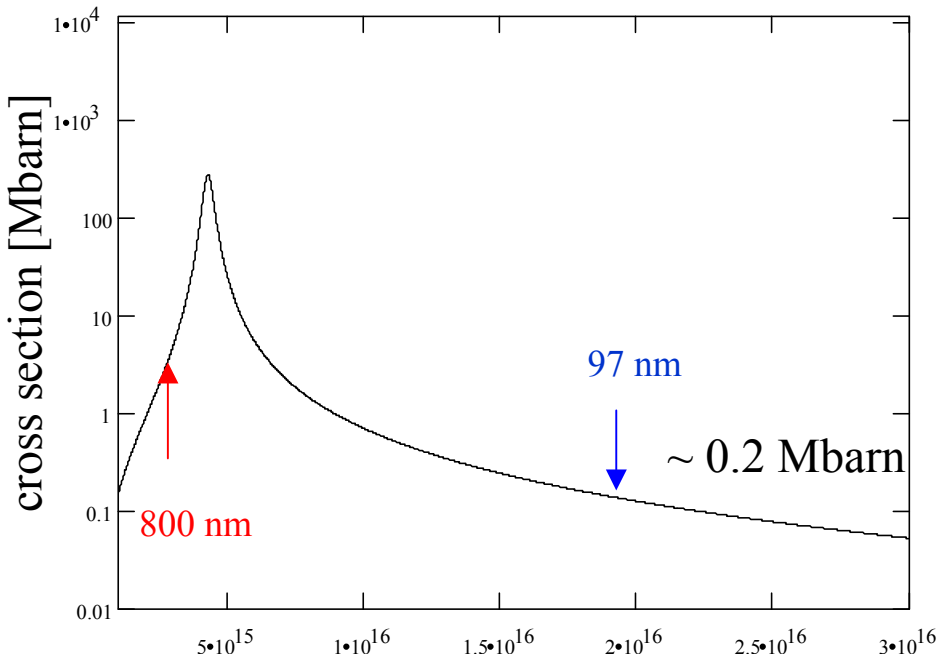
Classical Heating Mechanisms

Inverse Bremsstrahlung



laser frequency [1/s]

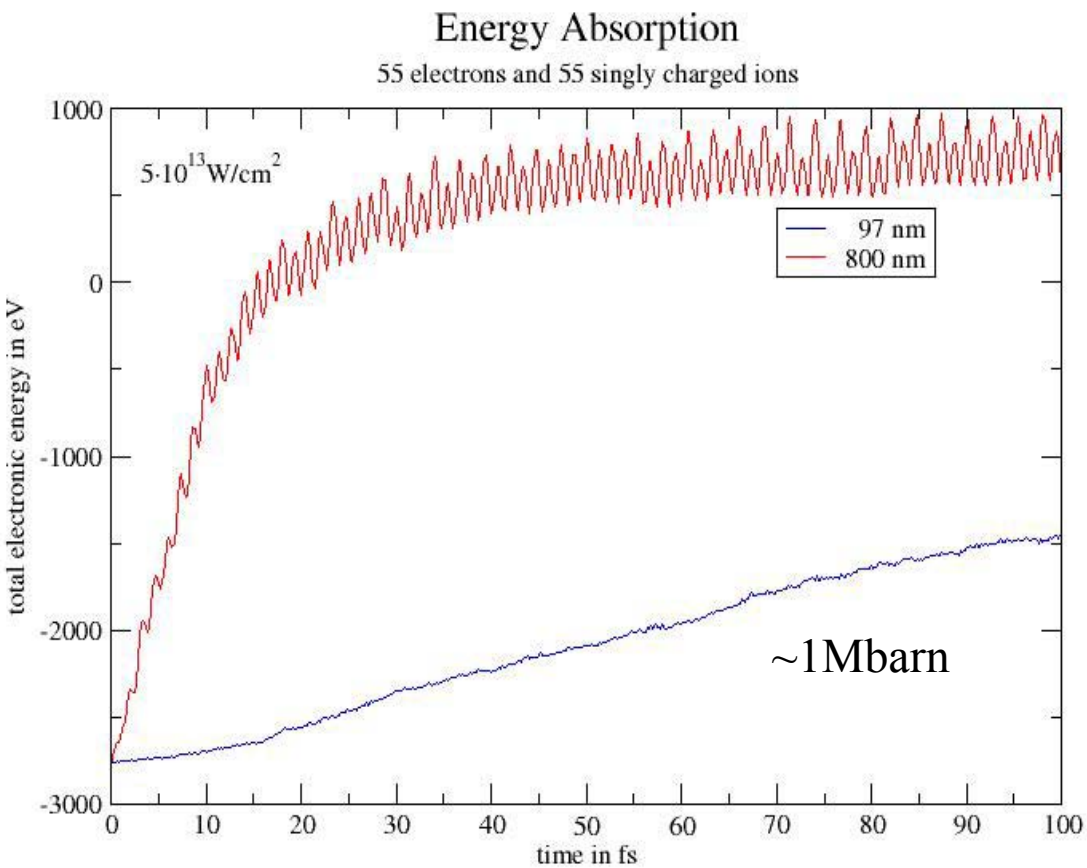
Plasmon Resonance



laser frequency [1/s]

Classical Simulation of Electron Trajectories

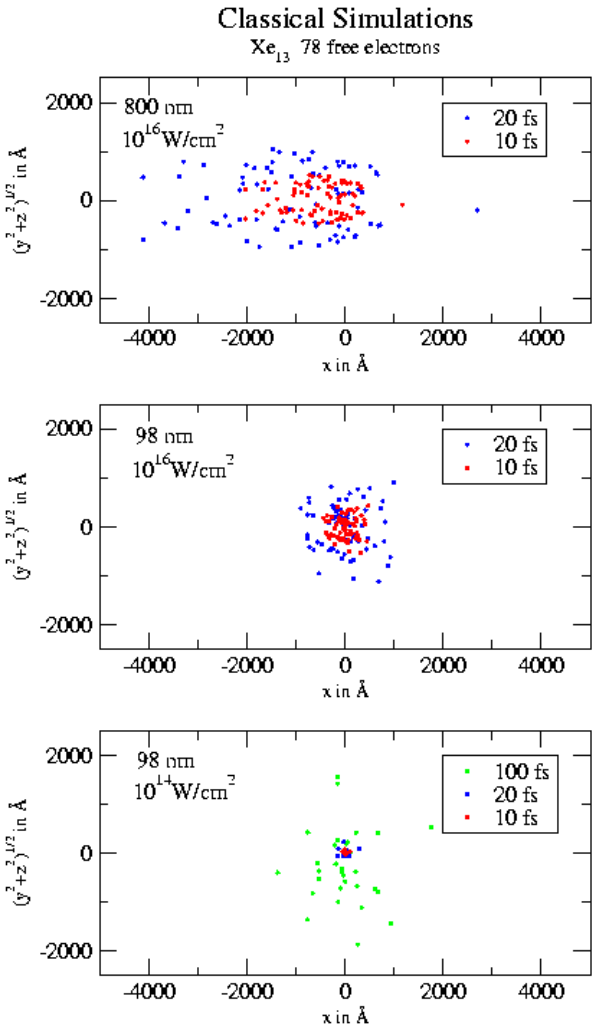
Classical particle simulation
Xenon cluster; N=55;
λ=97 nm, 800 nm;
I= $5.5*10^{13}$W/cm^2 ; T_{puls}=100fs



1 e$^-$/atom: 1 Mbarn
2 e$^-$/atom: 2.8 Mbarn
6 e$^-$/atom: 15 Mbarn

to low!
experimental value
10 Mbarn

Classical Simulation of Electron Trajectories



$\lambda = 800$ nm
field ionisation!

$\lambda = 98$ nm
thermionic emission!

Intermediate Absorption

insulator

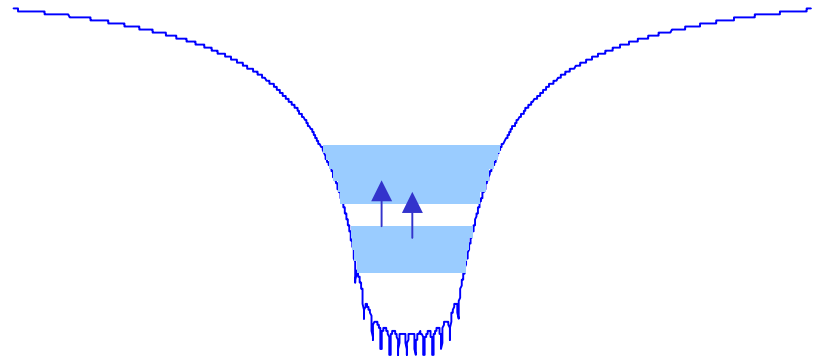
inert atoms, van-der-Waals binding

resonantly enhanced

electronic absorption

metallic behaviour ?

band structures, cesiumlike?



plasma

free electrons, ionic background

Conclusions

- Xenon clusters of variable size have been examinated.
- At 97nm with power density of 10^{14}W/cm^2 charge states up to Xe^{8+} with kinetic energies up to 2.5keV are visible.
- A large part of the results can be understood by classical trajectories simulations.
- Quantum mechanical effects have not been estimated so far.
- 97nm are on the high frequency side of the resonances.