Results obtained with the VUV-FEL in Phase I

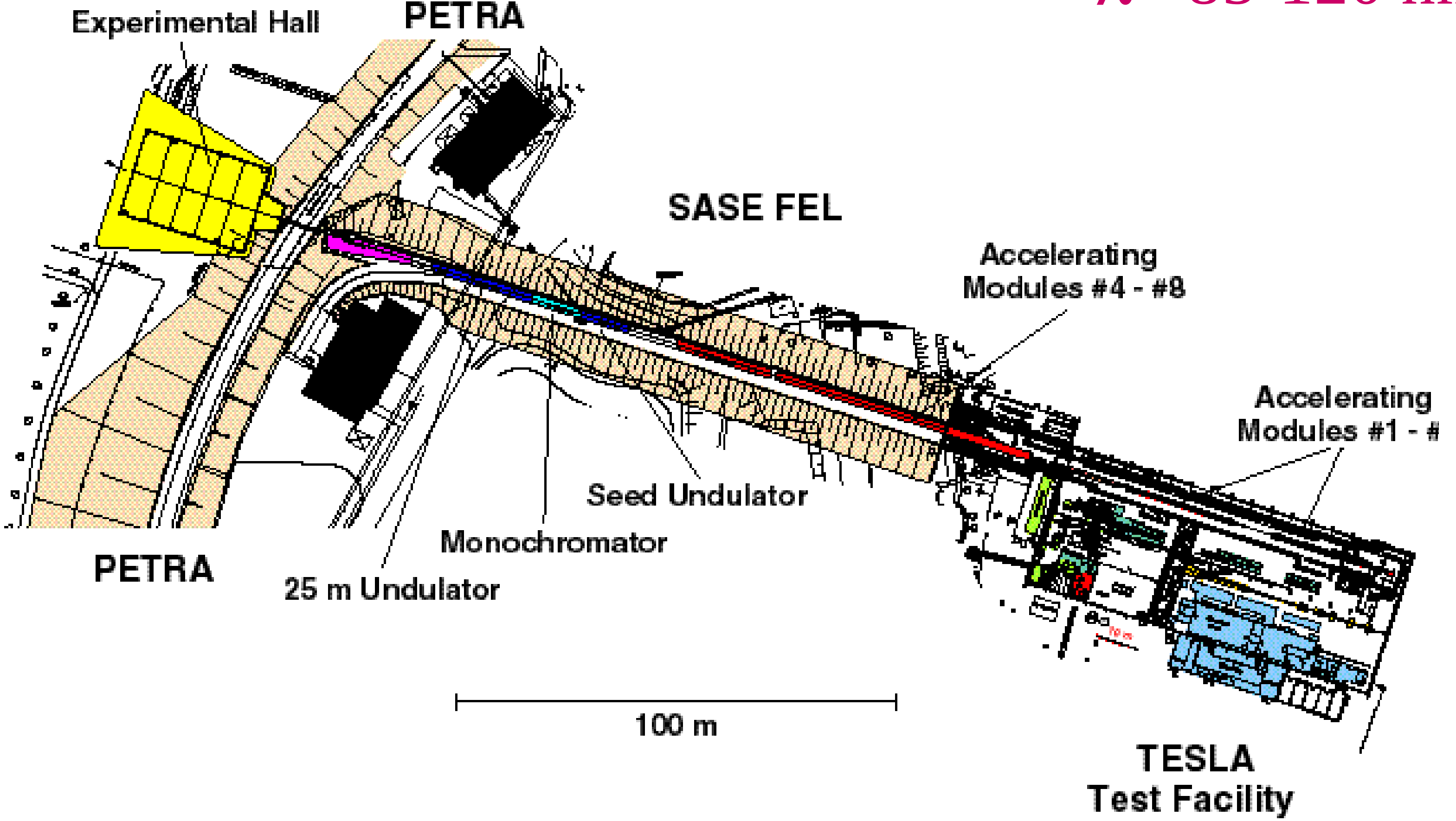
Hamburg, June 3, 2002

- **Parameters of the VUV-FEL**
- **Motivation**
- **Surfaces irradiated with high power VUV light**
  - **Radiation damage and ablation**
- **Interaction of intense pulses with molecules and clusters**
  - **Multi-photon absorption**
  - **Coulomb explosion**
- **Outlook**

VUV FEL at the TESLA Test Facility

Phase II 2004
user facility λ > 6 nm

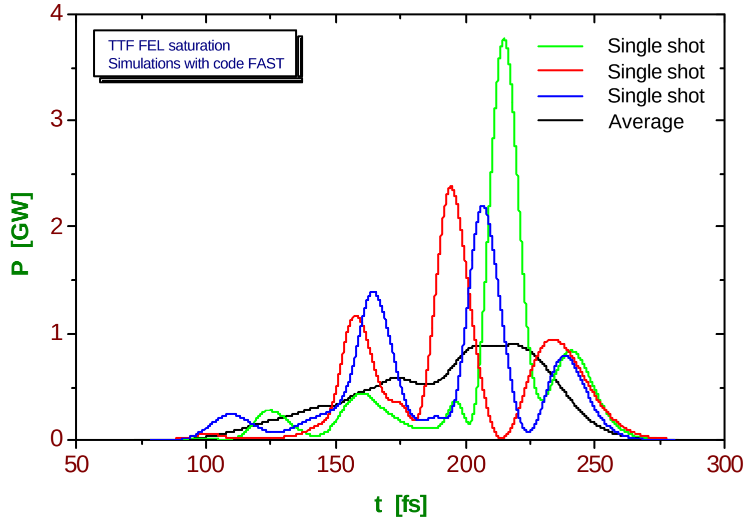
Phase I 2002
λ~ 85-120 nm

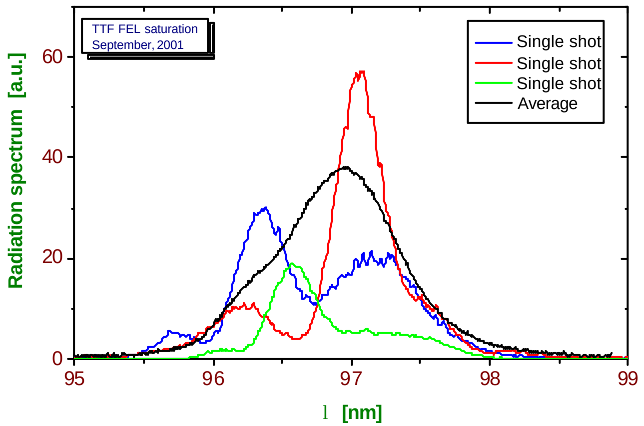


Time and spectral distribution

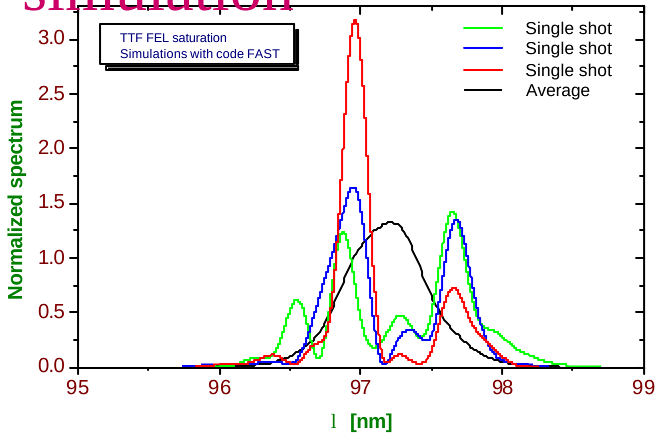
Simulated temporal distribution

measurement





simulation



Pulse length 50-100 fs (FWHM)

M. Yurkov et al

The VUVS-FEL is a unique light source

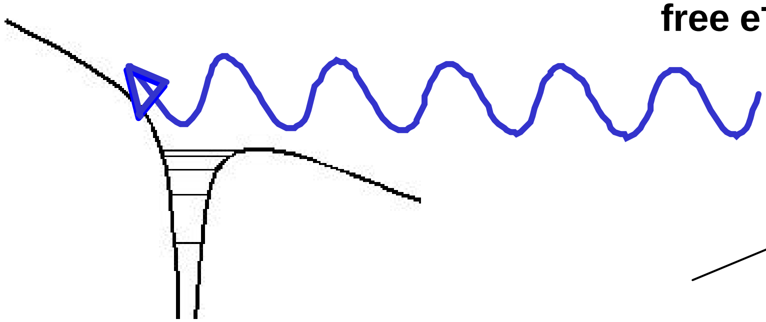
- Pulse length 30-100 fs
- Wavelength shorter than 100 nm
- Gigawatt peak power
- Fully coherent beam
- Powerdensity > 10^{14} Watt/cm^2

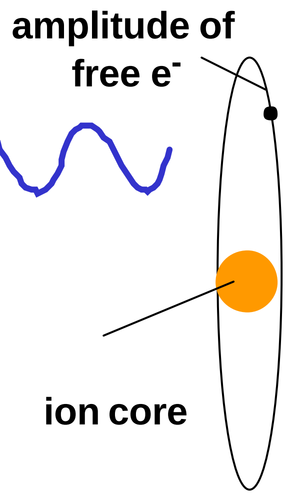
Multi-photon processes
Optical non-linear processes
Pump probe experiments

1000 times higher peak brilliance than any other source at this wavelength

Interaction of Intense Soft X-rays with Matter

laser-atom process at $I \sim 10^{14}$ W/cm^2, ponderomotive energy 10-100 eV

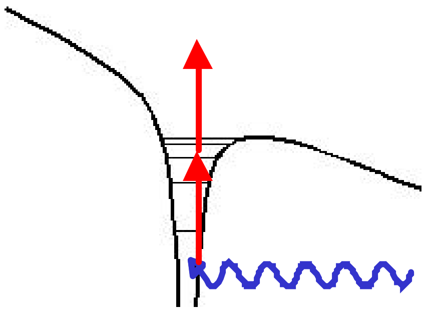




P. Bucksbaum et al

- **Field modulates the atomic potential at visible laser frequency**
- **Outer e$^-$ has time to tunnel or overcome the barrier:**
  $2U_p > I_p$ where $U_p \sim I\omega^{-2}$

VUV FEL laser-atom process at $I \sim 10^{14}$ W/cm^2, ponderomotive energy 10-100 meV

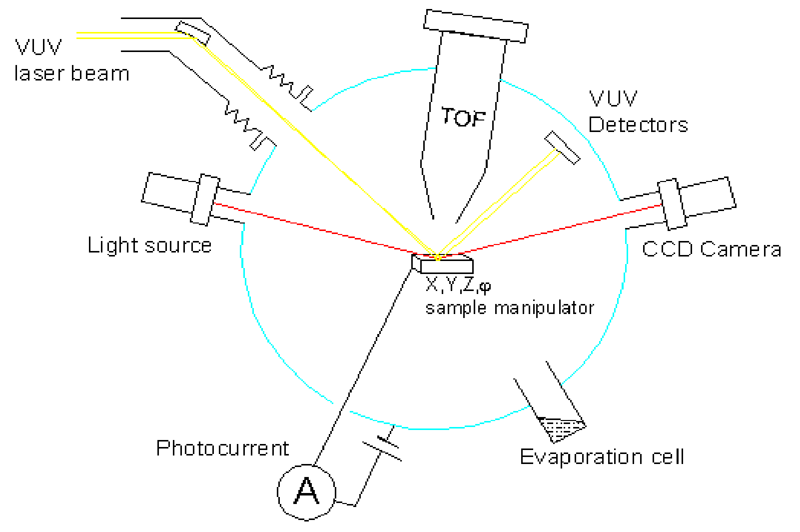


- **Field modulates the atomic potential at soft x-ray laser frequency**
- **e$^-$ do not have time to tunnel free**
- **multi photon process and innershell electrons are important**

Investigation of the damage threshold of optical components at the VUV TESLA FEL Phase I

J.Krzywinski [1,2],
A.Andrejczuk [1,3], U.Hahn [2],
M.Jurek [1,2],J.Pelka [1,2],
W.Sobala [4], M.Sikora[5],
R.Sobierajski [2,6]

[1]Polish Academy of Sciences, [2]HASYLAB at DESY, Germany, [3]University of Bialystok, Poland,[4]Institute of Nuclear Physics, Cracow,Poland [5]University of Mining and Metallurgy, Cracow, Poland [6]Warsaw University of Technology, Poland

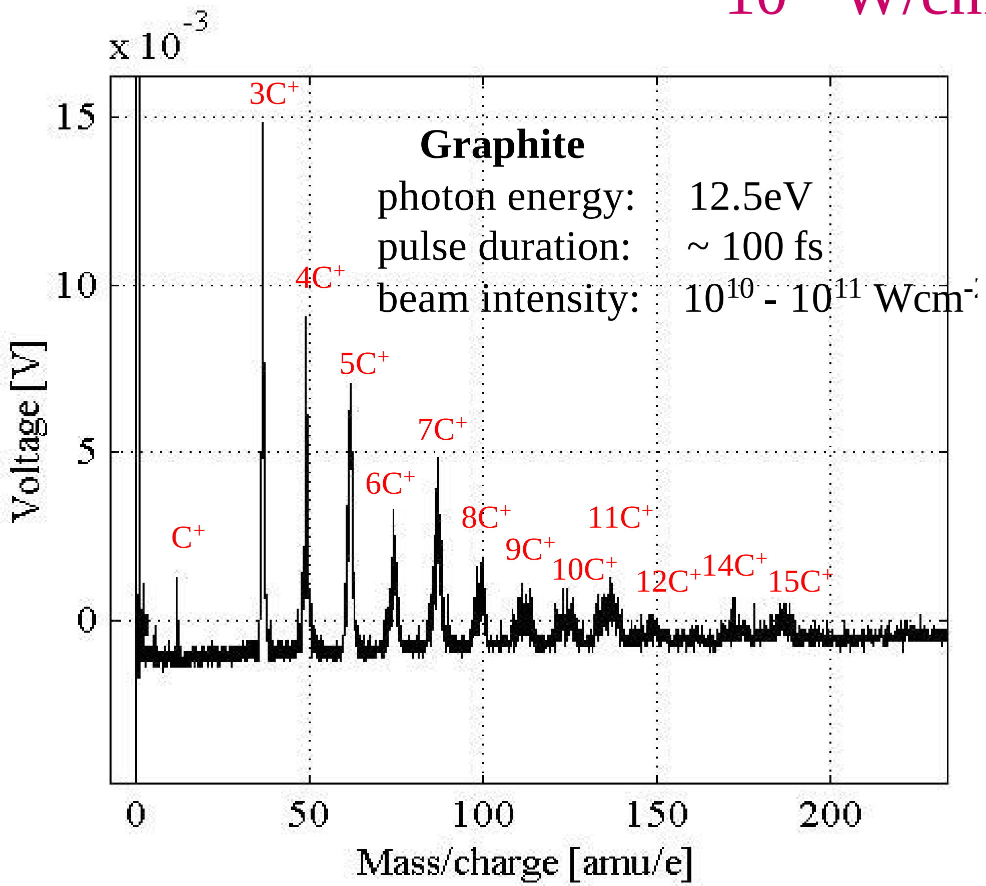


Pulse length	**100 fs**
Pulse energy	**10-100 mJ**
Wavelength	**98 nm**
Spot size	**100 mm**
Max. power density	**~10^{13} W/cm^2**

Experimental results

Sept. 2001

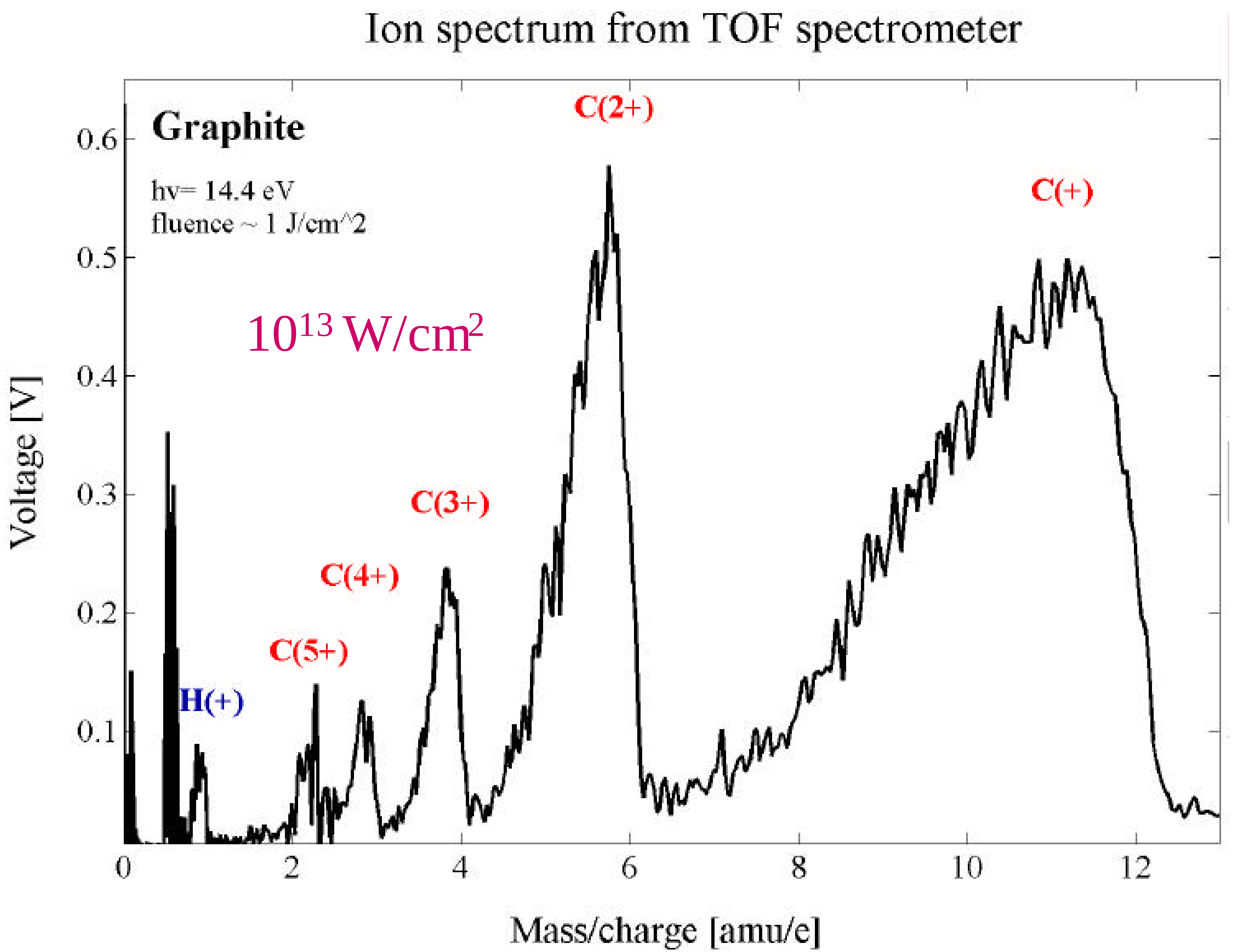
~ 10^{11} W/cm^2



Estimated damage thresholds:

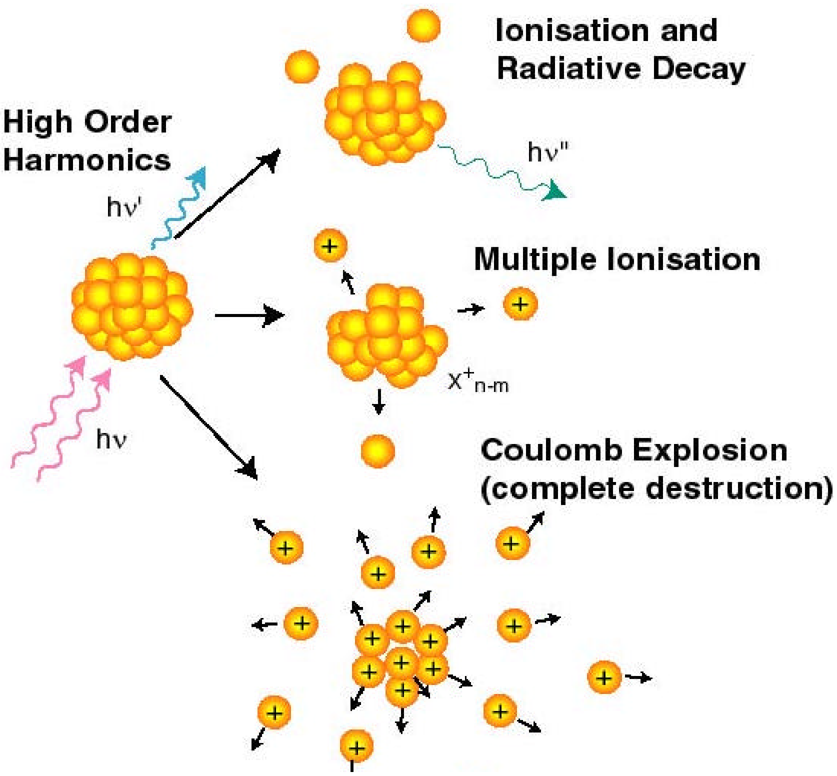
Sample/thickness		damage threshold [J/ cm^2]
Cu	bulk	0.5
Au	10 nm	0.04
Si	bulk	0.03
Graphite	40 nm	0.06
YAG	bulk	0.07

FELIS Jan. 2002



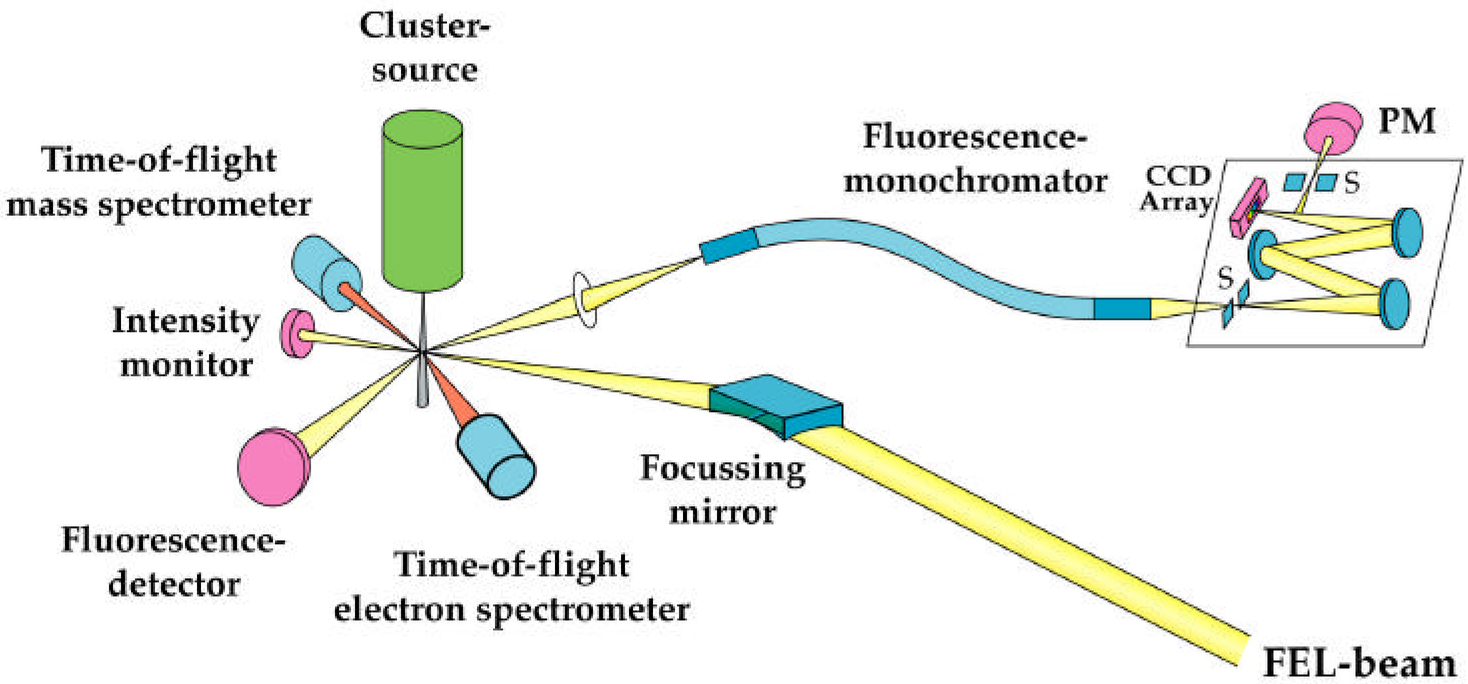
Idea of the experiment

interaction of intense soft x-rays with matter

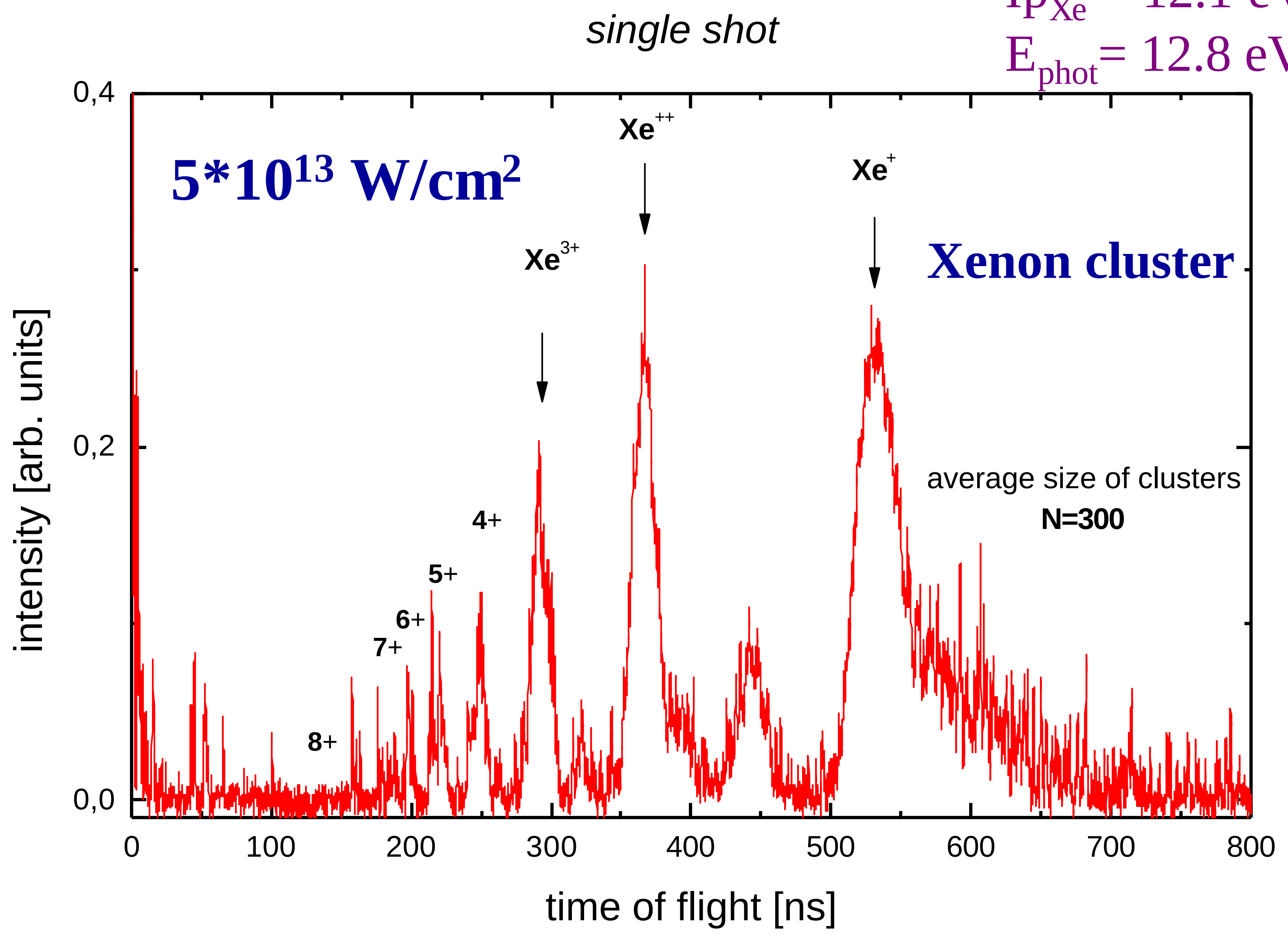


- **which multi-photon processes are observed**
- **cross sections (surface, bulk)**
- **which ions are prepared (charge state, electronically excited states)**
- **life time of intermediate states**
- **high-order harmonic generation**

FEL Cluster-Experiment

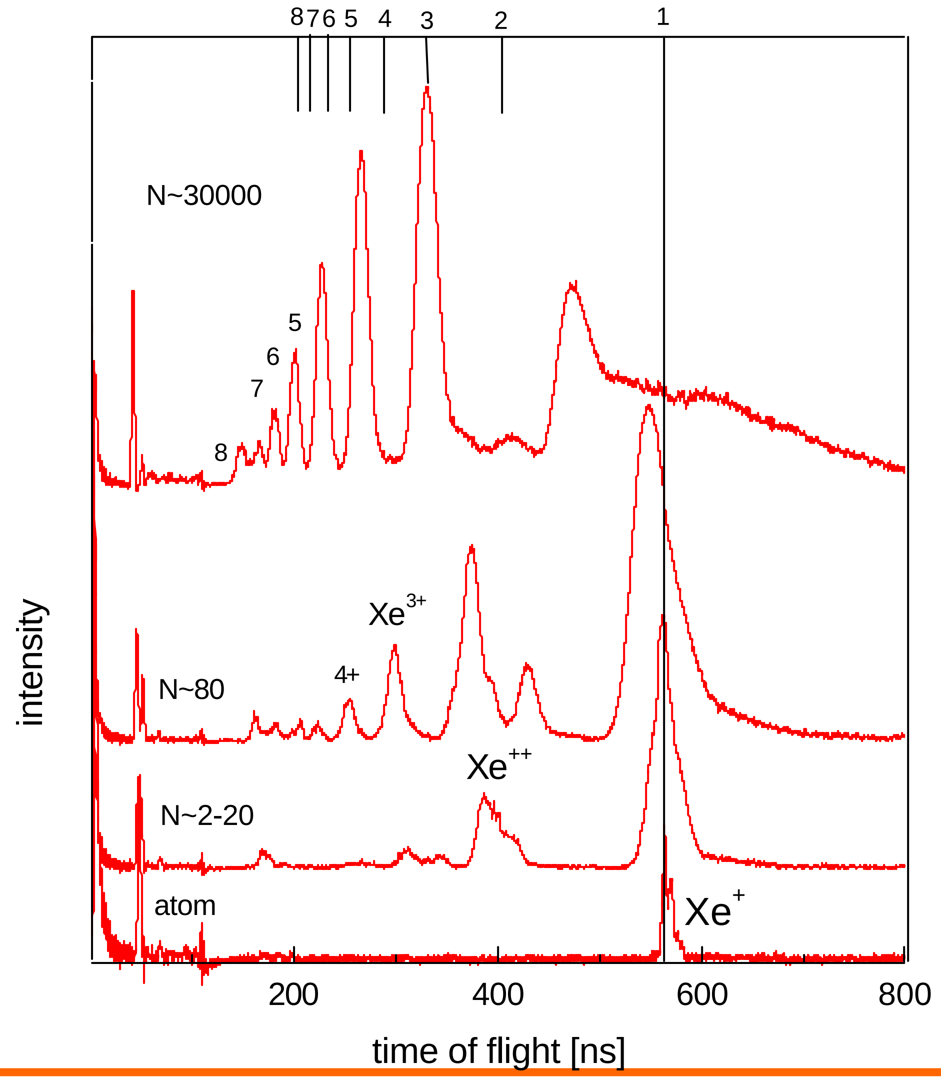


$Ip_{Xe} = 12.1$ eV
$E_{phot} = 12.8$ eV



σ = 50 Mbarn (single photon ionisation, 100 photons within σ)

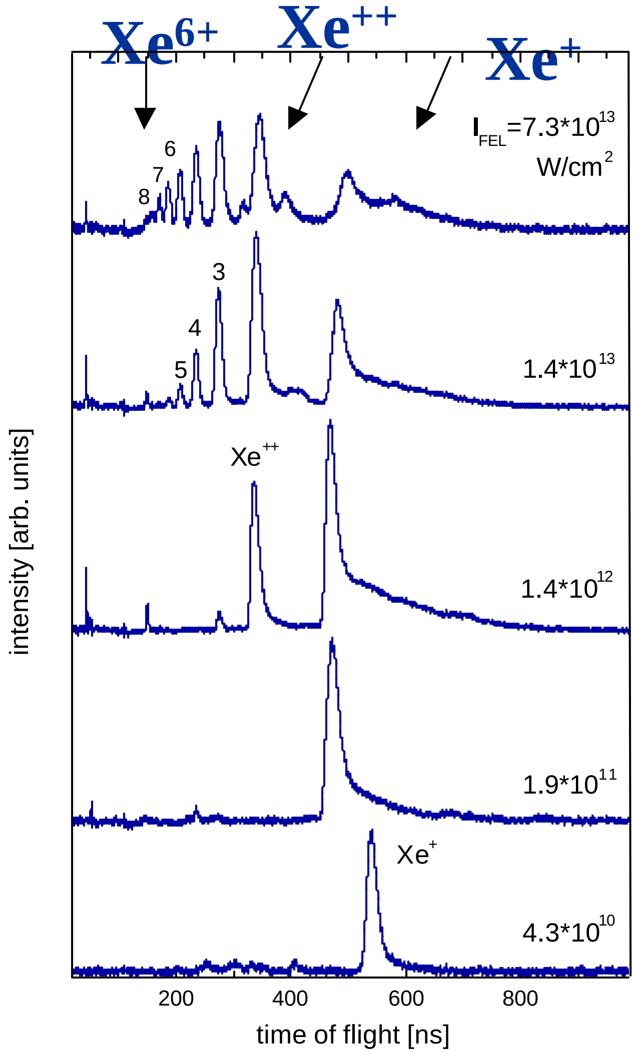
Time of flight mass spectra of Xe atoms and clusters



- multiply charged ions from clusters
- singly charged atoms

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

Dependence on the power density



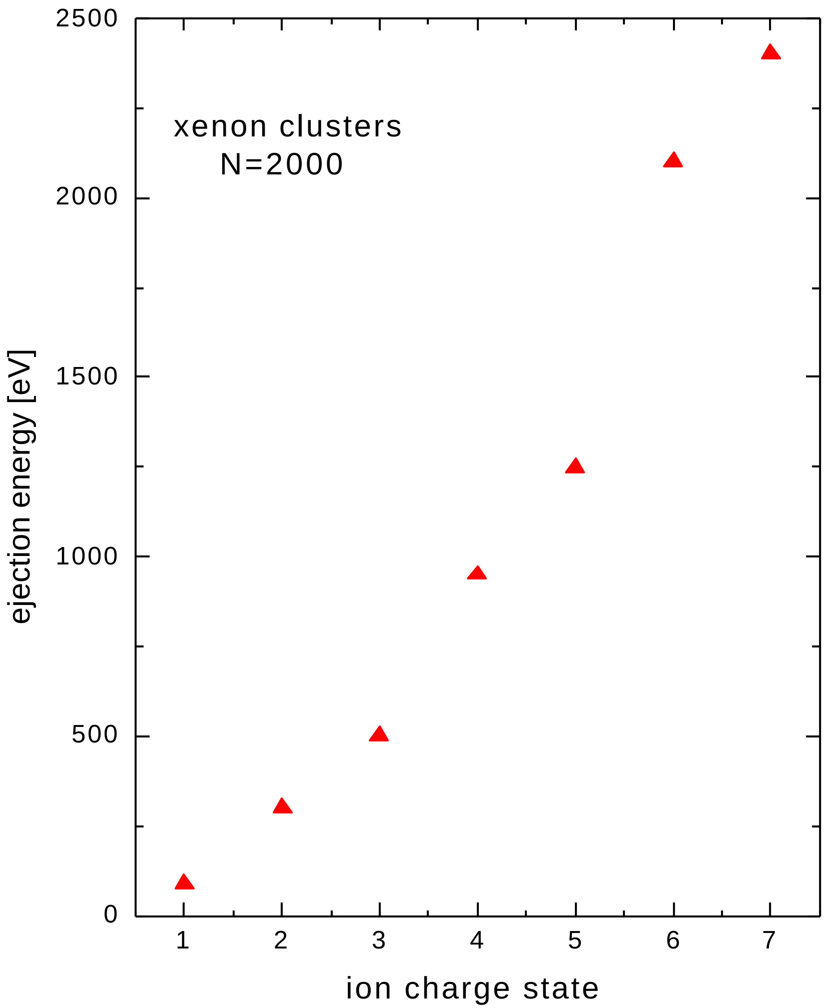
Time of flight [ns]

Xenon clusters, 1500 atoms

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

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

Kinetic energy of the ejected ions



- **Quadratic dependence on charge**
- **Coulomb explosion**
- **Up to 3 keV kinetic energy**
- **Each atom in the cluster absorbs 10-20 photons**

Three Questions

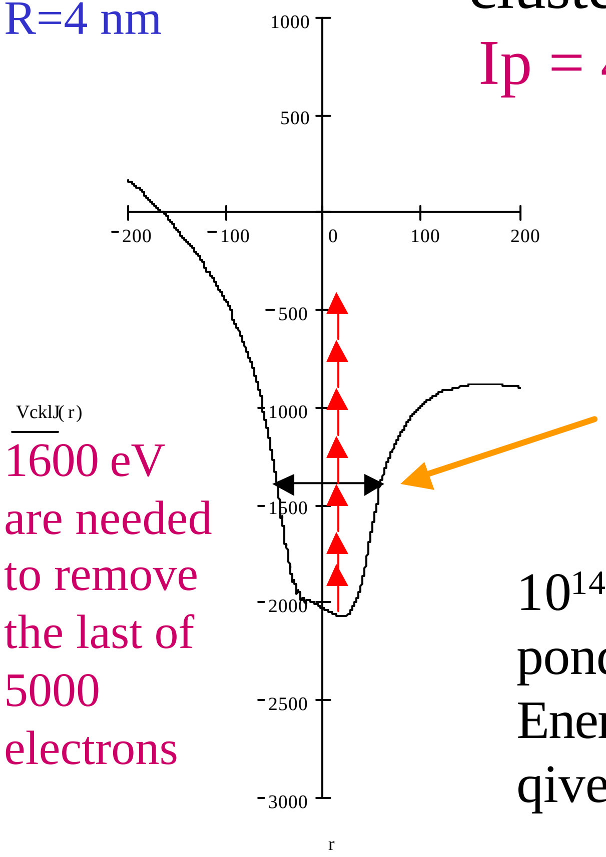
- Which process allows the absorption of up to 20 photons/per atom?
- What is the ionisation mechanism?
- How can we explain the high charge states?

Multi-photon versus fieldionization

N =5000,
Q=5000
R=4 nm

Ionization energy Ip of Q electrons in a cluster ~ Q^2

$Ip = 4.1*10^6$ eV (Xe_{5000}) for Q=5000



1600 eV are needed to remove the last of 5000 electrons

Field ionization by Coulomb-field

10^{14} Watt/cm^2
ponderomotive Energy 150 meV
qiver radius 0.008 nm

Inverse Bremsstrahlung

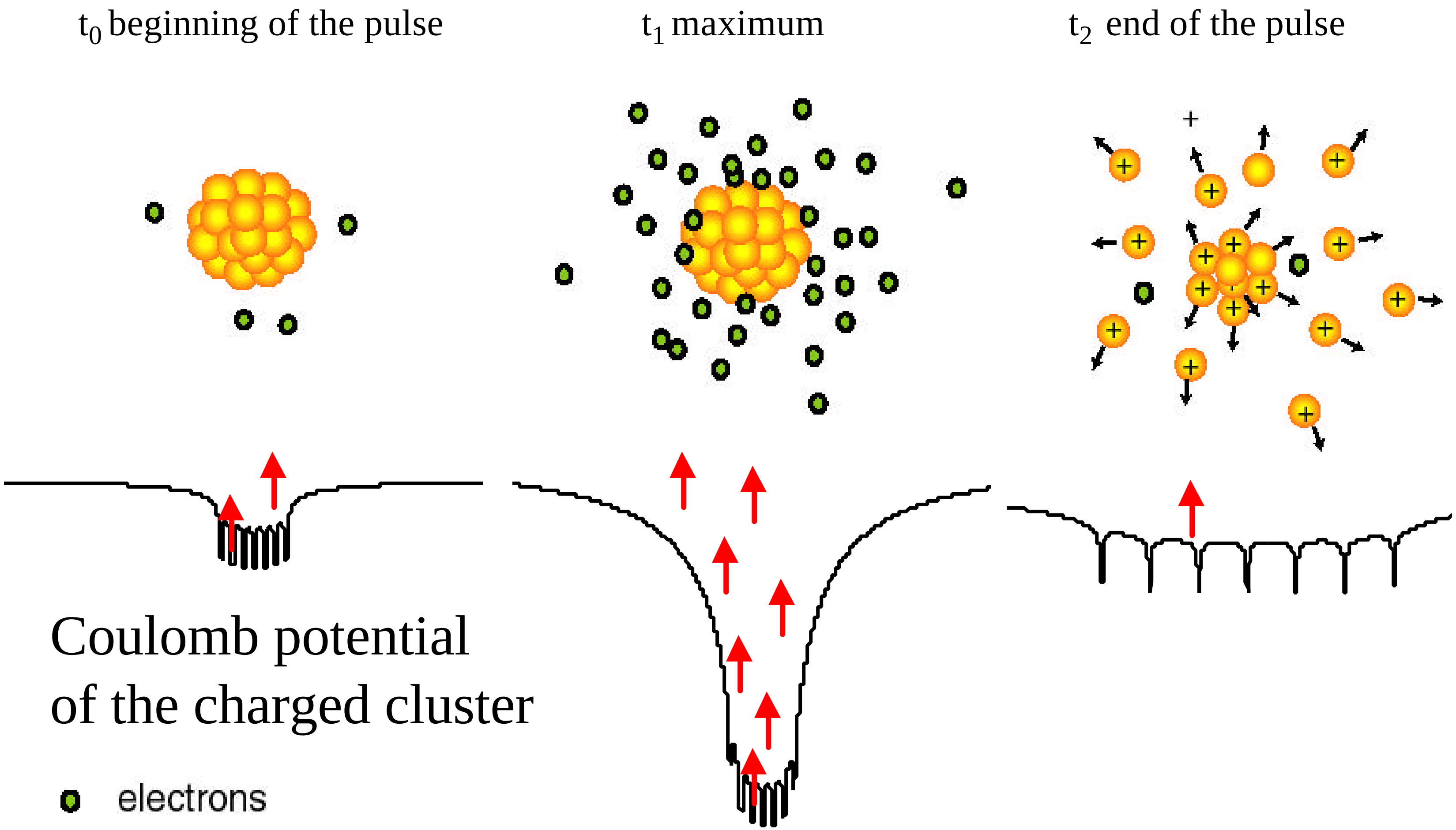
σ = 21 Mbarn, Te = 1eV

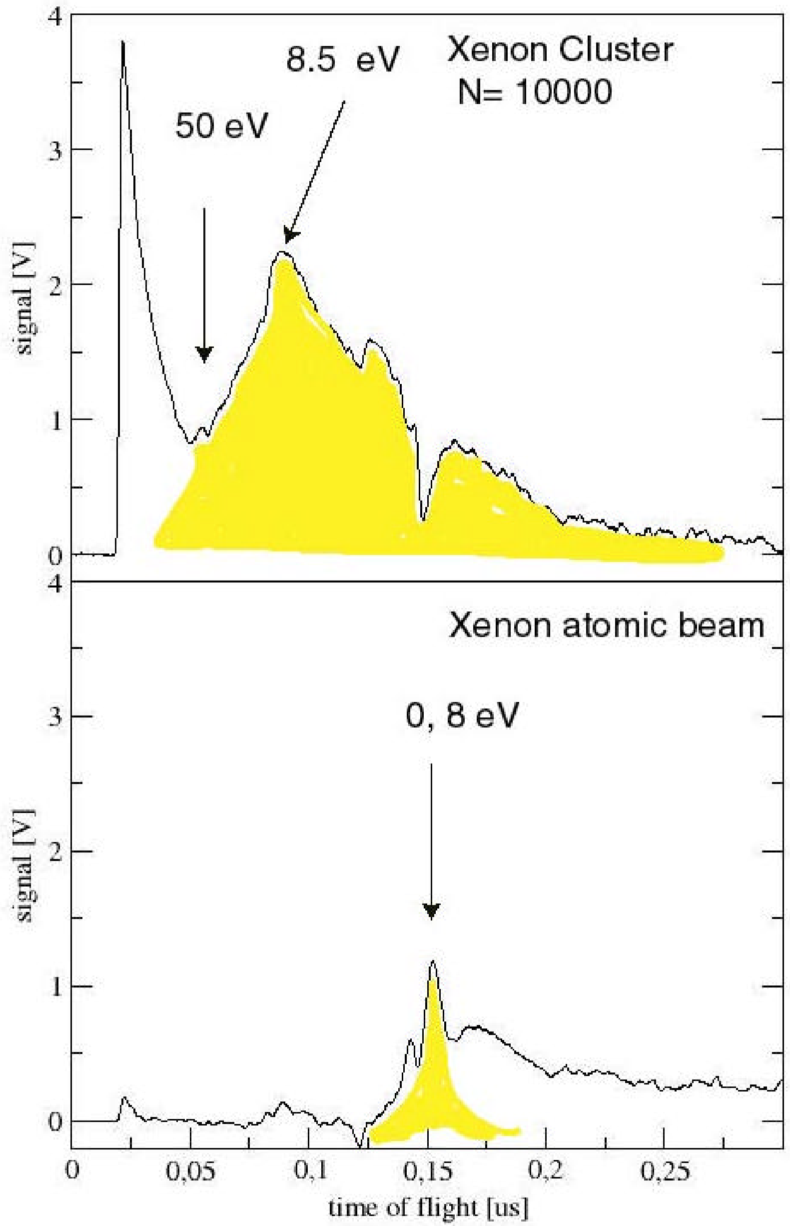
0.2 Mbarn, Te = 100 eV

Experiment 15 Mbarn

Electronic absorption?

Coulomb explosion of clusters induced by multi-photon absorption



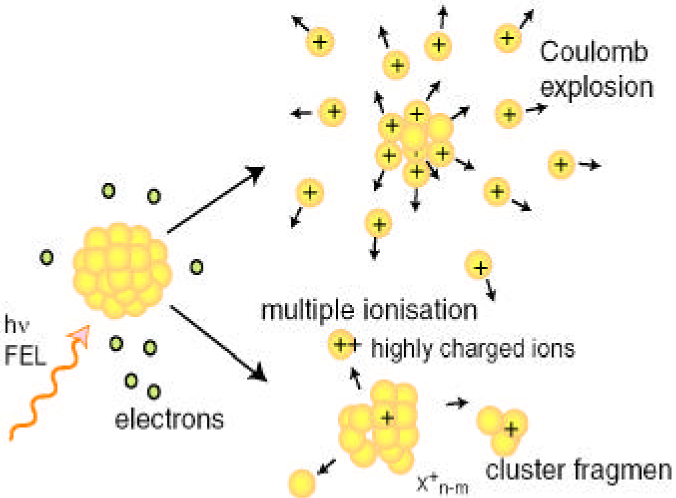


Time-of-flight photoelectron spectra

multi-photon and field ionization in clusters
E_{kin}= 0-50 eV

single-photon ionization in atoms (E_{kin} ~ 0.8 eV)

Present understanding



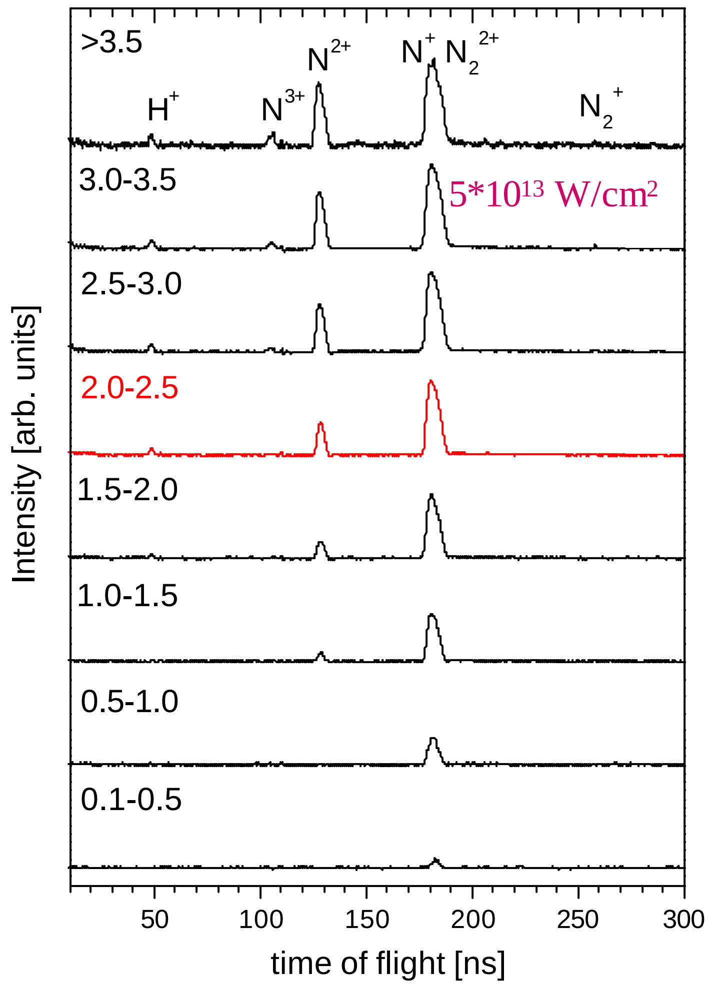
- **Nanoplasma formation: inner ionisation of all atoms**
- **production of high charge states by field ionisation at the cluster surface**
- **multi-photon absorption of up to 20 photons per atom in the cluster**
- **outer ionisation by combined multi-photon absorption and field ionisation**

Coulomb explosion, hot ions

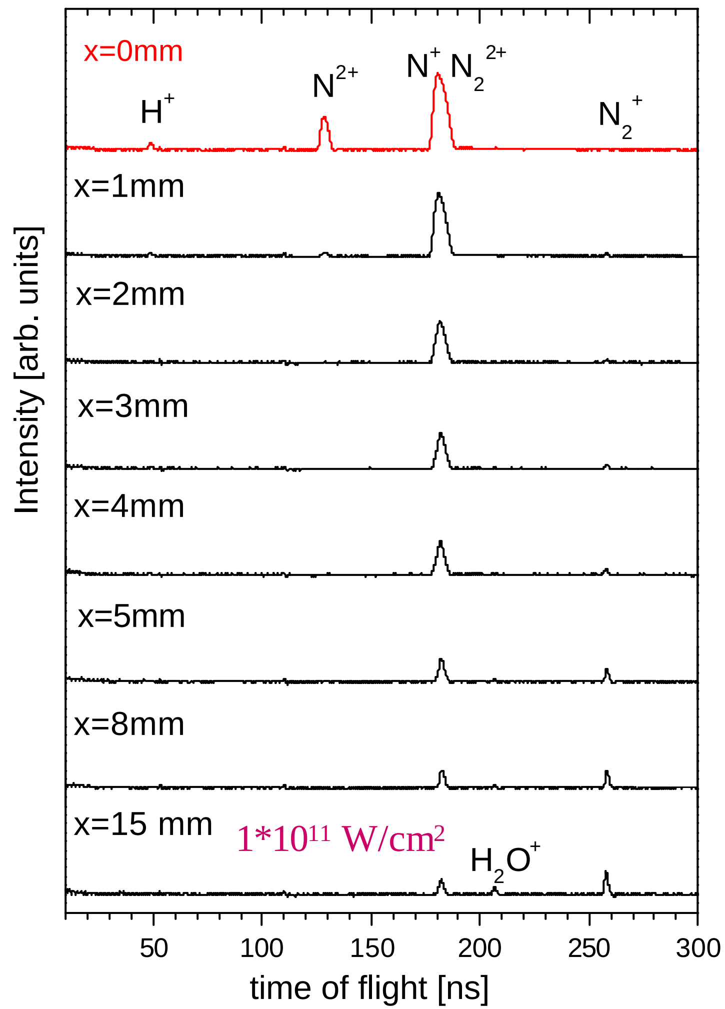
cold electrons

Photoionisation of nitrogen molecules

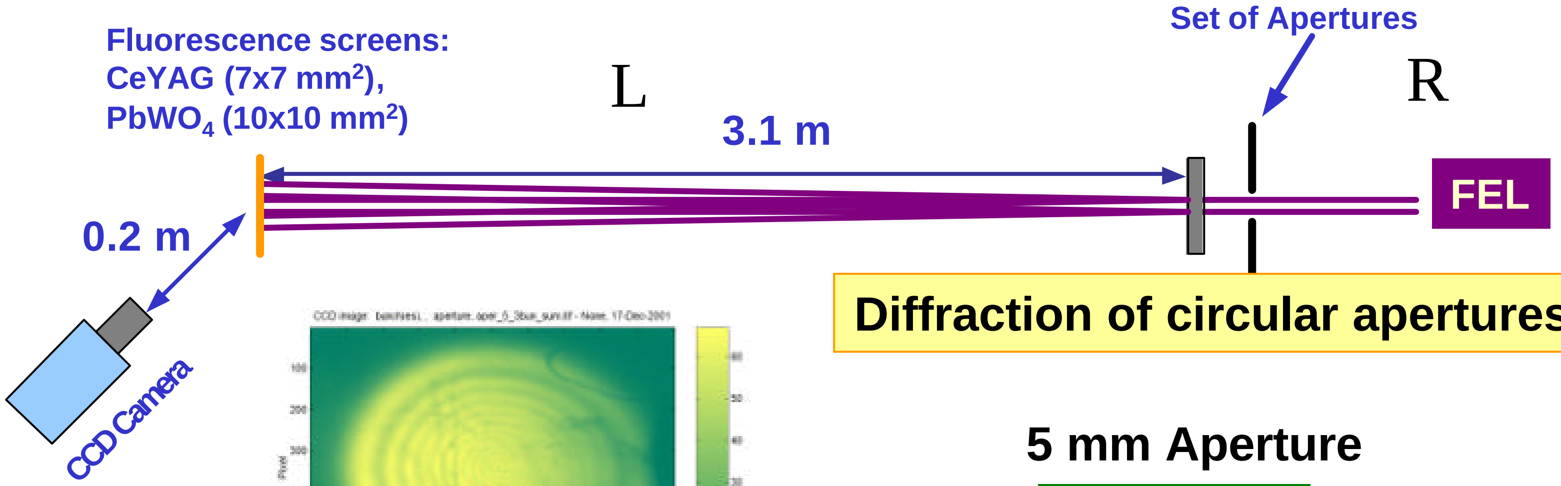
variation of the intensity

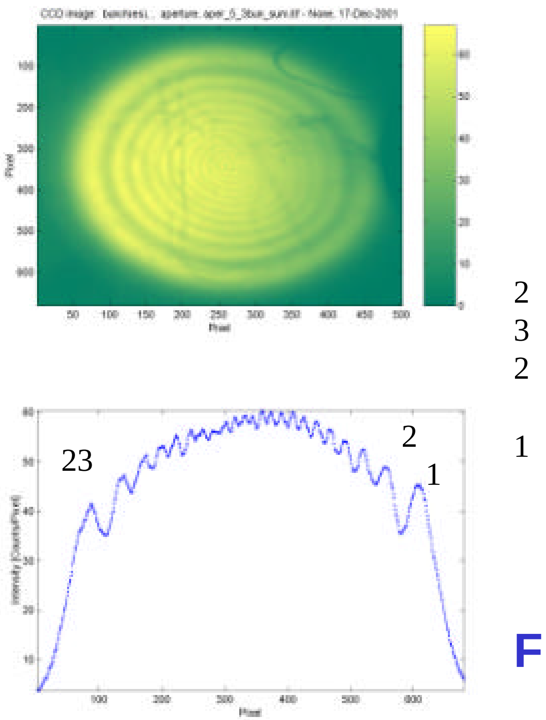


variation of the spot size



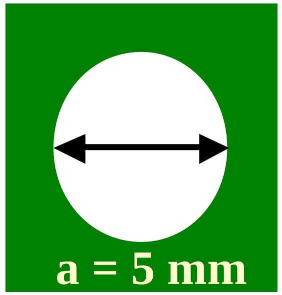
Measurement of Diffraction Patterns





Diffraction of circular apertures

5 mm Aperture



Fresnel Number:

$$F = \frac{a^2}{\lambda \cdot L} + \frac{a^2}{\lambda \cdot R} \quad (a \ll L;\ a \ll R)$$

R. Ischebek

Hubertus Wabnitz
Joachim Schulz
Peter Gürtler
Wiebke Laasch **Cluster experiment**
Tim Laarmann
Anja Swiderski
Klaus von Haeften

L**. Bittner, R. de Castro, R. Döhrmann, B. Faatz,**

J. Feldhaus, Ch. Gerth, U. Hahn, E. Saldin,

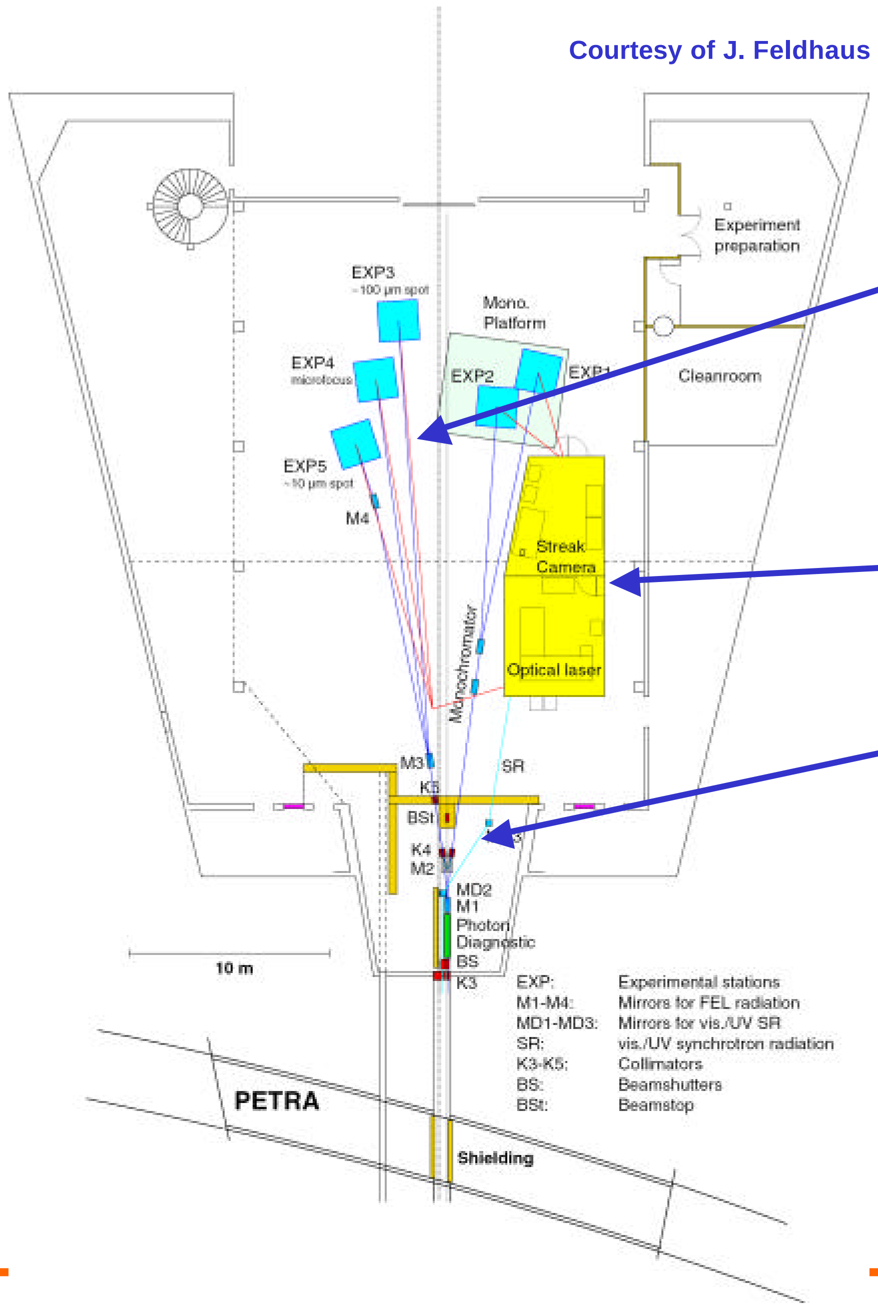
E. Schneidmiller, K. Tiedtke, R. Treusch, M. Yurkov

and the TTF-team

Summary and Outlook

- **VUV-FEL provides light for first experiment**
  high power and short pulses (<100 fs)
- **new physics**
- **experiments in Phase II 2004**
  Workshop in November 2001 on first experiments
  innershell electrons
  time resolved studies
  Workshop warm dense matter June 8,9, 2002
  ……

Layout of the experimental hall of the user facilty



Experiments using the direct Beam, different spot size

Laser/Streak Camera hutch

Photon diagnostic