Clusters in intense x-ray pulses
from 100 nm to .7 nm

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Outline:
- Introduction and motivation
- Spectroscopy of clusters
- Single shot imaging of clusters
- Conclusions

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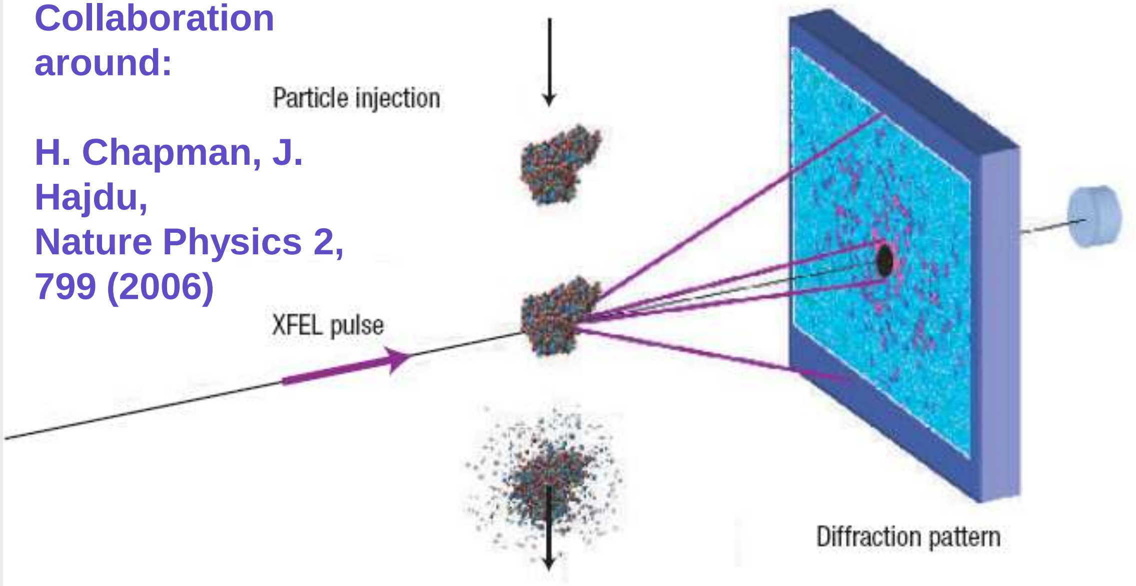
Structure determination with a FEL

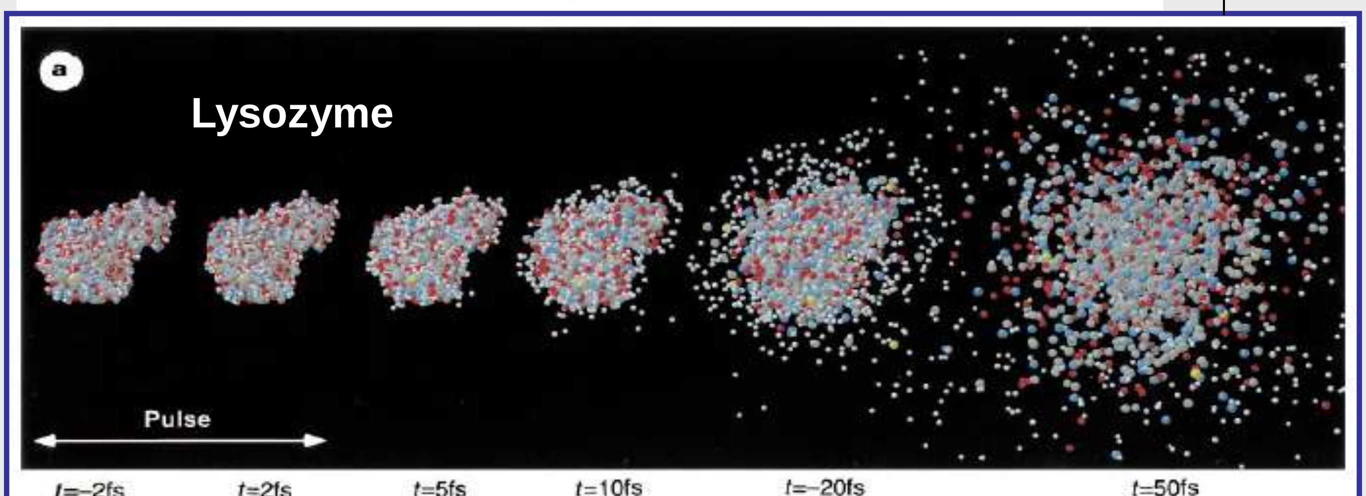
Molecules with atomic resolution

Collaboration around:

H. Chapman, J. Hajdu, Nature Physics 2, 799 (2006)



Crystal



R. Neutze, J. Haidu et al., Nature 406, 752 (2000)

Radiation damage and Coulomb explosion

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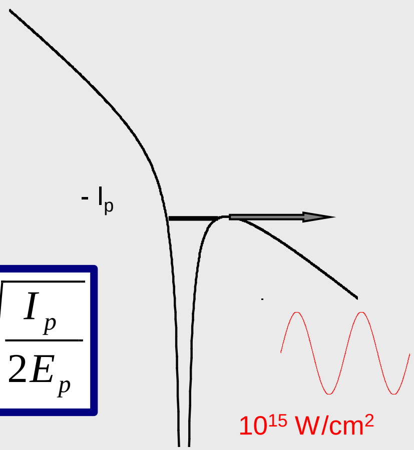
Radiation – matter interaction

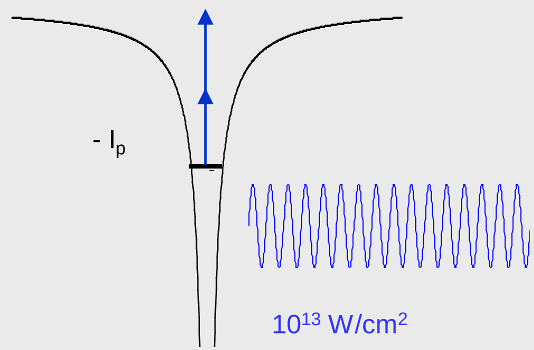
IR: quasistatic description

$$\gamma = \sqrt{\frac{I_p}{2E_p}}$$



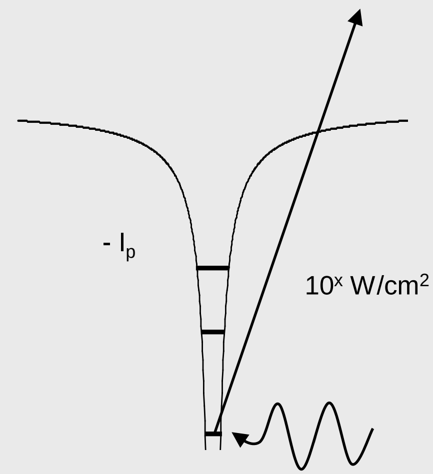
- Keldysh parameter $\gamma \ll 1$
- Tunnel / over the barrier ionisation
- Ponderomotive energy 10 eV – 10 keV

VUV FEL: intense photon source



- Keldysh parameter $\gamma \gg 1$
- Multi-photon ionisation
- Ponderomotive energy 10 meV

XFEL FEL: highly ionizing



- Angstrom wavelength
- Direct ionisation
- Secondary processes

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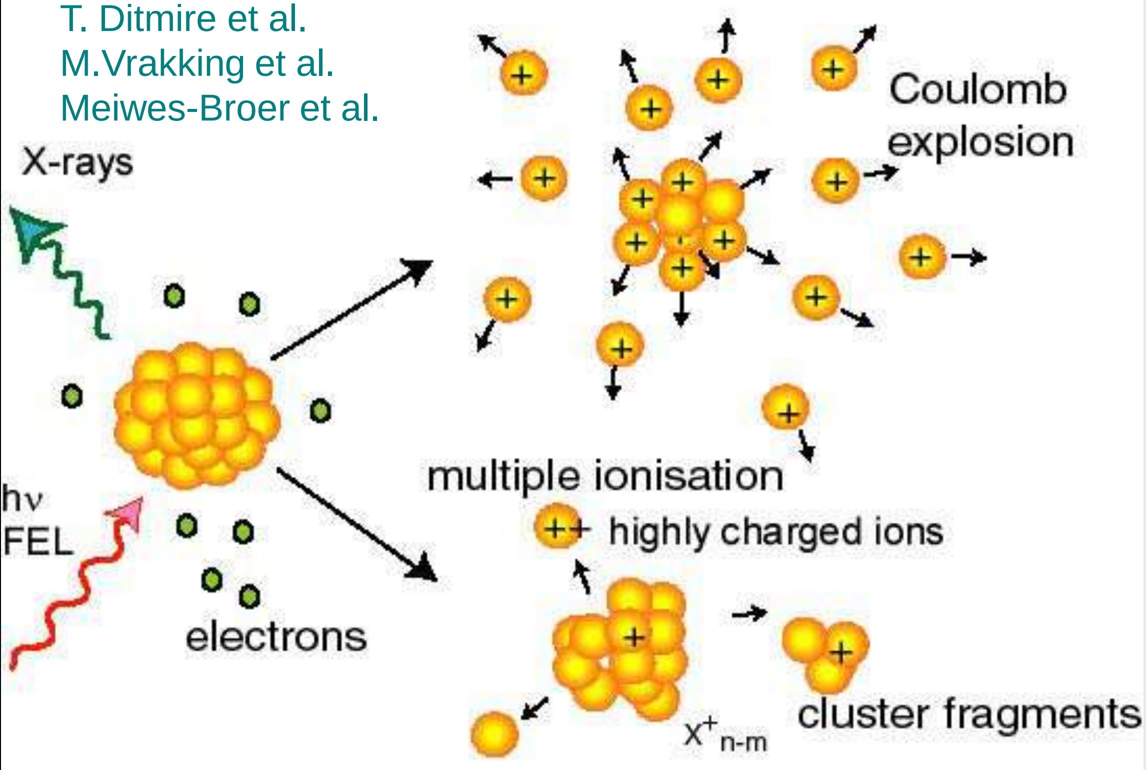
Non-linear cluster ionization

Infrared
T. Ditmire et al.
M.Vrakking et al.
Meiwes-Broer et al.



Clusters as „nanolab“:
- bulk density
- no energy dissipation
- intra- vs. interatomic effects

Driving questions:
- mechanism of absorption and ionisation
- are non-linear / multi-photo processes observed?
- time scale of electron emission and of ion motion

	FLASH		LCLS
λ=	**100nm (2002)**	**13 nm (2005)**	**now 0.7 nm**

Cluster physics yields insight into the fundamental questions on light – matter interaction

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FLASH: The VUV FEL at DESY

Phase I
2001

- **80-120 nm**
- **30-100 µJ**
- **1 GW_{peak}**
- **30-100 fs**

Linac and FEL extension for Phase 2

Experimental hall
Start of users operation 2005

- **5 - 50 nm**
- **10 – 30 fs**
- **20-150 µJ**
- **Upgrades underway (09/10)**

V. Ayvazyan *et al.*, *PRL* 88, 104802 (2002)
V. Ayvazyan *et al.*, *Eur. Phys. J.* A 37, 297 (2006)

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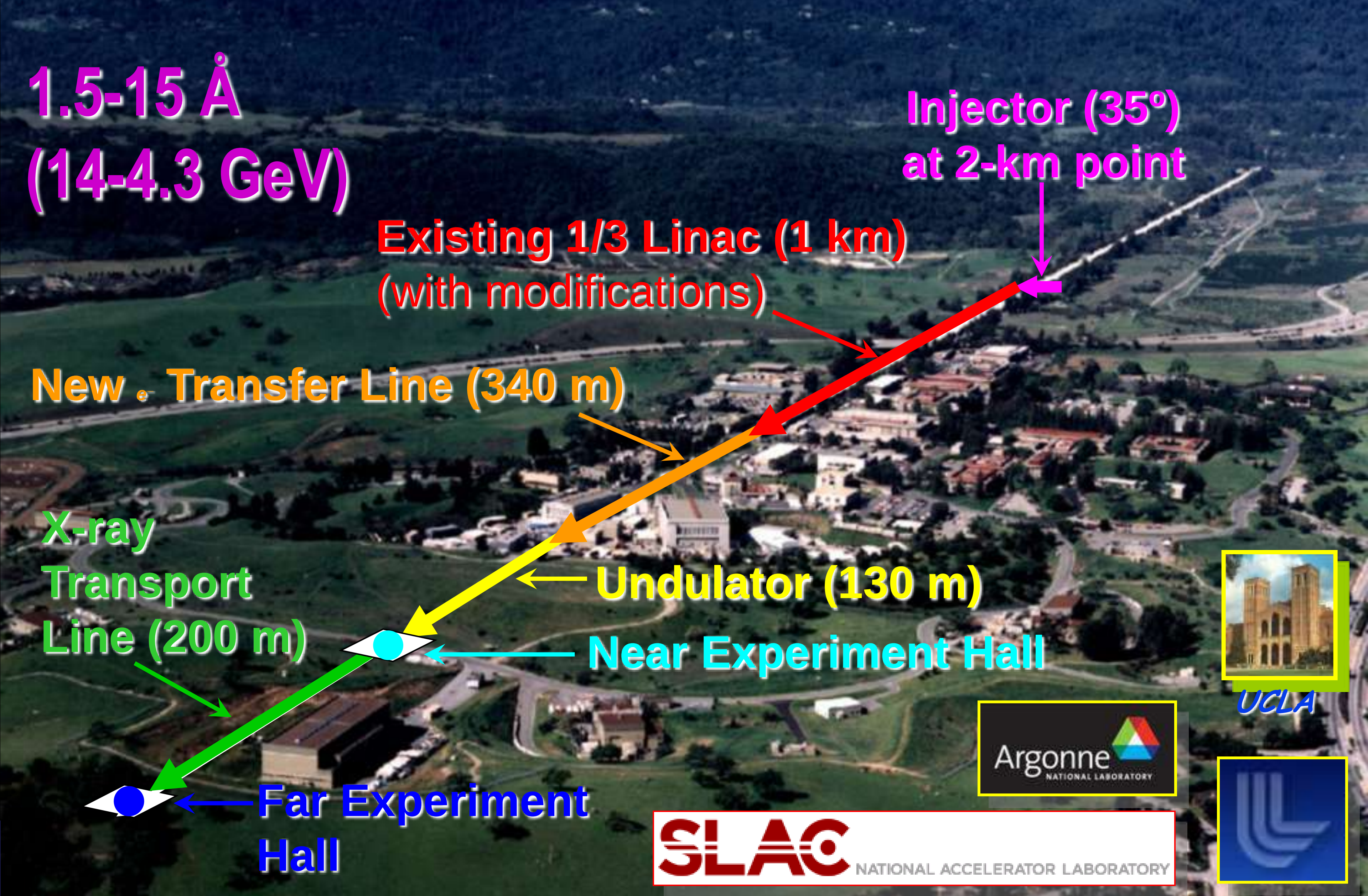
Linac Coherent Light Source at *SLAC*

X-FEL based on last 1-km of existing 3-km linac



Linac Coherent Light Source at *SLAC*

X-FEL based on last 1-km of existing 3-km linac

1.5

(14

New

X-r

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nature photonics

ARTICLES

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First lasing and operation of an ångstrom-wavelength free-electron laser

P. Emma[1]*, R. Akre[1], J. Arthur[1], R. Bionta[2], C. Bostedt[1], J. Bozek[1], A. Brachmann[1], P. Bucksbaum[1], R. Coffee[1], F.-J. Decker[1], Y. Ding[1], D. Dowell[1], S. Edstrom[1], A. Fisher[1], J. Frisch[1], S. Gilevich[1], J. Hastings[1], G. Hays[1], Ph. Hering[1], Z. Huang[1], R. Iverson[1], H. Loos[1], M. Messerschmidt[1], A. Miahnahri[1], S. Moeller[1], H.-D. Nuhn[1], G. Pile[3], D. Ratner[1], J. Rzepiela[1], D. Schultz[1], T. Smith[1], P. Stefan[1], H. Tompkins[1], J. Turner[1], J. Welch[1], W. White[1], J. Wu[1], G. Yocky[1] and J. Galayda[1]

The recently commissioned Linac Coherent Light Source is an X-ray free-electron laser at the SLAC National Accelerator Laboratory. It produces coherent soft and hard X-rays with peak brightness nearly ten orders of magnitude beyond conventional synchrotron sources and a range of pulse durations from 500 to <10 fs (10^{-15} s). With these beam characteristics this light source is capable of imaging the structure and dynamics of matter at atomic size and timescales. The facility is now operating at X-ray wavelengths from 22 to 1.2 Å and is presently delivering this high-brilliance beam to a growing array of scientific researchers. We describe the operation and performance of this new 'fourth-generation light source'.

CLA

Argonne NATIONAL LABORATORY

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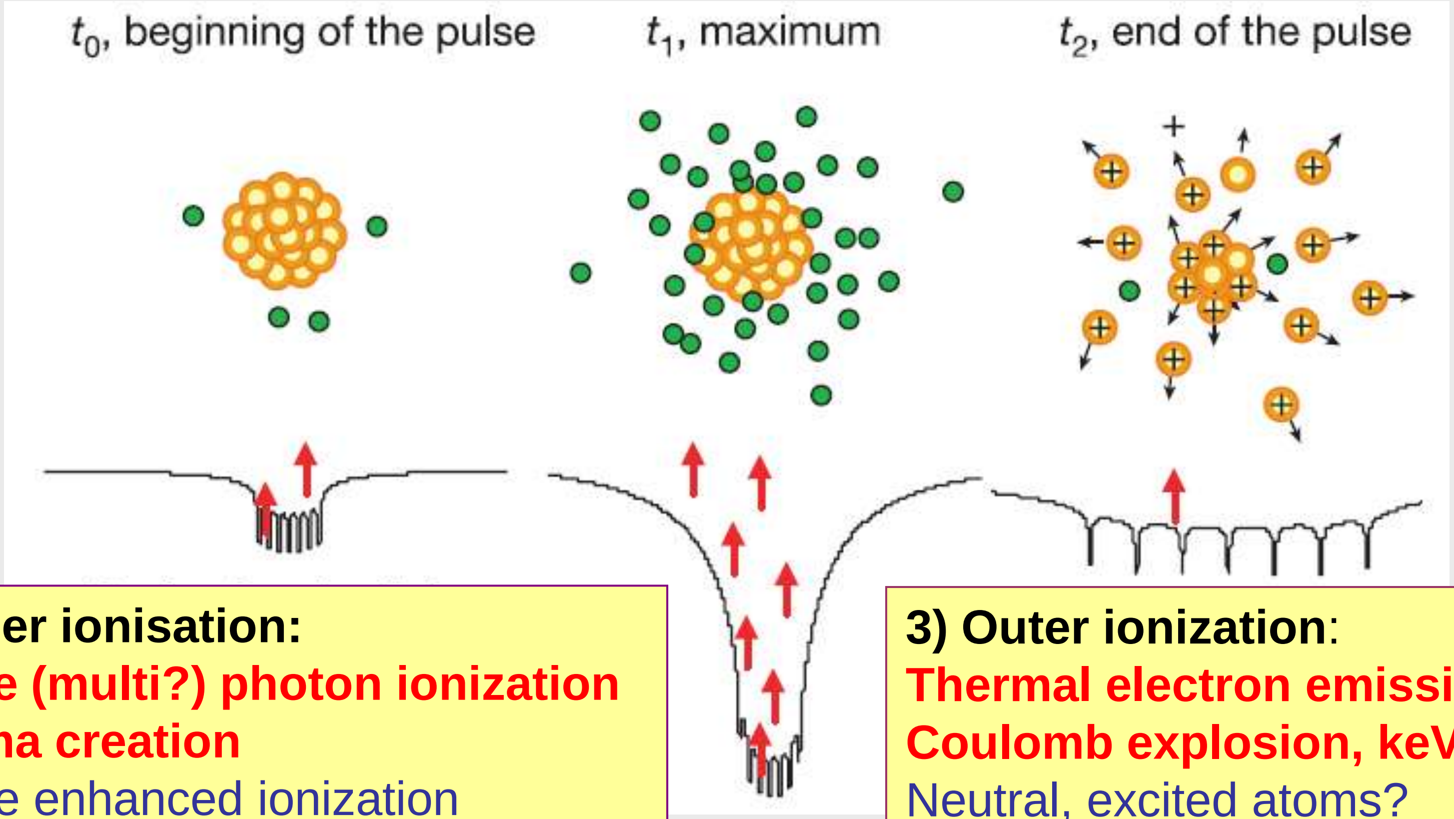
SLAC NATIONAL ACCELERATOR LABORATORY

100 nm: Model for Coulomb explosion



1) Inner ionisation:
Single (multi?) photon ionization
Plasma creation
charge enhanced ionization

3) Outer ionization:
Thermal electron emission
Coulomb explosion, keV energies
Neutral, excited atoms?

2) Cluster heating: **inverse bremsstrahlung / plasma absorption**
Enhanced rate due to electrons close to nuclei

Exps: Wabnitz et al, Nature **420**, 482 (2002), Laarmann et al, PRL **92**, 143401, PRL **95**, 063402
Theorie: Rost, Santra, Brabec, Ziaja …

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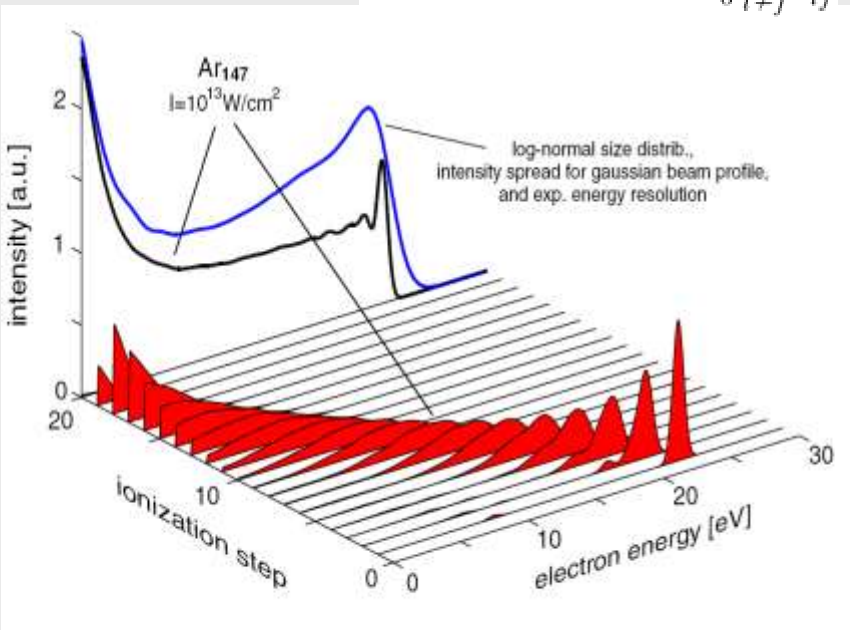
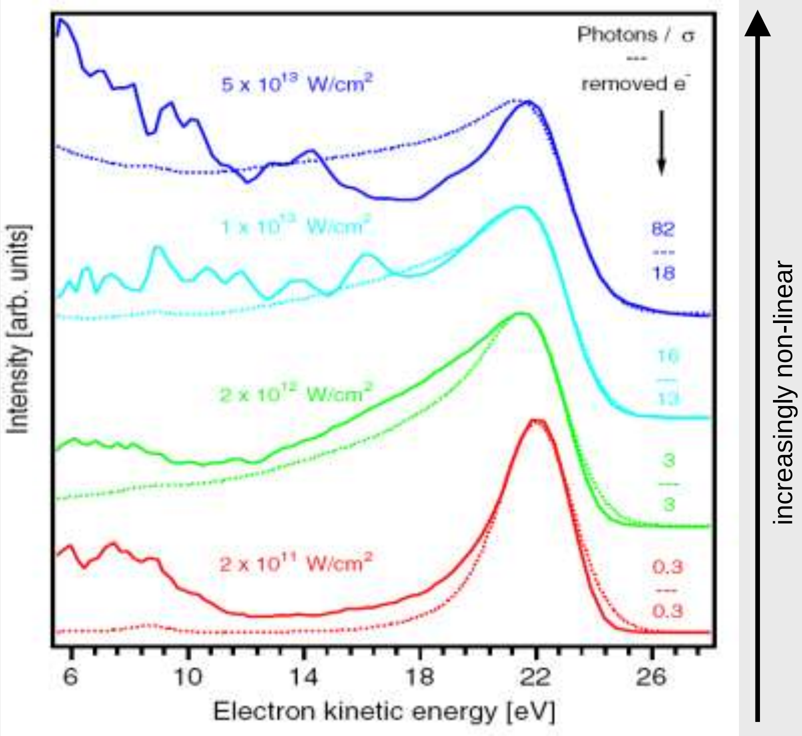
Cluster ionization at 32nm: multistep photoemission

Monte Carlo simulation

$$E_k = h\nu - I_p - \frac{e^2}{4\pi\epsilon_0}\sum_{i\neq j}\frac{q_i}{r_{ij}}$$



Data



No plasma heating – fundamentally different process compared to 100 nm / longer wavelength regime

Bostedt, Fennel, et al, Phys. Rev. Lett. 100, 133401 (2008)
More experiments at 60 nm: e.g. H. Fukuzawa et al., Phys. Rev. A 79, 031201(R) (2009)
More theory: B. Ziaja et al., New J. Phys. 11, 103012 (2009)

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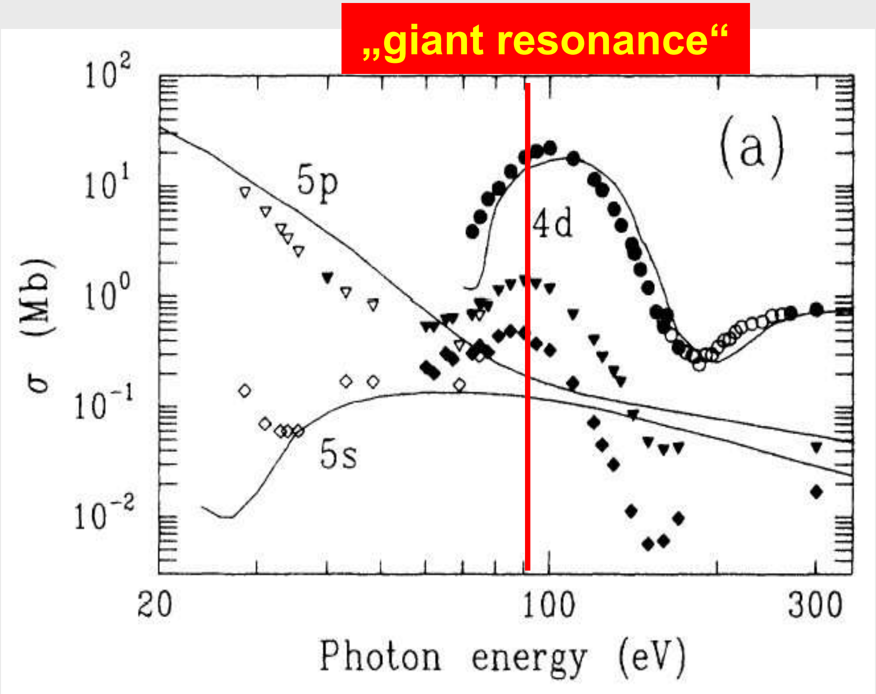
Towards x-rays: at 13 nm first core levels

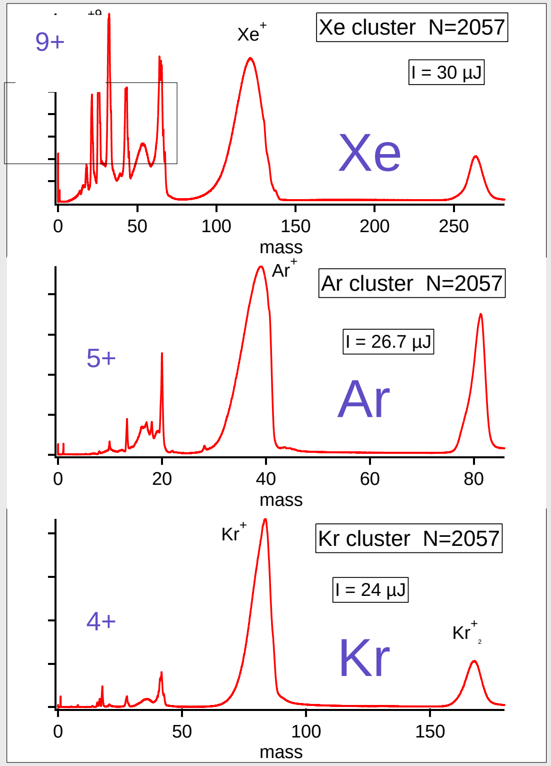
Electronic structure of Xe



U. Becker, PRA 39, 3902 (1989)

- **Strongly increased photoionization cross section**
- **Secondary processes become important**

Elemental dependencies



Cross sections: @ 90eV

Xe > 25 Mb
Kr ~ 0,5,
Ar ~0,2 Mb

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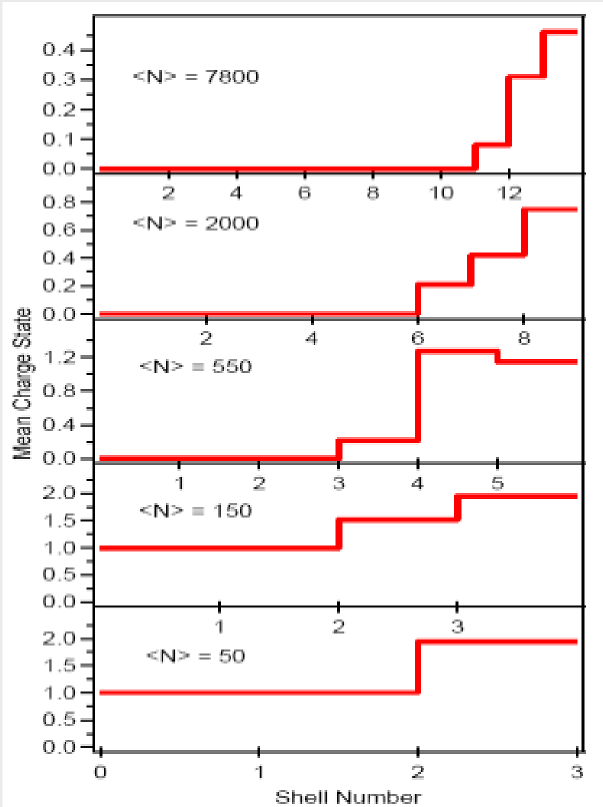
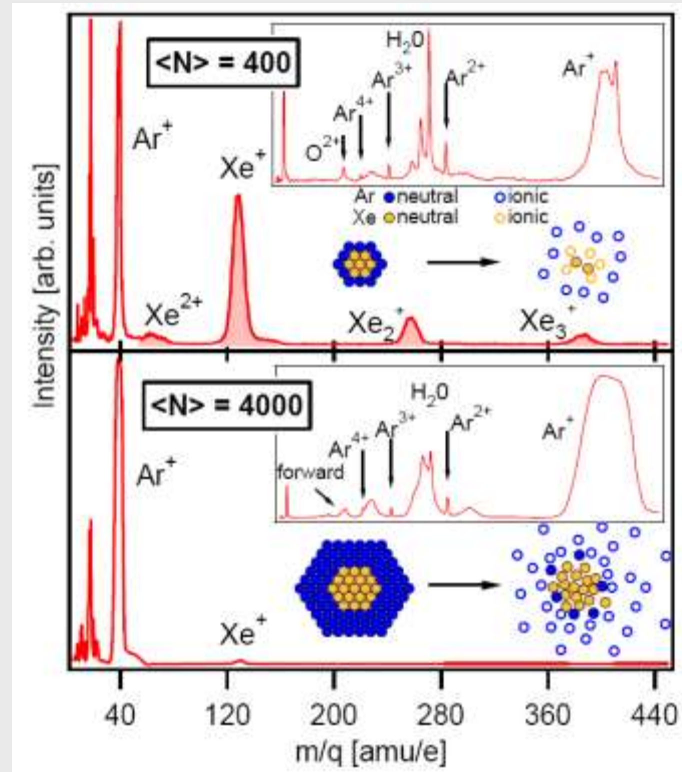
Coulomb explosion at 13.5 nm, 10^{14} W/cm^2

From pristine clusters



Thomas, Bostedt, J. Phys. B 42, 134018 (2009)

Core – shell systems



Hoener, Bostedt, et al, J. Phys. B – FTC 41, 181001 (2008)

- To explain kinetic energies need more charges than predicted by multistep
- Recombination of cluster nanoplasma core – tamper for bio- imaging
- Coulomb explosion turns into hydrodynamic expansion for core

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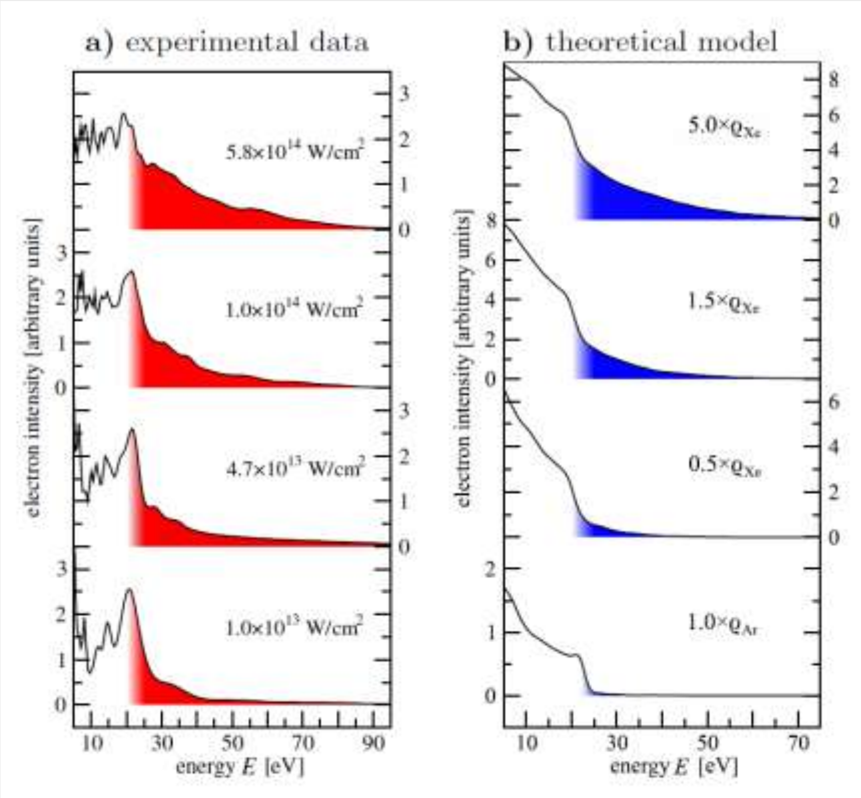
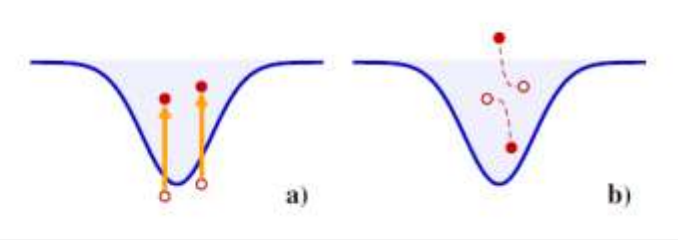
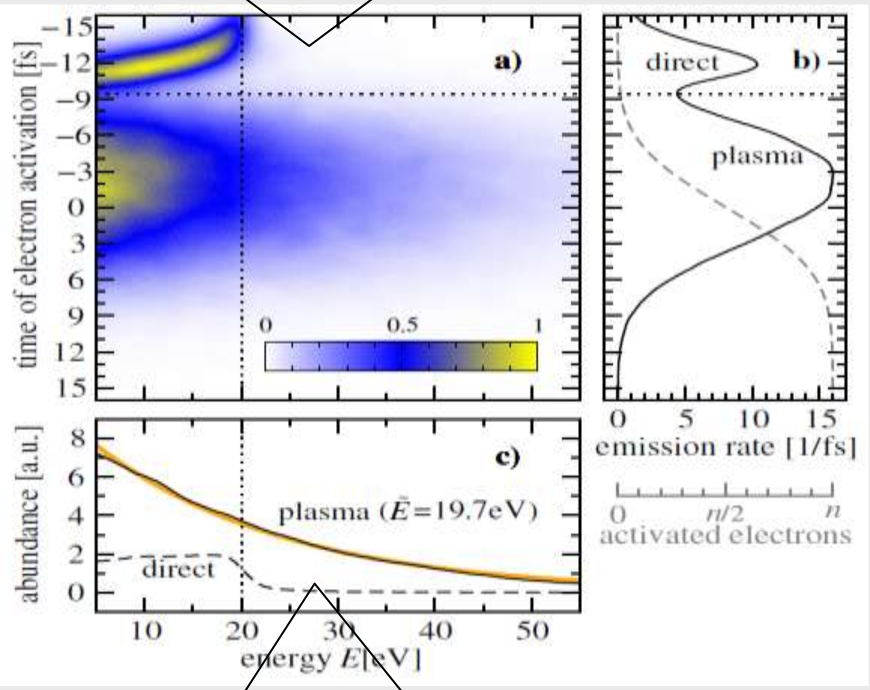
Xe at 13.5 nm: supra-atomic density plasma

Fast electrons through energy exchanging collisions





Time resolved photoemission



Direct vs plasma emission

Collisional auto-ionization after *direct* multistep ionization saturates

Bostedt, Saalmann, et al., New Journal of Physics 12 (2010) 083004

Theorie: Saalmann, Rost, et al. MPI-PKS

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Dynamics in Clusters

<u>LCLS / SLAC</u>

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Tais Gorkover, Thomas Möller

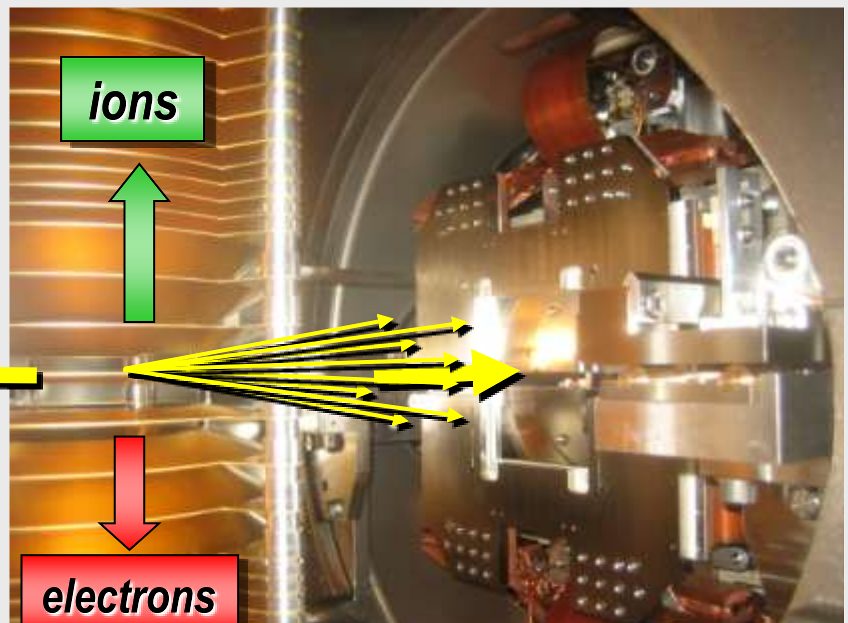
<u>Max-Planck ASG</u>

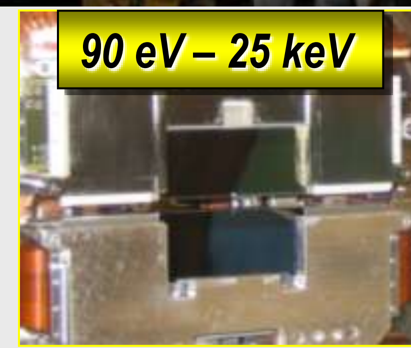
Artem Rudenko, Daniel Rolles,
Benjamin Erk, Benedikt Rudek,
Lutz Foucar, Sascha Epp,
Robert Hartmann, CAMP team

Project leaders: I. Schlichting, L. Strüder, J. Ullrich

CAMP endstation

- Focus in CAMP chamber
  A= 45 μm^2
- First imaging and photon – particle correlation exps
- Flexible setup, multiple injectors, spectrometers, etc





L. Struder et al., NIM A 614, 483 (2010)

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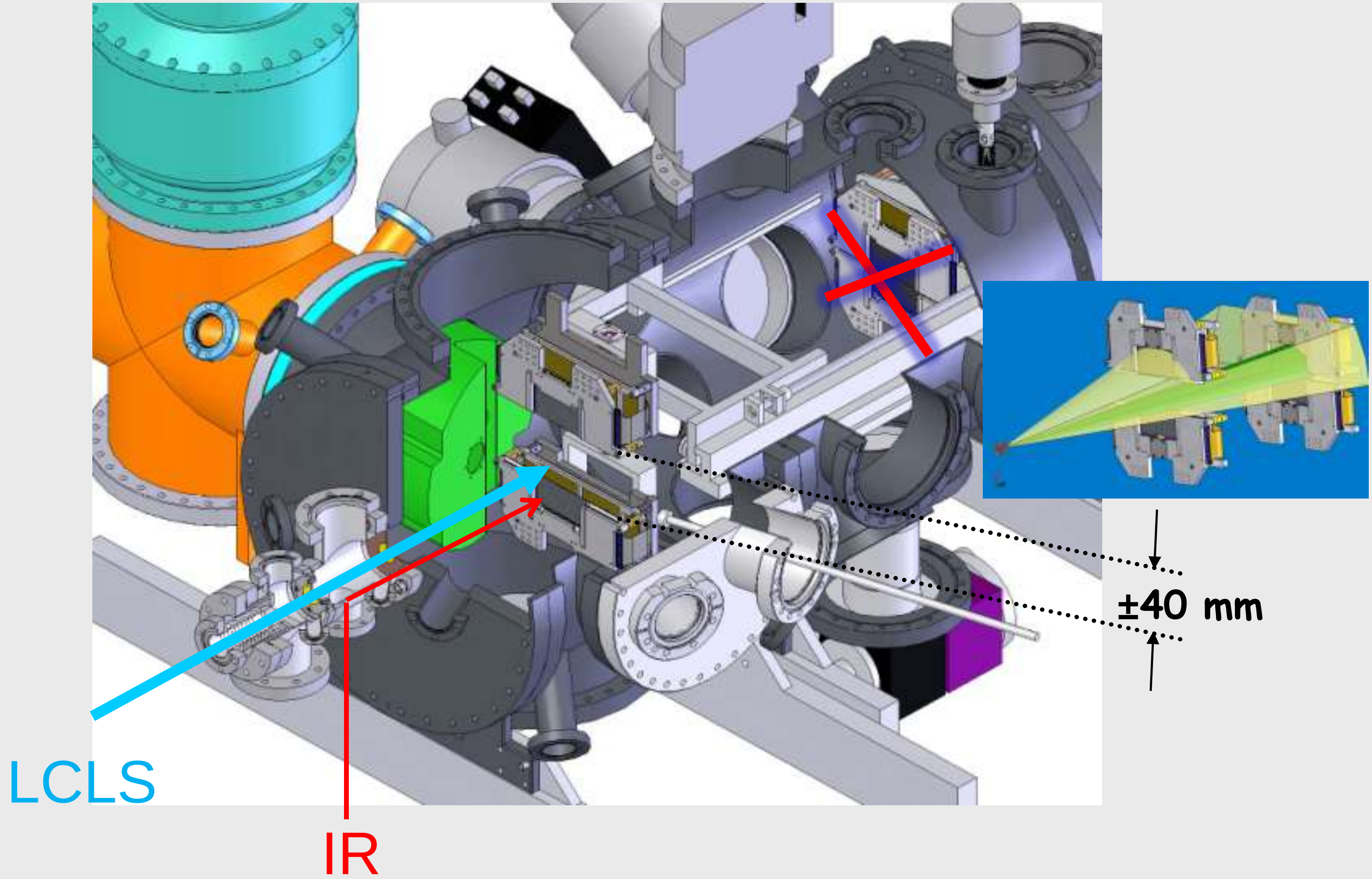
Exp Setup



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To be published

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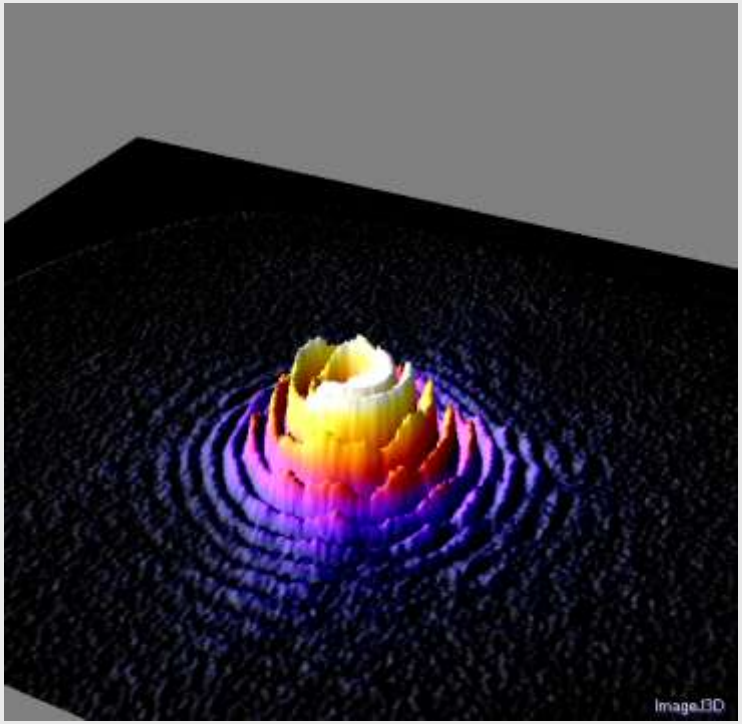
In conclusion:

For intense radiation – matter ineraction going towards x-rays the physics change

- Multistep ionization; collisional ionization in supra-atomic density plasma
- Nanoplasma recombination; less efficient energy absorption
- Single shot scattering from single clusters feasible
- Scatter data yields electronic structure information of transient states on ultrafast time-scales



Lots of exciting physics ahead of us!

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