Experience at FLASH
FELs provide unique opportunities and challenges for AMO physics due to essentially three reasons:
AMO at FLASH

1. huge integrated flux → dilute samples
   • Highly charged ions
   • Cold molecular ions

2. huge peak intensities
   • Atoms: non-sequential
   • Ions & molecules: sequential and state-prepared
   • Clusters and nano-particles

3. extreme short times → few fs dynamics
   • Ions, molecules, clusters

dedicated, novel instruments needed
Experience at FLASH

He Droplets
Xe Clusters

Few-Photon Pump&Probe

a variety of instruments is needed

MOTRIMS

Laser aligned Molecules
Velocity Map Imaging

Molecular Ions
**Experiments: LCLS**

1. **huge integrated flux** $\rightarrow$ **dilute samples**
   - Highly charged ions
   - Cold molecular ions

2. **huge peak intensities** $\rightarrow$ **multi photon**
   - Atoms: non-sequential
   - Ions & molecules: sequential

   - Cold and state-prepared

   - Clusters and nano-particles

3. **extreme short times** $\rightarrow$ **few fs dynamics**
   - Ions, molecules, clusters

**Experiments:**
- EBIT
- MOTRIMS
- X-ray CCD
1. huge integrated flux \( \rightarrow \) dilute samples
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Experience at FLASH

He-like ions for all elements!

~ $10^{10}$ cm$^{-3}$

Sascha Epp, PhD
Jose Crespo López-Urrutia

EBIT
Highly Charged Ions

FLASH
Experience at FLASH

MOTRIMS

Few-Photon-Processes

Molecular Ions

Pump & Probe Laser aligned Molecules

Velocity Map Imaging

He Droplets
Xe Clusters

Highly Charged Ions

EBIT
He-like ions for all elements!
Highly Charged Ions are everywhere in the Universe.

AGN
X-Rays
Galaxies
AGNs
Comets
Coronae

Highly Charged Ions

Astrophysics

Fundamental questions
Highly Charged Ions

Uranium

Hydrogen

Laser fields: \(10^{22}\) W/cm²

\(\Delta E \approx 500\) eV
\(Z \cdot \alpha \approx 1\)

\(\Delta E \approx 10^{-6}\) eV
\(Z \cdot \alpha \approx 10^{-2}\)
Highly Charged Ions

Fluorescence Spectroscopy

Resonance Laser

FLASH-EBIT

Photon energy (eV)

Year


Max-Planck-Institut für Kernphysik
Highly Charged Ions

FLASH-light

Fe$^{23+}$ ions

XUV-photons
Highly Charged Ions

Resolving Power:
- now: 2,000 - 5,000?
- then: ....200,000?

For “many” transitions in highly charged ions!

Expected improvement: factors 10 - 1000!

S. Epp, J. Crespo et al.
PRL 98 (2007) 183001
1. **huge integrated flux** → dilute samples
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EBIT @ LCLS

- Ionisation of ions
- Absorption by ions
- Precision spectroscopy: H-, He-like, ..
- Life-times: nano- to femtoseconds!
- Nuclear properties
- Plasma-physics
HI-LIGHT: Highly Charged Ions in the Ultra-brilliant Light of the LCLS

Proposal for user beam time at the Linear Coherent Light Source (LCLS) at the Stanford Linear Accelerator

Collaboration:
Peter Beiersdorfer, Al Osterheld, Greg Brown, Hui Chen, Ming Feng Gu, Ronnie Shepherd, Lawrence Livermore National Laboratory (LLNL), Livermore, USA
José R. Crespo López-Urrutia, Thomas M. Baumann, Martin Simon, Joachim Ullrich, Max-Planck-Institut für Kernphysik (MPI-K), Heidelberg, Germany
Sascha W. Epp, Artem Rudenko
MPG Advanced Study Group within CFEL (ASG), Hamburg, Germany
Alfred Müller, Stefan Schippers
University of Giessen, Germany

+ your name here (please express interest)
1. huge integrated flux \(\rightarrow\) dilute samples
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Experimental Hall Molecular Ions

Current Experiments

He Droplets Xe Clusters

Pump & Probe

Few-Photon-Processes

MOTRIMS

Laser aligned Molecules Velocity Map Imaging

Highly Charged Ions

Molecular Ions
Fragment Detection

H. Pederson, A. Wolf et al.
PRL 98 (2007) 223202

HeH+ + 32 nm - October 2006
How did molecules form in the early Universe?

How do molecules form in interstellar space?

Bio molecules → life

Part of ion chemistry cycle for oxygen-bearing molecules

H. Pederson, A. Wolf et al. PRL 98 (2007) 223202
Cold Molecular Ions

• **X-FEL opens completely new perspectives**
  - initial quantum-state prepared
  - final quantum-state completely measured
  - from simple molecules, complicated ones, bio-molecules, clusters, ..., grains, ..., dust

• **Among others important for:**
  - physics of inter-stellar, near-stellar clouds
  - physics of the upper atmosphere
AMO at FLASH

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EBIT

Reaction Microscope
Current Experiments

Vector momenta:
- electrons and ions
- often 100% solid angle
- very good resolution
He: Non-Sequential

Angular Correlation?

The most fundamental 2-photon - 2-electron non-linear reaction

$E_{hv} = 45 \text{ eV}$

$\text{He}^0 \rightarrow \text{He}^{2+}$
Theoretical papers (not complete)

Foumouo et al., JPB 39, 427 (2006)
Palacios et al., PRL 96, 143001 (2006)
Kheifets and Ivanov, JPB 39, 1731 (2006)
Barna et al., PRA 73, 023401 (2006)
Madine et al., JPB 39, 4049 (2006)
Cohen et al., JPB 39, 2693 (2006)
Hu et al., JPB 38, L34 (2005)
Themelis et al., JPB 37, 4281 (2005)
de Castro et al., PRA 72, 023410 (2005)

Experimental benchmark data are needed!
1. huge integrated flux $\rightarrow$ dilute samples
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Ne: Sequential Ionization

Energy (eV)

$E_{hv} = 45$ eV

$Ne^0 \rightarrow Ne^+$

$Ne^+ \rightarrow Ne^{2+}$

$E_{kin}$

$2s^24p^4 (^3P)$

$2s^24p^4 (^1D)$

$2s^24p^4 (^1S)$

-44.2 eV

$2s$

$2p$
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3. extreme short times → few fs dynamics
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Molecule Fragmentation

Wave packet dynamics? KER eV

Observed dissociation channels

Kinetic Energy Release: KER

Wave packet dynamics? relevant for upper atmosphere

Δt ~ 15 fs

E_{hv} = 45 eV

N_2

E (eV)

r (Angstroms)

N_2

N_2^3+(N_2^+ + ^3P)

N_2^{+2}(^2P)+N^+(^3P)

N_2^{+2}(^2P)+N^+(^3P)

N_2^+(^3P)+N^+(^3P)

N_2^{2+}(N_2^{+} + ^1D)

N_2^{2+}(N_2^{+} + ^1D)

N_2^{+}(^1D)+N_2^{+}(^3P)

N_2^{+}(^1D)+N_2^{+}(^3P)

Ehν = 45 eV

Δt ~ 15 fs

relevant for upper atmosphere
Molecule Fragmentation

Complete fragment imaging

N⁺ momenta

N⁺ + N⁺ coincidence
Complete fragment imaging

N\textsuperscript{2+} momenta

...plus photoelectron spectra

N\textsuperscript{+} + N\textsuperscript{2+} coincidence

Y. Jiang et al., in preparation
AMO at FLASH

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3. extreme short times $\rightarrow$ few fs dynamics
   - Ions, molecules, clusters
Current Experiments

Vector momenta:
- ions (… and electrons)
- ±0.8 μeV resolution
- excited / aligned states
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Experiments: LCLS

EBIT

Reaction Microscope
- Li: 1 or 2 Photons talk to 3 Electrons
- Li: Photon Correlation Function
- Na: Trace the Fate of “few” Electrons
- Na, K: Ultra-fast Optical Switches
- Rb, Cs: What about many Electrons?
- Plasma-Physics: Strongly Correlated
Tracing non-linear, ultra-fast many-electron processes in the super-brilliant light of the LCLS via high-resolution MOTRIMS

Experimental proposal for user beam time at the Linac Coherent Light Source (LCLS) at the Stanford Linear Accelerator Center

Collaboration:
Alexander Dorn, Jochen Steinmann, Ganjun Zhu, Robert Moshammer, Joachim Ullrich
Max-Planck-Institut für Kernphysik (MPI-K), Heidelberg, Germany

Ali Belkacem, Th. Weber
Lawrence Berkeley National Laboratory (LBNL), Berkeley, USA

Brett DePaola, Itzhak Ben-Itzhak, L. Cocke, B. Esry
Kansas State University, Manhattan, Kansas, USA

Bertold Krässig\textsuperscript{1}, Linda Young\textsuperscript{1}, Robin Santra\textsuperscript{1,2},....

\textsuperscript{1}Argonne National Laboratory, Argonne, Illinois, USA
\textsuperscript{2}University of Chicago, Chicago, Illinois, USA

Robert Sang, Dave Kielpinski
Griffith University, Brisbane, Australia

R. Hoekstra, Th. Schlathölter
KVI and University of Groningen, The Netherlands

Artem Rudenko, Daniel Rolles
MPG Advanced Study Group within CFEL (ASG), Hamburg, Germany
AMO at FLASH

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3. extreme short times $\rightarrow$ few fs dynamics
   - Ions, molecules, clusters
X-Ray CCD Detectors

MPI-HLL Detectors

With: Chapman, Bostedt, Möller, Hajdu et al.
1. huge integrated flux → dilute samples
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3. extreme short times → few fs dynamics
   • Ions, molecules, clusters

Experiments: LCLS

EBIT

Reaction Microscope
From simple to complex: Multi-particle correlation measurements on atoms, molecules and nano-particles.

Current members include:
A. Rudenko, S. Epp, D. Rolles, MPG Advanced Study Group (ASG), CFEL, Hamburg;
H. Chapman, CFEL/DESY/University of Hamburg;
A. Cavalleri, CFEL/MPG/ University of Hamburg;
I. Schlichting, MPI f. med. Forschung, Heidelberg;
S. Techert, MPI f. biophysikalische Chemie, Göttingen;
R. Hartmann, L. Strüder, MPI Halbleiterlabor, München;
Ch. Bostedt, Th. Möller, Technical University Berlin.
Experience at FLASH

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Current Experiments

- He Droplets
- Xe Clusters
- MOTRIMS
- Laser aligned Molecules
  Velocity Map Imaging
- Highly Charged Ions
- Molecular Ions
Laser Aligned Molecules

Next step: looking for revivals in dynamic molecular alignment

\[ \text{H}_2 + \text{FEL} \rightarrow \text{H}_2^+ \]
\[ \text{H}_2^+ + \text{IR} \rightarrow \text{H}^+ \]

Bond softening
IR+ FEL

Single photon ionization by FEL

Velocity
Map Imaging
AMOLF, Amsterdam
MPQ, Munic

- FROG-, SPIDER-type auto-correlation
- VUV-VUV pump-probe on molecules
Molecule Fragmentation

Wave packet dynamics

relevant for upper atmosphere
## Experiments: LCLS

<table>
<thead>
<tr>
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<td><strong>EBIT</strong></td>
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| II | Cold and state-prepared | **MOTRIMS** |
| III | Clusters and nano-particles | **X-ray CCD** |

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Current Experiments

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- MOTRIMS
- Laser aligned Molecules Velocity Map Imaging
- Highly Charged Ions
- Molecular Ions
End