Pulsed X-ray Sources

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21/01/2011
A late night mistake that revolutionized the world

Lysozyme molecule at -50fs, 0, and +50fs Relative to X-ray pulse

Applications

**Food Industry:**

Crystallisation of pure cocoa butter in real time.


**Archaeology:**

X-ray image revealing the inside of a 300 years old watch.


**Biology:**

Quantitative 3D imaging of whole, unstained cells by using X-ray diffraction microscopy

Applications

Biology:

FTPase molecule as an efficient rotary motor

Applications

Medical
Radiography, Computerized Axial Tomography
X-ray therapy to destroy malignant tissues

Pharmacy
X-ray Fluorescence Analysis, X-ray
Powder diffraction for finger printing
new chemical entities

Bio-Technology
Nature’s Smallest Rotary Motor: Structure of the Key enzyme in cellular energy interconversion (F1-type Adenosine Triphosphate Synthase, F1 ATPase)

This list can go on
Production

~300 grams
Production

[Images of different facilities with captions: Courtesy: European XFEL, Courtesy: Diamond, Courtesy: NIF]
Outline of the Talk

Basics of Laser Matter Interaction

Laser Generated X-ray Sources

Incoherent Sources

Coherent Sources

X-ray laser
High Harmonics
XFEL
Laser Matter Interaction

\[ I = \text{Energy/(spot area*pulse length)} \Rightarrow > 10^{20} \text{ Wcm}^{-2} \]

\[ |E| \approx 2700\sqrt{I} \Rightarrow |E| >> \text{Ionization Threshold} \]

\[ N_{\text{crit}} = (1.1 \times 10^{21}) \times (\lambda \text{ m})^{-2} \]

Electron Density (cm\(^{-3}\)) vs. Wavelength (m)
Electron in the EM Field

\[ \vec{F} = q \left( \vec{E} + \left( \frac{\vec{V}}{c} \wedge \vec{B} \right) \right) \]
Absorption mechanisms depend on laser intensity and angle of incidence

Absorption Leading to Hot Electrons Production

Resonant absorption (RA): Laser pulse + preplasma
plasma wave at critical density
hot electrons at front side

JXB heating:
hot electrons in the laser direction

Vacuum heating (VH):
Electrons are accelerated by laser electric field
perpendicular to target surface
(only works at oblique incidence)
hot electrons at target normal
Incoherent Sources
Back to School - Kα Generation

Beam Profile
(Spatial and Temporal)

Wavelength

Target Material and Surface Absorption

Hot Electrons

COLLISIONAL EXCIATATION OF K-SHELL

RADIATIVE DECAY

EMISSION

Hot Electron
Target

Bare: 12.5\(\mu\)m thick Ti foil

Coated: 12.5\(\mu\)m thick Ti foil coated with 0.2\(\mu\)m CH
(Parylene E)

Von Hamos Spectrometer
Crystal: Cylindrically curved 25mm wide and 15mm arc-length, LiF (200) with 5cm radius of curvature, 0.067\(+\)
0.003mrad reflectivity for Ti K\(_\alpha\)

Filter: 25\(\mu\)m Be with aluminised-Mylar (100nm-7\(\mu\)m)

Line of sight 48 degree
EXP-I (Pulse Shape)

P-polarized, 800nm pulses
Focal Spot (FWHM) at best focus is 3\(\mu\)mx8\(\mu\)m with about 25% energy content.

Small Power Mode

EXP-I (IR Beam at Best Focus, 70fs)
K-alpha yield Coated vs Bare Ti foil, IR

![Graph showing K-alpha yield Coated vs Bare Ti foil, IR](image-url)

- Coated
- Bare

Yield (Photons/J-Sphere)

Intensity (Wcm\(^{-2}\))
EXP-II (Schematic Layout)

ASTRA TA2

- Frequency Doubling Crystal
  - 0.7mm thick, Type-I KDP by Cleavland

- Turning Mirror

- X-ray CCD

- Von Hamos Spectrometer

- Gold Coated Off-Axis Parabola f/2.5

For Blue beam
The parabola is Ag-coated

- Ti foil

- Optical Relay

- IR/Blue Splitter

Frequency Doubling Crystal
- 800nm, 45fs

Retro System
EXP-II (Blue Beam at Best Focus-Spatial)

Frequency Doubled (400nm), 45fs (low energy mode)
FWHM is 5.25micron x 5.68micron
Energy contents in the FWHM are 55%
EXP-II (Beam Characteristics - Pulse)

Pulse-length

IR (Wavelength = 800nm, P-polarized)

Blue (Wavelength = 400nm, S-polarized)

Prepulse

Main Pulse

FWHM ~45fs

10^{-7}

10^{-8}

10^{-9}

10^{-10}

10^{-4}

10^{5}

10^{6}

10^{7}

10^{8}

10^{9}

10^{10}

10^{11}

10^{12}

10^{13}

10^{14}

time (ns)

Contrast

ASE

Pedestal

time (ps)
EXP-II (Blue Beam $K_{\alpha}$ Yield)

Yield for 20 degree incidence is Lower than that from the 45 degree incidence

45 degree geometry follows a pattern, though asymmetric as in the case of IR
IR Blue $K_\alpha$ Yield Comparison

20 Degrees

No conclusive difference

45 Degrees

About a factor of 6 increase in the $K_\alpha$ yield (Ph/J-Sphere) for the Blue
SEM micrographs-target surface

Ti foil

Smoked Ti

Fida Khattak, Physics, KUST
Ti K-\(\alpha\) and He-\(\alpha\) Exp with \(\sim\)45fs Blue

PET VonHamos Spectrometer
X-ray Streak Camera
(Kentech Low Mag, 2ps)

Differentially Filtered X-ray Streak Camera
(Axis Photonique, 700fs)

LiF Von Hamos Spectrometer
Ag Coated Off-Axis f/2.5 Parabola

Retro System

Calibrated Energy Monitor

Dielectric mirror

IR Dump
Bean Splitter

Crystal, KDP Type-I

Target

Ag mirror

X-ray CCD

\(\lambda\)

Beam Block

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Focal Spot at Best Focus

FWHM = 8x10 pixels ≈ 1.5μm x 1.9μm
Energy contents in the FWHM = 35%

Optical Image of the Focal Spot Laser in Low Energy Mode

Energy on target = 40-60mJ at best Focus
35% energy in ~2micron spot
Intensity ~$10^{19}$W/cm²

at 800 micron offset
100% energy in 320 micron spot
40mJ ---- I~$10^{15}$W/cm²
**K-α and He-α yield**

**Emission from smoked Ti irradiated at 45° with 400nm, 45fs P-polarized laser pulses**

![Graph showing emission from smoked Ti](image)

**K-alpha Emission from 12.5 μm Ti foil irradiated with 400nm, 45fs pulses**

- S-polarized 45°
- P-polarized 45°

![Graph showing K-alpha emission](image)

**Comparison of K-alpha yield from 12.5 μm Ti foil targets irradiated with 400nm, 45fs pulses at different angles**

- 30° P 12.5μm Ti
- 45° P 12.5μm Ti
- 60° P 12.5μm Ti

![Graph showing comparison of K-alpha yield](image)
Temporal profile of Ti emission

**K-alpha**

- Intensity (Arb. Units)
- Time (ps)
- FWHM of measured He-\(\alpha\) emission from:
  - 12.5 \(\mu\)m Ti foil = 3.8ps
  - Smoked Ti = 5.5ps
  - S/C resolution ~2ps

**He-alpha**

- Intensity (Arb. Units)
- Time (ps)
- FWHM of measured He-\(\alpha\) emission from:
  - Ti Foil (12.5\(\mu\)m), 30°P
  - Smoked Ti, 45° P

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K-alpha yield from Ti foil target irradiated with IR and blue ~45fs p-polarized pulses.  

Hard x-ray background per shot using IR and blue beam
Copper K-alpha

400nm, 45fs pulses, Thick foil

Yield (10^{11} Ph/J/Sphere) vs. Offset (μm)
Pump Power/m3

\[ \approx \frac{10^{-20}}{\lambda_{ul}^4 L} \sqrt{\frac{T}{M_N}}, \]
Schemes for x-ray laser (Recombination)

- Fully stripped ion
- Rapid cooling
- Strong 3-body recombination
- Collisional Radiative Cascading
- Population Inversion
- Lasing
Schemes for x-ray laser (Collisional Excitation)
### Collisional Soft X-ray Laser Types

<table>
<thead>
<tr>
<th>Pumping Conditions</th>
<th>Laser Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>10-500 J in 100-600 ps</td>
<td>Quasi Steady State</td>
</tr>
<tr>
<td>~J in 5-10ps</td>
<td>Transient</td>
</tr>
<tr>
<td>~J in ~400ps</td>
<td></td>
</tr>
<tr>
<td>~J in 50 fs</td>
<td>Optical Field Ionization (OFI)</td>
</tr>
</tbody>
</table>
Comparison of Normal to Grazing incidence

- Traditional two pulse sequence at normal incidence

- Grazing incidence pumping dramatically increases efficiency

\[ \theta = \sqrt{\frac{N_e}{N_c}} \]

Collisional Ionization

Ground State

\[ N_{\text{upper}}^{(K)^{-1}} \]

Auger Decay
\[ (\tau K \sim \text{fs}) \]

\[ N_{\text{lower}}^{(L)^{-1}} (L L)^{-2} \]

Photo-Ionization

Collisional Ionization

\[ \sigma_L/\sigma_K \sim 20 \text{ for } \sim 10 \text{ keV electrons} \]

Density limit
\[ \rho \sim 1/\tau K \sigma_L v_H \sim 10 \text{ mg/cc}, \]

Schemes for x-ray laser (II)
Our Approach (Moon and Eder)

C-Foam, 8mg/cc, 1mm LASANT

Al$_2$O$_3$, 500nm, Low Z, High Pass

Au, 100nm, X-ray flash

X-ray laser (44.6 Å) (Kα ~275 eV)

Line-Focus, 10micron, 1cm ~10$^{16}$ W/cm$^2$

Line-Focus, Travelling Wave Geometry (800nm, 45fs)
Filtered black body radiation

- Black body spectrum at $T=400\text{eV}$
- Black-Body Spectrum after high pass filtering with Al2O3

Position of Carbon K-edge
TA2- Chamber set-up

IR, \( \sim 50\text{fs} \)

Line Axis

Off-Axis Parabola

Target

X-ray laser

Line Focus

Spherical Gold Mirror

CCD coupled
4-pinhole camera

CCD coupled Flat-Field Spectrometer

Time
Preliminary Data

Line out of the spectrum,

Intensity (arb. units) vs. Pixel

4.06nm (He-like)
4.46nm (K-α)

Zn Filter
CH Filter
Ag Filter
Al Filter
Preliminary Data
High Harmonic Generation
HHG and features

Ionization potential of atom (medium dependent)

$I_{\text{cut off}} = I_P + 3.2U_P$

Ionization potential of atom (medium dependent)

$U_P = \frac{e^2 E_L^2}{4m_e \omega_L^2} \propto I \lambda^2$

Quiver energy of $e^-$

$U_P(eV) = 0.93 \times 10^{-13} I(Wcm^{-2}) \lambda^2 (\mu m^2)$

Increasing intensity
Extending cut off
Selectivity

REVIEWS OF MODERN PHYSICS, 80, 117 (2008)
Experimental Data - Gas

PRL 76,752 (1996)
PRL 77,1743 (1996)
PRL 78,1251 (1997)

FFG Spectrometer

10^{18}-10^{20} \text{ cm}^{-3}

gas puff

Incident Laser

Number of Photons

Harmonic Order
Moving Plasma Mirror Scheme - Solid

Observer

Incident Laser

\[ E_{inc} = E \sin \phi_L t \]

\[ \omega' = 4\gamma^2 \omega \]

\[ \tau' = \frac{\tau}{4\gamma^2} \]

\[ E_{ref} = E \sin \phi_L t + 2k_L X(t') \]

\[ t' = t + \mathcal{R} + X_m(t') \frac{c}{\gamma^2} \]

Plasma Vacuum Interface

Some Numbers

Incident

\[ \tau = 10\text{fs}, \lambda = 800\text{nm} \]

\[ P = 1\text{TW} \]

For \( \gamma = 33 \)

Reflected

\[ \tau = 25\text{as}, \lambda = 0.2\text{nm} \]

\[ P = 4\text{PW} \]
Experimental Realisation

Tsakiris et al, New J Phys 8, 19, 2006

High Density
Steep Profile

Femto-second pulses from a PetaWatt laser system using plasma mirrors for achieving high contrast

\[ a_L^2 = \frac{I_L \lambda_L^2}{(37 \times 10^{18} \text{Wcm}^{-2} \mu m^2)} \]

\[ \gamma_{\text{max}}^2 = (\gamma^2 + a_L^2) \]
Experimental /Theoretical Data

**Dromey et al., Nature Physics, 2, 456, 2006**

![Graph showing relative intensity vs. harmonic order](image1)

Asymptotic efficiency $\eta \sim n^{-\text{PREL}}$ (PREL=5/2…8/3) for $\gamma > 1$

Harmonics up to $n_{\text{max}} \sim 8^{1/2} \gamma^3$ (not $4\gamma^2$)

**Gordienko et al. PRL 93, 115001, 2004**

![Graph showing harmonic intensity vs. harmonic number](image2)

Diffraction limited performance and focusing

$a_L = 20$

For Power =30GW ,
λ = 0.1nm
Focal spot dia= 1 μm
Irradiance = 3.8×10^{18} \text{ W/cm}^2
This corresponds to \( E_p = 1.8\text{meV} \),
For optical laser with same parameter , \( E_p > \text{keV} \)

\[ E_p = \frac{e^2 E^2}{4m_e \omega^2} \]

**Photon atom interaction without ponderomotive disturbance**
FLASH

electron beam

Undulator

beam dump

low gain

exponential gain
(high-gain linear regime)

non-linear

$P(z) = P_0 \exp(z/L_{\text{gain}})$

$L_G = \frac{\lambda_u}{4\pi \rho_D}$

log (power)

saturation length $\sim 10 L_{\text{gain}}$

gain $\sim 10^5$

duration, length

photo beam
FLASH

Free electron LASer in Hamburg Characteristics

- Tunablility: 47 to 6.9 nm
- Flux $\sim 10^{13}$ photons/pulse
- Duration $\sim 10$-50 fs
- <vibration period of atoms in a solid
- Micron focusing

- Irradiance $\sim 10^{18}$ W/cm$^2$
- Critical Density $\sim 10^{24}$ cm$^{-3}$

- Temporal Evolution of Atomic Motion
- Phase Transition
- Plasma Expansion
- Chemical Reaction

Movie of molecular dance

- Isochoric heating
- Generation of HDM and WDM
- Isentropic expansion
- Probing solid density plasmas (X-ray scattering, nm scale,
  Phase contrast imaging, nm and fs scale diffraction of solids)
**LINAC Coherent Light Source Characteristics**

<table>
<thead>
<tr>
<th>Typical LCLS Operating Parameters</th>
<th>500–10,000</th>
<th>eV</th>
</tr>
</thead>
<tbody>
<tr>
<td>X-ray tuning range</td>
<td>up to 40</td>
<td>GW</td>
</tr>
<tr>
<td>Peak power</td>
<td>0.2 typical</td>
<td>% FWHM</td>
</tr>
<tr>
<td>Power bandwidth, 8,000 eV</td>
<td>0.5 typical</td>
<td>% FWHM</td>
</tr>
<tr>
<td>X-ray pulse duration</td>
<td>50–500</td>
<td>fs</td>
</tr>
<tr>
<td>Beam size at waist, 800 eV</td>
<td>20, typical</td>
<td>µm, RMS</td>
</tr>
<tr>
<td>Beam divergence, 800 eV</td>
<td>20, typical</td>
<td>µrad FWHM</td>
</tr>
<tr>
<td>Beam size at waist, 8,000 eV</td>
<td>15, typical</td>
<td>µm, RMS</td>
</tr>
<tr>
<td>Beam divergence, 8,000 eV</td>
<td>3, typical</td>
<td>µrad FWHM</td>
</tr>
<tr>
<td>Energy/Pulse</td>
<td>&gt;2 typical, 4.5 max</td>
<td>mJ</td>
</tr>
<tr>
<td>Pulse energy stability</td>
<td>5 typical</td>
<td>%</td>
</tr>
<tr>
<td>Pulse repetition rate</td>
<td>120</td>
<td>Hz</td>
</tr>
</tbody>
</table>

*3rd Harmonic > 24 keV (1% conversion)*

The Exotic

Multi-photon Absorption

Young et al, Nature 466, 56, 2010

Femto-second time delay x-ray holography


Peeling and coring as termed by Justin Wark

Wark, Nature 466, 35, 2010
The Exotic

Femtosecond diffractive imaging with soft XFEL


Decay of crystalline order

Galtier et al., Phys. Rev. Lett. accepted for publication

Turning Solid Al Transparent


Scattering from Hydrogen

Photo-ionization of multiple ion species
\[ K^xL^yM^z + h\nu_{\text{XFEL}} \rightarrow K^{x-1}L^yM^z + e \quad (x = 1,2; \ y = 1 \text{ to } 8; \ z = 1,2) \]

Auger decay of multiple ion species
\[ K^xL^yM^z + h\nu_{\text{XFEL}} \rightarrow K^{x-1}L^yM^z + e \rightarrow K^xL^{y-2}M^z + e \]

Sequential multiphoton ionization
\[ K^xL^yM^z + h\nu_{\text{XFEL}} \rightarrow K^{x-1}L^yM^z + e + h\nu_{\text{XFEL}} \rightarrow K^0L^yM^z + e + h\nu_{\text{XFEL}} \rightarrow K^0L^{y-1}M^z + e + h\nu_{\text{XFEL}} \rightarrow \ldots \]
\[ K^xL^yM^z + h\nu_{\text{XFEL}} \rightarrow K^{x-1}L^yM^z + e + h\nu_{\text{XFEL}} \rightarrow K^{x-1}L^{y-2}M^z + 2e \]

Direct multiphoton ionization
\[ K^xL^yM^z + 2h\nu_{\text{XFEL}} \rightarrow K^0L^yM^z + 2e \]
Thank You