Ultrafast Streak Camera Development at the Advanced Light Source

Introduction and Motivation

ALS Streak Camera Program

Applications

Future Plans

Publications

Acknowledgement

Brief Overview
Introduction

Front field: study the ultra small and ultra fast worlds

Ultra-Small

Nature
- Flea
- Human hair ~30 µm wide
- Red blood cells & white cell ~ 5 µm

Technology
- Head of a pin ~ 1 mm
- DVD track
- 1 µm Electrodes connected with nanotubes
- Carbon nanotube ~ 2 nm diameter
- Atomic corral ~ 14 nm diameter

Ultra-Fast

Nature
- Hydrogen transfer time in molecules is ~ 1 ns
- Spin precesses in 1 Tesla field is 10 ps
- Water dissociates in ~ 10 fs
- Bohr period of valence electron is ~ 1 fs

Technology
- Computing time per bit is ~ 1 ns
- Magnetic recording time per bit is ~ 2 ns
- Optical network switching time per bit is ~ 100 ps
- Shortest laser pulse
Ultra-fast X-ray Measurements

- Pump at \( dt \) before x-ray probe

- Pump at time during long x-ray probe
ALS Streak Camera Program

Transmission streak camera:
- Providing ultrafast magnetic dynamics study
- Improving temporal resolution

Reflection streak camera:
- Slicing diagnostic and related experiment

Dual-sweep streak camera
- Photocathode: Radiation-hard, alignment, high voltage, 25\(\mu\)m, 10\(\mu\)m
- Photo-conductive switch: fabrication technique, mounting mechanism, fast rise-time,
- Electron optics: large FOV, reducing fringe field
- Meander-plate: increase sweep speed, dv/dt, deflection aberration
- Start-to-end modeling
Ultrafast Detector: Streak Camera Principle

### Features:
- Good temporal resolution (at present psec, could be 100 fsec or better)
- Records the whole temporal response (ps-ns)
- Wide photon energy range 10ev to 10kev
- In principle could be used to record the temporal and spectrum simultaneously

Convert fast time information into space information that can be recorded on an area detector.
Ti:sapphire fs Laser Systems

Femto-laser Oscillator
Positive Light Legend Laser:
30 fsec, 1 mJ / pulse, 1 KHz

KMLab 62.5 MHz oscillator
Positive Light Legend Laser:
30 fsec, 0.6 mJ / pulse, 5 KHz
Solenoid Lens Field Distribution

R=0mm

Z=2.5mm

R=4mm

Z=4mm
3D Field Modeling: Start-to-end

Developed in MAFIA environment
- Photocathode-anode
  - User-defined initial SE distribution
  - Velocity dispersion
  - PIC space charge
- Deflector
  - Full 3D time-dependent EM field representation
  - User-defined input pulse
- Focussing system
  - 3D field map for magnetic or electric focussing
  - Lens aberrations included
ALS-made PC Switch Performance

- Semi-insulating GaAs
  - fabricated in-house
- Reliable 1kHz, 5 KHz operation at 600V
- 10-90% ramp \( t \approx 120-380 \) psec depending on cable length, switch mounting mechanism
- Switched efficiency \( \approx 75-90\% \)
- Saturation regime laser power: 60uj
Optical Layout for Streak Camera Measurement

Beam, 800nm, 1Khz, 50fs

@3m

Time Delay

266nm

UV M2

Δt1

UV M3

UV M4

Δt2

UV M5

UV M6

BS2

Positive Light regen

Legend amplifier
1 mJ, 1 kHz, 50 fsec

Femtolaser Osc.

Trigger

Diffuser

GaAs

oscilloscope

X-ray
Unfocus Beam: Measuring Photoemission Electron Energy Width

Angle = $\sqrt{E/V} \sin(\pi/4)$

Average: 0.54 ev, Au Work function: 4.2 ev, UV 4.7 ev

Au surface quality alignment
Static Mode: Basic Performance

25um Au Cathode
12kev, mesh 750 lp/mm
Period: 25um + 8um

12kev, mesh 1500 lp/mm
11um + 5.6um

Intensity (a.u.) vs. spatial resolution (um)

Resolution (um) vs. displacement on photocathode (mm)
High Spatio-temporal Resolution in Accumulation Mode

25 μm Au photocathode, 1000 shots

1) Good resolution in both time and space
2) Lens using same current for static and dynamic mode
3) Maintain over 53ps range
Jitter Measurement

We have 60fs jitter

\[ \tau_j = t_{ramp} \cdot \frac{\Delta E_L}{E_L} \cdot \frac{\alpha}{\alpha + 50\Omega \cdot E_L (\mu J)}, \tag{1} \]

where \( t_{ramp} \) is the combined rise time of the switch-generated ramping pulse and the deflection plates, \( \Delta E_L/E_L \) is the shot-to-shot laser energy fluctuation, \( \alpha \) is so called the sensitivity coefficient and \( E_L \) the incident laser energy.
World’s Fastest Streak Camera

- 233fs
- 400fs

Intensity (a.u.) vs Time (ps)

Intensity (a.u.) vs size (μm)
The detected voltage will be:

\[ V_{MI}(\tau) \propto \int_{-\infty}^{\infty} |E(t) - E(t - \tau)|^2 \, dt \]

\[ = \int_{-\infty}^{\infty} |E(t)|^2 + |E(t - \tau)|^2 - 2 \text{Re}[E(t)E^*(t - \tau)] \, dt \]

\[ V_{MI}(\tau) \propto 2 \int_{-\infty}^{\infty} |E(t)|^2 \, dt \quad \text{Pulse energy} \]

\[ - 2 \text{Re} \int_{-\infty}^{\infty} E(t)E^*(t - \tau) \, dt \quad \text{“Interferogram”} \]

Two photons process:

\[ V^{2P}(\tau) = \int_{-\infty}^{\infty} \left| [E(t) - E(t - \tau)]^2 \right|^2 \, dt \]
Pulse Measurement

Gaussian: 94fs in FWHM

Gaussian: 60fs in FWHM

Gaussian: 42.3fs in FWHM

Gaussian: 35fs in FWHM
Application: Ultrafast Magnetism Dynamics

What mechanisms and timescales are involved in ultrafast magnetization?
- using a laser field, using external magnetic field, using spin injection

Can we engineer new materials for ultrafast control of magnetization
- control by electric fields – eg. multiferroic materials

How does energy flow in a magnetic system when changing the magnetization?
- how is energy coupled from the field to the spin system to the lattice

The Key Tool: Time Resolved X-ray Magnetic Circular Dichroism (XMCD)
- psec temporal resolution
- can be allied with x-ray microscopy
- gives us information per element in a multi-element system
- gives us spin and orbital magnetic moments
Optical Layout for Magnetism Dynamics Experiment

- 800nm@4m
- Delay 1
- 266nm
- 3rd harmonics
- Delay 3
- X-ray
- Streak camera
- UV
- IR
- Sample
- KM 62.5 MHz Osc. Legend amplifier 0.6 mJ, 5 kHz, 50 fsec
- Delay 4
- PD
- Trigger
- Oscilloscope

4 beams with 4 delays (0.6 mJ total)
- IR pump beam
- IR to streak camera PC switch trigger
- UV for temporal fiducial to photocathode
- UV for timescale calibration to photocathode
Streaked X-ray Pulse

- Entire 50 ps fwhm captured with every laser shot
- 5 kHz laser repetition rate
- 500 MHz x-ray pulse repetition rate
TR-XMCD: Fe L3 Edge

60fs pump pulse

Normalized transmitted intensity

Normalized dichroism*

X-Rays

.5 mm

5 mm

Integrated Streak Intensity (ADU)

Dichroic contrast is lost in a few pico-seconds
TR-XMCD Spectra Map

H = +20 mT, right photon polarization

Time-resolved absorption spectra obtained by combining streaks at different photon energy

FeGd – Fe edge
Ultra-fast Magnetism Dynamics: FeGd

Simplified Sum Rules:

\[ m_s(\text{Fe}) \sim \frac{3}{2} (L_3 - 2L_2) \]
\[ m_l(\text{Fe}) \sim 2 (L_3 + L_2) \]
\[ m_s(\text{Gd}) \sim \frac{3}{2} (M_5 - \frac{3}{2} M_4) \]
\[ m_l(\text{Gd}) \sim 3 (M_5 + M_4) \]

Gd orbital moment vanishes for all delay

no transient increase of orbital momentum

After Deconvolution:

Fe: \( \tau = 1.1 \pm 0.7 \) ps
Gd: \( \tau = 2.4 \pm 0.3 \) ps
Future Plan

- **Short term**
  - Pulsed high accelerating voltage
  - Robust photocathode
  - Faster switch and circuit
  - Slow sweep
  - Laboratory 6-9ev source
  - RSC optimization

- **Long term**
  - New generation of ultrafast x-ray streak camera
  - Correction of time chirp in accelerating area
  - Ultimate temporal resolution in the X-ray range
ALS EXPERIMENTAL SYSTEMS GROUP :: ULTRAFAST STREAK CAMERA DEVELOPMENT AT THE ADVANCED LIGHT SOURCE

XFEL Application: Plasma Physics

400nm, 150fs, $10^{19}\text{w/cm}^2$, S-pol

Two distinct phases: 500fs, No uniform, hot dense plasma observed, need XFEL

- Single shot?
  - space charge limits # of electrons for a certain temporal resolution and accuracy

- Simultaneous spectroscopy
  - good imaging along slit needed; 2d high quality imaging
Dispersion Corrected Streak Camera

- 4 dipoles can be arranged to be double focusing, achromatic, zero angular time of flight dispersion and with defined $dT/dE$ for correction
- < 50 fsec resolution from initial simulation!

W. Wan
Ultra-fast PC-switch

- Combine the high switching voltage of the larger chip with high switching speed of smaller chip
- 1.5mm switch operates in linear regime to bias 100u strip line
- Works by pulse biasing the smaller chip for shorter times than required for breakdown
- 1.4 ps rise times
- Switching of up to 1.3kV
- Efficiencies of 60-70%
- Rise time independent of electric field

An x-ray streak camera with high spatio-temporal resolution

An ultrafast x-ray detector system at an elliptically polarizing undulator beamline

Element-specific spin and orbital moment dynamics of Fe/Gd multilayers

Streak camera temporal resolution improvement using a time-dependent field
Ji Qiang, John Byrd, Jun Feng, Gang Huang, Proceedings of Particle accelerator conference 2007, P3973

Progress on modeling of ultrafast x-ray streak cameras

Modeling of ultrafast streak cameras
G. Huang, J.M. Byrd, J. Feng, H. A. Padmore, J. Qiang, W. Wan
Proceeding of tenth European Particle Accelerator conference 2006, P1250

An Ultrafast X-ray Detection System for the Study of Magnetization Dynamics

An ultrafast x-ray streak camera for the study of magnetization dynamics

Ultrafast magnetization dynamics studies using x-ray streak camera
Acknowledgement

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Introduction

Front field: study the ultra small and ultra fast worlds

Ultra-Small

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Sample

Time integrating detector

Time resolving detector
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3D Field Modeling: Start-to-end

- Initial velocities: $\beta$
- Initial angles: $\theta$

**Developed in MAFIA environment**
- Photocathode-anode
  - User-defined initial SE distribution
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- Deflector
  - Full 3D time-dependent EM field representation
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**Solenoid $B_z$**
High Spatio-Temporal Resolution in Accumulation Mode

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World’s Fastest Streak Camera

Graphs showing time vs. intensity plots with the following details:

- **Top graph:**
  - Time (ps) range: 0.0 to 1.4
  - Intensity (a.u.) range: 0 to 60
  - Peak intensity at 0.6 ps, labeled '233fs'

- **Middle graph:**
  - Time (ps) range: 0.0 to 1.4
  - Intensity (a.u.) range: 0 to 70
  - Peak intensity at 0.8 ps, labeled '400fs'

- **Bottom graph:**
  - X-axis: size (μm)
  - Y-axis: Intensity (a.u.)
  - Intensity peaks at specific size values

Additional notes:
- 'World’s Fastest Streak Camera' caption
- 'ALS EXPERIMENTAL SYSTEMS GROUP :: ULTRAFAST STREAK CAMERA DEVELOPMENT AT THE ADVANCED LIGHT SOURCE' header
- 'size(μm)' label on the X-axis of the bottom graph
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