Pump-probe experiments with ps x-rays

Eric Landahl, XOR/TRR

1. Picosecond beamlines need flexibility
   a) Energy and energy bandwidth
   b) Fill pattern

2. Laser and laser synchronization must be part of the machine and beamline design
   a) Timing signal distribution
   b) Beamport for visible synchrotron light

3. Unique challenges undertaken by an enthusiastic and increasingly technically sophisticated User community
   a) Spatial and temporal laser pulseshaping
   b) Specialized x-ray techniques
Incomplete
Acknowledgements

• U.Michigan research groups (D. Reis, P. Bucksbaum, R. Merlin)
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• Sector 7 Staff (B. Adams, E. Dufresne)
• AOD Diagnostics (B. Yang)
• ASD Accelerator Physics (Y. Li)
Two types of pump/probe experiments

**X-Ray**

- Short probe/slow detector experiment
- Time resolution limited by probe duration; X-ray chopper may be required which will be more difficult with larger vertical beam emittance

**Laser**

- Long probe/fast detector experiment
- Time resolution limited by detector; poor sensitivity

Jitter is an issue with both types of experiment.

*Rousse et al., RMP 73, 17 (2001).*
Pulse energy vs. Repetition rate:
Femtosecond Lasers at Light Sources

1 Watt average power

Pulse energy (J)

Rep rate (pps)

Chirped-Pulse Amplification

Relativistic Intensity

Directly Pumped Amplifier

Cavity-dumped oscillator

Multiphoton Ionization

10^{-3}

10^{-6}

10^{-9}

10^{-3}

10^{0}

10^{3}

10^{6}

10^{9}

Hybrid singlet

Top-up

Adapted from R. Trebino class notes
# Battle to Become the Next-Generation X-ray Source

## X-Ray Visions: Today’s Synchrotrons and Beyond

<table>
<thead>
<tr>
<th>Machine</th>
<th>Photons per pulse</th>
<th>Pulse length</th>
<th>Pulses per second</th>
<th>Estimated cost</th>
<th># of beamlines</th>
</tr>
</thead>
<tbody>
<tr>
<td>3rd-Generation Synchrotron</td>
<td>$10^2$–$10^4$</td>
<td>~10–160 ps</td>
<td>5.4 million</td>
<td>&gt;$1 billion</td>
<td>~100</td>
</tr>
<tr>
<td>Slicing Source</td>
<td>$10^3$–$10^4$</td>
<td>~100 fs</td>
<td>10–10,000</td>
<td>$5 million</td>
<td>1 or 2</td>
</tr>
<tr>
<td>Short-Pulse Photon Source</td>
<td>$10^8$</td>
<td>~100 fs</td>
<td>10</td>
<td>$0.1 million to ?</td>
<td>1</td>
</tr>
<tr>
<td>Recirculating Linac</td>
<td>$10^4$–$10^7$</td>
<td>~100 fs</td>
<td>1000–10,000</td>
<td>$300 million to $500$ million</td>
<td>~10</td>
</tr>
<tr>
<td>Free Electron Laser (LCLS)</td>
<td>$10^{11}$–$10^{12}$</td>
<td>~200 fs</td>
<td>60–360</td>
<td>$250 million</td>
<td>1+</td>
</tr>
</tbody>
</table>

ps = picoseconds, or $10^{-12}$ seconds
fs = femtoseconds, or $10^{-15}$ seconds

| APS RF Orbit Deflection       | $10^4$–$10^5$     | 1-2 ps       | 6.5 million       | --                    | 2-6            |
The real competition

<table>
<thead>
<tr>
<th>Laser plasma</th>
<th>ID (3rd Generation)</th>
</tr>
</thead>
<tbody>
<tr>
<td>• “Perfect” synchronization</td>
<td>• picosecond synchronization</td>
</tr>
<tr>
<td>• &lt;500 fs</td>
<td>• 100 ps typical</td>
</tr>
<tr>
<td>• Low flux</td>
<td>• High flux</td>
</tr>
<tr>
<td>• Low brightness (4π)</td>
<td>• High brightness</td>
</tr>
<tr>
<td>• Limited tuning range</td>
<td>• Tuneable</td>
</tr>
<tr>
<td>• Limited pump-probe delay</td>
<td>• Arbitrary pump-probe delay</td>
</tr>
</tbody>
</table>

*Courtesy D. Reis*
Sub-picosecond structural phase transition

For $\phi = 24$ deg and x-rays grazing: $\sim 18$ fs/pixel

- Measures complete time history around $t=0$ in single shot

A. Lindenberg et al., SLAC
Sector 7 Ti:Sapphire CPA system

352 MHz storage ring reference

CW Nd:YVO$_4$ 2\(\omega\) pump laser

Ti:Sapphire Oscillator

352 MHz Filter

Nd:YLF 2\(\omega\) pump laser

Pockels Cell

amplifier

pulse stretcher

Sample

X-Rays

Storage Ring Electrons

pulse compressor
Femtosecond laser oscillators can be synchronized to stable rf to a few hundred fs.
However accelerators are not “perfect” rf sources

![Impulse Phase Error Response Graph]

SPPS LASER Oscillator
0.5 degree phase error injected on reference RF
streak camera resolves transient switch

Laser off

Laser on

~6 times the speed of sound: ambipolar diffusion.
The prominent laser-induced 4p resonance enables a simple x-ray — laser cross-correlation measure of x-ray bunch length.

ANL AMO Group
Single-shot timing by electrooptic sampling

200 mm ZnTe crystal

"e\textsuperscript{-}" temporal information is encoded on transverse profile of laser beam

Adrian Cavalieri et al., U. Mich.
Femtosecond lasers can be synchronized to within a pulse duration using optical techniques.

- This synchronization can be maintained throughout a laser amplifier system.
- Really hot new techniques can synchronize lasers to within an optical period (< 1 fs)!
- *We need this level of timing control to fully exploit the picosecond x-ray source*
LUX Timing Distribution Concept

Master Oscillator Laser + RF

Multiple Beamline Endstation Lasers

FEL Seed Laser

Crab cavity

Linac RF

Photo Injector Laser

EDFA (fiber amp)

cw reference laser interferometer

Path Length Control
\( \Delta L = \pm 2 \ \mu m \)
\( \Delta t = \pm 7 \ \text{fs} \)

L~100

PZT control path length

EDFA (fiber amp)

Beamline 1

Beamline 2

Master oscillator – stabilized laser/rf

17 dBm mixer

RF Clock 3.9 GHz

8PF 3.9 GHz

28 dB AMP

Modelocked Laser 81 MHz

error signal

LPF

Amplifier PZT driver
An Optical Sampling Scope

Bunch

Synchrotron Photons $\omega_1$

Laser Photons $\omega_2$

Mixed Photons $\omega_1 + \omega_2$

Non-linear crystal [BBO]

Filter $(\omega_1 + \omega_2)$

PMT

$\omega_1 + \omega_2 = \text{visible wavelength}$

laser pulse length $\ll$ bunch length

ALS: DeSantis et al.
High Dynamic Range

Camshaft/ Background ~ $10^3$

ALS: DeSantis et al.
Synchronous Phase Transients

ALS: DeSantis et al.
Bunch Length

RMS Bunch Width [ps] vs Bunch Number

ALS: DeSantis et al.
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