Laser Infrastructure and Timing Diagnostics for the SQS Scientific Instrument

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WP-85, Scientific Instrument SQS
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Satellite Meeting „Soft X-ray Instruments SQS and SCS”

Hamburg, 24.01.2017
Content

- Laser Infrastructure
  - Scientific Scope
  - Pump-Probe Laser
  - Beam Delivery

- Timing Diagnostics
  - Spectral Encoding
  - Terahertz Streaking

- Summary

- Acknowledgment
Scientific Scope of the SQS Scientific Instrument

Dynamic investigations of light-matter interactions in atoms, molecules and clusters, such as

- Non-linear phenomena
- Atomic multi-photon ionization
- Molecular dissociation dynamics
- Multi-particle coincidence spectroscopy
- Imaging of complex molecules and nano-scale objects
Time-Resolved “Pump-Probe” Experiments: Capturing reversible processes stroboscopically

Accessing ultrafast, electronic time scales with pulsed femtosecond laser sources in the visible and near infrared spectral range
Pump-Probe Laser Requirements

**XFEL Pulse Train:** Up to 2700 electron bunches every 0.1s → effective repetition rate 27 kHz

- Match XFEL pulse train: 10Hz burst mode & 0 - 4.5 MHz
- Ultrafast 800nm laser (down to fs range with few mJ’s energy)
- Arbitrary pulse pattern selection
- Frequency/wavelength conversion from THz to UV

Development of a versatile laser system by XFEL laser group – from left to right:
Guido Palmer, Laurens Wissmann, Martin Kellert, Moritz Emons, Max Lederer (PI),
Kai Kruse, Gerd Priebe, Jinxiong Wang, Ulrike Wegner, Mikhail Pergament

TALK: Tomorrow at 11:40 by Max Lederer
Non-collinear Optical Parametric Amplifier (NOPA)

- Time zero overlap of XFEL and optical laser (1)
- Pulse on demand with Acousto-Optical-Modulator (AOM) and Pockels Cell (PC) (2)
- Output of 800 nm 15 - 300 fs (3)
- Output of 1030 nm, 1 - 500 ps (4)

TALK: Tomorrow at 11:40 by Max Lederer
Basic laser parameters and set points from day one

<table>
<thead>
<tr>
<th>$\lambda$</th>
<th>800 nm Ultrafast fs excitations</th>
<th>1030 nm intense ps excitations</th>
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<tr>
<td>$\tau_{\text{FWHM}}$</td>
<td>15 – 300 fs (nearly Fourier transform limited)</td>
<td>&lt;1 ps or 400 ps (chirped)</td>
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</table>

<table>
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<tr>
<th>Set point</th>
<th>$f_{\text{rep}}$ [MHz] (within 600 μs burst)</th>
<th>$E_{\text{pulse}}$ [mJ] at 800 nm</th>
<th>$E_{\text{pulse}}$ [mJ] at 1030 nm</th>
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<td>0.05</td>
<td>1</td>
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<tr>
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<td>1</td>
<td>0.2</td>
<td>4</td>
</tr>
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<td>0.2</td>
<td>1</td>
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<tr>
<td>4</td>
<td>0.1</td>
<td>2</td>
<td>40</td>
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Pergament et al., Optics Express 22, 22202 (2014) & 24, 29349 (2016). TALK: Tomorrow at 11:40 by Max Lederer
PP-laser installation schedule

| Task 1: Laser tables and infrastructure in PP and ILH-hutches |
| Task 2: Components + commissioning in PP and ILH-hutches |
| Task 3: Beam to experiment for day-1 |

<table>
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<th>Jan 2017</th>
<th>Dec 2017</th>
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</table>

Pergament et al., Optics Express 22, 22202 (2014) & 24, 29349 (2016). TALK: Tomorrow at 11:40 by Max Lederer
PP Laser infrastructure at SASE 3 for the SQS instrument

- Laser Group responsibilities: Operation and Maintenance (PP Laser Hutch)
- SQS Group responsibilities: Delivery, Conditioning and Diagnostics (ILH and EH).
Challenge: Dispersion and non-linearities in beam propagation

- To obtain the shortest and cleanest possible laser pulse in the interaction region, it is first stretched to about 355fs, which reduces to less than 15fs on its way to the sample interaction region.

- Different wavelengths travel at different speeds through a medium since \( n_{\text{BLUE}} \neq n_{\text{Red}} \); thus different components arrive at different times stretching the broadband laser pulse in time.

- Solution: Pre-compensation of the dispersive behavior in the generation of the laser pulse.

- Keeping laser peak intensity low to avoid spectral broadening and accumulation of non-linear phase.
Pulse width control and beam conditioning

SASE 3 Pump Probe Laser Hutch

Chirped Mirror Stretcher „conjugate-fused-silica“

NOPA

SQS Instrument Laser Hutch (ILH)

- Collimation
- Pump-Probe Delay
- Intensity Attenuation
- Frequency DownConversion (OPA)
- Beam Diagnostics

SQS Experimental Hutch (EH)

- Polarization Control
- Frequency UpConversion (HHG)
- Final Pulse Compression (Silica)
- Focusing
- Beam Diagnostics
Laser Delivery in the SQS Instrument Laser Hutch (ILH)

From PP laser hutch

To SQS experimental hutch

Diagnostics not displayed for sake of simplicity

- Red mirrors: Curved mirrors (for collimation)
- Red beam path: 800nm pump light.
- Blue beam path: Timing Diagnostics – 10% of 800nm light.
- Violet beam path: 1030nm pump light.
- Green mirrors: Motorized mirror mounts
- Yellow sections: Beam stabilization feedback
- Grey mirrors: Beam splitters for beam stabilization

Ultrafast Pump:
800 nm light

Intense Pump:
1030 nm light

Timing Diagnostic:
Spectral Encoding
Splitting 10% off 800nm pump

Wavelength Conversion:
Optical Parametric Amplifier
Laser Delivery into the SQS experiment

Focusing parameters with exterior lens
- \( w_{\text{focus}} = 22 \, \mu\text{m} \) (1/e)
- \( I_{\text{peak}} = 5 \times 10^{15} \, \text{W/cm}^2/\text{mJ} \)

Tighter focusing possible with interior optics!

Laser in-coupling vacuum vessel
- UHV compatible mirror mounts with piezo actuators
- Stiff mirror mount holder
- Mechanical decoupling bellow
- XY out-of-vacuum precision positioning coupled to optical table
Beam propagation

PP laser hutch to sample interaction region – \( w_{\text{focus}} = 22 \, \mu\text{m} \) and \( I_{\text{peak,focus}} = 5 \times 10^{15} \, \text{W/cm}^2/\text{mJ} \)
Compression to 15 fs

From PP-laser room to interaction region

\[ B = \frac{2\pi}{\lambda} \int_0^L n_2 I(z) dz \]

\( I(z) \) is the optical intensity along the beam axis, 
z the position in beam direction, 
and \( n_2 \) the nonlinear refractive index quantifying the Kerr nonlinearity.

B Integral smaller than 0.8 at sample interaction region for a 2 mJ, 780 nm, 355 fs negatively chirped laser pulse passing:
28 mirrors + 19 m air + 4 silica windows + 3 quartz wave plates + silica compressor
Wavelength conversion

High Harmonic Generation (HHG)

HHG and OPA at 100 kHz mode

Optical Parametric Amplifier (OPA)
TOPAS prime
Light Conversion
http://lightcon.com/

Laser Input Parameters:
- OPA
  - 800 nm = 1.8 mJ @ 55 fs
- HHG
  - 800 nm = 1.8 mJ @ 55 fs
  - 2.4 mJ @ 15 fs
  - 1030 nm = 40 mJ @ 1 ps

Pergament et al., Optics Express 24, 29349 (2016).
TALK: Tomorrow at 11:40 by Max Lederer
Repetition rate control

Repetition rate can be controlled with Pockels cell and acousto optical modulator

TALK: Tomorrow at 11:40 by Max Lederer
Timing Diagnostics: Spectral/Spatial Encoding

Measuring the arrival time of the XFEL pulse with respect to the synchronized PP laser

- X-ray induce changes in the transmission of a membrane to map the relative delay onto a spectral coordinate
- About 25fs RMS resolution within a 3ps window
- High intra-burst rep rate will cause high thermal load on sample membrane at the damage threshold
- Single-shot measurements require high speed CCD camera working at MHz repetition rate
- Well established technique!

Bionta et al., Optics Express 19, 21855 (2011).
Timing Diagnostics: Terahertz Streaking

Measuring the arrival time AND pulse length of XFEL pulses

- X-rays photo-emit electrons from a noble gas, which are then dressed by a strong THz field and detected by an electron time-of-flight spectrometer.

- High temporal resolution (few fs) and high dynamic range (few hundreds of fs).

- Still in development/experimental stage

- 3-5mJ pulses of 1030nm should suffice to monitor 10fs XFEL with 20fs jitter

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J. Liu, Technical Note
XFEL.EU TN-2015-002-01
Workshop 1./2. June: Terahertz science at European XFEL

Registration on XFEL homepage: 1. March – 1. May

Confirmed speakers

Andrea Cavalleri (MPSD)
Stefano Bonetti (Stockholm)
Dmitry Turchinovich (U Mainz)
Aaron Lindenberg (SLAC)
Max Lederer (European XFEL)
Matthias Hoffmann (LCLS)
Franz Kärtner (DESY CFEL)
Michael Gensch (HZDR)
Mikhail Krasilnikov (PITZ@DESY)
Christoph Hauri (PSI)
Andrej Savilov (IAP, RAS, N. Novgorod)
Karsten Holldack (HZB)
Summary

- Pump Probe Laser operations are scheduled to begin mid of 2018.
- Pulse propagation simulations show that 15 fs ultrashort pulse will be properly delivered to sample.
- HHG of 800 nm and 1030 nm light successfully tested and is intended to be available from day one.
- OPA successfully tested and is intended to be installed after day one.
- Pockels cell and acousto-optical modulator allow for generating any pulse structure.
- Spectral encoding and terahertz streaking will be implemented for timing diagnostics.
Acknowledgments: Thank you!

SQS Scientific Instrument
- Alberto De Fanis
- Thomas Baumann
- Patrik Grychtol
- Markus Ilchen
- Tommaso Mazza
- Michael Meyer
- Yevheniy Ovcharenko
- Haiou Zhang
- Pawel Ziolkowski

Diagnostics @ XFEL
- Joakim Laksman
- Jia Liu
- Theophilos Maltezopoulos
- Marc Planas
- Johannes Risch
- Sonay Sayar
- Jan Grünert