Laser and accelerators

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DESY, Hamburg

• Photoinjector lasers
• Laser heater
• ESASE /Attosecond generation
• HHG
• Synchronization
Lasers for FELs

Generic layout of single pass FELs

- Injector
- Pre-linac
- Main linac
- Chicane
- Laser heater
- Photo-cathode
- RF
- EO
- Master Laser Oscillator
- Few cycle laser
- Plasma laser
- Pump-probe

> 100 m but < 100fs
# Parameters for classification

- **wavelength** $\lambda$  
  $2 \mu m \ldots 266nm$ (HHG 30 nm)

- **bunch repetition**  
  $1 \text{ Hz} \ldots 1 \text{ kHz}$ (continuous)  
  $10 \text{ kHz} \ldots 9 \text{ MHz}$ (burst pulse)

- **pulse duration**  
  $5 \text{ fs} \ldots 30 \text{ ps}$

- **pulse energy**  
  $1 \text{ nJ} \ldots 40 \text{ mJ}$ (30J)

- **pulse shaping**  
  yes or no?

- **beam shaping**  
  yes or no?

- **synchronization**  
  $10 \text{ ps} \ldots < 1 \text{ fs}$

- **stability**  
  single point of failure?  
  dedicated experiment!
# Photo-injector laser - photo cathode -

<table>
<thead>
<tr>
<th>Type</th>
<th>Metal cathode</th>
<th>Semi-conductor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Example</td>
<td>Cu</td>
<td>Cs$_2$Te</td>
</tr>
<tr>
<td>QE (UV)</td>
<td>$10^{-4} ... 10^{-5}$</td>
<td>0.5% ... 10%</td>
</tr>
<tr>
<td></td>
<td>Drops dramatically towards longer wavelength</td>
<td></td>
</tr>
<tr>
<td>$\varepsilon^N_{\text{Thermal}}$ ($\sigma_x=0.5\text{mm}$)</td>
<td>$\sim 0.6 \mu\text{m (ok)}$ (120MV/m)</td>
<td>$\sim 0.6-0.7 \mu\text{m (ok)}$ (40MV/m)</td>
</tr>
<tr>
<td>$E_{\text{laser UV @1nC}}$</td>
<td>$\sim 150 \mu\text{J}$</td>
<td>0.8 $\mu\text{J}$</td>
</tr>
</tbody>
</table>

V. Miltchev et al., Proc. of the 27th FEL conf., p. 560–563  
J.H. Han et al., Proc PAC05, p. 856–858
Photo-injector laser
- low repetition rate high energy -

100 MHz, 400 mW, 20 fs (5–100fs)

Kerr-lens mode locked Ti:Sa oscillator, 800 nm

CW pump laser 5 W

Stretcher

Pulse shaper

Regenerative Amplifier

Multi-pass Amplifier 2…13

Compressor

~4 nJ ~ 100 ps

~1 mJ ... 120Hz

~1 nJ

5–10 W pulsed pump

10–30 W pulsed pump

~40 mJ

~25 mJ

~2.5 mJ

Beam shaper

THG

Transport to photo cathode

Adapted from: B. White (SLAC)
Photo-injector laser
- beam shaper, transport, launch -

- aspheric Galilei type shaper
- variable telescope (r=0.6–1.5mm)
- relay imaging to cathode (20m)
- diagnostics + FB control

F1=200
F2=120
F3=-150
F4=F5=5000
F6=1500

Table in the tunnel

Courtesy: S. Gilevich (SLAC)
# Photo-injector laser
- beam shaper, transport, launch -

<table>
<thead>
<tr>
<th>Component</th>
<th>Surf.</th>
<th>Losses per surface</th>
<th>Transmission</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adjustment of the shaper input</td>
<td>2 lenses</td>
<td>4</td>
<td>1%</td>
</tr>
<tr>
<td>Transport Tube windows</td>
<td>2 windows</td>
<td>4</td>
<td>2%</td>
</tr>
<tr>
<td>Imaging system</td>
<td>6 lenses</td>
<td>12</td>
<td>1%</td>
</tr>
<tr>
<td>Launch system Mirrors upstairs</td>
<td>8 mirrors</td>
<td>8</td>
<td>2%</td>
</tr>
<tr>
<td>Launch system Mirrors, vault</td>
<td>4 mirrors</td>
<td>4</td>
<td>2%</td>
</tr>
<tr>
<td>Vacuum mirror</td>
<td>1</td>
<td>1</td>
<td>10%</td>
</tr>
<tr>
<td>Vacuum Window</td>
<td>1</td>
<td>2</td>
<td>2%</td>
</tr>
<tr>
<td>2 Beamsplitters</td>
<td>2</td>
<td>4</td>
<td>4% and 1%</td>
</tr>
<tr>
<td>Waveplate</td>
<td>1</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Energy Control</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Beamshaper</td>
<td>3 lenses</td>
<td>6</td>
<td>2%</td>
</tr>
<tr>
<td>Aperture</td>
<td></td>
<td></td>
<td>10%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
In cooperation of DESY and Max-Born-Institute, Berlin,
I. Will et al., NIM A541 (2005) 467,
S. Schreiber et al., NIM A445 (2000)

Photo-injector laser
- high repetition rate (burst) -

**Diode-pumped Nd:YLF Oscillator**

- Modulators (AOM EOM AOM)
  - 108 MHz 1.3 GHz 13.5 MHz
- Piezo tuning of cavity length
- Faraday isolator
- Fiber-coupled pump diodes
- Stabilized by quartz tubes
- Fast current control

**Diode pumped Nd:YLF amplifiers**

- Pulse picker
- Faraday isolator
- E\(_{\text{pulse}}\) = 0.3 µJ

**Flashlamp pumped Nd:YLF amplifiers**

- Relay imaging telescopes
- E\(_{\text{pulse}}\) < 0.3 mJ
- Fast current control

**Conversion to UV**

- LBO BBO
- E\(_{\text{pulse}}\) < 50 µJ
- 300 W
Chain of Linear Amplifiers

- 2 diode pumped and 2 flashlamp pumped single pass amplifiers
- Fully diode pumped version is being tested now at PITZ, DESY Zeuthen

- Flashlamps:
  → cheap, powerful (pulsed, 50 kW electrical/head)
  → current control with IGPT switches
  → allows flat pulse trains
  → energy up to 300 µJ (1 MHz), 140 µJ (3 MHz)

- Laser diodes:
  → 32 W pulsed, 805 nm
  → end pumped through fibers
  → energy from 0.3 µJ to 6 µJ/pulse
Burst-pulse trains

- Amplified laser pulse train – now up to 3 MHz possible, 9 MHz in preparation

After amplification (1 MHz)

800 µs

Output of the laser oscillator (27 MHz)

Electron beam pulse train (30 bunches, 1 MHz)

1.2 nC
Temporal pulse shaping

Motivation:
space–charge force distributed evenly across the bunch
⇒ decrease projected emittance

Spectral filtering:
\[ E_{in}(t) = \sqrt{I(t)} \cdot e^{-i\omega t + i\phi(t)} \]
\[ E(t) = [H \ast E_{in}](t) \]
\[ E(\omega) = T(\omega) \sqrt{I(\omega)} \cdot e^{-i[\psi(\omega) + i\phi(\omega)]} \]

Ripple < 1-10%
FWHM 5ps …20 ps
Rise/fall time 0.5ps …2 ps

Irregular rise/fall time
Amplitude modulation
Phase modulation
Temporal pulse shaping - bandwidth issue ...

\[ \Delta \lambda_{\text{FWHM}} = 2 \text{ nm} \Rightarrow \Delta \tau = 940 \text{ fs} \]

\[ \Delta \lambda_{\text{FWHM}} = 5 \text{ nm} \Rightarrow \Delta \tau = 370 \text{ fs} \]

Filter function: sinc

After frequency filter

- 10 ps
- ~1.3 ps
- ~0.5 ps

See also C. Limborg & P. Bolton LCLS-TN-04-16
Temporal pulse shaping
- bandwidth issue ...

\[ \Delta \lambda_{\text{FWHM}} = 2 \text{ nm} \Rightarrow \Delta \tau = 940 \text{ fs} \]
\[ \Delta \lambda_{\text{FWHM}} = 5 \text{ nm} \Rightarrow \Delta \tau = 370 \text{ fs} \]

After frequency filter

Imperfection of filter
e.g. truncation of sinc

Bandwidth critical impact on frequency Tripler! P. Bolton LCLS–TN–05–29
Temporal pulse shaping
- 4f LCP-SLM shaper -

- Grating maps frequency spectrum into spatial coordinates
- 4f configuration: dispersion-free shaper + beam spot is focused on mask
- spectral mask (Liquid crystal programmable spatial light modulator w/o wave plates)

Used also to compensate fiber transport (see A. Azima MOPCH011)

Optical express, Vol 14 No.3, 1314, 6 Feb. 2006
Acousto-optic programmable dispersive filter (AOPDS)

- Collinear acousto-optical modulation in birefringent crystal
- Input polarization propagates along the fast axis
- Traveling chirped acoustic wave is launched by transducer
- Acoustic wave diffracts light at \( z(\omega) \) to slow axis (\( k_2 = k_1 + K, \omega_2 = \omega_1 + \Omega \))

\[ \Rightarrow \text{Group delay depends upon diffraction position} \]
\[ \Rightarrow \text{Amplitude modulation depends on acoustic wave intensity} \]

- Output wave selected with polarizer


First results with purely amplitude (red)
And purely phase (modulation)

Courtesy: M.B. Danailov (Fermi)
Temporal pulse shaping
-direct space to time (DST)-

- Laser beam passes spatial mask
- Diffraction grating disperses the spatial pattern
- Lens performance a spatial Fourier transform

Edges 5–6ps
R&D towards 2ps

Laser heater

Motivation:
- Collective effect: SP/CSR drive micro-bunch instabilities
- Residual energy-spread \( \sim 1-3\text{keV} \) \( \Rightarrow \) No Landau damping
- Energy-spread can be larger for FELs \( (\sigma_E/E < \rho \sim 5\text{e}^{-4}) \)

\( \Rightarrow \) increase \( \varepsilon_E \rightarrow 10-50\text{ keV} \) (compression factor \( C! \))

Example LCLS design

\[ \text{Laser spot size approx. equal to electron spot size} \]

\( \Rightarrow \) Energy modulation amplitude is radial position of the electron
Laser heater

Residual $\sigma_E \sim 1\text{-}3\text{keV}$

heating $\sigma_L \sim 40\text{keV}$

$R_{52} = -0.024$

$\theta_B \approx 7.1^\circ$

$12.6 \text{ cm}$

$7.4 \text{ cm}$

$50 \text{ cm}$

$2.5 \text{ cm} = \eta_x$

$\sim 153 \text{ cm}$
Current enhanced SASE - ESASE -

Energy modulation

Peak current modulation

I = 3.4 kA

I > 15 kA for ESASE

Xray spikes (~300as)

Figure 1: A schematic of ESASE as applied to the LCLS. Significantly reduces gain length of SASE.
Attosecond pulse generation

Example:

- Ti:Sa laser
  - $V_{ceo}$ stabilized
- Undulator for energy modulation
- X-ray SASE FEL
  - $\lambda = 0.1$ nm
- Mono-chromator
- 100 fs SASE radiation pulse
- Beam dump
- 300 as X-ray pulse
- Target

MLO

- Two cycle laser
- Energy modulation
  - Slicing of electron bunch with fs-laser

A.A. Zholents et al. PRL 92 (2004) 224801
Higher Harmonic Generation

XUV pulse generation

Step 1
Optical field ionization

Step 2
e- Acceleration

Step 3
XUV emission on recollision


Cut-off harmonics: train of attosecond bursts

Paul et al, Science 292, 1689 (2001)
Tsakiris, Charalambidis et al, 2003

L’Huillier, Balcou, 1993, PRL 70, 774
Macklin et al, 1993, PRL 70, 766
Higher Harmonic Generation - 3rd/13th harmonic -

Scheme of experiment at SCSS

- Characterization of 3th/13th harm.
  photon energy/beam profile/waist position

See also: M. Labat et al. ,MOPCH002/MOPCH003

Courtesy: M. Labat
Layout of laser based synchronization

Master:
- Master RF Oscillator
  - 10MHz
  - 1.3GHz
- Master Laser Oscillator
- Optical Standard

Optical distribution:
- Path length stabilization of optical link
  - Link stability
    - RF < 50 fs
    - Opt. < 5 fs

Front ends:
- Laser to RF-converter
  - Photodiode, injection locking, opt. mixer
- Locking of lasers
  - optical cross-correlation, seeding, injection-locking
- Direct laser-pulse stream applications
  - with EO/AO modulators

Applications:
- LO generation
  - down converter LLRF
  - PPL for synchronization
  - RF signals for diagnostics
- Lasers for
  - photo-injector
  - pump-probe experiment
  - e-beam diagnostics
  - e-beam manipulation
- High precision appl.
  - Beam phase monitor
  - Laser phase monitor
  - Optical down converter
  - Chicane BPM

See also: A. Winter TUPCH028/TUPCH029, talks: Kim THOPA03, F.LöhL THOBFL01
Synchronization laser

Dispersion managed soliton fiber–laser with artificial saturable absorber

- Fiber stretcher for passive mode locking to RF generator
- Gain medium Erbium, 1550 nm wavelength
- High output power up to ~ 1 nJ (50 mW average)
- Pulse duration ~ 100 fs FWHM
- Repetition rate ~ 50 MHz

Polarization control for mode locking

Very low phase noise
Summary

• Laser systems have become key components of FELs
• Lasers substantially extend the capabilities of FELs
• The applications range from electron generation, beam conditioning, seeding and two color pump-probe experiments
• For user facilities ⇒ stability of laser system is the most critical item, especially for advanced systems
• New schemes and combinations for laser usage are expected in future