Fs-laser driven free-electron laser development @ ELI-BL

Alexander Molodozhentsev (ELI-BL, IoP)
Georg Korn (ELI-BL, IoP)
Andreas Maier (University of Hamburg, CFEL, DESY)
Florian Gruener (University of Hamburg, CFEL, DESY)
Gabriele Grittani (ELI-BL, IoP)
- Motivation
- Laser-driven FEL
- Main challenges
- Laser-driven FEL development at ELI-BL
- EUV laser-driven FEL at ELI-BL
Electron dynamics in molecules. Structure of non-reproducible biological particles like a living cell or a large virus.

X-ray Imaging. Movies of transient effects in large specimens

Initiate and study transient processes in molecular dynamics and material sciences

Sub-ps resolution of atomic scale structural dynamics (time resolved protein crystallography)

Properties in new surfaces and interfaces, charge and spin dynamics

Properties in new surfaces and interfaces, charge and spin dynamics

Secondary photon sources

Photon in/photon out experiments in the THz to Hard X-ray range

-fs to ms dynamics

Sub 50 fs Peak Brilliance

1E10 ph 10 fs 1 kHz

1E13 ph 300 fs 1 kHz

1E6 ph 5 fs 5 Hz

1E8 ph 20 fs 10 Hz

5 mrad 4 \pi sr

20 mrad

1 keV 100 keV 1 MeV
Linac-based FEL facilities

- wide range of the photon radiation wavelength $\lambda_1$ from 50 nm to 1 nm (tendency $\rightarrow$ 0.2 nm)
- electron beam energy: $1 \div 20$ GeV
- high repetition rate: from 10 Hz to 27 kHz
- peak brilliance up to $10^{33}$ ph/sec/mrad$^2$/mm$^2$/0.1%bw
- temporal photon distribution (FEL-SASE)
  - RMS $\sim 100$ fs
- ‘km’ scale facility ($E_{\text{acc}} < 40$ MV/m) / $\sim 1$ Billion Eur
- extremely stable electron and photon beams

Motivation

... what is next?
Laser-driven electron acceleration, the way to compact FEL sources

Laser wake-field acceleration (‘self-injection’ mechanism)

The principal of the laser wake-field acceleration is based on an ultra-high longitudinal electric gradient, created by the high-intensity laser pulse focused in the underdense plasma.

Assuming: \( n_e = 5 \times 10^{18} \text{ cm}^{-3} \)

\[
E_0 [\text{V/m}] = 96\sqrt{n_e [\text{cm}^{-3}]}.
\]

See for example ...
T. Tajima,

\( \lambda_p \sim 35 \mu \text{m} \)

\( E_0 \sim 70 \text{ GV/m} \)

> 1000 time higher than in existing accelerators

\( \tau_{\text{bunch}} < 5 \text{ fs} \)

\( W_e \sim 1 \text{ GeV} \)

\( L_{\text{acc}} < 5 \text{ cm} \)
Laser-driven FEL for:

\[ \lambda_{ph} = 13.5 \ (11.5, \ 6.x) \ \text{nm} \]

Motivation

Photon radiation wave-length \((\lambda_1)\) as a function of the electron energy (MeV) and the undulator gap-size (mm)

\[ K_0 = 1.3 \]

Electron beam energy in the range of 550 ÷ 800 MeV ...

Tunable source (change Gap or/and \(W_k\)...
Main challenges: electron beam parameters

Requirements for the electron beam for the laser-driven FEL:

- Electron energy ~ 300 ÷ 1000 MeV (and more)
- RMS relative energy spread < 1 %
- RMS transverse beam divergence < 1 mrad
- Bunch charge ~ 20 ÷ 50 pC
- Electron bunch length (RMS) ~ < 2 fs
- Stable beam with the repetition rate > 10 Hz

Laser parameters for the laser-driven FEL:

- Pulse energy ~ 2 ÷ 5 J
- Pulse duration ~ 30 fs
- Repetition rate 10 Hz (to kHz)

Recent experimental achievement in LWFA [##]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy, $W_{\text{kin}}$</td>
<td>MeV</td>
</tr>
<tr>
<td></td>
<td>300 ÷ 1000</td>
</tr>
<tr>
<td>RMS energy spread (projected), $\sigma_{\Delta p/p}$</td>
<td>%</td>
</tr>
<tr>
<td></td>
<td>&lt; 1 (~0.5)</td>
</tr>
<tr>
<td>Normalized RMS emittance, $\varepsilon_n$</td>
<td>$\pi$ mm.mrad</td>
</tr>
<tr>
<td></td>
<td>~ 0.2 (20÷50pC)</td>
</tr>
<tr>
<td>RMS bunch duration, $\sigma_t$</td>
<td>fs</td>
</tr>
<tr>
<td></td>
<td>3</td>
</tr>
<tr>
<td>RMS beam divergence, $\sigma_{x',y'}$</td>
<td>mrad</td>
</tr>
<tr>
<td></td>
<td>~ 0.5</td>
</tr>
</tbody>
</table>

Laser-driven FEL development at ELI-BL

ELI Beamlines master scheme

Parameters of FOCUSED laser pulses

- **L1**: 100 mJ / 10 fs  
  * 1 kHz  
  < 6x10^{20} W/cm^2

- **L2**: 20 J / 15 fs  
  10 Hz  
  < 3x10^{21} W/cm^2

- **L3**: 30 J / 20 fs  
  ** 10 Hz  
  < 1x10^{22} W/cm^2

- **L4**: 10 PW / 150 fs  
  0.1 Hz  
  < 3x10^{23} W/cm^2

*Installation in progress: (*) available during 2018  
(**) available during 2019

Location: Dolni Brezany (near Prague)
- Site area 65,000 m²
- Building(s) 28,645 m²
- Building volume 170,000 m³
- Experimental building 16,500 m²
- Laboratories 4,500 m²
- Offices 4,400 m²
- Multifunction areas 2,300 m²
- Total estimated construction costs of €65M
- Foundation raft slab thickness 1m;
- 1.6m shielded reinforced concrete walls in the underground;
HAPLS Laser @ ELI Beamlines up to 10 Hz, 1 PW, uses diode pumping of green pump lasers
Laser-driven LUX development at ELI-BL, UHH and DESY

Achievement: incoherent photon radiation using LUX

World-record performance (electrons)
- First world-wide demonstration of 24 hr operation of a plasma-accelerator
- 2% rms laser energy stability (24 hrs)
- 2% rms electron beam energy stability (24hrs)
- Electron beam in 98% of all laser shots
- More than 100,000 shots operation demonstrated

World-record performance (x-rays)
- Demonstrated x-rays from 4 nm – 10 nm
- Spontaneous undulator radiation
- \(10^4 – 10^5\) photons per pulse per pC
- Single-fs pulse length
- Synchronized to pump/probe beam

43,000 consecutive electron beams at 2% rms energy stability over 24 hrs
Coherent photon radiation ('Laser-driven' demo-FEL)

Photon flux per pulse $0.1\%BW > 10^{11}$

Peak brilliance $> 10^{29} \text{ph/pulse/mm}^2/\text{mrad}^2/0.1\%BW$

From $\lambda_{ph,1} \sim 40 \text{ nm}$ ... to 'hard' X-ray

'In-vacuum' hybrid PM planar Swiss-FEL type

$\lambda_u = 15 \text{ mm}$

$Gap = 3\div6 \text{ mm}$

$B_{peak} \sim 0.95 \text{ T}$ *

$K_0 = 1.30$ *

* gap=4.5mm

'‘DEMO’ LD-FEL: saturation in short undulator'

The electron beam line:

- 'momentum' filter
- 'decompression' scheme *
- planar undulator


'DEMO’ LD-FEL:

$W_e \sim 350 \text{ MeV}$

Schedule: end of 2022
FEL ANALYSIS:
‘water-window’ FEL $\rightarrow W_{\text{kin}}=1000$ MeV ($\lambda_{r,1}=5$nm, $E_{\text{ph},1}=250$eV)

- ‘Cryogenic’ undulator segments ($K=1.8$): $L_{\text{seg}}=2.5$m
- Space separation: 0.75m
- FODO focusing structure

LWFA-based’ water-window FEL in ELI-BL experimental hall E5:
electron beamline with the undulator’s segments and the photon beam line to the user station
Laser-driven FEL development at ELI-BL

Beyond the ‘demo-FEL’

→ $\lambda_{ph} \approx 13.5 \,(11.5,\,6.x)\,nm$

‘Swiss-FEL’ type undulator

$\lambda_u = 15\,mm$
Gap = 3÷6\,mm
$B_{peak} \sim 0.95\,T$ *
$K_0 = 1.30\,*$
* gap = 4.5mm

Electron beam parameters

<table>
<thead>
<tr>
<th>Gap (mm)</th>
<th>$\sigma_{x,y}$ (µm)</th>
<th>$Q_p$ (pC)</th>
<th>$\sigma_{\Delta p/p}$ (%)</th>
<th>$\varepsilon_n$ (π mm.mrad)</th>
<th>$T_{bunch}$ (fs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>25</td>
<td>30</td>
<td>0.2</td>
<td>0.3</td>
<td>5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$\lambda_{ph,1}$ (nm)</th>
<th>$E_{ph,1}$ (eV)</th>
<th>$W_e$ (MeV)</th>
<th>$L_{sat}$ (m)</th>
<th>$L_{und}$ (m)</th>
<th>Total Flux (ph/1%bw)</th>
<th>BW (%)</th>
<th>Peak Brilliance (ph/mm²/mrad²/0.1%bw)</th>
<th>Peak power (GW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>13.6</td>
<td>90.7</td>
<td>540</td>
<td>2.89</td>
<td>3</td>
<td>$7.1 \times 10^{12}$</td>
<td>0.5</td>
<td>$2.3 \times 10^{30}$</td>
<td>18.5</td>
</tr>
<tr>
<td>11.1</td>
<td>112</td>
<td>600</td>
<td>3.28</td>
<td>3.5</td>
<td>$5.7 \times 10^{12}$</td>
<td>0.45</td>
<td>$3.1 \times 10^{30}$</td>
<td>17.7</td>
</tr>
<tr>
<td>6.2</td>
<td>199.1</td>
<td>800</td>
<td>4.8</td>
<td>5</td>
<td>$3.2 \times 10^{12}$</td>
<td>0.32</td>
<td>$6.1 \times 10^{30}$</td>
<td>14.7</td>
</tr>
</tbody>
</table>

Peak power = 20 GW, Pulse = 5 fs
Peak photon energy ~ 100 µJ/pulse

Many knobs exist to get to 1÷5 mJ/pulse

Average power of 1 W (→ 50 W) requires the repetition rate of 10 kHz

High repetition rate laser development has started for this application

FZU

Source Workshop 2018

Date: 07.11.2018 | Page: 12 (14)
Conclusion

- ‘fs’ laser-driven free-electron laser opens the way to the 5th generation of FEL

- ‘demo’ laser-driven FEL is under development in ELI-beamlines in collaboration with University of Hamburg and DESY (CFEL)

- we are developing a tunable tool for applications

We are eager to hear from the EUV community in order to play with the right knobs to develop a tailored FEL for lithography applications
Thank you for your attention.
Laser-driven FEL development in ELI-BL

‘Demo’-FEL: different undulators

CHPMU – cryogenic hybrid pm undulator
HPMU – hybrid pm undulator

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Units</th>
<th>CHPMU</th>
<th>HPMU</th>
</tr>
</thead>
<tbody>
<tr>
<td>Undulator period</td>
<td>( \lambda_u ) mm</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>Undulator gap</td>
<td>Gap mm</td>
<td>3÷6</td>
<td>2÷6</td>
</tr>
<tr>
<td>Peak magnetic field</td>
<td>( B_0 ) T</td>
<td>1.267*</td>
<td>0.925*</td>
</tr>
<tr>
<td>Peak undulator parameter</td>
<td>( K )</td>
<td>1.77*</td>
<td>1.29*</td>
</tr>
<tr>
<td>Undulator length</td>
<td>( L_u ) mm</td>
<td>2000</td>
<td>2500</td>
</tr>
</tbody>
</table>

*... for the gap size of 4.5 mm

The saturation length is \(~ 2\)m (CHPMU) or \(2.5\)m (HPMU)

Estimation of the photon beam properties (‘demo’-FEL)

<table>
<thead>
<tr>
<th>Parameters</th>
<th>CHPMU</th>
<th>HPMU</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy, ( \varepsilon_{\text{ph,1}} )</td>
<td>eV</td>
<td>31.8</td>
</tr>
<tr>
<td>Radiation wavelength</td>
<td>nm</td>
<td>38.8</td>
</tr>
<tr>
<td>Pierce parameter, ( \rho )</td>
<td>( \times 10^{-2} )</td>
<td>0.83</td>
</tr>
<tr>
<td>Coherent normalized RMS emittance, ( \varepsilon_{\text{ph,coh}} )</td>
<td>( \pi \text{ mm.mrad} )</td>
<td>2.198</td>
</tr>
<tr>
<td>Cooperation length, ( L_{\text{coop}} )</td>
<td>( \mu ) m</td>
<td>0.28</td>
</tr>
<tr>
<td>Gain length (3D), ( L_{3D} )</td>
<td>m</td>
<td>0.107</td>
</tr>
<tr>
<td>Saturation length (3D)</td>
<td>m</td>
<td>(~ 2.0)</td>
</tr>
<tr>
<td>Radiation bandwidth</td>
<td>%</td>
<td>0.72</td>
</tr>
<tr>
<td>Photon flux per 0.1%bw</td>
<td>( \times 10^{13} # )</td>
<td>1.17</td>
</tr>
<tr>
<td>Photon brilliance</td>
<td>( \times 10^{30} # )</td>
<td>3.26</td>
</tr>
<tr>
<td>Photon pulse power</td>
<td>GW</td>
<td>10.9</td>
</tr>
<tr>
<td>Photon pulse energy</td>
<td>( \mu ) J</td>
<td>55</td>
</tr>
</tbody>
</table>