Review of the Worldwide SASE FEL Development

(Accelerator Based X-ray Laser)

Tsumoru Shintake
For all XFEL contributors

RIKEN/SPring-8

Current status
and
Future
The end of HERA operation is also the end of a great era. For many colleagues, a considerable part of their working life consisted of designing, constructing and operating HERA; for me it was 25 years. In the seventies, we actually planned an electron-positron storage ring at DESY with a circumference of 30 kilometers. Proposals for possible sites were already at hand, for example in the Lüneburg Heath. This project, however, was realized as LEP at CERN. The new HERA project seemed a bit suspect to many people, including me. Experience with protons already existed, but not with superconducting magnets. Moreover, the proton ring was supposed to be built by people from the research sector, an “amateur play group” with little accelerator experience, to which also I belonged. In case that this part of the project would be delayed, a positron injection was built to make positron electron collisions possible. As we all know, those fears were unnecessary. You should never underestimate ‘newcomers’!

(continued overleaf)
• **Circular Machine**  
  Quantized SR photon radiation → Energy spread  
  → higher horizontal emittance, longer bunch length 30 psec,  
  → FEL at short-wavelength becomes not feasible

• **Linear Accelerator Base**  
  No SR radiation → Small energy spread, and small emittance.  
  → longitudinal bunch length in femto-sec is possible  
  → FEL at short wavelength below 1 nanometer becomes possible.
Figure 1: IV generation synchrotron light sources based on short wavelength FEL world distribution. Red and blue labels: FEL projects based on normal conducting or superconducting technology respectively. White circles: first SASE demonstrative experiments.
# XFELs around the world

<table>
<thead>
<tr>
<th>Project</th>
<th>Type</th>
<th>Location</th>
<th>Country</th>
<th>e-Beam (GeV)</th>
<th>Photon (nm)</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>LEUTL</td>
<td>SASE</td>
<td>APS</td>
<td>USA</td>
<td>0.22</td>
<td>660-130</td>
<td>Since 2001</td>
</tr>
<tr>
<td>TTF I</td>
<td>SASE</td>
<td>DESY</td>
<td>Germany</td>
<td>0.3</td>
<td>125-85</td>
<td>Since 2002</td>
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<tr>
<td>SDL DUV-FEL</td>
<td>HGHG</td>
<td>SDL/NSLS</td>
<td>USA</td>
<td>0.145</td>
<td>400-100</td>
<td>Since 2002</td>
</tr>
<tr>
<td>FLASH (TTF)</td>
<td>SASE</td>
<td>DESY</td>
<td>Germany</td>
<td>1.0</td>
<td>12 - 6</td>
<td>Since 2006</td>
</tr>
<tr>
<td>SCSS Prototype</td>
<td>SASE</td>
<td>SPring-8</td>
<td>Japan</td>
<td>0.25</td>
<td>150-50</td>
<td>Since 2006</td>
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<tr>
<td>LCLS</td>
<td>SASE</td>
<td>SLAC</td>
<td>USA</td>
<td>15</td>
<td>0.15</td>
<td>In 2008</td>
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<tr>
<td>SCSS XFEL</td>
<td>SASE</td>
<td>SPring-8</td>
<td>Japan</td>
<td>8</td>
<td>0.1</td>
<td>In 2011</td>
</tr>
<tr>
<td>Euro XFEL</td>
<td>SASE</td>
<td>DESY</td>
<td>Germany</td>
<td>20</td>
<td>0.1</td>
<td>(in 2014)</td>
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<tr>
<td>SPARC</td>
<td>SASE</td>
<td>INFN Frascati</td>
<td>Italy</td>
<td>0.15</td>
<td>500</td>
<td>In 2007</td>
</tr>
<tr>
<td>FERMI</td>
<td>HGHG</td>
<td>Trieste</td>
<td>Italy</td>
<td>1.2</td>
<td>10</td>
<td>In 2009</td>
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<tr>
<td>Soft X-ray FEL</td>
<td>HGHG</td>
<td>BESSY</td>
<td>Germany</td>
<td>2.3</td>
<td>64 - 1.2</td>
<td>proposal</td>
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<tr>
<td>SPARX</td>
<td>HHG</td>
<td>INFN Frascati</td>
<td>Italy</td>
<td>1 – 2</td>
<td>1.5</td>
<td>proposal</td>
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<tr>
<td>4GLS</td>
<td>HGHG</td>
<td>Daresbury</td>
<td>GB</td>
<td>0.6</td>
<td>100 - 19</td>
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<tr>
<td>ARC-EN CIEL</td>
<td>HHG</td>
<td>Saclay</td>
<td>France</td>
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<tr>
<td>PAL XFEL</td>
<td>SASE</td>
<td>Pohang</td>
<td>Korea</td>
<td>3.7</td>
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<td>proposal</td>
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<td>PSI XFEL</td>
<td>SASE</td>
<td>PSI</td>
<td>Swiss</td>
<td>3.7</td>
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<td>proposal</td>
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</table>
## XFELs Technology Choice

<table>
<thead>
<tr>
<th>Project</th>
<th>Electron Gun</th>
<th>Main Accelerator</th>
</tr>
</thead>
<tbody>
<tr>
<td>LEUTL</td>
<td>S-band RF-Photocathode</td>
<td>NRM– S</td>
</tr>
<tr>
<td>TTF I</td>
<td>L-band RF-Photocathode</td>
<td>SCC– L</td>
</tr>
<tr>
<td>SDL DUV-FEL</td>
<td>S-band RF-Photocathode</td>
<td>NRM– S</td>
</tr>
<tr>
<td>FLASH (TTF)</td>
<td>L-band RF-Photocathode</td>
<td>SCC– L</td>
</tr>
<tr>
<td>SCSS Prototype</td>
<td>Pulse HV Themionic Gun</td>
<td>NRM–C</td>
</tr>
<tr>
<td>LCLS</td>
<td>S-band RF-Photocathode</td>
<td>NRM– S</td>
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<tr>
<td>SCSS XFEL</td>
<td>Pulse HV Themionic Gun</td>
<td>NRM–C</td>
</tr>
<tr>
<td>Euro XFEL</td>
<td>L-band RF-Photocathode</td>
<td>SCC– L</td>
</tr>
<tr>
<td>Soft X-ray FEL</td>
<td>L-band RF-Photocathode</td>
<td>SCC– L</td>
</tr>
<tr>
<td>SPARC</td>
<td>S-band RF-Photocathode</td>
<td>NRM– S</td>
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<tr>
<td>SPARX</td>
<td>S-band RF-Photocathode</td>
<td>NRM– S</td>
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<tr>
<td>FERMI</td>
<td>S-band RF-Photocathode</td>
<td>NRM– S</td>
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<tr>
<td>4GLS</td>
<td>DC HV Photocathode</td>
<td>NRM– S</td>
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<tr>
<td>ARC-EN CIEL</td>
<td>L-band RF-Photocathode</td>
<td>SCC– L</td>
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<tr>
<td>PAL XFEL</td>
<td>S-band RF-Photocathode</td>
<td>NRM– S</td>
</tr>
<tr>
<td>PSI XFEL</td>
<td>S+L-band RF Gun with Field Emission Array</td>
<td>NRM– S</td>
</tr>
</tbody>
</table>
From SR to FEL

SR or ERL
Spontaneous Radiation

- $N$-electrons random distribution
- $E_{spt} \sim \sqrt{N} E_1$
- $P_{spt} \sim N P_1$

FEL: Free Electron Laser
Coherent Radiation

- $N$-electrons micro-bunched
- $E_{coherent} \sim N E_1$
- $P_{coherent} \sim N^2 P_1$

Optical Power Enhancement
$x \times 10^5 \sim 10^8$
Feeling & Experience are very important in science.

Radiation2D simulator gives you reality as if you are in front of running noisy electron.

Radiation2d, available from (freeware)

http://www-xfel.spring8.or.jp

or

www.ShintakeLab.com

Power Spectrum
Scattering Model
• Undulator field produces curved trajectory. From this slope, the tangential component of EM wave creates longitudinal field.

$E_{\parallel} = E \sin(\alpha) \sim 1/\gamma$

$E_{\parallel}$ creates micro-bunching.
Shot Noise

Exponential Signal Amplification

Saturation

Seeding or Infinitely Long Undulator

Seeding

Shot Noise

Distance Along Undulator

FEL Power

T. Shintake
2007.01
Crystal Diffraction Analogy

Scattering by Electron

Random multiple electrons

Wave diffraction by non-crystal material

Crystal Structure
xy-random, only z is regular.

\[ \lambda' = 4 \, \mu m \]

Bragg Diffraction

Power on Screen

\[ \pi/2 \]

\[ -\pi/2 \]

\[ \theta = 0 \]

Screen

Radiation Pattern

Speckle

T. Shintake, 2006

SRI2006 Shintake
Peak brilliance will be enhanced by factor of $10^{10}$ from 3rd generation SR to XFEL.

$10^{10} = 10^1 \times 10^1 \times 10^1 \times 10^7$

= peak current by factor 10
x lowered emittance by 10
x energy spread lowered by 10
x interference effect $10^7$ by micro-bunching formation.
Why 1 Angstrom?

- Photo-ionization becomes lower as X-ray energy.

- Around 1 Å, 8 keV, photo-ionization becomes low enough to see coherent scattering.

- Spatial resolution becomes a few Angstrom, which resolves macromolecular crystal in biology.

  → Imaging, crystallography

- **Water window** (2.3-4.4nm light) is also another candidate.

  (a few micron-meter thick water)
Protein Crystal ~0.1 mm

Rodopsin Structure

Courtesy of M. Yamamoto

Dr. Masashi Miyano
We need high energy electron beam

- **1 Angstrom X-ray**
  - Using undulator: Period = 30~40 mm, $K = 2\sim3$
  - Electron energy = $\sim20\text{ GeV}$ large scale accelerator

- **Water Window 3 nm**
  - Using undulator: Period = 30~40 mm, $K = 2\sim3$
  - Electron energy = $\sim3\text{ GeV}$ middle scale accelerator

  - SCSS Concept
    Using short period undulator: Period 18 mm, $K = 1.5$,
  - Electron energy = $1\text{ GeV}$ small scale accelerator
  (need low emittance beam, use thermionic gun 0.6 $\pi\text{.mm.mrad}$)
We need low emittance beam and high peak current

\[
L_g = 1.67 \left( \frac{I_A}{I} \right)^{1/2} \frac{(\varepsilon_n \lambda_u)^{5/6}}{\lambda^{2/3}} \frac{(1 + K_{rms}^2)}{K_{rms} A_{JJ}} \left(1 + \delta \right),
\]


- For 0.1 nm, and L <= 10 m (Saturation ~100 m)
- Beam emittance ~ 1 \, \pi.\text{mm.mrad} (normalized, slice)
- Peak current ~ a few kilo Amp.
How to obtain such high quality beam

- RF-photocathode gun + magnetic bunch compression

  $\text{RF-Photocathode gun } 0.5 \text{ nC, } 10 \text{ psec, } 50 \text{ A}$

  $\rightarrow \text{Chicane Compression } 1/100 \rightarrow 100 \text{ fsec, } 5 \text{ kA}$

- Thermionic gun + velocity bunching + magnetic bunch compression

  $\text{Thermionic gun } 0.5 \text{ nC, } 500 \text{ psec, } 1 \text{ A}$

  $\rightarrow \text{Velocity Bunching } 1/20 \rightarrow 20 \text{ psec, } 20 \text{ A}$

  $\rightarrow \text{Chicane Compression } 1/150 \rightarrow 150 \text{ fsec, } 3 \text{ kA}$

$\text{Big technical challenge!}$
To Realize XFEL
Technical Challenges

• Need high density electron cloud. (high peak current ~ kA)
  → bunch compressions, CSR problem, short bunch monitoring.

• Maintain overlap of electron and undulator radiation in a same axis for long distance. (highly accurate undulator field, and tight beam alignment ~ a few μm / 10 m)
  → undulator tuning, BPM, beam based alignment

• Minimize radiation spread, thus we need parallel electron flow, needs very low emittance. (1 π.mm.mrad normalized)
  → RF-photocathode gun, thermionic gun

• Low energy spread (10^-4), do not run beam in circle at high energy.
## Comparison of X-ray FELs

<table>
<thead>
<tr>
<th>Projects</th>
<th>Euro-XFEL</th>
<th>LCLS</th>
<th>XFEL/SPring8 (SCSS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength</td>
<td>6 – 0.085 nm</td>
<td>1.5 – 0.15 nm</td>
<td>6 – 0.08 nm</td>
</tr>
<tr>
<td>Beam Energy</td>
<td>10 - 20 GeV</td>
<td>14.3 GeV</td>
<td>2 - 8 GeV</td>
</tr>
<tr>
<td>Main Accelerator</td>
<td>Super Conducting</td>
<td>S-band Normal Conducting</td>
<td>C-band Normal Conducting</td>
</tr>
<tr>
<td>Accelerator Length</td>
<td>2.1 km</td>
<td>1 km</td>
<td>400 m</td>
</tr>
<tr>
<td>Gradient x Active Length</td>
<td>23.5 MV/m x 900 m</td>
<td>19 MV/m x 800 m</td>
<td>35 MV/m x 230 m</td>
</tr>
<tr>
<td>Undulator Period</td>
<td>26 mm</td>
<td>30 mm</td>
<td>18 mm</td>
</tr>
<tr>
<td>Total undulator Length</td>
<td>133 m</td>
<td>113 m</td>
<td>90 m</td>
</tr>
<tr>
<td>Total Length</td>
<td>3.4 km</td>
<td>1.6 km</td>
<td>700 m</td>
</tr>
<tr>
<td>Undulator Lines (X-ray)</td>
<td>3 (5)</td>
<td>1 (5)</td>
<td>1 (3), max 5</td>
</tr>
<tr>
<td>Construction Cost</td>
<td>850 M-Euro</td>
<td>380 M$</td>
<td>300 M$</td>
</tr>
</tbody>
</table>
Linac Coherent Light Source at SLAC

X-FEL based on last 1-km of existing linac

Injector (35°) at 2-km point

Existing 1/3 Linac (1 km) (with modifications)

Near Experiment Hall (underground)

Undulator (130 m)

New $e^-$ Transfer Line (340 m)

X-ray Transport Line (200 m)

CONSTRUCTION HAS STARTED
Beam Transport Hall (BTH) Construction (Jan. 2007)

Beam Transport Hall (previously FFTB*)

Linac

Facing West

* Final Focus Test Beam

B. Hall
Undulator Hall (UH) Construction (Jan. 2007)

Undulator Hall

Facing East
Near Experimental Hall (NEH) Construction (Jan. 2007)
First Measurements and the SLAC MMF

There are 7 production undulators now at SLAC, 1 at ANL.

The vendor has roughly 4 more and is completing > 2 per week.
RF Gun Fabrication and Cold RF Testing Finished & Preparing for High-Power Tests

Gun only pictures

CAD cut away view of gun interior
**LCLS Injector Layout**

Gun through BC1-Chicane at 250 MeV

Injector Electron Commissioning April – August, 2007
First Electron Beam on April 5, 2007

(YAG screen 80 cm from gun cathode)
Projected Emittance Measured 80 Times Over 8 Hours

\[ \langle \gamma \varepsilon_x \rangle = 1.382 \pm 0.006 \, \mu m \]

RMS variation = 0.089 \, \mu m

\[ \chi^2/N = 2.859 \]
Transverse RF Deflector Used to Time-Resolve Emittance (into “slices”)

OTR screen with RF deflector OFF

OTR screen with RF deflector ON

Time-Sliced Emittance and $\beta$-Match

200 pC, $R = 0.8$ mm

Emittance still variable - parameters not design yet
## Approximate and Typical LCLS Machine Parameters at Present

<table>
<thead>
<tr>
<th>Parameter</th>
<th>sym</th>
<th>dsgn</th>
<th>meas.</th>
<th>unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Final $e^-$ energy</td>
<td>$\gamma m c^2$</td>
<td>250</td>
<td>250</td>
<td>MeV</td>
</tr>
<tr>
<td>Bunch charge</td>
<td>$Q$</td>
<td>1000</td>
<td>200</td>
<td>pC</td>
</tr>
<tr>
<td>Init. bunch length (fwhm)</td>
<td>$\Delta t_0$</td>
<td>10</td>
<td>6.5</td>
<td>ps</td>
</tr>
<tr>
<td>Fin. bunch length (fwhm)</td>
<td>$\Delta t_f$</td>
<td>2.3</td>
<td>1.5</td>
<td>ps</td>
</tr>
<tr>
<td>Initial peak current</td>
<td>$I_{\text{Pk}0}$</td>
<td>100</td>
<td>30</td>
<td>A</td>
</tr>
<tr>
<td>Final peak current</td>
<td>$I_{\text{Pk}f}$</td>
<td>450</td>
<td>130</td>
<td>A</td>
</tr>
<tr>
<td>Projected norm emittance</td>
<td>$\gamma \varepsilon_{x,y}$</td>
<td>1.2</td>
<td>1.5, 1.8</td>
<td>$\mu$m</td>
</tr>
<tr>
<td>Slice norm. emittance</td>
<td>$\gamma \varepsilon_{x,y}^s$</td>
<td>1.0</td>
<td>1.2, 1.3</td>
<td>$\mu$m</td>
</tr>
<tr>
<td>Slice rel. E-spread (rms)</td>
<td>$\sigma_E/E$</td>
<td>$&lt;10$</td>
<td>$&lt;10$</td>
<td>keV</td>
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<tr>
<td>Single bunch rep. rate</td>
<td>$f$</td>
<td>120</td>
<td>10-30</td>
<td>Hz</td>
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<tr>
<td>RF gun field at cathode</td>
<td>$E_g$</td>
<td>120</td>
<td>110</td>
<td>MV/m</td>
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<tr>
<td>Laser energy on cathode</td>
<td>$u_i$</td>
<td>250</td>
<td>250</td>
<td>$\mu$J</td>
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<tr>
<td>Laser wavelength</td>
<td>$\lambda_i$</td>
<td>255</td>
<td>255</td>
<td>nm</td>
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<tr>
<td>Laser diameter on cath.</td>
<td>$2R$</td>
<td>1.5</td>
<td>2</td>
<td>mm</td>
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<tr>
<td>Cathode material</td>
<td>-</td>
<td>Cu</td>
<td>Cu</td>
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<tr>
<td>Cathode quantum eff.</td>
<td>$QE$</td>
<td>2</td>
<td>0.4</td>
<td>$10^{-5}$</td>
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<tr>
<td>Commissioning duration</td>
<td>-</td>
<td>8</td>
<td>5</td>
<td>mo</td>
</tr>
</tbody>
</table>
LCLS Installation and Commissioning Time-Line

- Drive-Laser Commissioning
- Controls Checkout
- LTU/und. Install
- First Spont. Light
- LTU/und. hall “ready”
- Linac/BC2 Commissioning
- Gun/Inj./BC1 Install (8/21 – 2/20)
- Gun/Inj./BC1 Commissioning
- Linac/BC2 Install
- Oct. 18, 2006
“X-ray Free Electron Laser, XFEL”
National Project of Next-Generation Light Source

RIKEN-JASRI Joint-Project Team for SPring-8 XFEL Construction
SCSS: SPring-8 Compact SASE Source

- Low Emittance Injector ➔ Short Saturation Length
- High Gradient Accelerator ➔ Short Accelerator Length
- Short Period Undulator ➔ Lower Beam Energy 
  Short Saturation Length

Kitamura’s In-Vacuum Undulator: $E = 1\text{GeV}$, $\lambda_u = 15\text{ mm}$, $\lambda_x = 3.6\text{ nm}$
SCSS Test Accelerator

- C-band Accelerator
- 50 MW Klystron x 2
- Acc Structure 1.8 m x 4
- 250 MeV

- Undulator 4.5 m x 2 unit
- 15 mm period
- 4 mm gap
C-band Accelerating Structure for SCSS

- HOM Damping by Choke-Mode Cavity
- 1.8 m long, 91 Cells, CG-structure
- $3\pi/4$-mode
- Brazing Bonding
- SiC by Tungsten wire-spring.
- Double-feed Coupler
- High-power test will be Summer 2003
CeB$_6$ Cathode & Heater Assembly

- CeB$_6$ Cathode 3 mm Diameter
- Emittance 0.4 $\pi$.mm.mrad (thermal emittance, theoretical)
- Beam Current 3 Amp. at 1450 deg.C (using graphite heater)
- Current Density $> 40$ A/cm$^2$
CeB₆ Thermionic Gun provides stable beam.
First Lasing at SCSS Prototype Accelerator.

- The first lasing: 49 nm
- E-beam energy: 250 MeV
- Bunch charge: 0.25 nC
- Bunch length: (< 1 pse)
- Peak Current: (> 300 A)

At moment spectrum width 0.5 nm is dominated by e-beam energy fluctuation ~ 0.2%.
First Lasing at SCSS Prototype Accelerator.

- The first lasing: 49 nm
- E-beam energy: 250 MeV
- Bunch charge: 0.25 nC
- Bunch length: (< 1 pse)
- Peak Current: (> 300 A)

- Laser pulse length has not yet measured, (will be ~ 100 fsec).
- Peak power estimation assumed 1 psec width.
Q-scan Emittance Measurement

- Q-magnet provide horizontal focusing.
- From image width emittance is estimated.
- (~ 100 micron-meter)
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Prototype</th>
<th>X-ray FEL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam Energy</td>
<td>$E$</td>
<td>0.25</td>
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<tr>
<td>X-ray Wavelength</td>
<td>$\lambda$</td>
<td>60</td>
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<tr>
<td>Beam Emittance</td>
<td>$\varepsilon_n$</td>
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</tr>
<tr>
<td>Bunch Length</td>
<td>$\Delta z$</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>FWHM</td>
<td>0.3</td>
</tr>
<tr>
<td>Transverse Beam Size</td>
<td>$\sigma_{x,y}$</td>
<td>100</td>
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<tr>
<td>Peak Current</td>
<td>$I_p$</td>
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</tr>
<tr>
<td>Charge per bunch</td>
<td>$q$</td>
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<tr>
<td>Undulator Parameter</td>
<td>$\lambda u$</td>
<td>15</td>
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<tr>
<td></td>
<td>$K$</td>
<td>1.3</td>
</tr>
<tr>
<td>Length</td>
<td>$L$</td>
<td>10</td>
</tr>
<tr>
<td>FEL Saturation Length</td>
<td>$L_{sat}$</td>
<td>20</td>
</tr>
</tbody>
</table>
• 2006 April, Funding was made, 300 M$
  \text{ injector, accelerator, one undulator line, user lines, infrastructure.}$

• 2007 June, Construction of tunnel started
• 2007 June, Production of the accelerating cavity started.

• Beam commissioning will start in end of FY2010
Tunnel Construction started June 2007

- Accelerator tunnel, on surface.
- Site length 700 m
RF Acceleration System in 8 GeV SPring-8 XFEL

- Gun: 238 MHz, 476 MHz
- Injector: L-band
- BC-0: 50 MeV
- BC-1: 450 MeV
- BC-2: 1.5 GeV
- BC-3: 4.5 GeV
- BC-4: 8 GeV

- S-band: Klystron 64, Acc. Str. 128, 6 GeV
- C-band: (1-16)
European XFEL Project Status and Industrialisation Programme

R. Brinkmann, DESY

for the XFEL team
Introduction


Approval by German government Feb. 2003 as European Project

Commitment for 50% of funding + 10% by Hamburg & Schleswig-Holstein, 40% European & international partners

TESLA XFEL
First Stage of the X-Ray Laser Laboratory
Technical Design Report Supplement

October 2002
Introduction cont’d

TESLA Test Facility and the VUV-FEL:

- Pilot facility regarding practically all aspects (accelerator technology, beam physics, FEL process, user operation) of the XFEL
- Test bed for technical developments specifically required for the XFEL
- Injector development at PITZ, DESY-Zeuthen
New technologies for new science: Soon X-ray free-electron lasers will enable us to probe ultrafast physical, chemical and biochemical processes at atomic resolution, opening new frontiers for science and technology. At long last we may see, and not just model, how molecular machines really work.
Properties of XFEL radiation

X-ray FEL radiation (0.2 - 14.4 keV)
- ultrashort pulse duration <100 fs (rms)
- extreme pulse intensities $10^{12}$-$10^{14}$ ph
- coherent radiation $\times 10^9$
- average brilliance $\times 10^4$

Spontaneous radiation (20-100 keV)
- ultrashort pulse duration <100 fs (rms)
- high brilliance
The European X-Ray Laser Project

On-going programme:
- increase the gradient on the cathode from 40 MV/m to 60 MV/m
- further improve the transverse and longitudinal laser profile (collab. Max-Born Institute, Berlin)
- PITZ gun now part of FLASH injector

Design value at XFEL undulators (0.9 from gun)
The superconducting linear accelerator

The electron injector section is followed by five 12-meter-long accelerator modules containing eight superconducting cavities each. The cavities are made from pure niobium and consist of nine cells. An important property of superconductors is that their resistance does not vanish in alternating electromagnetic fields, in contrast to the direct current case. In a microwave cavity the oscillating magnetic field of the RF wave penetrates into the superconductor to a depth of about 50 nm and induces forced oscillations of those electrons which are not bound in superconducting pairs. The microwave surface resistance is many orders of magnitude smaller than in normal copper cavities but is nevertheless responsible for non-negligible Ohmic heat generation at the inner cavity surface. The heat must be guided through the cavity wall into the liquid-helium bath. It constitutes a significant heat load on the helium refrigerator.

The exponential dependence of the resistance on temperature, predicted by the Bardeen-Cooper-Schrieffer (BCS) theory, is observed over a wide temperature range. Below 2 K one observes a residual resistance of a few nΩ caused by surface impurities. In the XFEL an accelerating field of more than 15 MV/m is needed to reach an FEL wavelength below 0.1 nm. Although the quality factor exceeds the excellent value of $10^{10}$, the RF energy dissipation in the cavity walls would be far too large for the liquid-helium plant if the cavities were operated in continuous mode. The necessary reduction of the cryogenic load by about a factor of 100 is the only – and unfortunate – reason to operate the cavities in pulsed mode with a duty cycle of 0.01.

Preparation of the superconducting cavities in the DESY cleanroom:
A string of eight cavities, each welded into its own liquid-helium tank, is being assembled and prepared for installation in an acceleration module. On the right: a single nine-cell cavity equipped with vacuum flanges and a radio-frequency input coupler for the performance test in a liquid-helium bath cryostat.
Alternative fabrication – large grain Nb

Fabrication from large-grain Niobium – cut sheets directly from ingot (method pioneered at JLAB)

After initial good results with single cells, fabricated and tested three 9-cell cavities – only BCP-treated, no EP!

→ Will build 6 more cavities, possibly alternative fabrication/treatment procedure
→ Could later choose the more economic method for industrial production
Overall layout of the European XFEL

3.4km
Accelerator technology - collaborative effort

Industrial study module assembly (M6 done, M8 autumn 2007)

2 more cryostats (TTF3/INFN) delivered

Superferric magnet (CIEMAT)

BPM (Saclay)

Integrated HOM absorber

Length quantized $n\cdot \lambda/2$ (possibility of ERL)

TTF3-type coupler

Industrialization launched (Orsay)

Tuner w/piezo (Saclay)

Industrialization in preparation

LLRF development (collab. Warsaw/Lodz)
The European X-Ray Laser Project

High Power RF System
(Modulator, Pulse Cable, Pulse Transformer, Klystron)

L1 10 kV  S1
1400 µF
80Ω
MOV
100 µF
C2
2 mF
L2
330 µH

CHARGING
3 H
70 kJ
1400 µF
100 µF
MOV

HV Power Supply
Capacitor Bank
Bouncer
XFEL site in Hamburg/Schenefeld
... after construction (computer simulation)
 XFEL Radiation Characteristics

• High Peak Power ~ GW
  → high field non linear physics
  → high flux photons for single shot diffraction imaging
    single molecular structural analysis

• Short Pulse 10 ~ 100 fsec
  → Time resolving experiment (Pump probe)
    Chemical reaction

• Coherent
  → Holography, Coherent Imaging
A NEW MICROSCOPIC PRINCIPLE

By Dr. D. GABOR
Research Laboratory, British Thomson-Houston Co., Ltd., Rugby

It is known that the spherical aberration of electron lenses sets a limit to the resolving power of electron microscopes at about 5 Å. Suggestions for the correction of objectives have been made; but these are difficult in themselves, and the prospects of improvement are further aggravated by the fact that the resolution limit is proportional to the fourth root of the spherical aberration. Thus an improvement of
Dream of X-ray Microscope for single molecular imaging

  
  ~ No coherent light source was available for 10 years.

- 1957, Laser was invented: C. Townes and A. L. Schawlow
- 1960, The first working laser was made by T. H. Maiman

- 1963, 3D Hologram was made by E. N. Leith and J. Upatnieks Twin-image problem was solved.

- 1970’s X-ray holography was studied theoretically

  ~ No intense coherent X-ray source was available for 30 years.

- 2000~ VUV laser 90 nm was realized by SASE FEL at DESY TTF.
- 20XX 3D single molecular imaging
Problems in Holographic Imaging using X-ray

- It becomes hard to obtain **spherical reference wave** at X-ray wavelength with enough NA (Numerical aperture).
- **Speckle** on reference wave dominates image quality.
- Fresnel diffraction lens or X-ray mirror **limit NA small**, thus resolution is limited.

- **Eliminate Reference Wave** → **Diffraction Microscopy**
  - Direct phase retrieval on object Wave
  - XFEL provides high peak power and highly coherent beam, thus high quality object wave.
X-ray Diffraction Microscopy
- historical background -

- Possibility of Phase Retrieval by Oversampling X-ray Diffraction Pattern

- Iterative Phase Retrieval Method

- Concept of X-ray Diffraction Microscopy for Non-Periodic Objects

- Experimental Demonstrations

- Image Reconstruction Exclusively from X-ray Diffraction Data

- Single Shot Experiment
Multilayer mirror:

Si, Mo, and B₄C, gradually increasing from 18 nm to 32 nm period. Variation matches angle of incidence (30° to 60°) to maintain Bragg condition for $\lambda = 32$ nm.

Reflectivity: 45% over the surface for 32 nm.

The mirror protects the CCD and works as a (i) bandpass filter (bandwidth = 9 nm at 45°) (ii) filter for off-axis stray light (1% reflectivity)
Image Reconstructed from an Ultra-Fast (25 fs) FEL Diffraction Pattern at **FLASH**

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Starting Image (etched into silicon nitride film)

1st shot diffraction pattern before destruction

Reconstructed Image

The 20-μm-wide square film was destroyed by the laser pulse, but a computer algorithm reconstructed the original image from the diffraction pattern.

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H. Chapman, J. Hajdu

Reconstruction by A. Barty, Feb. '06

\[ \lambda = 32 \text{ nm} \]
X-ray free-electron lasers may enable atomic-resolution imaging of biological macromolecules.

One pulse, one measurement

Particle injection

10-fs pulse

Noisy diffraction pattern

Combine $10^5 - 10^7$ measurements

Classification

Averaging

Orientation

Reconstruction

H. Chapman
• XFEL technology will provide powerful probe to look into atomic scale structure and femto-sec time frame evolution, which will contribute in material science, nanotechnology, and biology, etc.

• XFEL technology development will also provide feedback into future accelerators, including ILC.

• There are many technical challenges, waiting your contributions. Thank you!