Current Status of X-ray FEL Project at SPring-8

Tsumoru Shintake

For Joint XFEL/SPring-8 Team
May 09 2009

SPring-8
Operating ten years

XFEL/SPring-8
Building construction completed March 2009

SCSS Test Accelerator
Since 2006, EVU user facility
**Concept of XFEL/SPring-8**

1) **Electron gun**  
   - **Low emittance** ($\varepsilon_N \sim 0.7\pi$ mm*mrad)  
   - Higher electron density at the undulator.

2) **C-band accelerator**  
   - **High gradient** ($E_a \sim 35$ MV/m)  
   - Compact accelerator.

3) **In-vacuum undulator**  
   - **Short period** ($\lambda_u \sim 18$ mm)  
   - Shorter wavelength with lower electron energy.
SCSS to XFEL/SPring-8 Timeline

- **2001~2003** SCSS R&D  CeB₆ thermionic gun  
  \[0.6 \pi \text{mm.mrad @ 1 A DC, 500 kV}\]

- **2004~2005** **SCSS Test Accelerator** Construction

- **2006 June**  First Lasing 49 nm at test accelerator.

- **2007 Oct.**  Saturation at 50~ 60 nm  
  \[0.7 \pi \text{mm.mrad @ 300 A, 0.7 psec, 250 MeV, 0.3 nC}\]

- **2006 April**  **XFEL/SPring-8 Construction** was funded.  
  Beam optics design. Technical design.  
  2007 Technical design, contract.

- **2008**  Mass-production of hardware components.

- **2009 March**  Linac, Undulator hall building completed.  
  Hardware installation.

- **2010 Oct.**  High power processing 8 GeV accelerator.

- **2011 April**  Beam commissioning. First lasing at 1 A.

- **X 300 Compression**

- **X 10 Compression**

- **0.8 \pi \text{mm.mrad @ 3k A, 8GeV}**
Single-crystal CeB$_6$ Cathode for the SCSS Low-emittance Injector

No HV breakdown for 4 years daily operation

After 20,000 hours operation 1 crystal changed.

Diameter : $\phi 3$ mm
Temperature : $\sim 1500$ deg.C
Beam Voltage : 500 kV
Peak Current : 1 A
Pulse Width : $\sim 2 \mu$s
Use Small Size Cathode
...First Strategy for smaller thermal emittance

- **Thermionic cathode**
  
  **3mm** diameter cathode (CeB6) is used in a low emittance injector. (SCSS SPring-8/RIKEN)
  
  Operating Temperature 1450°C
  
  \[
  w_e = \frac{3}{2} k_B T = 223 \text{ meV}
  \]

  Thermal Emittance
  
  \[
  \varepsilon_{xN} = \frac{\gamma r_c}{2} \sqrt{\frac{k_B T}{m_0 c^2}} = 0.4 \pi \text{ mm-mrad}
  \]

- **RF photo-cathode injector.**
  
  Today’s RF photo injectors use ~ 1 mm spot radius.
  
  \[
  \varepsilon_{xN} = \frac{\gamma r_c}{2} \sqrt{\frac{k_B T_e}{m_0 c^2}} = 0.35 \pi \text{ mm-mrad}
  \]

  \(T_e\) is “measured” effective electron temperature of copper cathode using 266 nm laser (ref. 2). \(k T_e = 0.27 \text{ eV} \ (2360°C)\).
SCSS Test Accelerator Performance

- 2006 First lasing at 49 nm
- 2007 Full saturation at 60 nm
- 2008 User operation stat

**E-beam**
- Charge: 0.3 nC
- Emittance: 0.7 π.mm.mrad (measured at undulator)

**In-Vacuum Undulators**
- Period = 15 mm, K=1.3
- Two 4.5 m long.

**476 MHz booster**

**S-band buncher**

**C-band accelerator**

**In-vacuum undulator**

**238 MHz buncher**

**500 kV Pulse electron gun**
- CeB6 Thermionic cathode
- Beam current 1 Amp.

**520 MHz buncher**

**S-band**

**C-band**

**In-vacuum**

**accelerator**
CeB₆ Thermionic Gun provides stable beam.

Beam Profile
CCD Image
Scale 10 mm

500 kV Gun

50 MeV Injector Out

250 MeV Compressor
Undulator Input
Undulator Output
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.
Japanese Latecomer Joins Race To Build a Hard X-ray Laser

X-ray free-electron lasers are the next big thing in high-energy probes of matter. With U.S. and European machines in the works, Japan wants into the club.

SAYO, HYOGO PREFECTURE, JAPAN—It’s the scientific version of keeping up with the Joneses. Once researchers in one region plan a big, new experimental device, researchers everywhere want their own. The latest example: x-ray free-electron lasers (XFELs), which promise beams that are vastly brighter and with higher energy and shorter pulses than today’s workhorse synchrotron x-rays.

These “hard” x-ray wavelengths—down to 0.1 nanometer—promise to reveal the structure of proteins, the motions of molecules, and the precise times of chemical reactions. As a result, they have captured the broad interest for science, it is no surprise that [researchers] in three regions of the world want to have a facility of their own,” says Reinhard Brinkmann, who leads the European effort based at the German Electron Synchrotron (DESY) research center in Hamburg. “Free-electron lasers are amazing things which herald a new era in photon science,” says Janos Hajdu, a synchrotron radiation specialist at Uppsala University in Sweden.

XFELs rely on new approaches to generating or oscillating in lockstep—a quality missing from synchrotron light.

Although all three planned systems share the same basic setup, subtle differences give each of them strengths and weaknesses. “The final targets of the XFEL projects are the same, but the means are different,” says Tsumoru Shintake, who heads accelerator development for Japan’s XFEL.

The first project to come online will be Stanford’s LCLS. Much of the key research underpinning XFELs was done at SLAC beginning in the early 1990s. And SLAC got a head start by using a 1-kilometer stretch of its now-idled linear accelerator, or linac. The SLAC group estimates that reusing its linac has saved more than $300 million, giving a total construction cost of $379 million. LCLS will have one undulator providing hard and soft x-rays to up to six experimental stations. Galayda says the group expects to generate its first x-rays by July 2008 and to start experiments by March 2009.

Japan’s entry is the SPring-8 Compact SASE Source (SCSS), just now getting under construction here. Latecomers to the field, the team is using some homegrown technology to cut cost and size. “We’re taking the first step toward making XFELs smaller and cheaper so more [institutions] can consider developing their own,” boasts SCSS project leader Tetsuya Tsumorake. Whereas the other two machines will generate electrons by firing a laser at a metal target, the SCSS heats a cathode to produce electrons. Eliminating the laser simplifies the system but requires careful compression of the cloud of electrons before they go into the linac.

The wavelength of the output x-rays is a tradeoff between the energy of the electrons and the number of photons generated. At the high-energy end, the wavelength is short, but the photon flux is low. At the lower energy end, the wavelength is long enough to probe many biological structures, but the flux is higher. The advanced status of a project can be seen in the planned energy range of its XFEL output: 20 teraelectronvolts (TeV) and up for SLAC, 1.5 to 10 TeV for LCLS, and 0.5 to 6 TeV for SPring-8.

With U.S. and European machines in the works, Japan wants into the club.
First Lasing at SCSS Prototype Accelerator.

- The first lasing: 49 nm
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- Bunch charge: 0.25 nC
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SCSS Test Accelerator User Run Has been Started in 2008

- 50~60 nm, 30 µJ/pulse
- Multi-photon absorption
- Coherent diffraction imaging
- etc.
Peak Brilliance Evolution

- 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.
Undulator

Electron Beam

Magnetic Field

X-ray Radiation

Permanent Magnets
Freeware Radiation2D is available at http://ShintakeLab.com
From SR to FEL

**SR or ERL**
- Spontaneous Radiation
  - \( E_{spt} \sim \sqrt{N} E_1 \)
  - \( P_{spt} \sim N P_1 \)
- N-electrons random distribution

**FEL: Free Electron Laser**
- Coherent Radiation
  - \( E_{coherent} \sim N E_1 \)
  - \( P_{coherent} \sim N^2 P_1 \)
- N-electrons micro-bunched

Optical Power Enhancement
\[ x 10^5 \sim 10^8 \]
• Undulator field produces **curved trajectory**. From this slope, the tangential component of EM wave creates **longitudinal field**.

\[ E_{//} = E \sin(\alpha) \sim 1/\gamma \]

\[ E_{//} \text{ creates micro-bunching.} \]
Shot Noise
Seedin

Exponential Signal Amplification
Saturation

Seeding or Infinitely Long Undulator

FEL Power

Distance Along Undulator

T. Shintake
2007.01
Basic Machine Layout of XFEL/SPring-8
## Expected Performance of XFEL/SPring-8

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength</td>
<td>&lt; 0.1 nm</td>
</tr>
<tr>
<td>Peak Power</td>
<td>~ 20 GW</td>
</tr>
<tr>
<td>X-ray Pulse Length</td>
<td>200 fs ~ 20 fs</td>
</tr>
<tr>
<td>X-ray Pulse Energy</td>
<td>Max 0.4 mJ</td>
</tr>
<tr>
<td>Photon Flux</td>
<td>$2 \times 10^{11}$ p/pulse</td>
</tr>
<tr>
<td>Peak Brightness</td>
<td>$1 \times 10^{33}$ p/mm$^2$/mrad$^2$/0.1% BW</td>
</tr>
<tr>
<td>X-ray Pulse Repetition</td>
<td>10 ~ 3000 pps (50 bunch x 60 Hz)</td>
</tr>
<tr>
<td>Bunch per Pulse</td>
<td>1 ~ 50 (4.2 nsec spacing)</td>
</tr>
<tr>
<td>e Beam</td>
<td>8 GeV x 0.3 nC 0.8 $\pi$mm.mrad, 3 kA</td>
</tr>
</tbody>
</table>

![Expected X-ray pulse of 0.1 nm (SIMPLEX simulation)](chart.png)
RF Acceleration System in 8 GeV SPring-8 XFEL

Gun 238 MHz 476 MHz L-band

50 MeV

s1 S-band s4 450 MeV

BC-0

BC-1

2 GeV

C-band Sector-1

1.5 GeV

BC-2

c1-12

c1-16

C-band Sector-2

C-band Sector-3

C-band Sector-4

4 GeV

Klystron 64
Acc. Str. 128
6 GeV

8 GeV
To Undulator
C-band is High Gradient (35 MV/m, max 40 MV/m)

- Modulator + Control Cabinet have to fit within 3.9 m each.
  → Need to make “Compact Modulator”
- High packing efficiency = Active Length/Actual Length
  \[
  \frac{(1791 \times 8)}{(15462+806)} = 0.88 \quad \text{(Active 35 MV/m -> Average 30 MV/m)}
  \]
C-band System Configuration

400 V, 3φ

C-band Klystron

DCF 600V

PFN 50 kV

25 kV, 5000 A

50 MW, 3 usec
RF 5712MHz

Klystron Modulator

Highly stable PFN charger < 100 PPMp-p

DC 600V → DC 50 kV

PFN 50 kV

50 kV, 1 A

25 kV → 350 kV

C-band Accelerator
35 MV/m

600V, 80 A

50 MW

75 MW

RF Compression

Klystron Voltage

50 MW RF

150 MW RF
Single Tank Modulator (PFN circuit + Transformer)
Compact Modulator for 50 MW Klystrons

- Output Power 50 MW RF x 60 pps
- 50 kV PFN, 1:16 Trans, 350 kV klystron.
- Compact 1 m x 1 m x 1.5 m,
- Very low noise
  (<10 Vpp on 200 V heater line)
- Water cooled. Max surface temp 45 deg.
Modulator Mass Production at NICHICON

70 modulators
Mass-production of 70 Modulators for Klystron at NICHICON
Modulators are Arriving to XFEL/SPring-8
All modulator are tested with high power at 50 kV, 60 pps, 8 hour before installation.
Installed modulator to klystron gallery, waiting WG connection.
Mass Production of Klystrons at TOSHIBA

- 64 C-band klystron
- 4 S-band klystron
- 1 L-band klystron

C-band Klystron
5712 MHz, 50 MW
4 μsec, 60 pps
45 % efficiency
Three-cell traveling wave output
how the cloud of electrons whizzing around an atom’s nucleus gets arranged by the forces of attraction to the nucleus and repulsion from other electrons. These extremely excited atoms may themselves be harnessed to make a unique laser.

Plasmas are hot, dense soups of ionized atoms—atoms missing electrons—and free electrons. Scientists need high-density plasmas in the attempt to make fusion energy. LCLS’s x-rays will be able to pass through these plasma “pellets” to scrutinize their nature and behavior.

A type of plasma called warm dense matter is believed to exist inside proto-stars and giant planets like Jupiter, accounting for much of the universe’s matter. LCLS will create and probe this extreme state of matter to further study the universe.

**Nanoscale Dynamics**

Electronic devices, computer chips, and the liquid crystal displays on digital watches already use nanoscale materials. These materials are only billionths of a meter in size and have specially designed properties.

Building machines and computers from components containing only a few thousand atoms has moved from a daydream to a real endeavor. LCLS will observe these nanomachines in action to see how forces like magnetism affect each part in a material, how large-scale characteristics like viscosity result from the motion of individual molecules, and other dynamics that happen on ultra-fast time scales.

As engineered materials continue to get smaller and faster, LCLS will provide the data to build better technology.

*With its fast “shutter” speed and super brightness, LCLS could take pictures of an important class of proteins that cannot be x-rayed any other way.*

Operating with ultrafast pulses, LCLS will take images of molecules dropped into the x-ray beam. Scientists will merge the series of diffraction patterns of the molecules in many different positions. The resulting three-dimensional reconstruction will reveal the structures of proteins that cannot be crystallized and thus studied any other way.
C-band Accelerator for Multi-bunch Option


13,000 cells are under mass production.

Higher Order Mode Damping for Multi-bunch operation. Maximum 50 bunches x 1 nC, at 4.2 nsec spacing

X-ray 4.2 nsec x 50 bunches will be key for Single bio-molecule imaging to improve Luminosity.

Sadao Miura, MITSUBISHI Heavy Ind, April 20
HITACHI Cable Co. completed mass production of C-band cell. June 2009

We made 13,000 pieces of C-band accelerator cell.
Mass Production of C-band Accelerator at MITSUBISHI Heavy Ind. 2007 ~ 2009

Laser Guided Precision Machining
MITSUBISHI-Team completed 100 tubes (out of 128) C-band Accelerator. Photo March 2009
Routinely Operation: C-band High Gradient Test

- Sample test from mass production.
- C-band 1 unit for one month.
- **35 MV/m** is routinely achieved.
  (Very low trip rate.)
- Processing up to 40 MV/m, 60 pps.

T. Sakurai, PAC2009
Beam Monitor Devices

By Y. Otake team.

Cavity BPMs 0.2 μm resolution was confirmed with beam...
COM-Free BPM

TM010 mode does not couple out to pickup antenna. will be used for C-band Accelerator Alignment
Control rack installation started, from downstream.
VME MADCA control, Digital RF, C-band driver amp., water temp control.
Thanks to extensive effort by Mitsubishi Electric TOKKI System, etc.
SP-8 XFEL Undulator Line

- GV, PM, CT, BPM
- Focusing Q
- Phase Shifter
- Steering Coils

18 Undulator Segments

- Drift Section
  - GV, PM, CT, BPM
  - Focusing Q
  - Phase Shifter
  - Steering Coils
Undulator is ready for mass production.
## Undulator Parameter

<table>
<thead>
<tr>
<th>Undulator Type</th>
<th>In-Vacuum Planer Undulator</th>
</tr>
</thead>
<tbody>
<tr>
<td>Active Length</td>
<td>5 m</td>
</tr>
<tr>
<td>Undulator Period</td>
<td>18 mm</td>
</tr>
<tr>
<td>Magnetic Circuit</td>
<td>Hybrid (NdFeB+Permendur)</td>
</tr>
<tr>
<td>Peak Field</td>
<td></td>
</tr>
<tr>
<td>Maximum</td>
<td>1.31 T</td>
</tr>
<tr>
<td>Nominal</td>
<td>1.13 T</td>
</tr>
<tr>
<td>K</td>
<td></td>
</tr>
<tr>
<td>Maximum</td>
<td>2.2</td>
</tr>
<tr>
<td>Nominal</td>
<td>1.9</td>
</tr>
<tr>
<td>Gap</td>
<td></td>
</tr>
<tr>
<td>Minimum</td>
<td>3.5 mm</td>
</tr>
<tr>
<td>Nominal</td>
<td>4.5 mm</td>
</tr>
<tr>
<td>Maximum Attractive Force</td>
<td>~ 6 ton</td>
</tr>
</tbody>
</table>
Undulator for XFEL/SPring-8

Outlook of 5 m long in-vacuum undulator for X-ray FEL.

NeFeB magnet array, undulator period is 18 mm.
Field Measurement System: SAFALI

- SAFALI: Self-Aligned Field Analyzer with Laser Instrumentation
- Laser guiding positioning system in the vacuum chamber, which carries hole probe for magnetic field measurement.
Can we run our XFEL/SPring-8 at 1 kHz repetition?

Rep rate is determined by the heat loading on every component over the entire machine.

\[ P_{\text{wallplug}} \propto f_{\text{rep}} \times G^2 \]

Machine 5 MW
Facility 10 MW

Using C-band, our machine can run 40 MV/m at 60 Hz, provides 8 GeV and 1 Angstrom X-ray at 60 pps.

Scale down to lower gradient.

\[ G = 40 \text{ MV/m} \rightarrow 10 \text{ MV/m} \]
\[ G^2 \quad 1 \rightarrow 1/16 \]
\[ f_{\text{rep}} \quad 60 \text{ Hz} \rightarrow 60 \times 16 = 960 \text{ Hz} \approx 1 \text{ kHz} \]

Using C-band, we can run 10 MV/m at 1 kHz, which will provide 2 GeV, 1.6 nm, Soft-X-ray.
Summary

- So many different efforts are coherently contributing to the project. They are almost on the time schedule.

- Building construction has been completed.
- Accelerator component installation has been started.
  ~ 1 year installation.

- October 2010, We start high power operation of accelerator.
- Spring 2011, we start beam commissioning.
Who is Shintake?

- Date of Birth 1955, Miyazaki, Kyushu Japan
- 1992~1996 FTFB – SLAC “Spot Size Monitor” (Shintake Monitor) 60 nm e with 1 μm wave
- 1996~2000 “C-band R&D” for LC at KEK 5 cm wave.
- 2000~2006 SCSS R&D Leader e- beam
- 2006 First Lasing at SCSS Prototype Accelerator 49 nm wave
- 2006~Now constructing 8 GeV XFEL/SPring-8 for 0.1 nmm wave
中学

50cc オートバイ、エンジン
カート作り走り回る。
道路に出て、本物の車との差を痛感！

アンテナ

電波（ノイズ）

マルコーニの実験、再現
ラジコンボート
春の田んぼ、水面走る。
Design accelerator as creating images like art
Klystron Modulator for
C-band, S-band 50 MW Klystrons
Nanometer Beam Size Measurement

e+e- Linear Collider R&D

Spot-size Monitor based on Laser Interferometry

T. Shintake 1990
Experimental Test at FFTB

SLAC Two-mile Accelerator & FFTB

Laser Interferometer Table

2-mile Linac (3.2 km)

KEK-Kawasaki
Before XFEL

1996~2000  C-band R&D at KEK

C-band accelerator runs at 37 MV/m

1992~1996  FFTB at SLAC

Laser interferometer for Spot size measurement.
Technology transfer

Year of 2000 ~

KEK C-band

High energy e+e- collider

SPRING-8 XFEL

Photon Science