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

Tsumoru Shintake

For Joint XFEL/SPring-8 Team
SPring-8
Operating ten years

XFEL/SPring-8
Building construction completed March 2009

SCSS Test Accelerator
Since 2006, EVU user facility
SCSS to XFEL/SPring-8 Timeline

• 2001~2003 SCSS R&D  CeB₆ thermionic gun  0.6 $\pi$.mm.mrad @ 1 A DC, 500 kV
  X 300 Compression
• 2004~2005 SCSS Test Accelerator Construction
• 2006 June  First Lasing 49 nm at test accelerator.
• 2007 Oct.  Saturation at 50~60 nm  0.7 $\pi$.mm.mrad @ 300 A, 0.7 psec, 250 MeV, 0.3 nC
  X 10 Compression
• 2006 April  XFEL/SPring-8 Construction was funded. Beam optics design. Technical design. 0.8 $\pi$.mm.mrad @ 3k A, 8GeV
  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.
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: ~1500 deg.C
Beam Voltage: 500 kV
Peak Current: 1 A
Pulse Width: ~2 $\mu$s
Basic Machine Layout of XFEL/SPring-8

- **Beam energy (MeV)**
- **Time (ps)**
- **Peak current (A)**
- **Beam energy**
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 x 10^{11} p/pulse</td>
</tr>
<tr>
<td>Peak Brightness</td>
<td>1 x 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 \text{mm.mrad}, 3 kA</td>
</tr>
</tbody>
</table>

![Expected X-ray pulse of 0.1 nm (SIMPLEX simulation)](image)
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
  = (1791 x 8) / (15462 + 806) = 0.88  (Active 35 MV/m -> Average 30 MV/m)
C-band System Configuration

400 V, 3φ

Klystron Modulator

600V, 80 A

Highly stable PFN charger < 100 PPm-p

DC 600V → DC 50 kV

PFN 50 kV

25 kV, 5000 A

50 kV, 1 A

25 kV → 350 kV

C-band Klystron

50 MW, 3 usec

RF 5712MHz

C-band Accelerator

35 MV/m

50 kV, 1 A

Klystron Voltage

50 MW RF

150 MW RF

RF Compression

150 MW

75 MW

75 MW

50 MW RF

75 MW
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.
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 nanochines 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.

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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.

Sadao Miura, MITSUBISHI Heavy Ind, April 20

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

Cavity BPMs
0.2 μm resolution was confirmed with beam

By Y. Otake team.

OTR Radiator
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

Electron Beam

Bending Magnet

Undulator Lines

Experimental Stations

FEL light

~110 m

1.2 m

5 m

~110 m

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 Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Undulator Type</td>
<td>In-Vacuum Planer Undulator</td>
</tr>
<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>
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</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>
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<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.
\[ G = 40 \text{ MV/m} \rightarrow 10 \text{ MV/m} \]
\[ G^2 = 1 \rightarrow 1/16 \]
\[ f_{\text{rep}} = 60 \text{ Hz} \rightarrow 60 \times 16 = 960 \text{ Hz} \approx 1 \text{ kHz} \]

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.