Introduction of Japanese X-FEL

Yuji Otake, RIKEN, XFEL project
Location, Where is X-FEL (RIKEN, HARIMA)

Located 600 km west of Tokyo.
Configuration of Japanese X-FEL

- Thermionic Electron Gun
- Conventional LINAC
- In-Vacuum Undulators
- Beam Dump
- Magnet Chicane
- C-band Accelerator
- Magnet Chicane
- In-Vacuum Undulators
- Beam Dump

- 800 m
- 60 m
- 250 MeV prototype accelerator

- Electron Beam
- Bunching
- Beam Dump
- X-FEL
In the case of the prototype accelerator

- We have confirmed feasibility of:
  1. 500 kV CeB6 Thermionic Electron Gun
     (Small Emittance (less than $2\pi$ mm mrad) and Dark Current),
  2. C-band high gradient acceleration
     (High Gradient Acceleration (more than 35 MV/m)),
  3. Acceleration stability & a peak current (1 kA) for lasing.
## Summary of Machines

<table>
<thead>
<tr>
<th></th>
<th>Prototype</th>
<th>X-FEL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam Energy (MeV)</td>
<td>250</td>
<td>8000</td>
</tr>
<tr>
<td>Peak Current [A]</td>
<td>800</td>
<td>3000</td>
</tr>
<tr>
<td>Normalized Emittance ((\pi\text{mm.mrad}))</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Electron Beam Brightness ((A/\pi^2\text{mm}^2\text{.mrad}^2))</td>
<td>200</td>
<td>3000</td>
</tr>
<tr>
<td>総電荷量 (nc)</td>
<td>0.2~0.3</td>
<td>0.2~1</td>
</tr>
</tbody>
</table>
Beam Transport of the SCSS Prototype & 8GeV Injector Accelerator

![Graph showing RMS beam size over Z (m) with markers for S-APS, S-TW, L-APS1, and L-APS2.]
Thermionic Electron Gun

1. Steering
2. Magnetic Lens
3. Vacuum Valve
4. CT monitor
5. CT monitor
6. Steering
7. Deflector
8. Collimator
9. Steering
10. Magnetic Lens
11. Temp. Meter

Input Pulse
Cable Connector
Dummy Tube
Oil-filled Pulse Tank
HV Bushing
CeB₆ Cathode
Pulse Transformer

Company Name
Electron Gun Detail

- **CeB₆ cathode**
- **Graphite Sleeve**
- **Graphite Heater**
- **SiN Ceramic Base**
- **Molybdenum Current Lead**

**CeB₆ Single Crystal φ3mm**

**Cathode Temperature**

~ 1450°C

Measured with the Radiation Thermometer graphite sleeve

**High Voltage Pulse Wave Form**

1 μs, 500 KV

**Voltage** 500kV

**Emission Density (A/cm²)**

![Graph showing emission property vs. temperature](image)

**V**oltage  500k**V**
Beam from Electron Gun

Beam Profile

Phase Space Distribution

Screen (100μm) at 3.5 m from the electron gun (Fluorescence)

Projected Emittance: $1.1\pi$ mm mrad

2 ns beam width produced with the high voltage deflector
C-band (5712MHz) Accelerator

RF Pulse Compressor SLED

150 MW peak more

Cross-section of the accelerator guide

Total Length : 1.8m
Weight : 200kg
Cell Number : 89
+2 coupler cell
Acceleration Mode : $3\pi/4$

C-band Choke Mode Accelerator Guide

37 MV/m Achieved

Company Name
In-Vacuum NdFeB Undulator

- **Movable Gap**
- **Magnet Unit** (period, about 15 mm)
- **Magnetic field alignment** (Phase)

### Specifications
- \( \lambda_u : 15 \text{ mm} \)
- Length/Segment : 4.5 m
- Number of Periods : 300
- Gap : Max. 35 mm, Min. 2 mm, Nominal 3.5 mm
- K Value : Max. 1.8, Min. 1.3
Low-Level RF System of SCSS Prototype Accelerator

PSK Operation for SLED

- Carrier Signal
- 238 MHz
- 476 MHz
- 2380 MHz
- 2856 MHz
- 5236 MHz
- 5712 MHz

- Master Oscillator
- 10 W CW RF Amplifier

- FPGA 8ch Delay VME Module
- FPGA Memory
- Arbitrary Wave Function Generator (2 bit D/A) VME Module
- VME D/A
- Wave Memory (A/D) 12 bit VME Module

- 5712 MHz
- 60 or 120 Hz trigger pulse

- C-Band High Power Klystrons
- Solid-State Amplifier

- 238 MHz
- 476 MHz
- 2380 MHz
- 2856 MHz
- 5236 MHz
- 5712 MHz

- 90 deg. Shift
- SLED-II

- RF distributor

- 238 MHz

- Synchronization

- 500 W C-Band High Power Klystrons
The control parameters of $K$, $Ti$, $Td$, and $Q$ are 0.1, 0.001, 0, and 1 s.

The 238 MHz cavity phase is controlled within 0.5 deg. In the case of 5712 MHz, the phase stability is almost same. Phase difference between the cavity and setting phases is artificial.
Inverter & Modulator

C-band Klystron

Inverter HV power supply

1 m

1.5 m

Modulator (Oil tank)

50 MW 2μs

rf pulse

50 MW 2μs

Modulator pulse

Inverter charging pattern

Circuit
## Major Specification of Inverter Power Supply

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Output voltage range</td>
<td>0 - 50 kV</td>
</tr>
<tr>
<td>Average current</td>
<td>1.5 A</td>
</tr>
<tr>
<td>Charge rate average</td>
<td>&gt;30 kJ/sec</td>
</tr>
<tr>
<td>Charge rate peak</td>
<td>&gt;37.5 kJ/sec</td>
</tr>
<tr>
<td>Output voltage regulation (p-p)</td>
<td>&lt;0.2 %</td>
</tr>
<tr>
<td></td>
<td>&lt;0.04 %</td>
</tr>
<tr>
<td></td>
<td>(Under development)</td>
</tr>
<tr>
<td>Power factor at full load</td>
<td>&gt;85 %</td>
</tr>
<tr>
<td>Power efficiency at full load</td>
<td>&gt;85 %</td>
</tr>
</tbody>
</table>
The trigger system of the SCSS prototype accelerator

- **VME Master Trigger Module**
- **Trigger Module**
- **N Divider**
- **Buffer**

**Trigger Pulse Train**
- **1 - 120 Hz Synchronization**
- **Balanced Line 100 ohm transmission**

**Pulse Repeater**
- **50 ohm line Single End**
- **Buffer**

**From Master Oscillator**
- **External 60Hz Sinusoidal Wave**

**Master Oscillator**
- **AC 100V**
- **AC 5V**
- **D F/F**

**Balanced Line**
- **100 ohm transmission**
- **10 V Trigger Pulse Train**

**Inhibit, 8 Channels Hardware Control**

**Trigger Delay Unit**
- **24 bit Counter x 8 ch.**
- **FPGA**

**Level Converter**
- **Pulse Input, PECL Level**
- **Selectable**

**To instruments such as the klystron modulator.**

**We replace this part to an optical fiber system in 8 GeV case.**

- **5712 MHz RF Signal**
- **238 MHz RF Signal**
- **10 W Amp**
- **FPGA**
- **AMP**
- **Buffer**
- **INV.**
- **Selecting 10V, TTL, NIM Levels**
- **Pulse Output**

**AC 100V**

**AC 5V**

**Single End**

**10 dB**

**10 dBm**

**10 V**
The measurement result of the time jitters of the trigger delay unit. The jitters are less than 1ps that satisfies our requirement. The temperature dependence of the jitter is very low.

<table>
<thead>
<tr>
<th>IC Devices</th>
<th>NBSG 11</th>
<th>NBSG 14</th>
<th>NBSG 53A</th>
<th>Wire</th>
<th>Risk Margin</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Skew [ps]</td>
<td>TYP</td>
<td>6</td>
<td>25</td>
<td>5</td>
<td>5</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>MAX</td>
<td>15</td>
<td>50</td>
<td>20</td>
<td>12</td>
<td>13</td>
</tr>
<tr>
<td>Jitter (RMS) [ps]</td>
<td>TYP</td>
<td>0.2</td>
<td>0.2</td>
<td>0.5</td>
<td>0.02</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>MAX</td>
<td>1</td>
<td>1</td>
<td>1.5</td>
<td>0.1</td>
<td>0.9</td>
</tr>
</tbody>
</table>

Calculated data

A delay time change of the unit dependent on the temperature was about 400 fs/ °K.

A temperature controller using a heater to stabilize the temperature of the flip/flops circuit within +/- 0.1 °K.
Cavity Beam Position Monitor

RF-BPM consists of a position detection cavity (TM110) and a reference cavity (TM010).

- The frequency is intentionally shifted from the acceleration RF (5712 MHz) to suppress any background from the dark current.

Coupling slots of the position detection cavity are designed to couple with the TM110 mode selectively, and to be insensitive to the TM010.

Loaded Q factor: ~90, Signal amplitude: 16 mV/nC/mm
### Present Circuit

**Res. 5 μm**

- **BPM**
- **4760 MHz**
- **Log amp**
- **Phase det.**
- **Switch**
- **LO 5236 MHz**
- **100 ns delay**
- **SO 476 MHz**
- **Switch**
- **VME Waveform Digitizer [6]**
- **Amplitude**
- **Phase**
- **50ns/div**
- **0.5V/div**

### Next Version

**Target, Sub-micron meter**

- **High dynamic range by the attenuator array**
- **Beam**
- **RF-BPM**
- **LO 4760 MHz**

**RF switch tree -60~0dB**

**attenuator array**

**RF switch tree**

**Amp +40dB**

**IQ mixer**

- **-50~10dBm**
- **0dB**
- **90°**
- **-6dB**
- **To ADC I**
- **Q**

- **High dynamic range by the attenuator array**
- **Can not distinguish tilt & position signals**
- **Next Version.**

**High dynamic range by the log amplifier**

**Company Name**
Position Resolution Measurement

- Four BPMs in the undulator line were used.

![Diagram showing BPMs and residual calculations]

- Position resolution can be measured by three adjacent BPMs.
- The 1st and 3rd BPMs determine the expected position at the 2nd BPM.
- The residual, which is the difference between the detected position of the 2nd BPM and the expectation, is calculated on a shot-by-shot basis.

\[
\sigma_{BPM} = \sqrt{\frac{2}{3}} \cdot \sigma_{res}
\]

- BPM-B Res. X 1.7 μm, Y 3.6 μm
- BPM-C Res. X 5.3 μm, Y 4.9 μm

Position resolution was 5 μm, or better.
Milestone of the Prototype Accelerator

Commissioning detail

- **05/12** Confirmed spontaneous light at 125 MeV.
- **06/1-4** Improved the accelerator system, and finish the construction.
- **06/5/8** Restart the tuning of the accelerator to aim SASE Amplification at 250 MeV.
- **06/6/20** First Lasing (49 nm, confirm)
- **06/8-11** Preparation of RF feedback control to obtain the stable amplification.
- **06/11** Reproduce SASE light (177 nm) at 150 MeV.
Emittance Measurement by Q scan method

Good agreement between the measured beam profile and the calculated profile.
Dark Current of the electron gun

Horizontal data projected from the screen monitor intensity.
PRM, down stream of the 238 MHz SHB
Small Dark Current ( <0.2% of the core beam )

Black Line : Noise level,  Red Line : Usual operation current level + deflector off
Stability of Beam Trajectory

- Trajectory stability ($1\sigma$): 1/5~1/10 of the beam pulse width at the undulator
- Energy stability ($1\sigma$): 0.06% at 250MeV

Beam position displacement at the undulator

- $\sigma_x = 13\mu m$
- $\sigma_y = 21\mu m$

Energy stability ($1\sigma$):

0.06% at 250MeV
RF stability

With PID feedback control, $1\sigma$ of phase and amplitude data.

<table>
<thead>
<tr>
<th>Source</th>
<th>Amplitude</th>
<th>Phase</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gun Vk</td>
<td>0.07%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>238MHz pickup</td>
<td>0.17%</td>
<td>0.10 deg</td>
<td>1.2 ps</td>
</tr>
<tr>
<td>476MHz pickup</td>
<td>0.10%</td>
<td>0.07 deg</td>
<td>0.41 ps</td>
</tr>
<tr>
<td>2856MHz Kly fwd</td>
<td>0.12%</td>
<td>0.08 deg</td>
<td>0.078 ps</td>
</tr>
<tr>
<td>5712MHz SLED fwd</td>
<td>0.14%</td>
<td>0.42 deg</td>
<td>0.20 ps</td>
</tr>
</tbody>
</table>
Amplitude & Phase Data (2856MHz)

**2856 Intensity (Trend)**

![Graph showing intensity trend over time](image)

**2856 Intensity (Histogram)**

![Histogram chart with statistical data](image)

- Entries: 300
- Mean: 0.6864
- RMS: 0.0007971
- $\chi^2 / ndf$: 43.16 / 15
- Constant: 33.67 ± 2.73
- Mean: 0.6864 ± 0.0001
- Sigma: 0.0008135 ± 0.0000448

**2856 Phase (Trend)**

![Graph showing phase trend over time](image)

**2856 Phase (Histogram)**

![Histogram chart with statistical data](image)

- Entries: 300
- Mean: 173.5
- RMS: 0.09302
- $\chi^2 / ndf$: 51.78 / 15
- Constant: 39.63 ± 3.15
- Mean: 173.5 ± 0.0
- Sigma: 0.08212 ± 0.00396
VUV計測系

<table>
<thead>
<tr>
<th>Measurement Items</th>
<th>Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Optical intensity (0.1 pJ ~ 0.1 mJ/pulse)</td>
<td>Photo Diode, Gas chamber</td>
</tr>
<tr>
<td>2. VUV Spectrum (λ=60 nm ~ 700 nm, λ/Dλ&gt;1000)</td>
<td>Spectrometer</td>
</tr>
<tr>
<td>3. Pulse width</td>
<td>CSR spectrum (Beam dump BM)</td>
</tr>
<tr>
<td>4. Spatial profile</td>
<td>0&lt;sup&gt;th&lt;/sup&gt; order diffraction light (Slit position)</td>
</tr>
</tbody>
</table>

1. Photo Diode, wide dynamic range $10^9$

- IRD: SXUV100, -RPD
  (~ 0.01 A/W, ~ 0.002 A/W)
- IRD: PA100 ($\times1k$ ~ 5000k)
- IRD: BT120 ($\times1$)
- API: APD DUV (~ 30 A/W)

Flat Mirror

Diffraction Grating

CCD

Company Name
SASE Amplification

Power (MW)

SASE Laser

Spontaneous

Light Power

Arbitrary

Charge (nc)

1.5
1
0.5
0
0
0.1
0.2
0.3
0.4
0.5

Wave Length (nm)

46
47
48
49
50
51
52

SASE Laser

Spontaneous
Double Slit Image

SASE
(1 shot, bunching condition)

Spontaneous radiation
(debunching condition, 100 shots)
Evaluation of Beam and Laser Light Quality

Amplification factor dependent on the K values.
Simulated by 3-dimensional FEL simulation in one undulator (5m)
-> Electron beam brightness
270~315 A/$\pi^2$mm$^2$.mrad$^2$

<table>
<thead>
<tr>
<th>Peak Current</th>
<th>1500A</th>
<th>832A</th>
</tr>
</thead>
<tbody>
<tr>
<td>1250A</td>
<td></td>
<td></td>
</tr>
<tr>
<td>750A</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1070A</td>
<td></td>
<td></td>
</tr>
<tr>
<td>937A</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Charge 0.25nC
Emittance = 2$\pi$mm.mrad
Energy Spread $\sigma_{E/E} = 0.001$

Ratio (SASE/Spontaneous)
Beam quality evaluated form the laser amplification condition (using 3 dimensional FEL simulation)

Radiation Intensity vs. Charge amount
Evaluated by 1 D FEL model
-> Electron beam brightness
240 $A/\pi^2 \text{mm}^2 \cdot \text{mrad}^2$

49nm@250MeV
Continuous high power Amplification

Before and after the rf phase and amplitude feedback control at the 238, 476, 2856 MHz rf cavity,
Summary

1. Evaluated the beam quality by the 1D & 3D simulation using the laser amplification condition.

2. We almost realized the target specification of the beam that is 800 A peak current and a normalized emittance of $2\pi$ mm.mrad.

3. 0.2 % dark current of the core beam from the gun.

We confirmed feasibility of

- **OK** 1. 500 kV CeB6 Thermionic Electron Gun (Small Emittance and Dark Current),
- **OK** 2. C-band high gradient acceleration (High Gradient Acceleration 37 MeV/m),
- **OK** 3. Acceleration stability. (dE = 0.06% at 250MeV)