SACLA X-ray FEL

How did we make it…..

Tsumoru Shintake

FEL Prize Lecture
SACLA Accelerator

Low emittance injector with CeB6 E-gun

C-band accel. system

Short period In-vacuum undulators

700m
SCSS : SPring-8 Compact SASE Source

- **Short Period Undulator**
  - In-Vacuum Undulator: $\lambda_u = 18$ mm, $K=1.9$, $\lambda_x < 1$ Å $\rightarrow$ $E = 8$ GeV,
  - SLAC-LCLS: $\lambda_u = 30$ mm, $K=3.7$, $\lambda_x \sim 1.5$ Å $\rightarrow$ $E = 14$ GeV
  - Euro-XFEL: $\lambda_u = 36$ mm, $K=3.3$, $\lambda_x < 1$ Å $\rightarrow$ $E = 17.5$ GeV

- **High Gradient Accelerator**
  - 8 GeV, C-band 35 MV/m $\rightarrow$ 230 m
  - SLAC-LCLS: S-band 19 MV/m $\rightarrow$ 740 m

- **Thermionic Electron Source**
  - Thermionic gun + velocity bunching $\rightarrow$ 0.8 $\pi$.mm.mrad @ 3k A, 8GeV
  - multi-bunch operation, smooth & quiet beam for seeding
Operational Experience of 500 kV Gun in SCSS Test Accelerator

- Applying 500 kV pulse.
- 3 micro-sec pulse driven by klystron modulator.
- Gun sits inside HV pulse tank, filled with oil.

• No HV breakdown at 500 kV for 4 years, daily operation.
8 GeV, 400 m C-band Accelerator
Running at 35 MV/m in daily operation from March 2011 at 10 ~ 60 Hz.
90 m long Undulator line. 18 unit of In-Vacuum Undulator. Variable-gap provides fast change of X-ray wavelength.
Spatial Profile (pointing is very stable)

YAG-Screen 100 m downstream from undulator
Laser Spectrum (K=1.5)
1992 Summer, at SLAC cafeteria, Prof. Herman Winick suggested me to join to the study group on X-ray Free Electron Laser: later it became LCLS.

“Yes, I will join, later, since I am now FFTB project”, I said.
I was at SLAC (1992-1995) as visiting researcher to serve international collaboration FFTB.

60 nm spot measurement
By laser interferometer and Compton backscattering.

Tsumoru Shintake (KEK) (left) and David Burke (SLAC) in front of a spot size monitor. In May 1994, SLAC’s FFTB generated the narrowest beam ever. Led by David Burke, groups from the Budker Institute, DESY, Fermilab, KEK, LAL, MPI Munich and SLAC worked together to produce a beam whose height was only one-tenth the wavelength of light. Their accomplishment proved that the large compression factors required for next-generation linear colliders are within reach.
We proved 60 nm spot size creation using 50 GeV beam, which was key for e+e- linear collider design.
~1995: We discussed lot on high gradient accelerator technology for LC.

- While, SLAC was developing X-band technology.
- I proposed C-band for LC.

- The reason is that “C-band (6GHz) is easier than X-band (11GHz), even S-band (3GHz) conventional, or L-band (1.3GHz) super conducting cavity”

“You are wrong this time”, Burton said.
“But, I am sure C-band is the best”, I said.
Hirotaka Sugawara, former KEK director, decided to start C-band R&D at KEK from 1995.

“\textit{I am particle theorist, I do not know technology details, but I believe you, make it for us, for JLC}”

…Hirotake said 1995.

\textbf{C-BAND LINAC RF-SYSTEM FOR $e^+e^-$ LINEAR COLLIDER}

T. Shintake, N. Akasaka, $^{1}$K.L.F. Bane, H. Hayano, $^{1}$K. Kubo $^*$, H. Matsumoto, S. Matsumoto, K. Oide, and K. Yokoya

National Laboratory for High Energy Physics, 1-1 Oho, Tsukuba-shi, Ibaraki, 305 Japan

$^{1}$SLAC: Stanford Linear Accelerator Center, Stanford University, Stanford CA, 94309 USA
JLC C-band (5712 MHz) Main Linac Tunnel

Granite: stable ground

Diameter: 3.0 m
Diameter: 4.2 m

Active Length: 14 km

36 MV/m

RF pulse compressor

Gain: x 3.5

Conventional wave-guide system

BPMs

36 MV/m (45 MV/m)

Accelerator 1.8 m each

Beam

50 MW x 2

2.5 μsec
In SACLA, to lower the risk, we prepared power supply for individual klystron.
C-band R&D 1995-2000: To show 35 MV/m acceleration at C-band.

C-band SAMURAI s
Dr. Hiroshi Matsumoto contributed high power components R&D, for a long period.

1996 at KEK

2010 at SACLA
In klystron development at a new frequency, there is “chicken or the egg causality dilemma” on rf components. Especially the rf-window.

1995, Prof. G. A. Loew (former accelerator division director) gave an old C-band 5 MW klystron as a gift, which has been sleeping quite a long time at SLAC storage, it was originally used for RF particle separator R&D at CERN.

We quickly made resonant-ring test stand, which enhanced the rf power from 5 MW to 70 MW. Also, we used an modulator power supply from old medical accelerator to drive 5 MW klystron. Using this, we tested our ceramic rf window: a key of 50 MW klystron.
# C-band R&D 2000: Summary after 4 years work.

## Table-1: Results of Phase-I R&D and future task in Phase-II.

<table>
<thead>
<tr>
<th>Items</th>
<th>Phase-I R&amp;D Target</th>
<th>Future R&amp;D Task (Phase – II)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Klystron</strong></td>
<td>Output 50 MW, Efficiency &gt;45% Pulse width &gt;2.5 µsec Pulse repetition 100 pps Focusing Power &lt; 5 kW</td>
<td>Refine design details for the mass-production and reducing cost.</td>
</tr>
<tr>
<td></td>
<td>All of No.1, 2, 3 tubes achieved 50 MW output, pulse width 2.5 µsec and 50 pps. No. 3 tube showed 47% power efficiency. Focusing power 4.6kW. Life test No.2 &gt; 5000 hours. PPM tube is under development.</td>
<td>Example of output,</td>
</tr>
<tr>
<td><strong>Pulse Modulator Supply</strong></td>
<td>350 kV, 2.5 µsec pulse generation, power efficiency &gt;50% Smart Modulator, No. 1 Operating for klystron life-test. Power efficiency &gt;52.4%</td>
<td>Smart Modulator No. 2 Design refinement for Cost reduction, Modular component, Efficiency Improvement &gt; 60% Study on switch device. Improve thyratron tube life-time.</td>
</tr>
<tr>
<td>Component</td>
<td>Specification</td>
<td>Improvement/Detail</td>
</tr>
<tr>
<td>----------------------------</td>
<td>-------------------------------------------------------------------------------</td>
<td>-----------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>RF Pulse Compressor</td>
<td>Power gain $&gt;3.5$, Power efficiency $&gt;70%$</td>
<td>High Power Model Test</td>
</tr>
<tr>
<td></td>
<td>Cold Model Test</td>
<td>Improve Power Efficiency $&gt;70%$</td>
</tr>
<tr>
<td></td>
<td>Power Gain 3.25, Efficiency 65%</td>
<td>Refine cavity design.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Utilize pulse rising part of modulator.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Low thermal expansion metal.</td>
</tr>
<tr>
<td>Accelerating Structure</td>
<td>Multi-bunch 1.6 nC, 80 bunch</td>
<td>Refine design details.</td>
</tr>
<tr>
<td></td>
<td>Acceleration gradient $&gt;35$ MV/m</td>
<td>Optimization for mass-production.</td>
</tr>
<tr>
<td></td>
<td>ASSET test at SLAC</td>
<td>Lowering cost.</td>
</tr>
<tr>
<td></td>
<td>demonstrated damping performance of the choke-mode cavity.</td>
<td></td>
</tr>
<tr>
<td>RF-BPM</td>
<td>Straightness of structure $&lt; 50$ μm</td>
<td>Optimization for multi-bunch beam.</td>
</tr>
<tr>
<td></td>
<td>Resolution of RF-BPM $&lt;100$ nm</td>
<td>Detection circuit for multi-bunch.</td>
</tr>
<tr>
<td></td>
<td>Position accuracy $&lt; 10$ μm</td>
<td>Damping HOM in RF-BPM.</td>
</tr>
<tr>
<td></td>
<td>Resolution $\sim 25$ nm (FFT test)</td>
<td></td>
</tr>
</tbody>
</table>
• Year of 2000, KEK stopped C-band R&D for JLC.

• Technical choice of ILC International Linear Collide merged to 1.3 GHz L-band Cold Technology.
We brought C-band to RIKEN/SPring-8 in 2000

Dr. Hideo Kitamura invited me to come RIKEN to continue C-band R&D and start FEL research.

Dr. H. Kamitsubo, former director of SPring-8, supported us to start FEL research.
1. Using thermionic cathode of CeB$_6$ or LaB$_6$ single crystal.

2. Use C-band accelerator at 35 MV/m.

3. Use in-vacuum undulator

4. Final target is 1 Angstrom X-ray.
Milestone of SPring-8 SCSS

SCSS Test Accelerator

X-ray FEL

SPIE 2001 July.
Milestone of SPring-8 SCSS

SPIE 2001 July.

X-ray FEL

Visible

VUV

X-ray

1000

100

10

1

0.1

0.1

2001 02 03 04 05 2006 2010

Year

SCSS SPring-8

TESLA 180~80 nm

15 nm

6 nm

3.6 nm

SLAC-LCLS

0.1 nm

X-ray FEL 2006 60 nm

2011 0.1 nm

SCSS Test Accelerator
Single-crystal CeB$_6$ Cathode for XFEL/SPring-8 & SCSS Low-emittance Injector

No HV breakdown for 4 years daily operation

After 20,000 hours operation 1 crystal changed.

500 kV Electron Gun

Single-crystal CeB$_6$

Operating Cathode

Diameter : $\phi 3$ mm
Temperature : $\sim 1500$ deg.C
Beam Voltage : 500 kV
Peak Current : 1 A
Pulse Width : $\sim 2$ $\mu$s
Beam Chopper: 1 nsec

Dr. K. Togawa
Measured Emittance at the cathode, long pulse.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy</td>
<td>500 keV</td>
</tr>
<tr>
<td>Peak current</td>
<td>1 A</td>
</tr>
<tr>
<td>Pulse width (FWHM)</td>
<td>3 µs</td>
</tr>
<tr>
<td>Repetition rate</td>
<td>10 Hz</td>
</tr>
<tr>
<td>Normalized emittance (rms, 100% electrons)</td>
<td>$1.1\pi$ mm mrad</td>
</tr>
<tr>
<td>Normalized emittance (rms, 90% electrons)</td>
<td>$0.6\pi$ mm mrad</td>
</tr>
</tbody>
</table>

$< 1\pi$ mm mrad
To show emittance preservation, construct Test Accelerator 2004~2006
SCSS Test Accelerator

- 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 μ.mm.mrad (measured at undulator)
- Four C-band accelerators
  - 1.8 m x 4
  - $E_{\text{max}} = 37 \text{ MV/m}$
  - Energy = 250 MeV
- **In-Vacuum Undulators**
  - Period = 15 mm, $K=1.3$
  - Two 4.5 m long.

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

**238 MHz buncher**
**476 MHz booster**

**In-vacuum undulator**
CeB$_6$ 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 49 nm in SCSS

June 15, 2006
SACLA 8 GeV Beam Parameter Design

Proved at SCSS Test Accelerator

x3000 times compression
No laser heater was prepared.

Dr. Hitoshi Tanaka
Dr. Toru Hara
Dr. Yuji Otake made tremendous contributions on SACLA construction.

- Highly stable RF reference signal distribution and processing circuitry.
- Various beam diagnostic system, including BPM, deflector.
- Others
Highly Stable RF System

Klystron power supply stabilization.
- 30 PPM stability of HV charger with IGBT switching.
- All metal shield tank.

Team from Nichicon Co.

Dr. K. Shirasawa & C. Kondo
Reliable RF Acceleration System

- Fabrication of components with special care at Mitsubishi Heavy Ind. and Hitachi Cable.

We made 13,000 pieces of C-band accelerator cell.

Sadao Miura, MITSUBISHI Heavy Ind,
Mass Production of C-band Accelerator at MITSUBISHI Heavy Ind. 2007 ~ 2009

Laser Guided Precision Machining
Brazing of C-band Accelerators

• A number of technical improvements have been made.

• 1~2 columns per week.
Reliable High Power RF Acceleration System

• High power test on rf components is key to develop reliable system.
• Tested up to 40 MV/m.
• Careful installation into the tunnel.

T. Sakurai and T. Inagaki
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
Summary of SACLA Construction

- SACLA is working nicely, thanks to daily effort by operation team.
  …..Status report will be presented by T. Hara.

- C-band at 35 MV/m acceleration voltage is reliable.

- CeB6 thermionic gun is providing stable beam, while we need to change cathode after ~10,000 hours operation.
Future Perspective on X-ray Laser and Electron Microscopy based on High Performance Particle Beams

“microscopy of bio-molecule”
Two Different Microscopes for Atomic Resolution

**Free Electron Laser**

- **E-Source**
- **Accelerator**
- **Undulator**
- **Specimen**
- **X-ray Detector**

High-energy relativistic electron beam
10 GeV, 3 kA

**Electron Microscope (TEM)**

- **E-Source**
- **Magnetic Lenses**
- **Electron Detector**

Non-relativistic electron beam
100 ~ 300 keV, 1 nA

Mag. x1000 ~ x1000,000
Features (benefits)

X-ray FEL
(1~3 km, expensive)

Femtosecond Intense X-ray Pulse

Flying Living Wet Sample

Diffraction (Fourier Image)

EM (2~4 m)

Frozen Sample

Magnified Real Image
Typical TEM for cryo-microscopy for bio-sample. $V=100\sim300$ kV

Dr. K. Namba at Osaka University
TEM image on ice-embedded bio-sample.

Highly coherent e-beam makes phase contrast image, thus we may observe bio-sample without stain.

Bacteriophage T4

Courtesy of Davide Demurtas @EPFL
State of art Cryo-electron Microscopy

Assembled by 5000 images
4 Å resolution.

Bovine Papillomavirus (60nm dia)
Courtesy of Dr. Matthias Wolf

Ice embedded virus, without staining.
Hole diameter 1 micrometer
Ice thickness 80~100 nm
Recorded on film at , 20 e/A² dose.
FEI Tecnai F30 @300kV
**X-ray Interaction**

**Incident X-ray (~10 keV)**

- Electric field of incoming X-ray wave causes dipole oscillation of group of electrons.
- \[ I \propto Q^2 = (eZ)^2 \]
- Coherent Diffraction (Thomson Scattering)
- Direct Beam (no interaction)

**Electron Interaction**

**Incident High Energy Beam (100~300keV)**

- Back-scattered Electron (BSE)
- Inelastic Scattering
- Direct Beam (no interaction)
- Secondary Electrons
- Space charge force causes plasmon and inner-shell excitation (damage)
- Electric static field created by nucleus deflects electron orbit.
- \[ I \propto Z \]

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*OIST* OKINAWA INSTITUTE OF SCIENCE AND TECHNOLOGY GRADUATE UNIVERSITY
Interaction with matter

**X-ray Interaction**

- **Fluorescence X-ray**
  - a few keV
- Coherent Diffraction
  - spread due to temperature 0.1 eV
- Energy 10 keV

There is no plasmon like energy loss because X-ray is charge-less and transferring energy is quantized at the photon energy (10keV). Therefore diffraction signal becomes very clean.

**Electron Interaction**

- **Zero-loss**
  - Inner-shell edges a few keV
  - Plasmon 50~100 eV
  - Energy 100~300 keV

Plasmon excitation creates inelastic components, which closely mixed with zero-loss beam, which make EM imaging difficult and low contrast.

--> **advanced energy filtering technology.**

\[ \Omega \text{-filter} \]
What can we learn from EM?

• **FEL+EM**: Combination of EM and FEL will be good idea.
  – Identity sample quality before/at FEL experiment.
  – Jet injection +FEL followed by gas deposition on graphene +SEM

• **FEL → EM**
  RF-Gun will makes Femto-TEM possible. Plasmon excitation becomes larger as higher electron density.

• **EM → FEL**
  Environmental FEL will be important.

• **FIB → FEL**
  FIB + FEL, sample milling in-situ, making S/N better. About FIB, visit such as SII corp.
FEL has various potential applications, and we need more FELs.

- Because interaction of X-ray with matter is rather simple, and provides cleaner signal $\rightarrow$ imaging, spectroscopy

- X-ray is charge less: Bose particle, thus infinitely intense beam can be formed in principle. $\rightarrow$ new physics

- Femto-second pulse form is very unique. $\rightarrow$ mode locking, pump-probe

- Polarization control will provide another channel.

For young students, you have more chance in FEL community.