SACLA X-ray FEL

How did we make it…..

Tsumoru Shintake

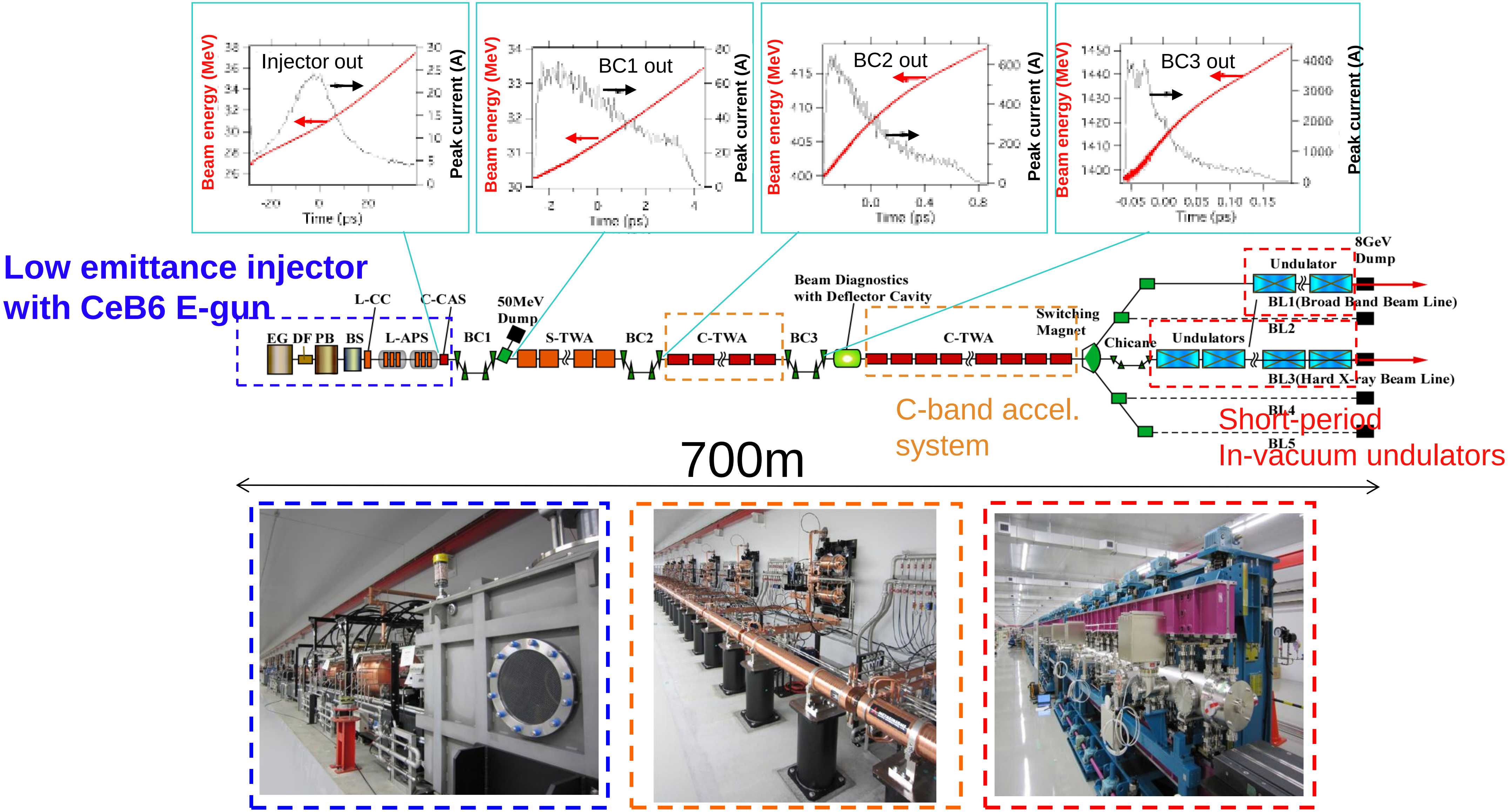
FEL Prize Lecture

OIST
OKINAWA INSTITUTE OF SCIENCE AND TECHNOLOGY

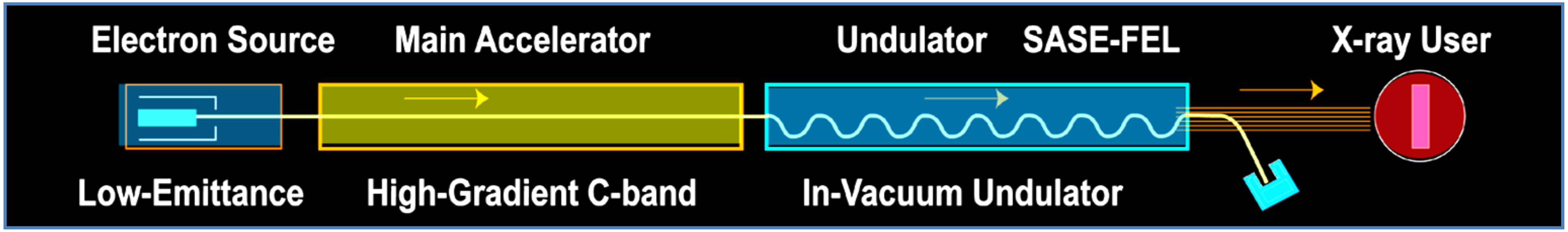

SPring-8 1997~
3rd Generation SR Light Source
SACLA 2011~
X-ray Free Electron Laser

SACLA First Lasing June 7, 2011

SACLA Accelerator



SCSS : SPring-8 Compact SASE Source



- **Short Period Undulator** → **Lower Beam Energy**

  In-Vacuum Undulator : λ_u= 18 mm, K=1.9, λ_x < 1 Å → E= 8 GeV,

  SLAC-LCLS : λ_u= 30 mm, K=3.7, λ_x~ 1.5 Å → E= 14 GeV

  Euro-XFEL : λ_u= 36 mm, K=3.3, λ_x < 1 Å → E= 17.5 GeV

- **High Gradient Accelerator** → **Short Accelerator Length**

  8 GeV, C-band 35 MV/m → 230 m

  SLAC-LCLS : S-band 19 MV/m → 740 m

- **Thermionic Electron Source** → **Short Saturation Length**

  Thermionic gun + velocity bunching → 0.8 π.mm.mrad @ 3k A, 8GeV

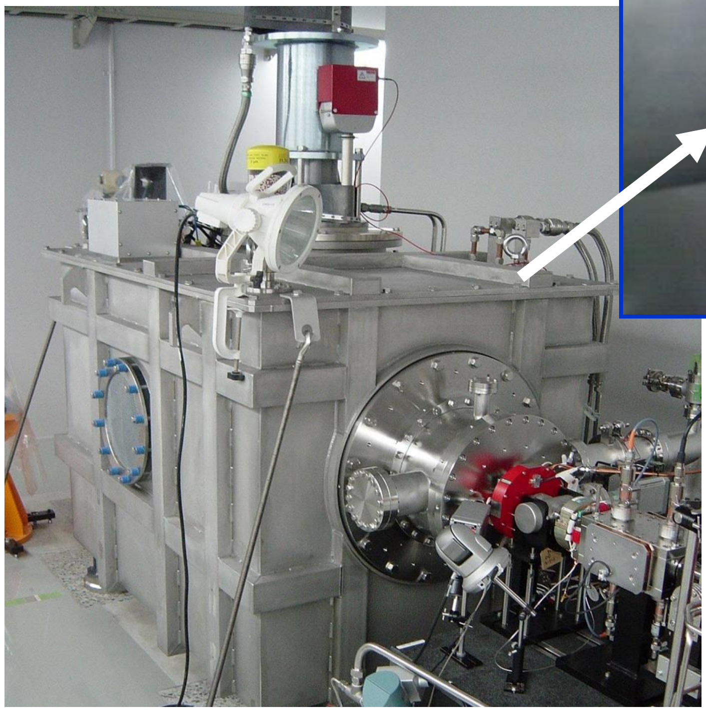
  → multi-bunch operation, smooth & quiet beam for seeding

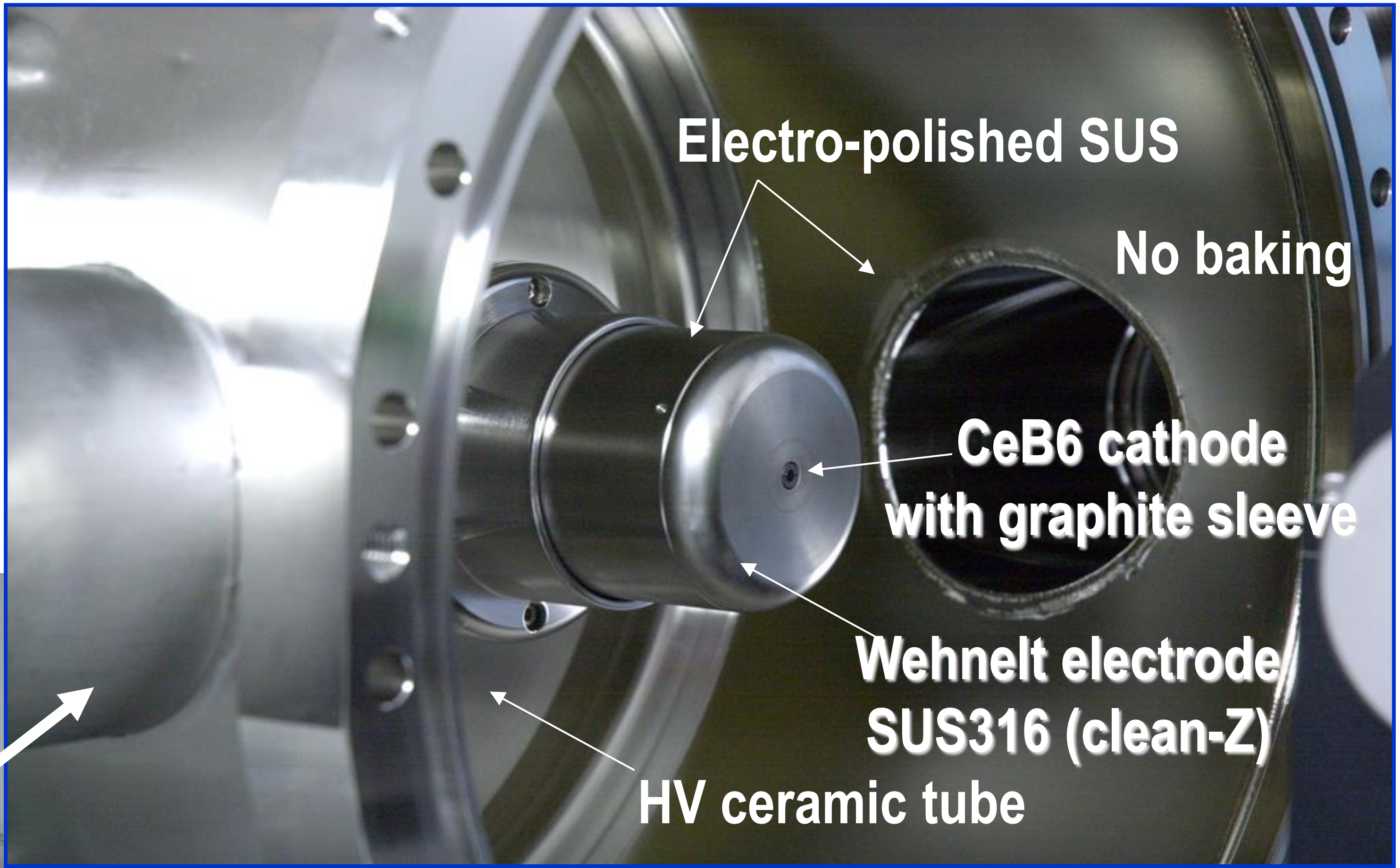
Operational Experience of 500 kV Gun in SCSS Test Accelerator

■Applying 500 kV pulse.

■3 micro-sec pulse driven by klystron modulator.

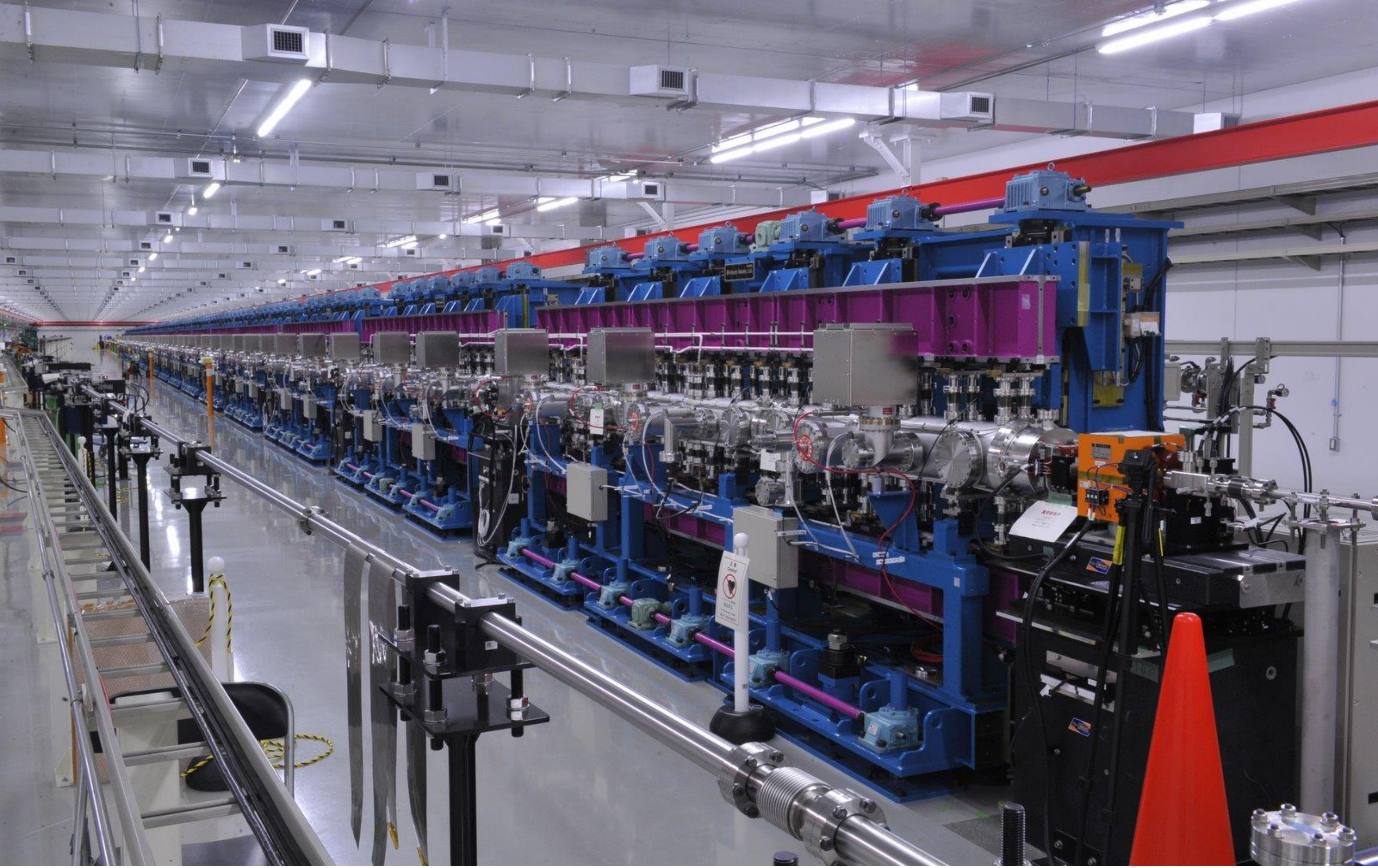
■ Gun sits inside HV pulse tank, filled with oil.





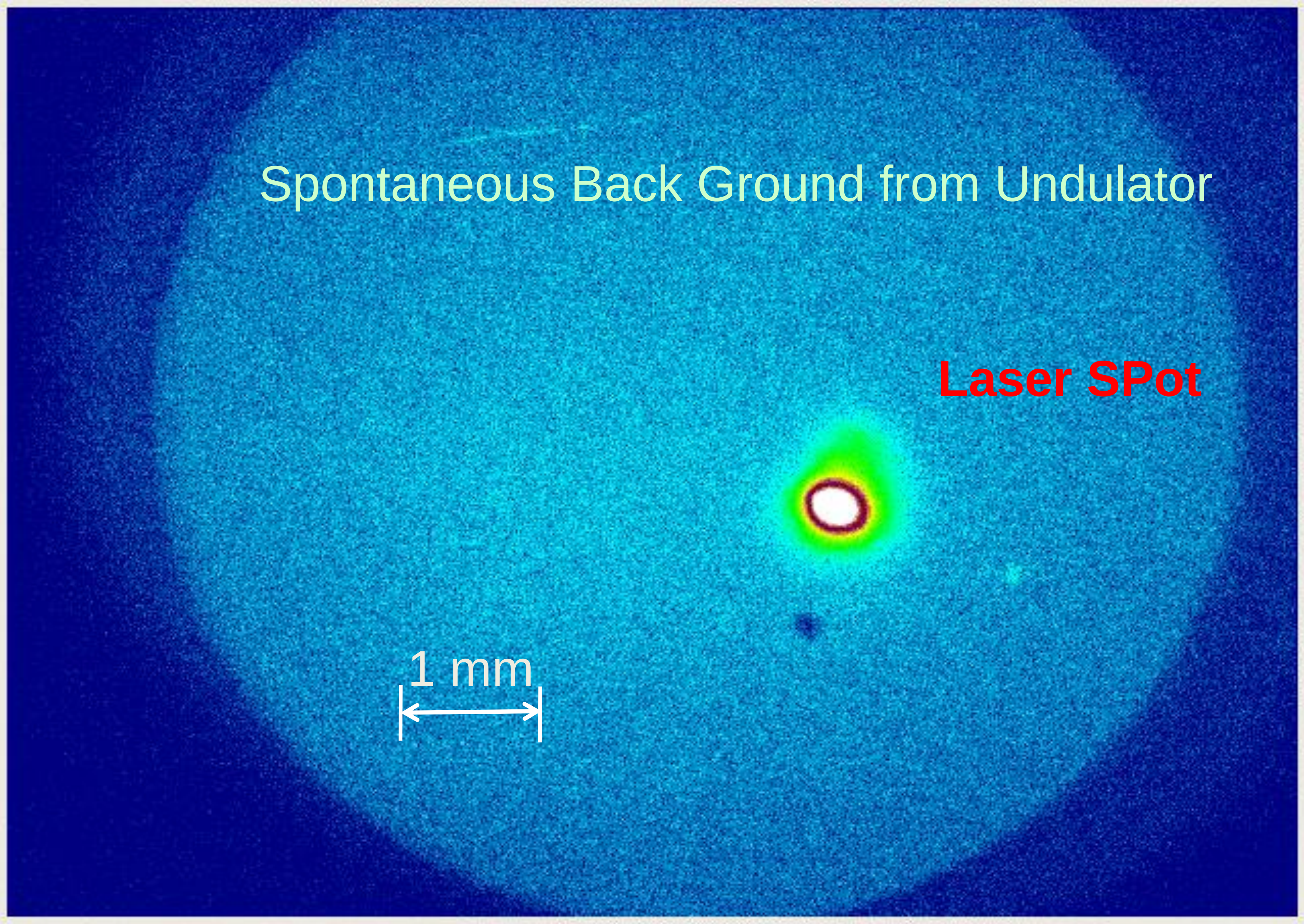
- *No HV breakdown at 500 kV for 4 years, daily operation.*

8 GeV, 400 m C-band Accelerator
Running at 35 MV/m in daily operation from March 2011 at 10 ~ 60 Hz.



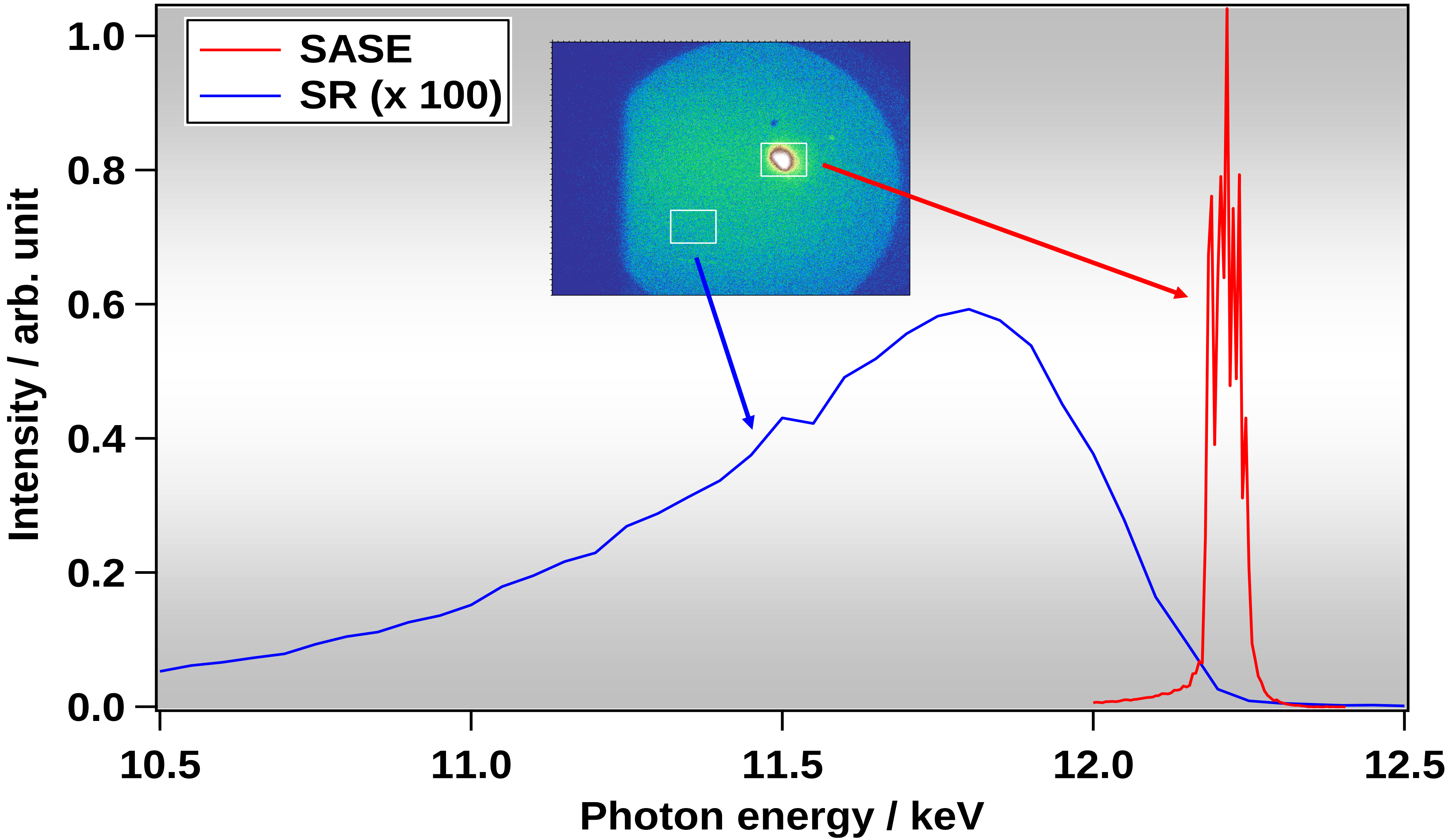
90 m long Undulator line. 18 unit of In-Vacuum Undulator.
Variable-gap provides fast change of X-ray wavelength.

Spatial Profile (pointing is very stable)

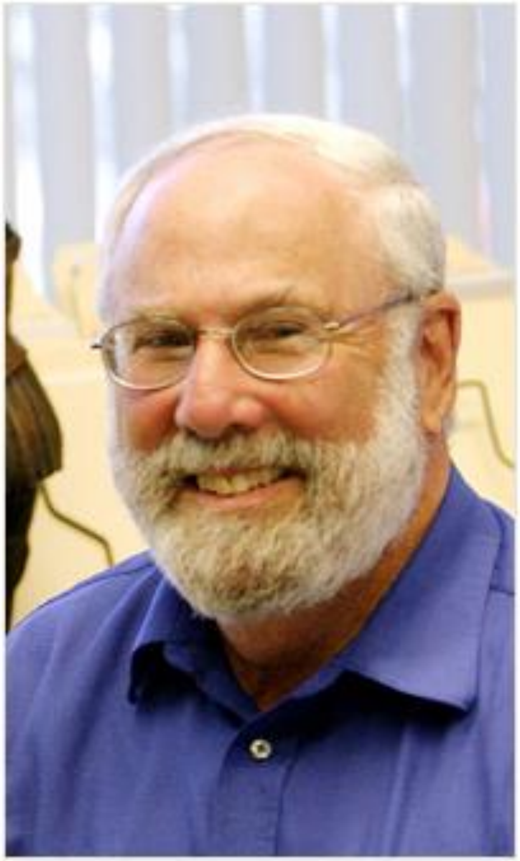


YAG-Screen 100 m downstream from undulator

Laser Spectrum(K=1.5)



Story started 1992

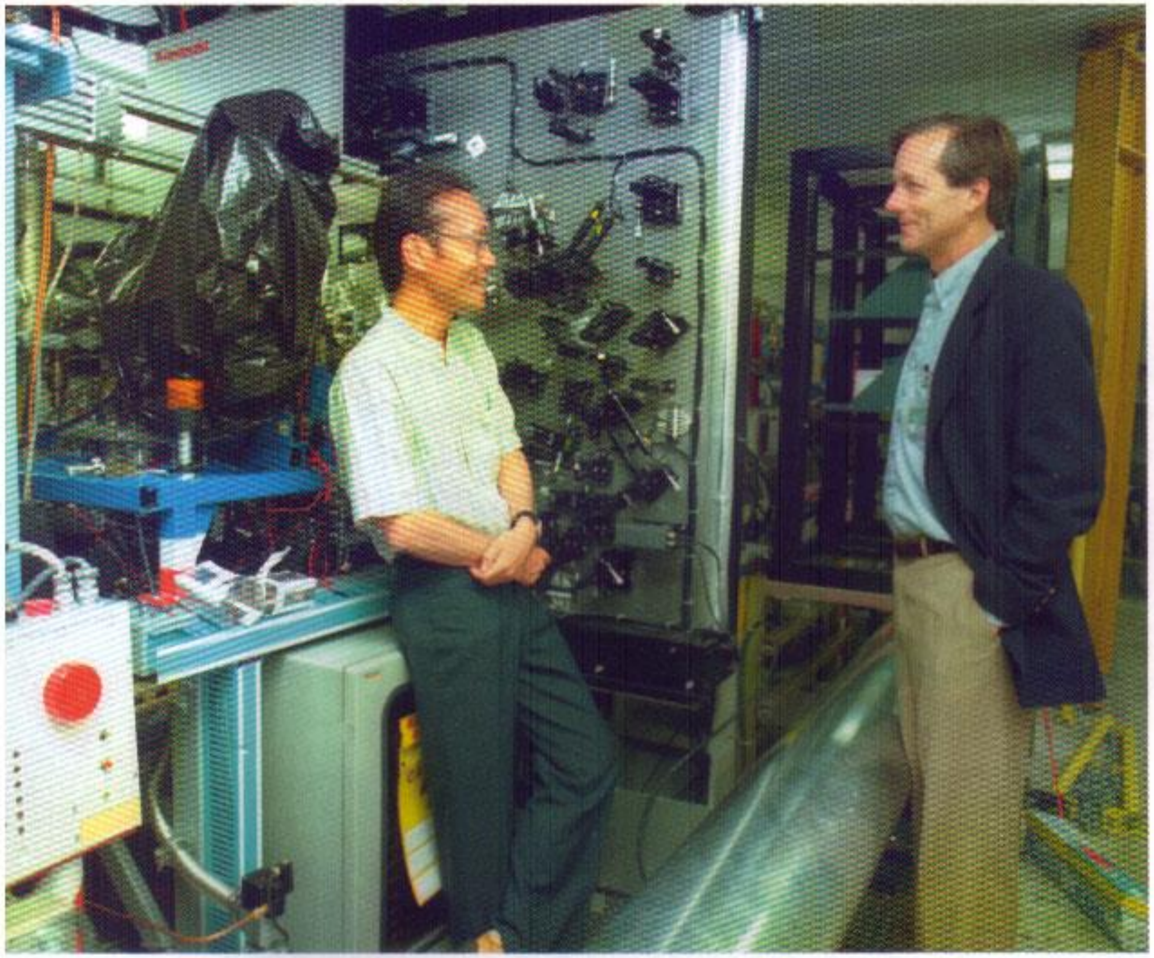


Herman Winick

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.

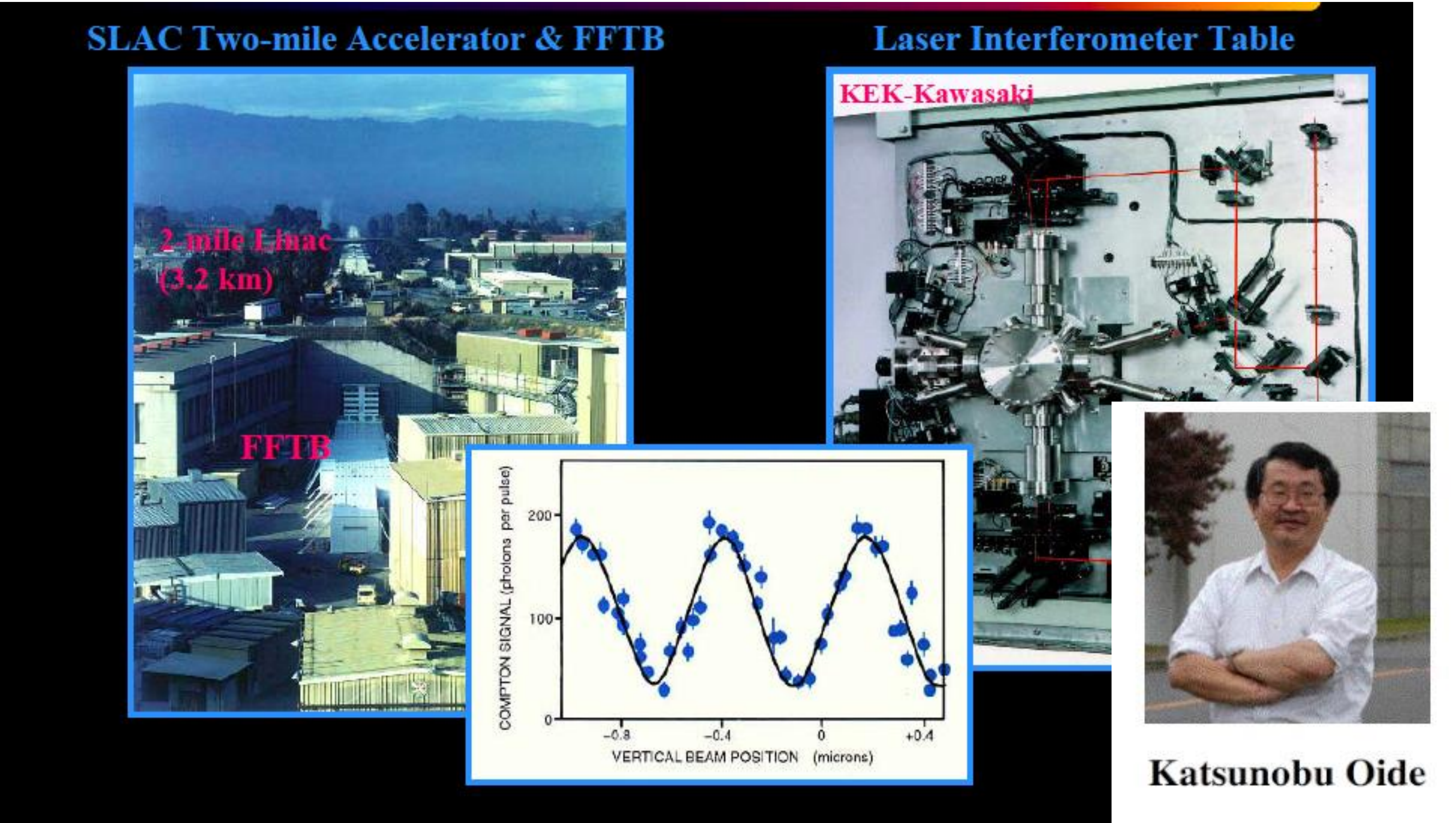
I was at SLAC (1992-1995) as visiting researcher to serve international collaboration FFTB.



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.

Prof. Burton Richter

- 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.

"I am particle theorist, I do not know technology details, but I believe you, make it for us, for JLC"

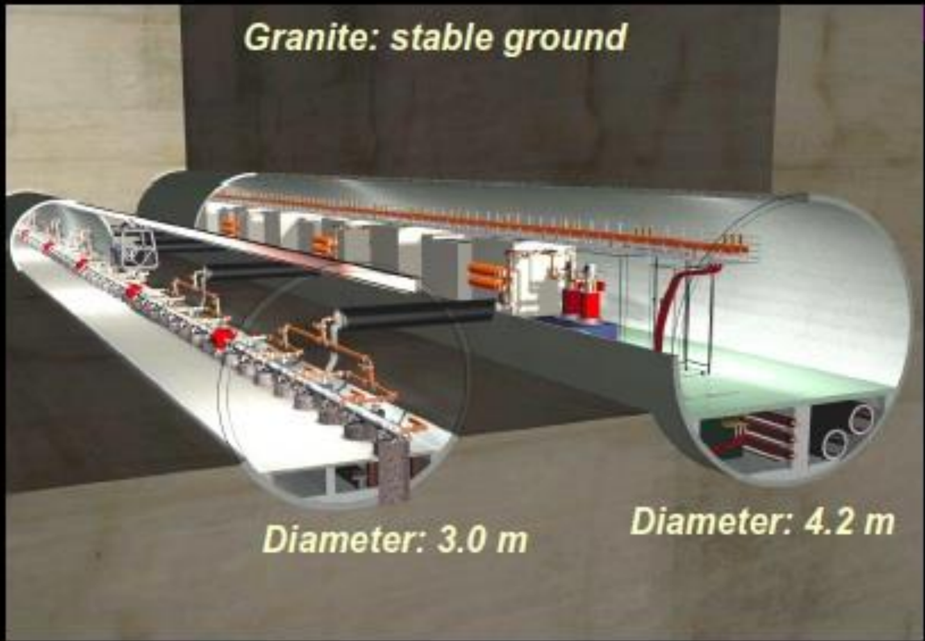
…Hirotake said 1995.

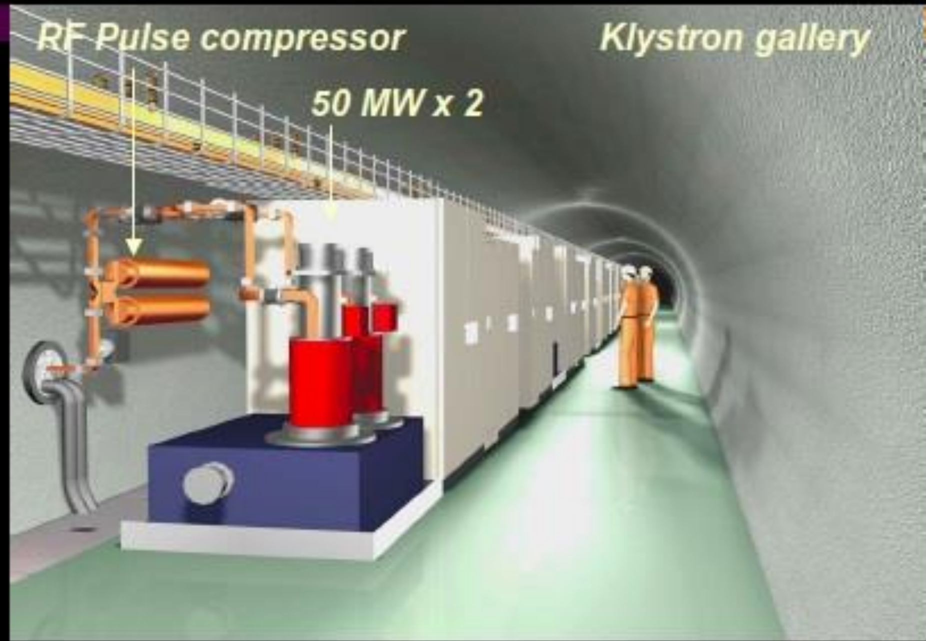
PAC95

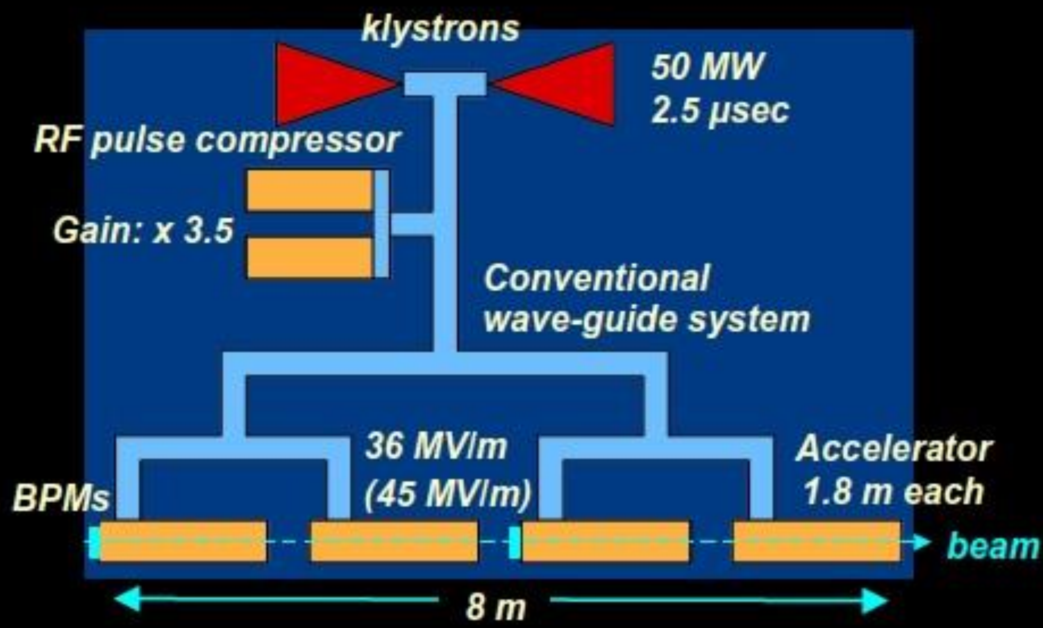
C-BAND LINAC RF-SYSTEM FOR e^+e^- LINEAR COLLIDER

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

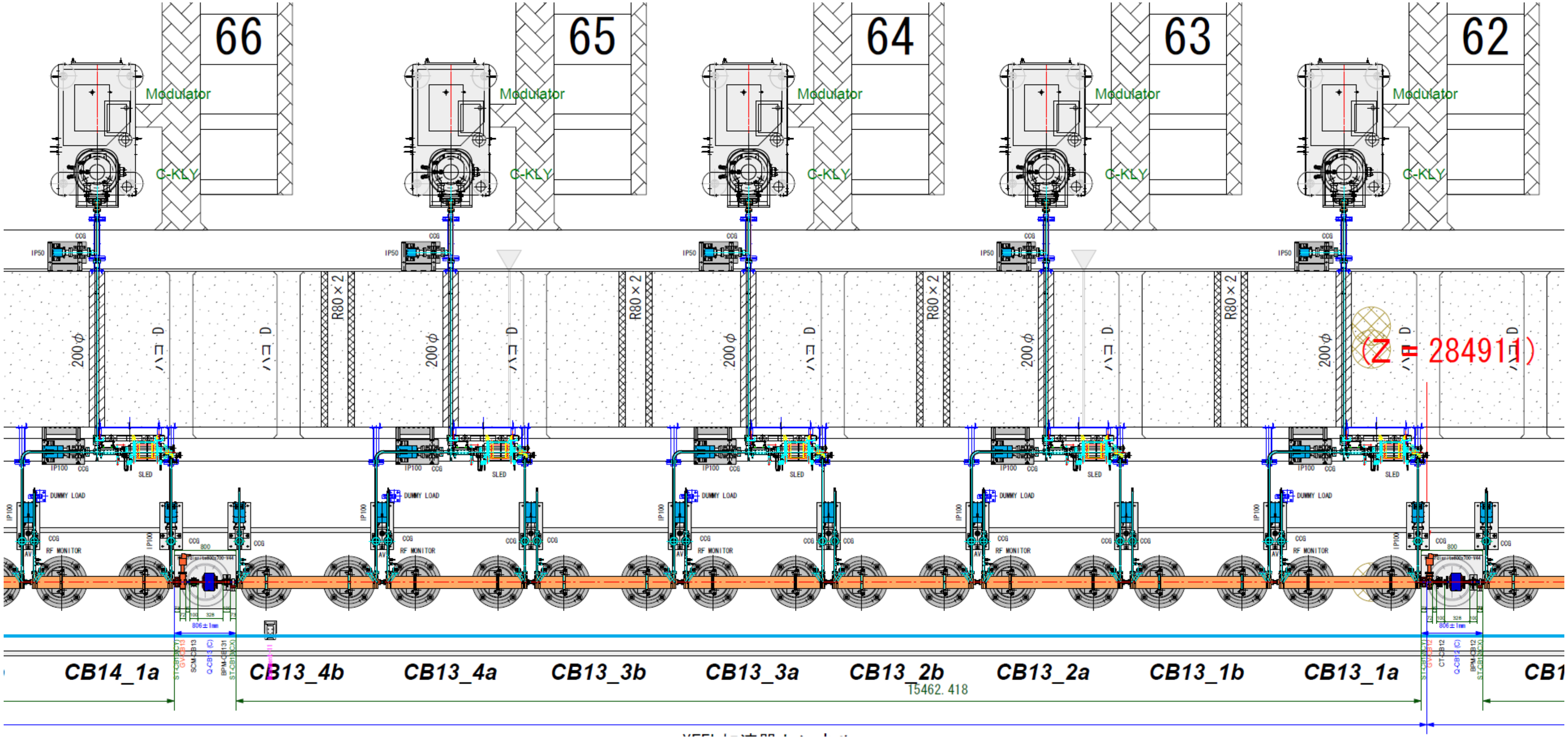
JLC C-band (5712 MHz) Main Linac Tunnel





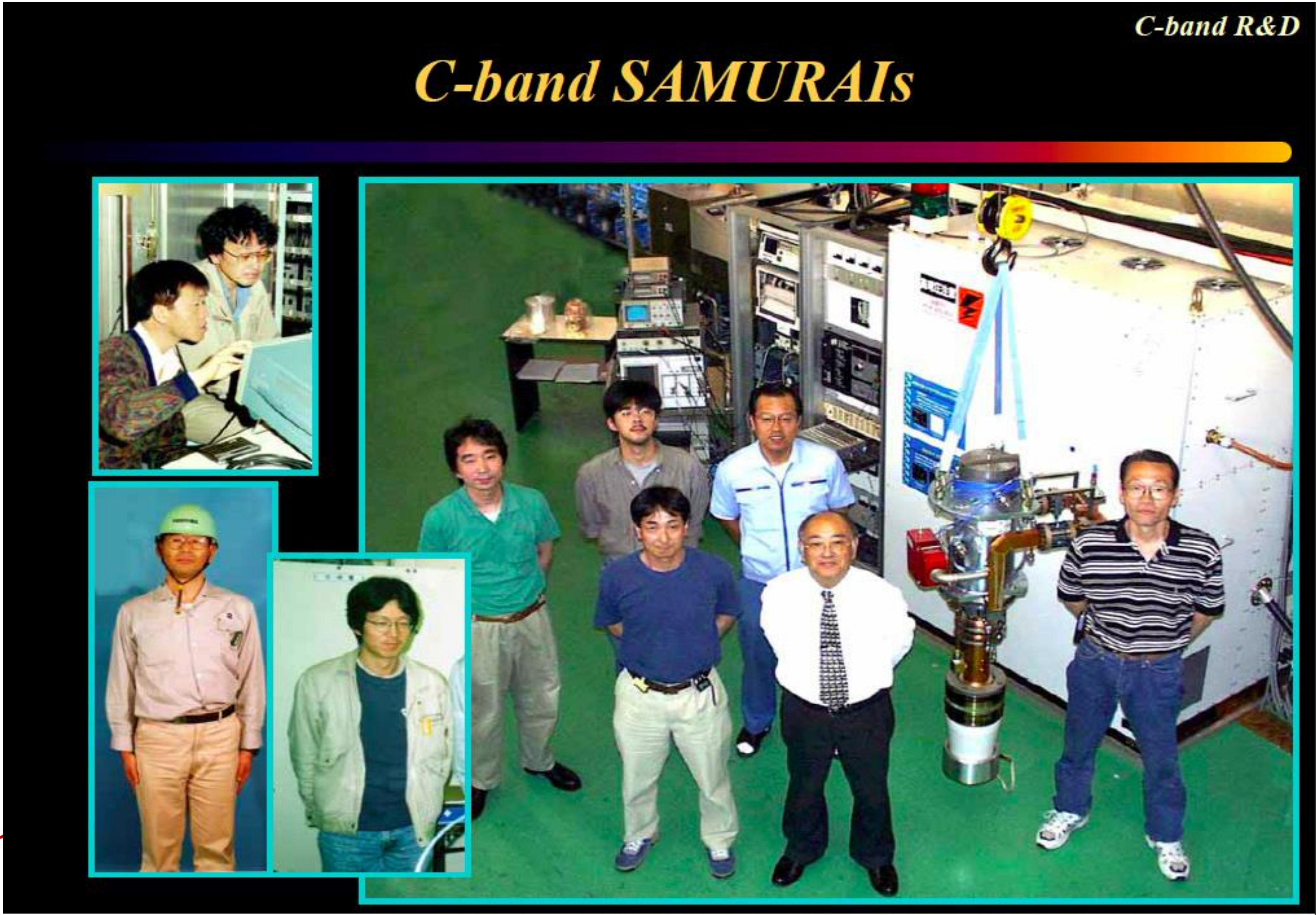


In SACLA, to lower the risk, we prepared power supply for individual klystron.

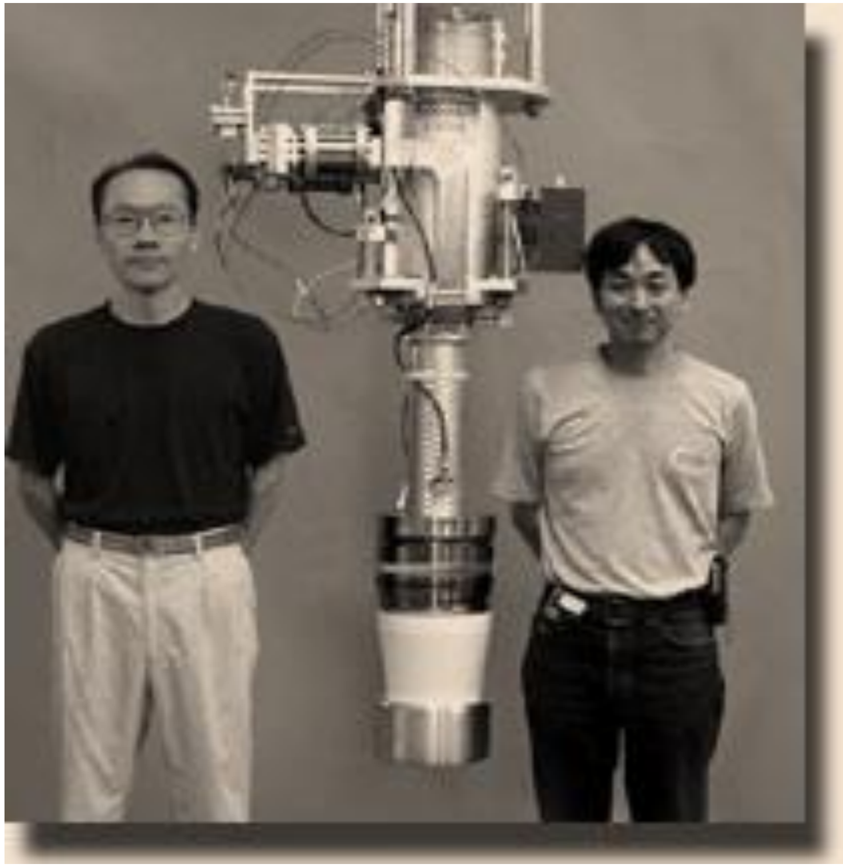



May 2010

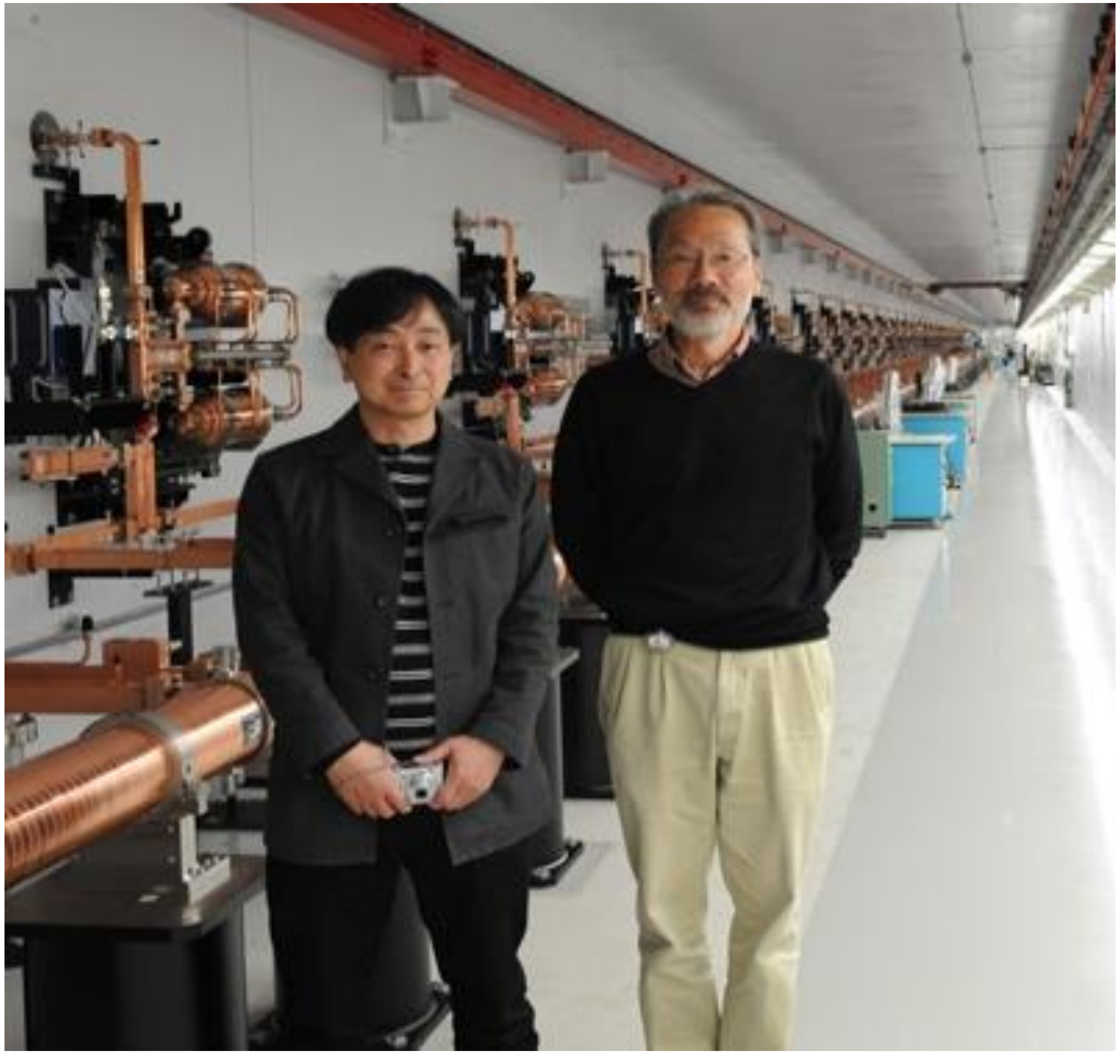
C-band R&D 1995-2000: To show 35 MV/m acceleration at C-band.



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.

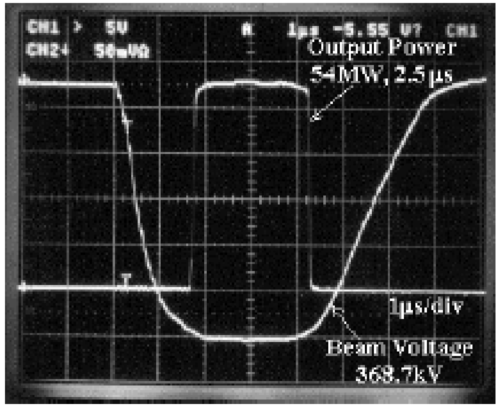
Photo credit: Visual Art Services

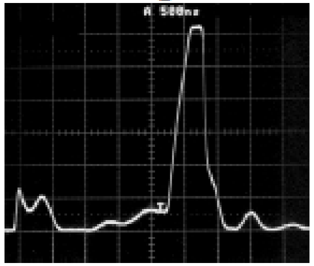
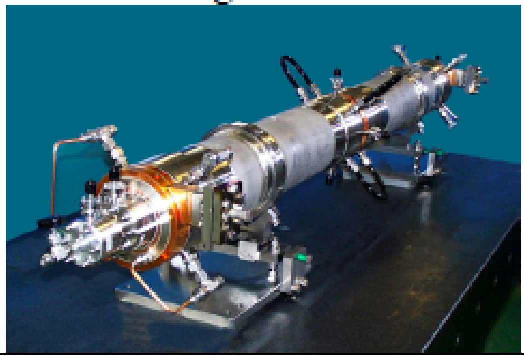
1995, Prof. G. A. Loew (former accelerator division director) gave an old C-band 5 MW klystron as a gift, which has been sleeping quite a ling time at SLAC storage, it was originally used for RF particle separator R&D at CERN.

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.

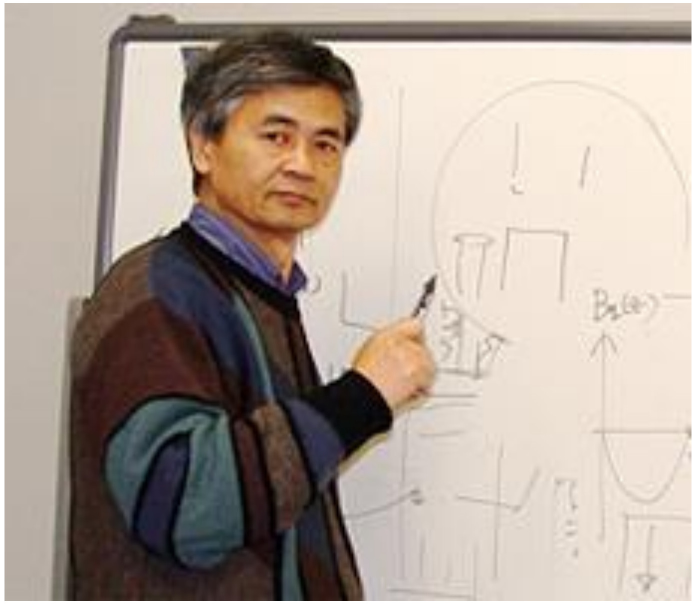
Table-1 : Results of Phase-I R&D and future task in Phase-II.

Items	Phase-I R&D Target	Future R&D Task (Phase – II)
	Achieved Results	
Klystron 	Output 50 MW、 Efficiency >45% Pulse width >2.5 μsec Pulse repetition 100 pps Focusing Power < 5 kW	Refine design details for the mass-production and reducing cost.
	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 > 5000 hours. PPM tube is under development.	 Example of output,
Pulse Modulator Supply 	350 kV、2.5 μsec pulse generation, power efficiency >50%	Smart Modulator No. 2 Design refinement for Cost reduction, Modular component, Efficiency Improvement > 60% Study on switch device. Improve thyratron tube life-time.
	Smart Modulator, No. 1 Operating for klystron life-test. Power efficiency >52.4%	

RF Pulse Compressor 	Power gain >3.5、 Power efficiency >70% Cold Model Test Power Gain 3.25, Efficiency 65%	High Power Model Test Improve Power Efficiency >70 % Refine cavity design. Utilize pulse rising part of modulator. Low thermal expansion metal.
Accelerating Structure 	Multi-bunch 1.6 nC, 80 bunch Acceleration gradient> 35 MV/m ASSET test at SLAC demonstrated damping performance of the choke-mode cavity.	Refine design details. Optimization for mass-production. Lowering cost.
RF-BPM 	Straightness of structure < 50 μm Resolution of RF-BPM <100 nm Position accuracy < 10 μm Resolution ~ 25 nm (FFTB test) Position accuracy < 10 μm	Optimization for multi-bunch beam Detection circuit for multi-bunch. Damping HOM in RF-BPM.

- 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.

Submitted to SPIE's 46th Annual Meeting,
The International Symposium on Optical Science and Technology, 29 July – 3 August 2001, San Diego, California, U

SPring-8 Compact SASE Source (SCSS)

Tsumoru Shintake[*a], Hiroshi Matsumoto[a], Tetsuya Ishikawa[b] and Hideo Kitamura[**b]
[a]High Energy Accelerator Research Organization
[b]Harima Institute, RIKEN, SPring-8

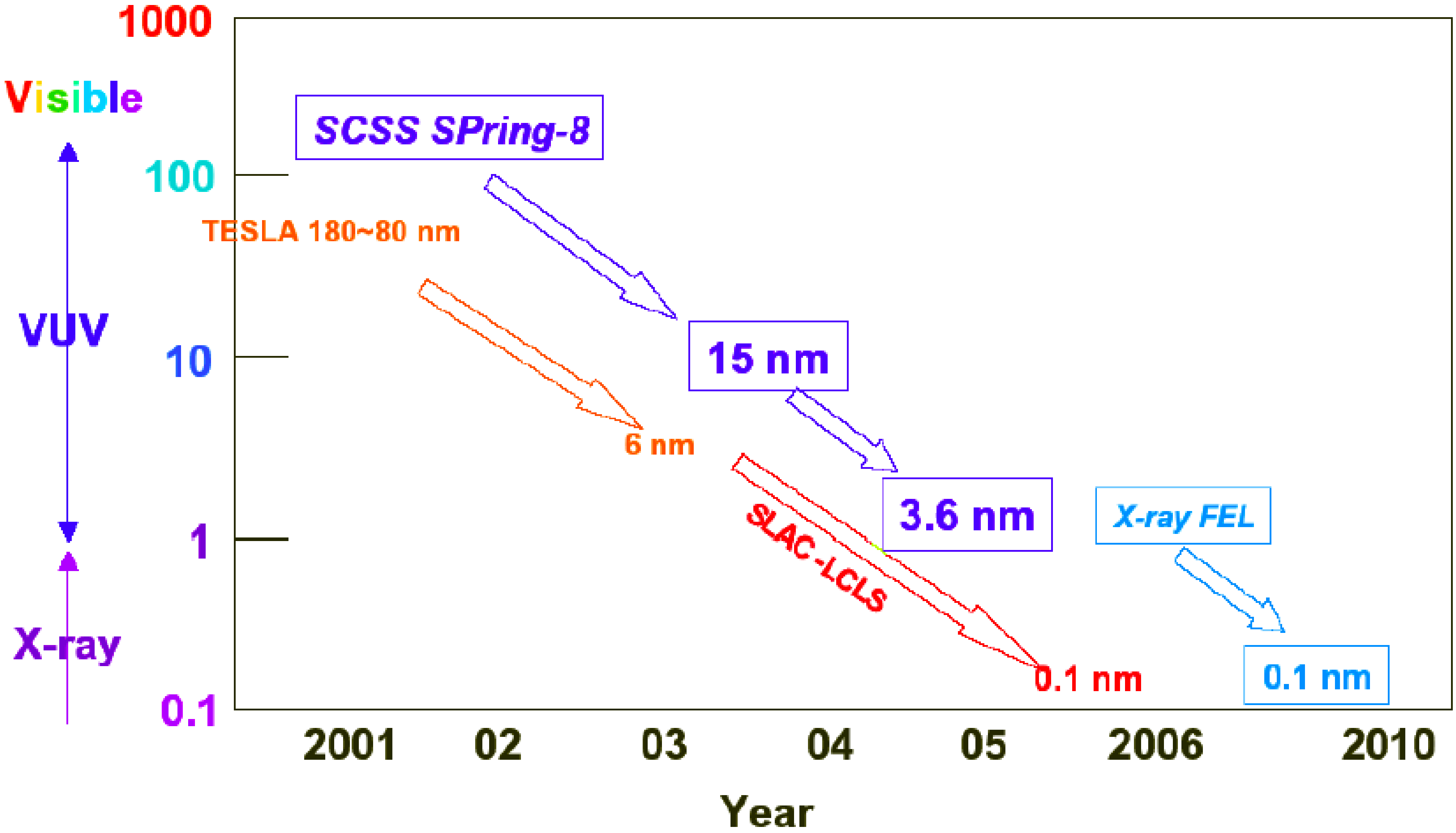
SPIE 2001 July.

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

X-ray FEL

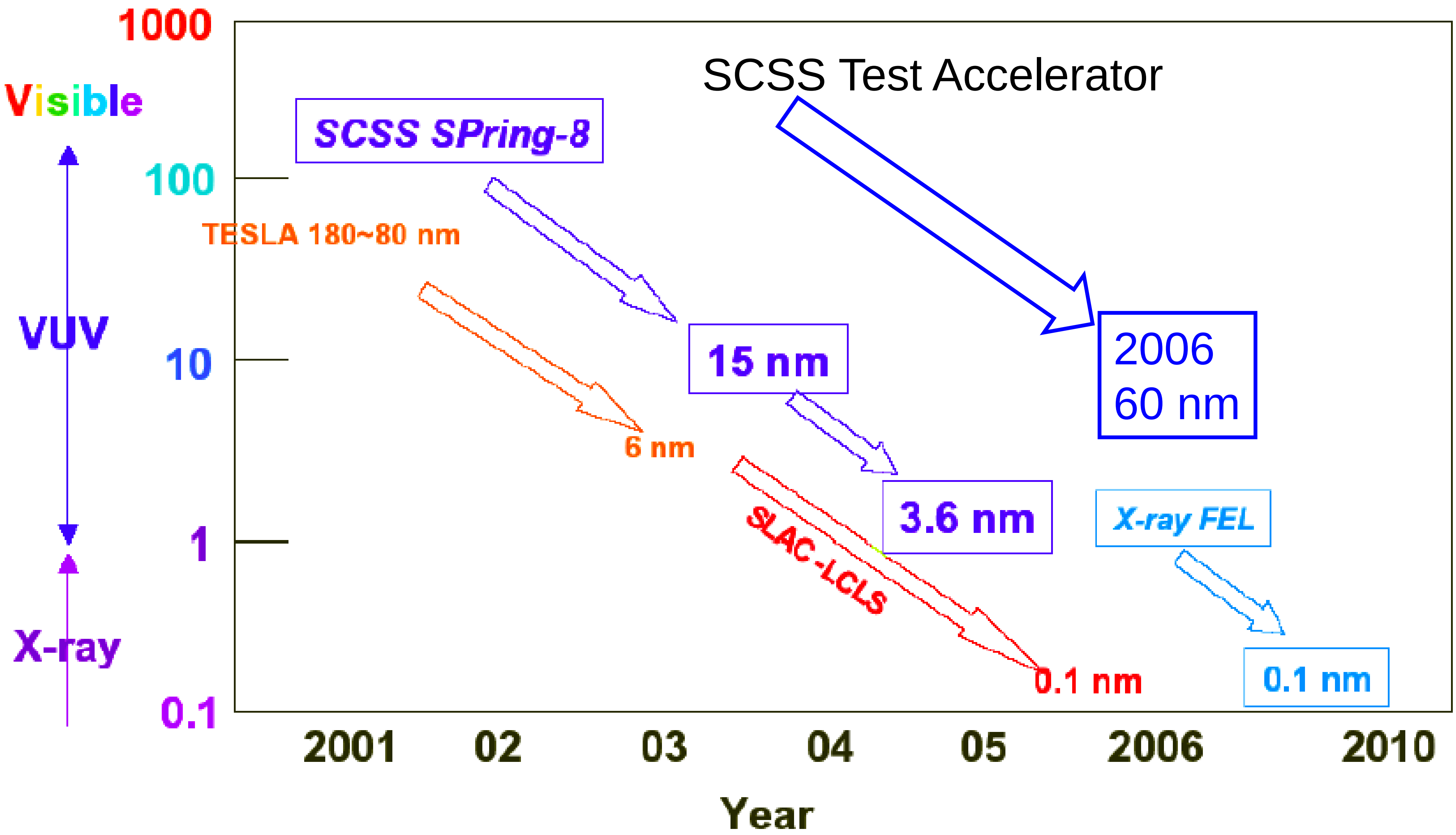
SPIE 2001 July.



Milestone of SPring-8 SCSS

X-ray FEL

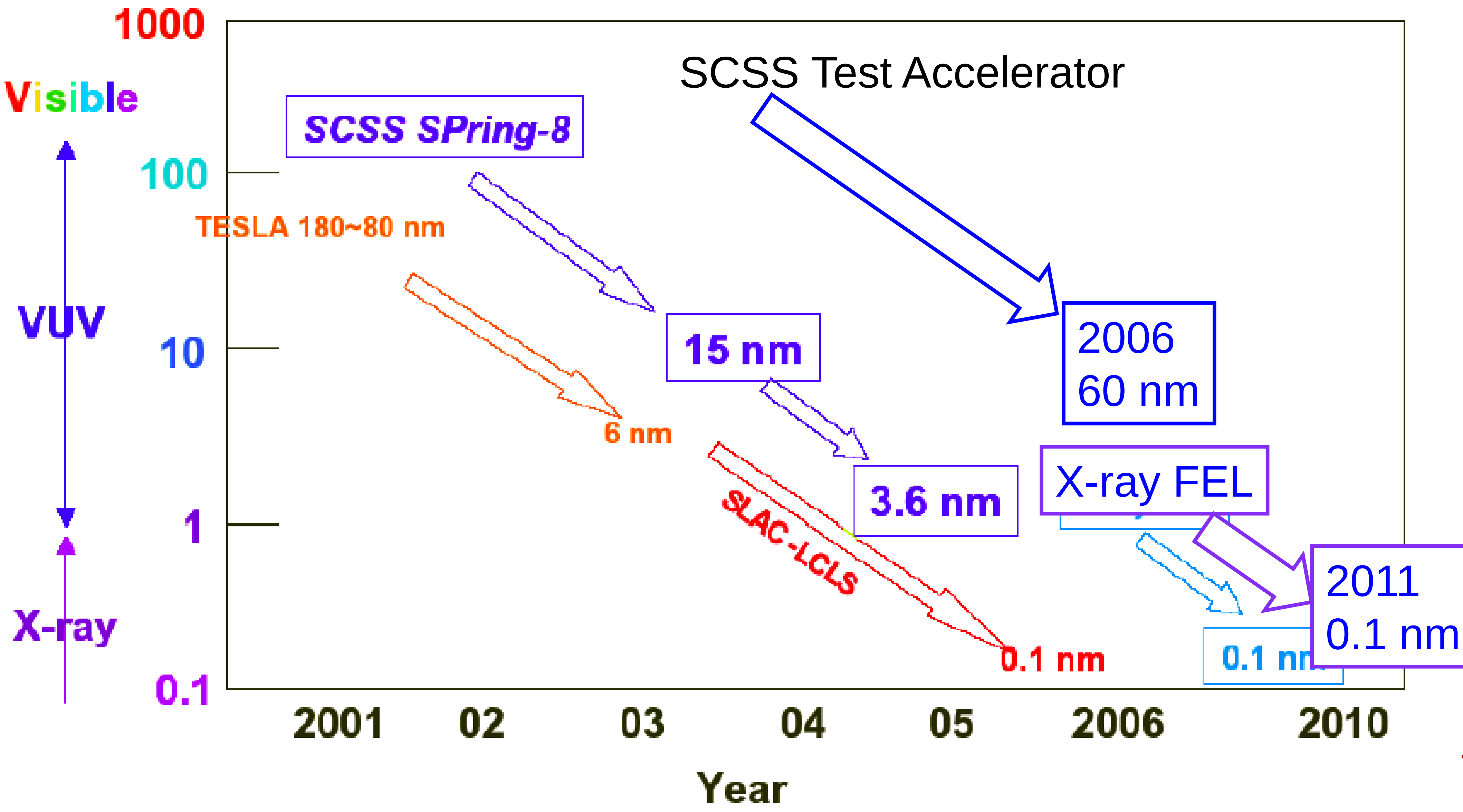
SPIE 2001 July.



Milestone of SPring-8 SCSS

X-ray FEL

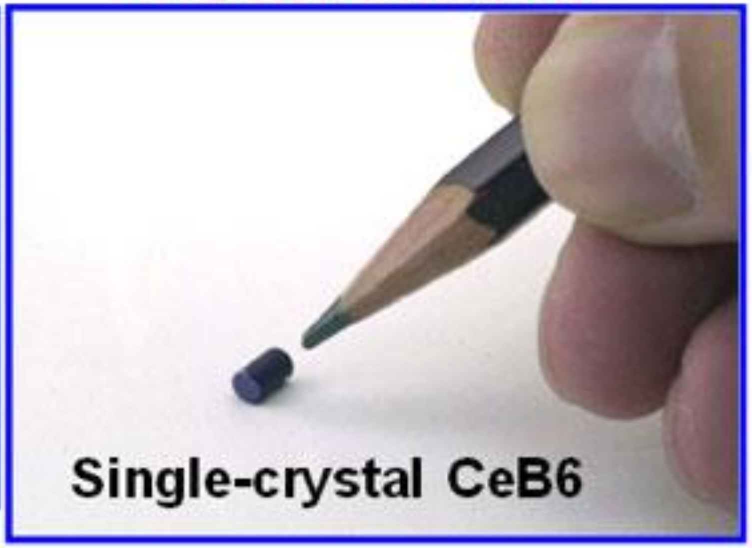
SPIE 2001 July.

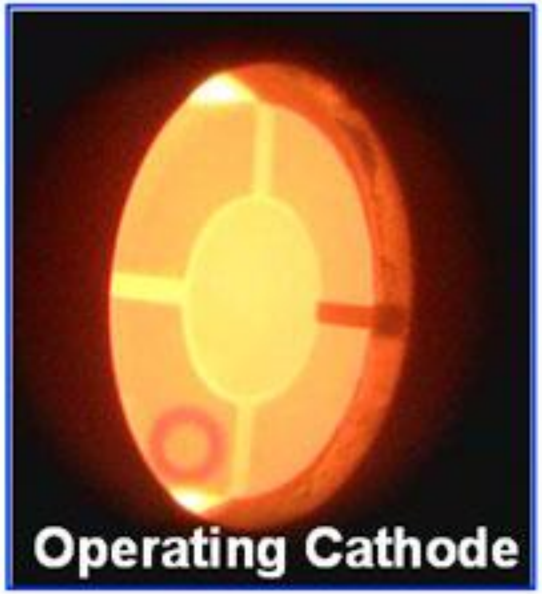


Single-crystal CeB_6 Cathode for XFEL/SPring-8 & SCSS Low-emittance Injector

No HV breakdown for 4 years daily operation

After 20,000 hours operation 1 crystal changed.

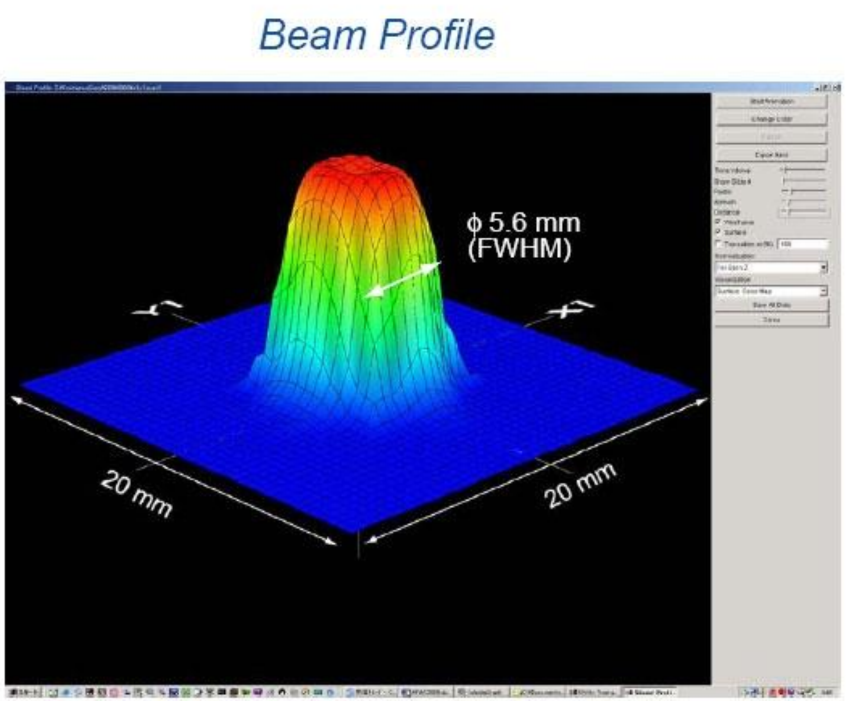


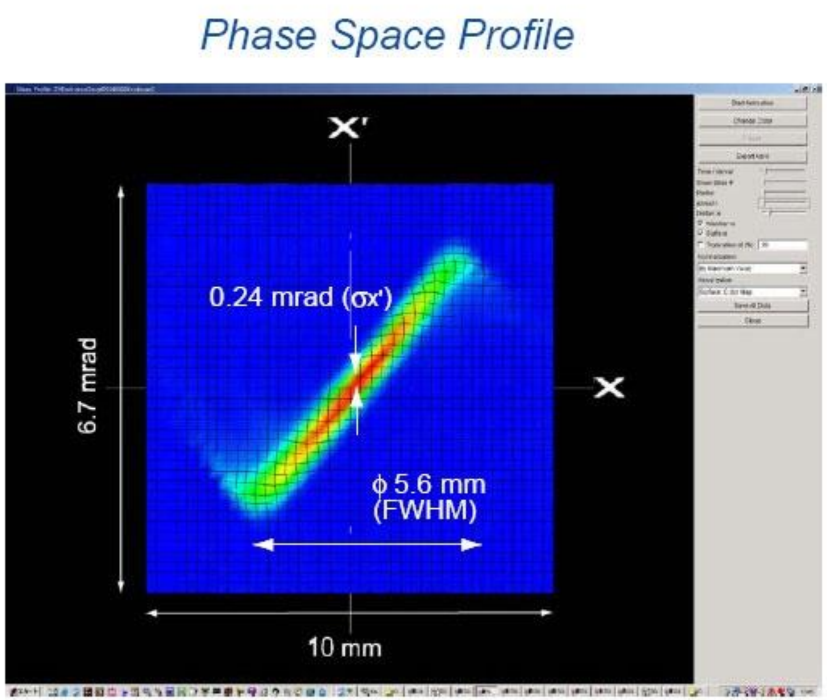


Diameter : ϕ3 mm
Temperature : ~1500 deg.C
Beam Voltage : 500 kV
Peak Current : 1 A
Pulse Width : ~2 μs
Beam Chopper: 1 nsec

Dr. K. Togawa

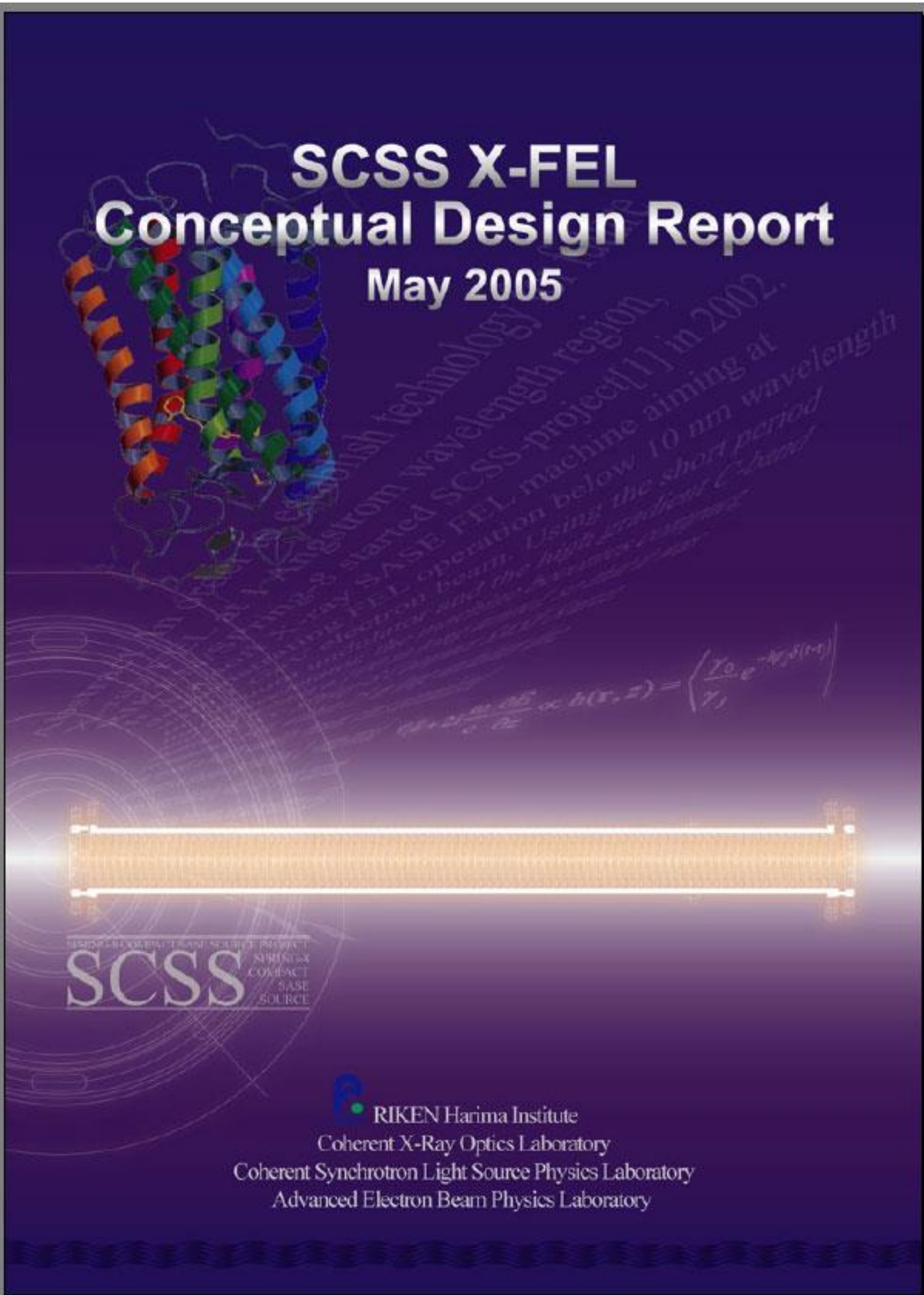
Measured Emittance at the cathode, long pulse.

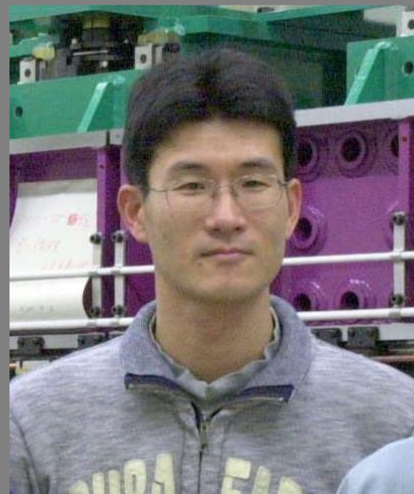




Beam energy	500 keV
Peak current	1 A
Pulse width (FWHM)	3 μs
Repetition rate	10 Hz
Normalized emittance (rms, 100% electrons)	1.1π mm mrad
Normalized emittance (rms, 90% electrons)	0.6π mm mrad

< 1 πmm.mrad


SCSS X-FEL
Conceptual Design Report
May 2005
SCSS
RIKEN Harima Institute
Coherent X-Ray Optics Laboratory
Coherent Synchrotron Light Source Physics Laboratory
Advanced Electron Beam Physics Laboratory

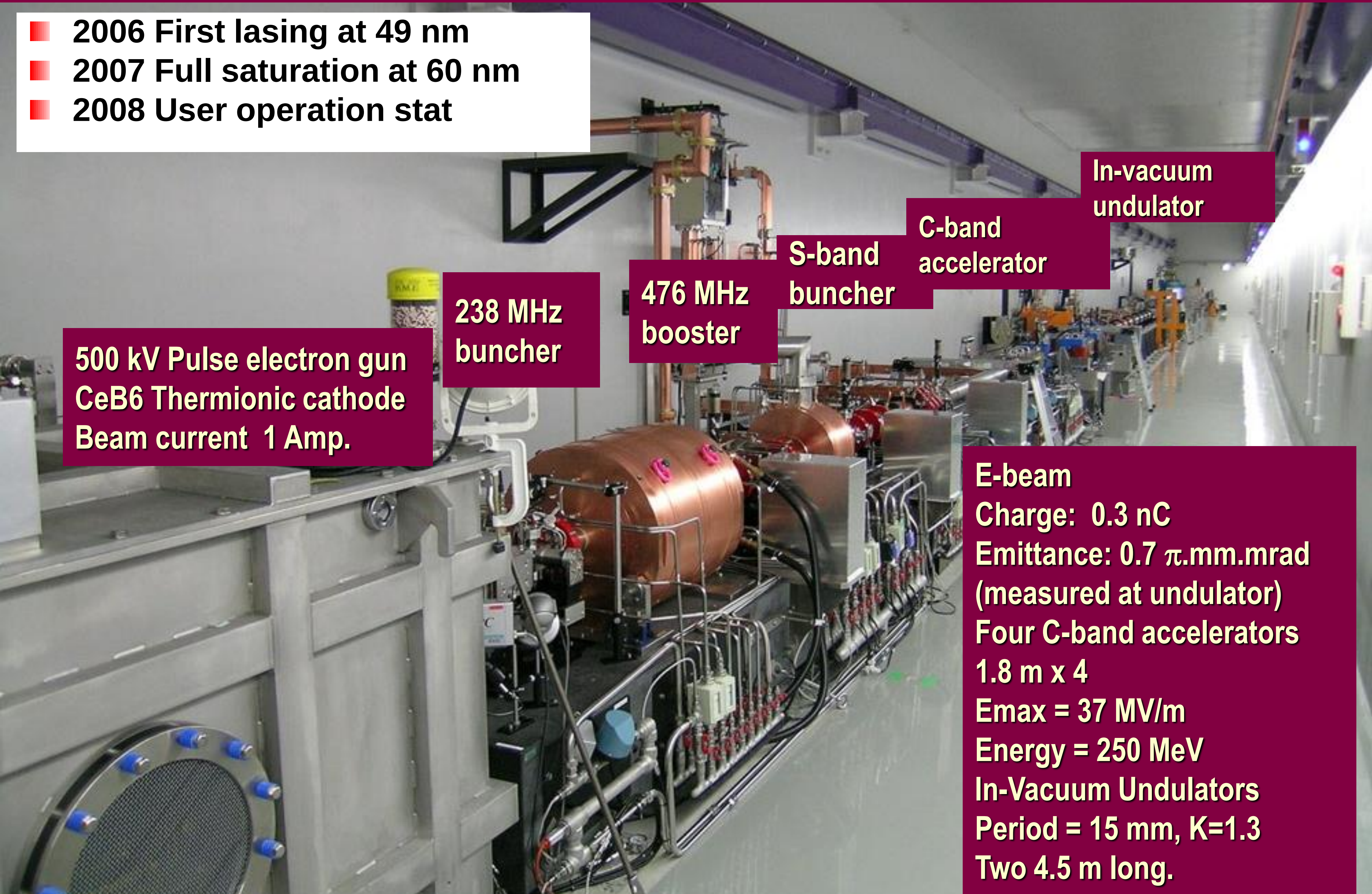


SCSS Technical Review Committee 2005 March

To show emittance preservation, construct
Test Accelerator 2004~2006

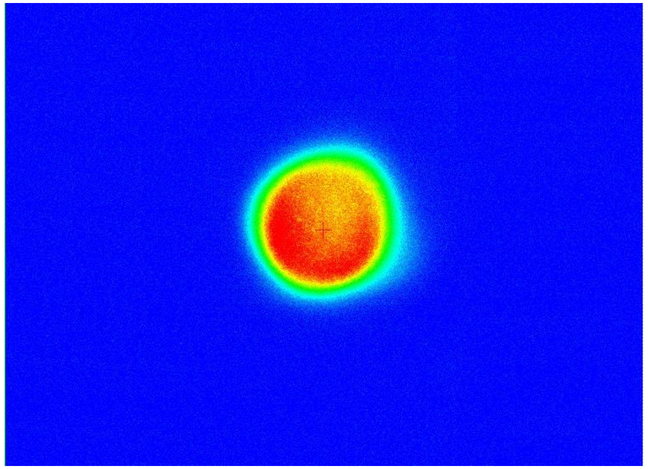
SCSS Test Accelerator

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

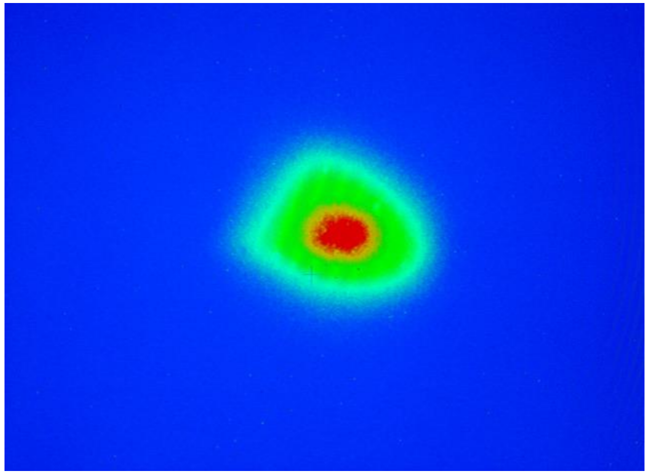


CeB_6 Thermionic Gun provides stable beam.

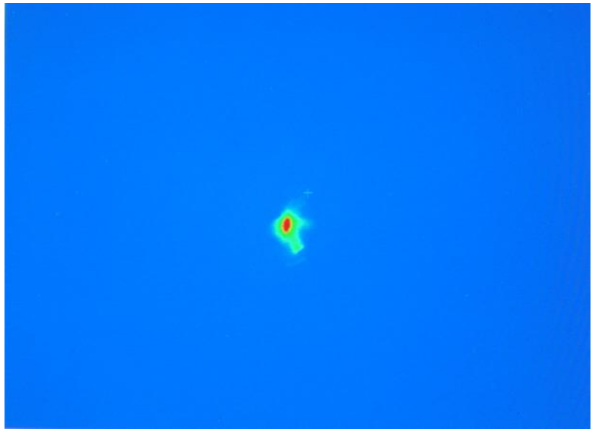
Beam Profile
CCD Image
Scale 10 mm



500 kV Gun

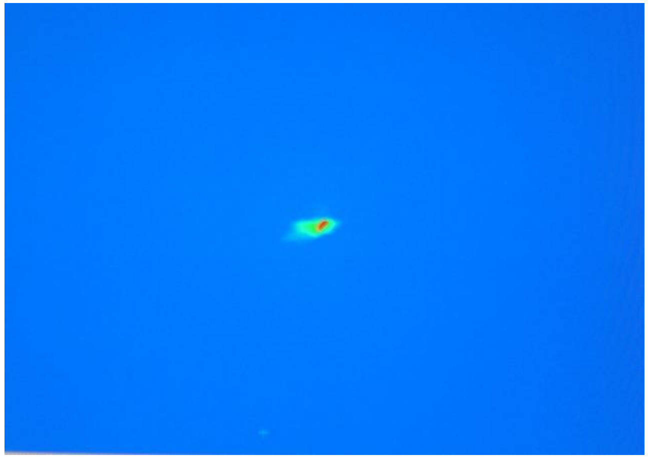


50 MeV Injector Out



250 MeV Compressor

Undulator Input

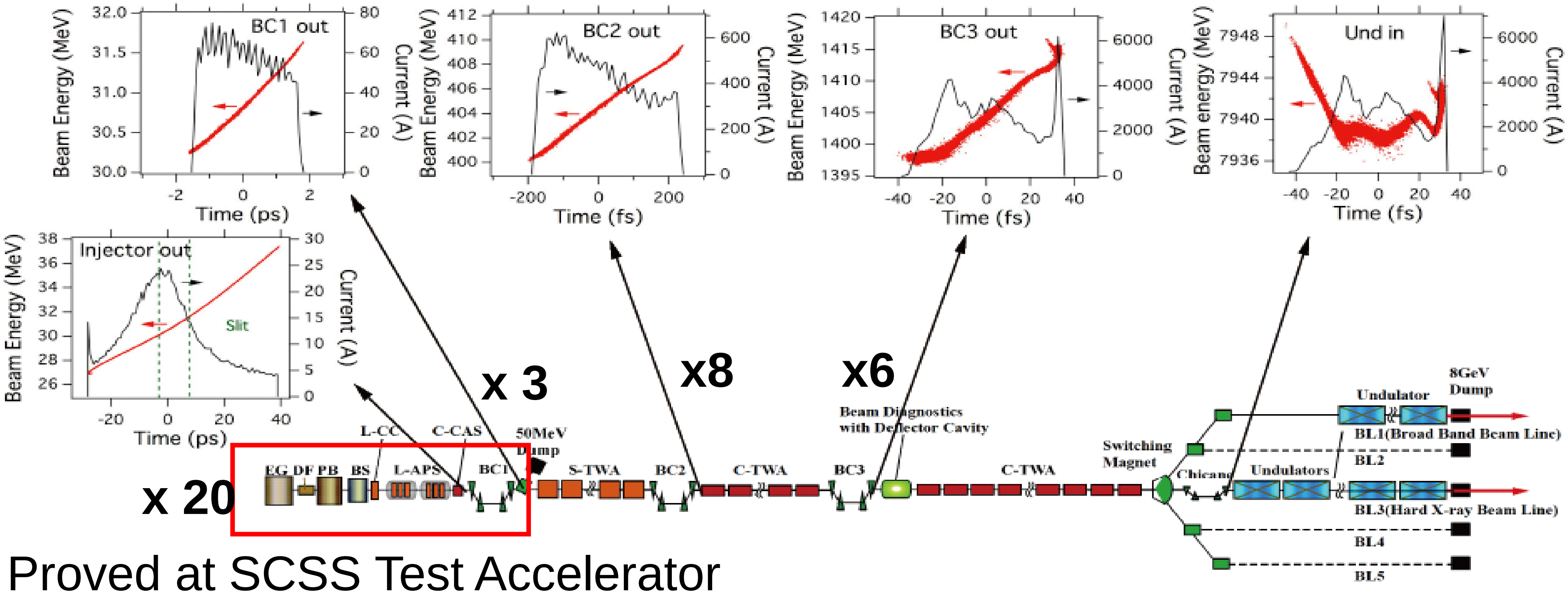


Undulator Output

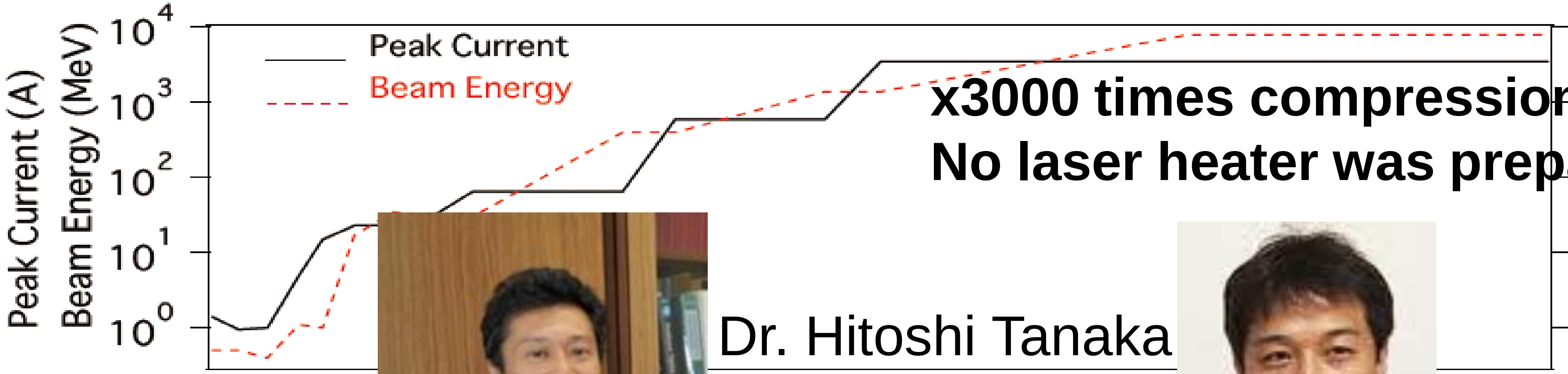
First Lasing at 49 nm in SCSS

June 15, 2006

SACLA 8 GeV Beam Parameter Design



Proved at SCSS Test Accelerator



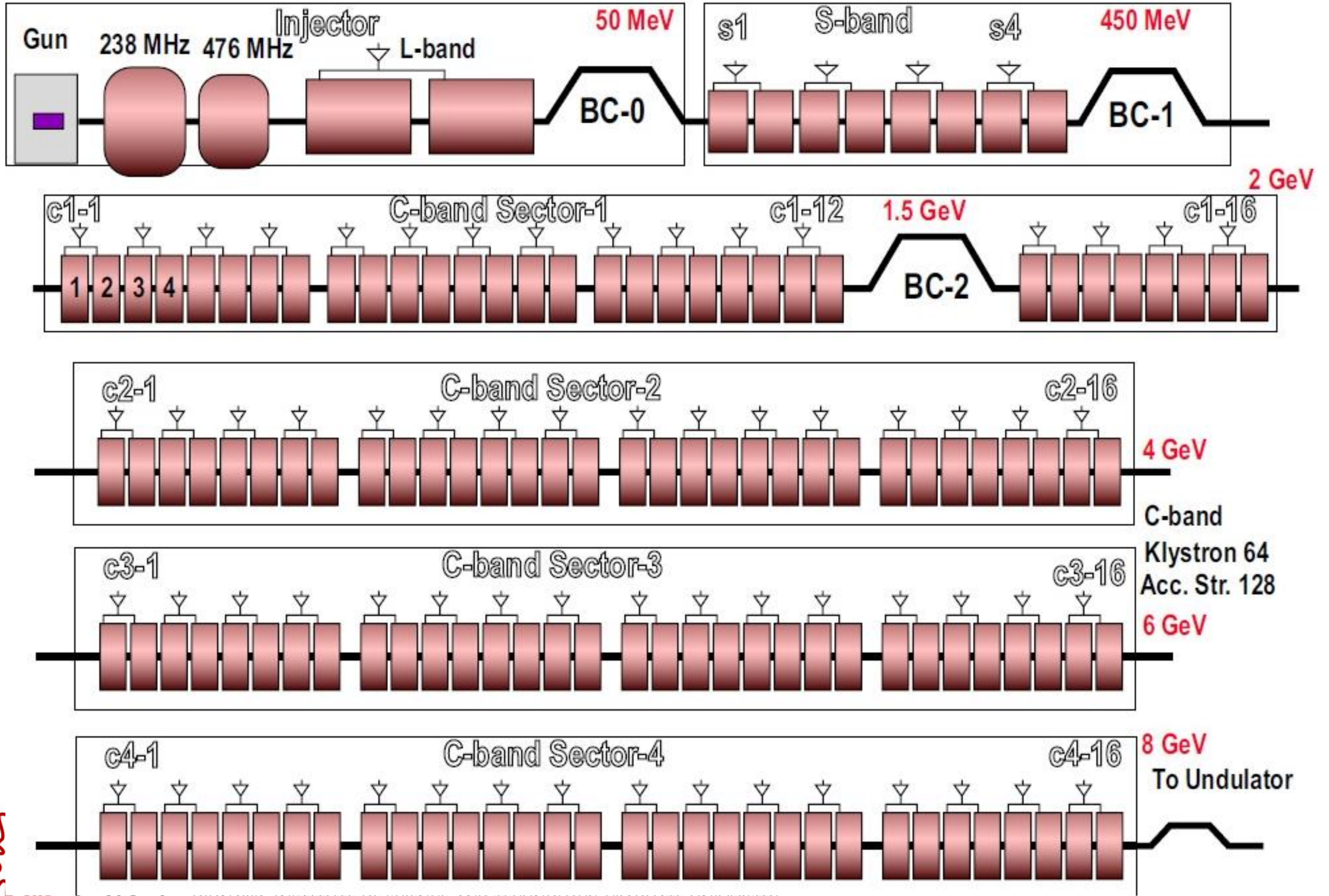
x3000 times compression

No laser heater was prepared.

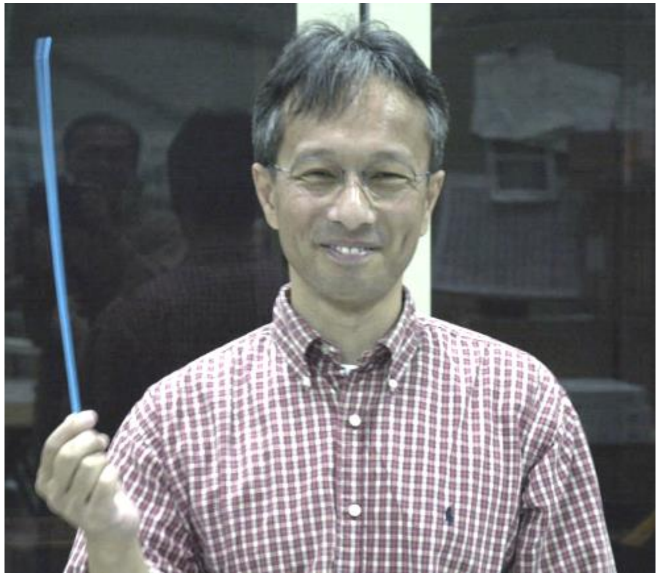
Dr. Hitoshi Tanaka

Dr. Toru Hara

RF Acceleration System in XFEL/SPring-8

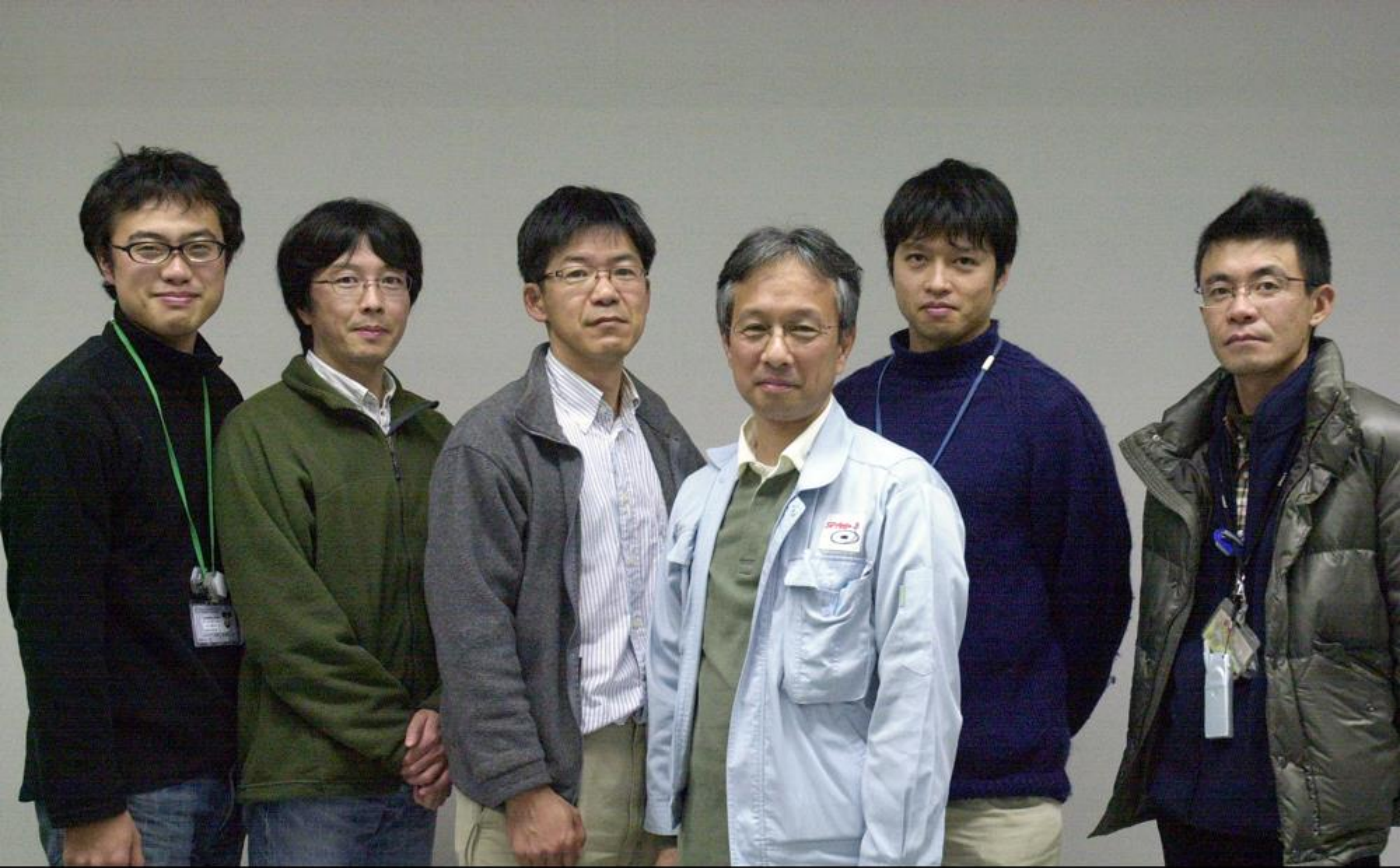


Dr. Yuji Otake made tremendous contributions on SACLA construction.



Dr. Yuji Otake

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



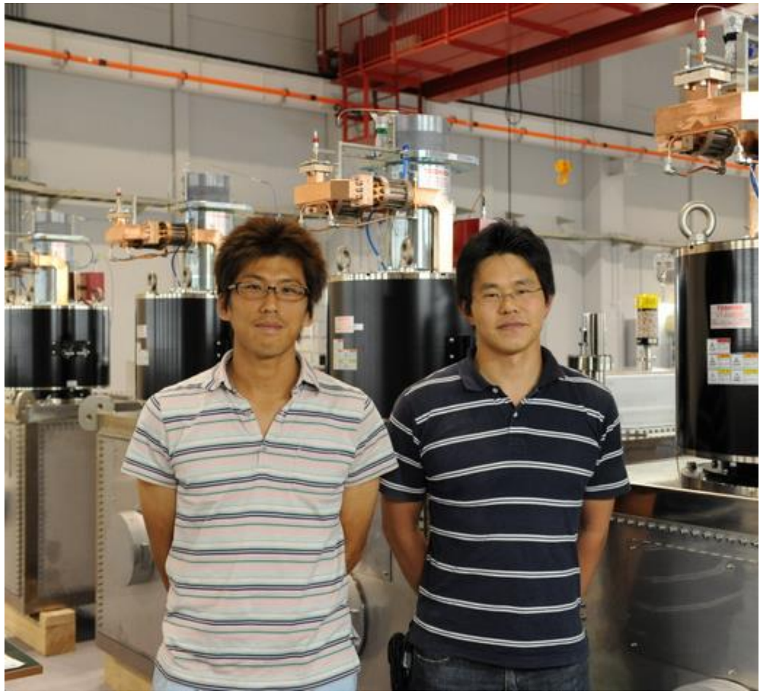
Matsubara Hosoda Oshima Otake Maesaka Inoue

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

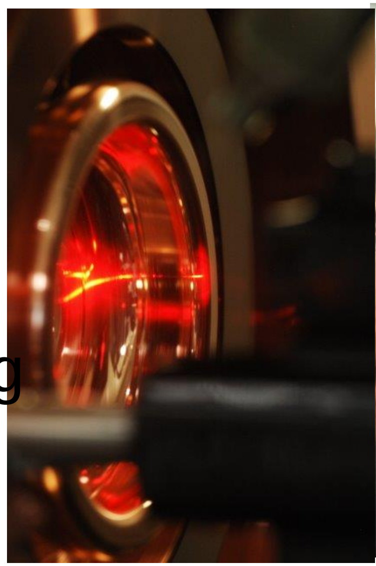
- Fabrication of components with special care at Mitsubishi Heavy Ind. and Hitachi Cable.

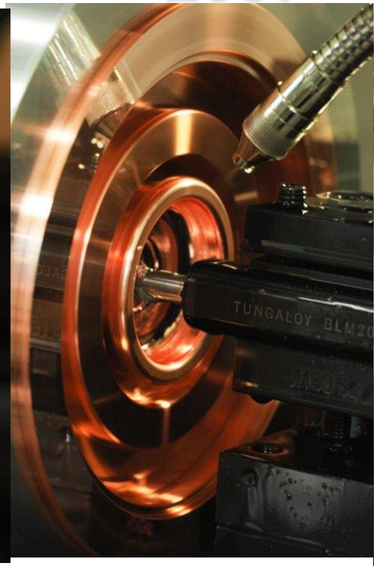
We made 13,000 pieces of C-band accelerator cell.

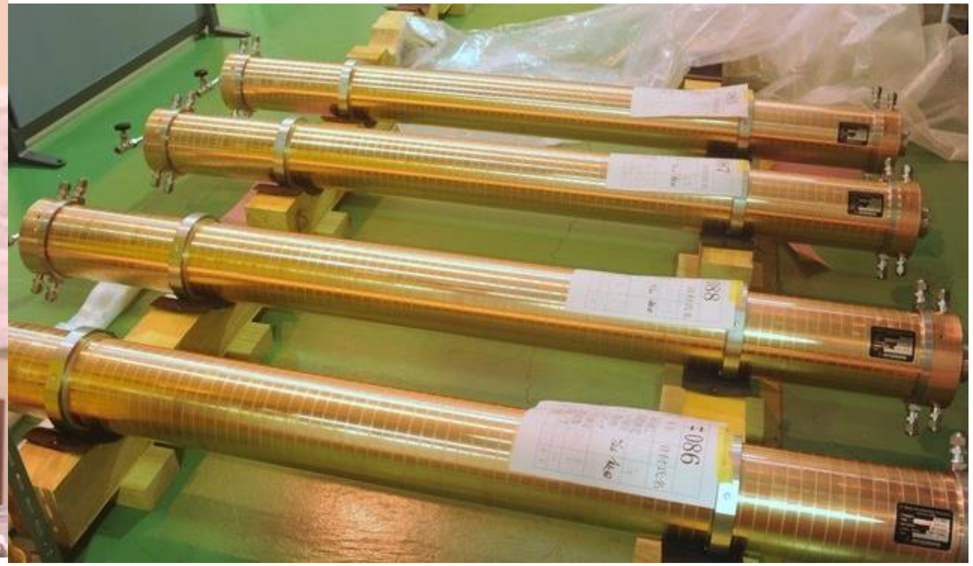
Sadao Miura, MITSUBISHI Heavy Ind,

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

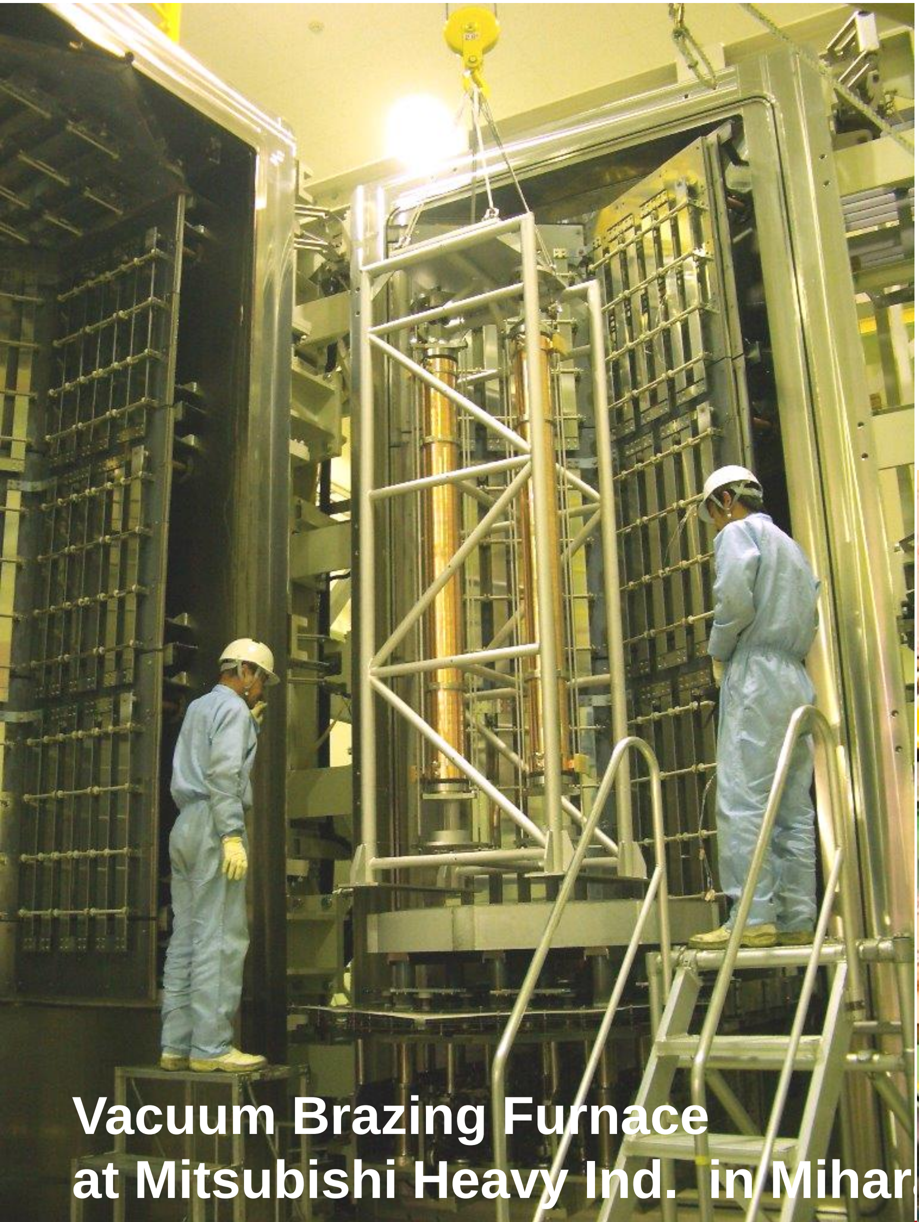
Laser Guided Precision Machining







Brazing of C-band Accelerators



- A number of technical improvements have been made.

- 1~2 columns per week.

Reliable High Power RF Acceleration System

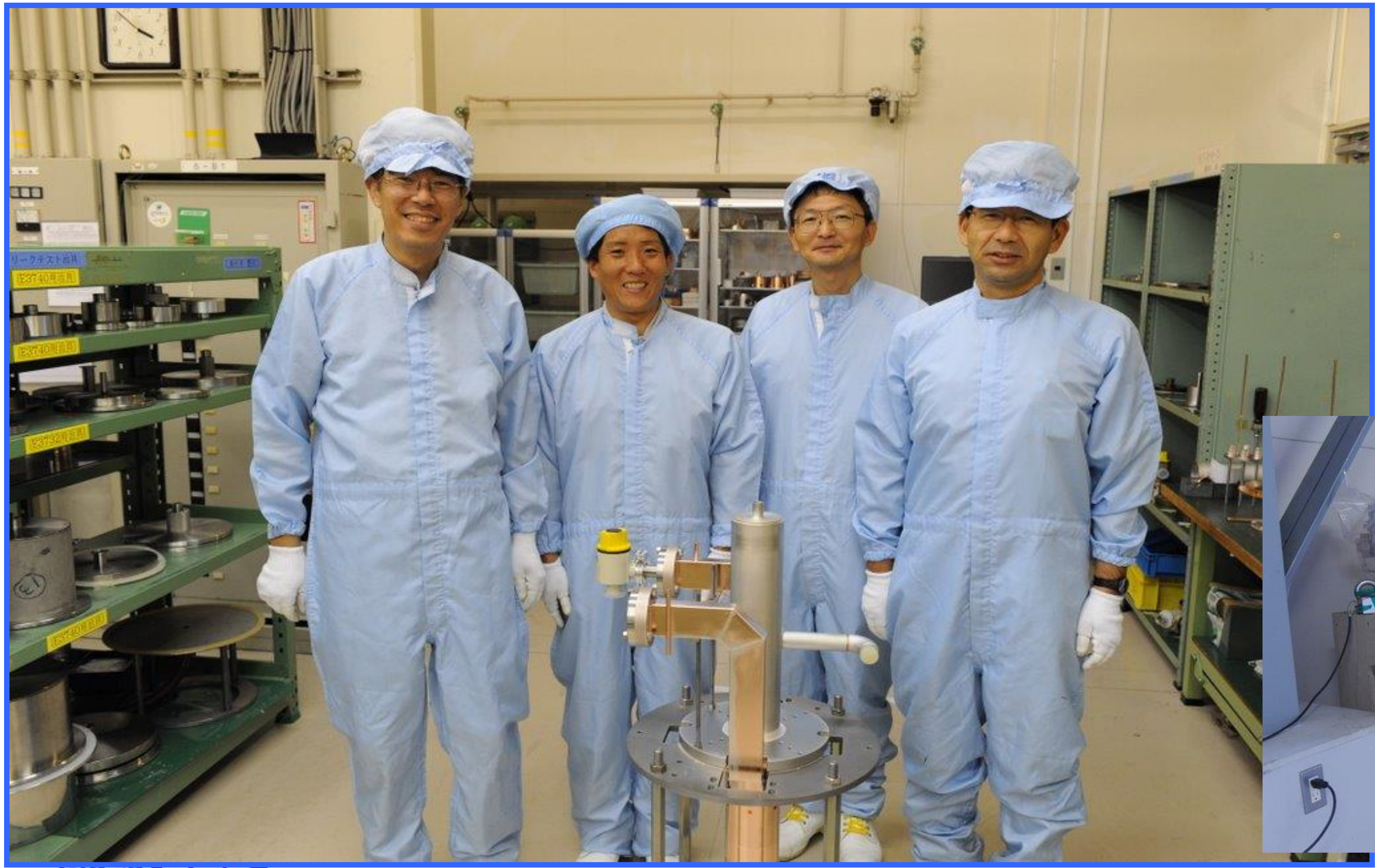
- High power test on rf components is key to develop reliable system.
- Tested up to 40 MV/m.
- Careful installation into the tunnel.

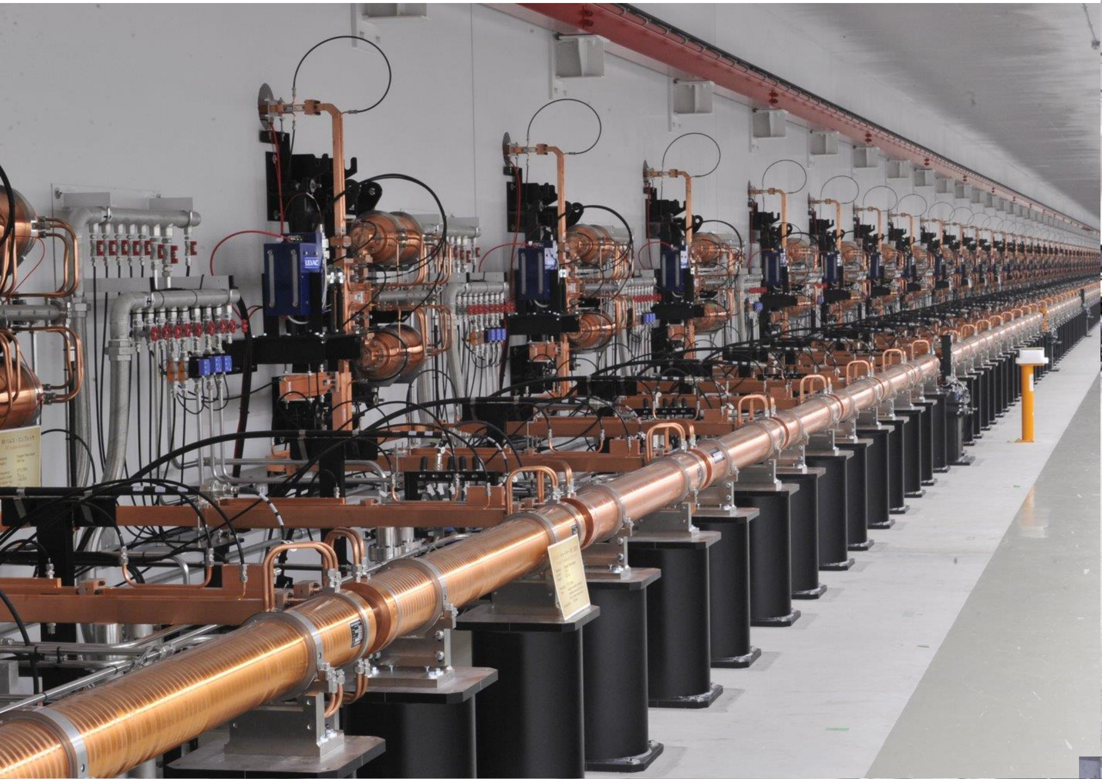
T. Sakurai and T. Inagaki

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.

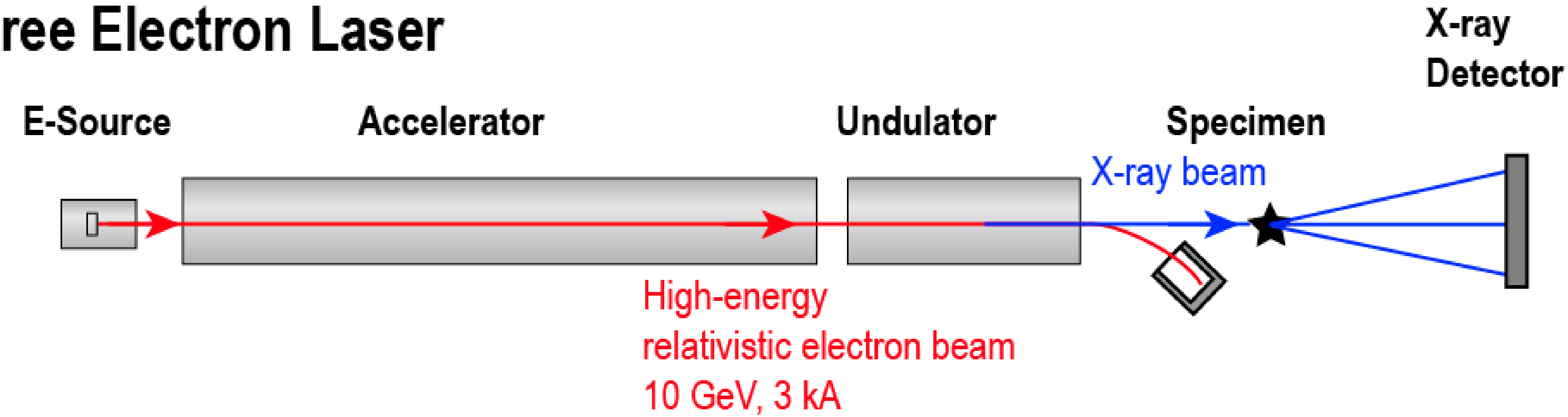
- CeB_6 thermionic gun is providing stable beam, while we need to change cathode after ~10,000 hours operation.

Future Perspective on X-ray Laser and Electron Microscopy based on High Performance Particle Beams

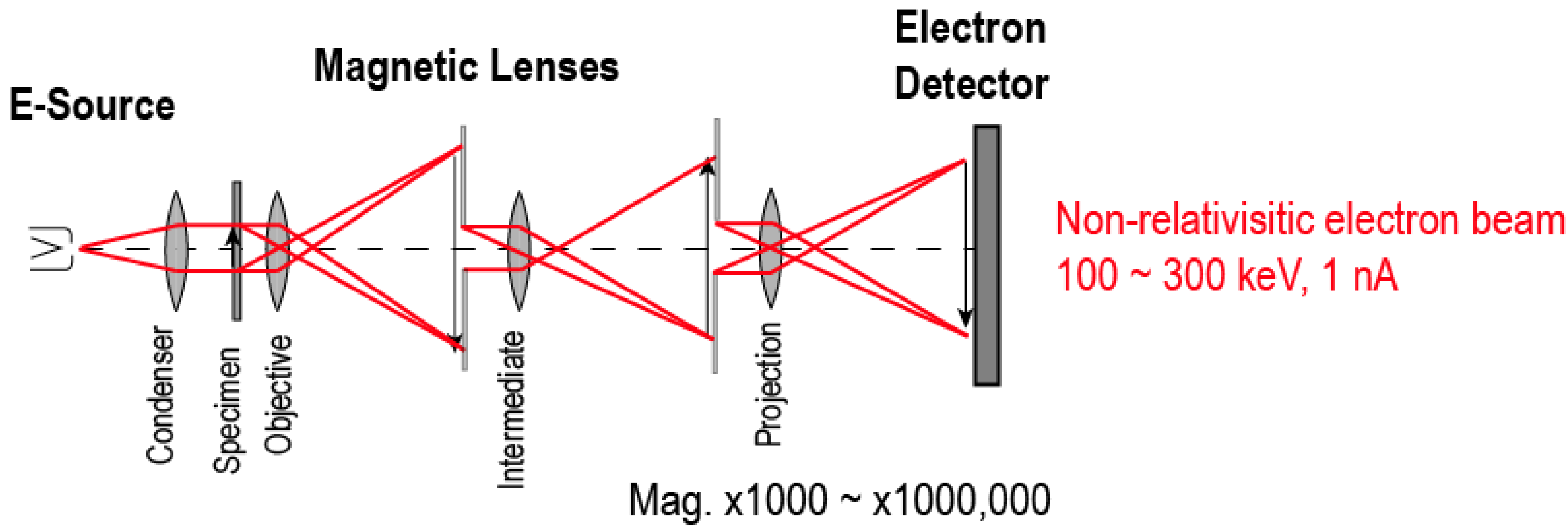
“microscopy of bio-molecule”

Two Different Microscopes for Atomic Resolution

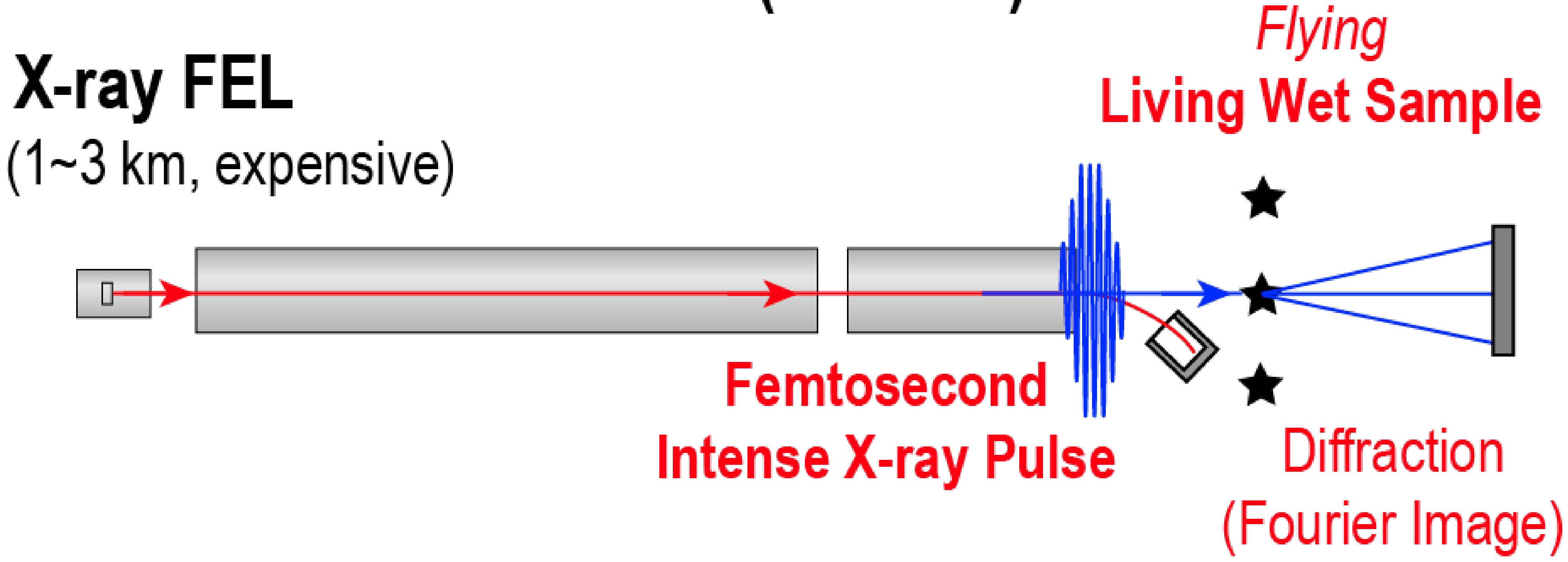
Free Electron Laser

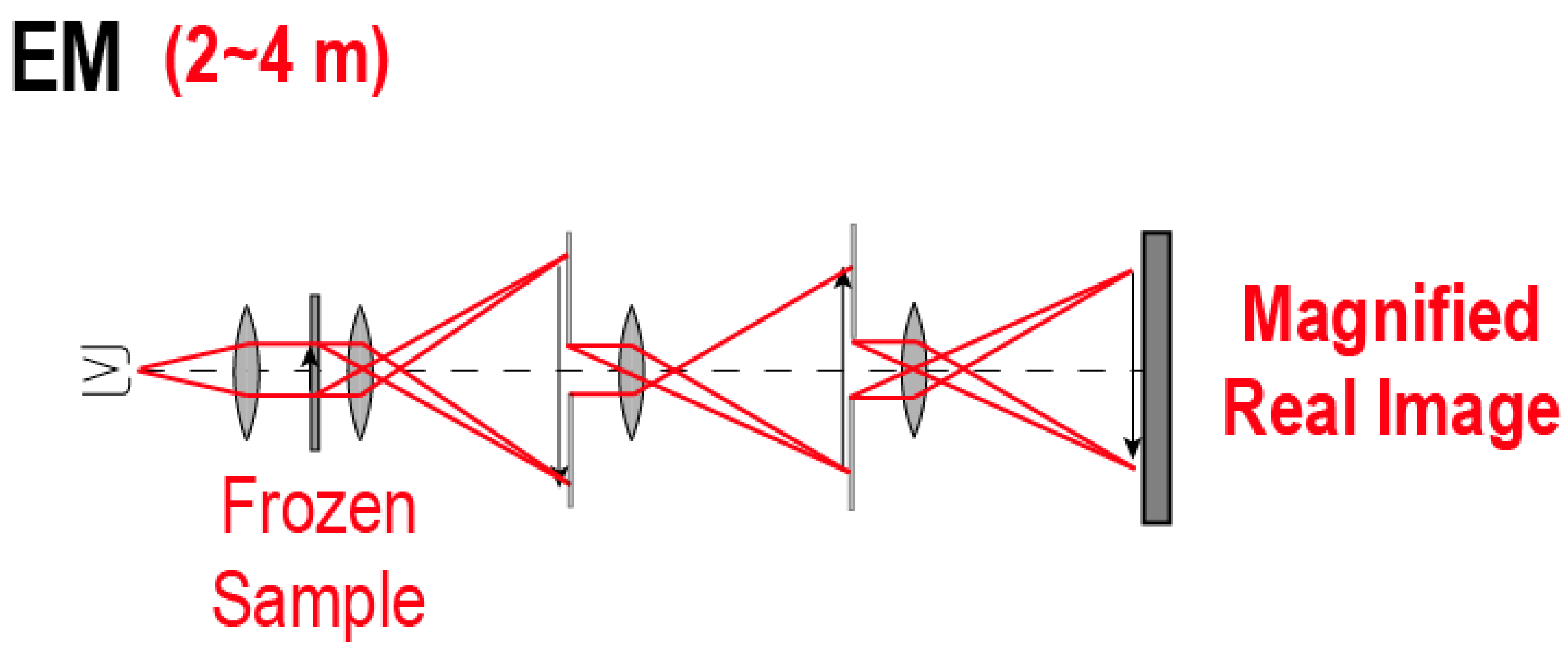


Electron Microscope (TEM)



Features (benefits)

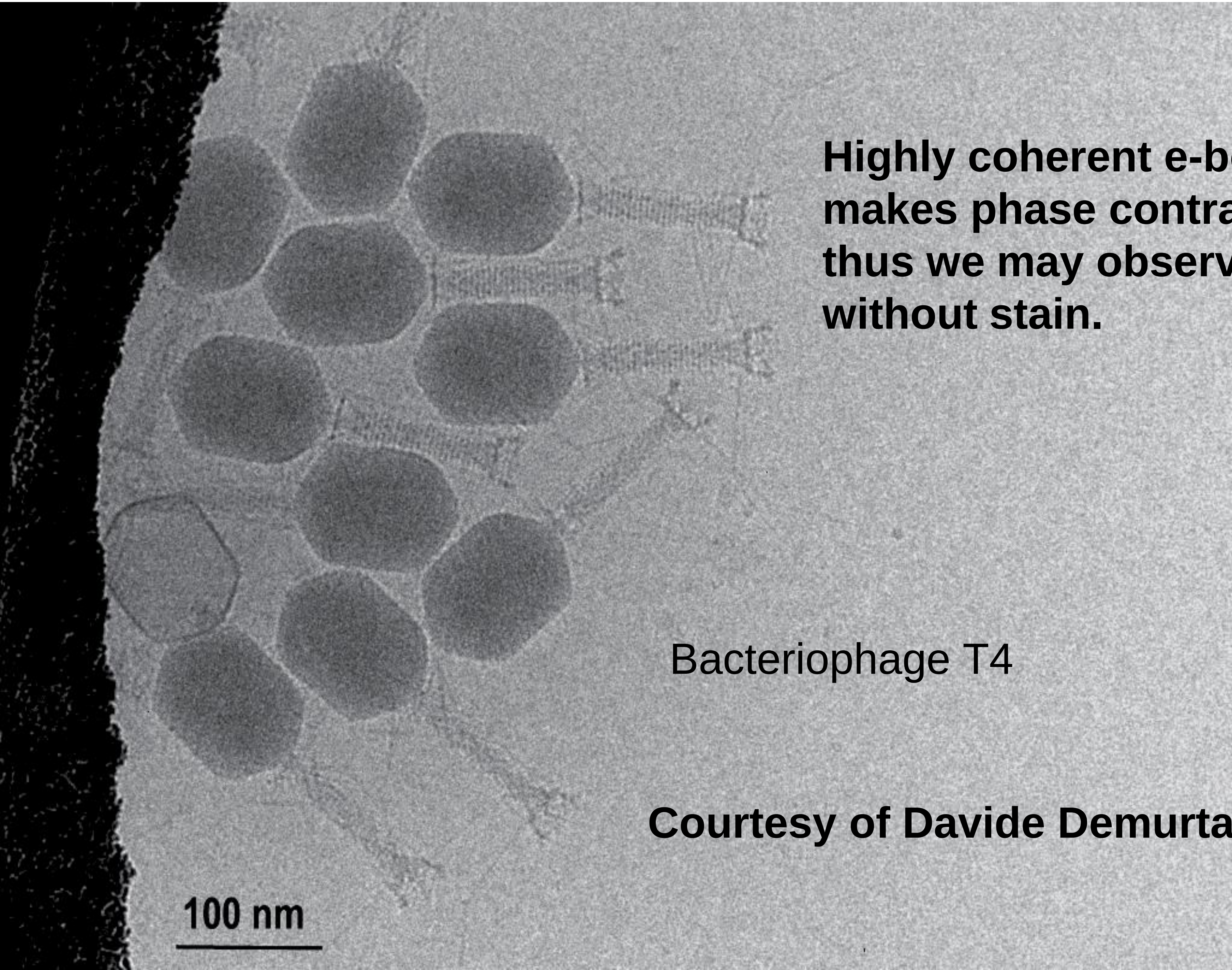




Typical TEM for cryo-microscopy for bio-sample.
V=100~300 kV

Dr. K. Namba at Osaka University

TEM image on ice-embedded bio-sample.

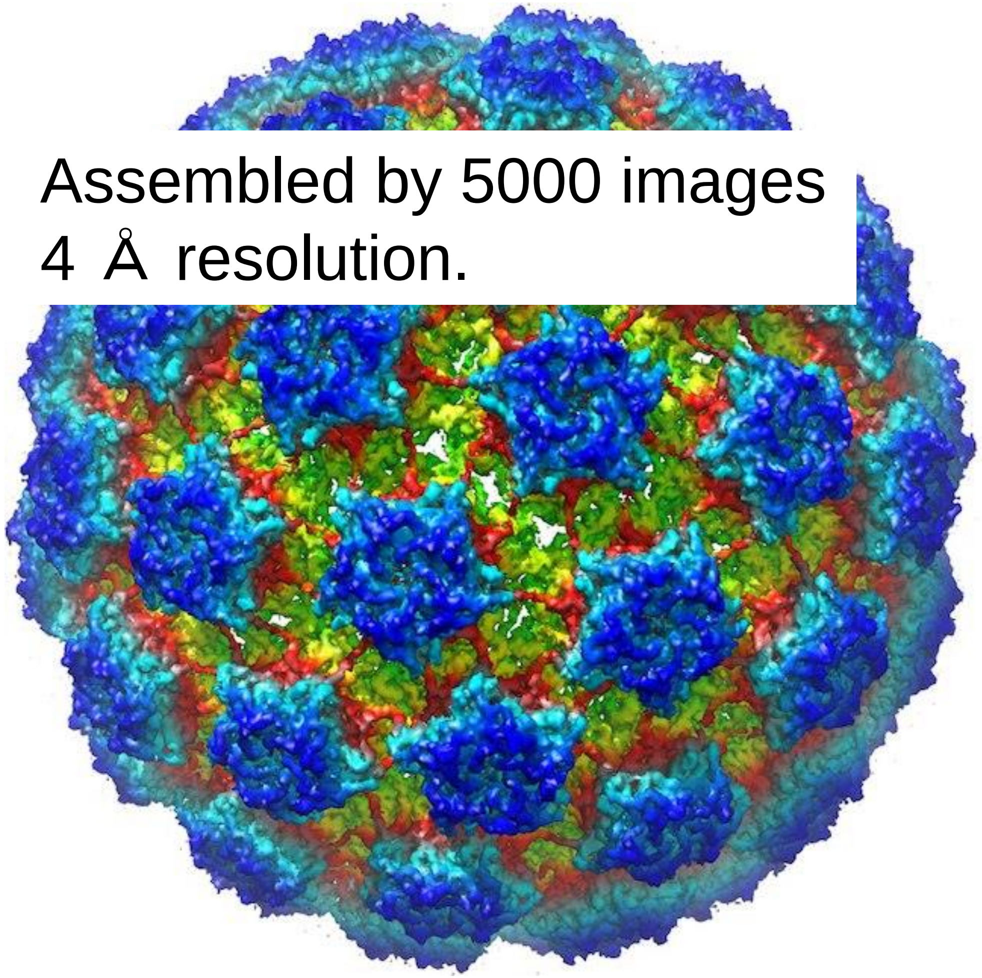


Highly coherent e-beam makes phase contrast image, thus we may observe bio-sample without stain.

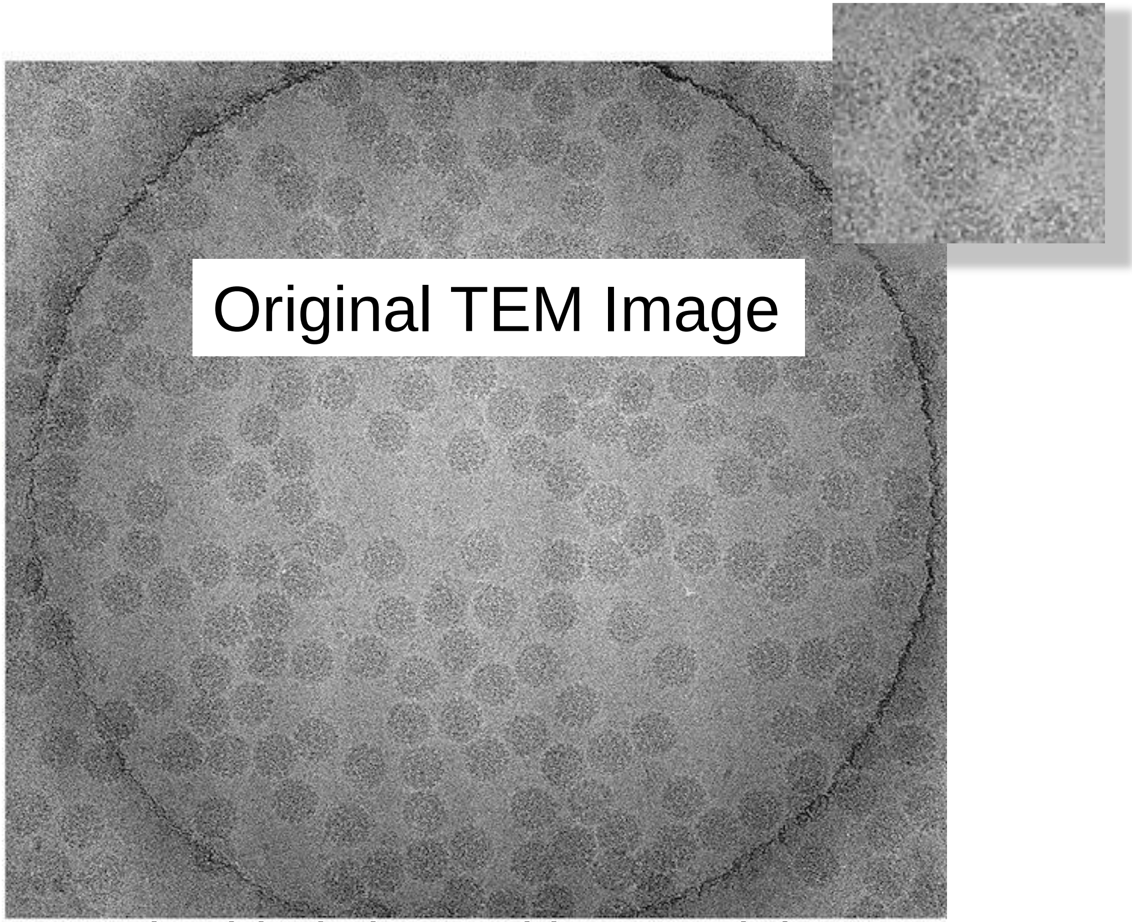
Bacteriophage T4

Courtesy of Davide Demurtas @EPFL

State of art Cryo-electron Microscopy



Assembled by 5000 images
4 Å resolution.



Original TEM Image

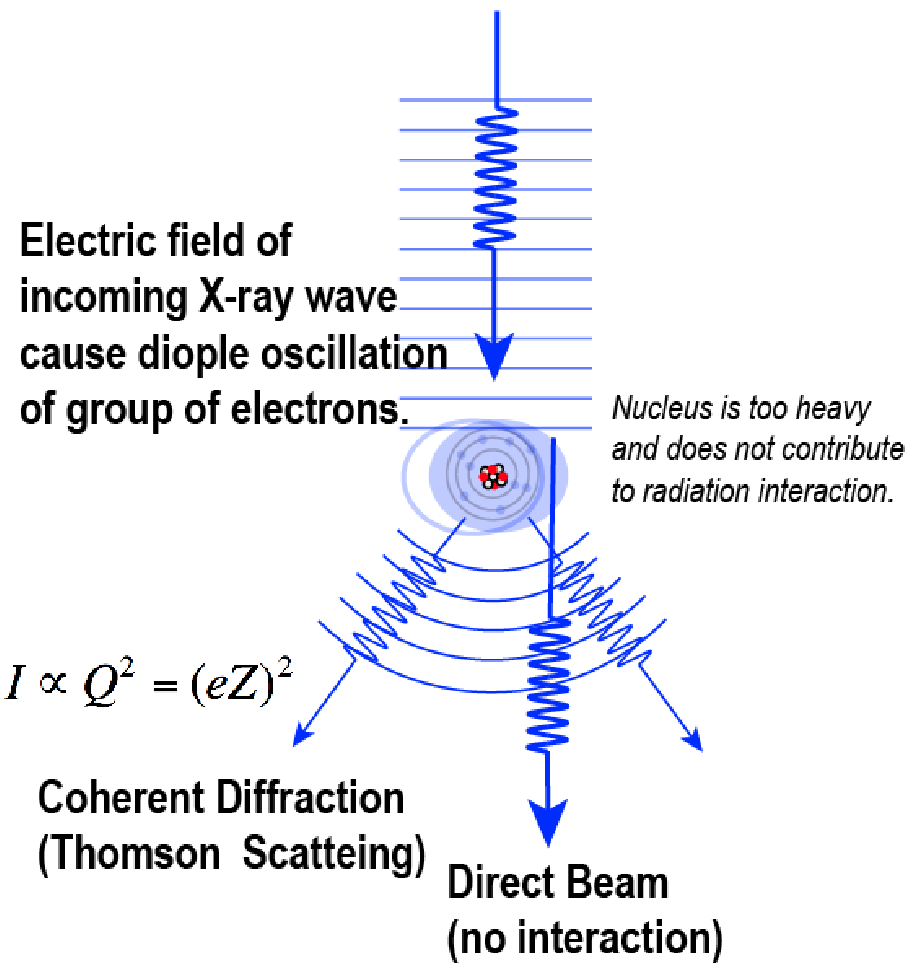
Ice embedded virus, without staining.
Hole diameter 1 micrometer
Ice thickness 80~100 nm
Recorded on film at , 20 e/A^2 dose.
FEI Tecnai F30 @300kV

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

T. Shintake 2012

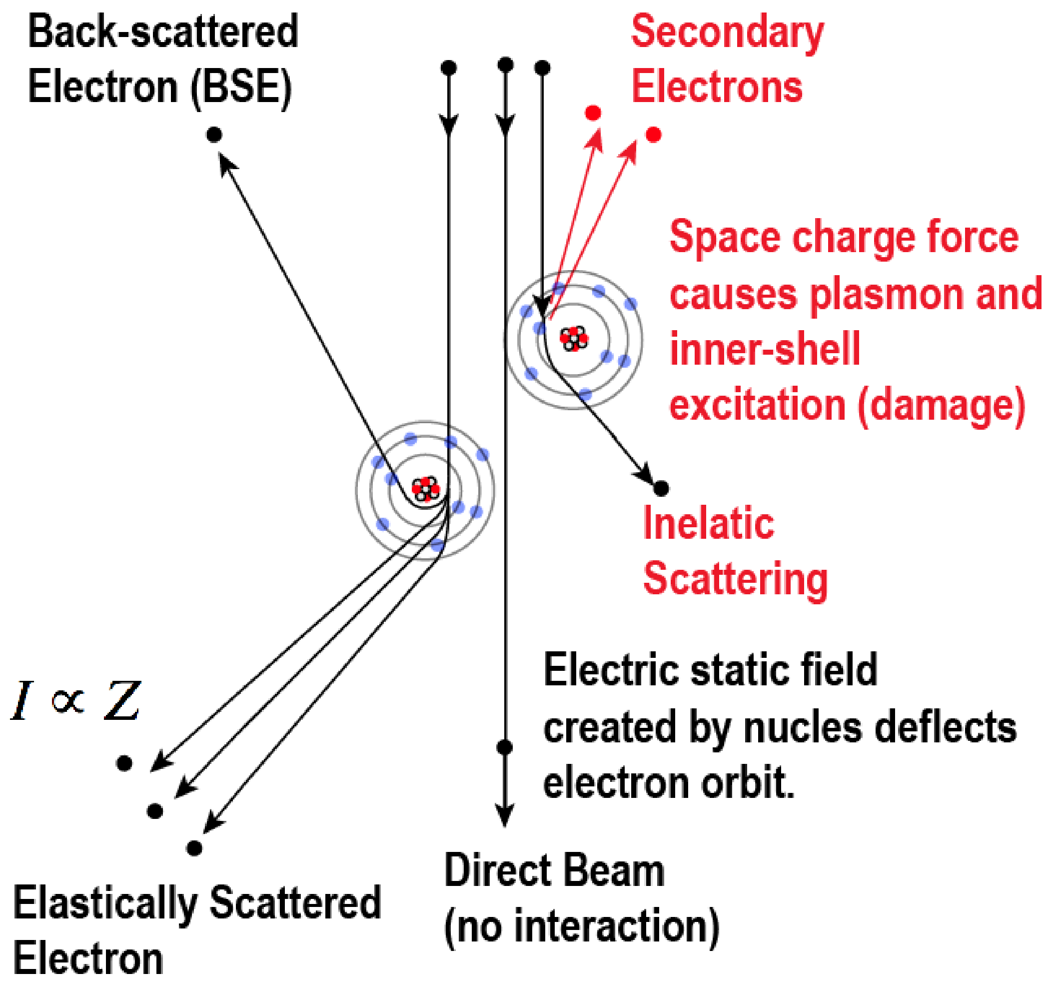
X-ray Interaction

Incident X-ray (~10 keV)

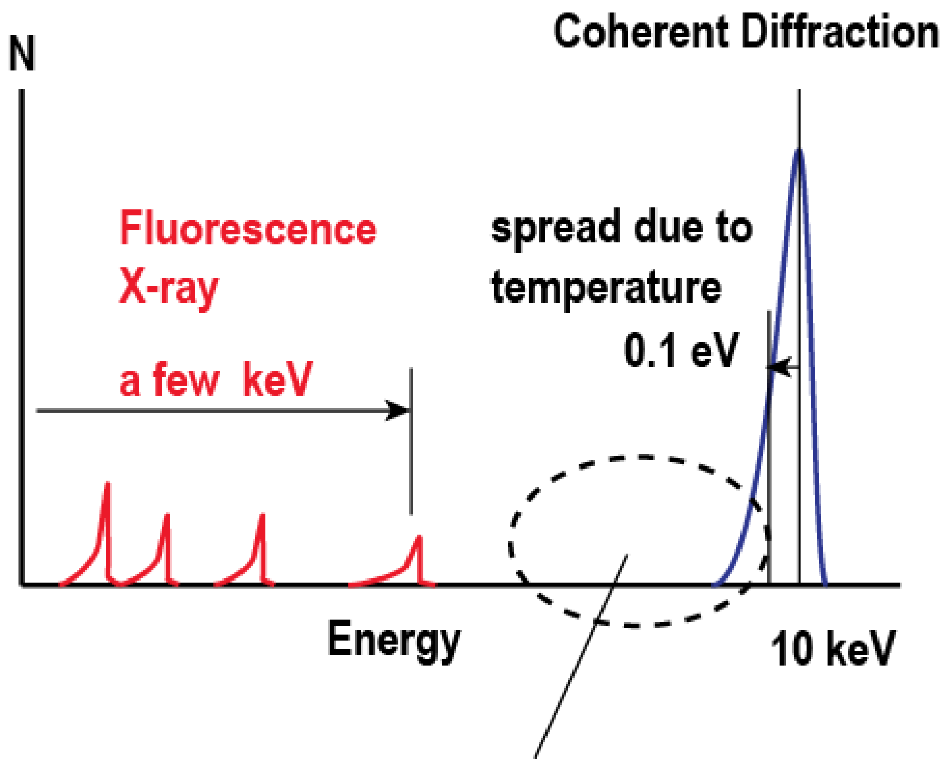


Electron Interaction

Incident High Energy Beam (100~300keV)

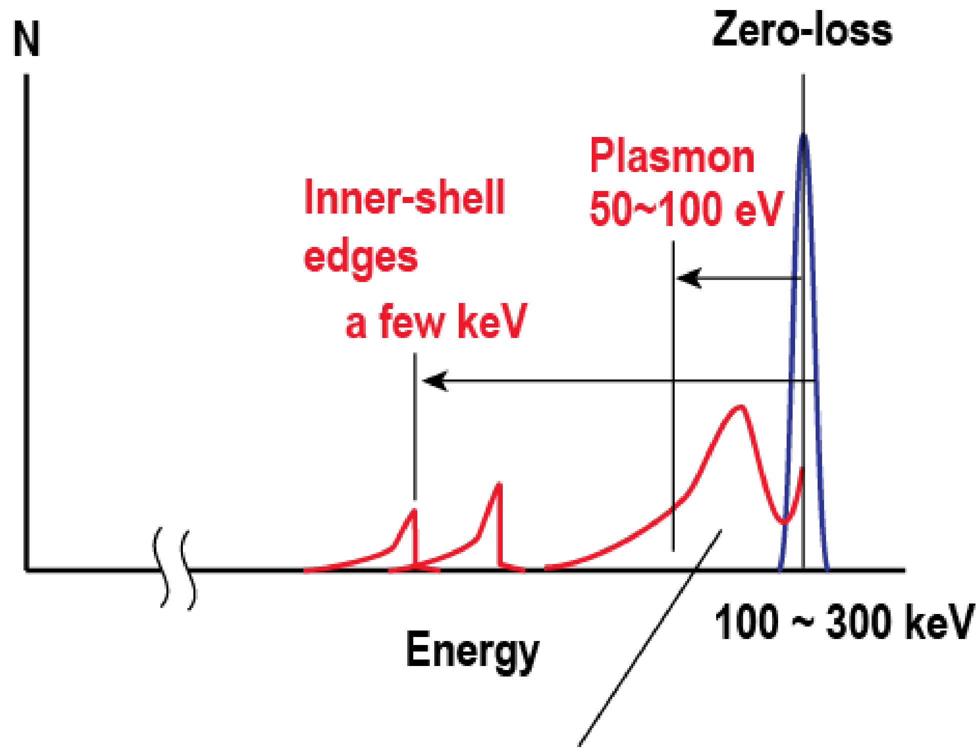


X-ray Interaction



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



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

--> advanced energy filtering technology.

Ω–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 → imaging, spectroscopy
- X-ray is charge less: Bose particle, thus infinitely intense beam can be formed in principle. → new physics
- Femto-second pulse form is very unique. → mode locking, pump-probe
- Polarization control will provide another channel.

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