SACLA X-ray FEL Based on C-band Technology

(Gersch Budker Prize Presentation)

Tsumoru Shintake

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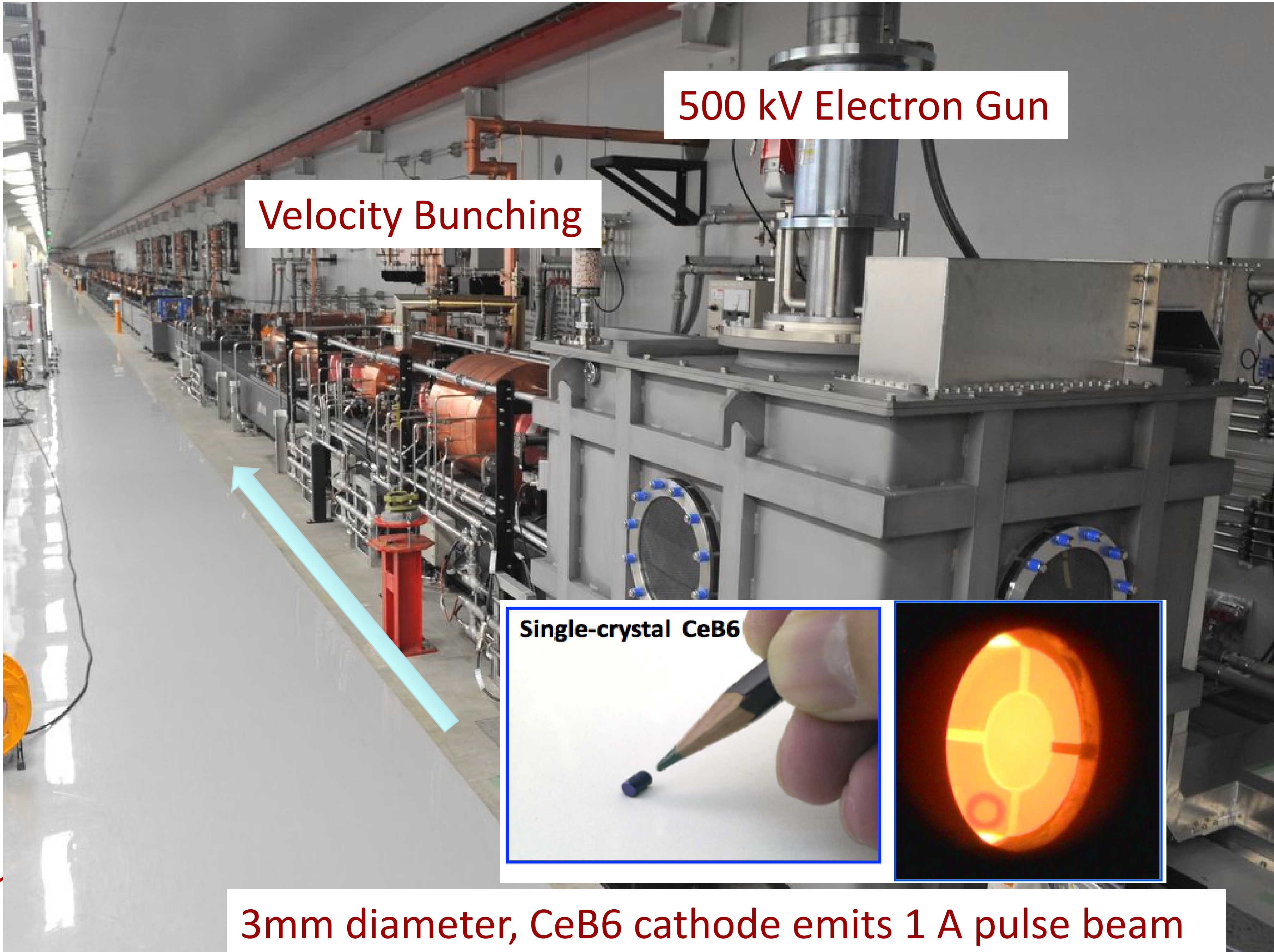
Onna-son Okinawa 904-0495 Japan

OIST

OKINAWA INSTITUTE OF SCIENCE AND TECHNOLOGY GRADUATE UNIVERSITY

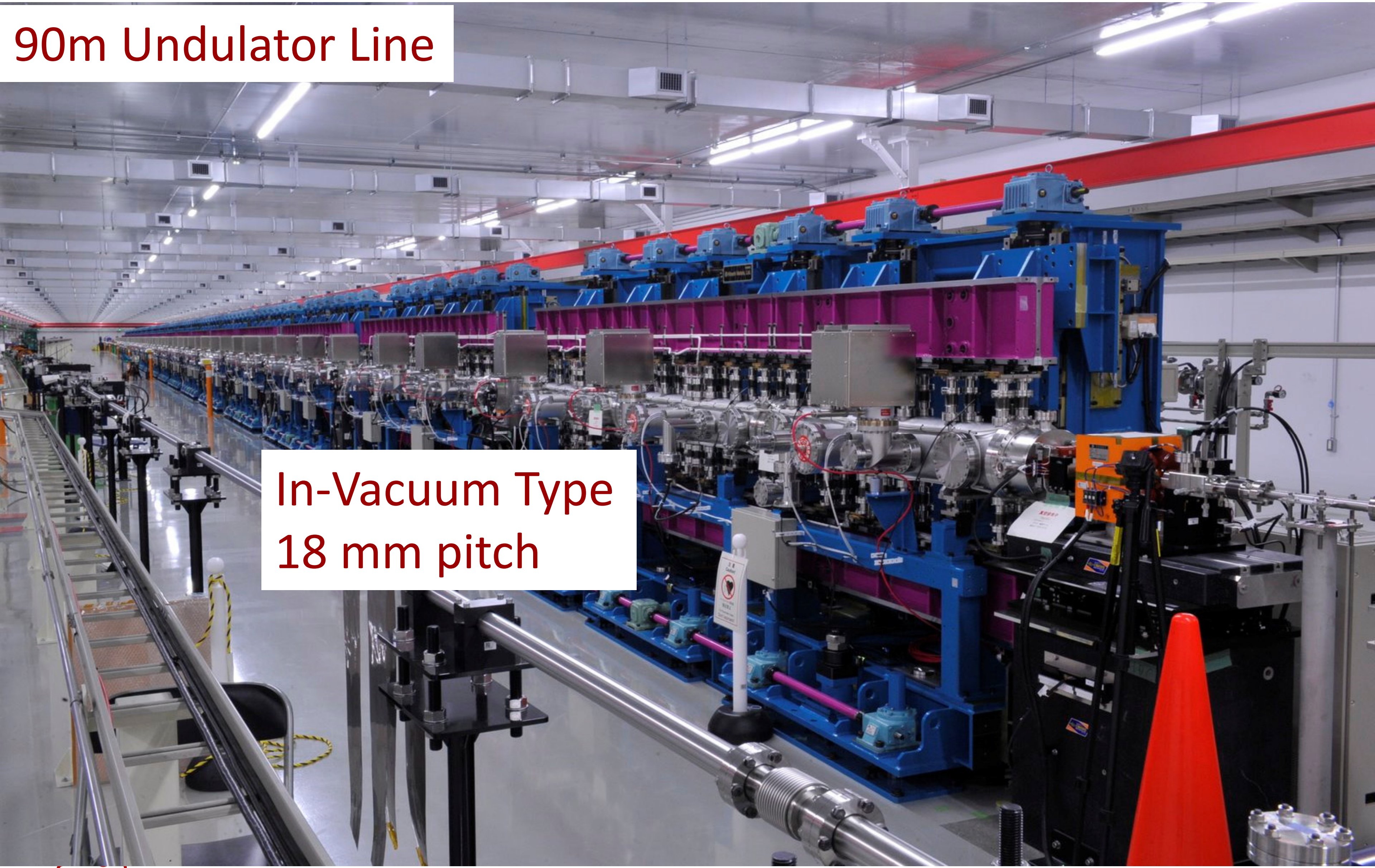

SPring-8 1997~
3rd Generation SR Light Source
SACLA 2011~
X-ray Free Electron Laser


500 kV Electron Gun
Velocity Bunching
Single-crystal CeB6
3mm diameter, CeB6 cathode emits 1 A pulse beam

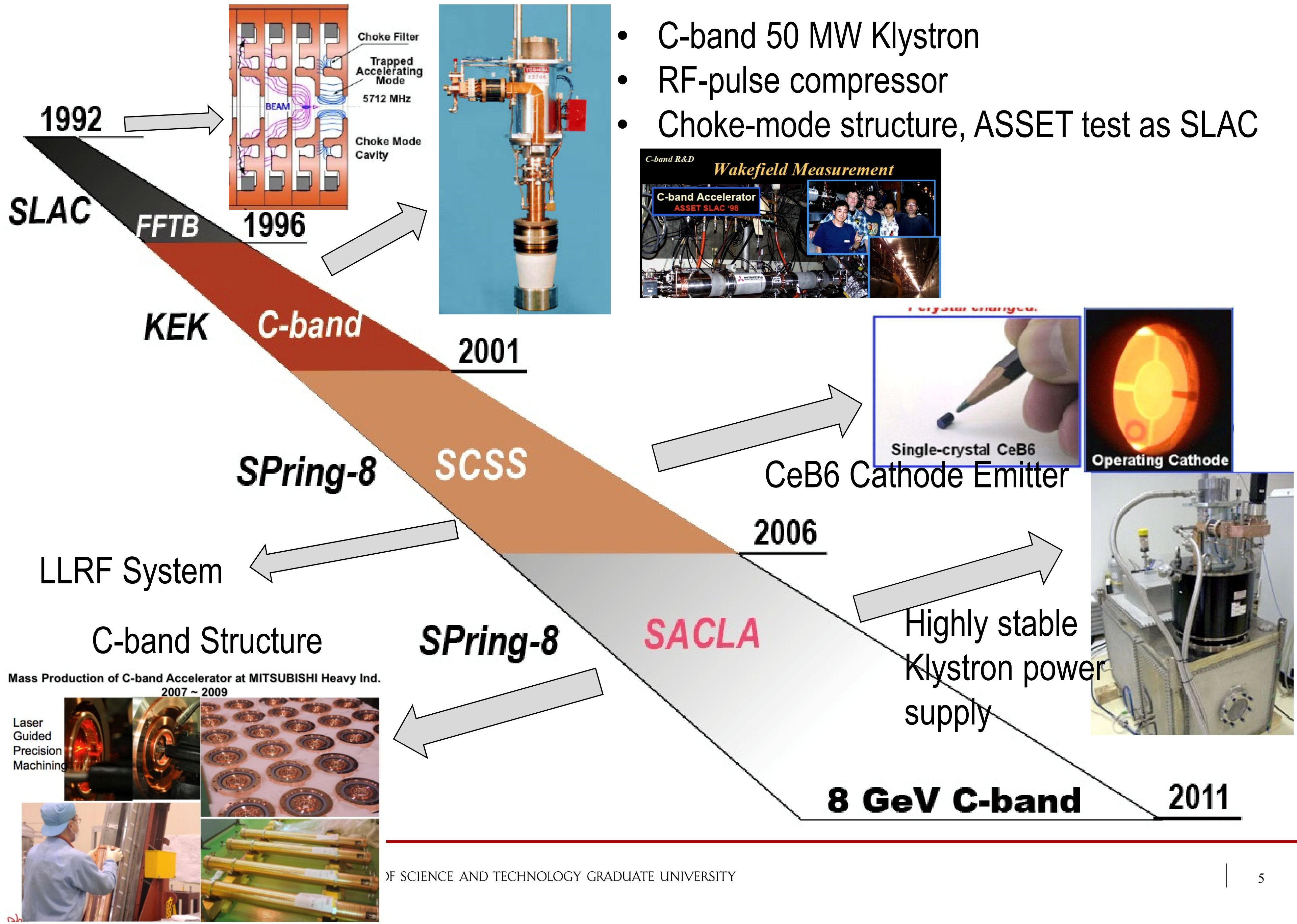
C-band Main Accelerator (8GeV, 400 m total)

5712 MHz
35 MV/m

90m Undulator Line



In-Vacuum Type
18 mm pitch



C-band 50 MW Klystron
RF-pulse compressor
Choke-mode structure, ASSET test as SLAC
1992
SLAC
FFTB
1996
KEK
C-band
2001
SPring-8
SCSS
2006
SPring-8
SACLA
8 GeV C-band
2011
Choke Filter
Trapped Accelerating Mode
5712 MHz
BEAM
Choke Mode Cavity
C-band R&D
Wakefield Measurement
C-band Accelerator
ASSET SLAC '98
Single-crystal CeB6
Operating Cathode
CeB6 Cathode Emitter
Highly stable Klystron power supply
LLRF System
C-band Structure
Mass Production of C-band Accelerator at MITSUBISHI Heavy Ind.
2007 ~ 2009
Laser Guided Precision Machining

T. Shintake, “C-band Proposal for e+e- Linear Collider”

JLC Group, "JLC-I", KEK Report 92 - 16, December 1992, A/H/M

LC92

Drive Frequency Band: L, S, C, X, Xu

ECFA WORKSHOP ON e^+e^- LINEAR COLLIDERS

GARMISCH PARTENKIRCHEN

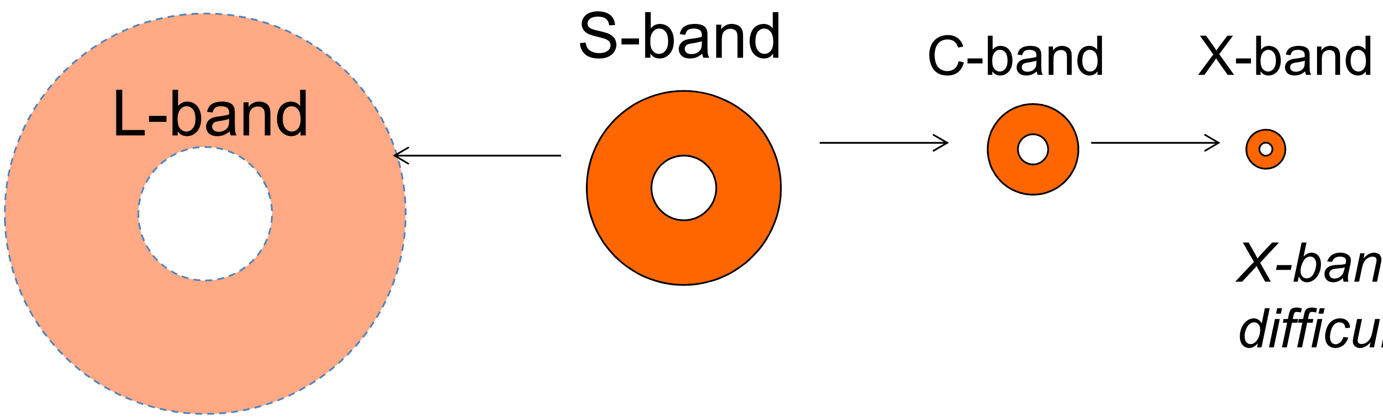
25 July - 2 August 1992

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

"C-band is the beast choice as the normal conducting high-gradient accelerator"



X-band is difficult to make.

Power efficiency

$$r \propto \omega^{1/2}$$

No big change on shunt-impedance

Stored energy

$$w \propto \int \frac{1}{2}\varepsilon_0 E^2 dv \propto \pi b^2 E_a^2 \propto \left(\frac{E_a}{\omega}\right)^2$$

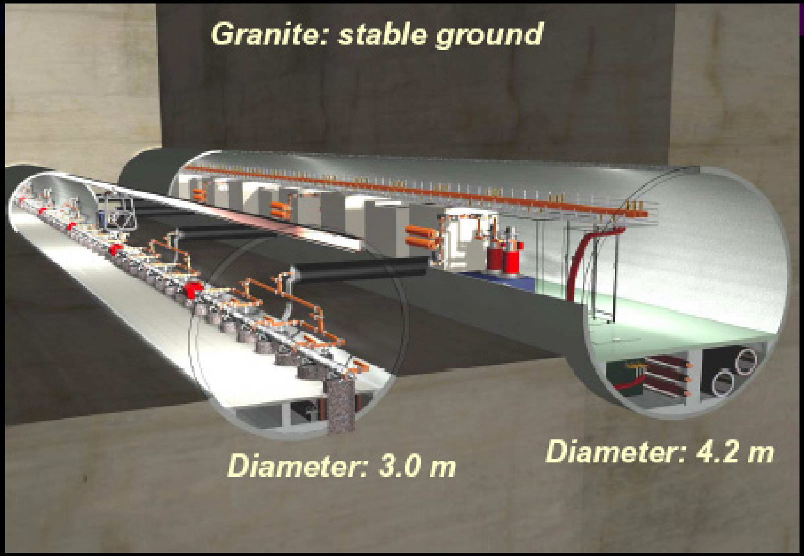
C-band stored energy becomes 4 times smaller, which makes klystron and modulator easier.

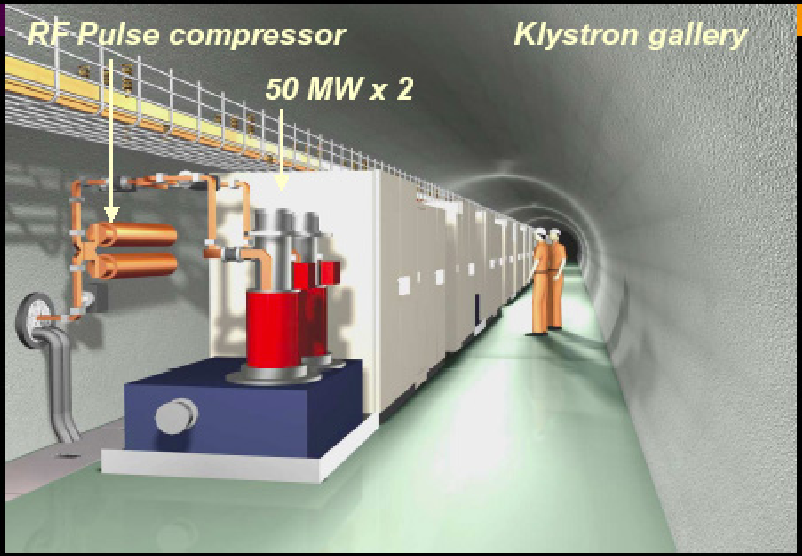
Filling time, and length of structure

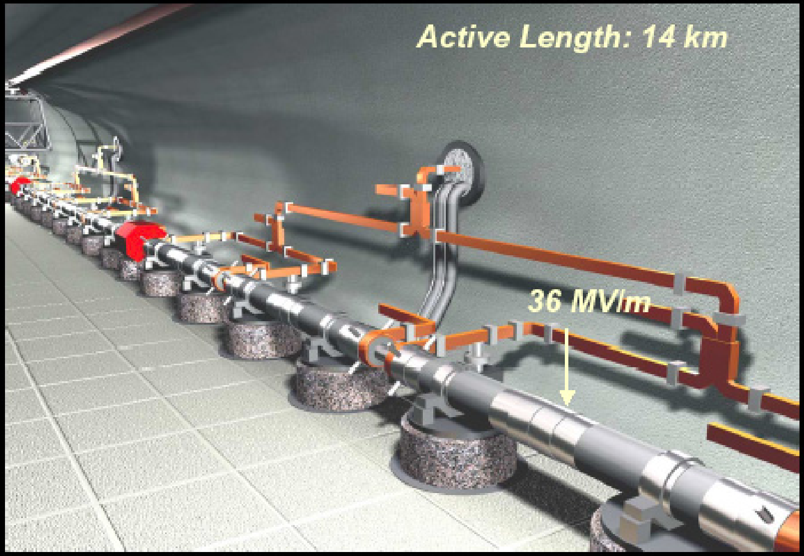
$$t_F = \frac{2Q}{\omega}\tau \propto \omega^{-3/2}$$

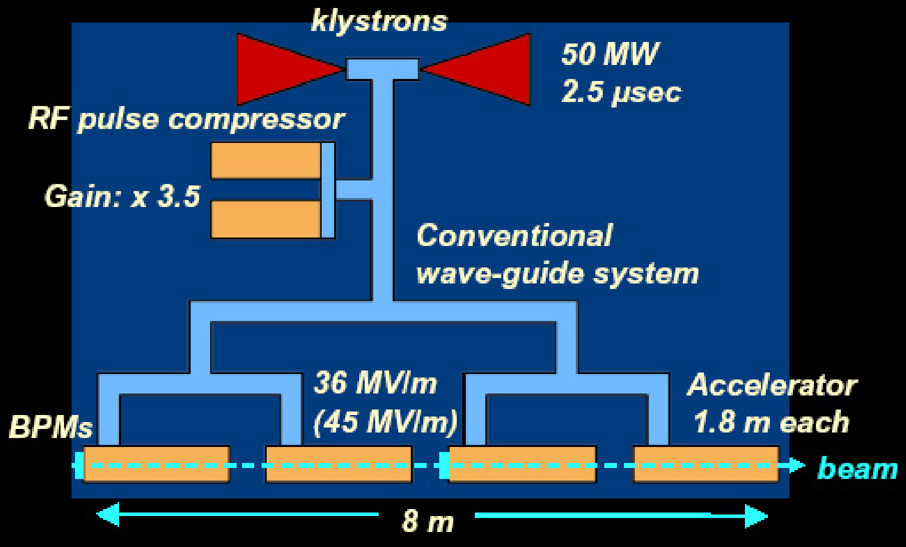
Attention! 3 times smaller at C-band.
Accelerating structure becomes short.

JLC C-band (5712 MHz) Main Linac Tunnel

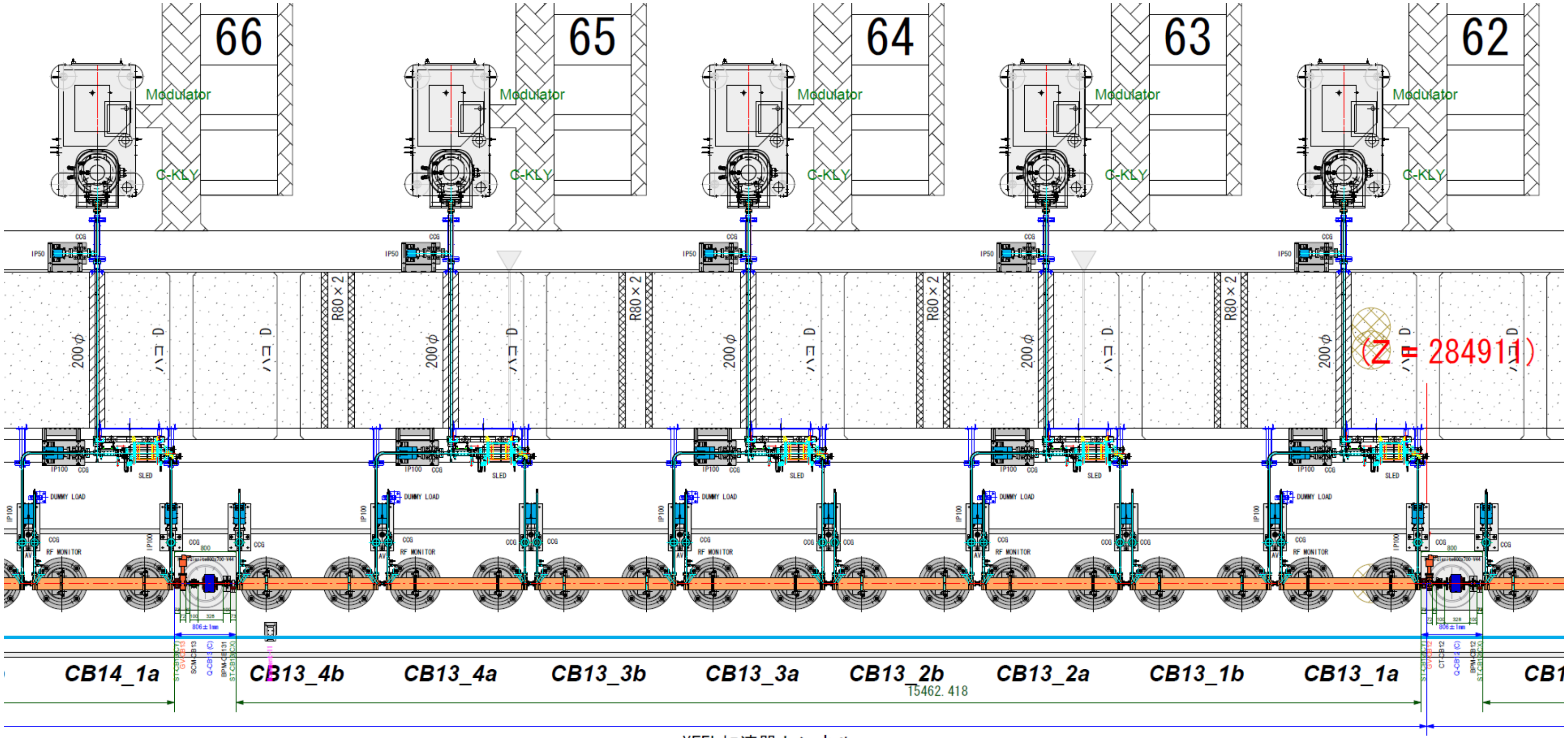




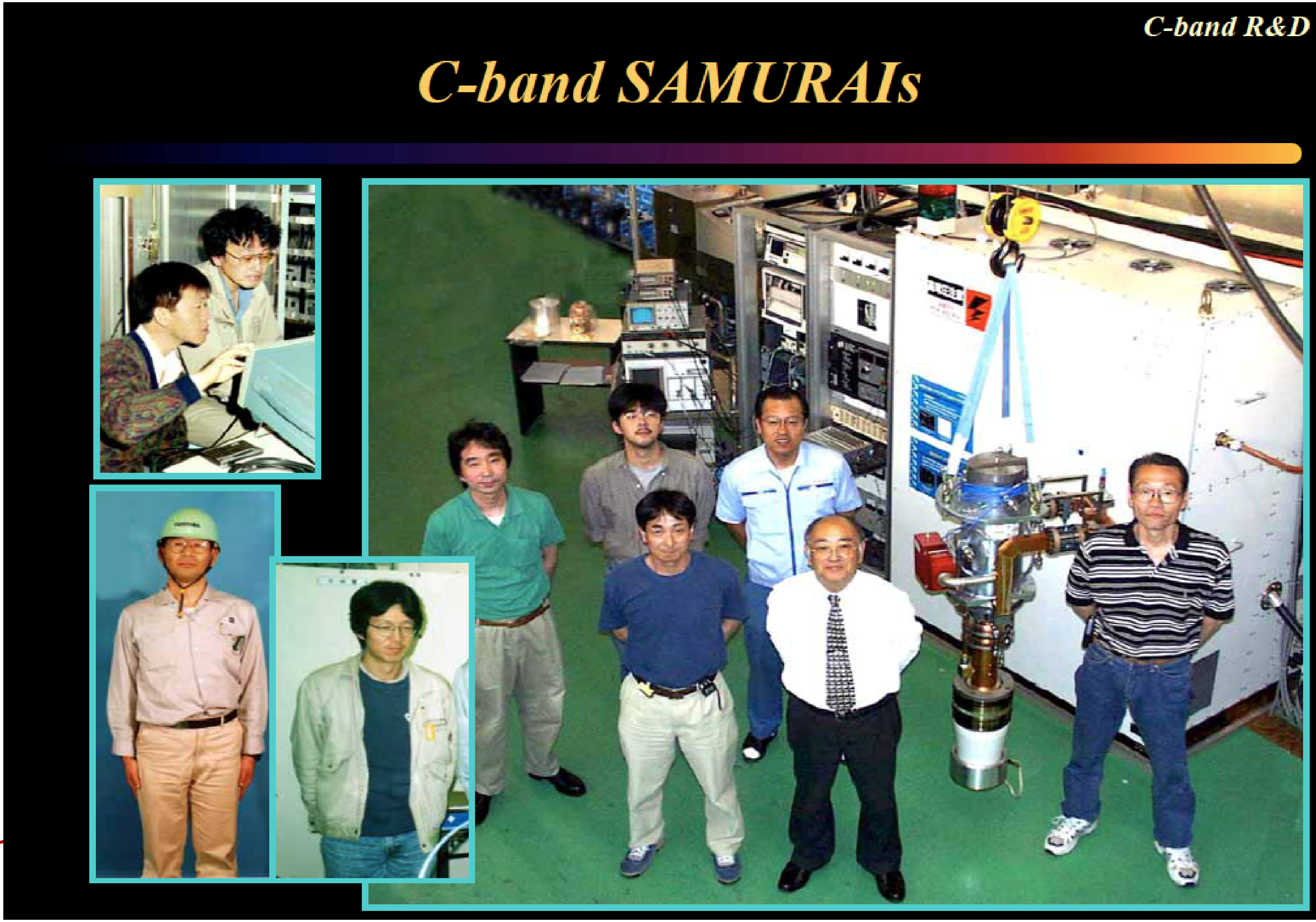




In SACLA, to lower the risk, we prepared power supply for individual klystron. As a result, the klystron modulators have to be packed in small spaces.



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



C-band 50 MW Klystron production tube

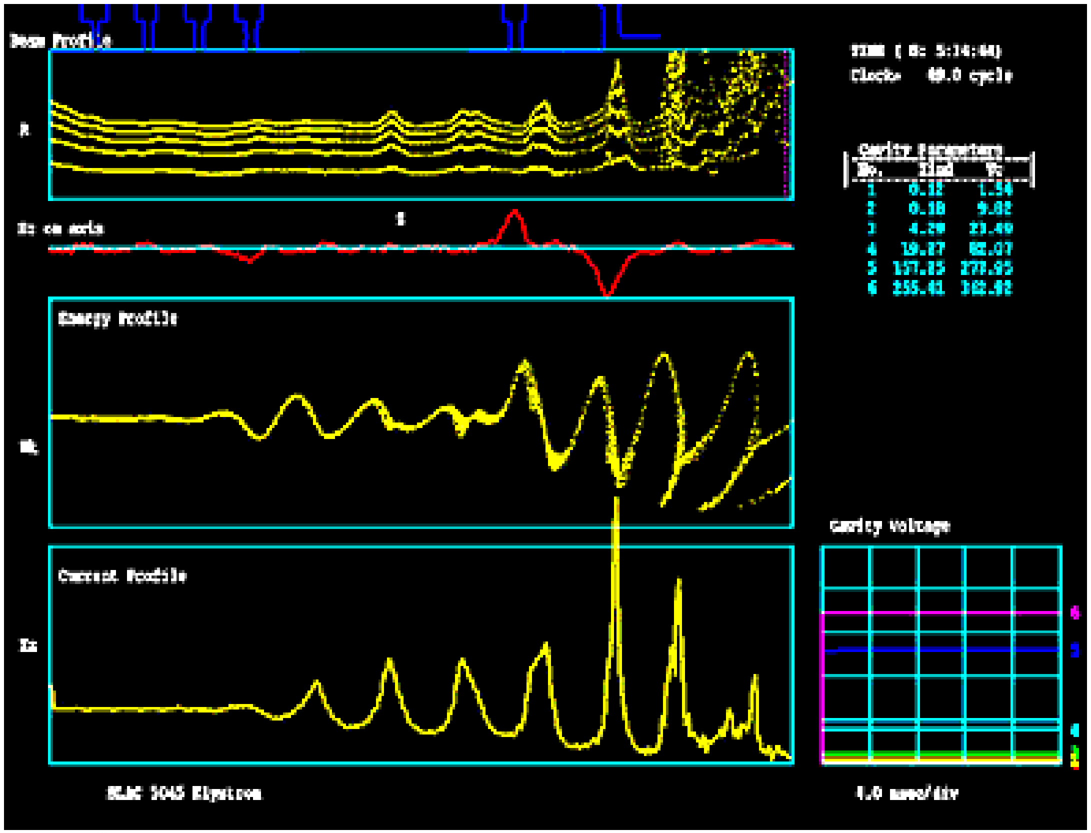
E3746, E3748

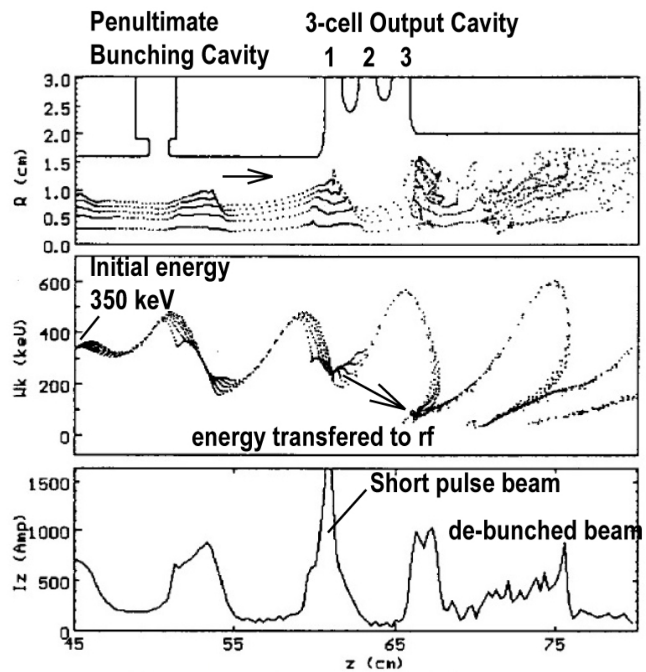
3-Cell Output Cavity

Operation Frequency	5712	MHz
Peak Output Power	50	MW
Signal Gain	52	dB
Power Efficiency	47	%
Pulse Duration	2.5	usec
Pulse Repetition	60	pps
Gun Voltage	354	kV
Beam Perveance	1.53	$uA/V^{1.5}$
Beam Current	315	A
Solenoid Focus	4	kW
RF Window	Double	Traveling wave
Traveling-wave Output	π/2-mode	3 cell

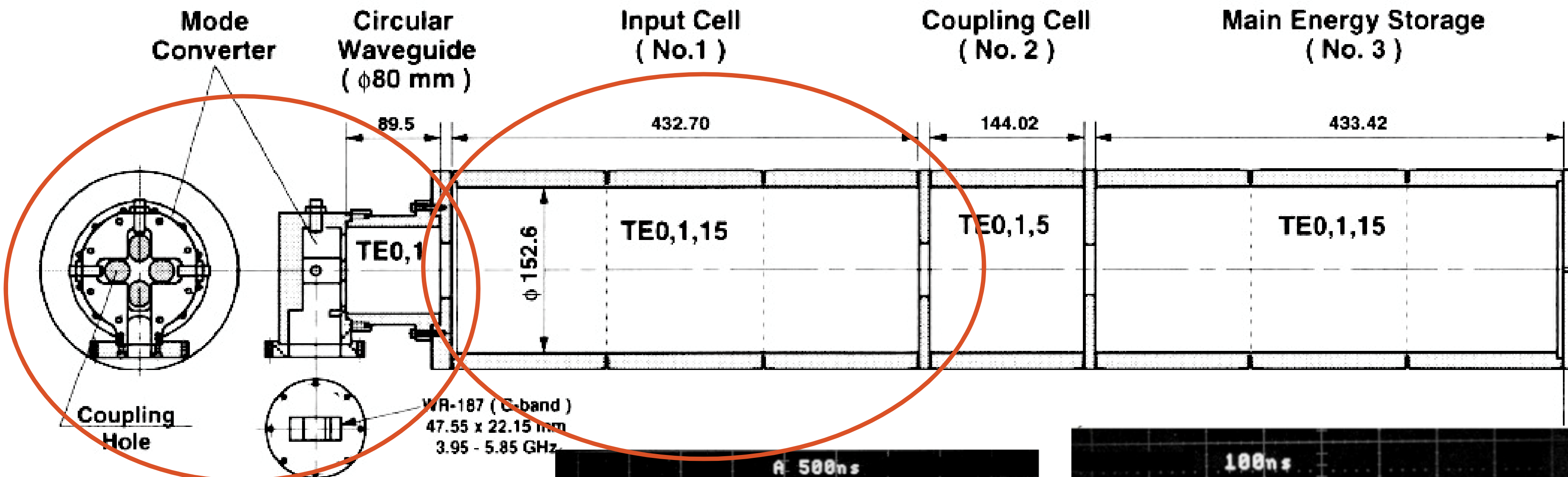
Frascati, Chinghai FEL, SwissFEL, SR in Tohoku Jpanan

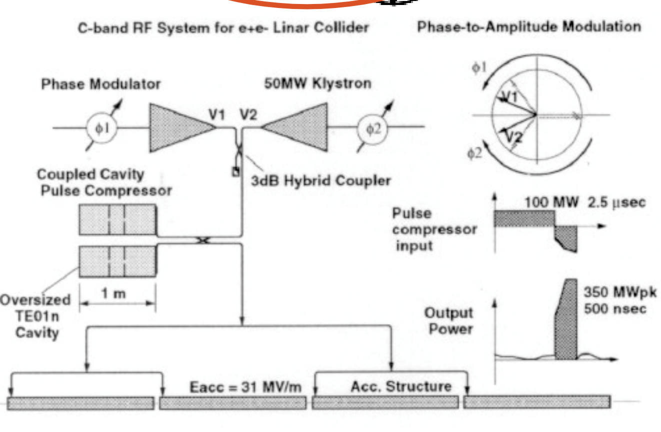
FCI Klystron Simulation (PIC model) cont.

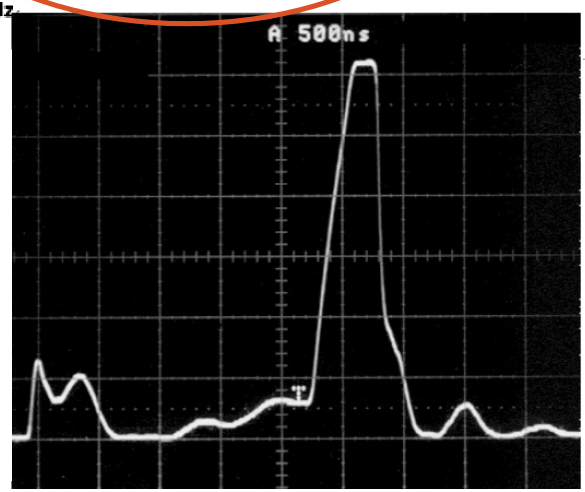


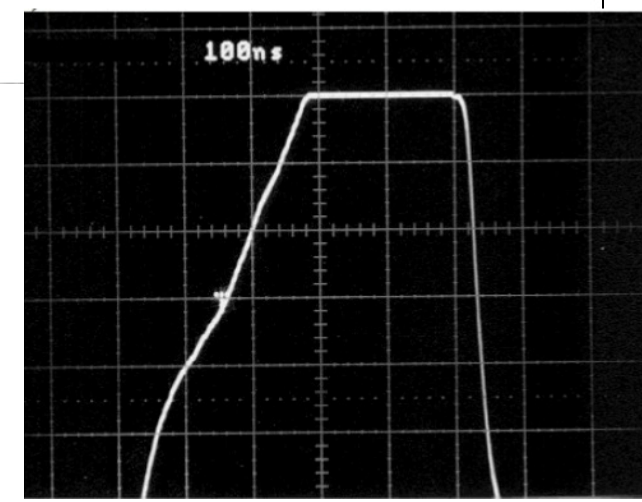


C-band RF-pulse Compressor at 1996~97



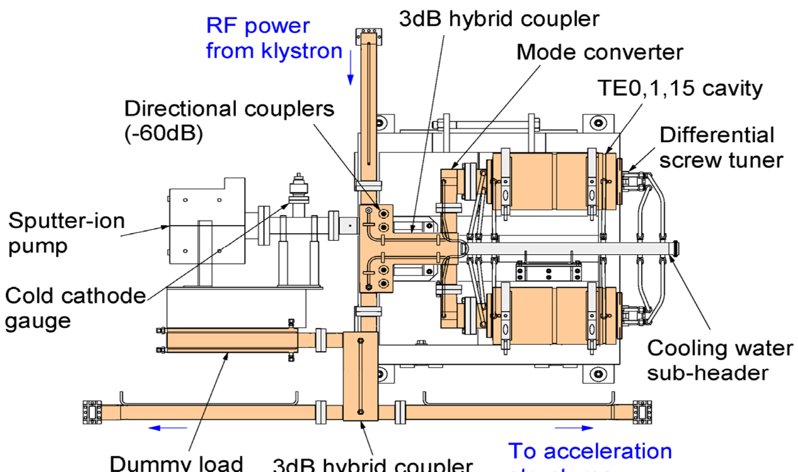


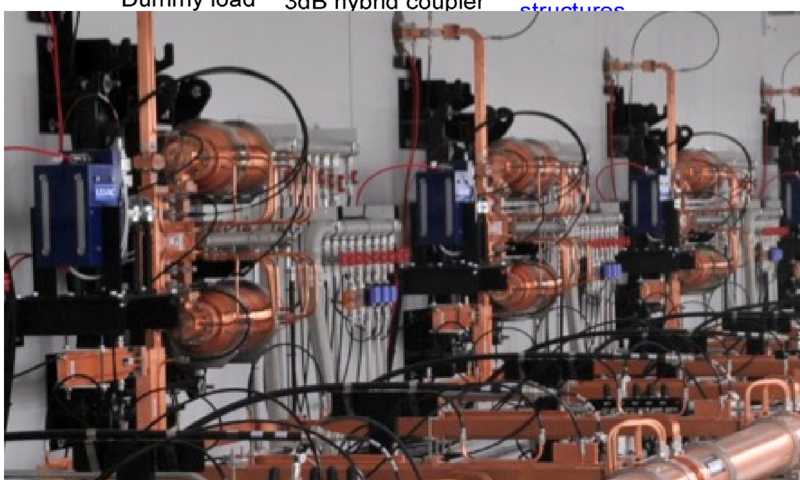


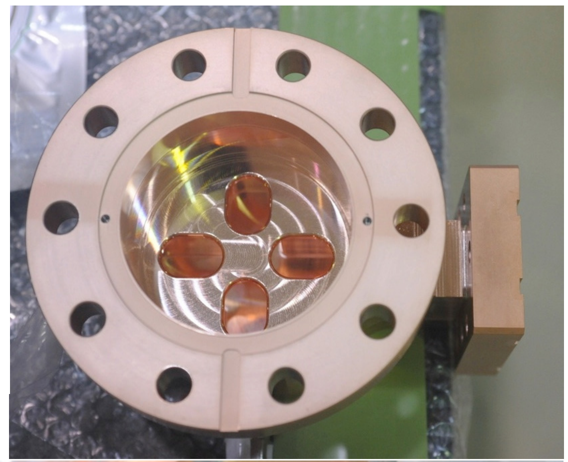


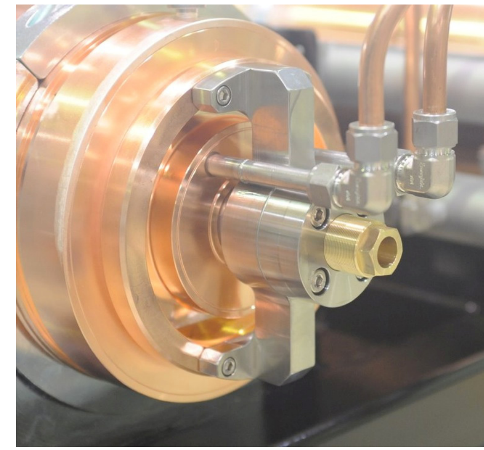
T. Shintake, N. Akasaka and H. Matsumoto, "Development of C-band RF Pulse Compression System for e+e- Linear Collider", PAC97

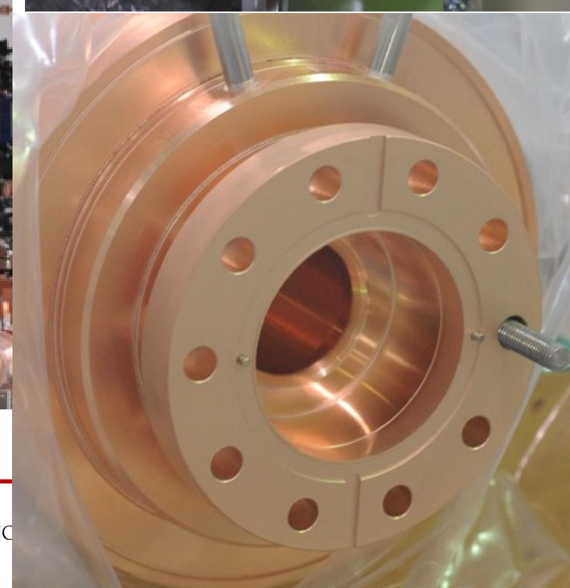
C-band RF-pulse compressor in SCALA

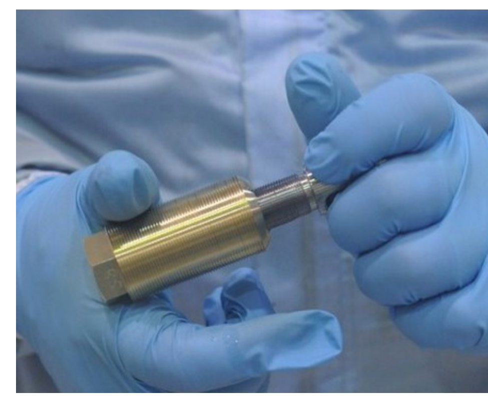












From 2001, I moved to SPring-8 RIKEN
Started FEL R&D

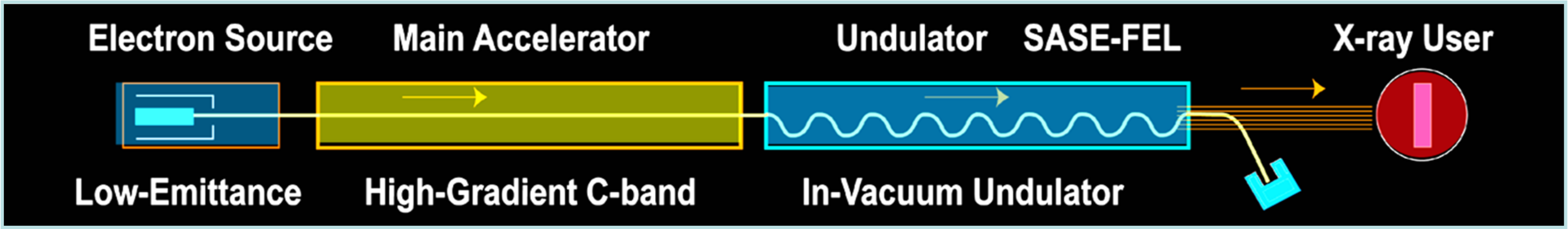
Submitted to SPIE's 46th Annual Meeting,
The International Symposium on Optical Science and Technology, 29 July – 3 August 2001, San Diego, California, U

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.

SCSS : SPring-8 Compact SASE Source



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

In-Vacuum Undulator : λ_u= 18 mm, K=2.1, λ_x < 1 Å → E= 8 GeV,

SLAC-LCLS : λ_u= 30 mm, K=3.5, 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**

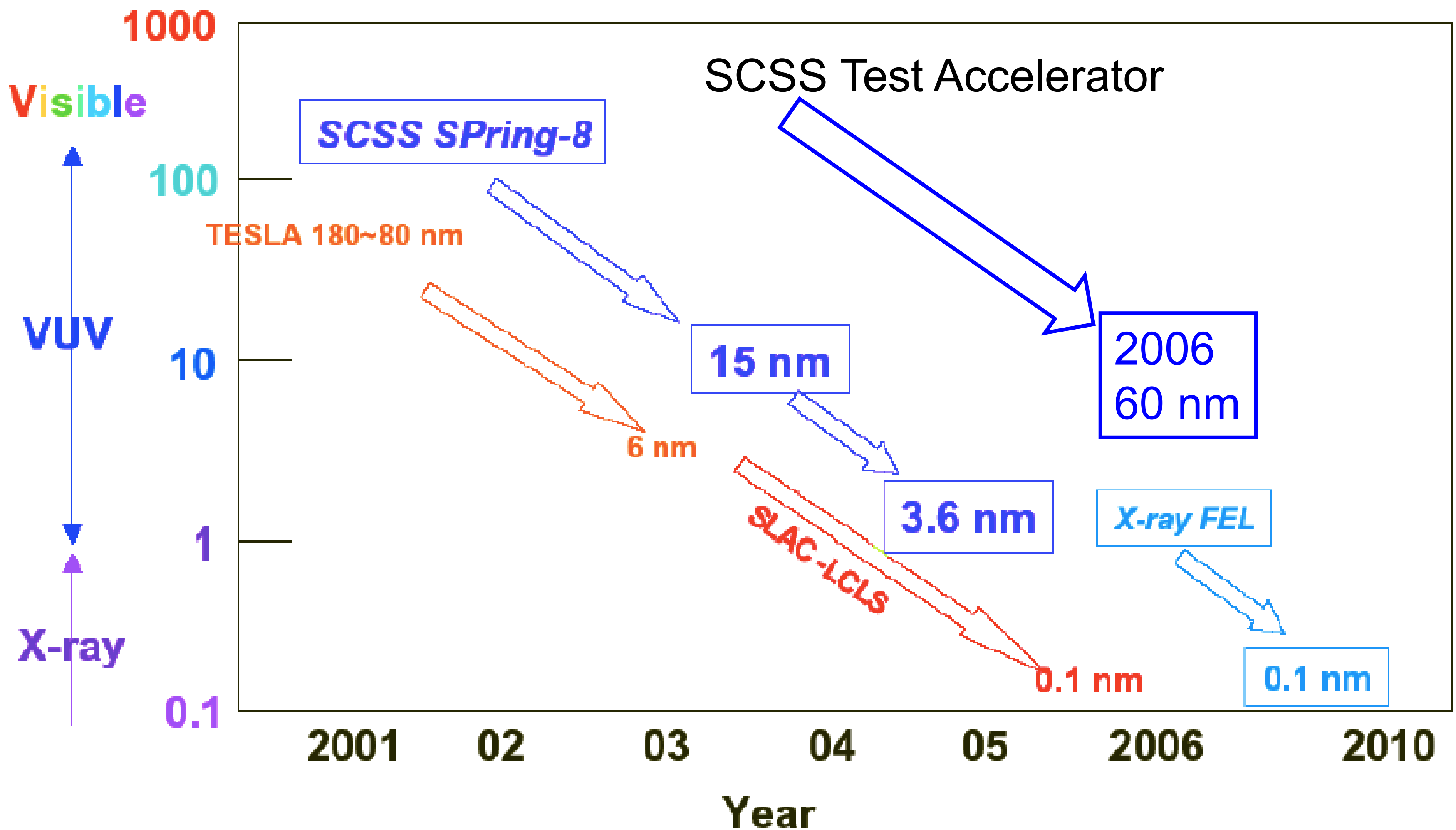
Thermionic gun + velocity bunching → 0.8 π.mm.mrad @ 3k A, 8GeV

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

Milestone of SPring-8 SCSS

X-ray FEL

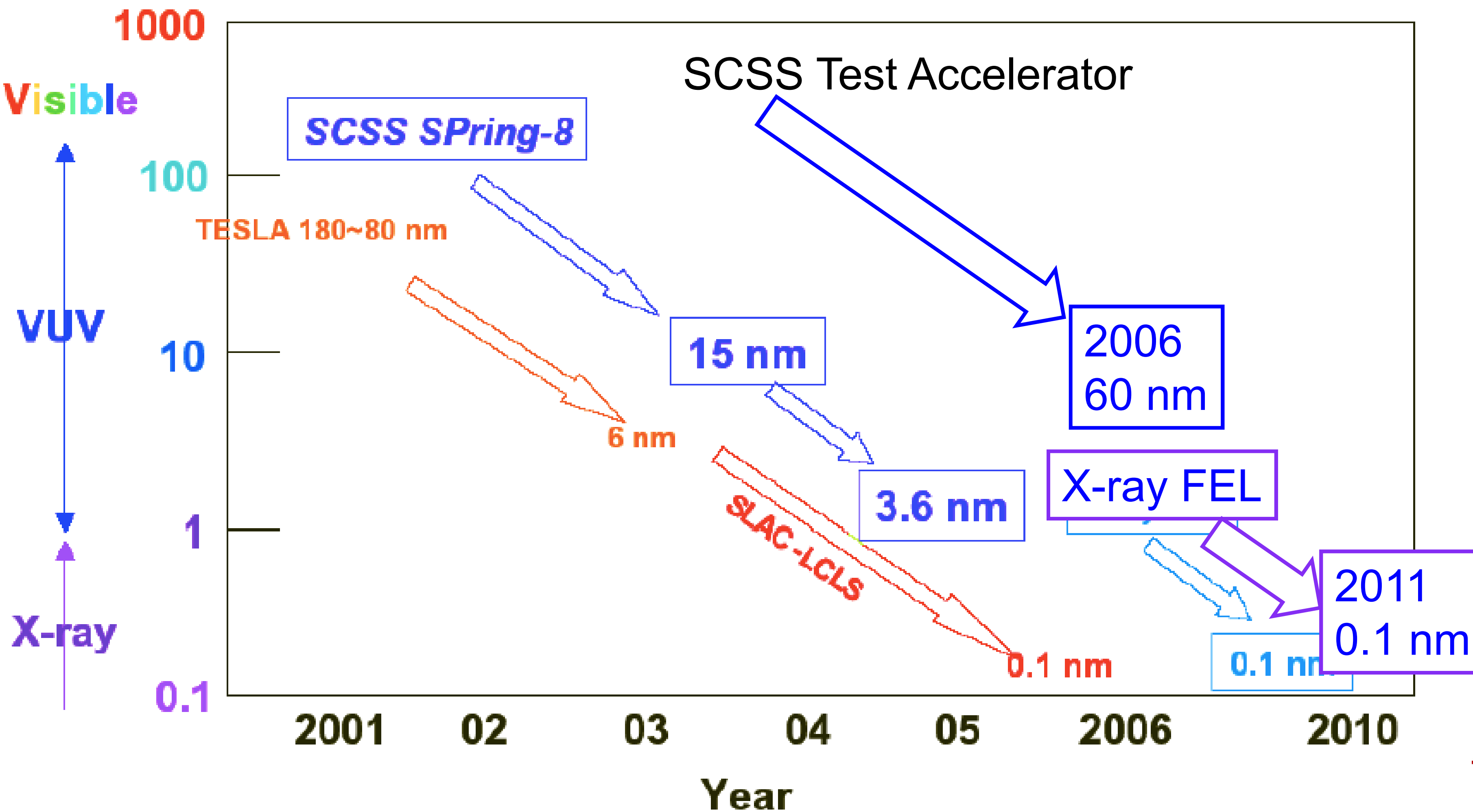
SPIE 2001 July.



Milestone of SPring-8 SCSS

X-ray FEL

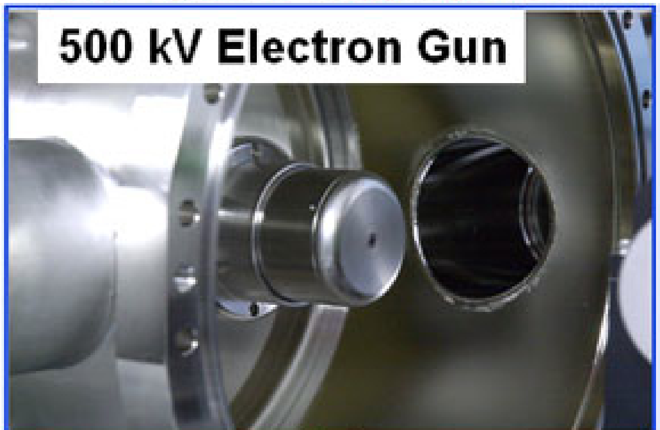
SPIE 2001 July.

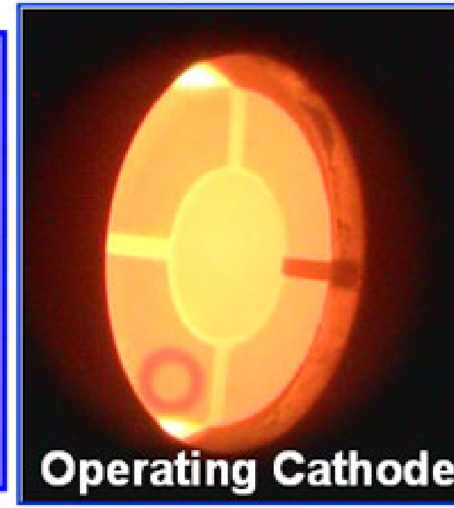


Single-crystal CeB_6 Cathode for XFEL/SPring-8 & SCSS Low-emittance Injector

No HV breakdown for 4 years daily operation

After 20,000 hours operation 1 crystal changed.

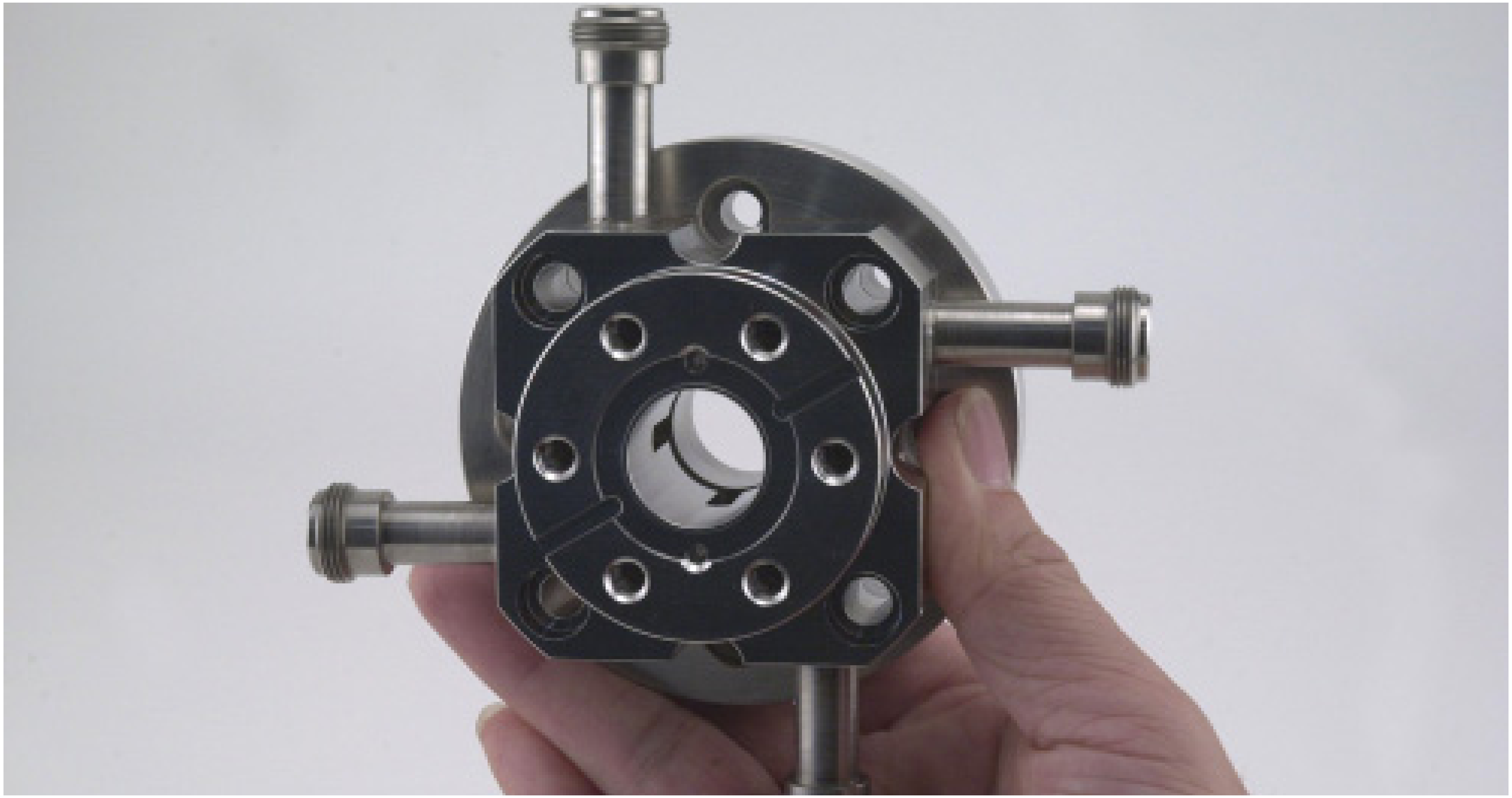




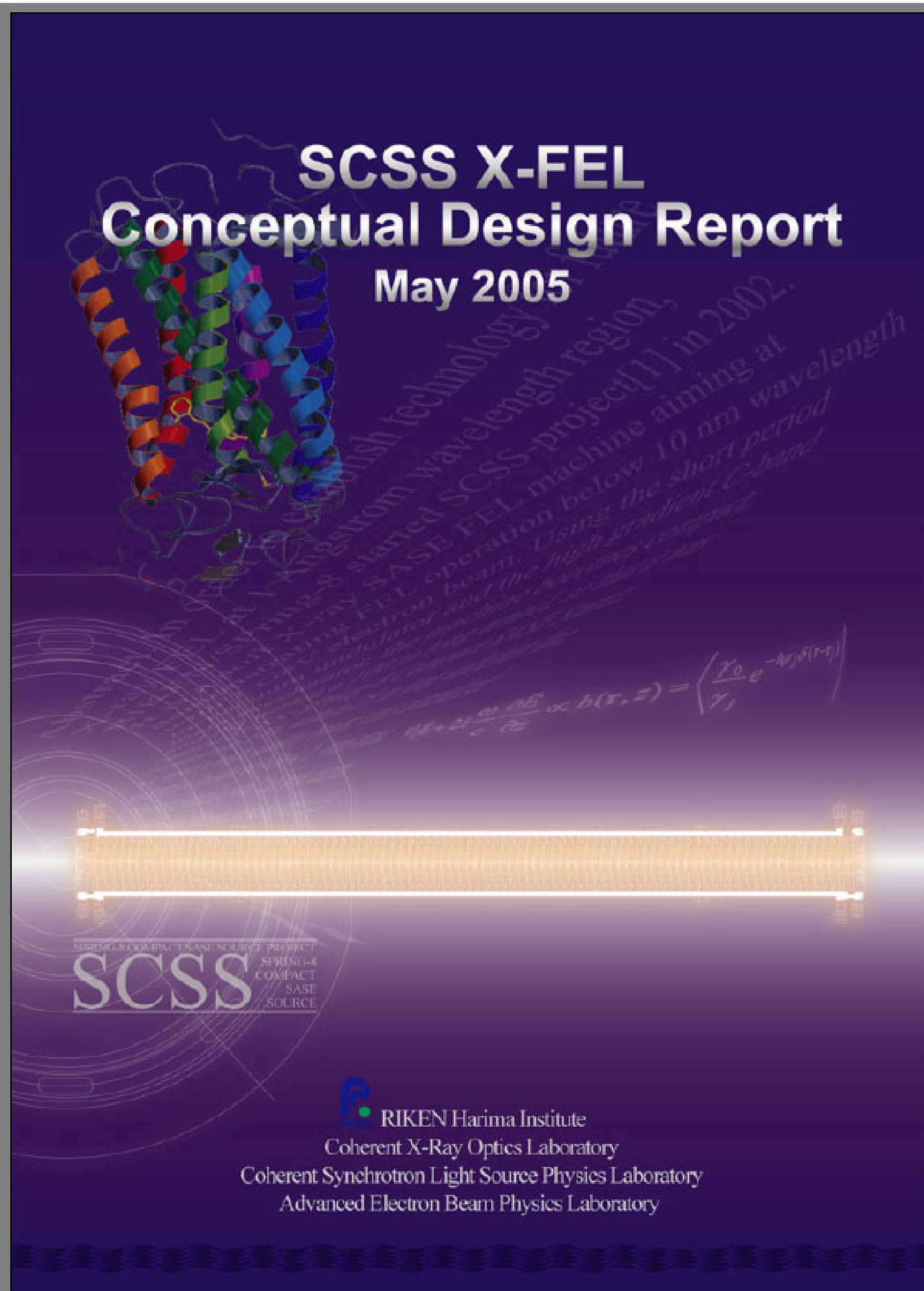
Diameter : ϕ3 mm
Temperature : ~1500 deg.C
Beam Voltage : 500 kV
Peak Current : 1 A
Pulse Width : ~2 μs
Beam Chopper: 1 nsec

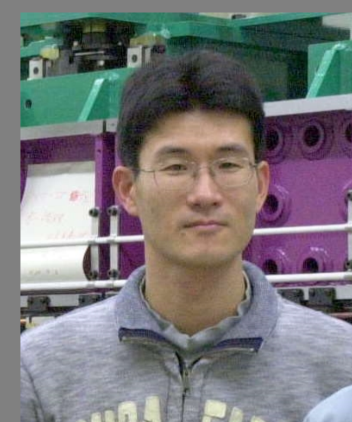
Dr. K. Togawa

Cavity-BPM for Beam Based Alignments for Undulator Line with Sub-µm Resolution



→ Dirk Lipka DESY → EuroXFEL, PSI SwissFEL


SCSS X-FEL
Conceptual Design Report
May 2005
SCSS
SPRING-8
COMPACT
SASE
SOURCE
RIKEN Harima Institute
Coherent X-Ray Optics Laboratory
Coherent Synchrotron Light Source Physics Laboratory
Advanced Electron Beam Physics Laboratory

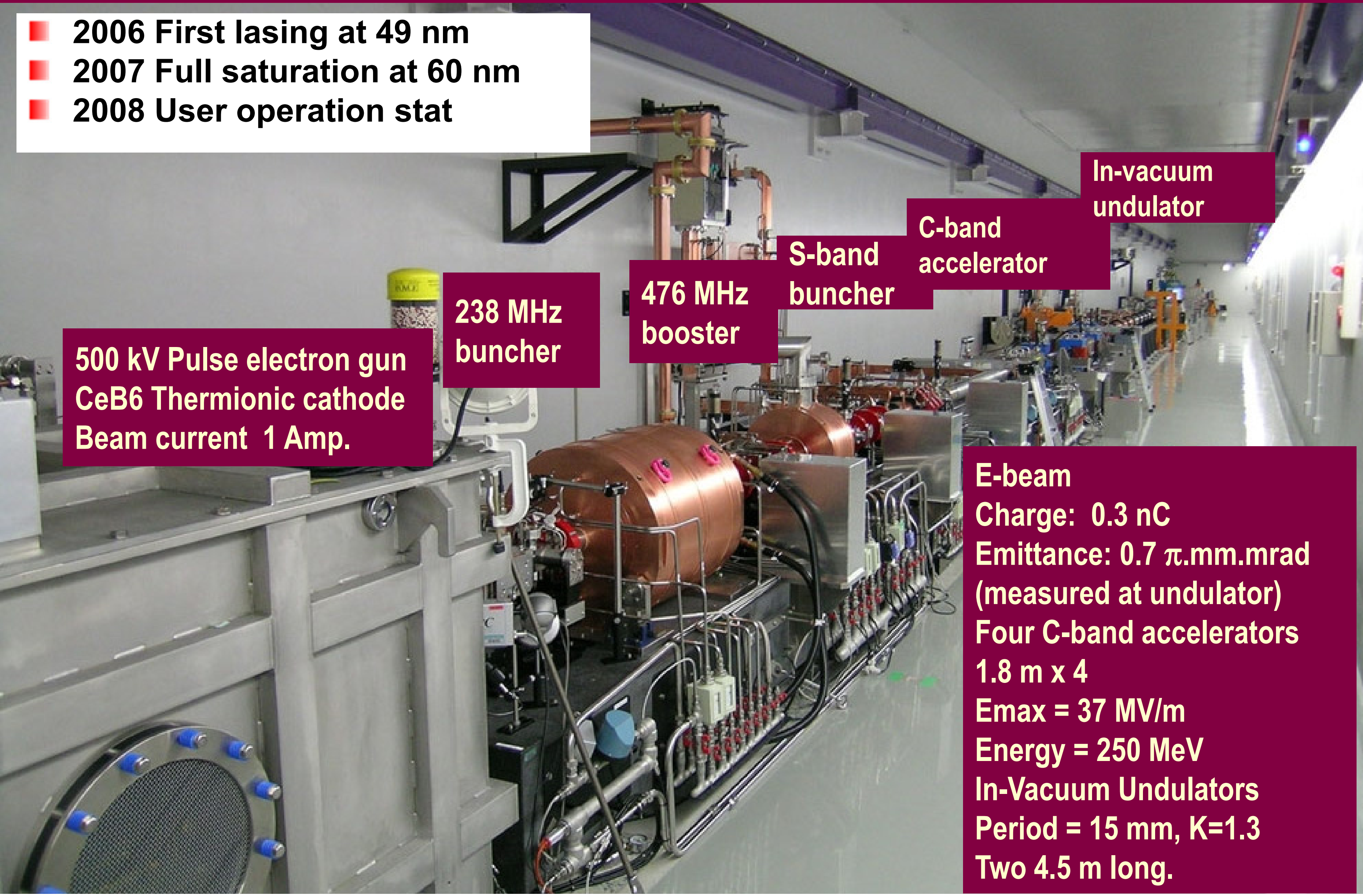


SCSS Technical Review Committee 2005 March

To show emittance preservation, construct
Test Accelerator 2004~2006

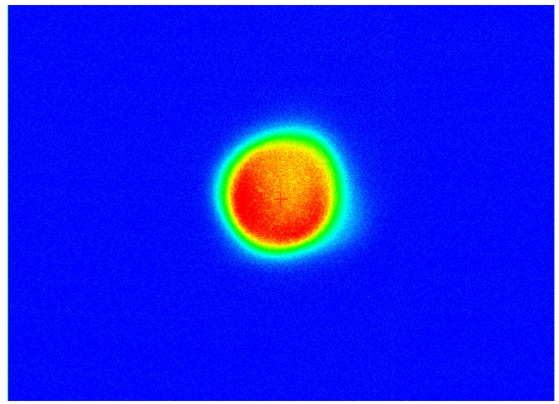
SCSS Test Accelerator

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

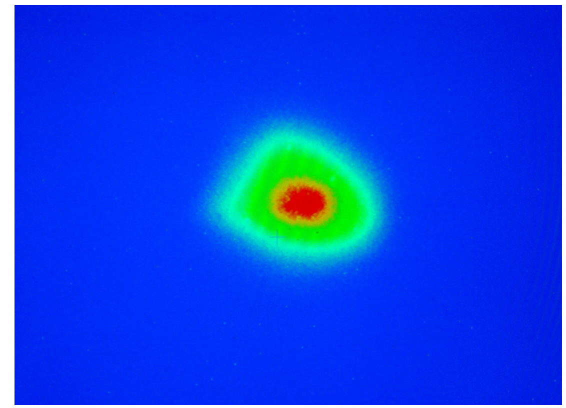


CeB_6 Thermionic Gun provides stable beam.

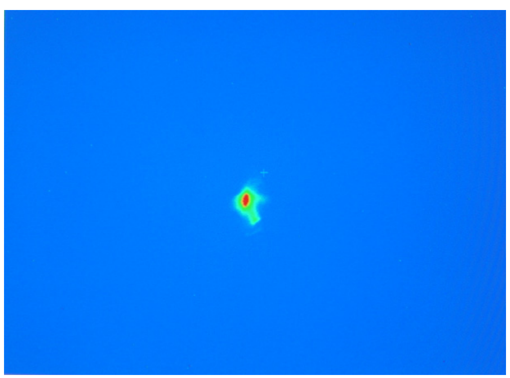
Beam Profile
CCD Image
Scale 10 mm



500 kV Gun

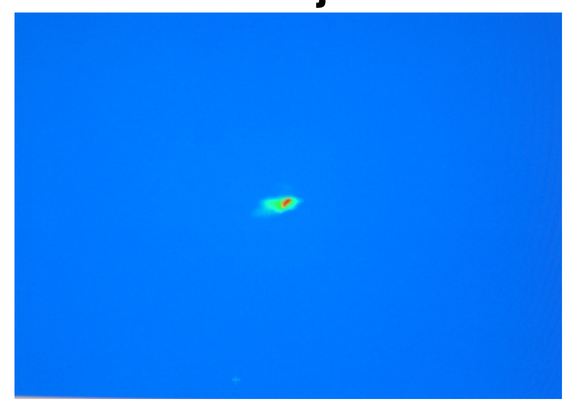


50 MeV Injector Out



250 MeV Compressor

Undulator Input



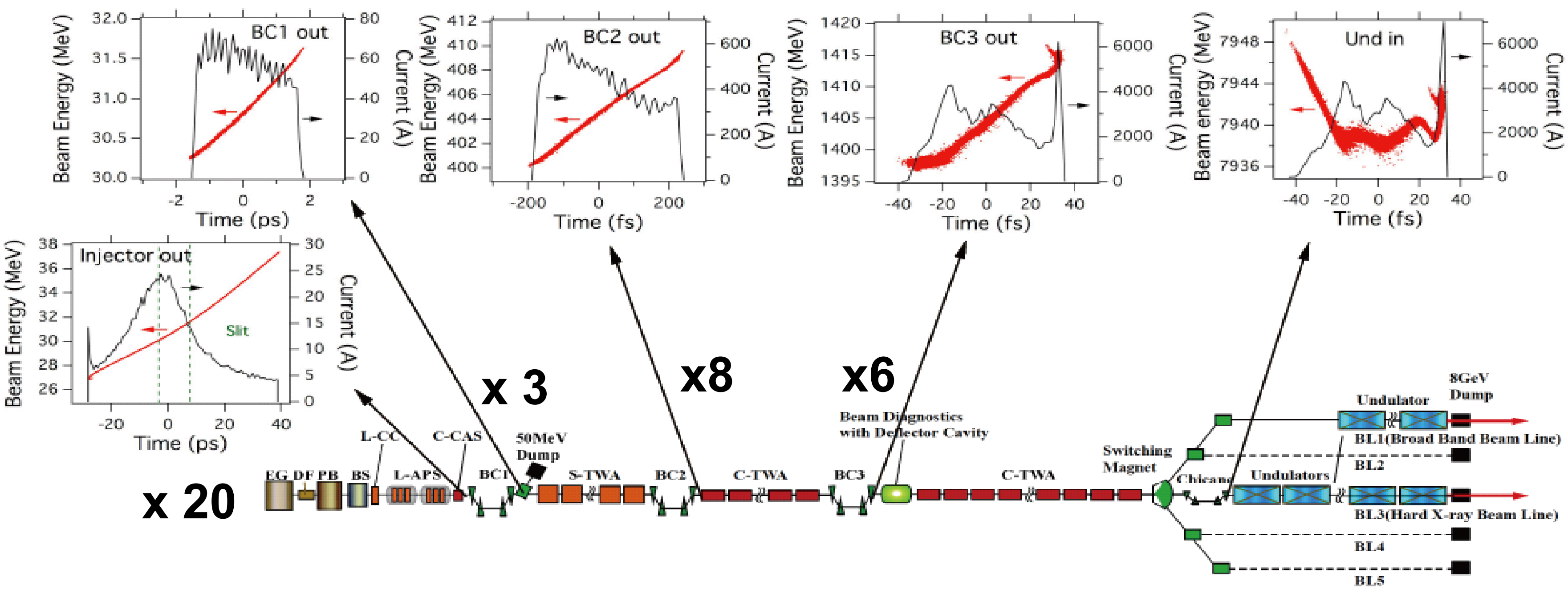
Undulator Output

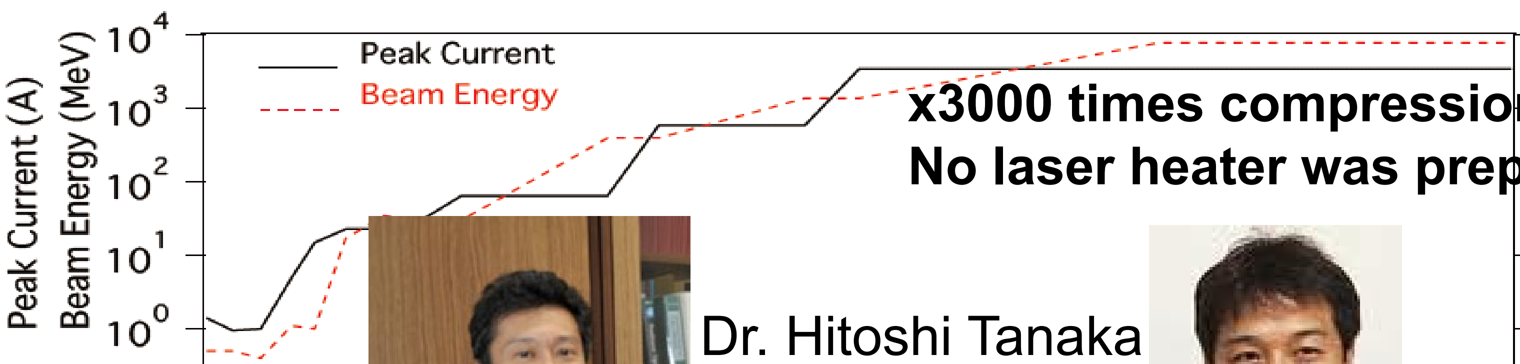
First Lasing at 49 nm in SCSS

June 15, 2006

8 GeV XFEL Construction 2008 May

SACLA 8 GeV Beam Parameter Design





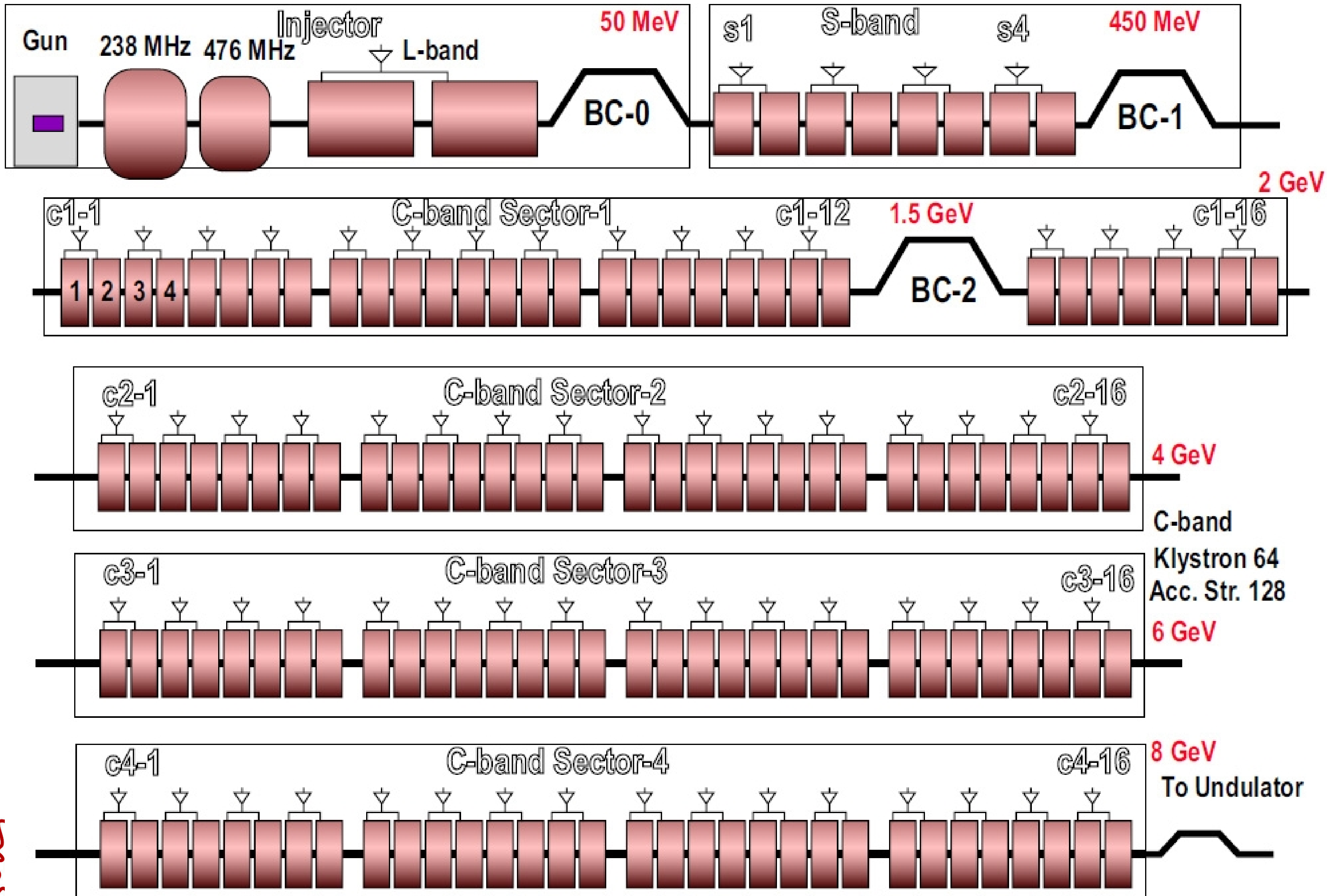
x3000 times compression

No laser heater was prepared.

Dr. Hitoshi Tanaka

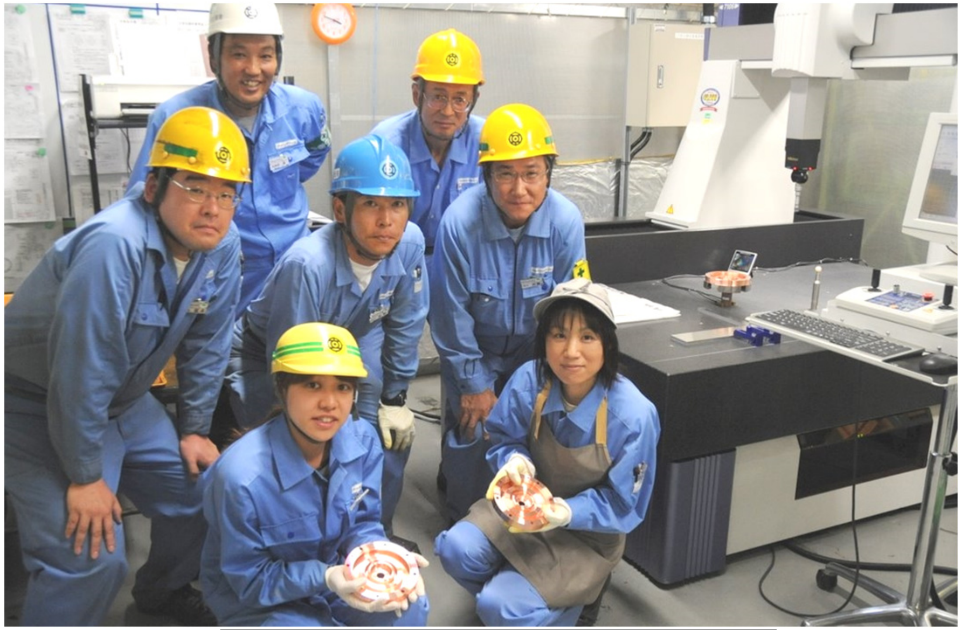
Dr. Toru Hara

RF Acceleration System in XFEL/SPring-8



Reliable RF Acceleration System

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

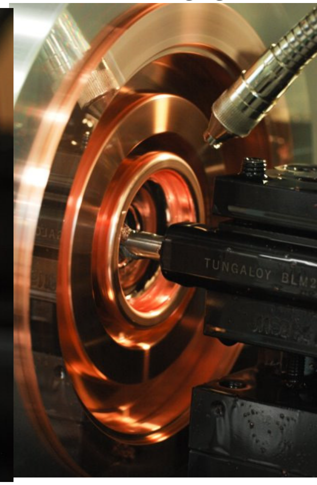
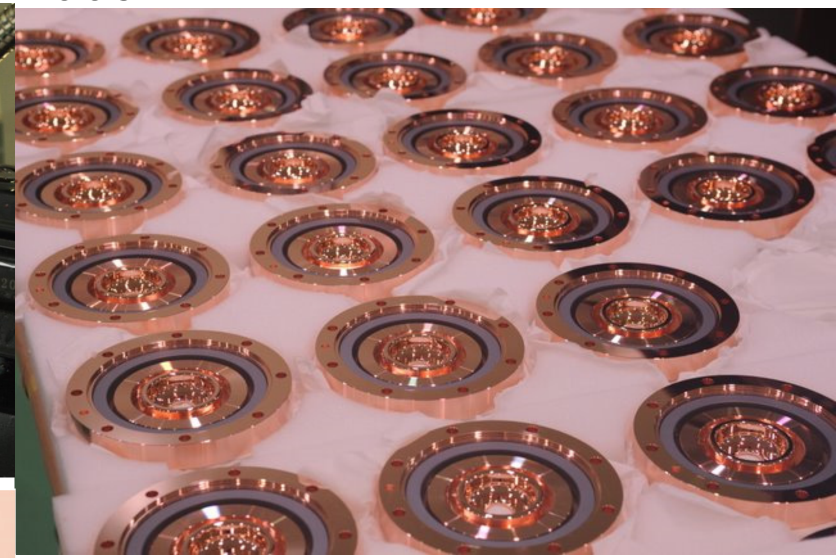


Sadao Miura, MITSUBISHI Heavy Ind,

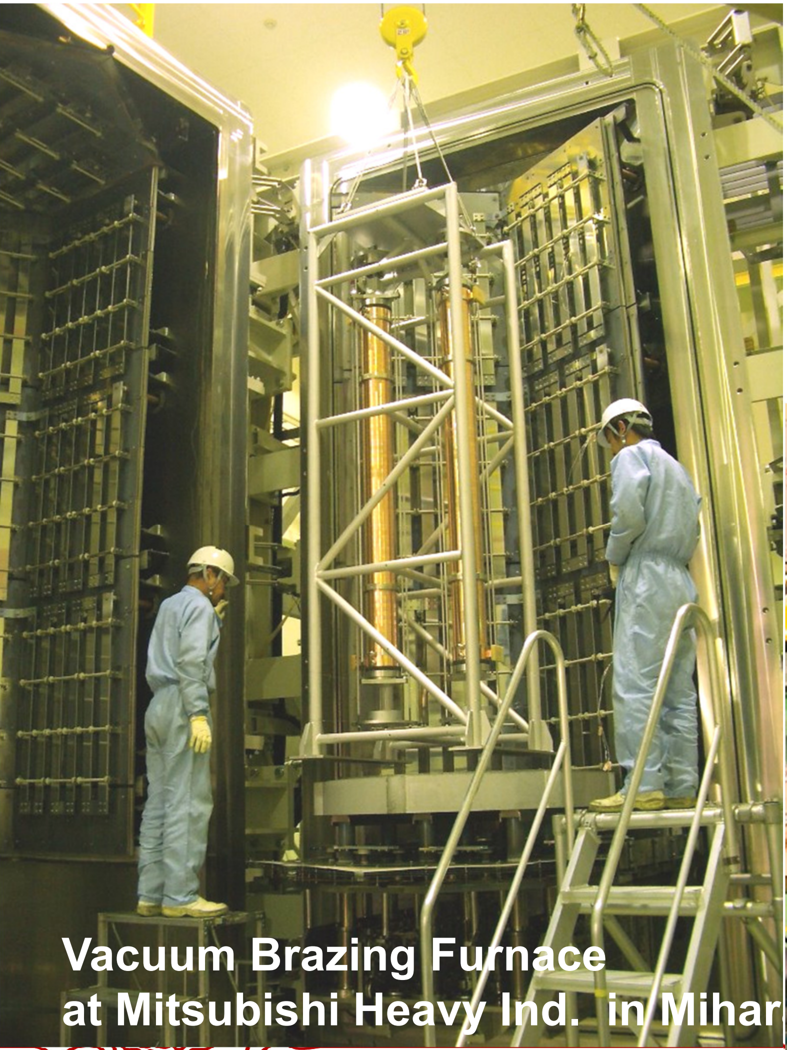
We made 13,000 pieces of C-band accelerator cell.

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

Laser
Guided
Precision
Machining

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

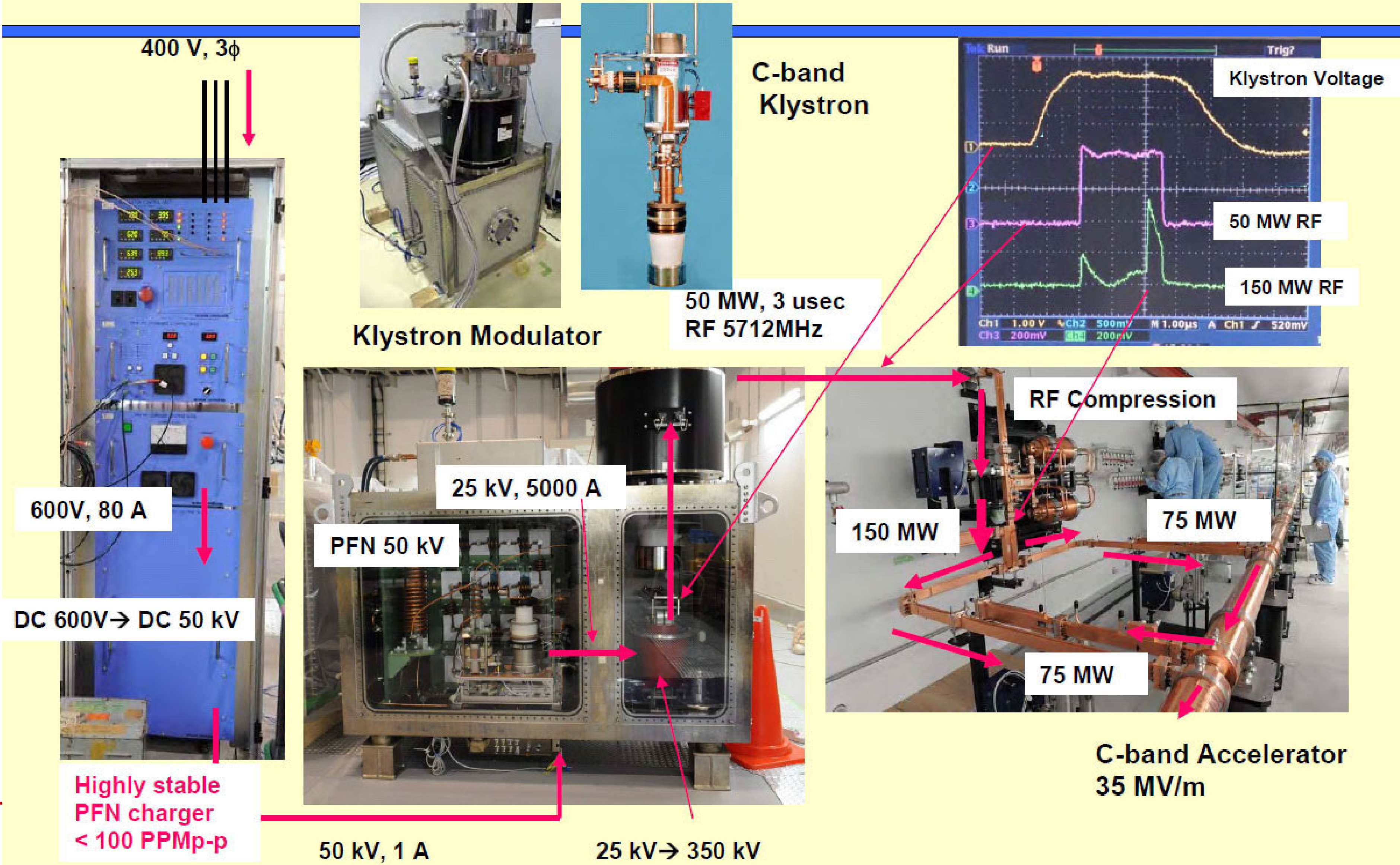
Mass Production of Klystrons at TOSHIBA

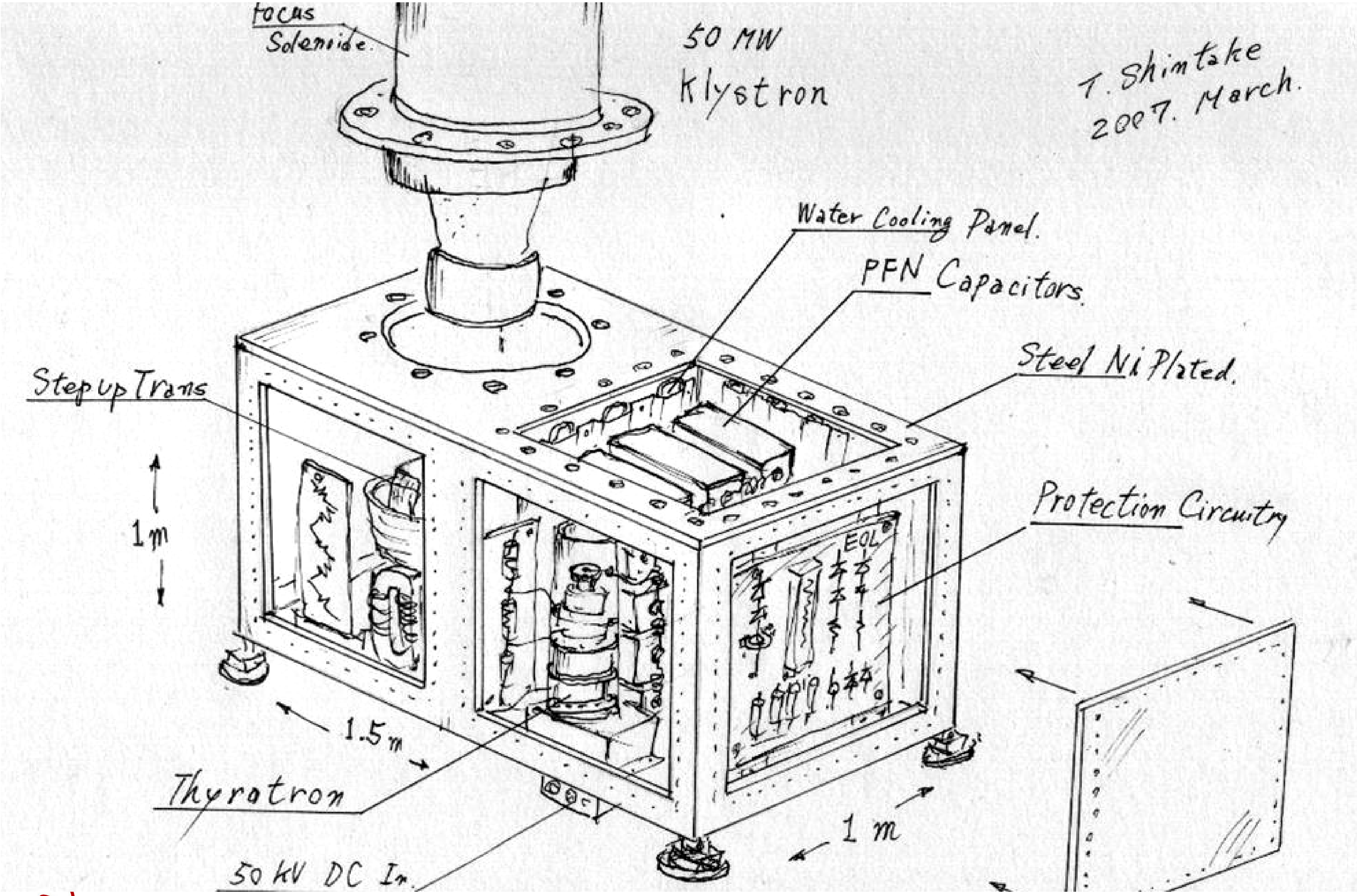
- 64 C-band klystron
- 4 S-band klystron
- 1 L-band klystron

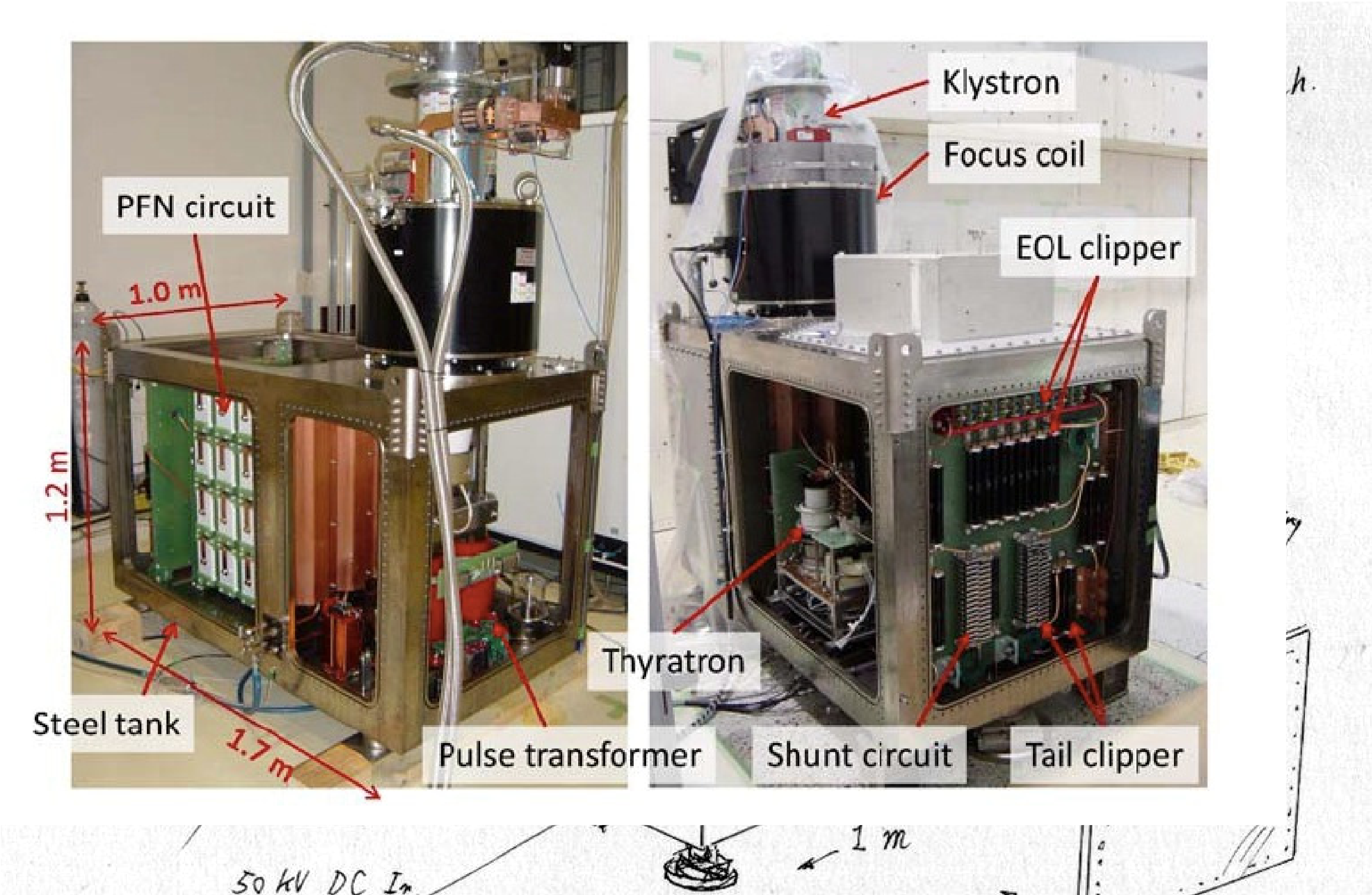
C-band Klystron
5712 MHz, 50 MW
4 μsec, 60 pps
45 % efficiency
Three-cell traveling wave output

Klystron Gallery

C-band System Configuration




Focus
Solenoide.
50 MW
Klystron
T. Shintake
2007. March.
Water Cooling Panel.
PFN Capacitors.
Steel Ni Plated.
Step up Trans
1m
Protection Circuitry
EOL
1.5m
Thyrotron
1 m
50 kV DC In.

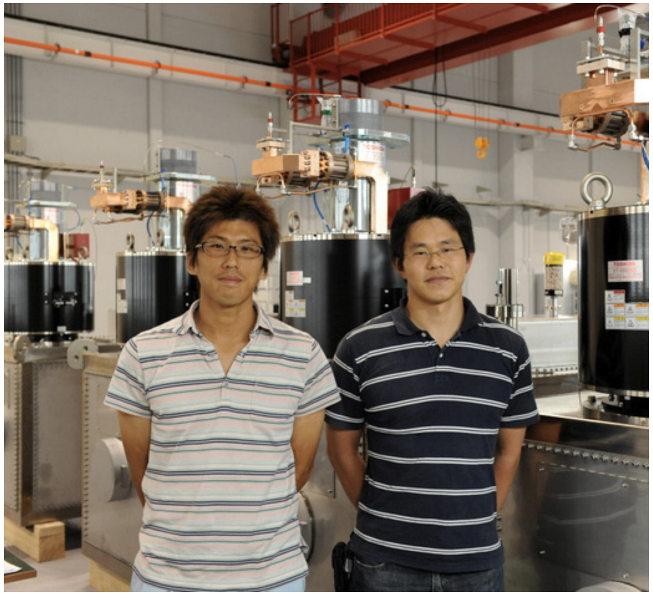

PFN circuit
1.0 m
1.2 m
1.7 m
Steel tank
Pulse transformer
Thyratron
Klystron
Focus coil
EOL clipper
Shunt circuit
Tail clipper
50 kV DC In
1 m

Klystron Modulator

Klystron power supply stabilization.

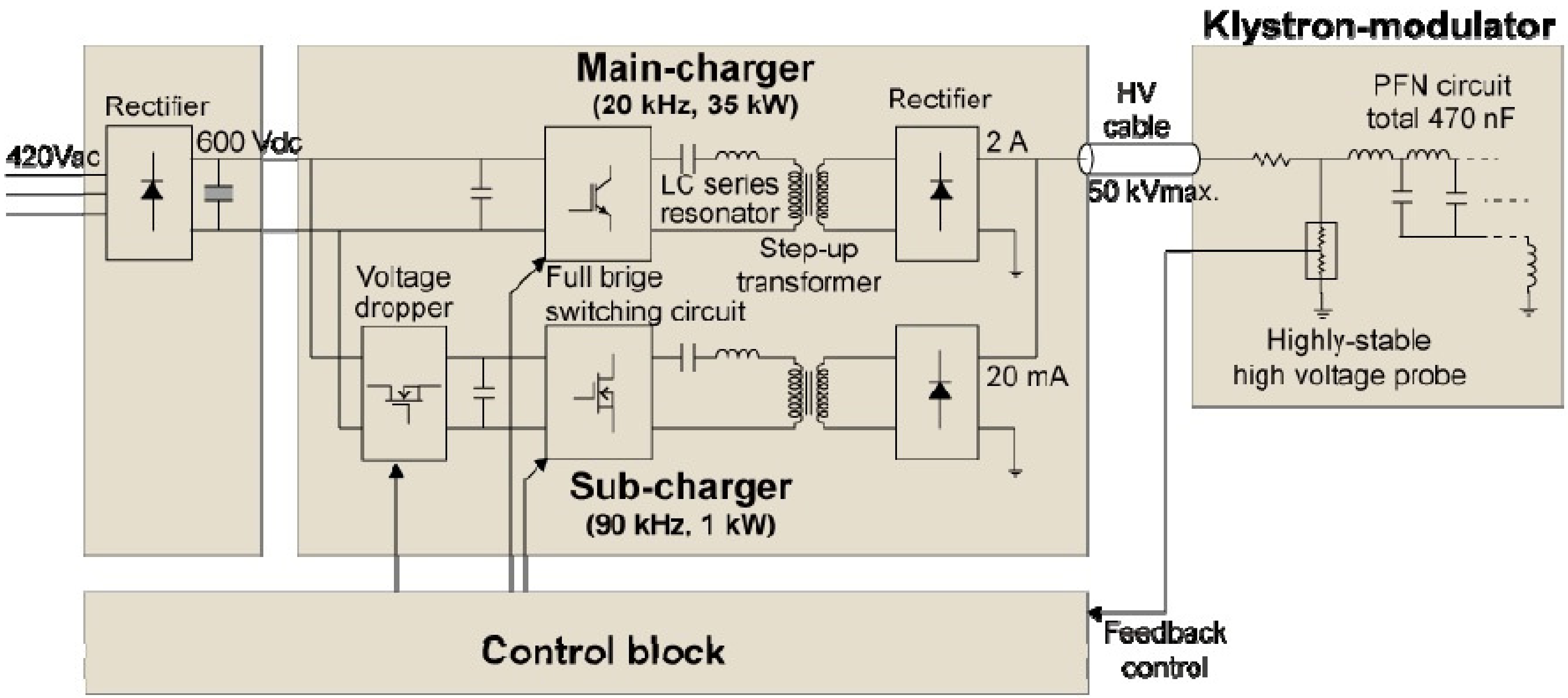
- 10 PPM stability of HV charger with IGBT switching.
- All metal shield tank.

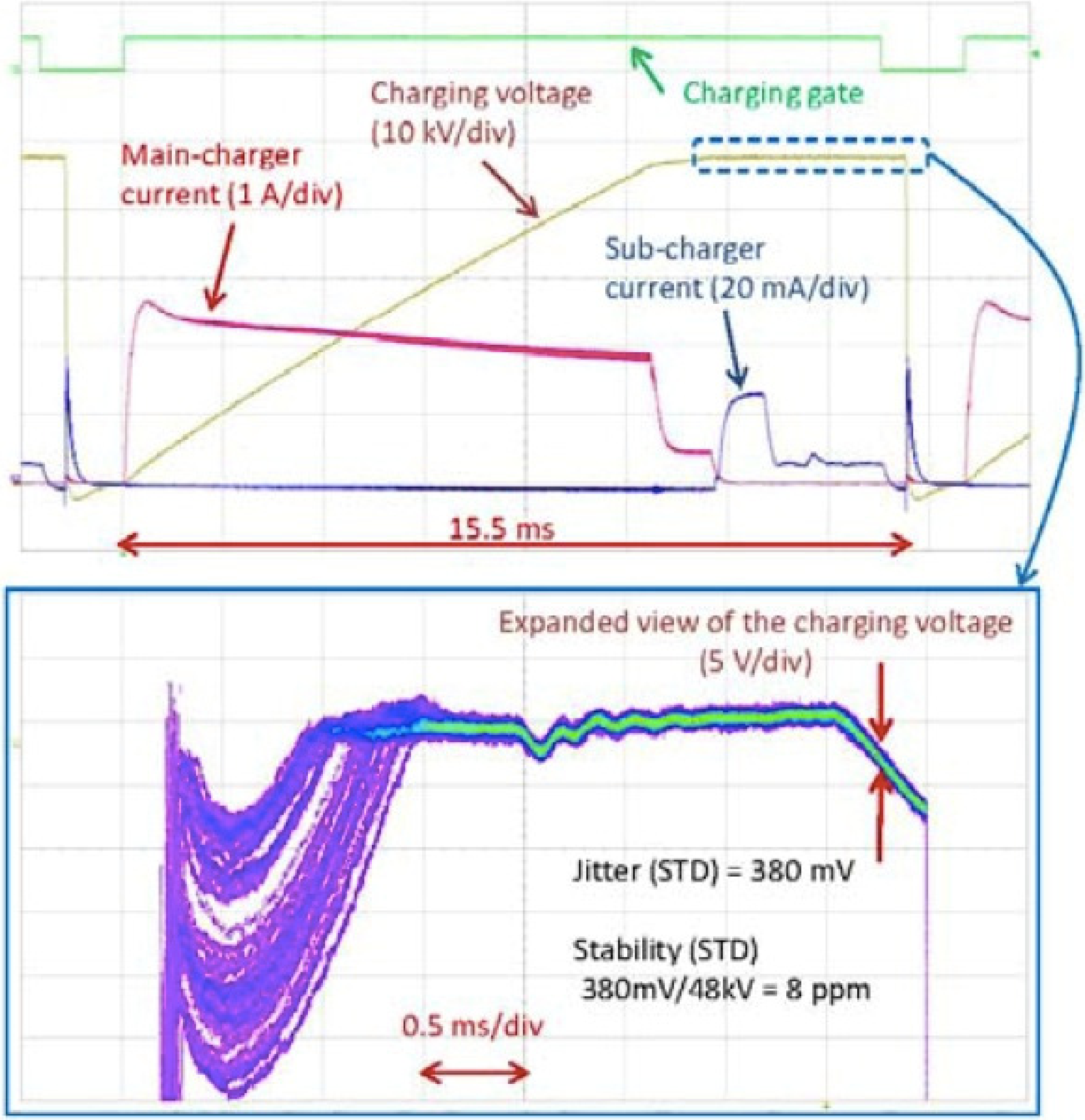
Team from Nichicon Co.



Dr. K. Shirasawa & C. Kondo

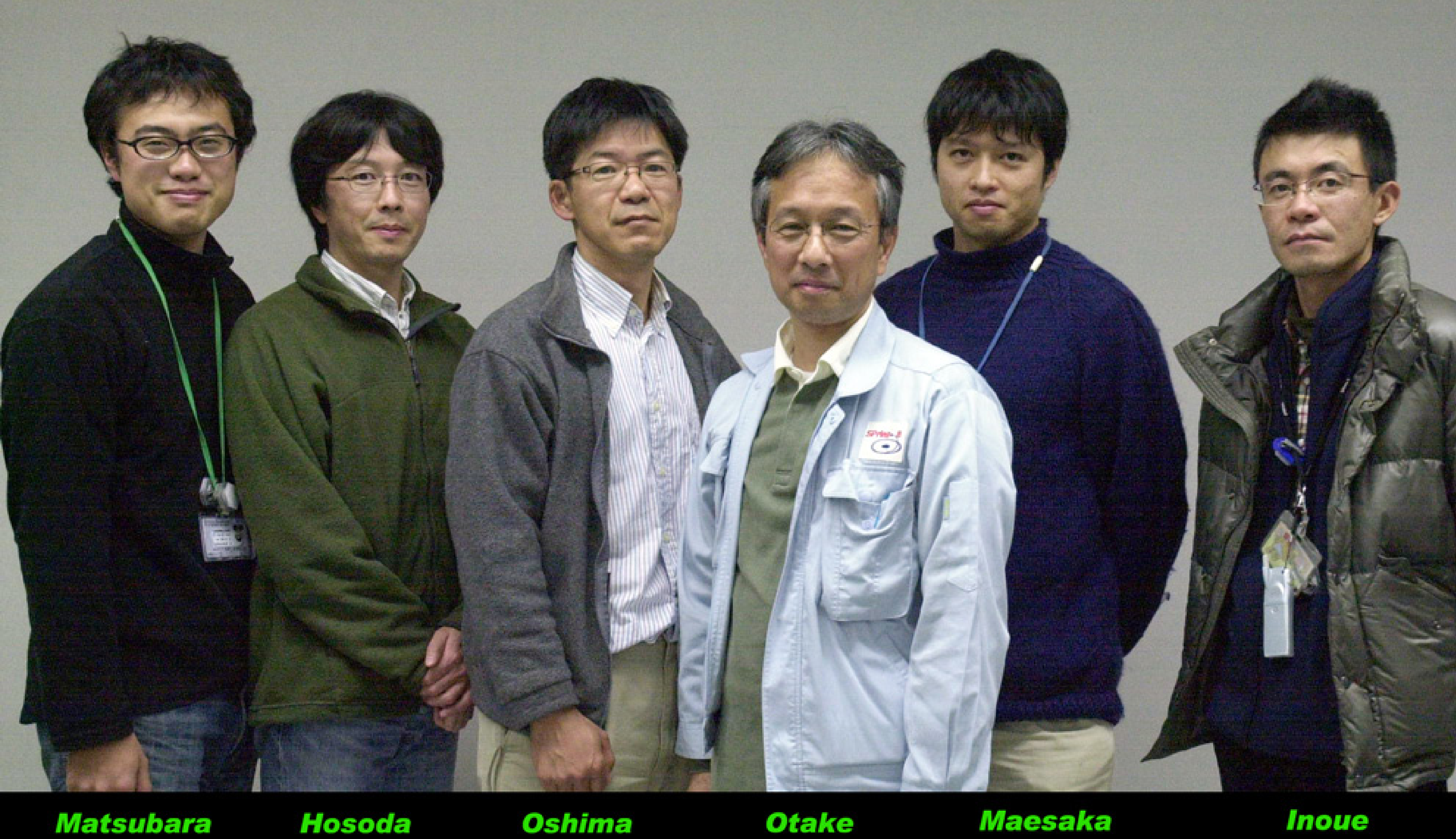
High Precision Inverter PFN Capacitor Charger





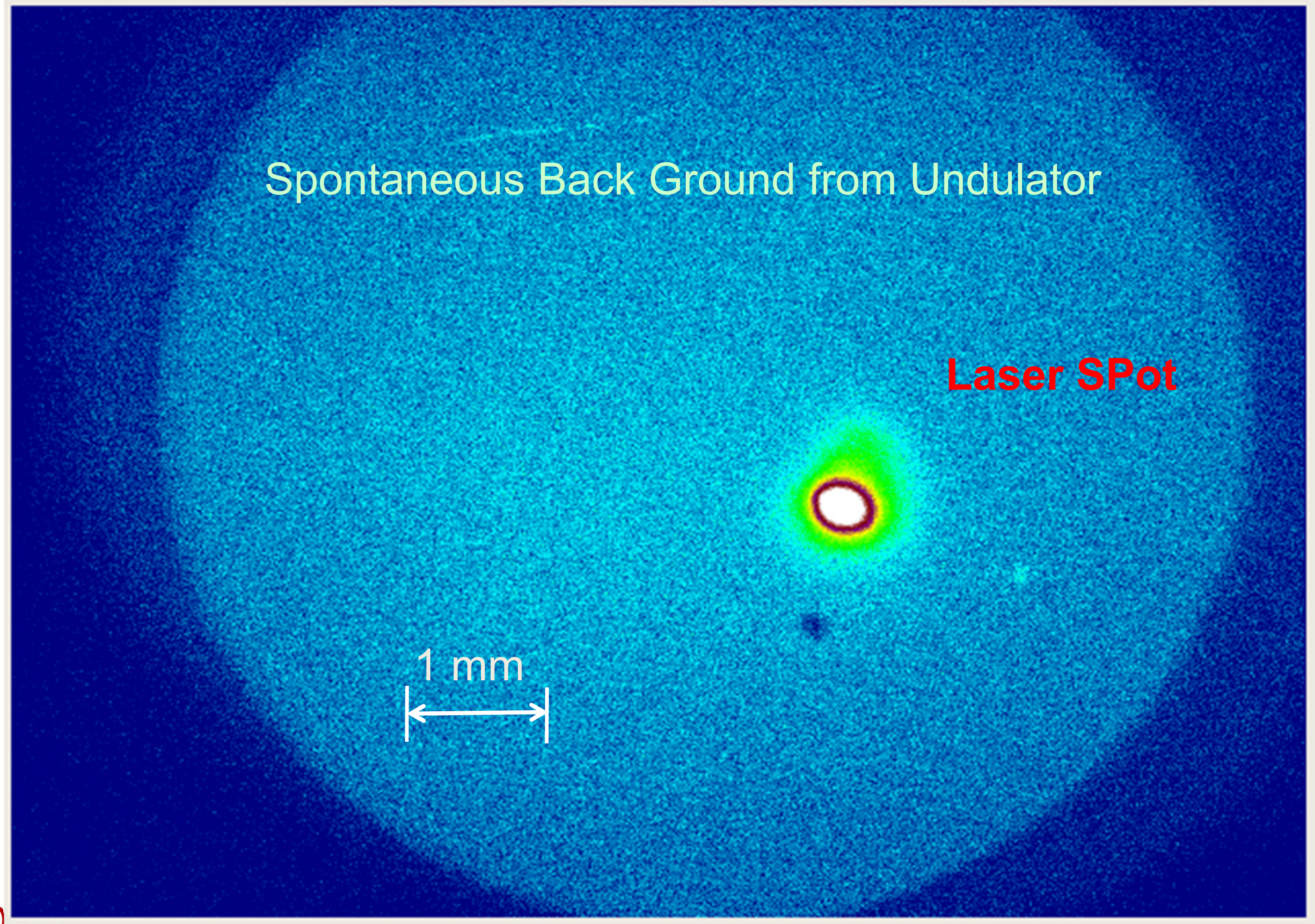
10 ppm stability

Precise LLRF System, Beam Diagnostics



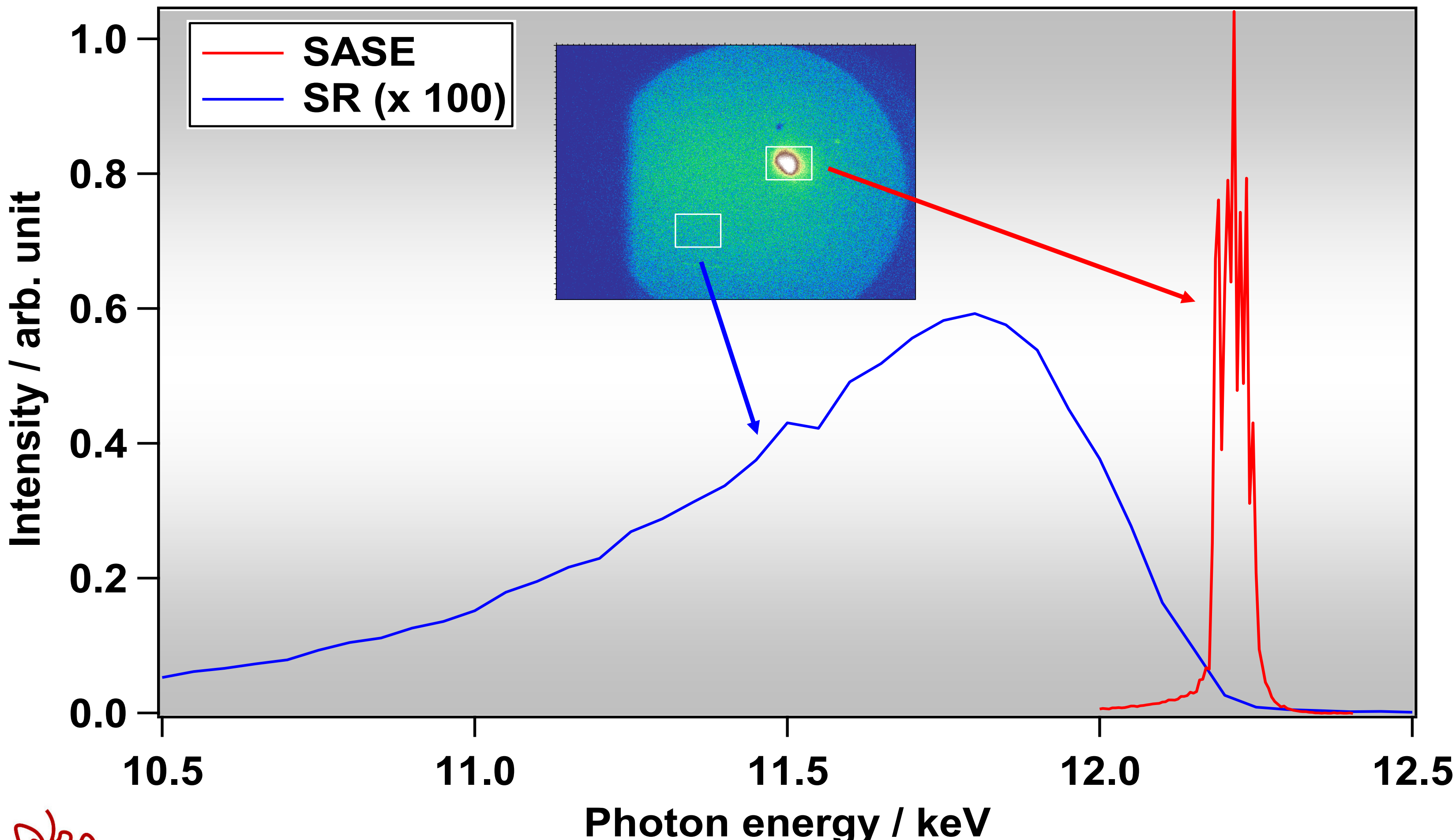

SACLA First Lasing June, 2011

Spatial Profile (pointing is very stable)



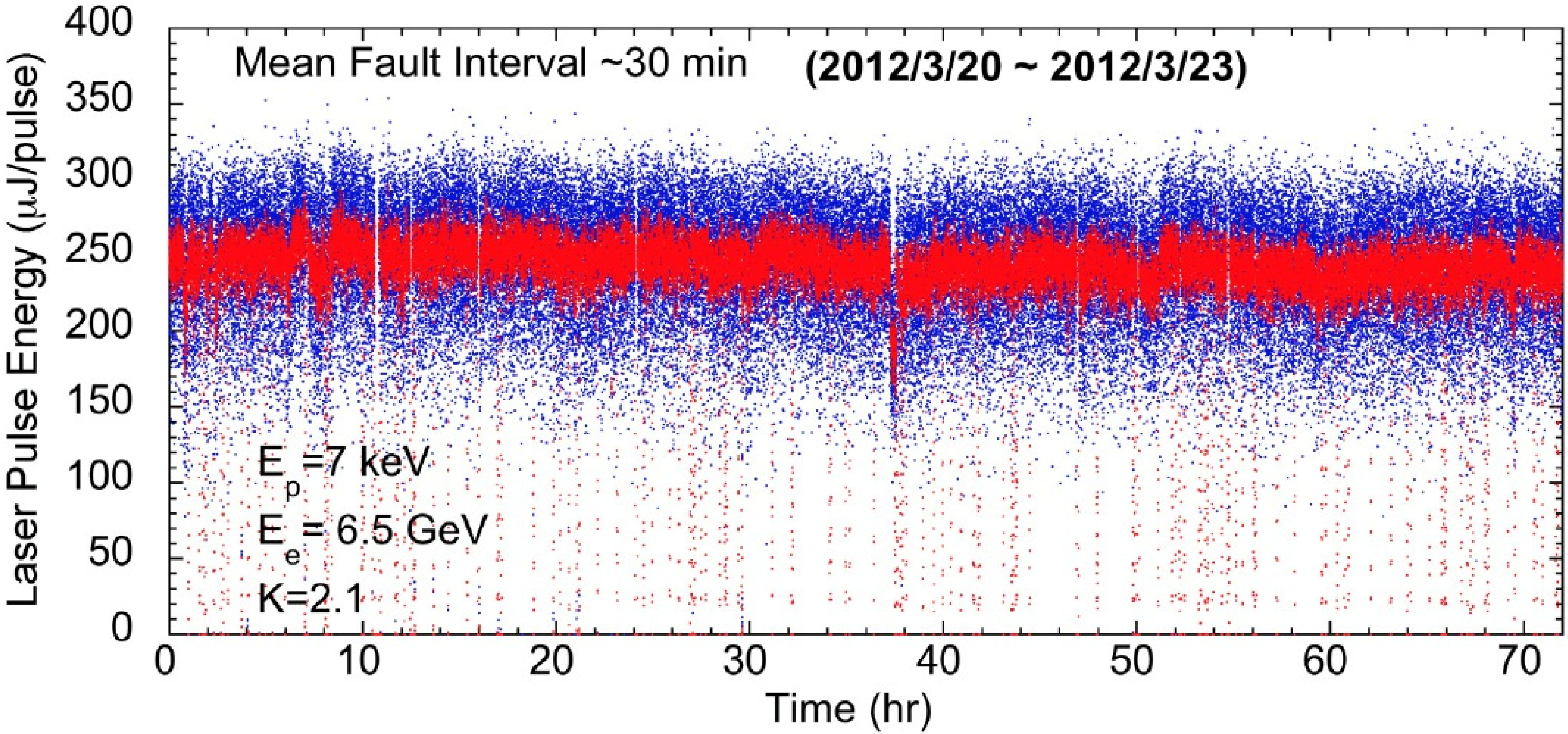
YAG-Screen 100 m downstream from undulator

Laser Spectrum(K=1.5)

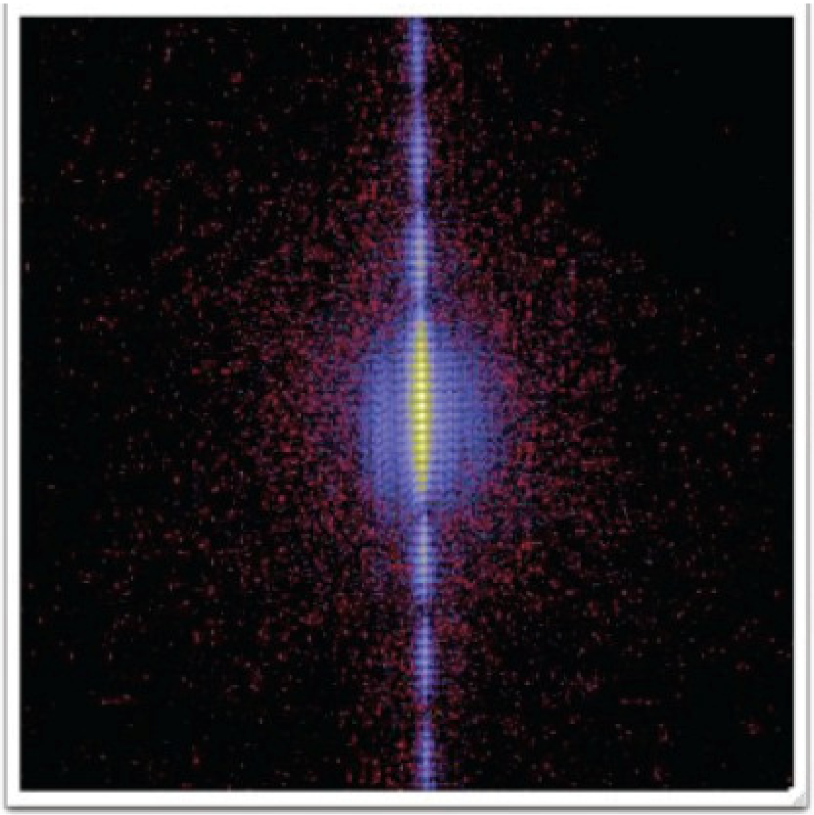


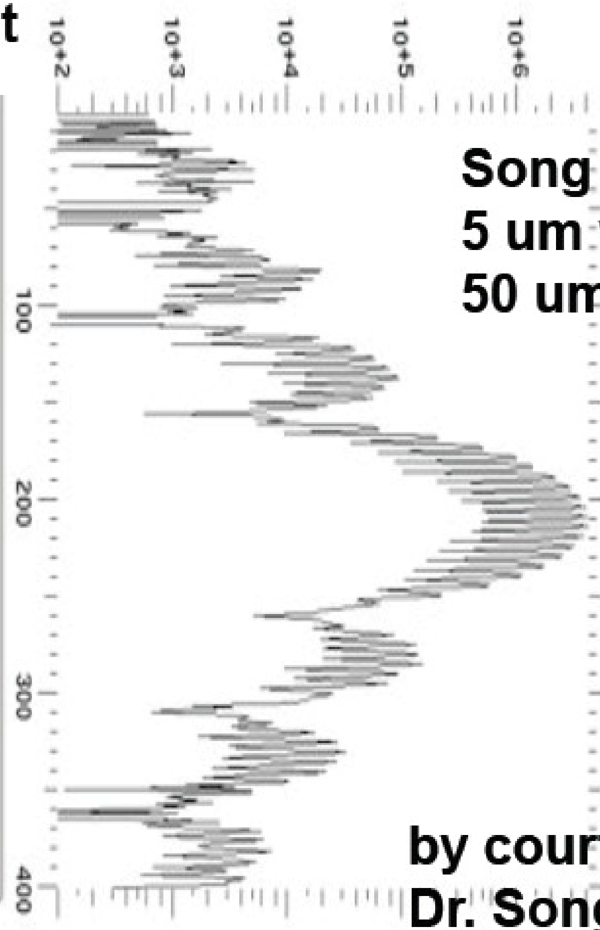
X-ray laser intensity trend.

H. Tanaka, IPAC2012



Evaluation with Young' s double slit

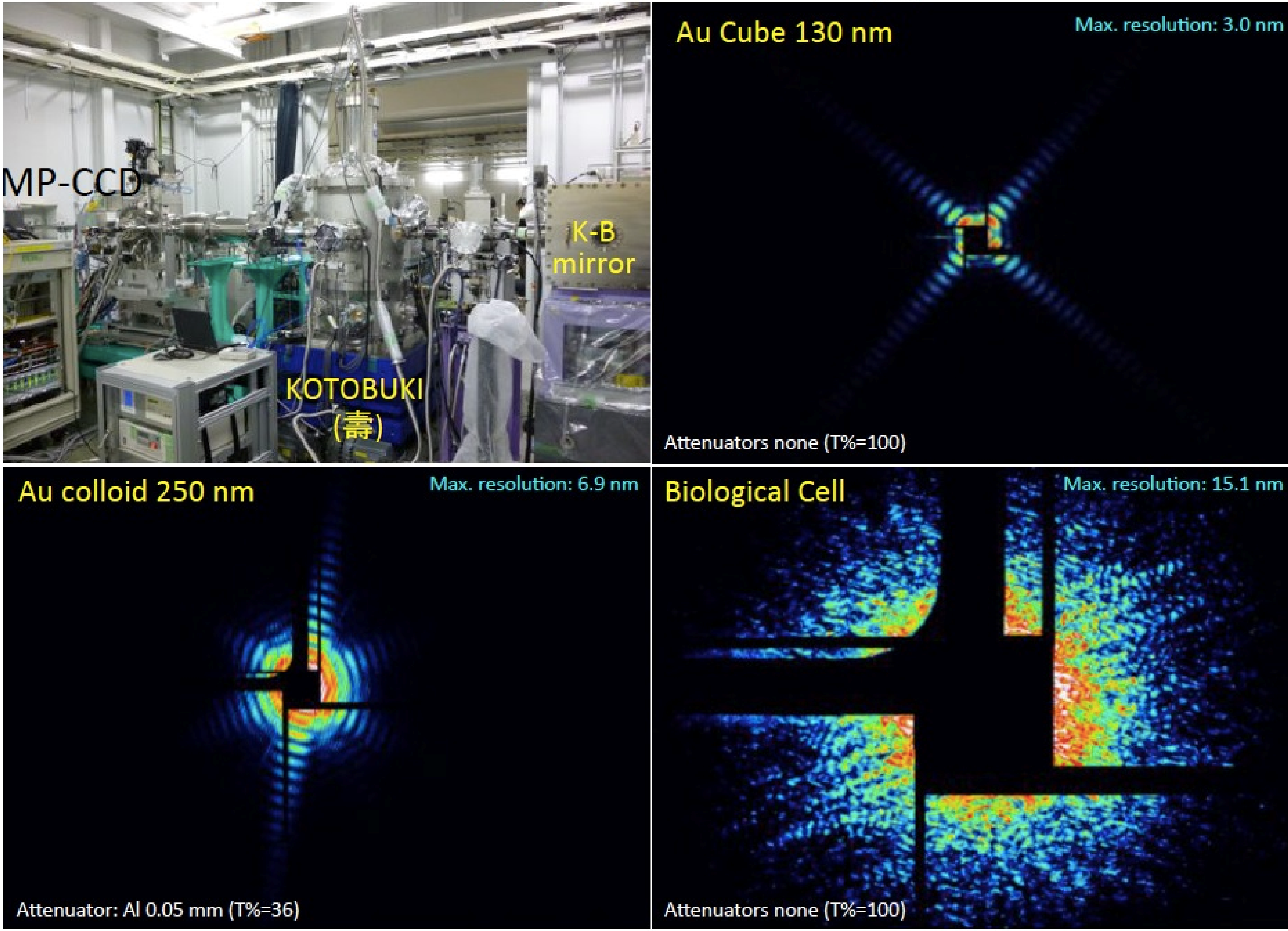




Song et al
5 um width
50 um separation

by courtesy of
Dr. Song (RIKEN)

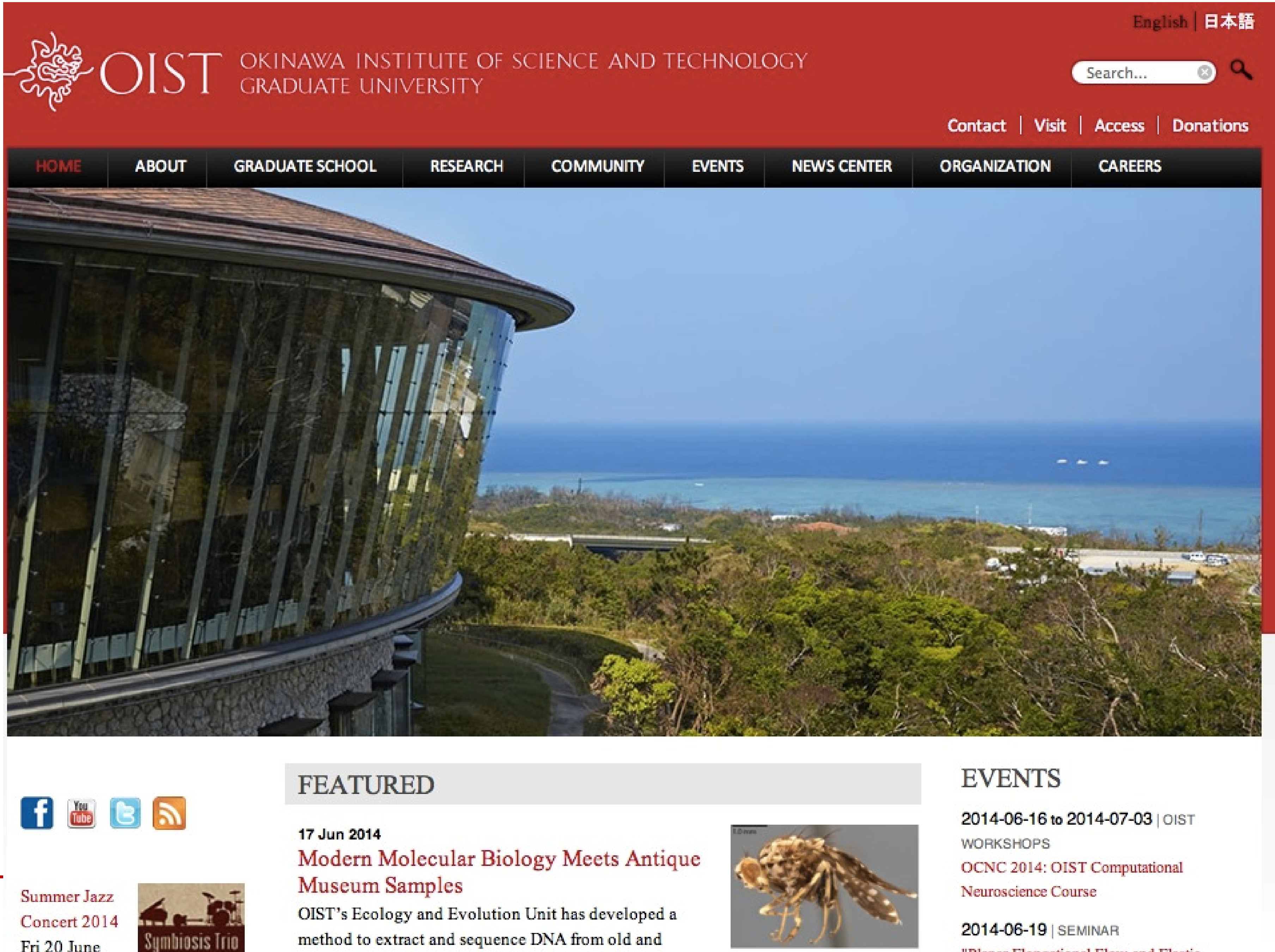
Coherent X-ray diffraction imaging using the KOTOBUKI (壽) diffractometer at 66 K



Summary of SACLA Construction

- SACLA is working nicely, thanks to all contributors at SPring-8 site, also all contributors from industry, and operation team.
- C-band is very stable at designed accelerating gradient at 35 MV/m.
- CeB_6 thermionic gun is providing stable beam, while life times exceeds ~20,000 hours operation, we routinely replace crystal with new every year.
- Since 2012, user beam operation started.

SPring-8 → OIST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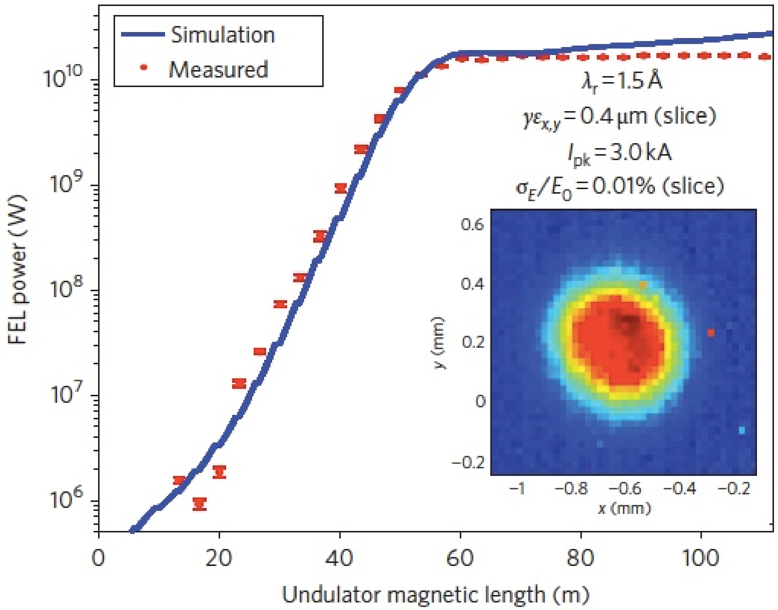
If I redo the same project again, what do I change?

- ***I will chose C-band again.***
  - *If we do not run in multi-bunch, standard disk-loaded structure, without HOM damping, will be also fine.*

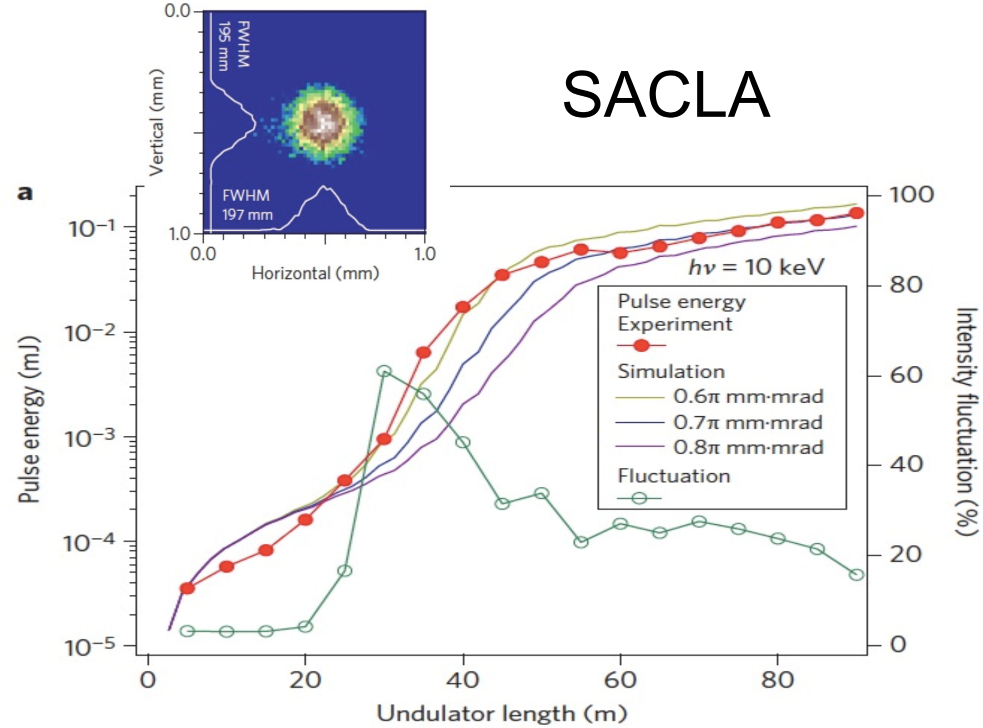
- ***Need more beam energy: 8 GeV → 10 GeV or higher.***
  - *We can go high K value in undulator, increase photon power.*

- ***I will chose CeB6 cathode gain.***
  - *L-band choice was our mistake. Need go back to SCSS desing using S-band, then CSR instability in chicane will be much lowered or stopped.*
  - *Photo-shottoky emission from CeB6 at ~1000 deg-C, using pulse laser at a few 10 psec will provide very reliable e-source.*

LCLS



SACLA



LCLS		SACLA	
Q	0.25 nC	Q	(0.25 nC)
E	13.6 GeV	E	7.0 GeV
K	3.5	K	1.8
Gain Length	3.5 m	Gain Length	**
Wavelength	1.5 A	Wavelength	1.2 A
Peal Power	15-40 GW	Peal Power	16 GW
W-photons	1.5-3.0 mJ	W-photons	0.3 mJ
Pulse Length	70-100 fs	Pulse Length	20-30 fs

$$P \propto \rho \cdot E \cdot I$$

$$W_{photon} \propto \rho \cdot E \cdot Q$$