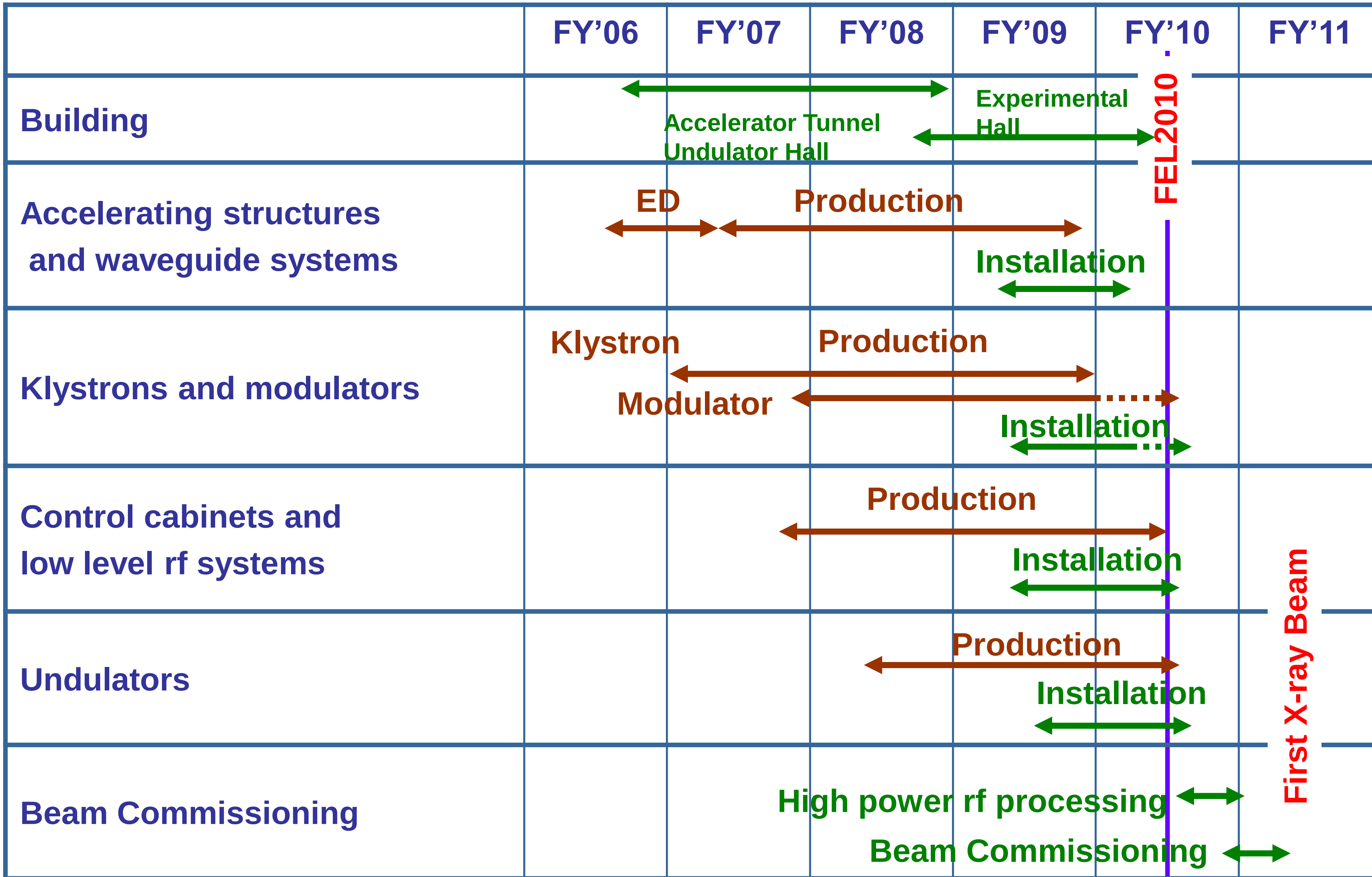
XFEL/SPring-8 Construction and SCSS EUV Laser Operation Status

Tsumoru Shintake

as representing Joint XFEL/SPring-8 Construction Team

R&D Technical Director XFEL/SPring-8
Chief Scientist RIKEN SPring-8 Center

Status of XFEL/SPring-8 Construction



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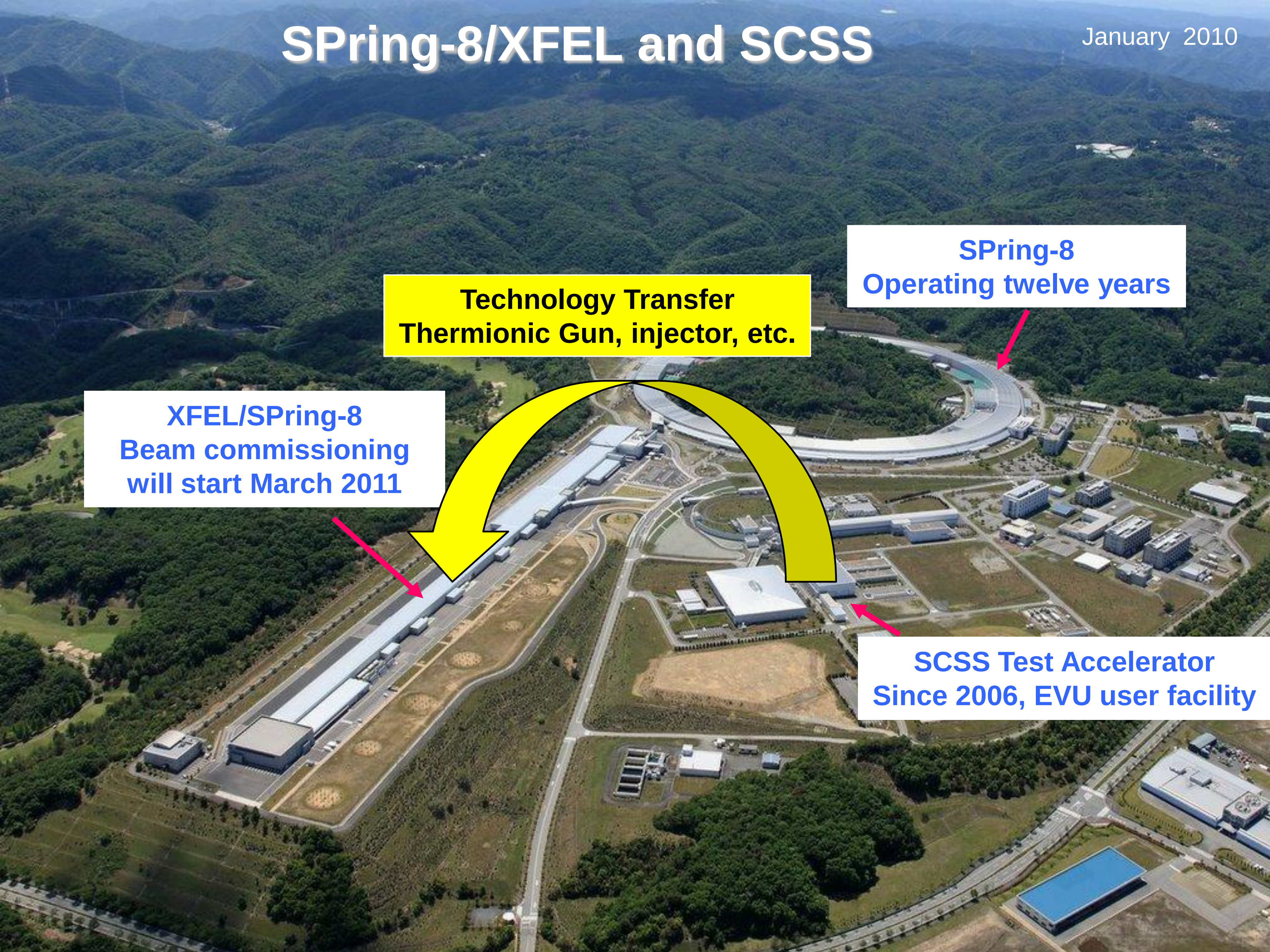
SPring-8/XFEL and SCSS

January 2010




50 m Experimental Hall
200 m Undulator Hall
400 m Accelerator Tunnel
Klystron Gallery
Machine Assembly Hall


2007 May

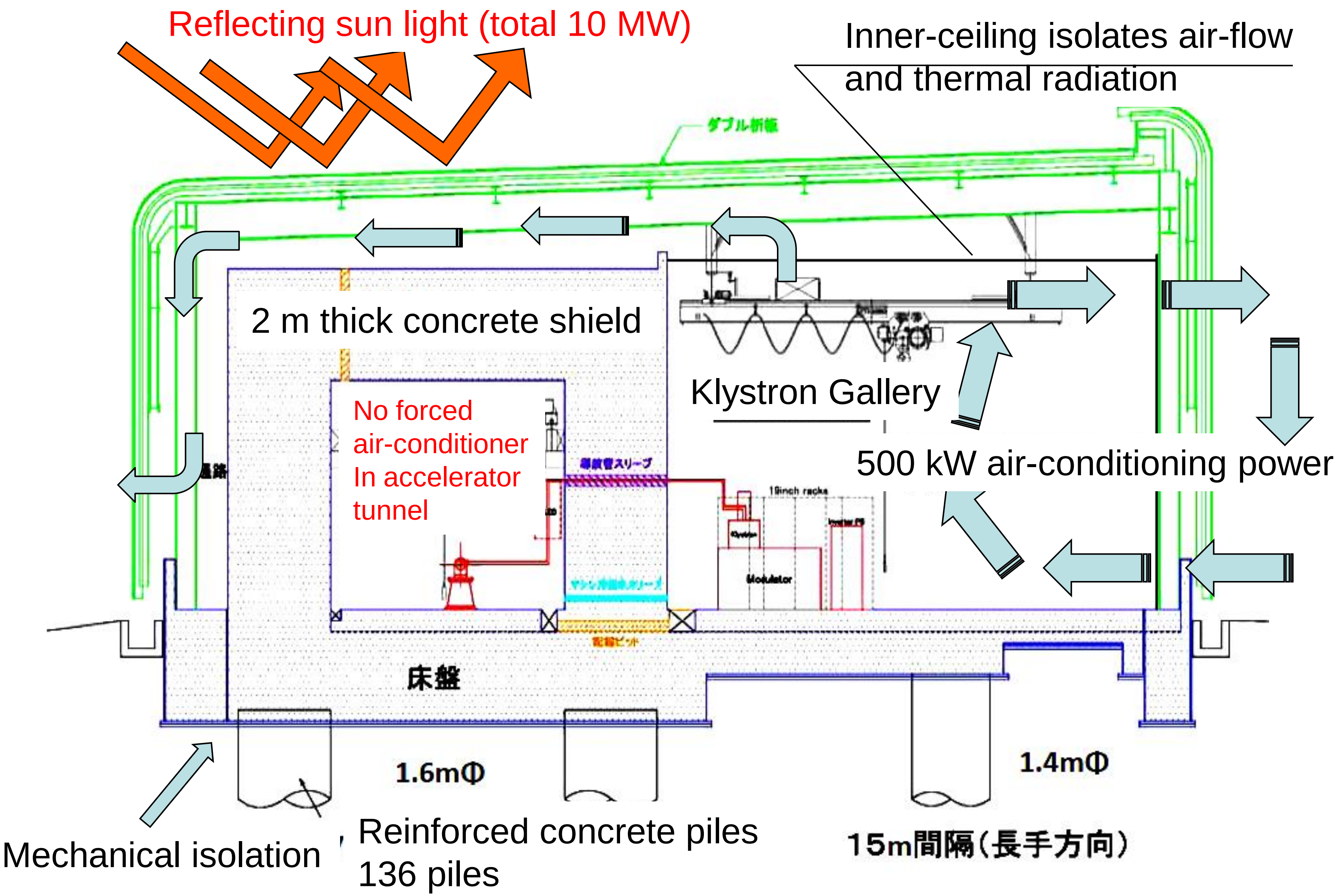
Excavating 17 m deep at undulator area, replaced with crashed stones on base rock, which took 8 month. Only -1.7 mm vertical movement was observed for 2 year after completion. Extremely stable basement was made for undulator hall.


2008 May


2008 Oct


2009 April

Temperature Regulation 1 deg was achieved for Non-under Ground Tunnel



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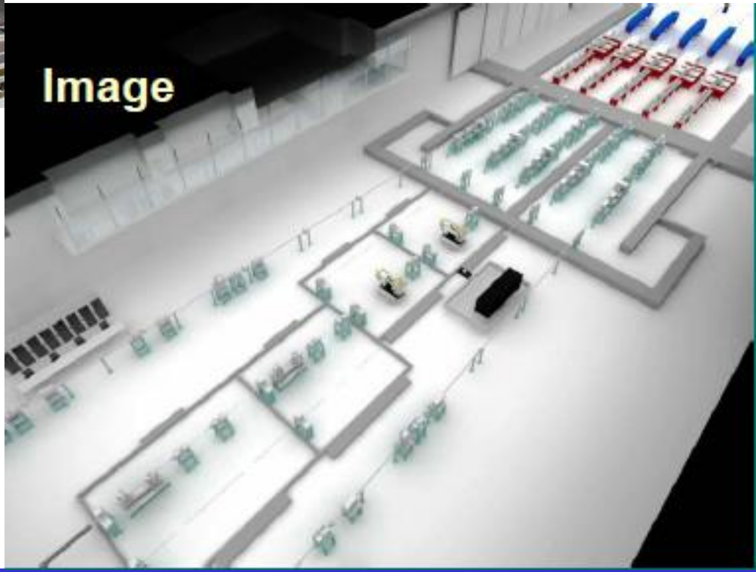
Experimental Hall



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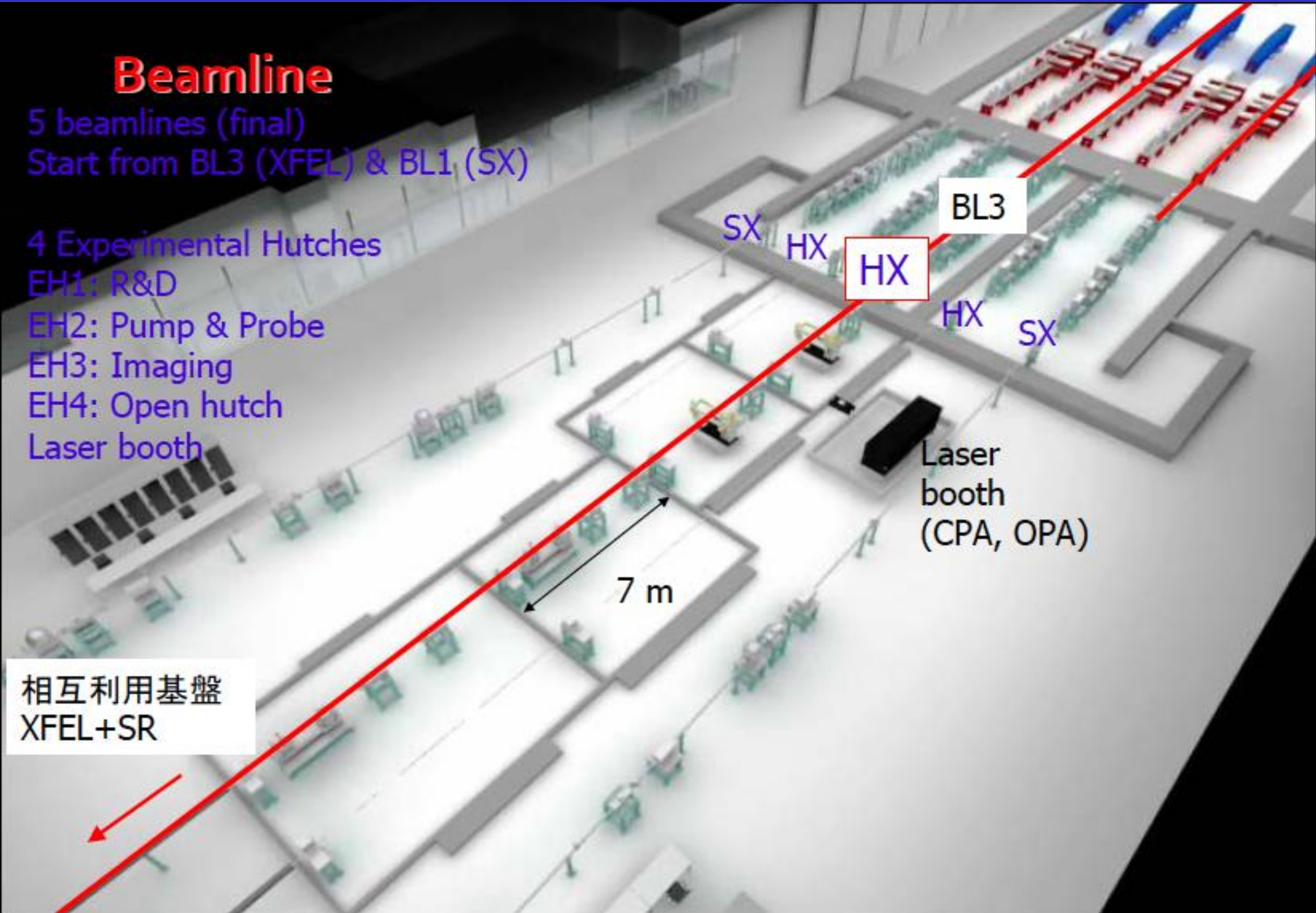
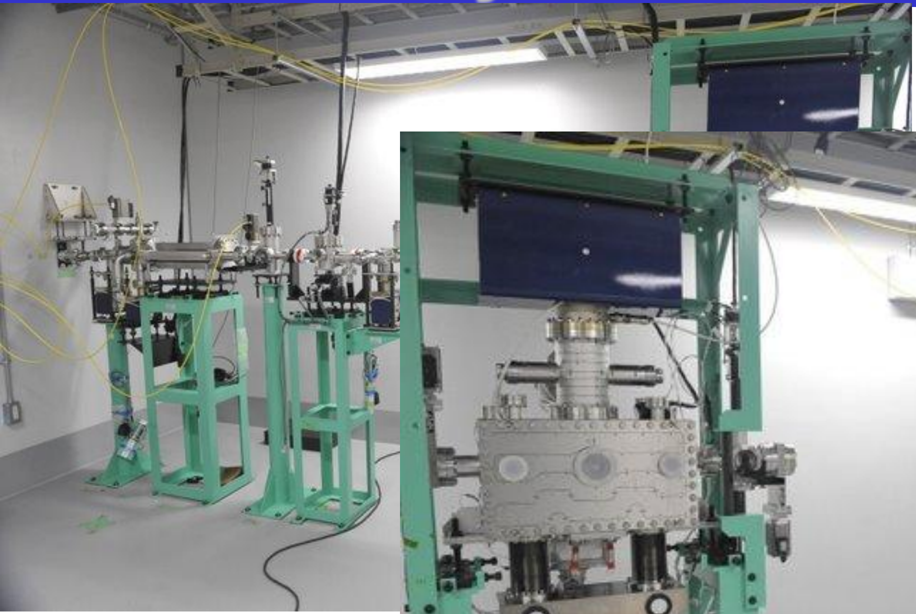
Beam Lines


Beamline
5 beamlines (final)
Start from BL3 (XFEL) & BL1 (SX)
4 Experimental Hutches
EH1: R&D
EH2: Pump & Probe
EH3: Imaging
EH4: Open hutch
Laser booth
BL3
SX
HX
HX
HX
SX
Laser
booth
(CPA, OPA)
7 m
相互利用基盤
XFEL+SR

Experimental Hall, 4 Hutches are ready

X-ray Beam Line Front-End Mirrors



2009 July

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Accelerator installation

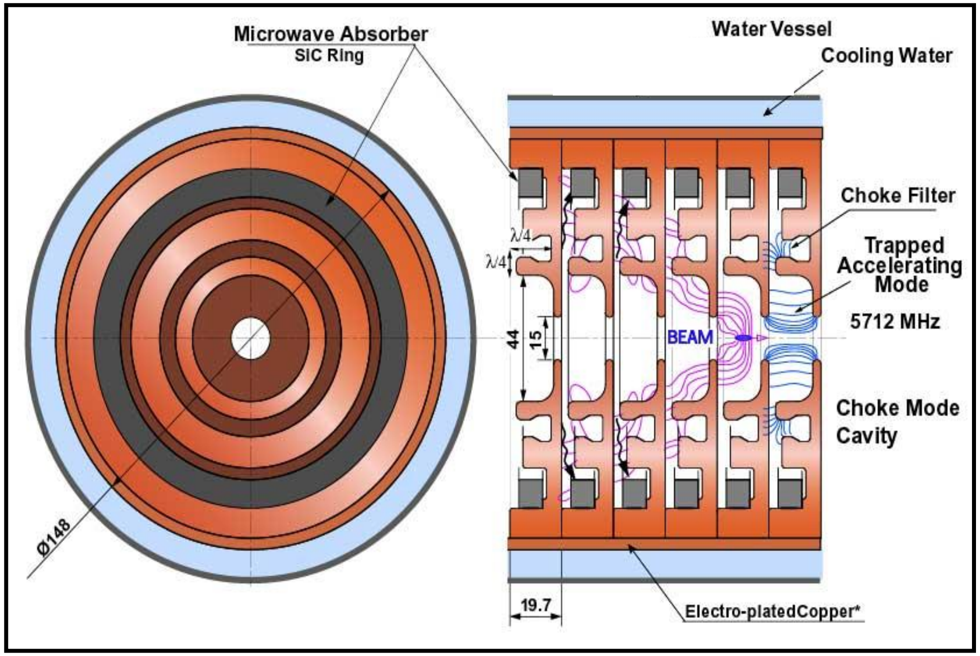

2009 Aug

2009 Aug

WEOC3

T. Inagaki, "Construction of 8-GeV C-band Accelerator for XFEL/SPring-8",

C-band Accelerator for Multi-bunch Option



13,000 cells are under mass production.

T. Shintake, "Choke Mode Cavity",
Jpn. J. Appl. Phys. Vol. 31 pp. L1567-L1570, November 19

Sadao Miura, MITSUBISHI Heavy Ind, April 20

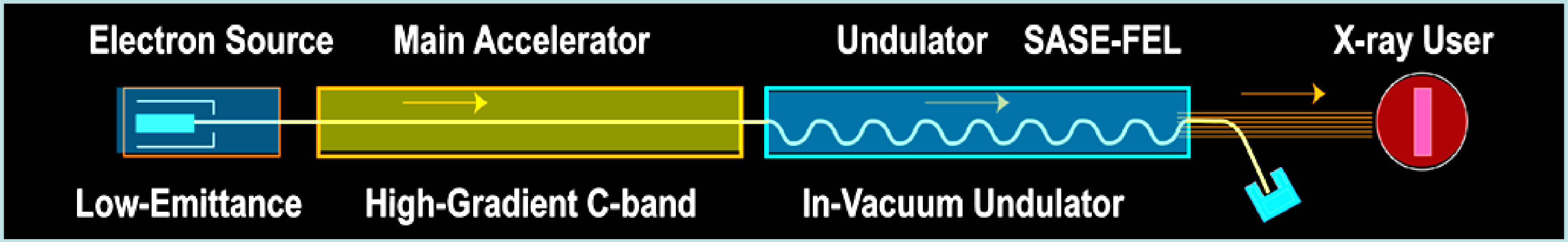
Higher Order Mode Damping for Multi-bunch operation.
Maximum 50 bunches x 1 nC, at 4.2 nsec spacing

X-ray 4.2 nsec x 50 bunches will be key for
Single bio-molecule imaging to improve Luminosity.

Testing Modulator & Klystron

May 2010

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

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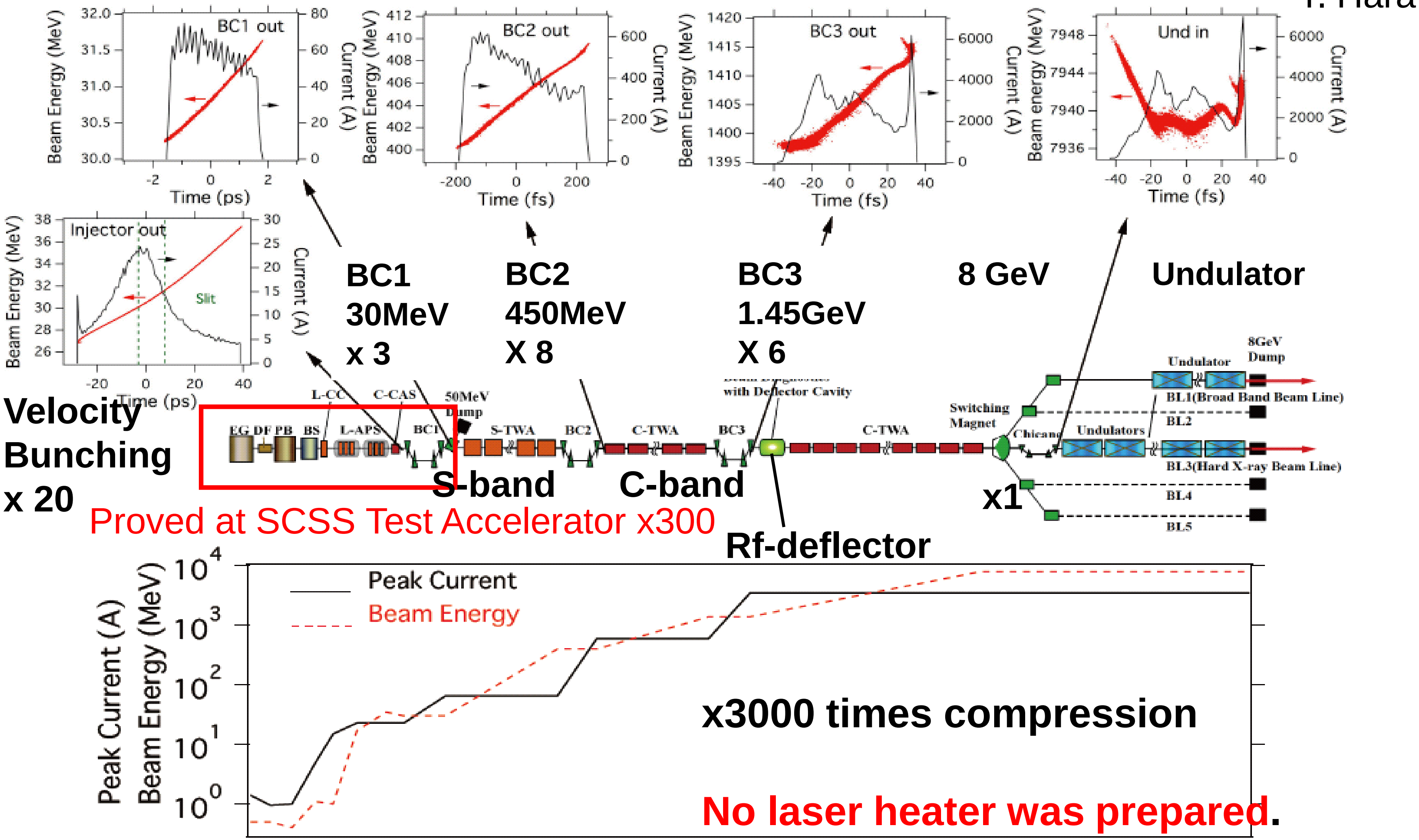
Beam Acceleration and Compression

T. Hara



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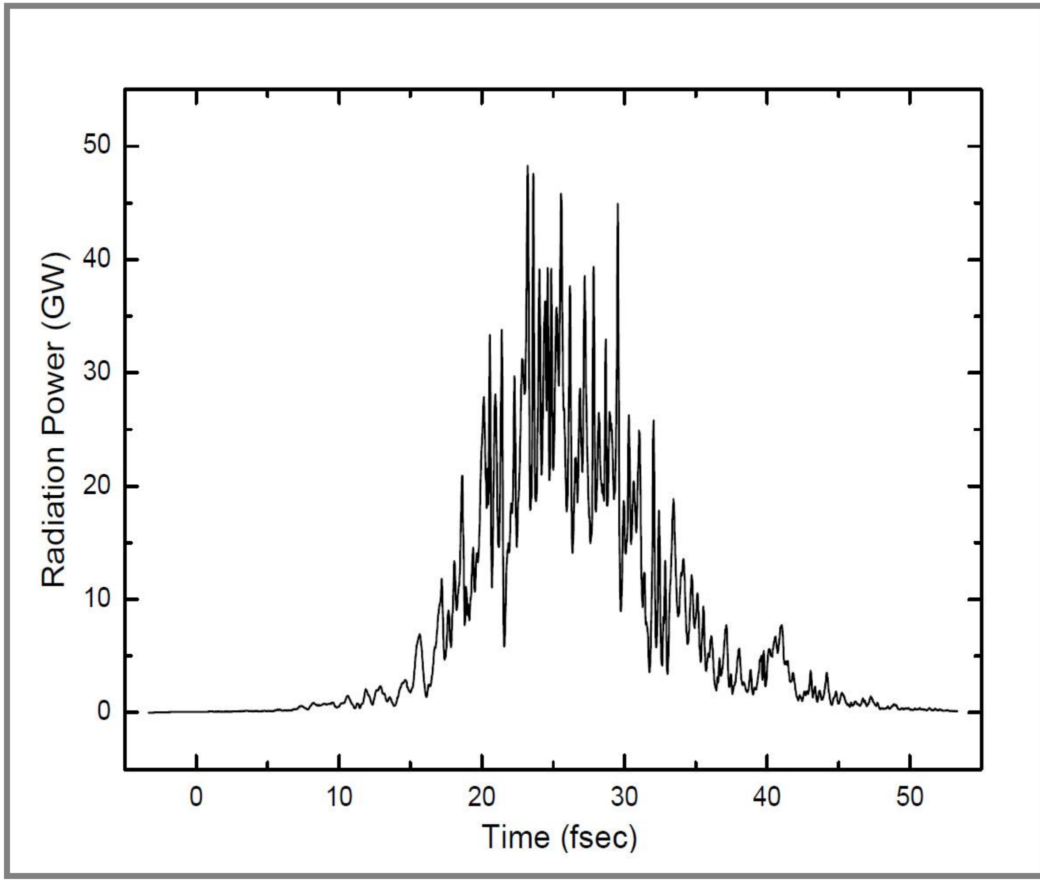
Expected Performance of XFEL/SPring-8

Wavelength	**< 0.1 nm**
Peak Power	**~ 20 GW**
X-ray Pulse Length	**200 fs ~ 20 fs**
X-ray Pulse Energy	**Max 0.4 mJ**
Photon Flux	**2 x 10^{11} p/pulse**
Peak Brightness	**1 x 10^{33} p/mm^2/mrad^2/0.1% BW**
X-ray Pulse Repetition	**10 ~ 3000 pps (50 bunch x 60 Hz)**
Bunch per Pulse	**1 ~ 50 (4.2 nsec spacing)**
e Beam	**8 GeV x 0.3 nC 0.8 πmm.mrad, 3 kA**



Expected X-ray pulse of 0.1 nm (SIMPLEX simulation)

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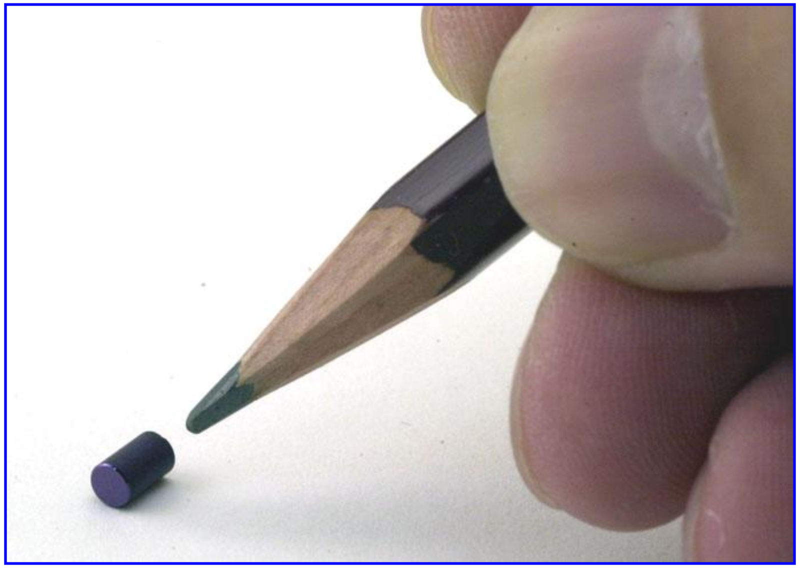
Operating Temperature 1500° C

$$w_e = \frac{3}{2} k_B T = 223 \text{ meV}$$

Thermal Emittance

$$\varepsilon_{xN} = \frac{\gamma r_c}{2} \sqrt{\frac{k_B T}{m_0 c^2}} = 0.4\,\pi \text{ mm-mrad}$$

Use Small Cathode 3mm



Current Density

$$\frac{I_e}{\pi r_c^2} = \frac{1 \sim 2\text{ A}}{3.1 \times 0.15_{cm}^2} = 14 \sim 30 \text{ A/cm}^2$$

LaB_6 or CeB_6

Twice longer lifetime

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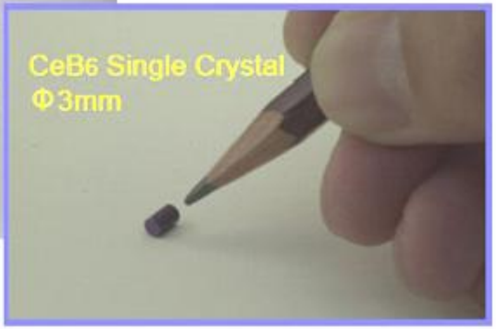
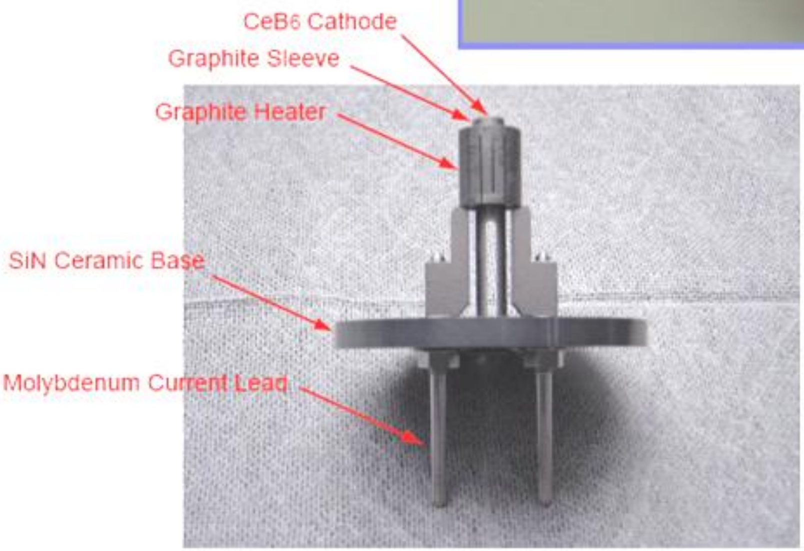
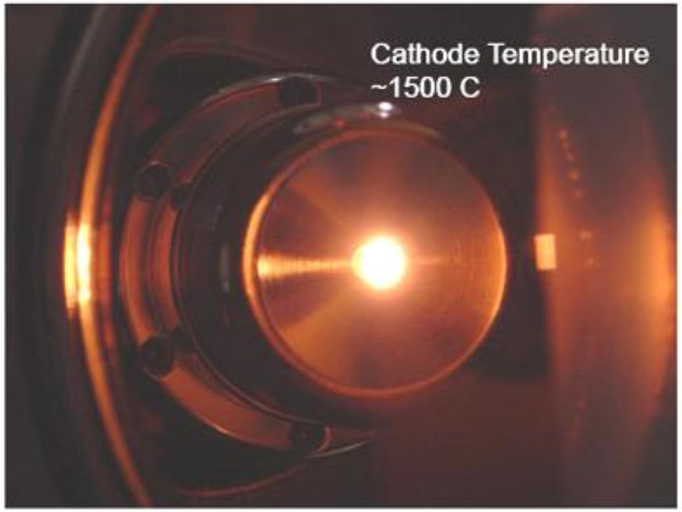
CeB6 Thermionic Electron Gun *K. Togawa*

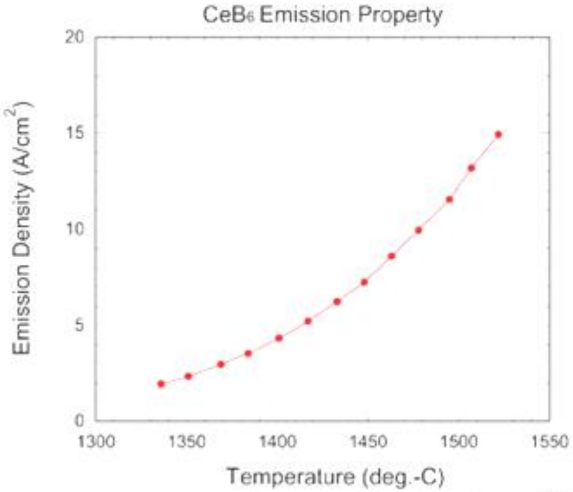
Cathode Assembly





Heated Cathode in Stem

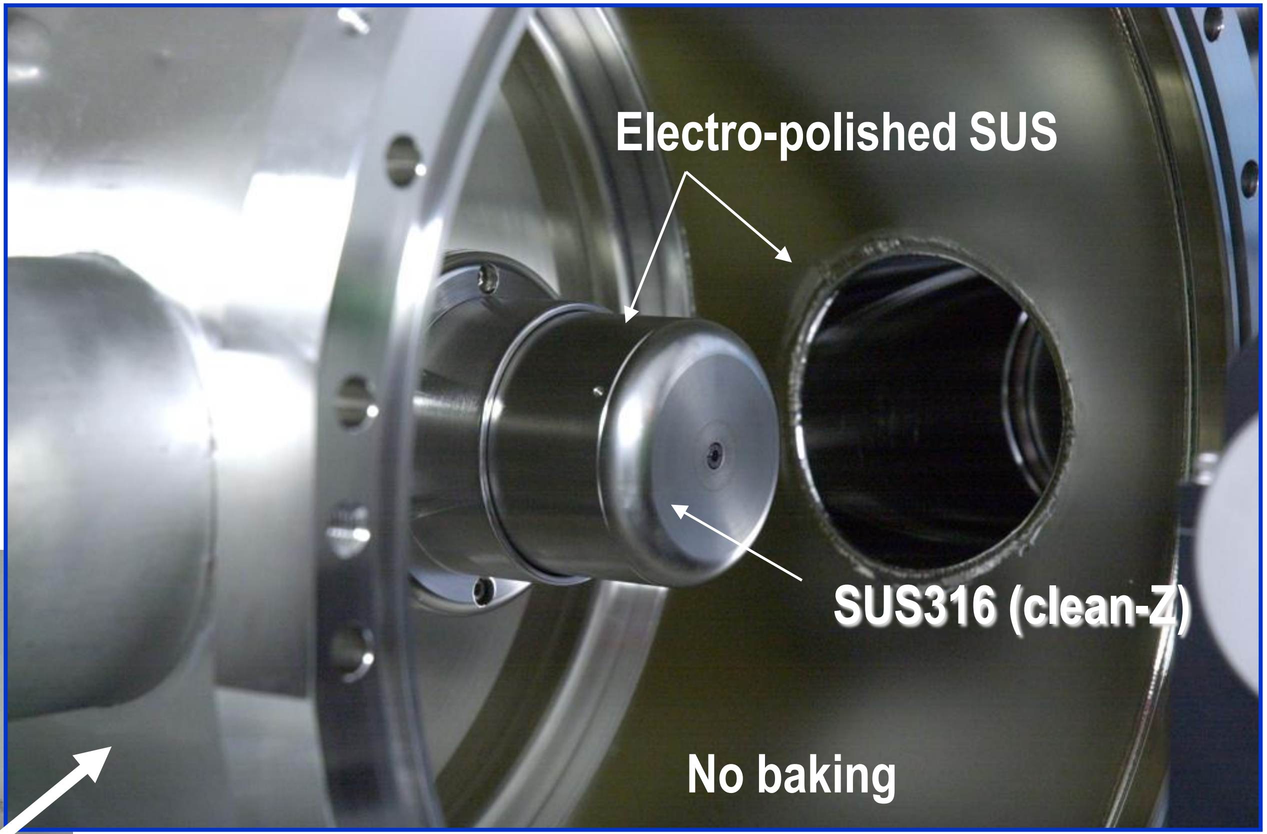




The gun voltage=500 kV
Temperature was measured at t
sleeve by a radiation monitor.

Operational Experience of 500 kV Gun

- 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.***

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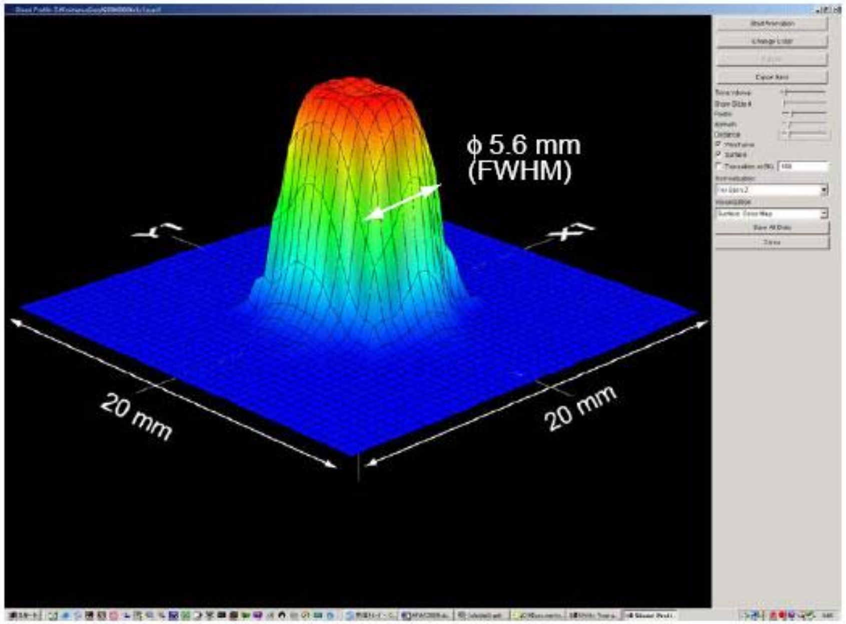
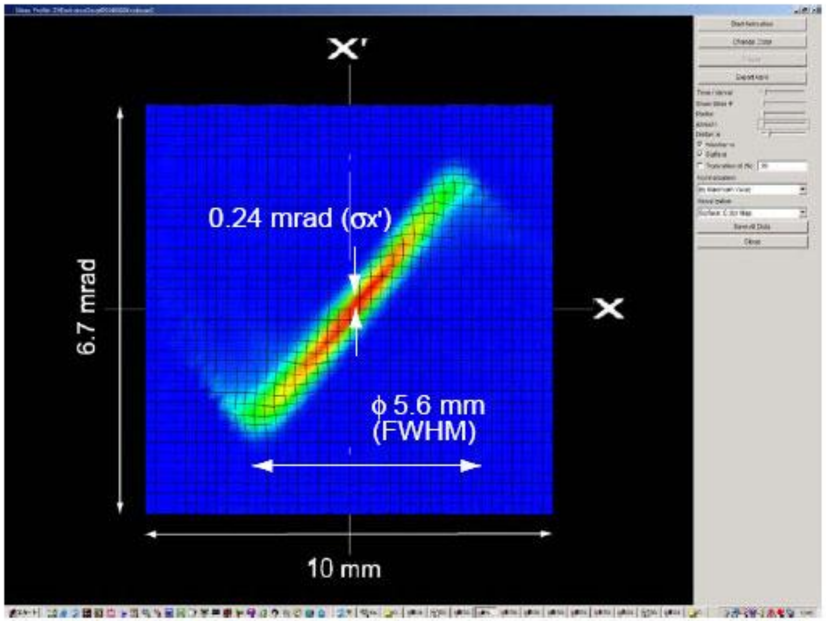
Measured Emittance at the Gun

Beam Profile



Phase Space Profile



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

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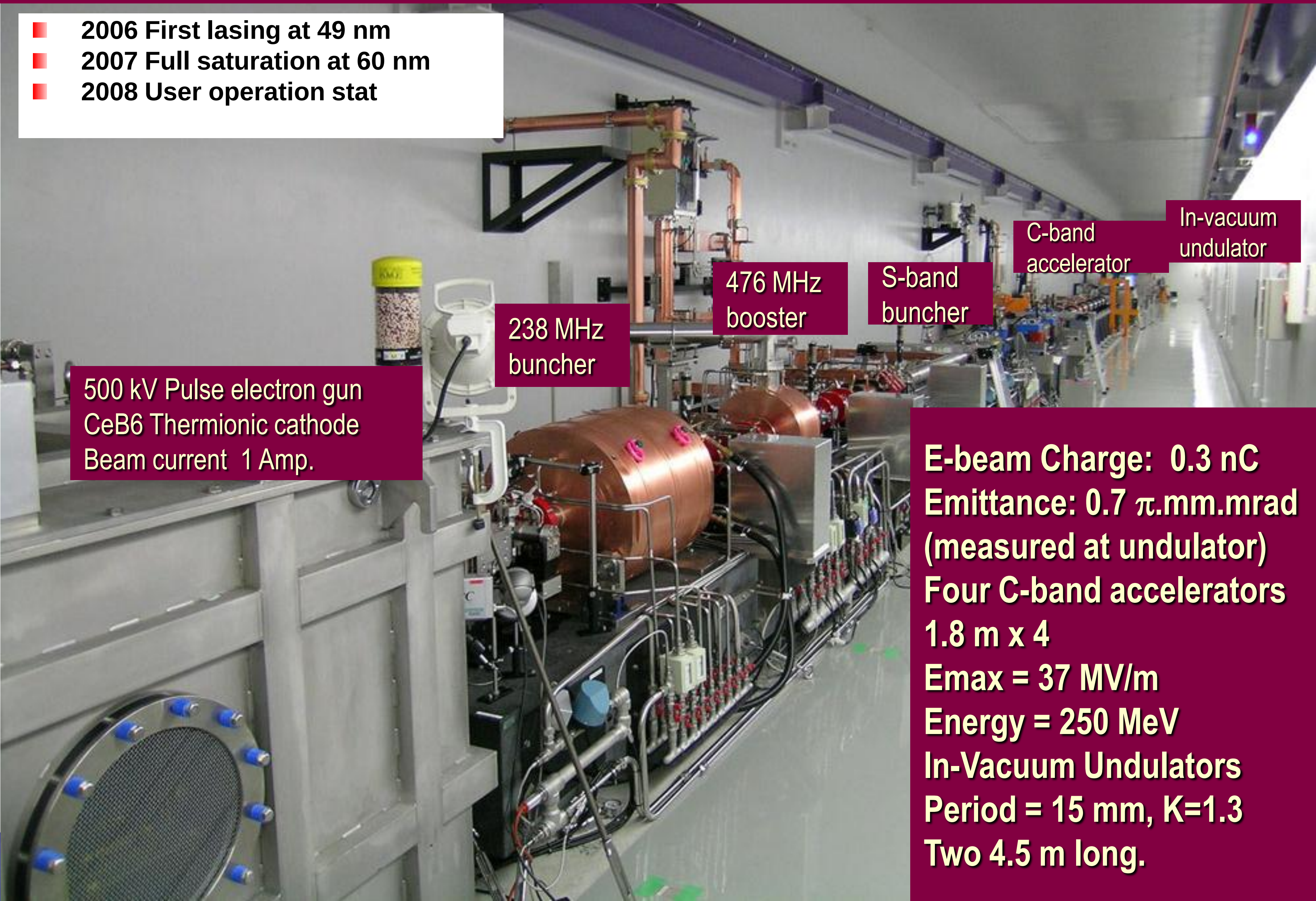
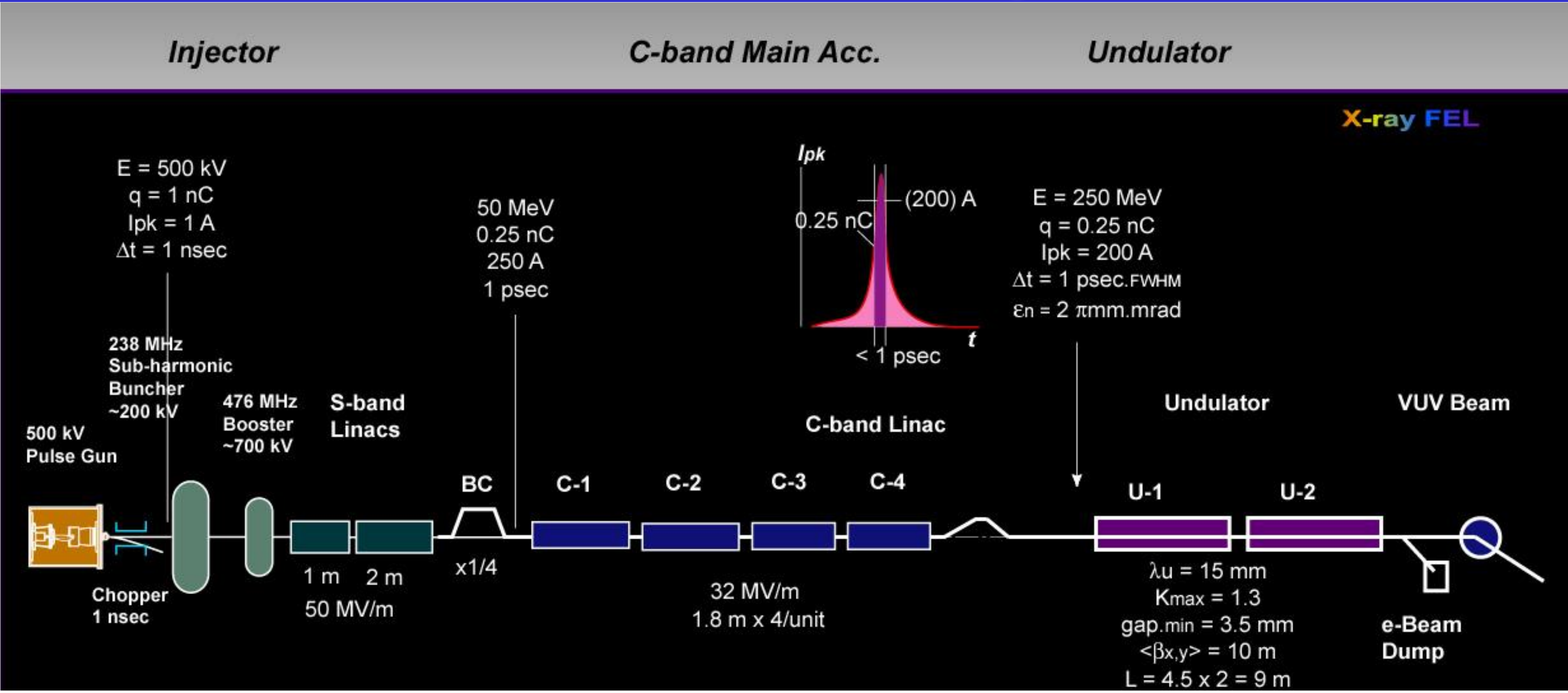
SCSS Test Accelerator Performance

- 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 π.mm.mrad (measured at undulator)
Four C-band accelerators
1.8 m x 4
Emax = 37 MV/m
Energy = 250 MeV
In-Vacuum Undulators
Period = 15 mm, K=1.3
Two 4.5 m long.

Test Accelerator Configuration



Velocity Bunching x 100 ~ x 300

1 nsec (chopper)

1 A, 3 usec gun → **1 A, 1 nsec** → **300 ~ 800 A**
200 fs ~ 70 fs

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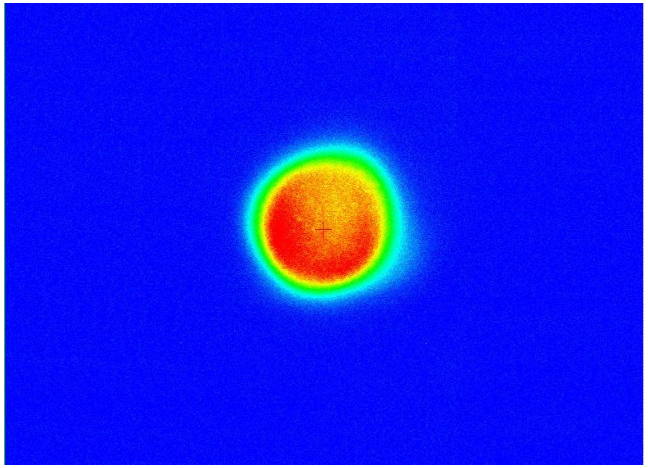
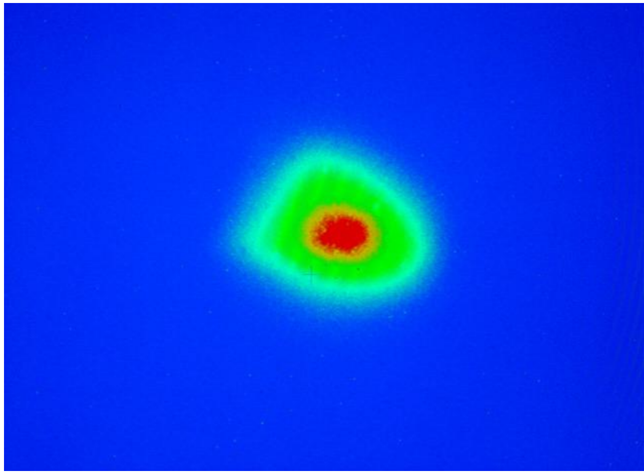
CeB_6 Thermionic Gun provides stable beam.

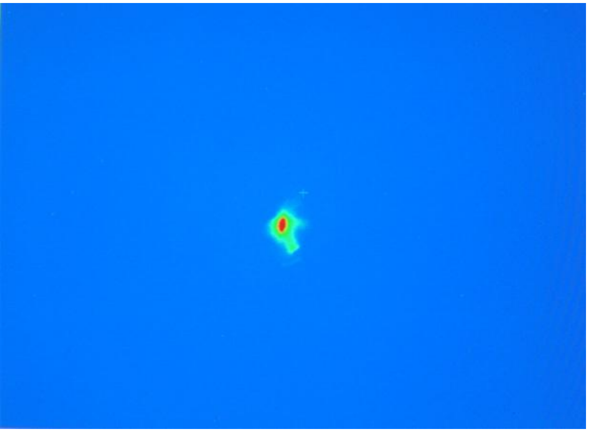
Beam Profile
CCD Image
Scale 10 mm



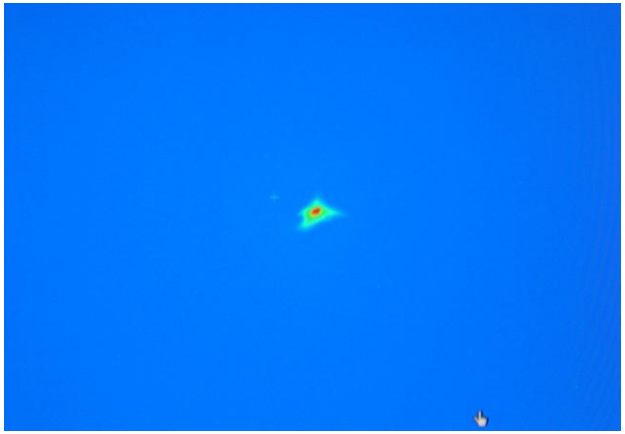
500 kV Gun



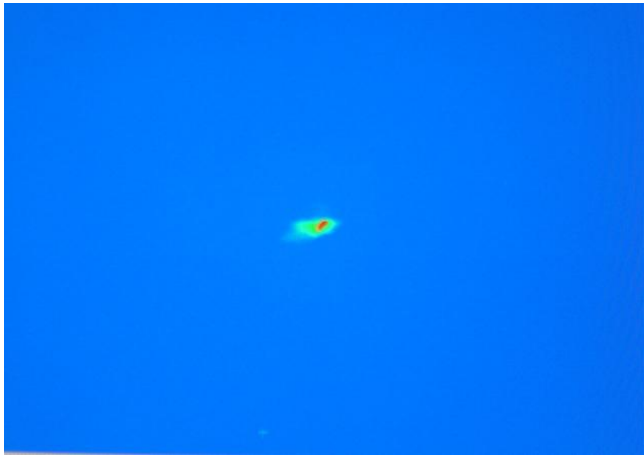
50 MeV Injector Out



250 MeV Compressor

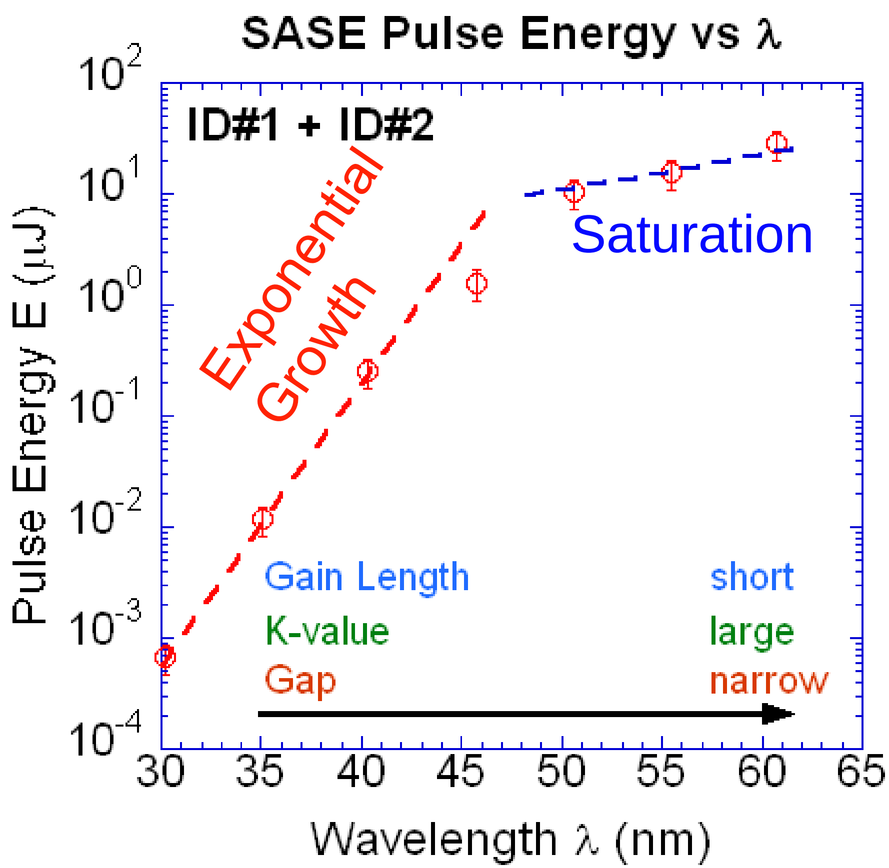


Undulator Input



Undulator Output

The slice emittance is estimated to be 0.7 μm (normalized)



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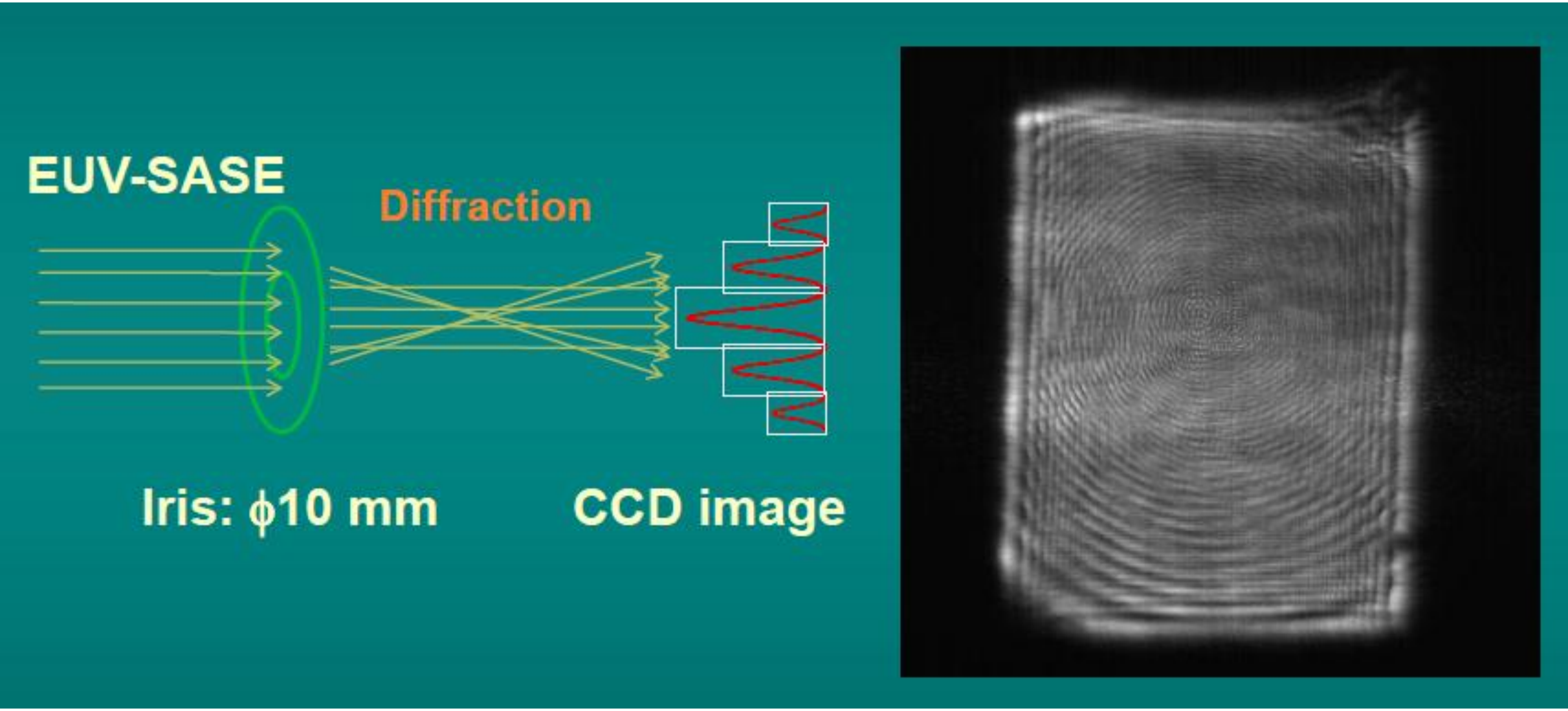
It’s laser light at EUV



60 nm, courtecy of Nishino.

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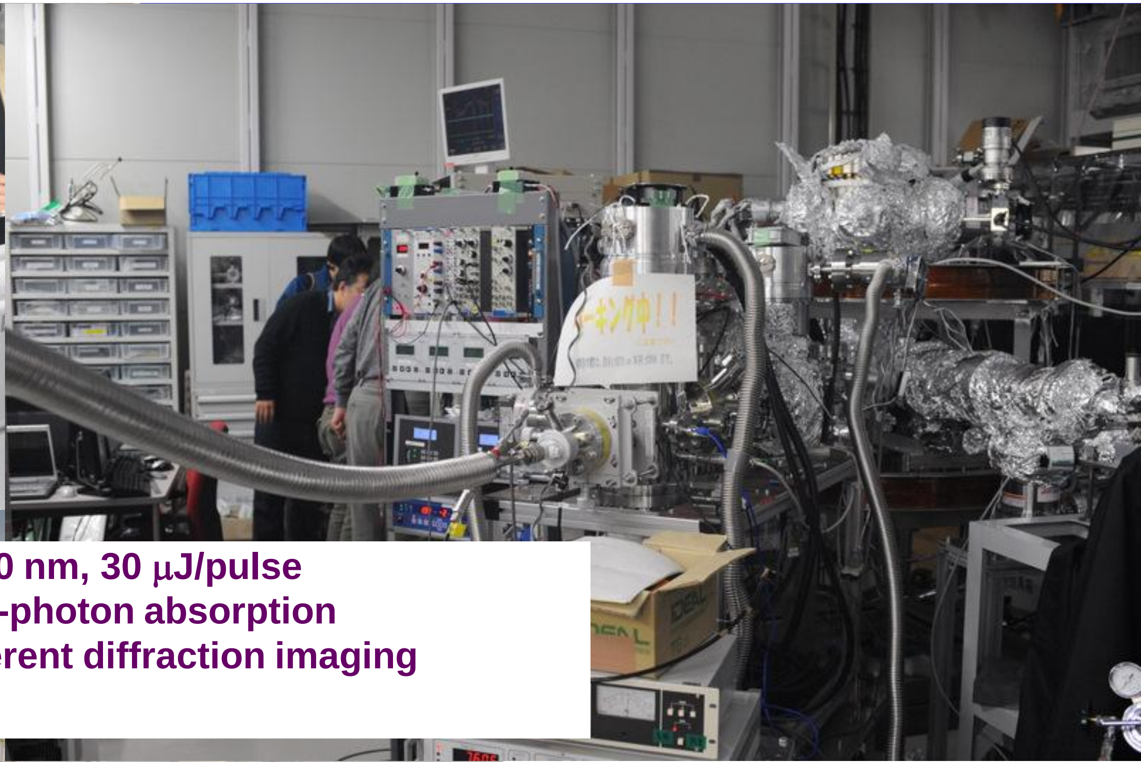
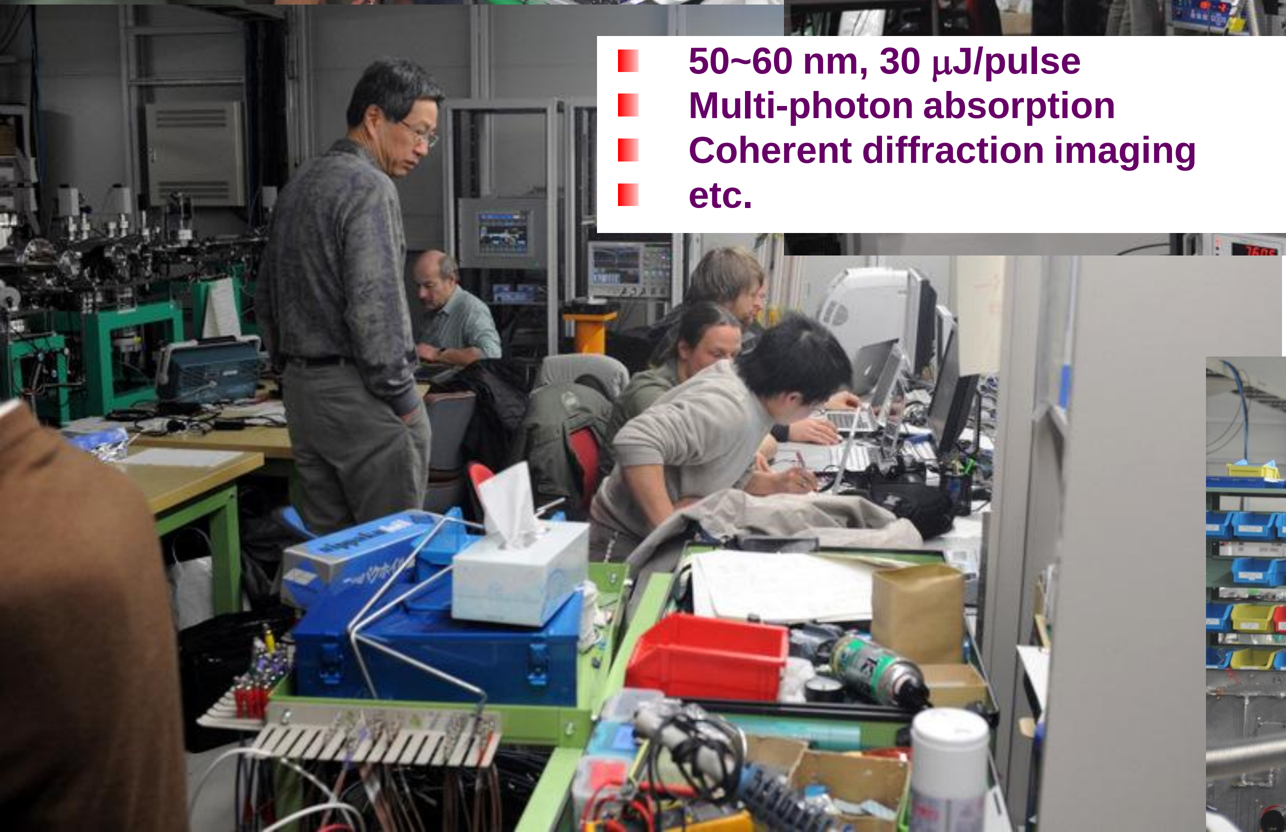
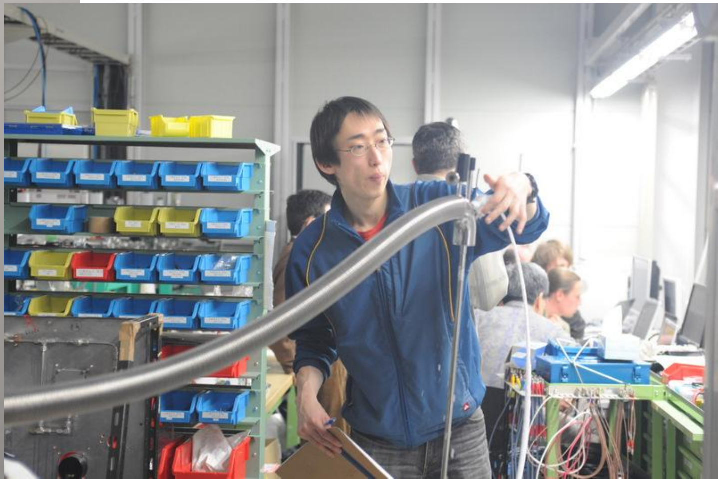
SCSS Test Accelerator User Run Has been Started in 2008



- 50~60 nm, 30 μJ/pulse
- Multi-photon absorption
- Coherent diffraction imaging
- etc.





Thermionic cathode & velocity buching system can generate short bunch with small jitter

- **Bunch length in SCSS < 50 fsec (XFEL case it will be < 5 fsec, with additonal two chicane by 1/10 compression)**

- **Timing jitter is SCSS < 50 fsec (XFEL case it will be < 5 fsec+residual)**

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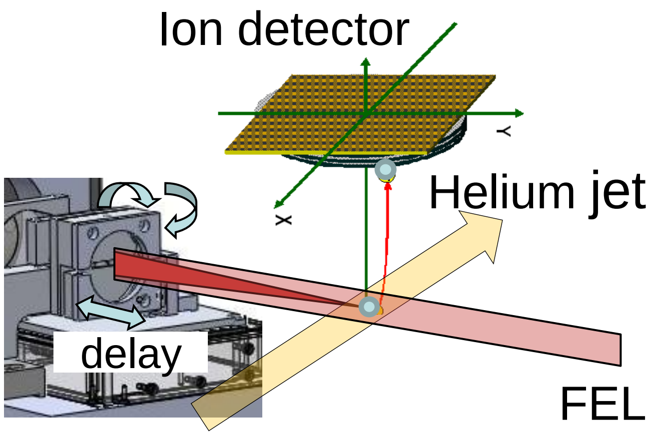
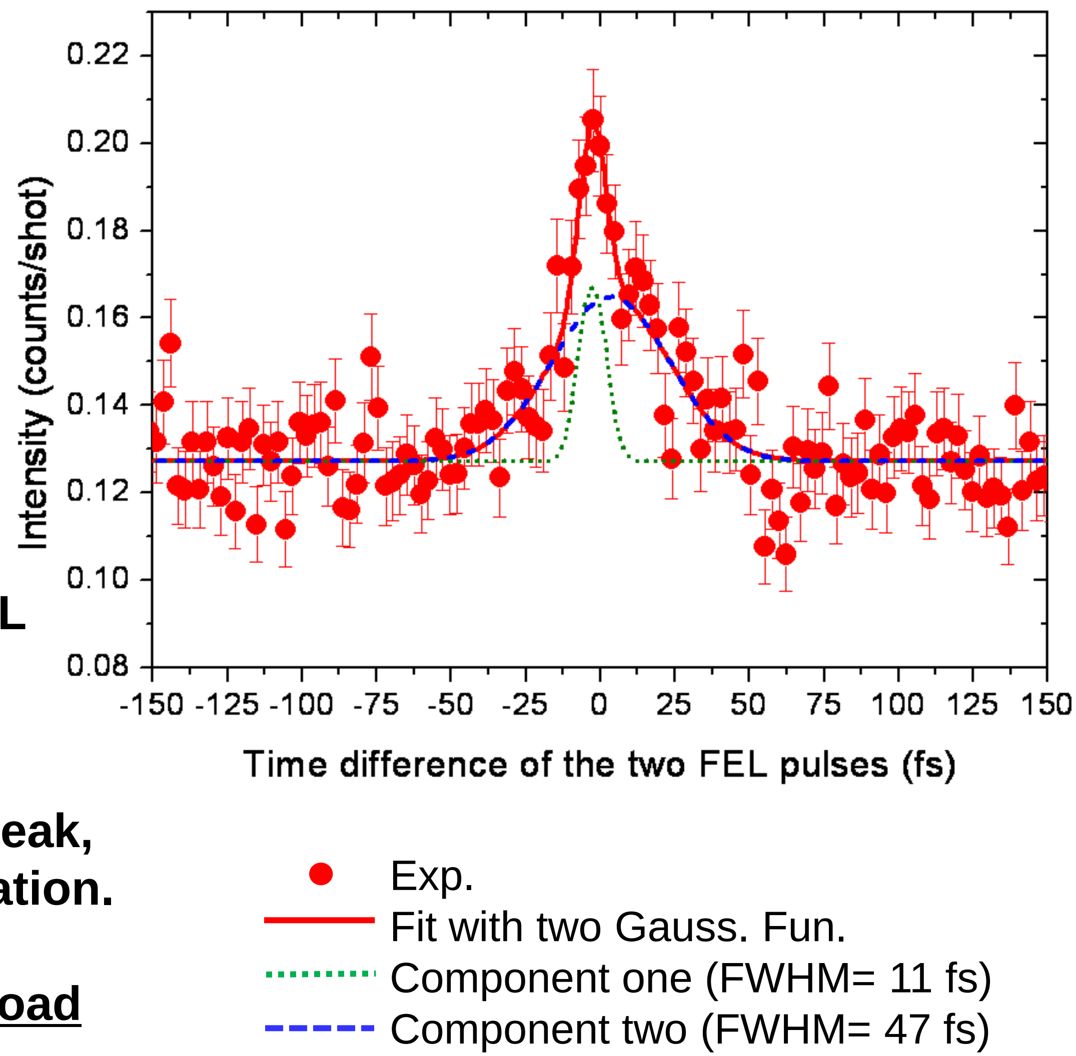
Split mirror setup



Delay stage: MPI-K, MPQ, CFEL
Mirror: LBNL

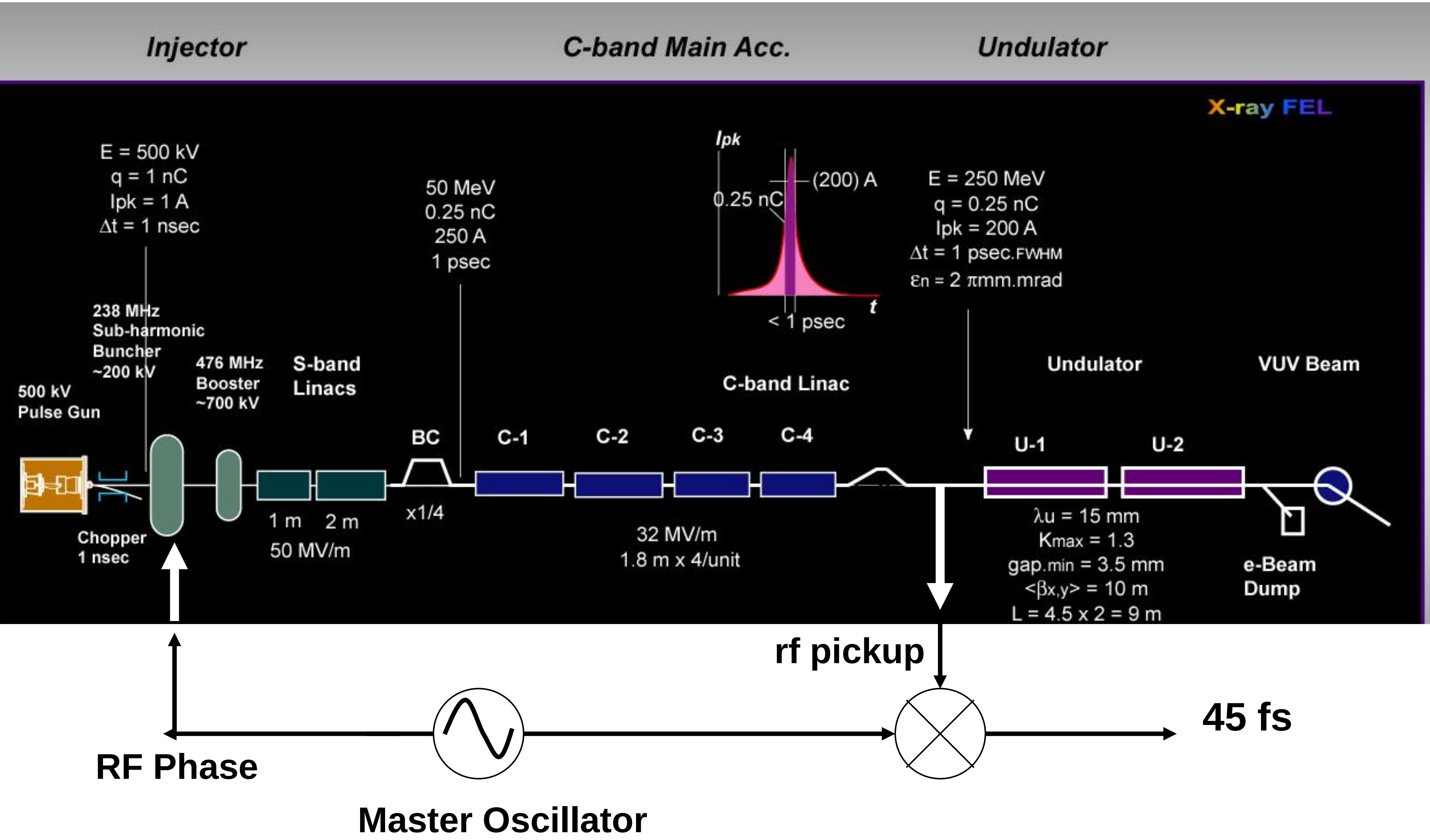
Detection system: Tohoku U.



From the width of the broad peak, we can get the FEL pulse duration.
<u>FEL pulse duration ~30 fs</u>
(Pulse duration = FWHM of <u>broad component</u> $/\sqrt{2}$)

…Kiyoshi Ueda

Timing Jitter



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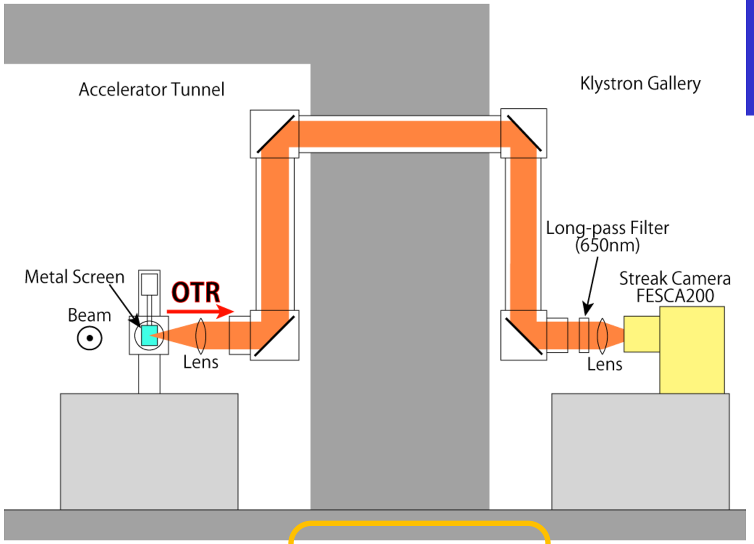
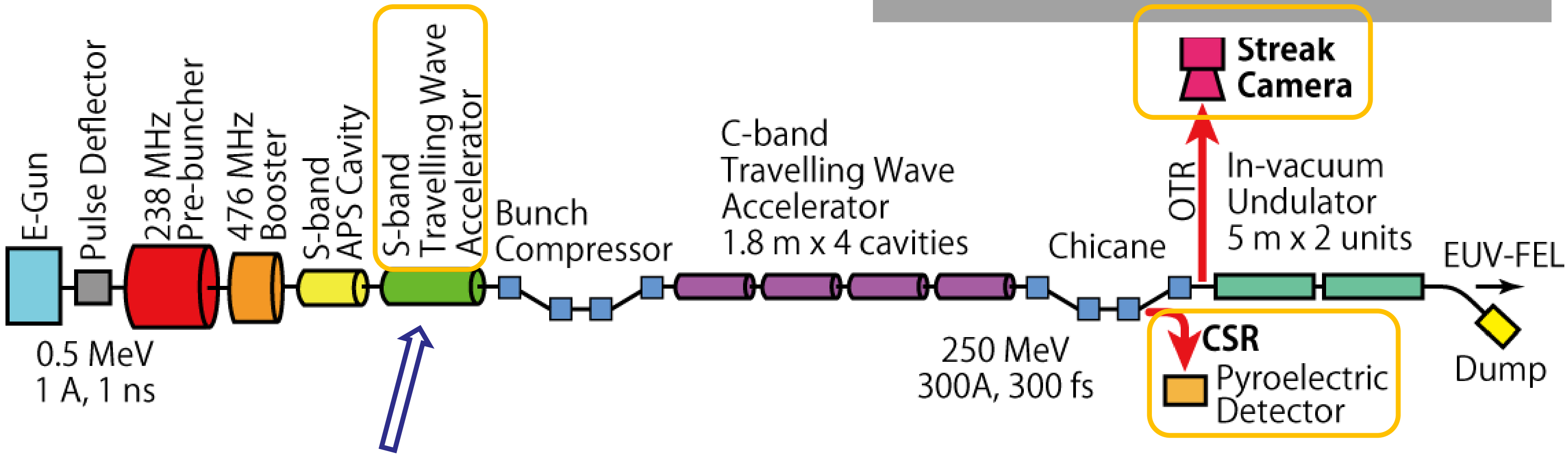
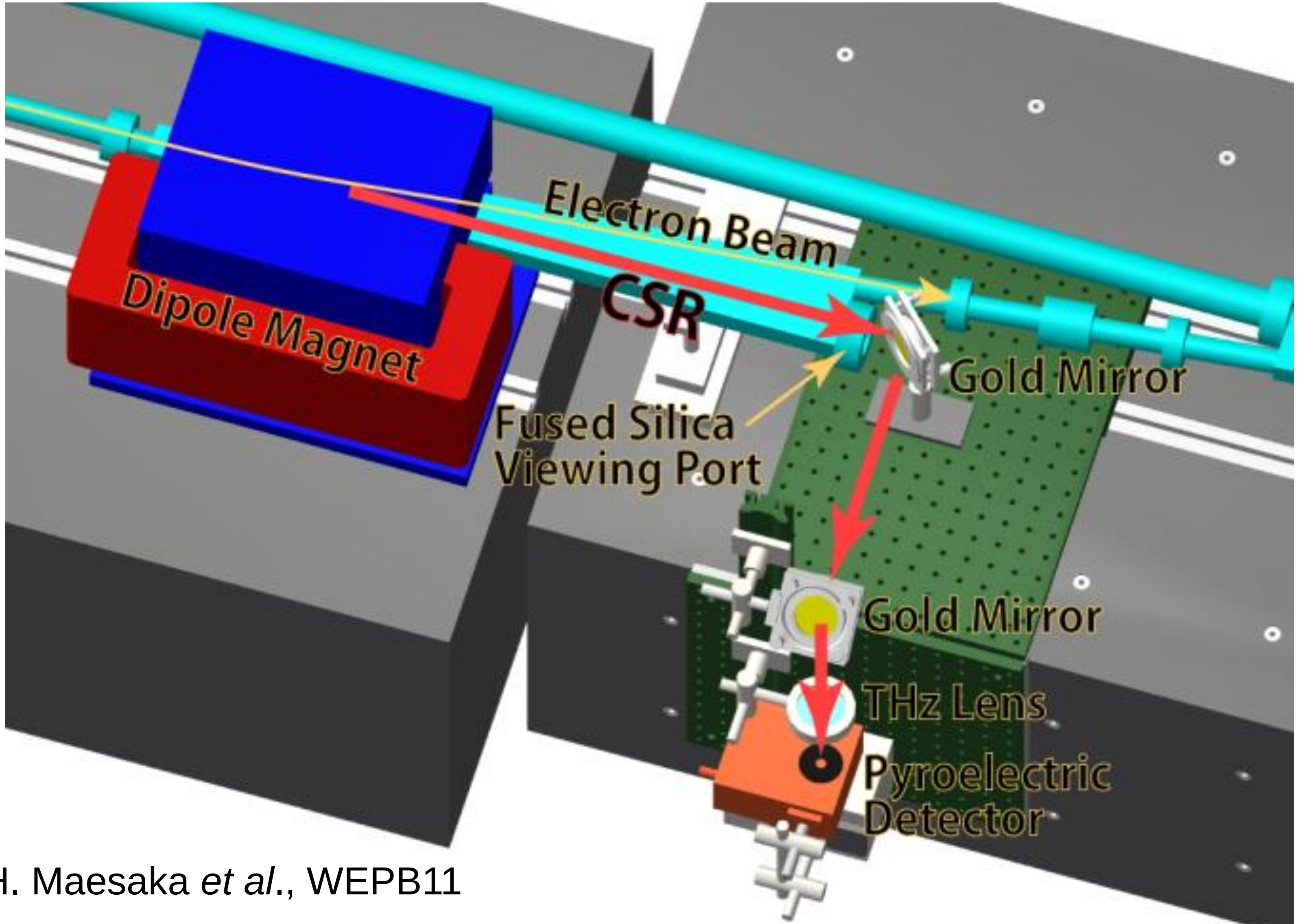
- Bunch length was monitored by a CSR monitor and a streak camera at the SCSS test accelerator.
- H. Maesaka *et al*., WEPB11





- Bunch length was changed by the rf phase of the S-band travelling wave accelerator before the bunch compressor.

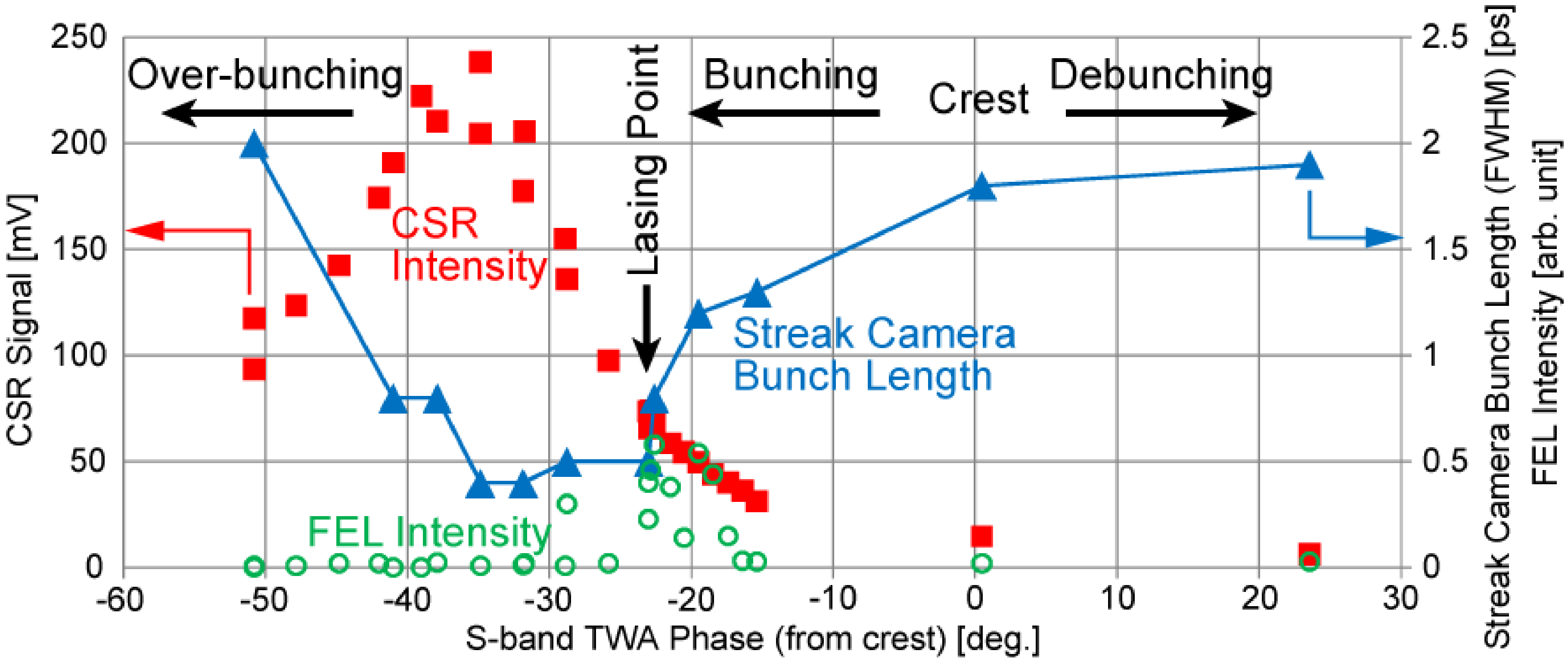
CSR Monitor from 3rd Magnet in chicane at 250 MeV



H. Maesaka *et al*., WEPB11

Measured CSR intensity and Bunch length by streak camera

H. Maesaka *et al.*, WEPB11



- R56 = 20 mm in bunch compressor at 45 MeV.
- Incoming bunch length = 2 psec (0.6 mm)
- Max energy chirp 0.6 mm/20 mm = 3% at 45 MeV, 0.6% at 250 MeV
- Bunch compression factor x 1 ~ x 5

Thermionic Gun Produces "Smooth Beam"

- No CSR instability was observed.
- OTR, CSR radiations at chicane magnet are stable, for wide range of bunch compression change.

- → conclusion: there is no density modulation on incoming bunch into chicane compressor
- → thermionic cathode generates smooth beam.

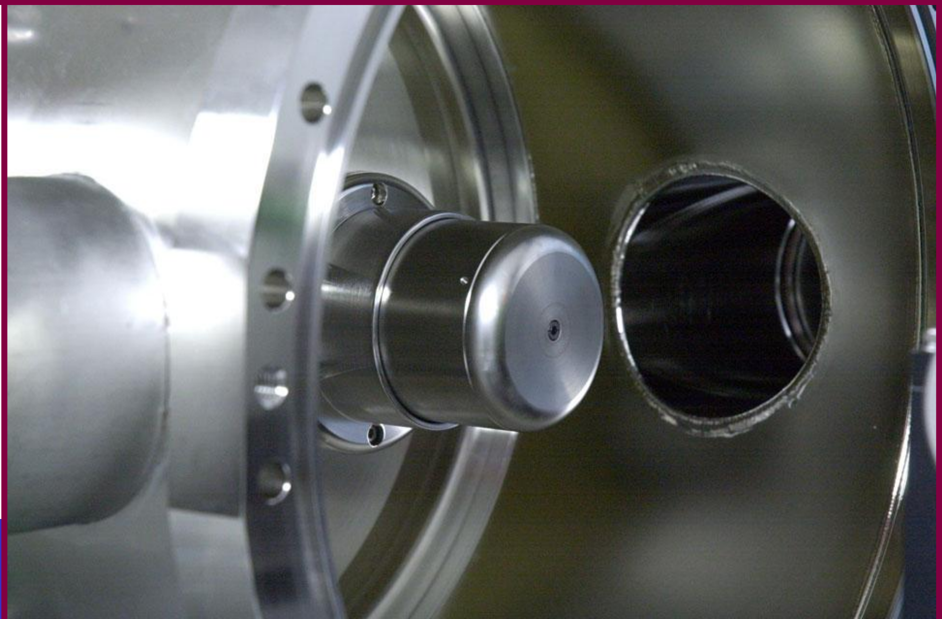
- → **We confirmed no laser heater is required in our system.**

CeB6 Cathode Performance

- We changed cathode twice in SCSS test accelerator.
  - 2005 installed first cathode
  - 2008 January, 1st cathode was changed.
  - 2010 August, 2nd cathode was changed.
- Lifetime > 10,000 hours (~2 years)
- At end of lifetime, emission decreased, but emittans is OK.

2008/01/28 *First experience, but team did nice work.*

We replaced CeB6 crystal in SCSS accelerator, after 20,000 hour operation.



Anode flange had color change.

CeB6 cathode after 20,000 hour use.

It was found the cathode surface became concave of 0.2 mm deep from the initial flat surface.
It corresponds to evaporation speed of 10 nm/hour (10 nm/h x 20,000 h = 200 micron-meter)
Concave geometry made beam slightly focusing, but did not break emittance.
Electron microscope study showed (1) Surface is fairly smooth, (2) covered by carbon contamination (lowered electron emission).

Electron Gun and Injector

1. CeB6 Cathode: emission was tested…. OK.
2. Gun: 500 kV operation in bunker….OK
3. 238 MHz, 476 MHz, L-correction, C-correction cavities and RF….OK
4. L-band RF is OK, but APS cavity is under fabrication. …Waiting

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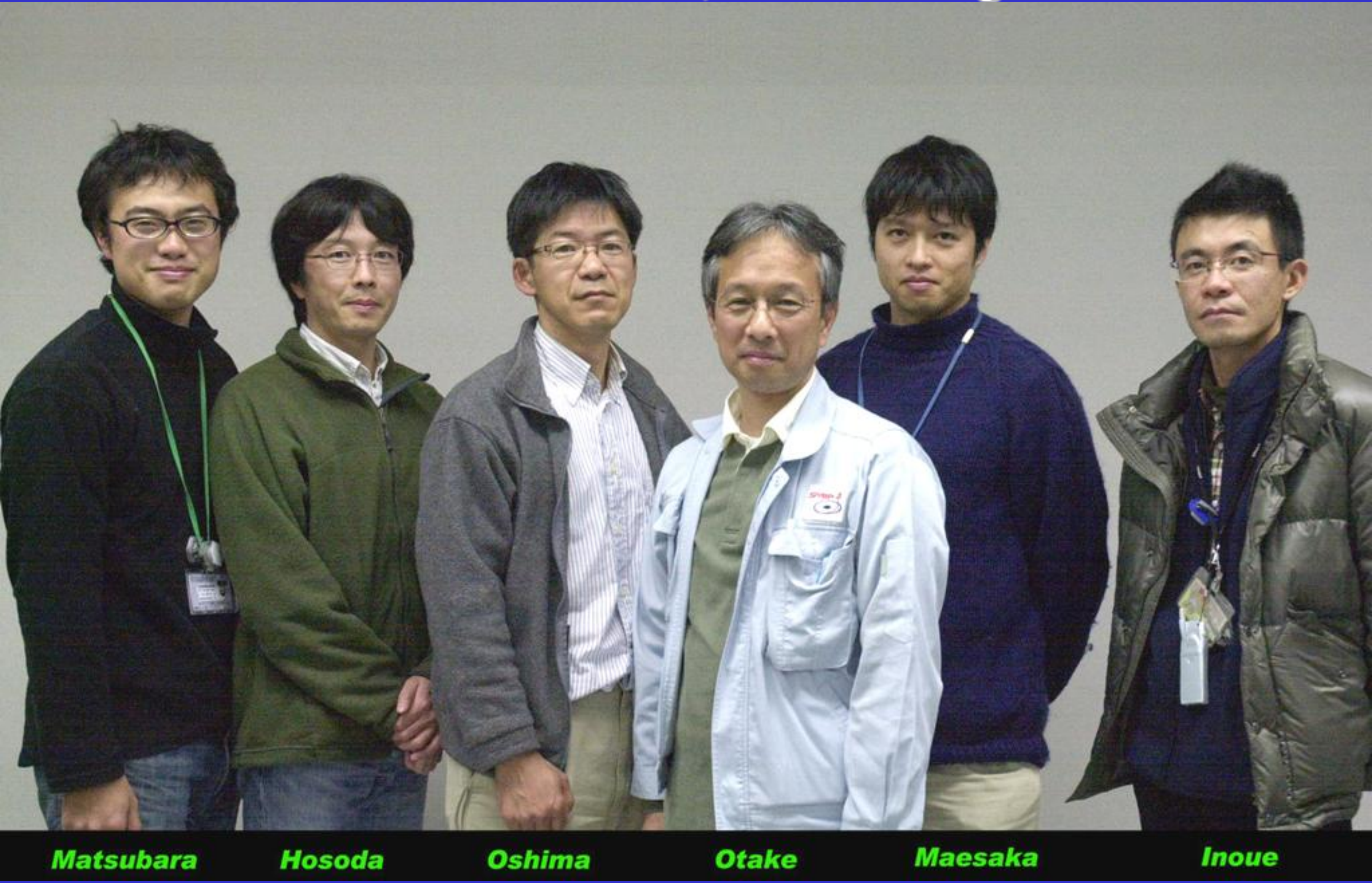
Otake's Team: LLRF, Beam Diagnostics



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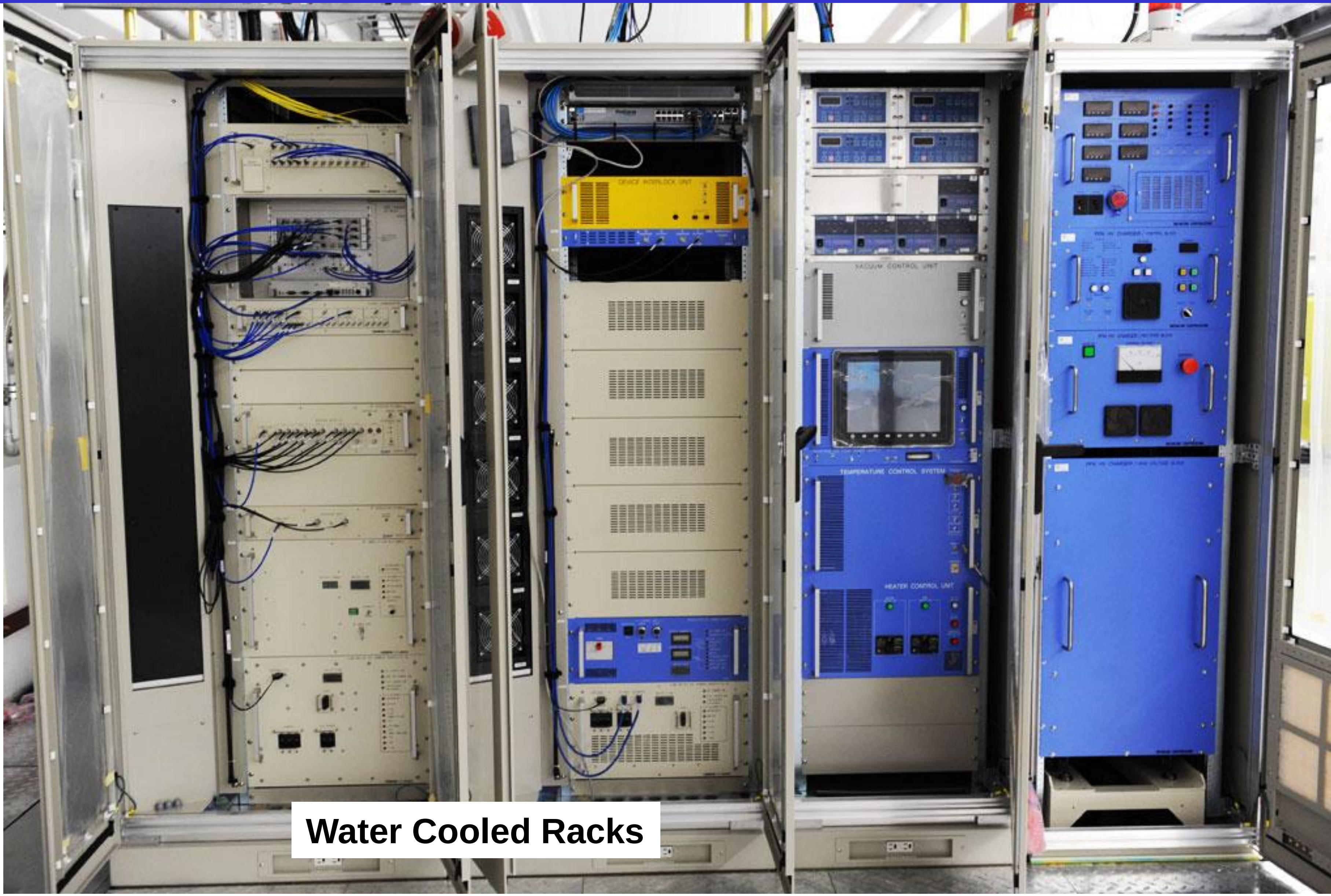
MADOCA Controls, LLRF, Temp Feedback, PFN Charger

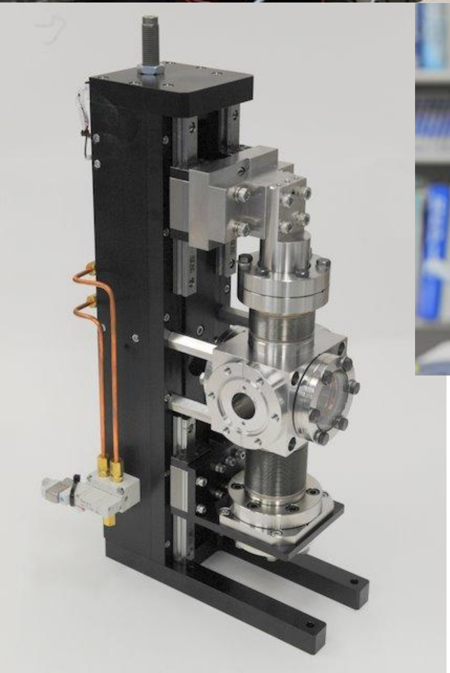


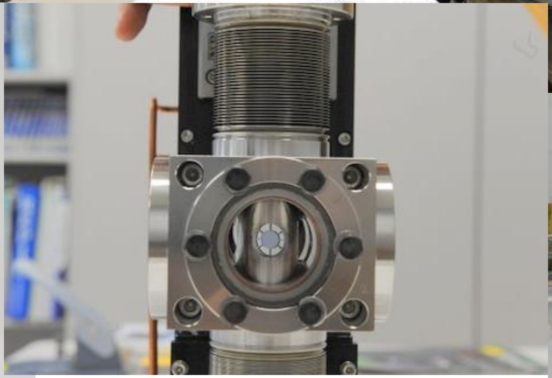
Beam Monitor Devices

By Y. Otake team.

BPM Calibration

Cavity BPMs
0.2 μm resolution was confirmed with beam





OTR Screen Monitor

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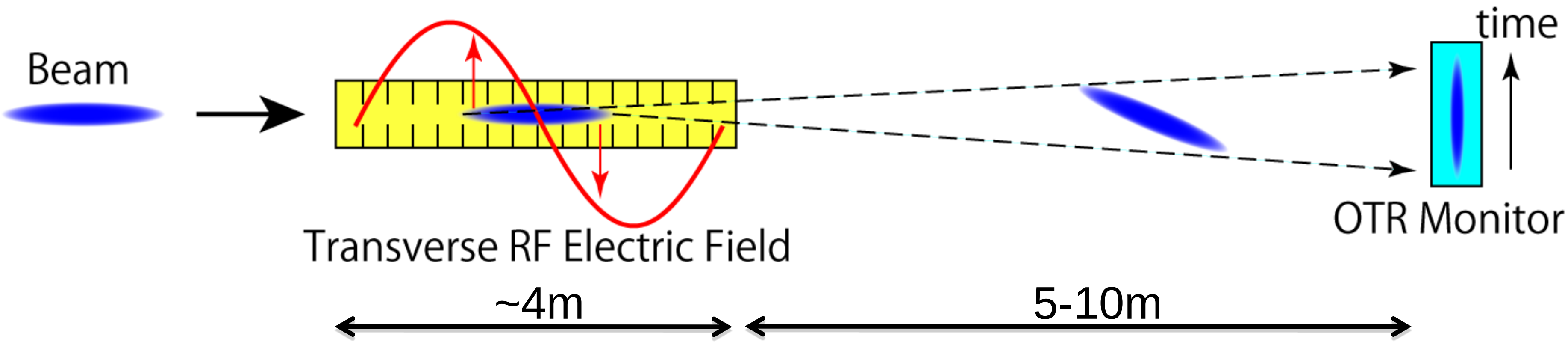
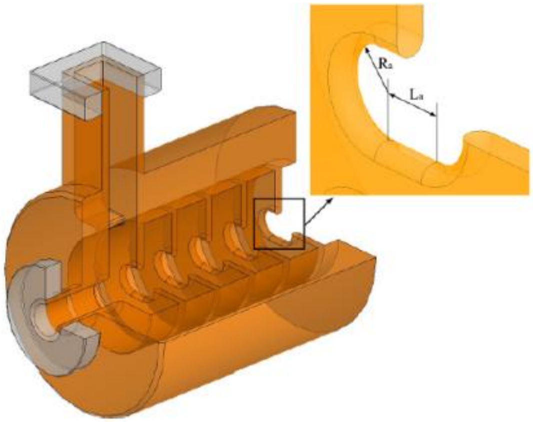
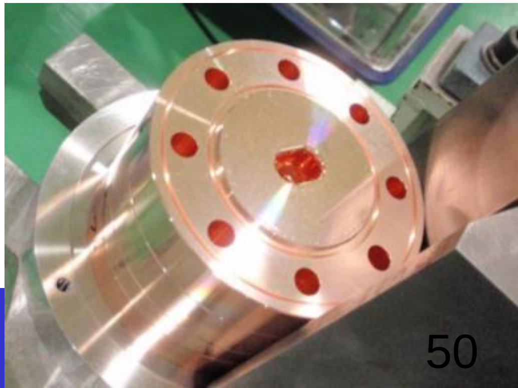
C-Band RF Deflector has been developed



- RAIDEN-Cavity
  - Race-track iris provide xy-mode separation
  - Backward HEM11-5π/6 mode

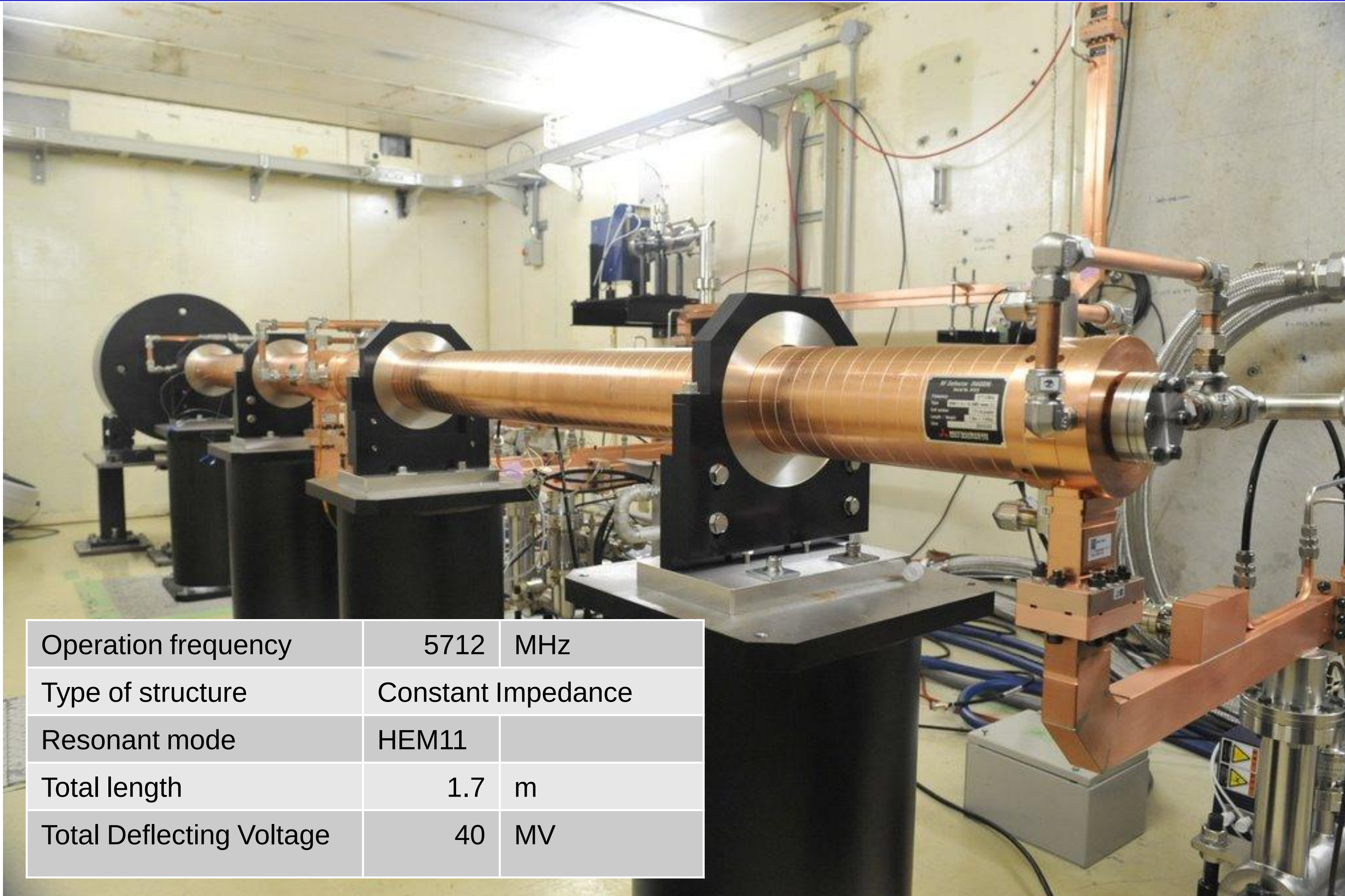




H. Ego, Y. Otake *et al.*, “Design of the Transverse C-band Deflecting Structure for Measurement of Bunch Length in X-FEL”, Proceedings of EPAC’08.

50

Two RAIDEN structures are under high power testing.



Operation frequency	5712	MHz
Type of structure	Constant Impedance	
Resonant mode	HEM11	
Total length	1.7	m
Total Deflecting Voltage	40	MV

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All undulators (18) have been installed in Augost

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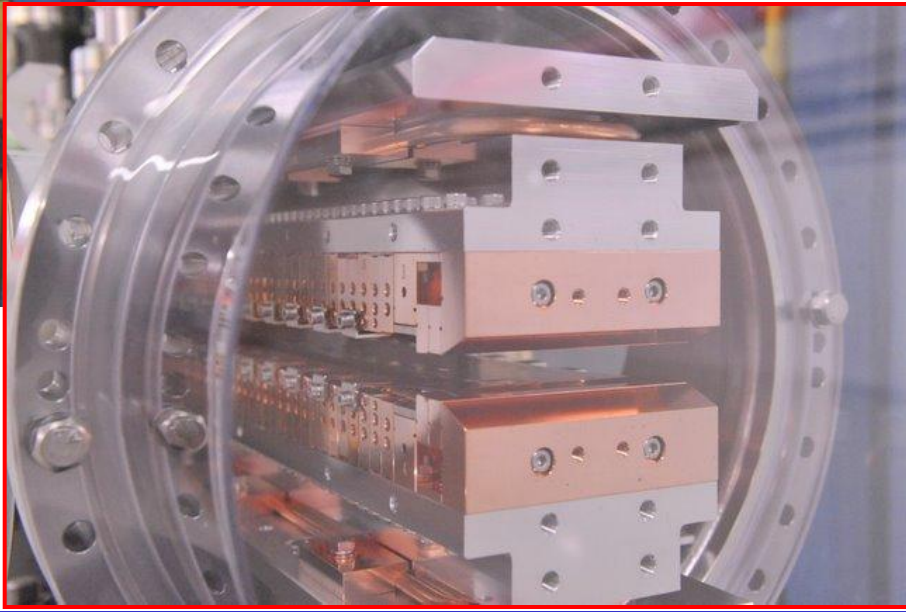
Undulator for XFEL/SPring-8

Undulator Type		In-Vacuum Planer Undulator
Active Length		5 m
Undulator Period		18 mm
Magnetic Circuit		Hybrid (NdFeB+Permendur)
Peak Field	Maximum	1.31 T
	Nominal	1.13 T
K	Maximum	2.2
	Nominal	1.9
Gap	Minimum	3.5 mm
	Nominal	4.5 mm
Maximum Attractive Force		~ 6 ton

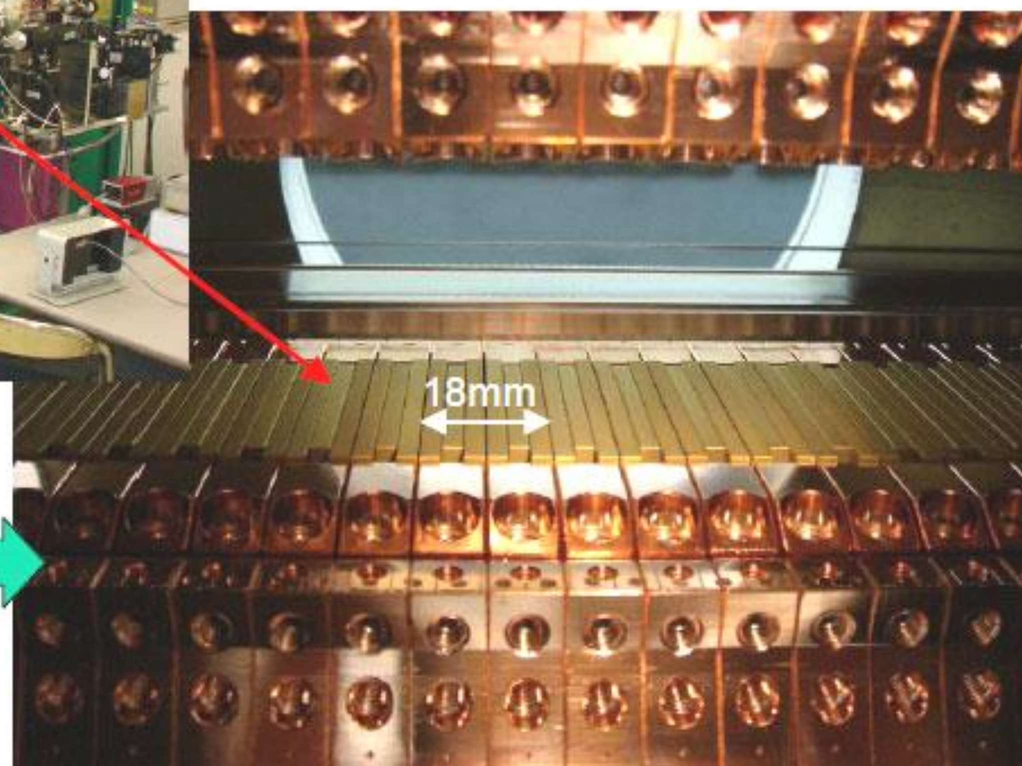
In Vacuum Undulator



Undulator for XFEL/SPring-8

The undulator for XFEL is made by the team guided by H. Kitamura and T. Tanaka

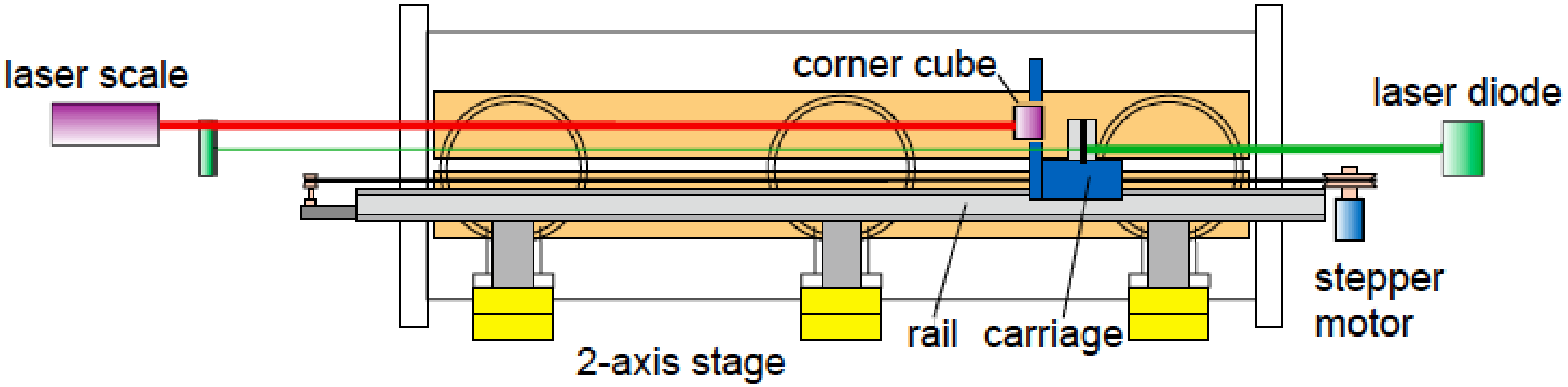
Outlook of 5 m long in-vacuum undulator for X-ray FEL.



NeFeB magnet array, undulator period is 18 mm.

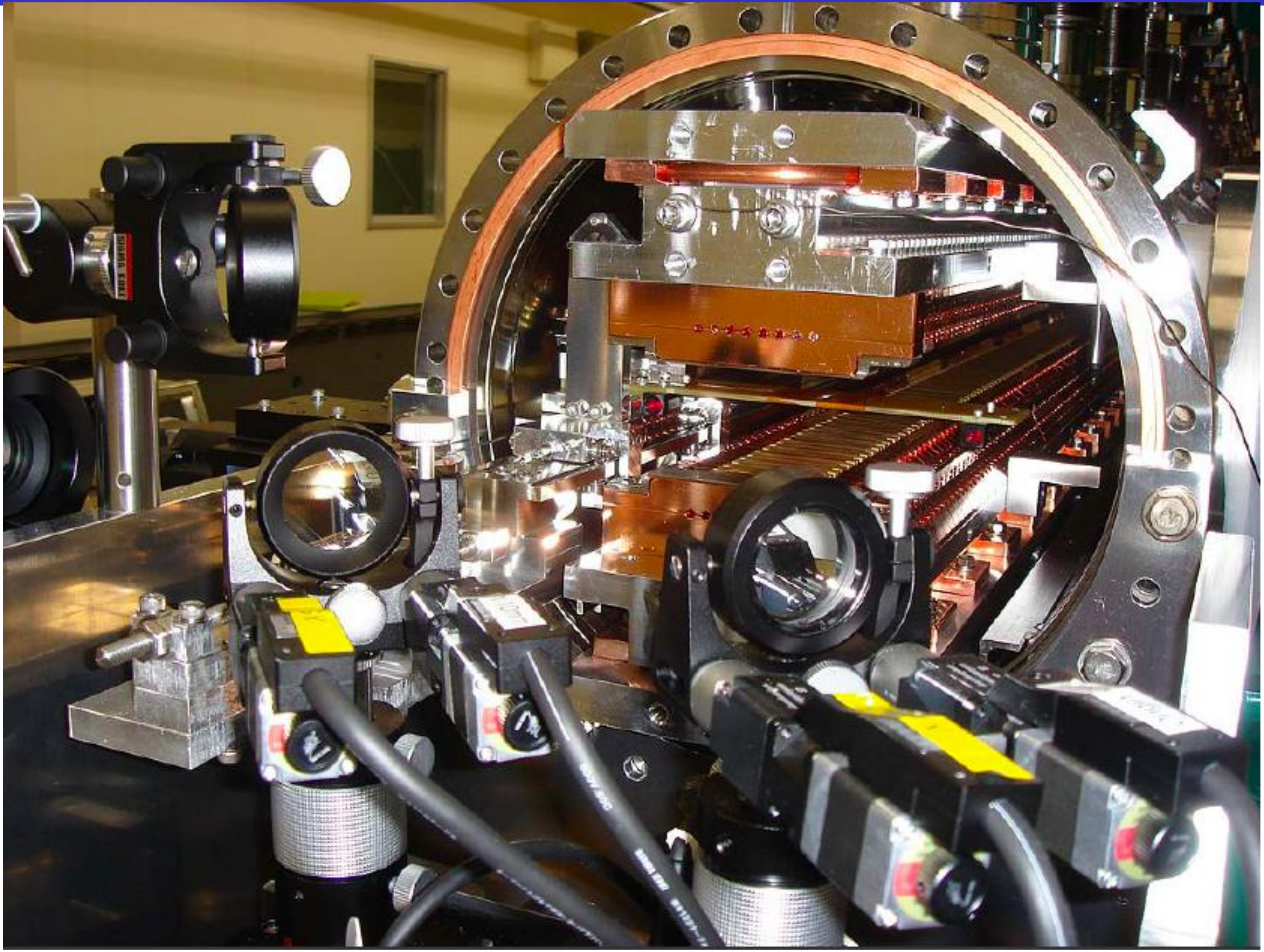
SAFALI Field Measurement System

- SAFALI: Self-Aligned Field Analyzer with Laser Instrumentation
  - Simple mover of hole probe.
    - fit within vacuum chamber.
  - Laser beam guide for xy-displacement, and position feedback on guide rail.
  - Laser distance meter for z-location.



Tuning magnet and gap on site, including earth magnetic field effect.

SAFALI in-situ field measurement



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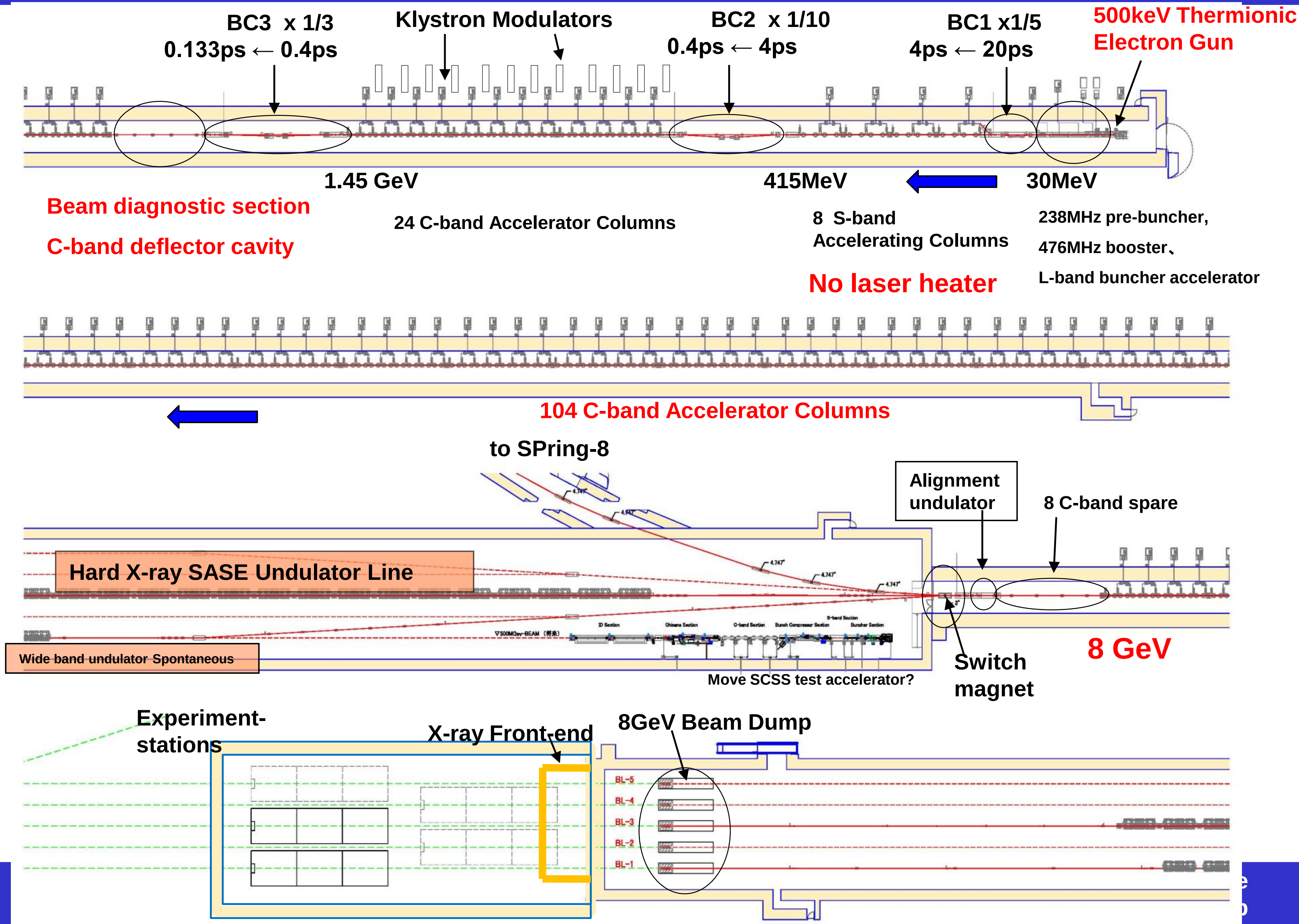
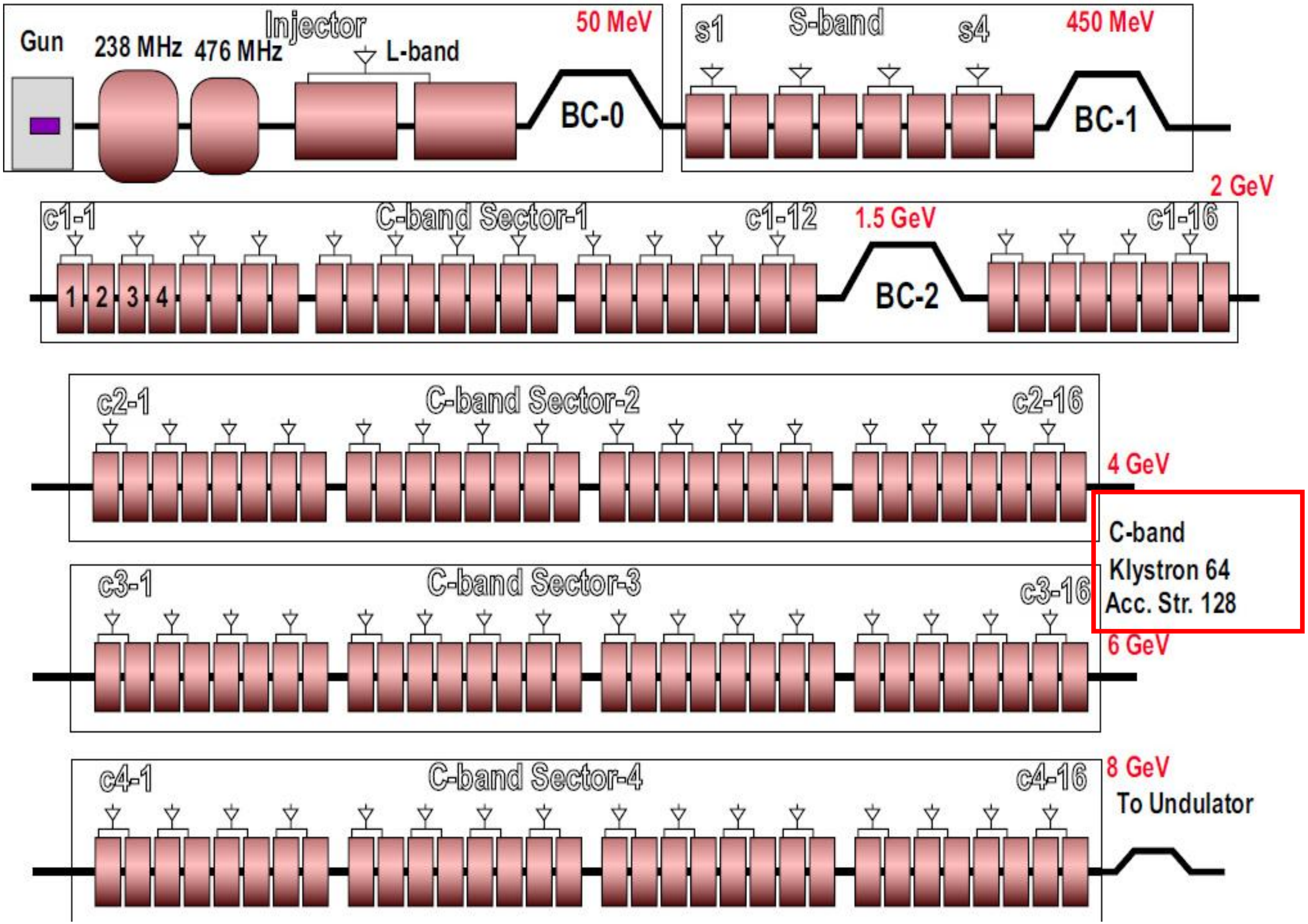
Summary & Schedule

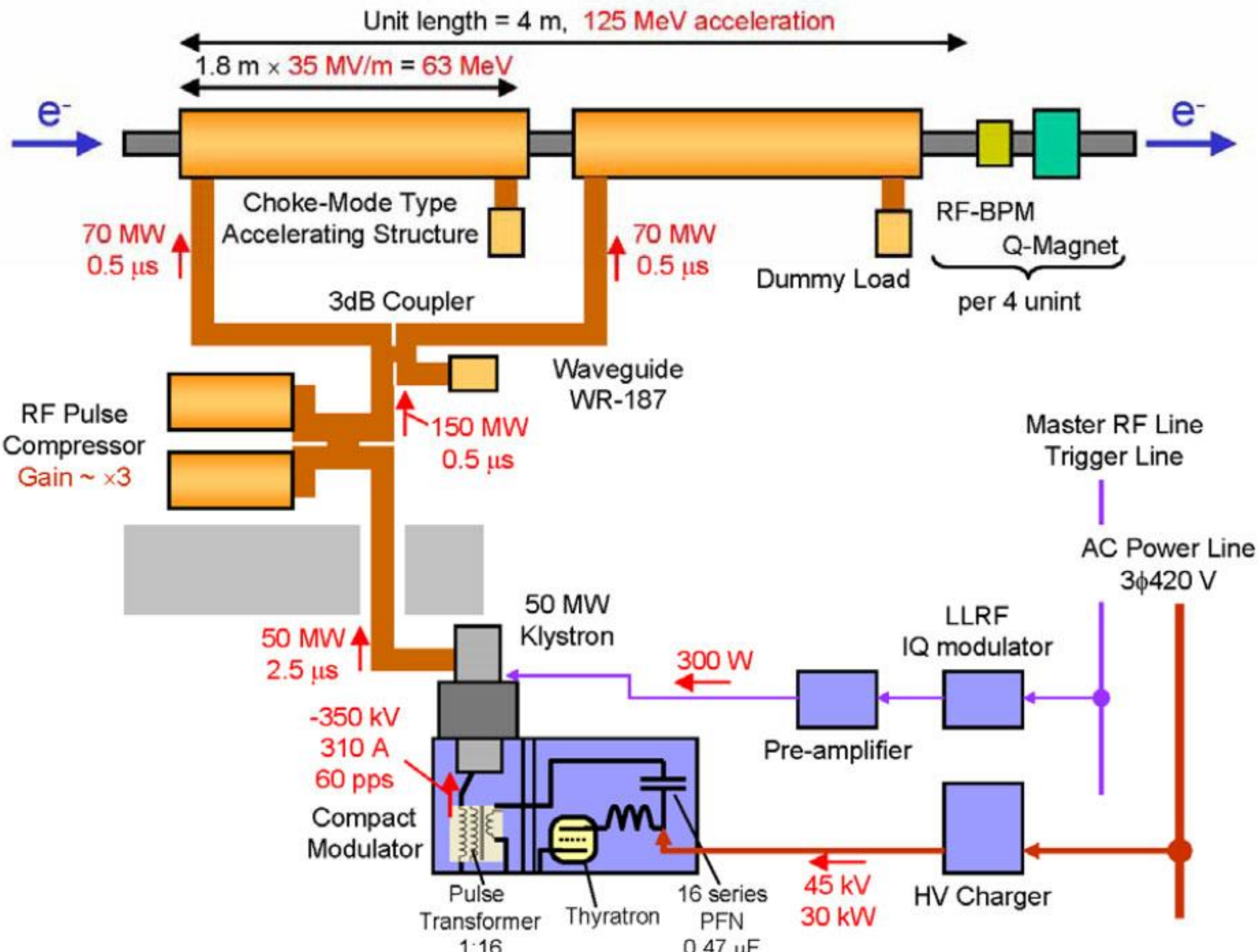
- 2010 Sept. Complete installation.
- 2010 Oct. ~ 2011 Feb. High power processing.
- 2011 March First beam to the undulator.
- 2011 April - July ..... Beam commissioning, and the first FEL Lasing?

XFEL Machine Configuration



RF Acceleration System in XFEL/SPring-8

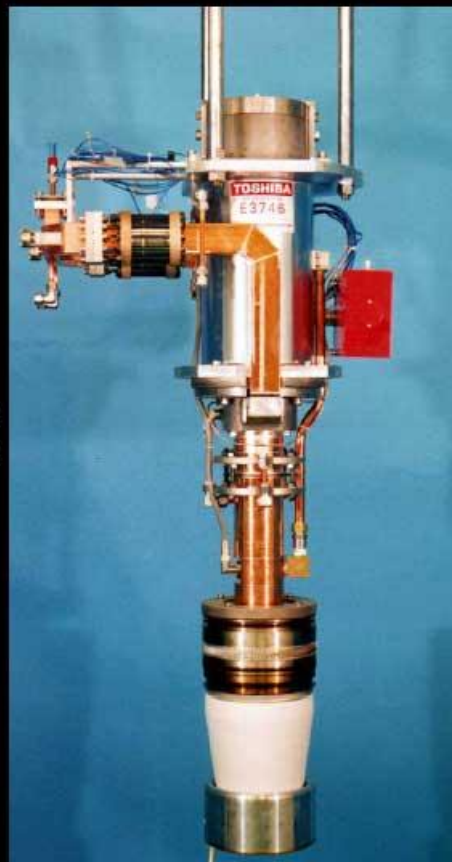




Unit length = 4 m, 125 MeV acceleration
1.8 m × 35 MV/m = 63 MeV
e-
e-
Choke-Mode Type
Accelerating Structure
70 MW
0.5 μs
70 MW
0.5 μs
RF-BPM
Q-Magnet
Dummy Load
per 4 unint
3dB Coupler
Waveguide
WR-187
150 MW
0.5 μs
RF Pulse
Compressor
Gain ~ ×3
Master RF Line
Trigger Line
AC Power Line
3ϕ420 V
50 MW
Klystron
50 MW
2.5 μs
LLRF
IQ modulator
300 W
-350 kV
310 A
60 pps
Pre-amplifier
Compact
Modulator
Pulse
Transformer
1:16
Thyratron
16 series
PFN
0.47 μF
45 kV
30 kW
HV Charger

C-band Klystron Development

Under life test since April 1999



Traveling-wave output structure

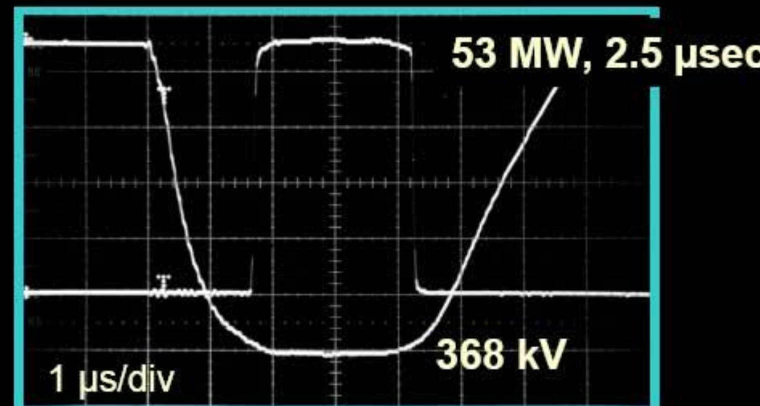
Solenoid Focus (4.6kW)

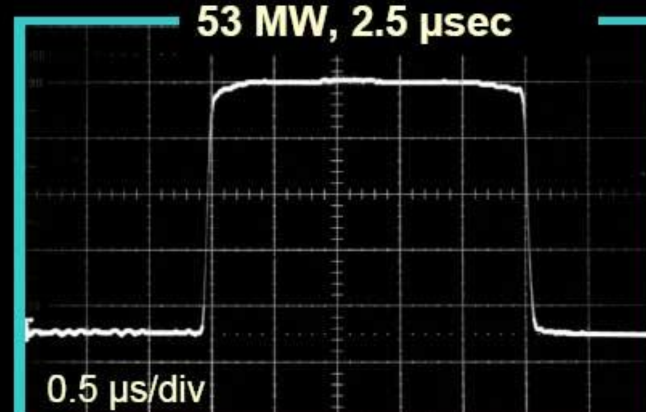
1.5 µP

Dispenser Cathode (D74.5mm,6.3A/cm^2)

53 MW, 2.5 µsec, 50 pps, 47%

TOSHIBA E3746 No.3





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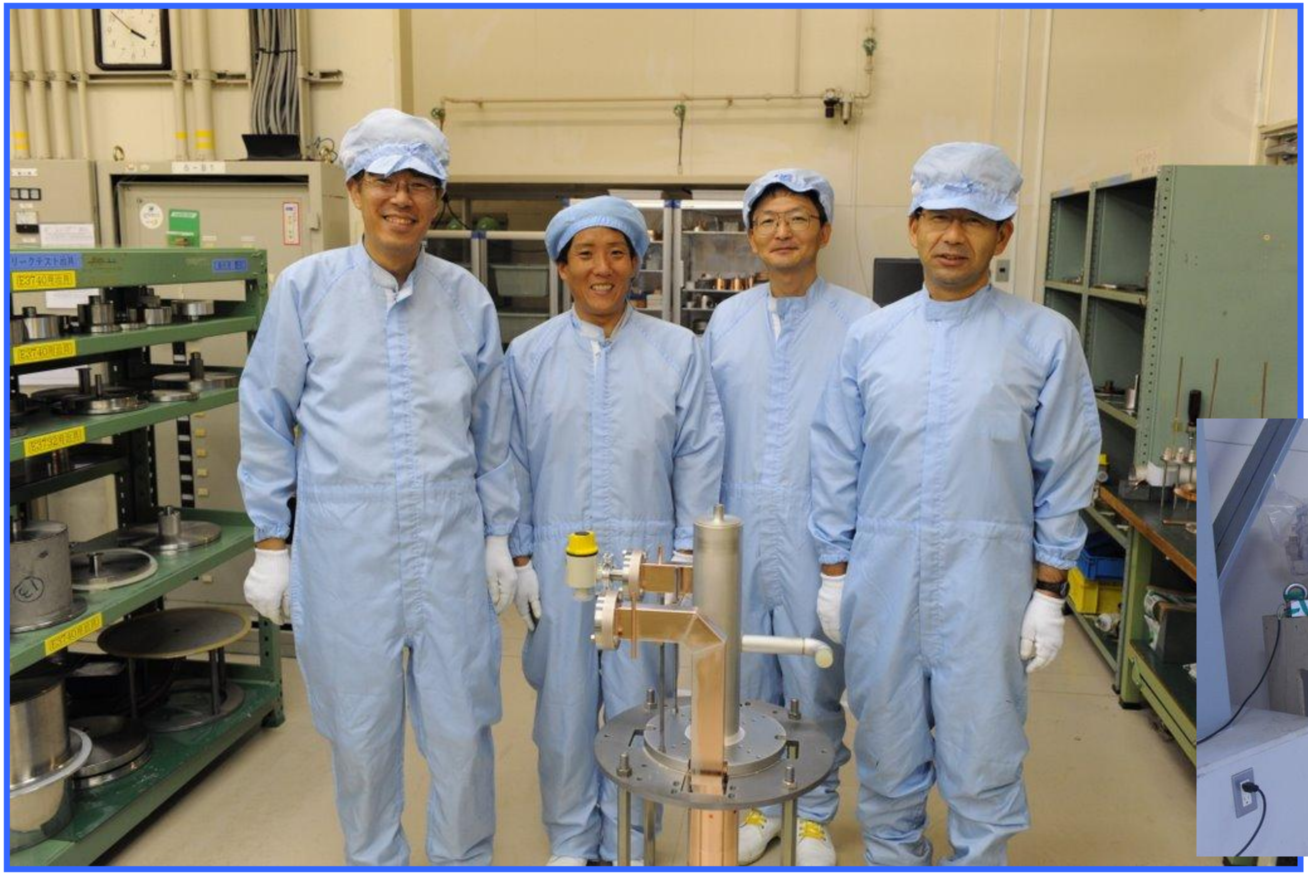
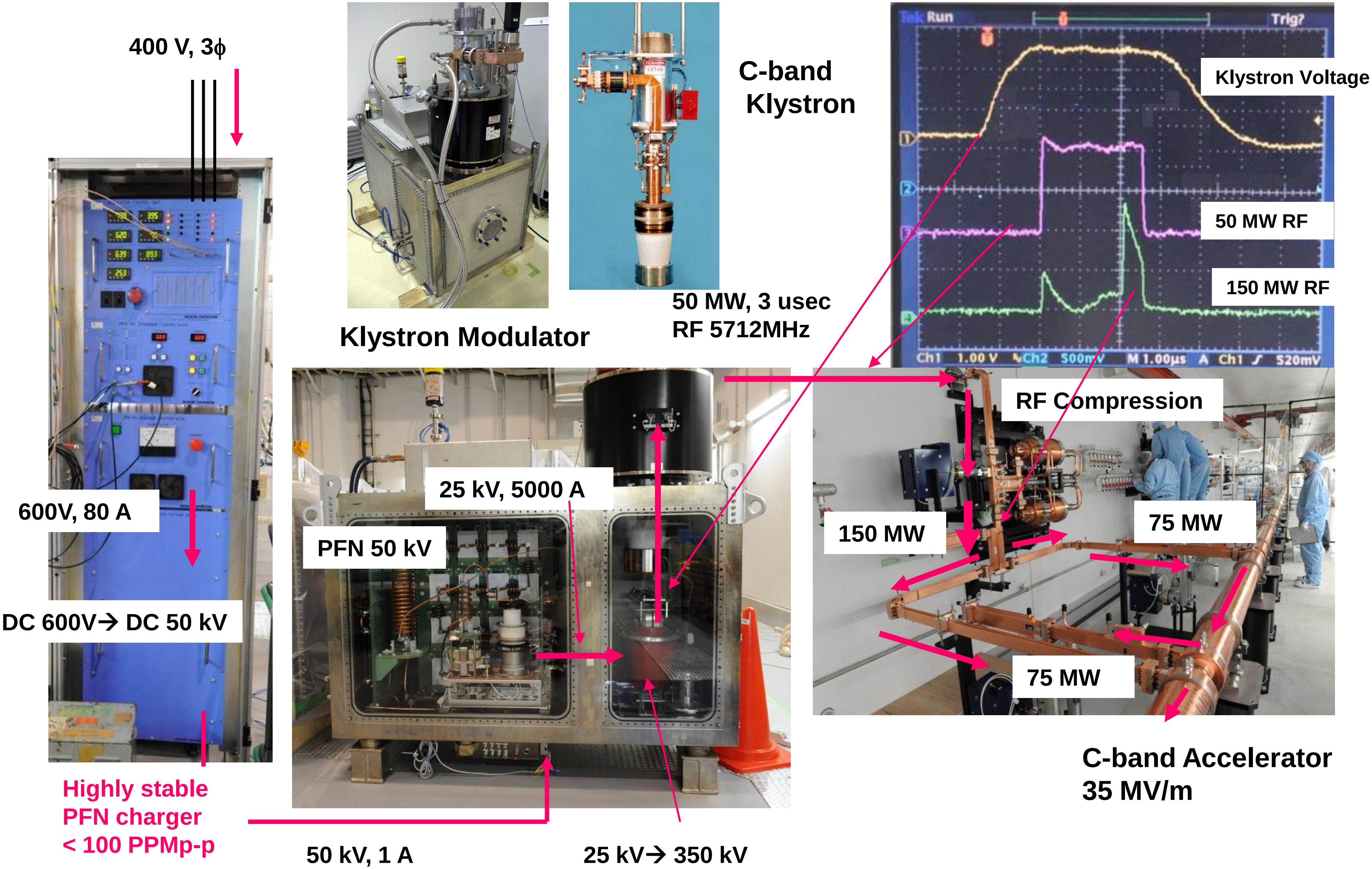
Mass Production of Klystrons at TOSHIBA

- 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

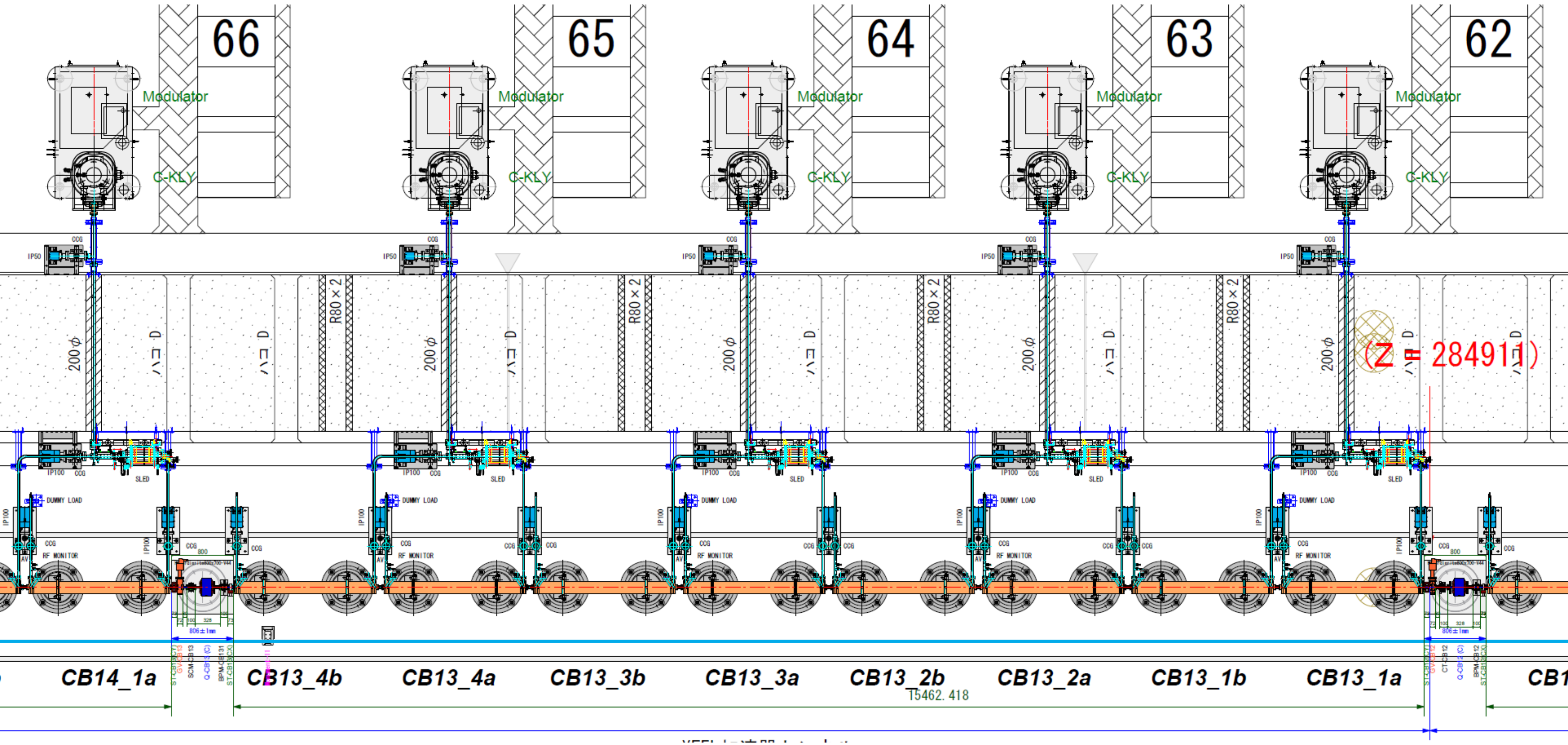


C-band System Configuration



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**



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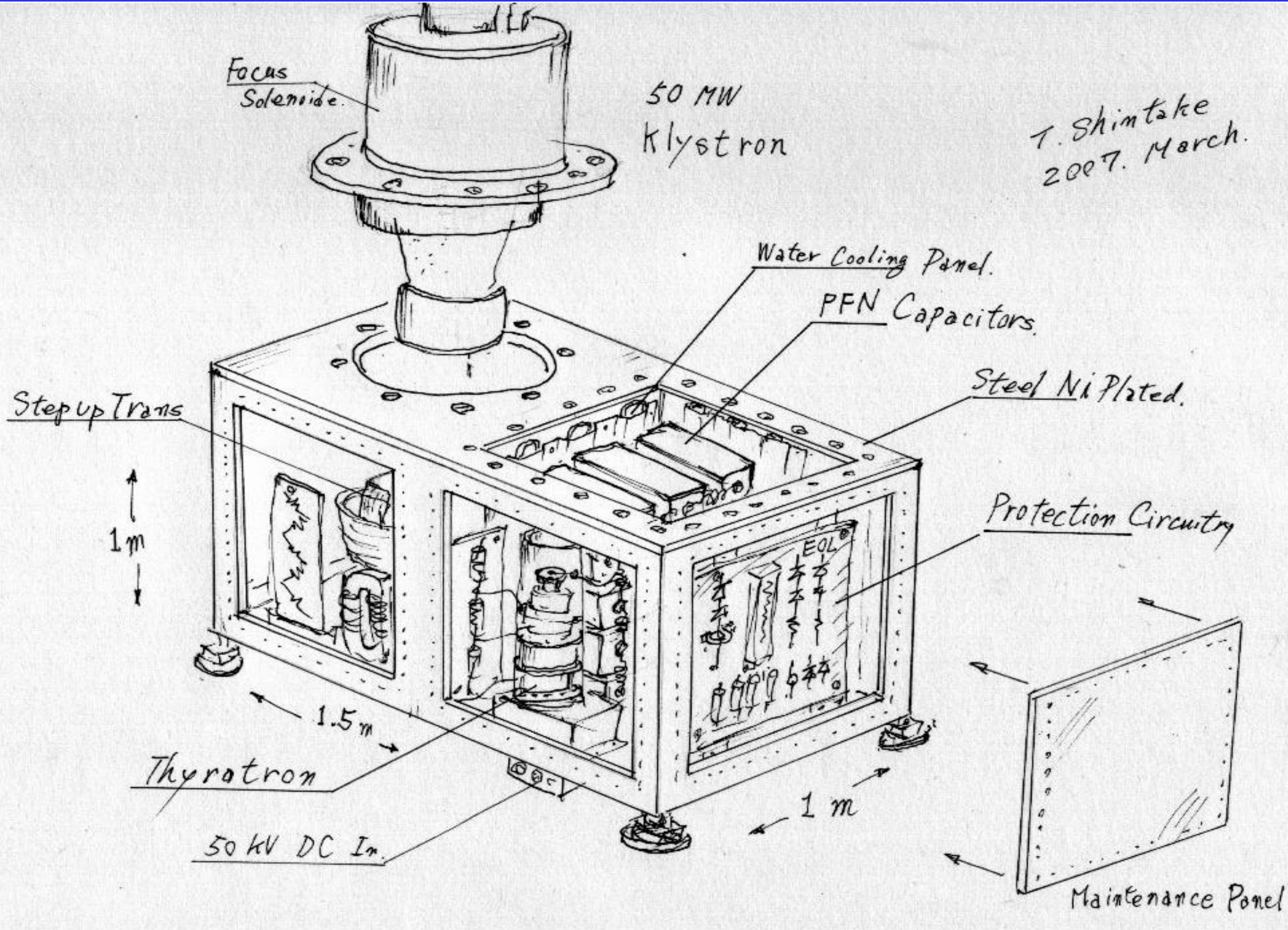
Single Tank Modulator (PFN circuit + Transformer)



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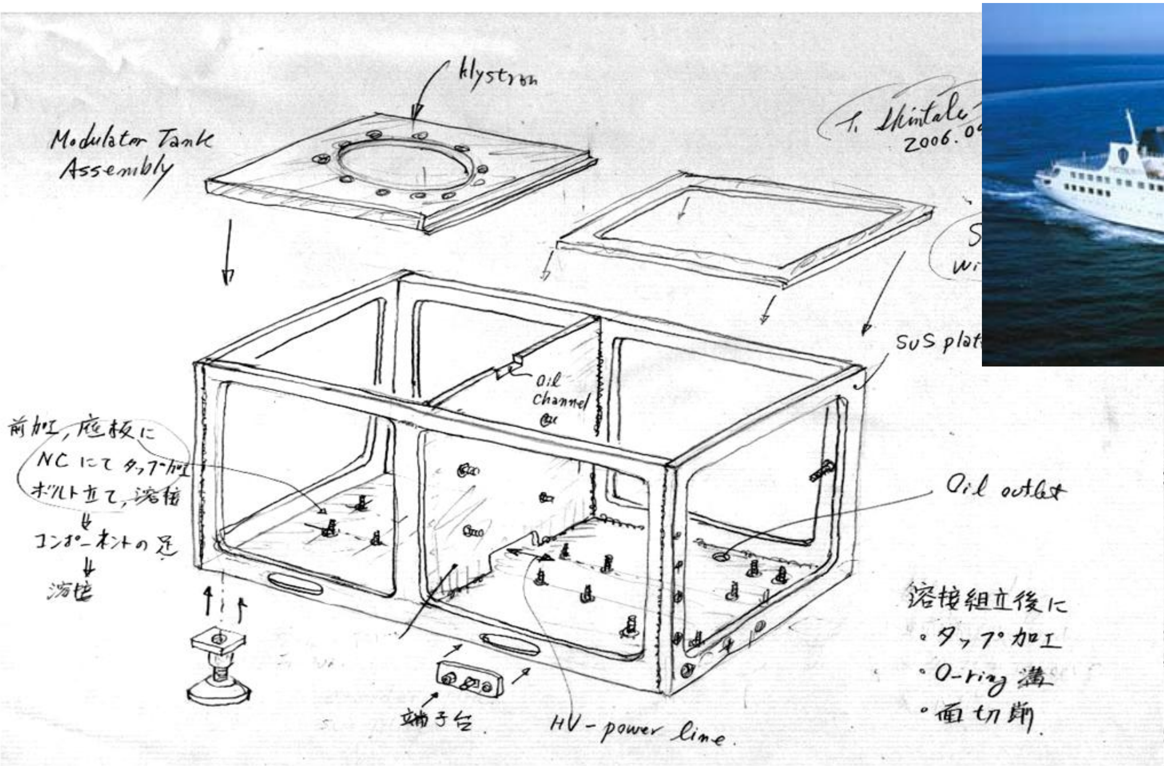
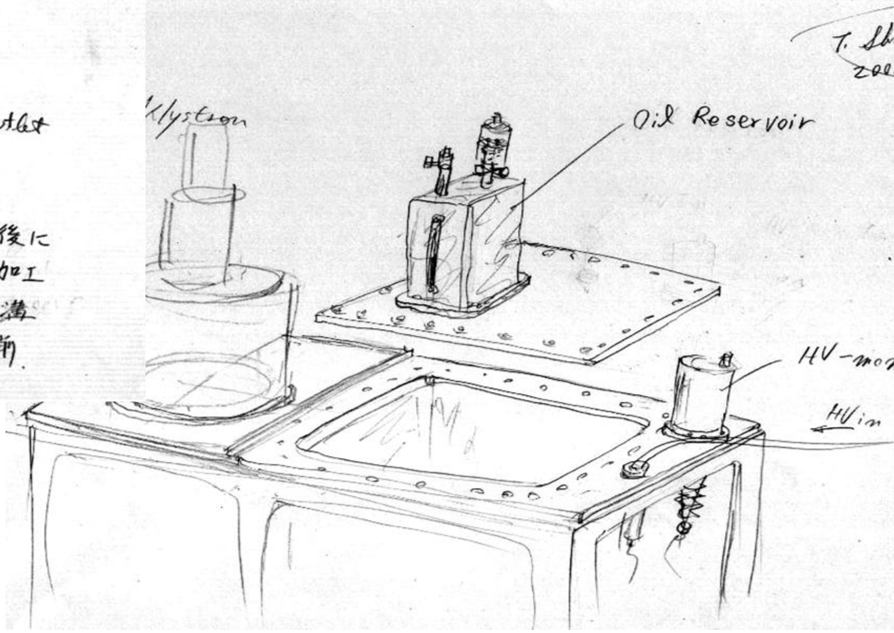
At the R&D, Ship Engine Make at AIOI contributed.





Made by steel (easier than SUS)
Suitable for mass-production.

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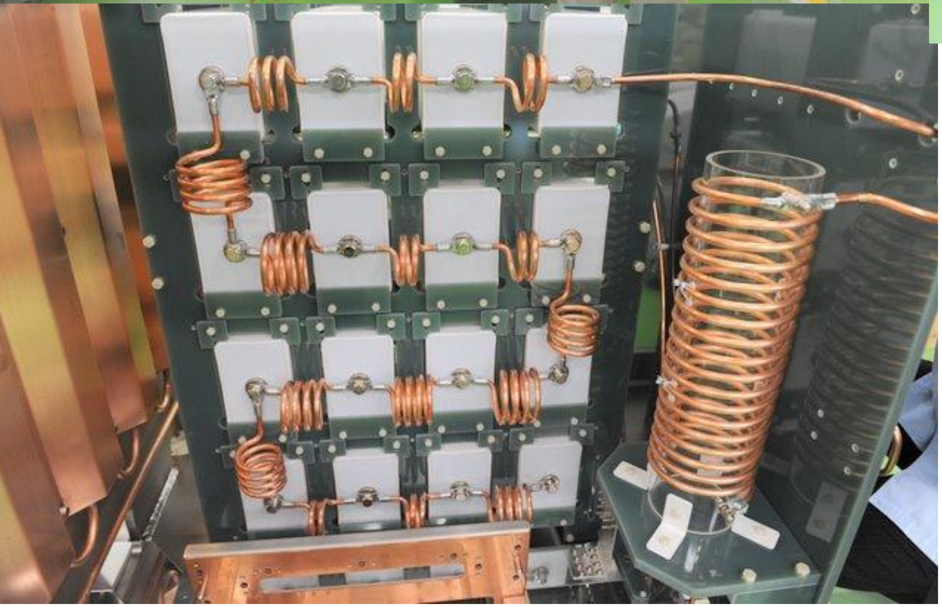
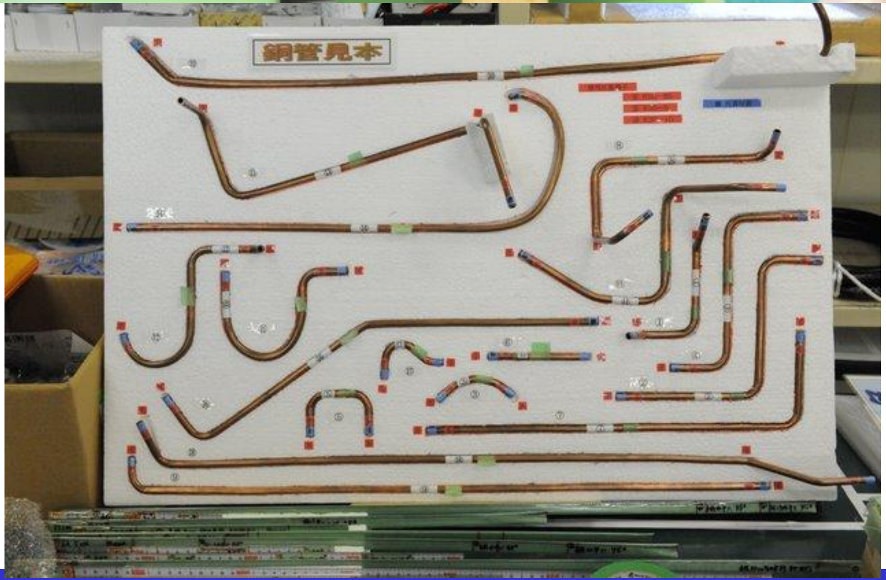
Modulator Mass Production at NICHICON

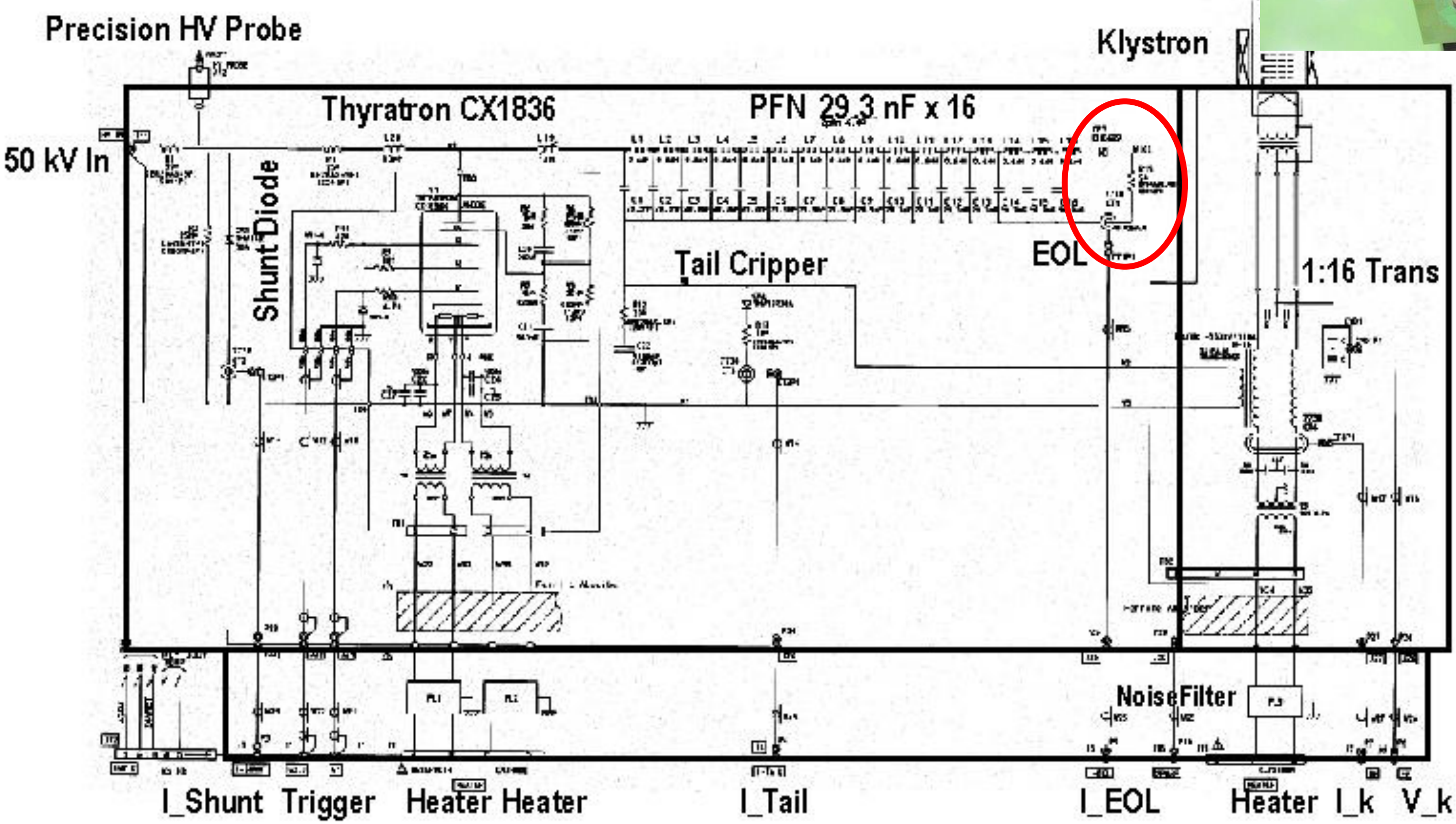
Modulator Tank Fabrication





EOL Diode Failure Problem

- When the klystron gun made HV break down, the EOL diodes broke. (short mode)
- Frequent failure.



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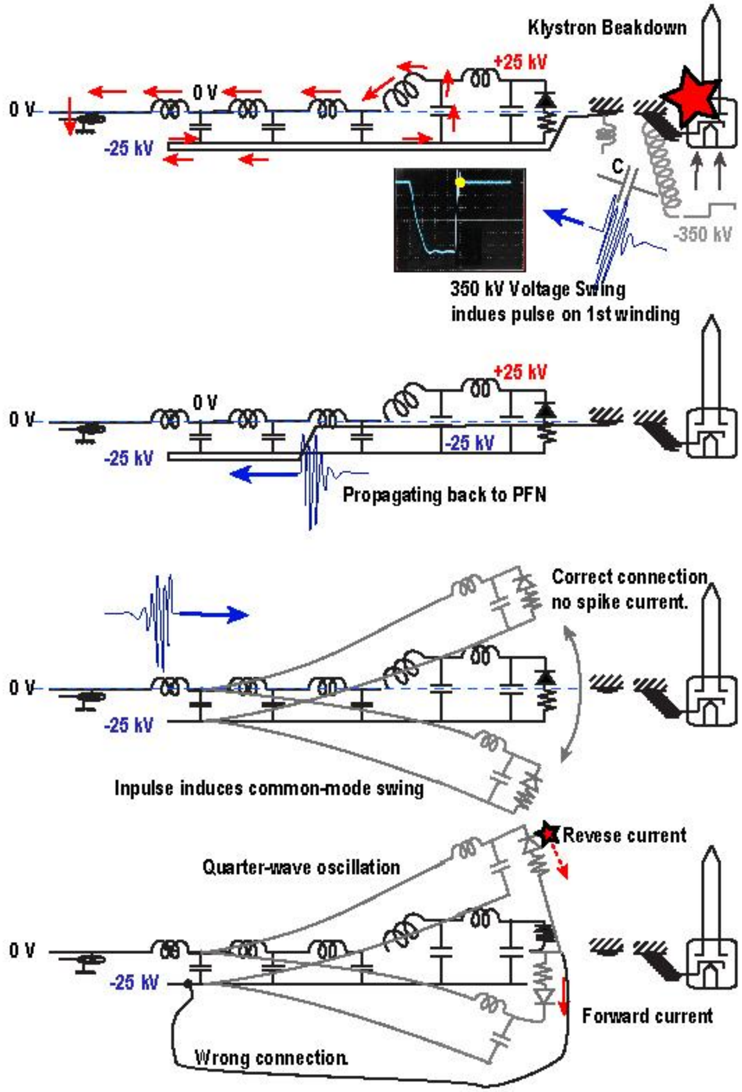
Cause was wrong connection of ground line.



HV breakdown on klystron gun.

Shockwave jumps over the transformer windings, with capacitive coupling.

Frequency is to high ~100 MHz, shockwave runs ground line on PFN.

It reflects back at EOL side as open end, creates standing wave.

EOL diode turns ON very short time, then voltage reverses quickly.
Before the carrier extinction time, voltage reverses, and charge remains in depletion region with high field.
Charge is accelerated and hit anode!

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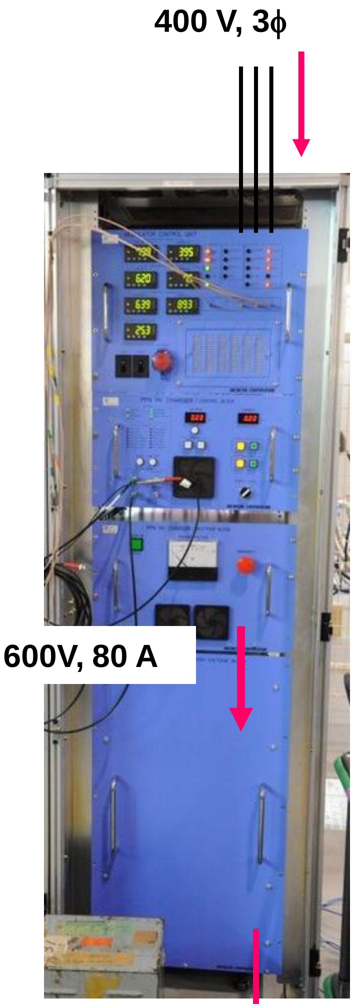
First Modulator was Installed.

Summer 2009

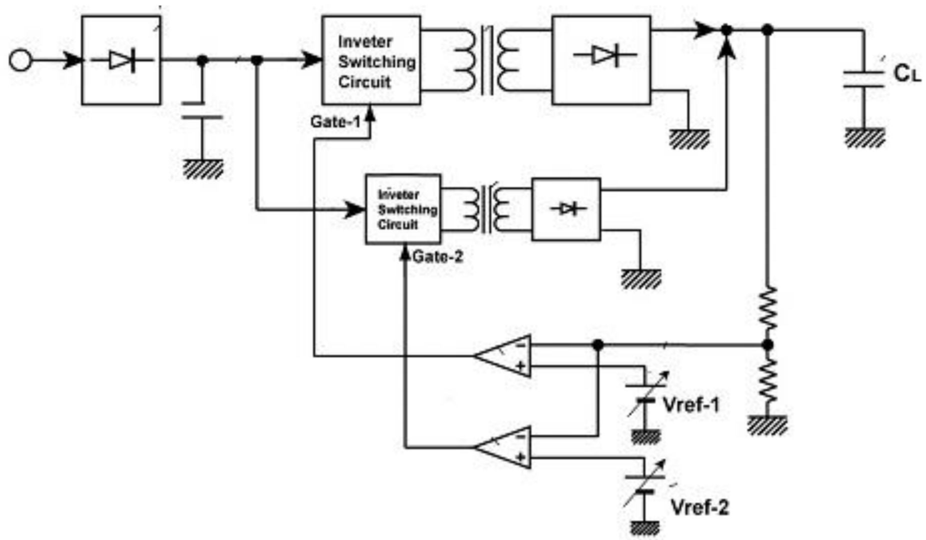
Highly Stable Inverter Type PFN Charger for stable operation of XFEL.



Highly stable
PFN charger
< 100 PPMp-p

- High power capacitor charging system.
- 1.8 Apeak at 50 kV
- Pulse to Pulse < 100 ppm.pp

- Main Switching at 20 kHz, IGBT
- Sub switiching at 80 kHz, FET



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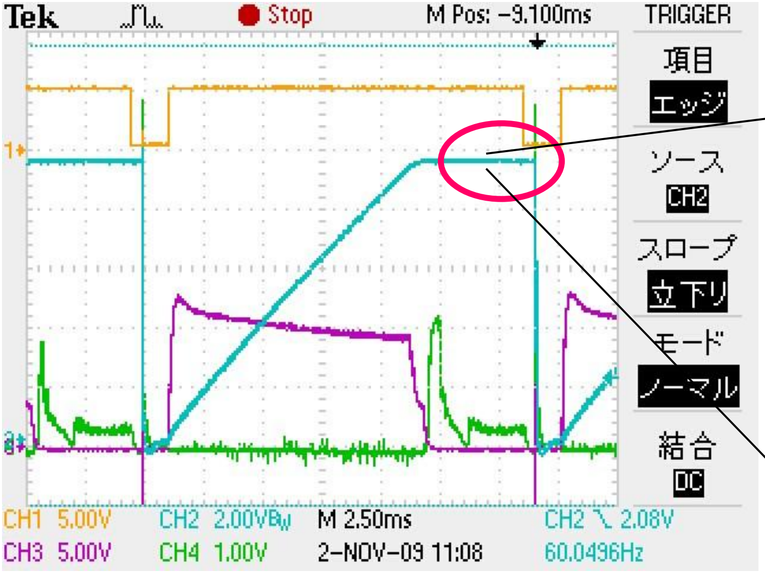
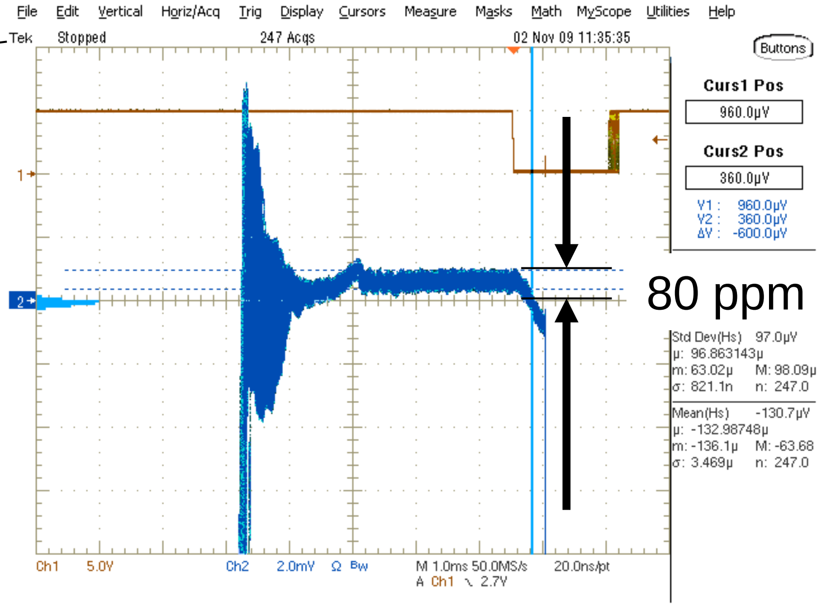
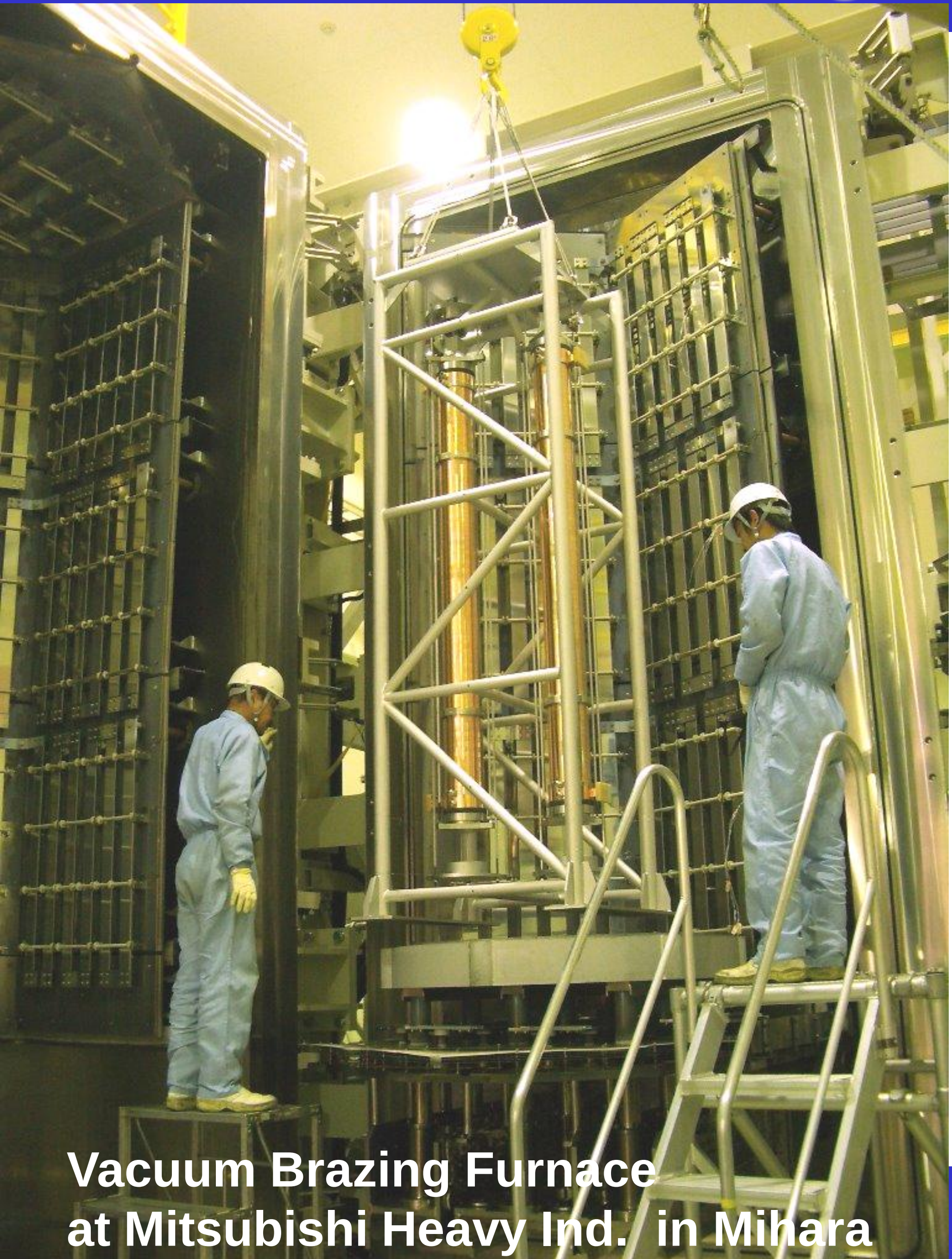
When voltage approaches to target, sub-inverter controls the voltage in fine mode.





- Achieved PFN Charging voltage stability
  - 80 ppm (peak-peak) for 1 minute
  - 190 ppm (peak-peak) for 8 hours.

Brazing of C-band Accelerators



Vacuum Brazing Furnace
at Mitsubishi Heavy Ind. in Mihara

- A number of technical improvements have been made.

- 1~2 columns per week.

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Mass-production of
128 tubes of the C-band Accelerating Structure for 8 GeV linac.
@ MITSUBISHI Heavy Ind.

MITSUBISHI-Team completed 100 tubes (out of 128) C-band Accelerator.

Photo March 2009

Routinely Operation: C-band High Gradient Test

T. Sakurai, IPAC2010

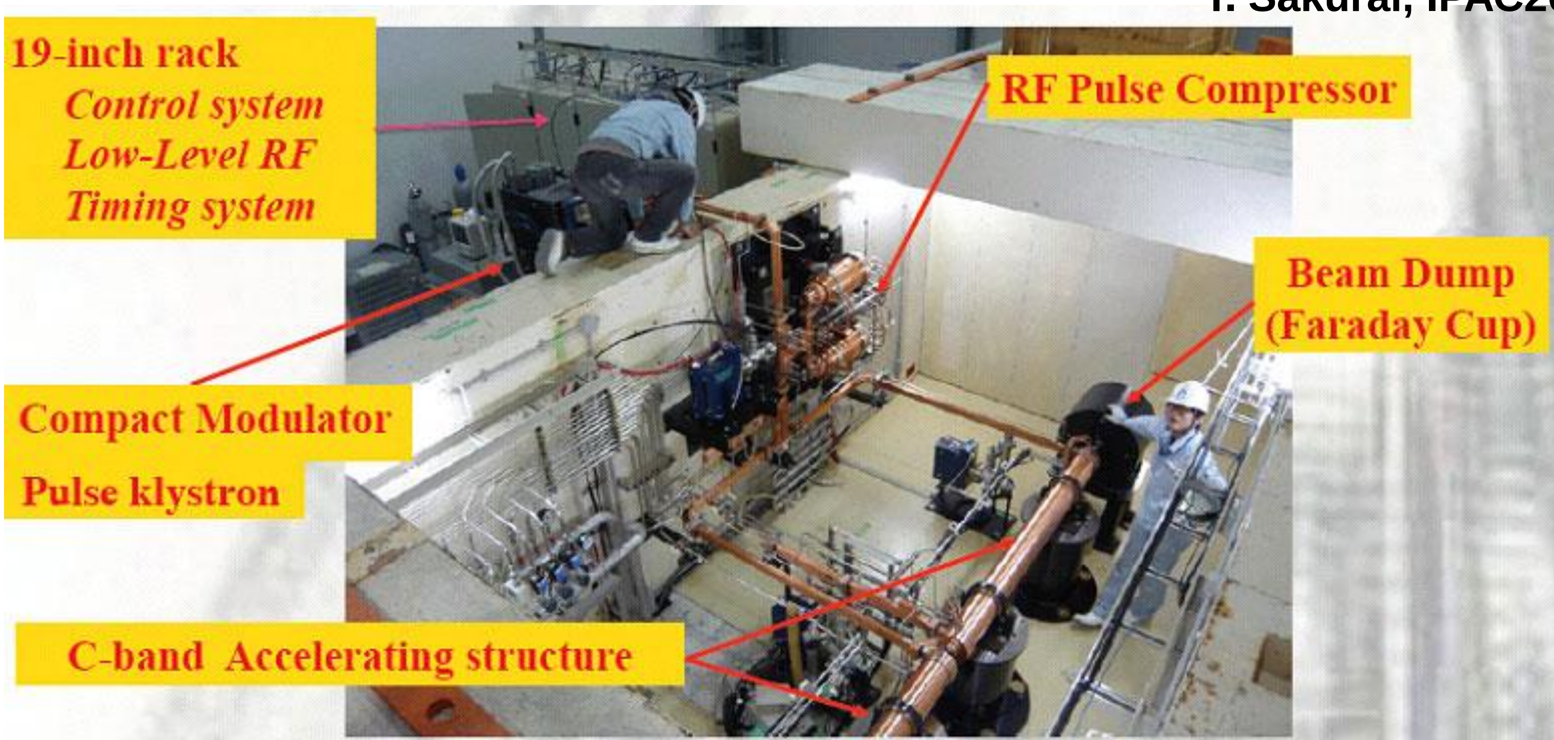

Fig.2 Birds'eye view of the test bunker.

- 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.

RF Pulse Compressor

Q_0 : > 180000, β : > 8.0

Two TE0,1,15 cavities

RF power Gain : (typ.) 3

Installed C-band Accelerator

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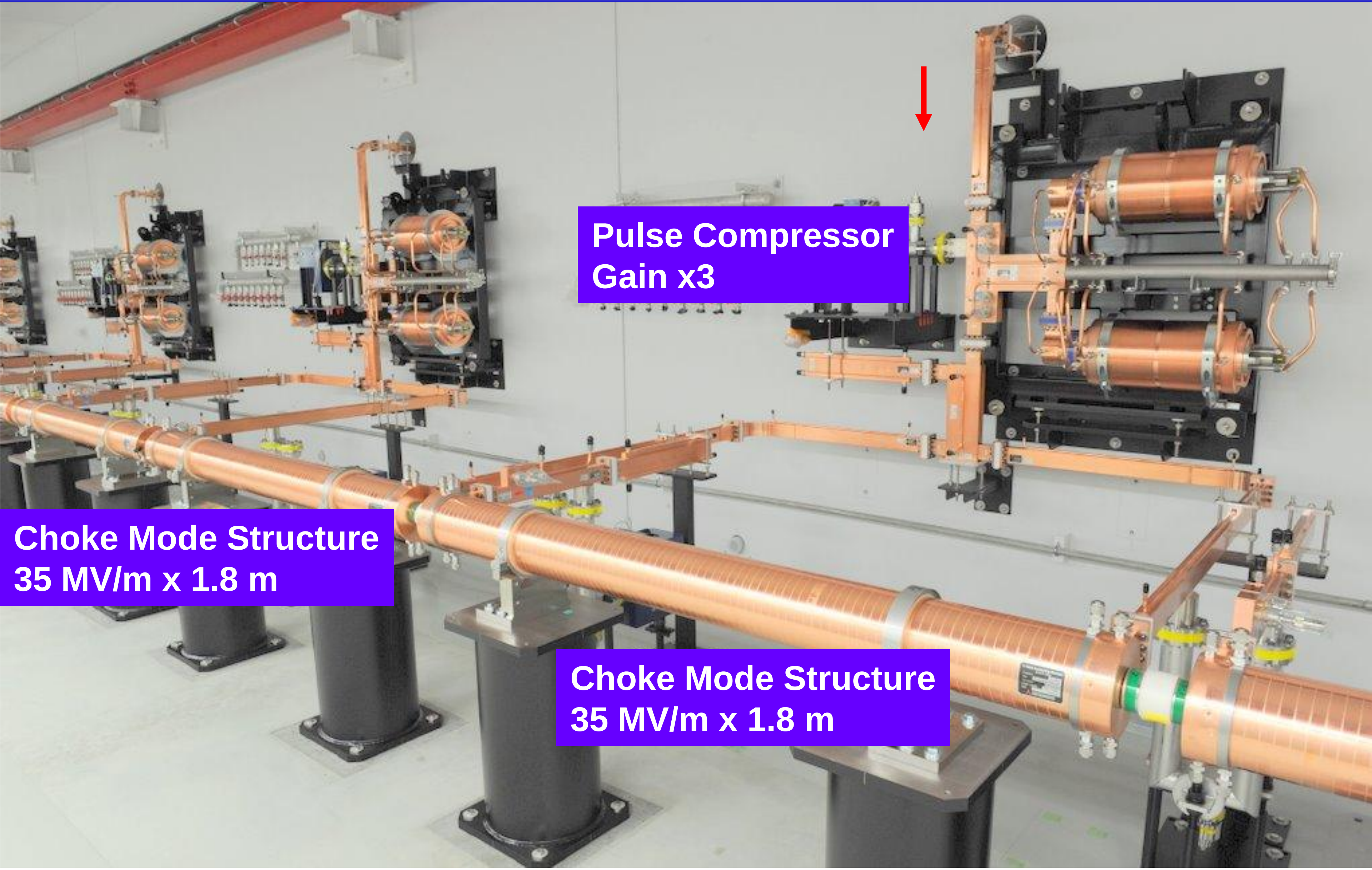
C-band Accelerator



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Summary

- CeB6 thermionic performance was fully investigated, and found to be matched to XFEL/SPring-8.
- Various new hardware components have been developed in this laboratory, LLRF, single-tank klystron modulator, high precision power supply, etc.
  - Those components will be useful to other accelerator projects including FELs, light source injectors and also ERLs.
- We will contribute to accomplish X-ray lasing of XFEL/SPring-8, expected Summer 2010.
- This laboratory will keep activity for future upgrade of XFEL/SPring-8.

Acknowledgement

- We would like to acknowledge to all of colleague here and also from outside for their various help and encouragements to our laboratory.
- We wish thank to people from industries for their collaborative efforts on development of all hardware components.
- We would like to say thank to people at secretaries office in this institute, and director office.