Status of XFEL/SPring-8 Construction

Tsumoru Shintake

as representing Joint XFEL/SPring-8 Construction Team

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

May 09 2009


SPring-8
Operating ten years
XFEL/SPring-8
Building construction
completed March 2009
SCSS Test Accelerator
Since 2006, EVU user facility


2007 May


2007 Dec


2008 May


2008 Oct

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Experimental hall

Dec. 2009

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Accelerator installation

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2009 Aug


2009 Aug

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Testing Modulator & Klystron

Welcome to
Laboratory Tour on Saturday
SPring-8
Ticket available till this evening.

Undulator Line

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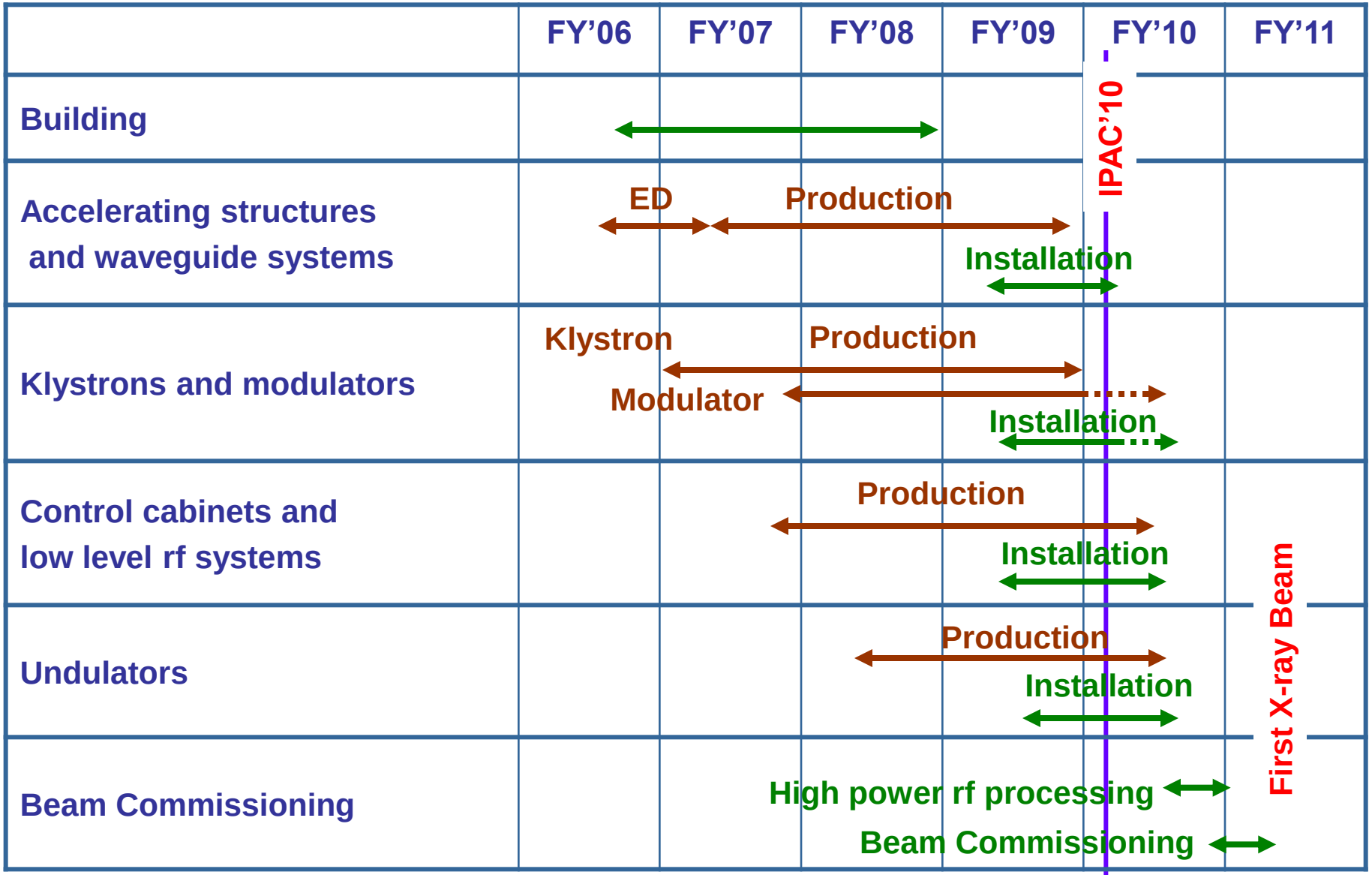
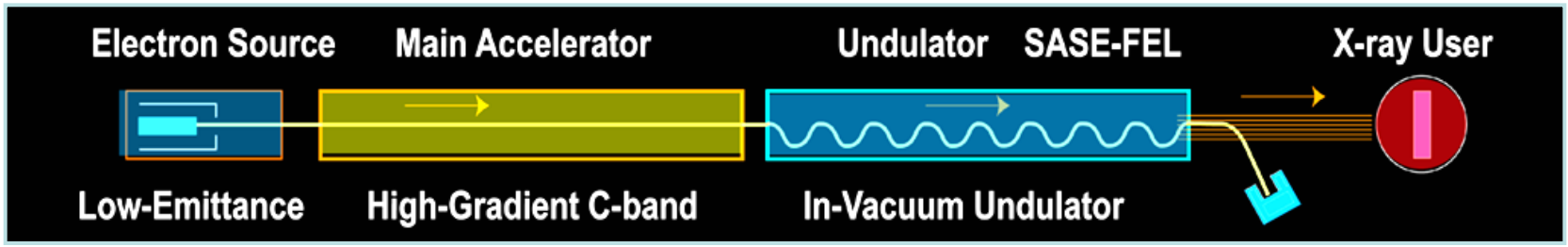
Status of XFEL/SPring-8 Construction



SCSS : SPring-8 Compact SASE Source



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

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

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

  Euro-XFEL : λu= 36 mm, K=3.3, λx < 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

- **Low Emittance Injector** → **Short Saturation Length**

Thermionic gun + velocity bunching → 0.8 π.mm.mrad @ 3k A, 8GeV
→ Saturation length 90 m

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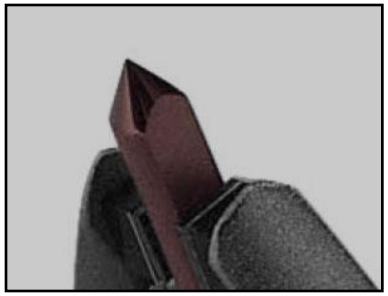
Why Thermionic Cathode?

based on perception on technology

■ **Established Technology on Single Crystal Cathode for Electron Microscope, LaB6 or CeB6**



- ■high quality crystal available from shelf.
- ■long life > 10,000 hs
- ■strong against contamination → easy handling.
- ■very stable emission at > 30 A/cm^2

■ **High power klystron beam dynamics**

- ■→ stable velocity bunching,
- ■ but 100 times or more!
- ■→ SCSS Test Accelerator, proved emittance preservation.

■**X-band LC R&D → 500 kV pulse gun for klystron.**

Use Small Size Cathode
…First Strategy for smaller thermal emittance

Thermal Emittance

Operating Temperature 1500° C

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

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

Use Small Cathode 3mm

Current Density

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

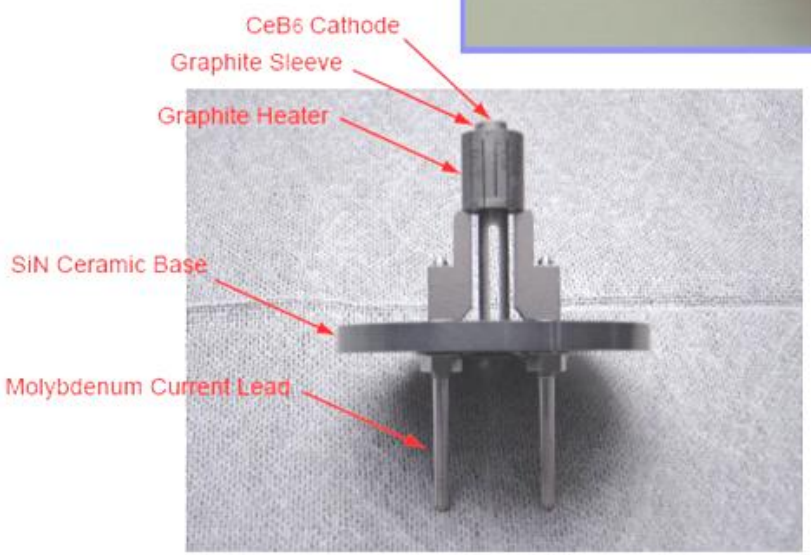
LaB_6 or CeB_6

Twice longer lifetime

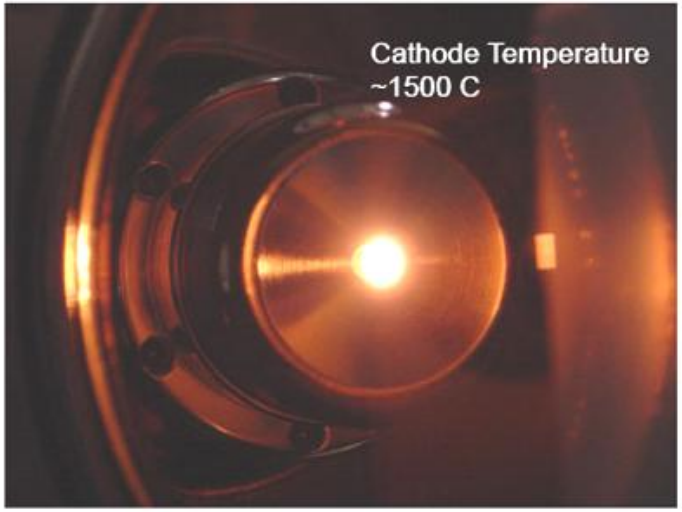
CeB6 Thermionic Electron Gun

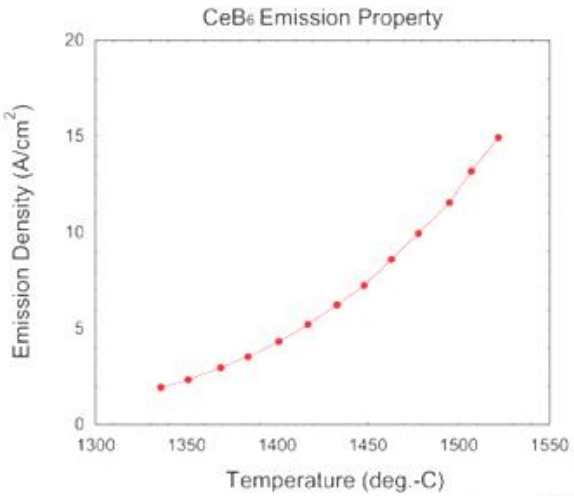
K. Togawa

Cathode Assembly



Heated Cathode in Stem





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

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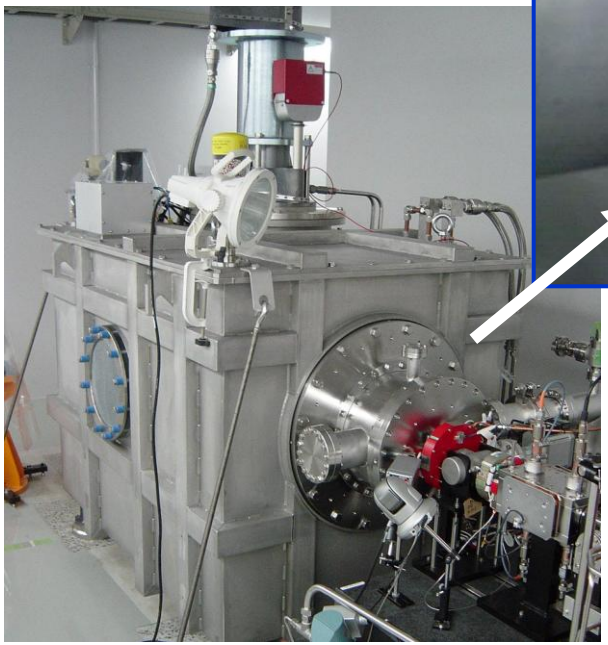
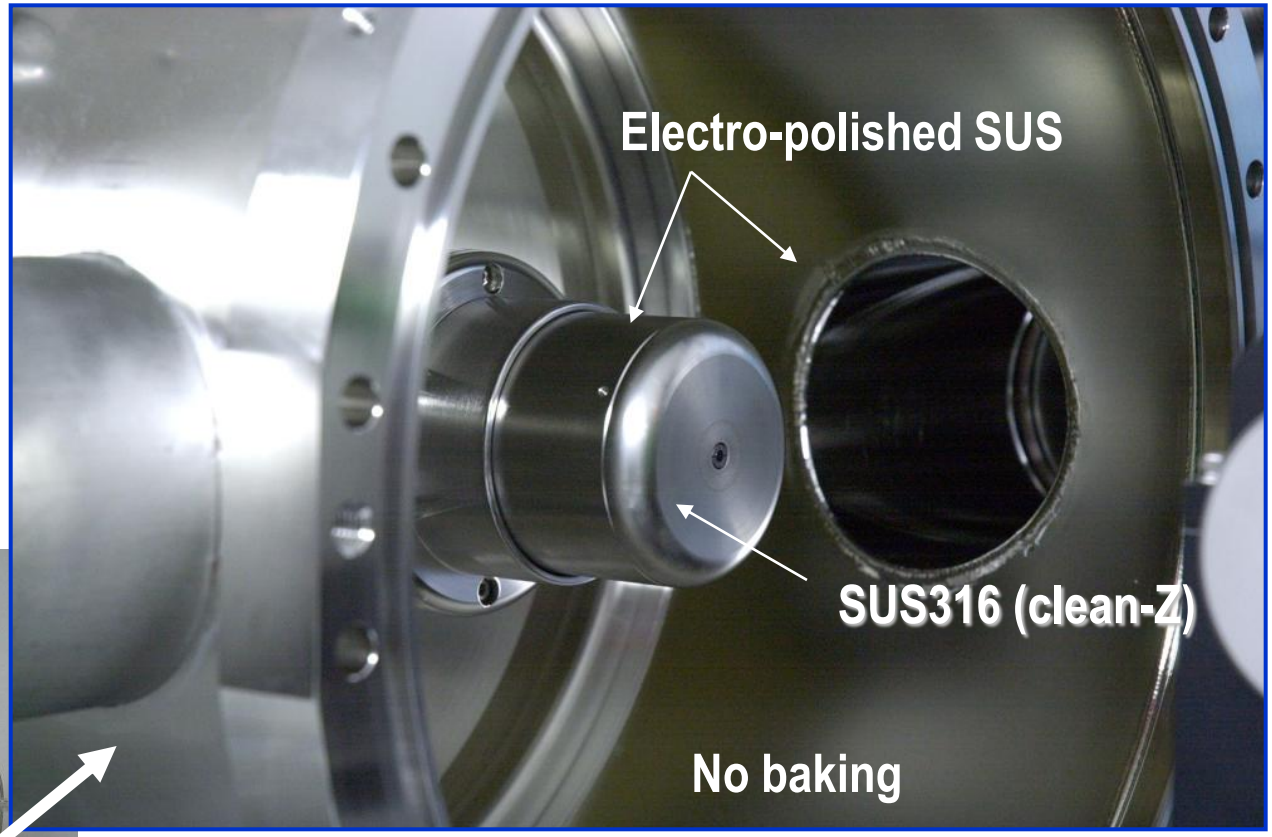
Operational Experience of 500 kV Gun

- 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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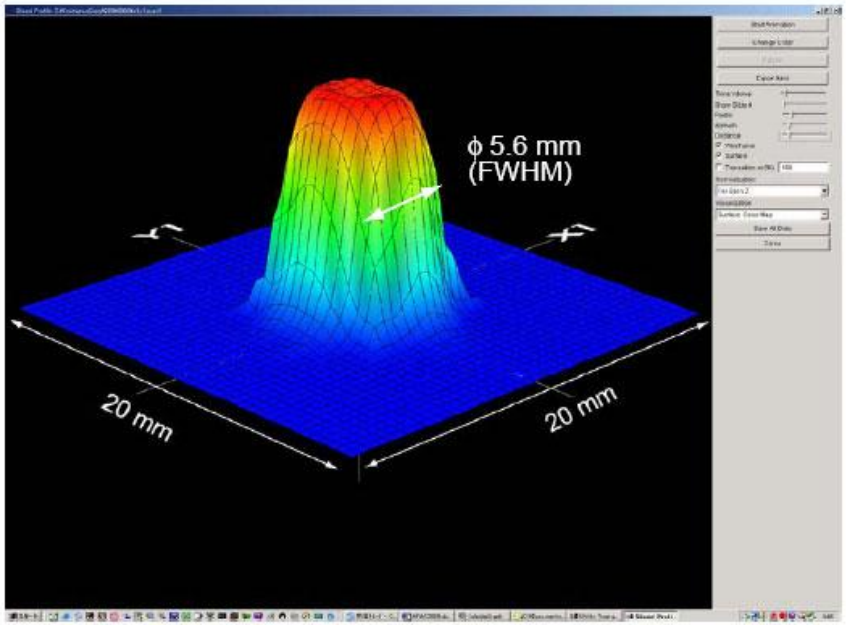
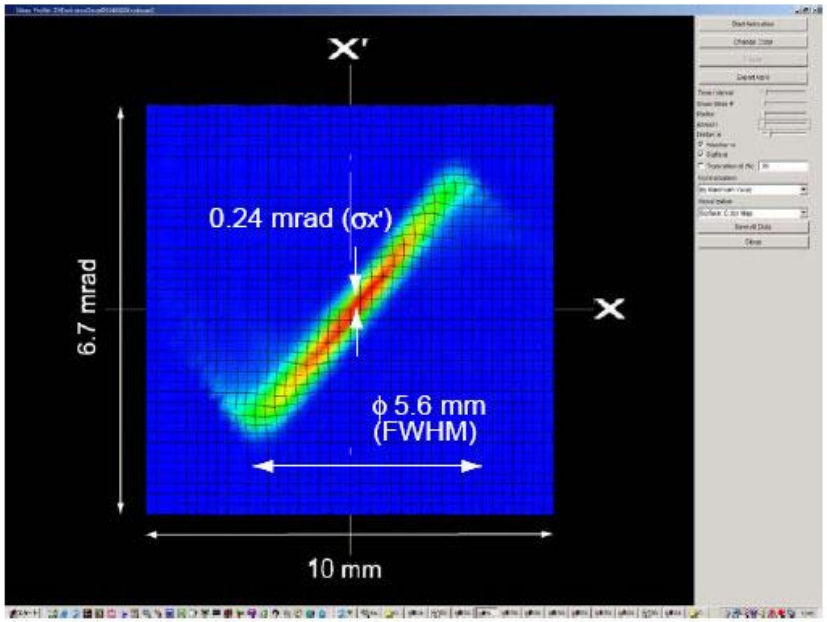
Measured Emittance at the Gun

Beam Profile

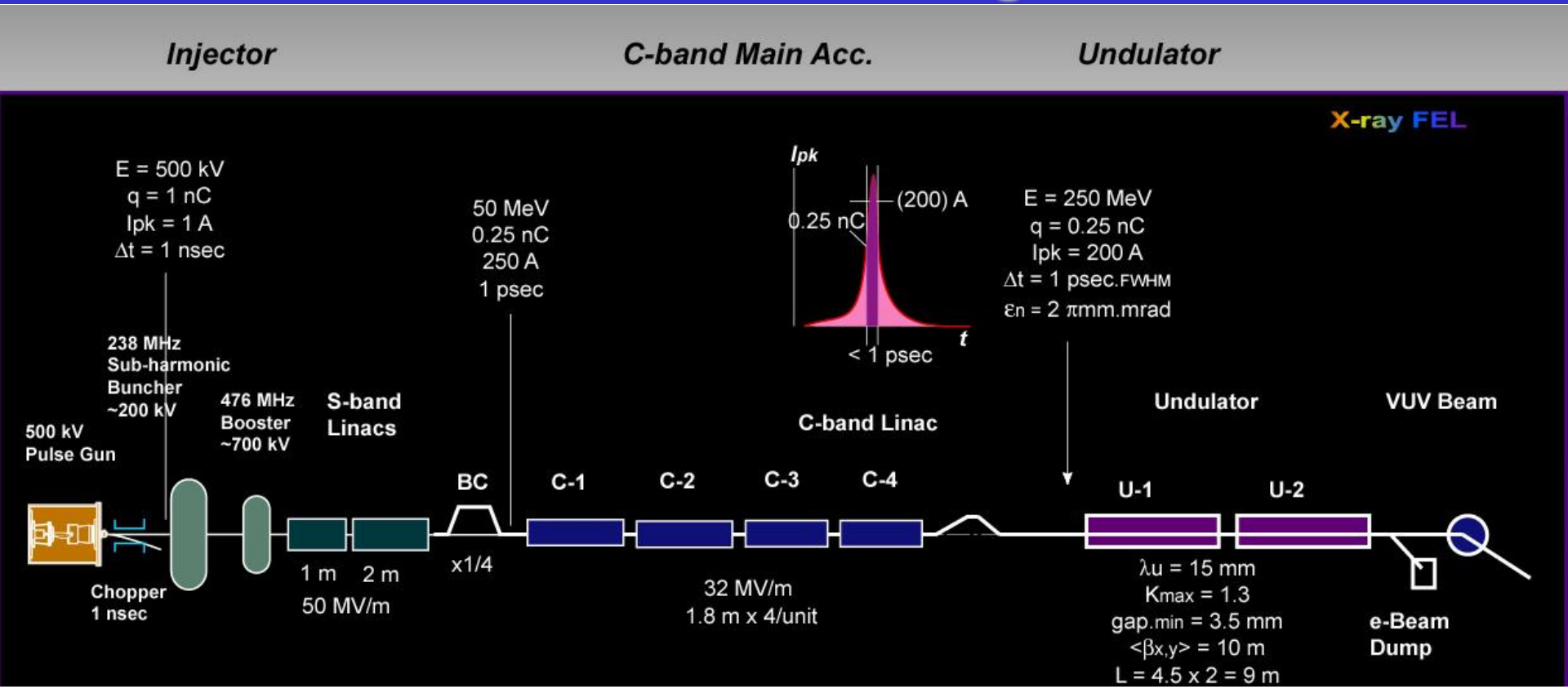


Phase Space Profile



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

Test Accelerator Configuration



1 nsec (chopper)

Velocity Bunching x 100 ~ x 300

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

Chicane Bunching x 3

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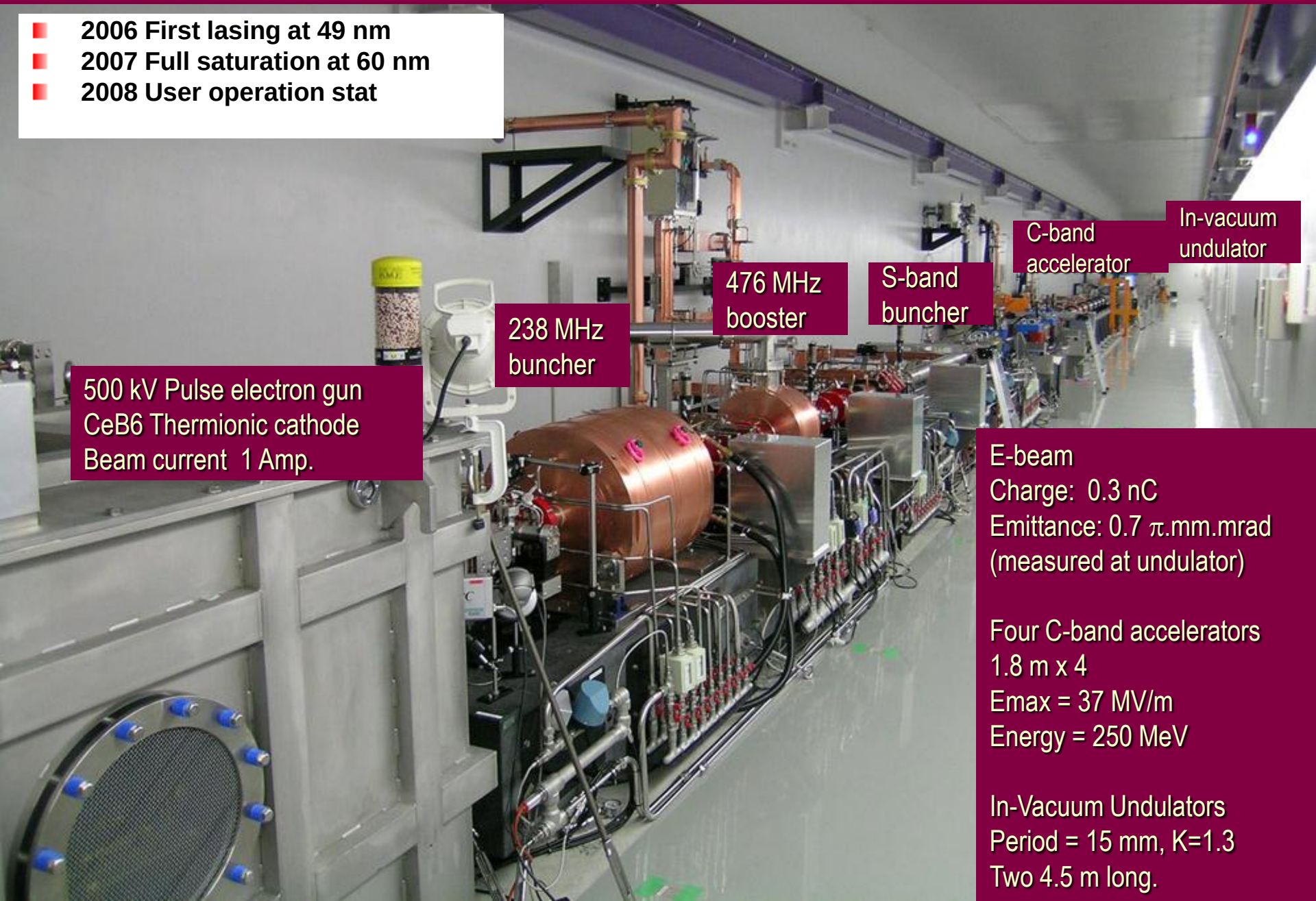
SCSS Test Accelerator Performance

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



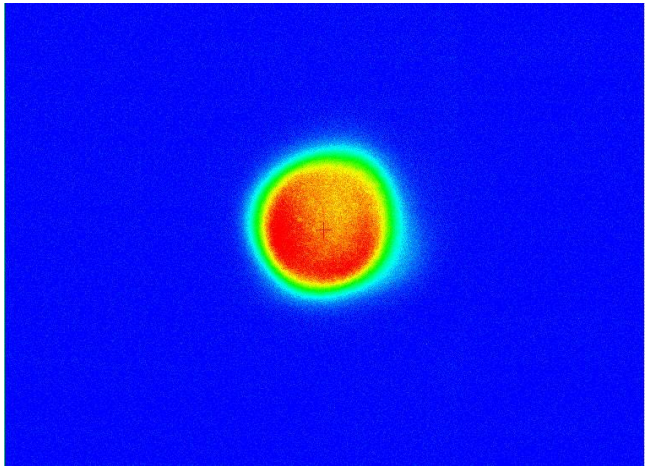
E-beam
Charge: 0.3 nC
Emittance: 0.7 π.mm.mrad
(measured at undulator)

Four C-band accelerators
1.8 m x 4
Emax = 37 MV/m
Energy = 250 MeV

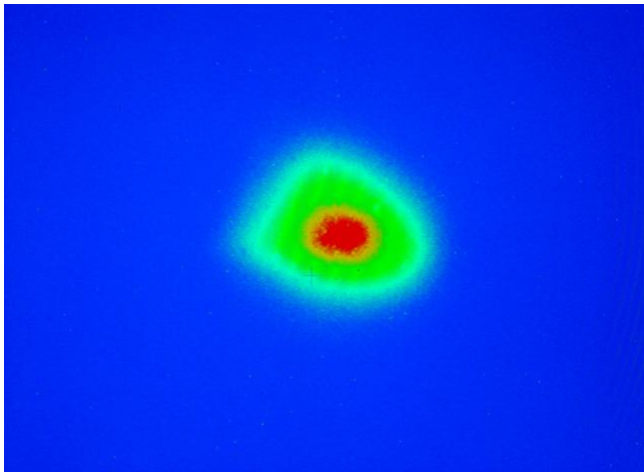
In-Vacuum Undulators
Period = 15 mm, K=1.3
Two 4.5 m long.

CeB_6 Thermionic Gun provides stable beam.

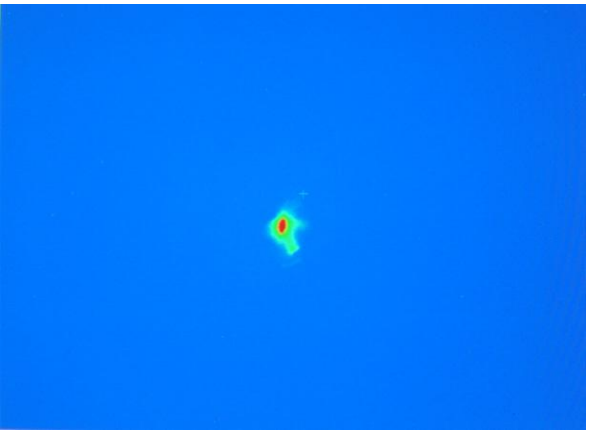
Beam Profile
CCD Image
Scale 10 mm



500 kV Gun

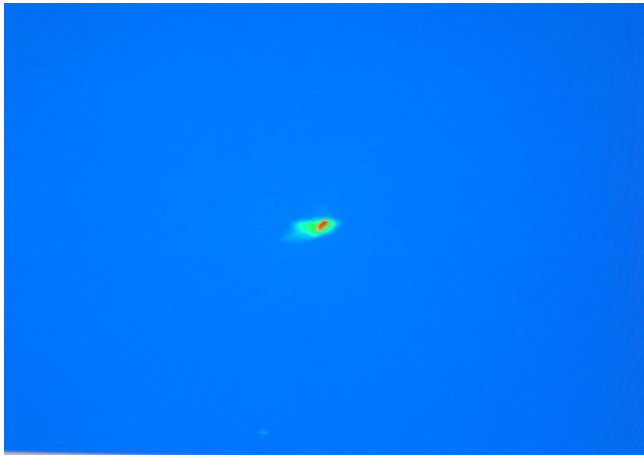


50 MeV Injector Out



250 MeV Compressor

Undulator Input



Undulator Output

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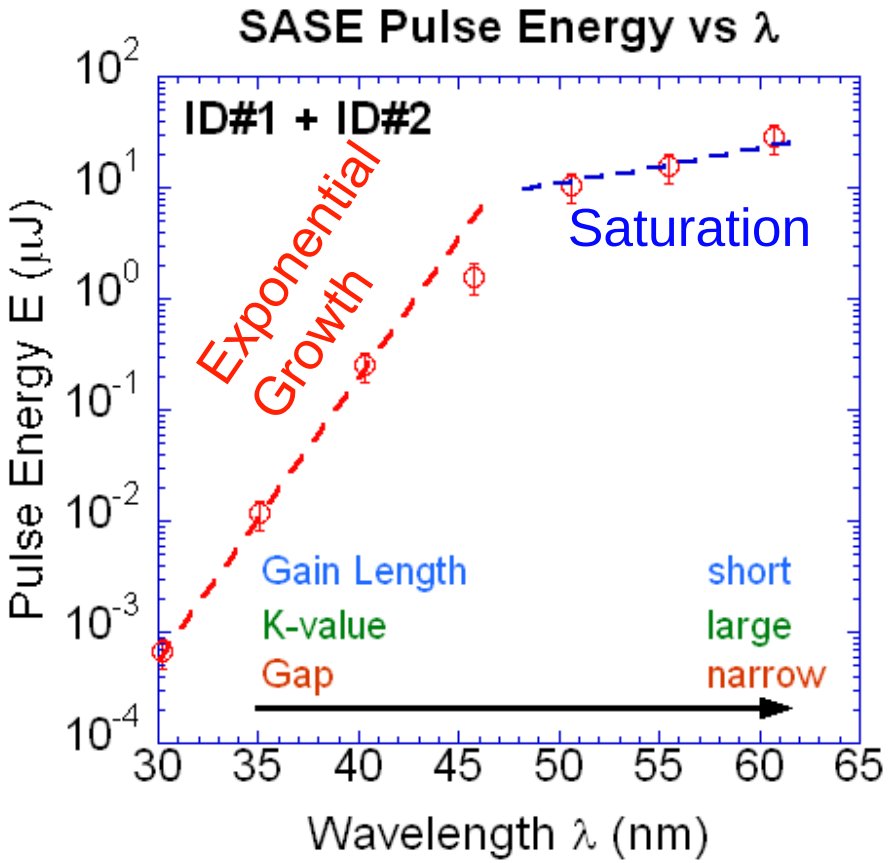
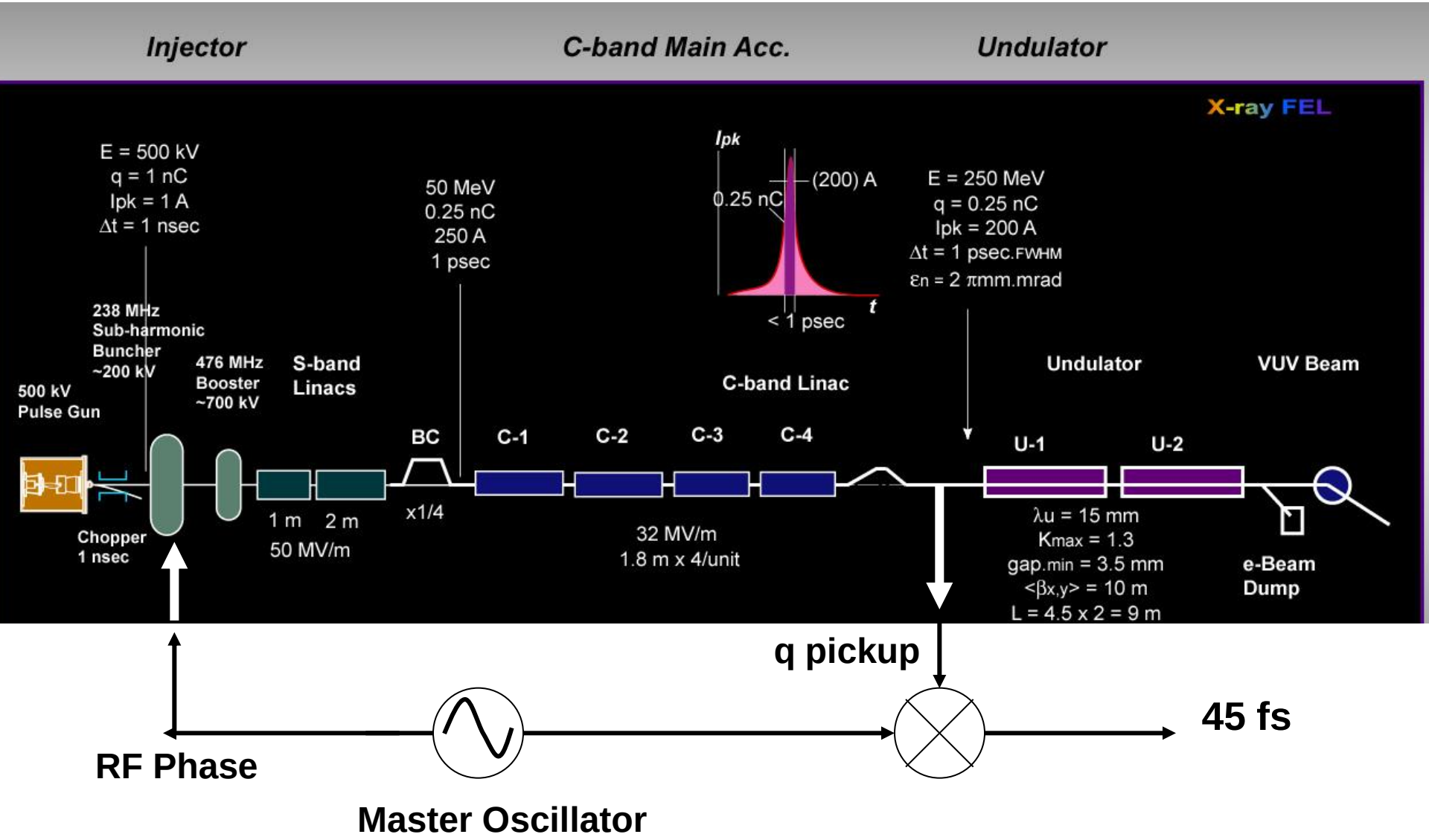
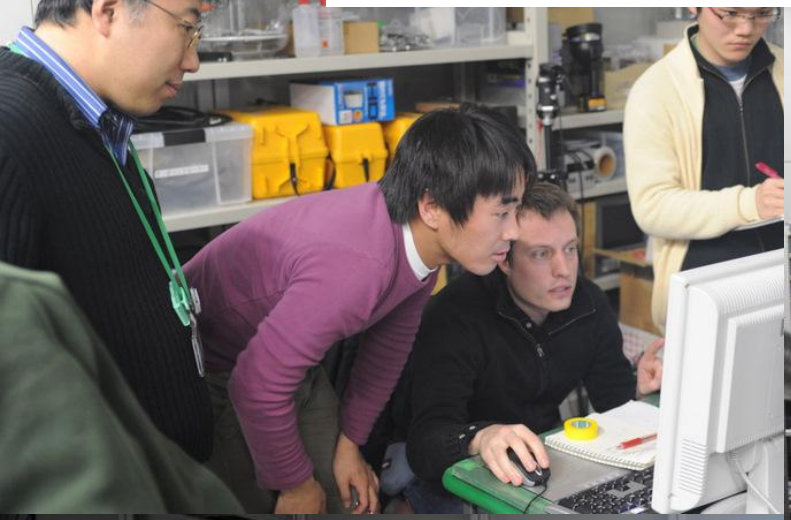
The normalized emittance is estimated to be 0.7πmm.mrad

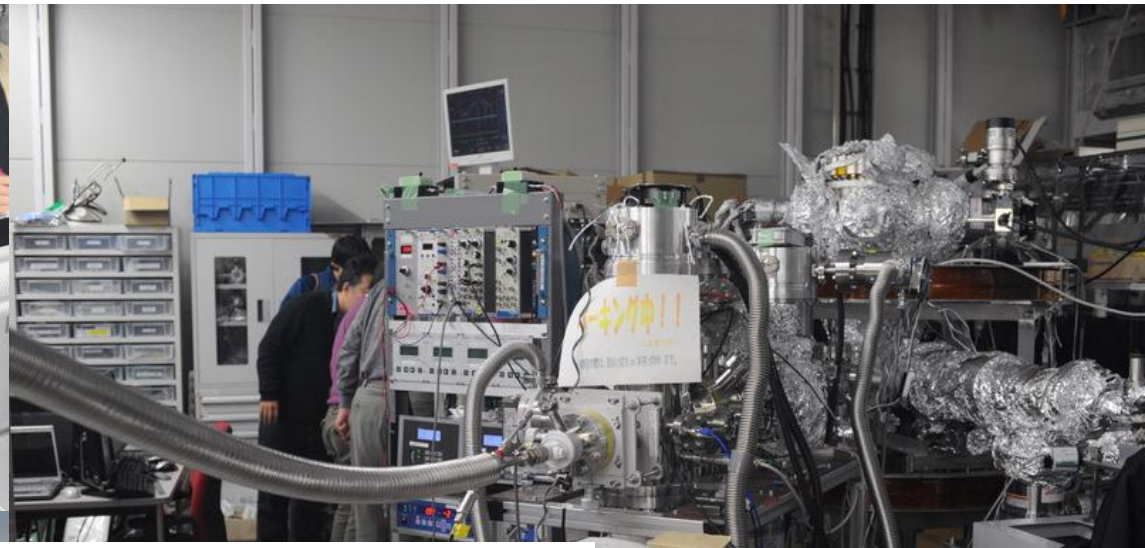


Timing Jitter

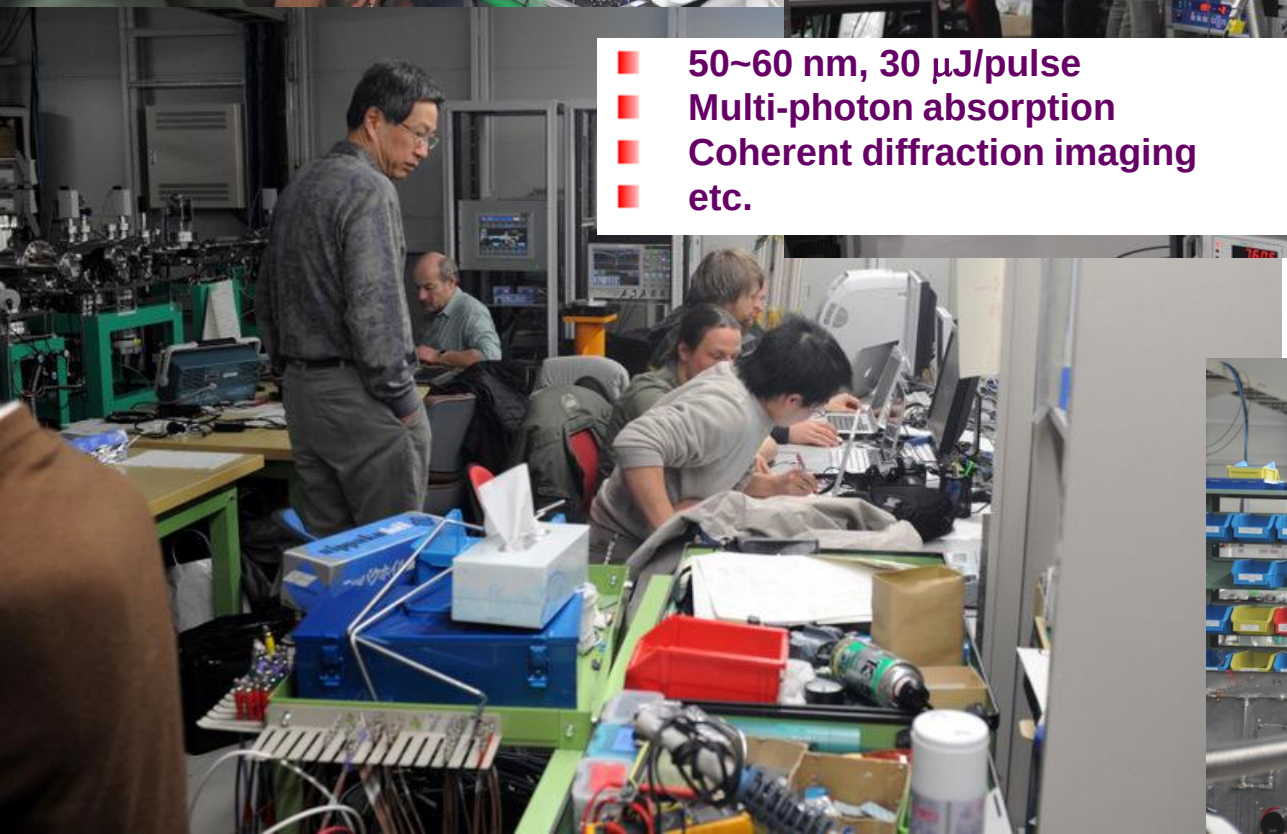


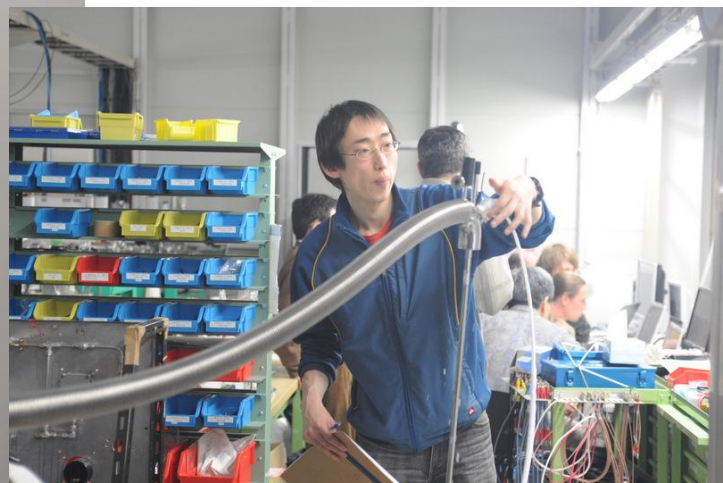
SCSS Test Accelerator User Run Has been Started in 2008





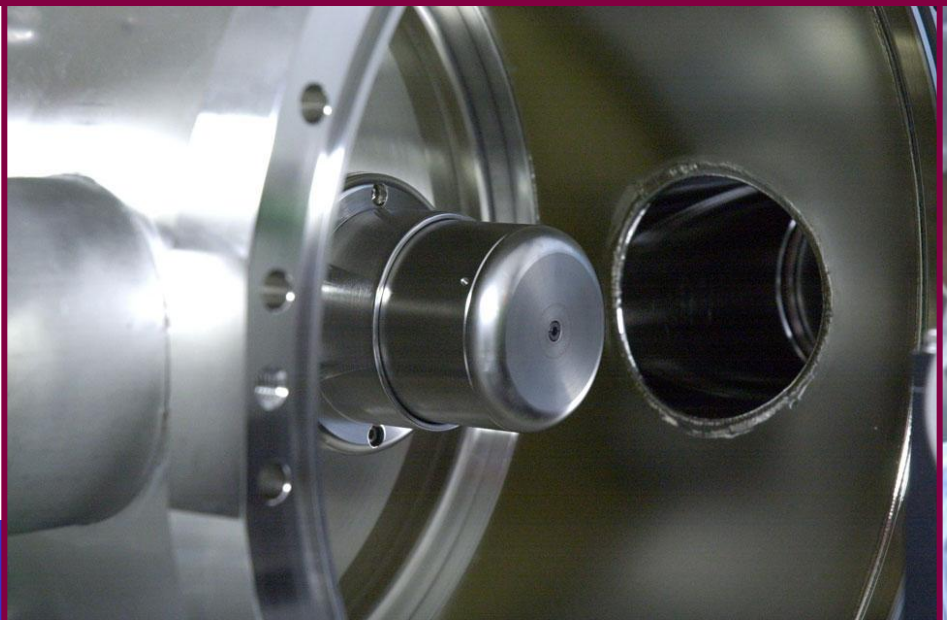
- 50~60 nm, 30 μJ/pulse
- Multi-photon absorption
- Coherent diffraction imaging
- etc.





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

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



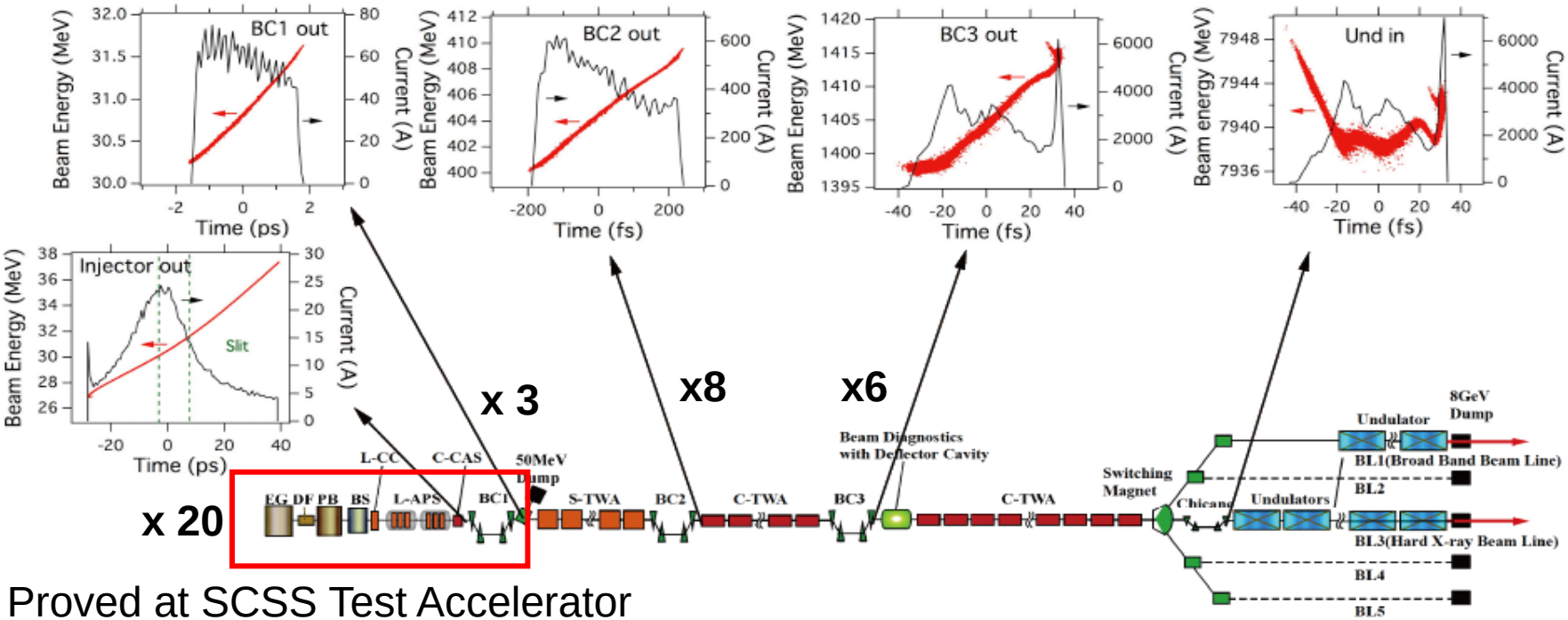
Anode flange had color change.

CeB6 cathode after 20,000 hour use.

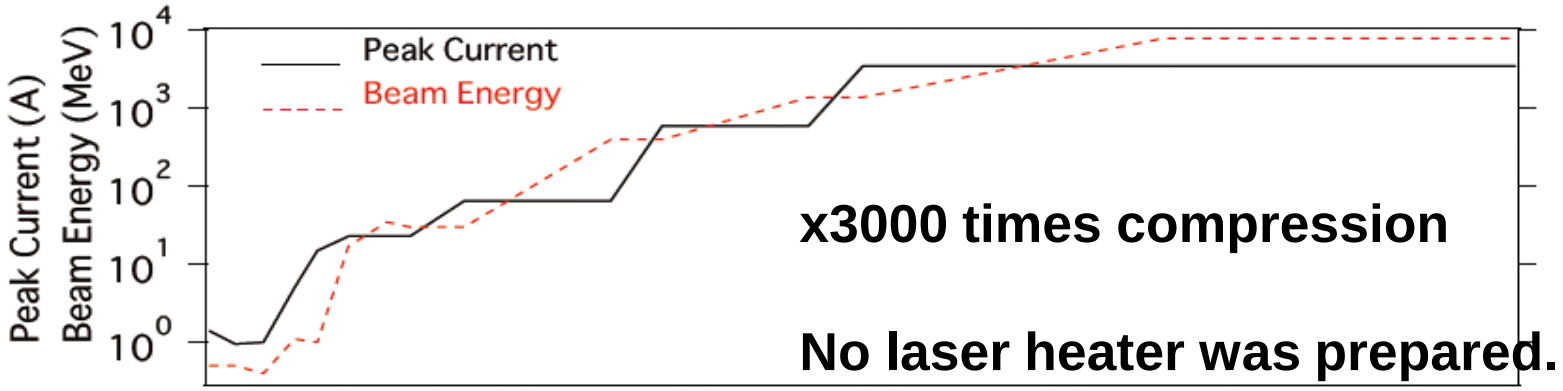
It was found the cathode surface became concave of 0.2 mm deep from the initial flat surface.
It corresponds to evaporation speed of 10 nm/hour (10 nm/h x 20,000 h = 200 micron-meter)
Concave geometry made beam slightly focusing, but did not break emittance.
Electron microscope study showed (1) Surface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


XFEL/SPring-8
Building construction
completed March 2009
Experimental Hall
(under construction)
Undulator Hall
400 m Accelerator Tunnel
Klystron Gallery
Machine Assembly Hall

Beam Acceleration and Compression



Proved at SCSS Test Accelerator



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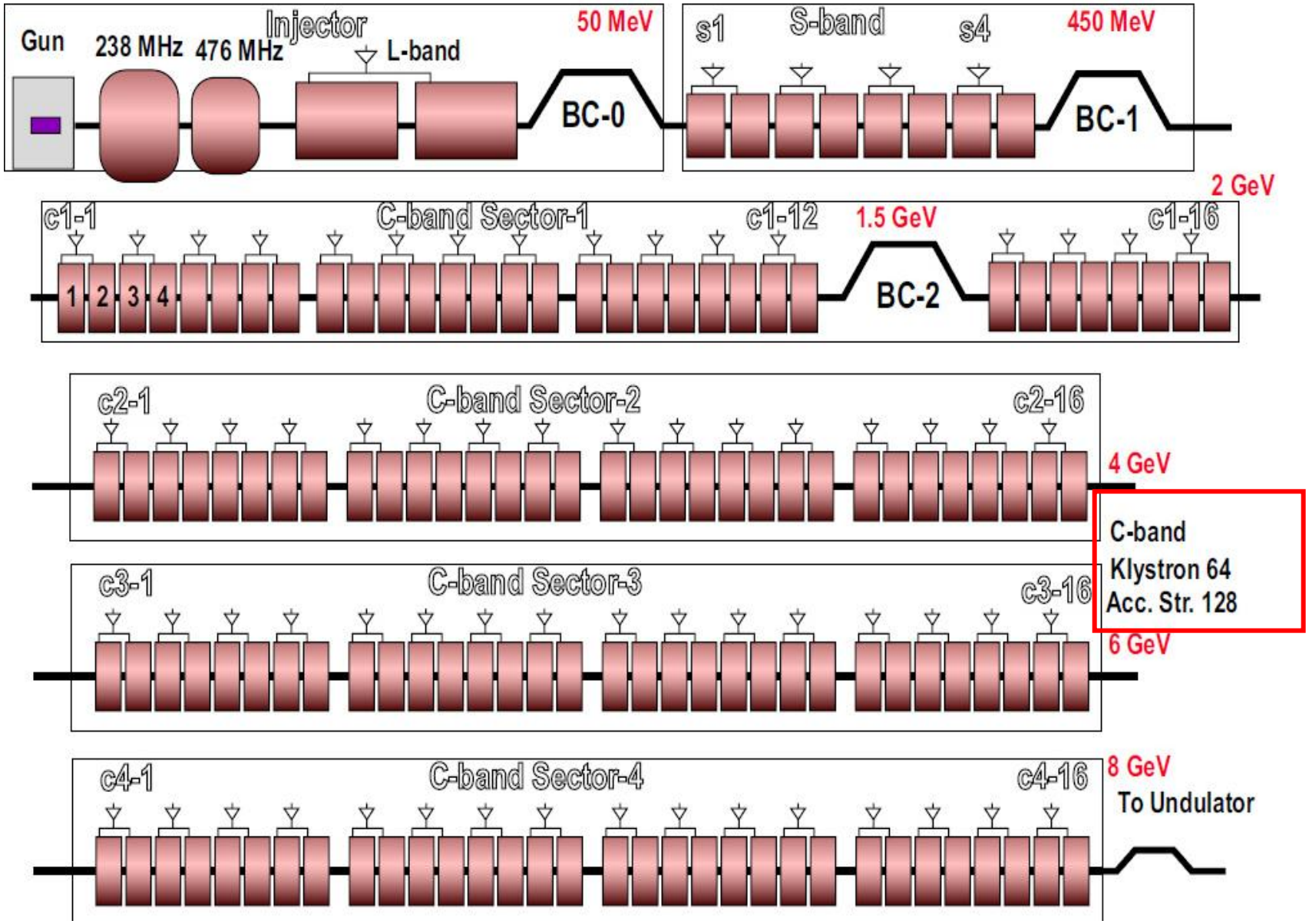
RF Acceleration System in XFEL/SPring-8



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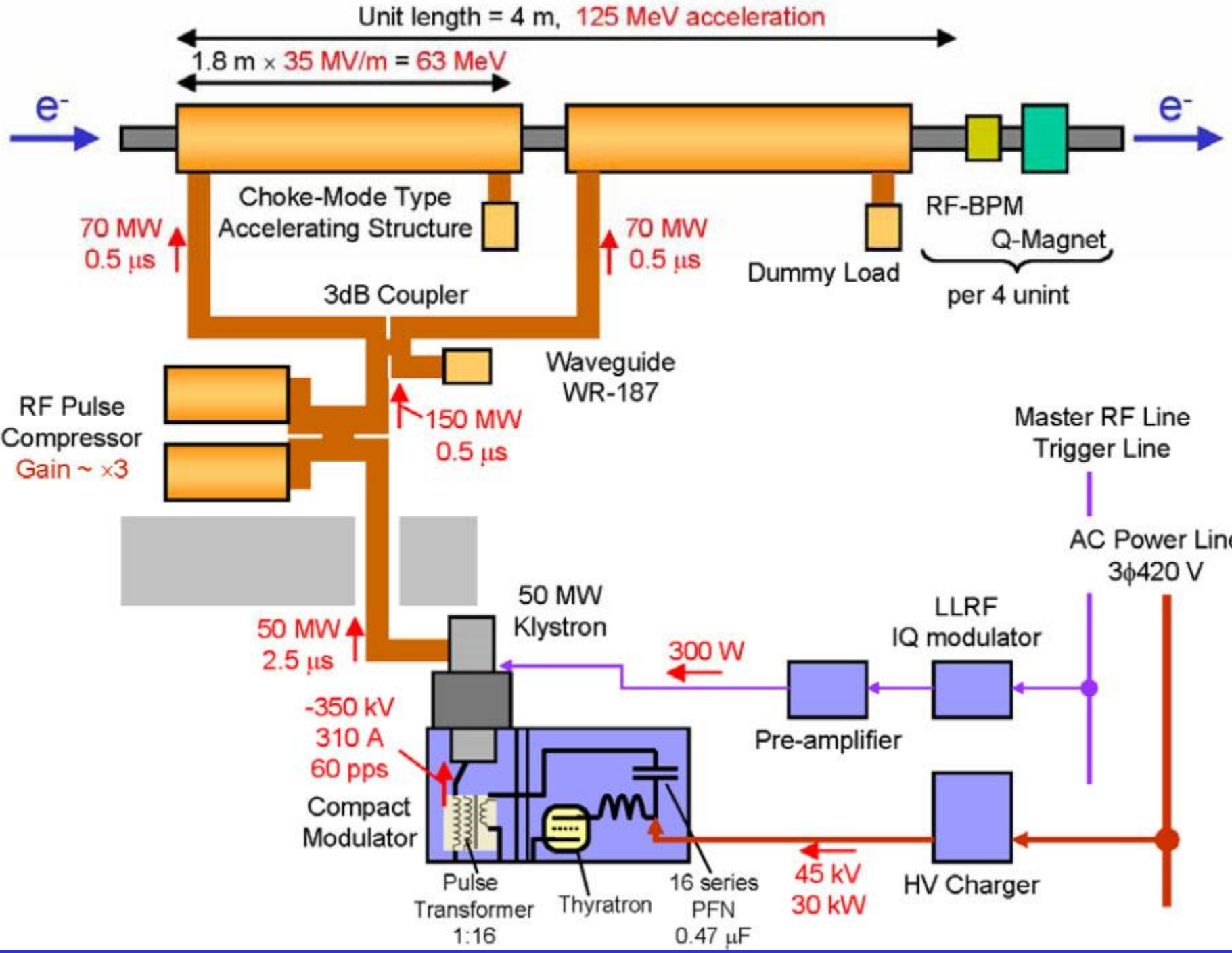

Unit length = 4 m, 125 MeV acceleration
1.8 m × 35 MV/m = 63 MeV
e⁻
e⁻
Choke-Mode Type
Accelerating Structure
70 MW
0.5 μs
70 MW
0.5 μs
3dB Coupler
Waveguide
WR-187
Dummy Load
RF-BPM
Q-Magnet
per 4 unint
RF Pulse
Compressor
Gain ~ ×3
150 MW
0.5 μs
Master RF Line
Trigger Line
AC Power Line
3ϕ420 V
50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

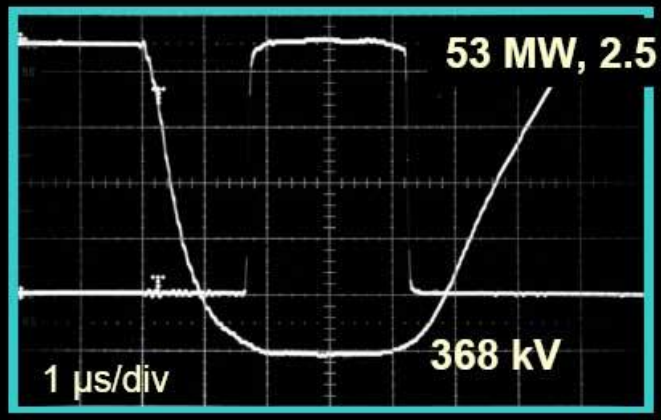
Traveling-wave output structure

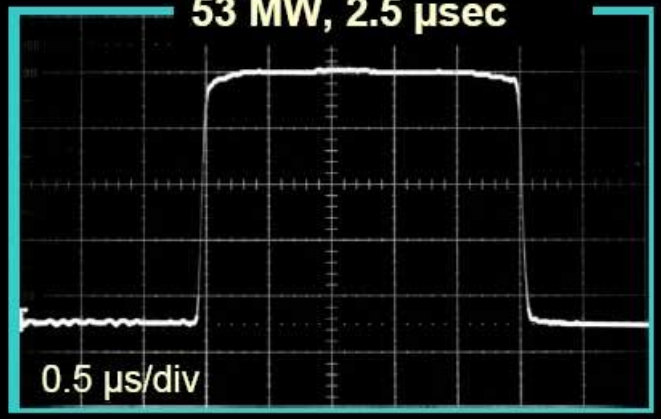
Solenoid Focus (4.6kW)

1.5 μP

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

TOSHIBA E3746 No.3





53 MW, 2.5 μsec, 50 pps, 47%

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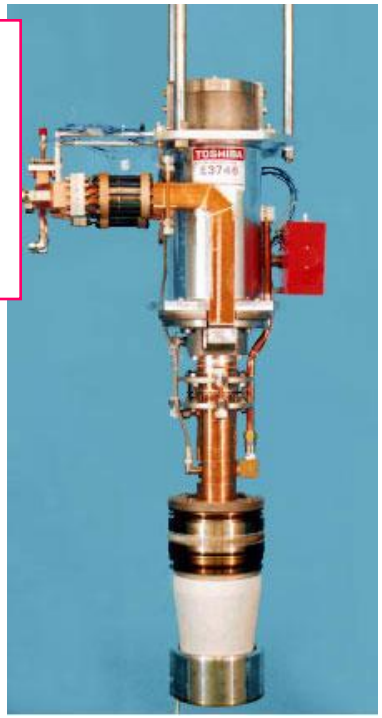
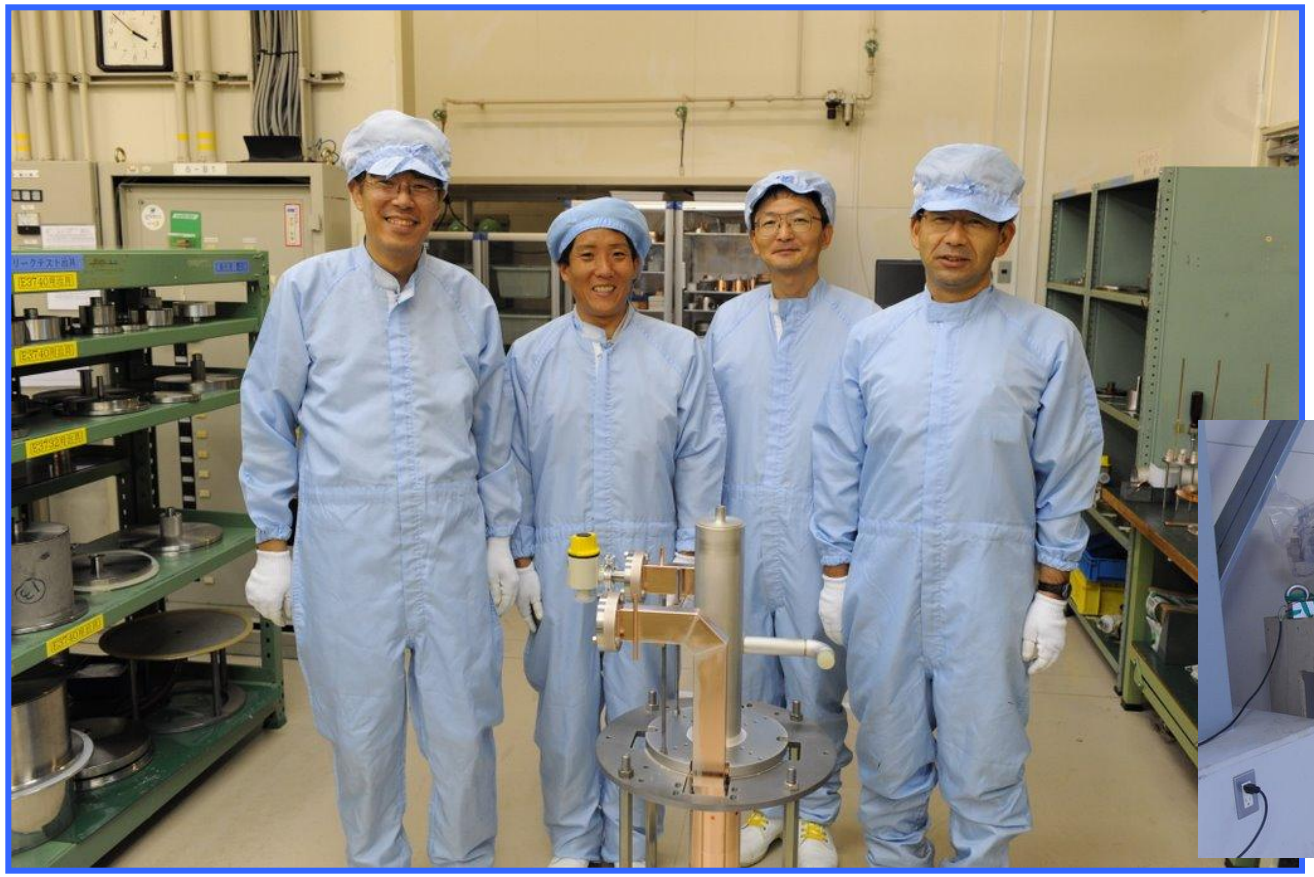
Mass Production of Klystrons at TOSHIBA

- 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





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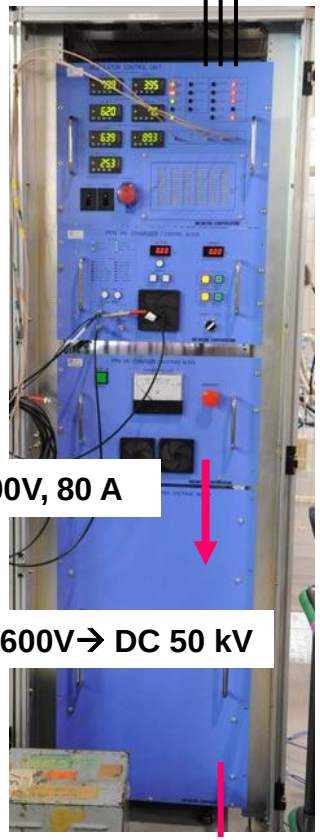
C-band System Configuration

400 V, 3ϕ



600V, 80 A

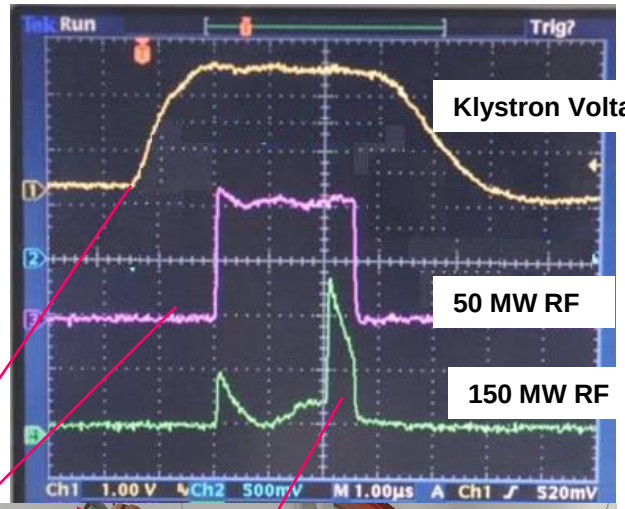
DC 600V→ DC 50 kV

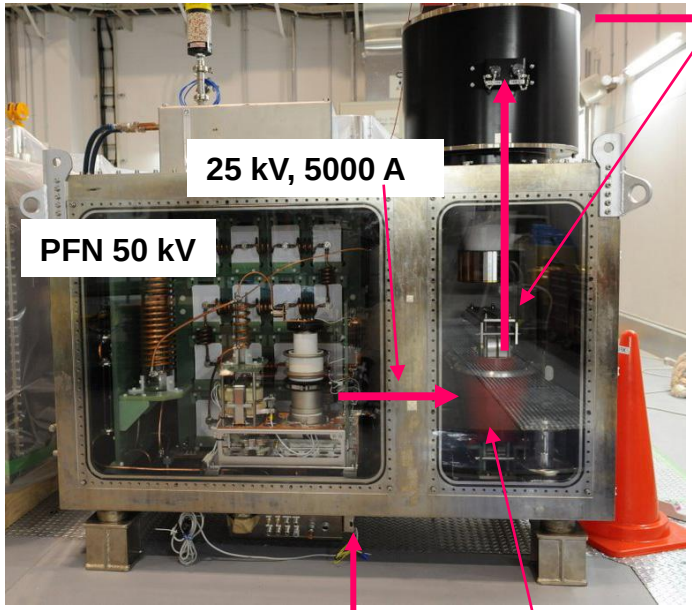
Highly stable
PFN charger
< 100 PPMp-p

Klystron Modulator

C-band
Klystron

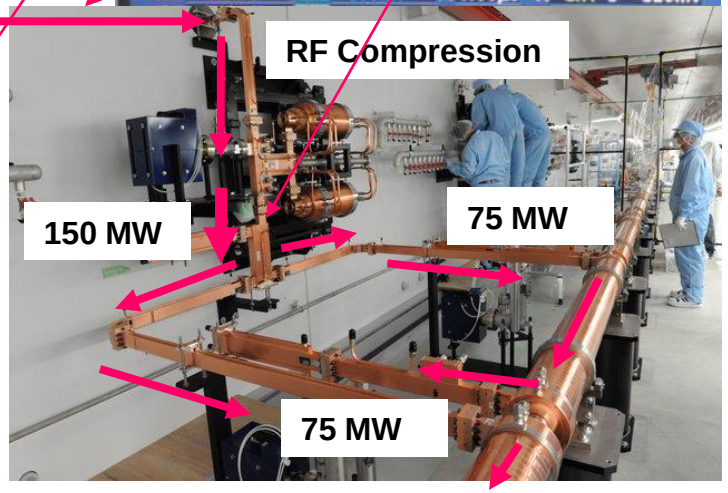
50 MW, 3 usec
RF 5712MHz





50 kV, 1 A

25 kV→ 350 kV



C-band Accelerator
35 MV/m

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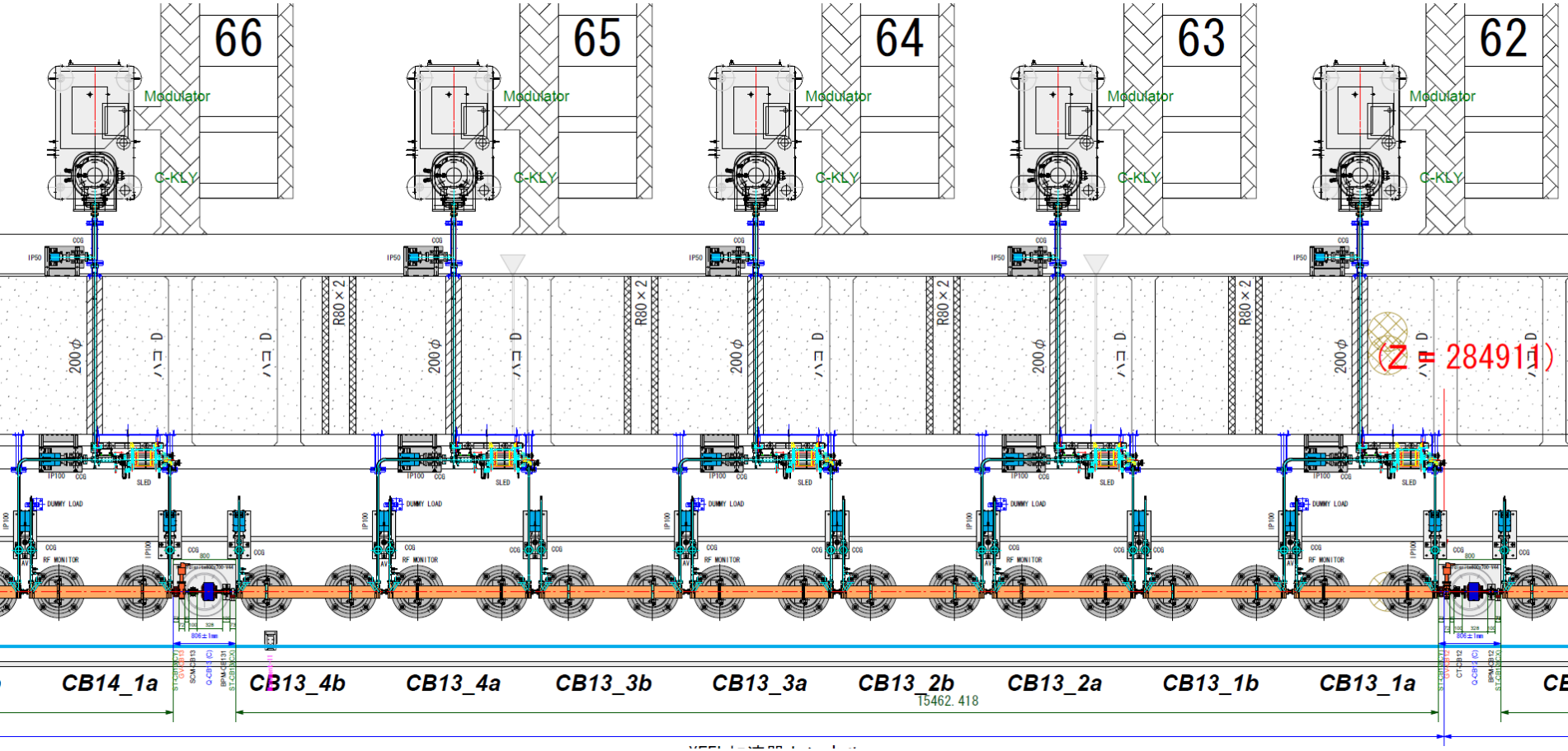
C-band is High Gradient (35 MV/m, max 40 MV/m)

- **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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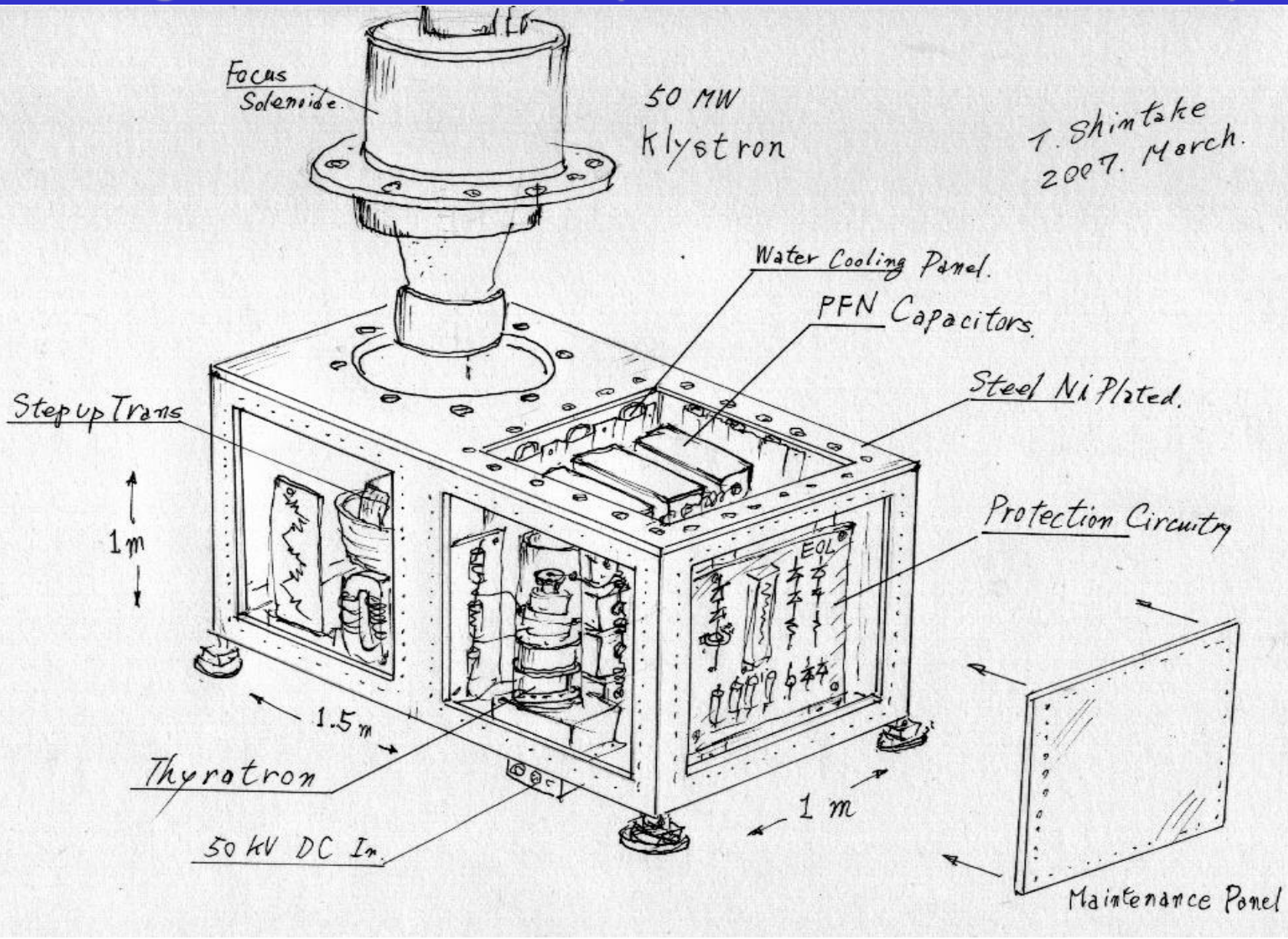
Single Tank Modulator (PFN circuit + Transformer)



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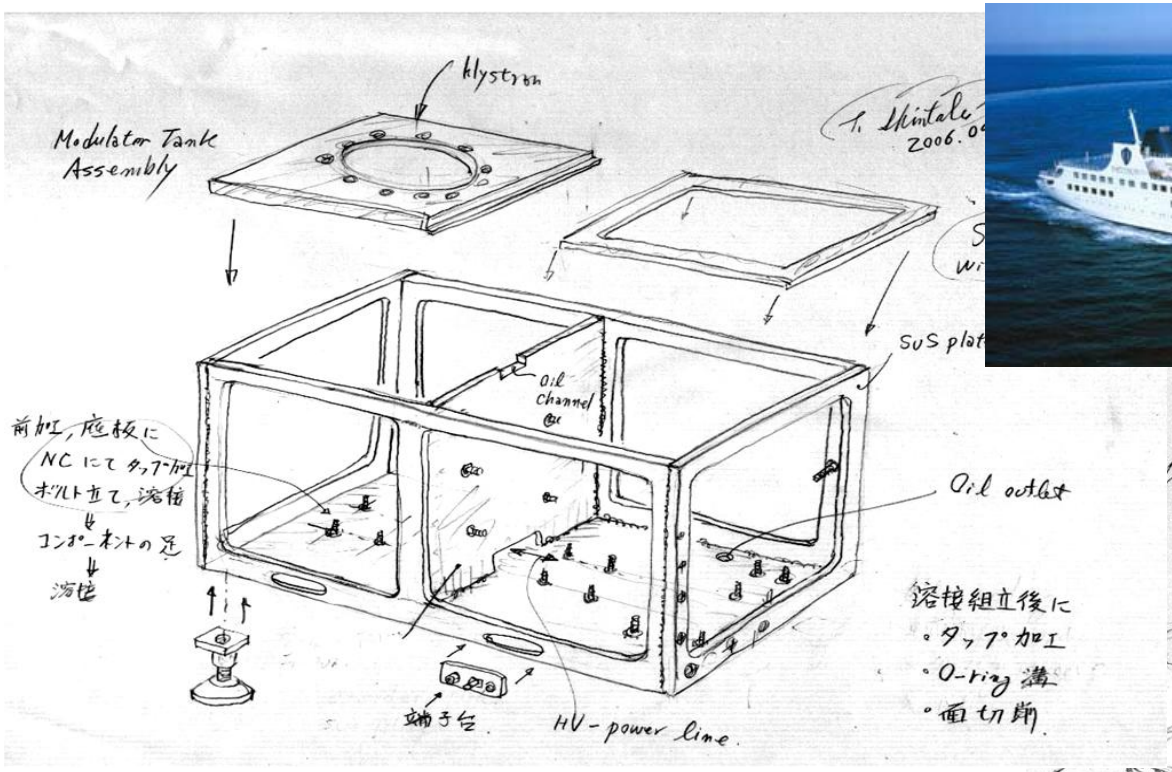
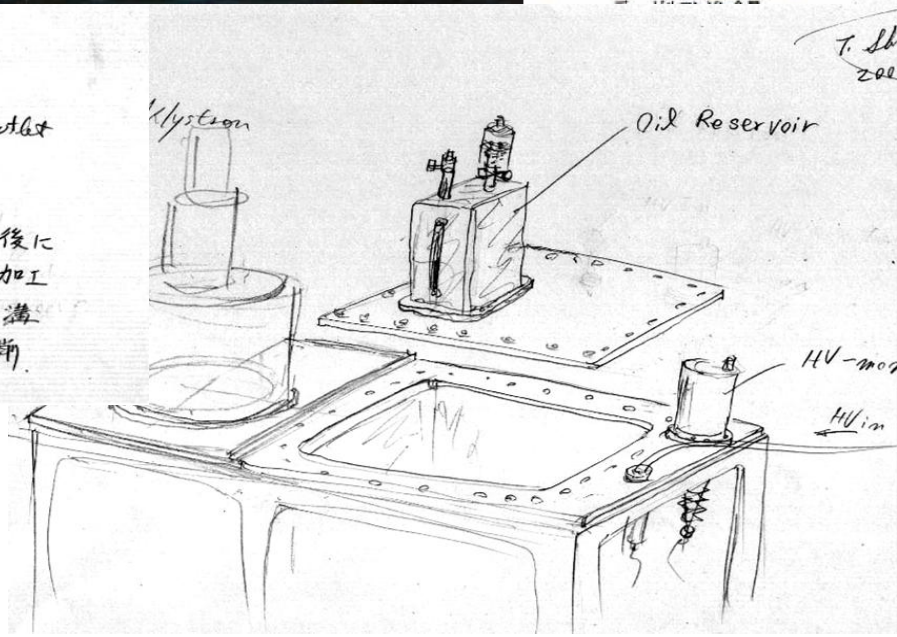
At the R&D, Ship Engine Make at AIOI contributed.

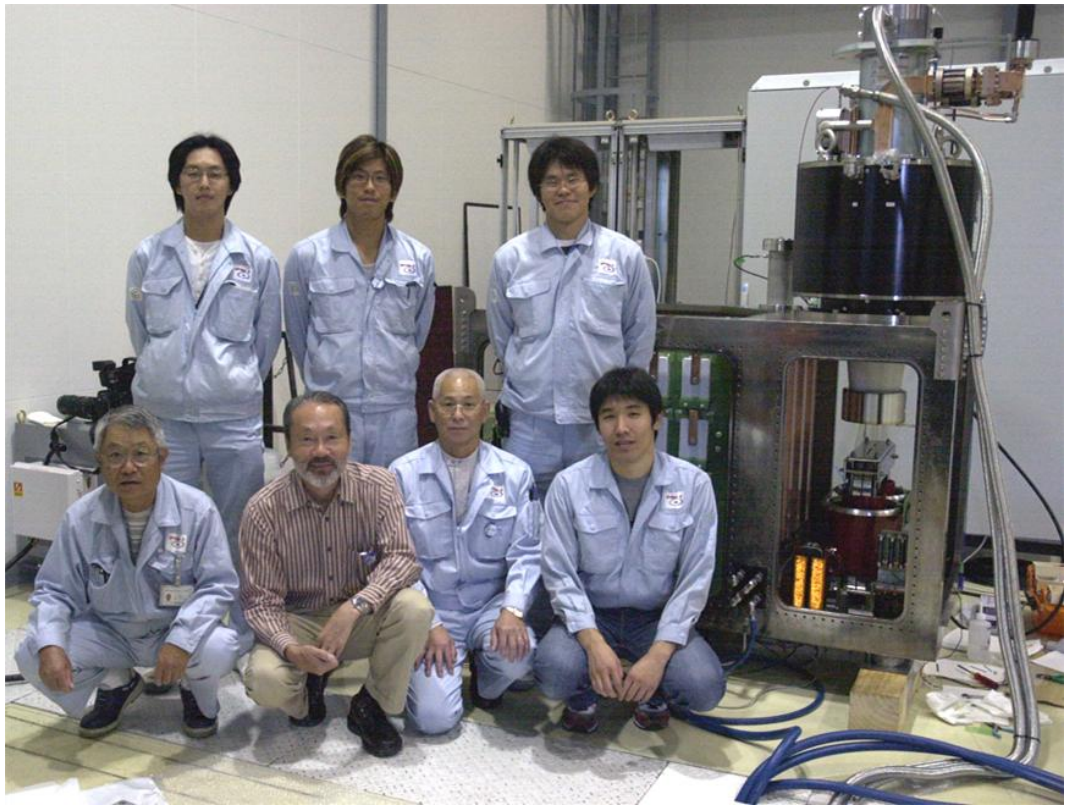




Made by steel (easier than SUS)
Suitable for mass-production.

Compact Modulator for 50 MW Klystrons

- Compact 1 m x 1.2 m x 1.7 m,
- Very low noise
  (<10 Vpp on 200 V heater line)
- Water cooled. Max surface temp 45 deg
  at max-operation.



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Modulator Mass Production at NICHICON

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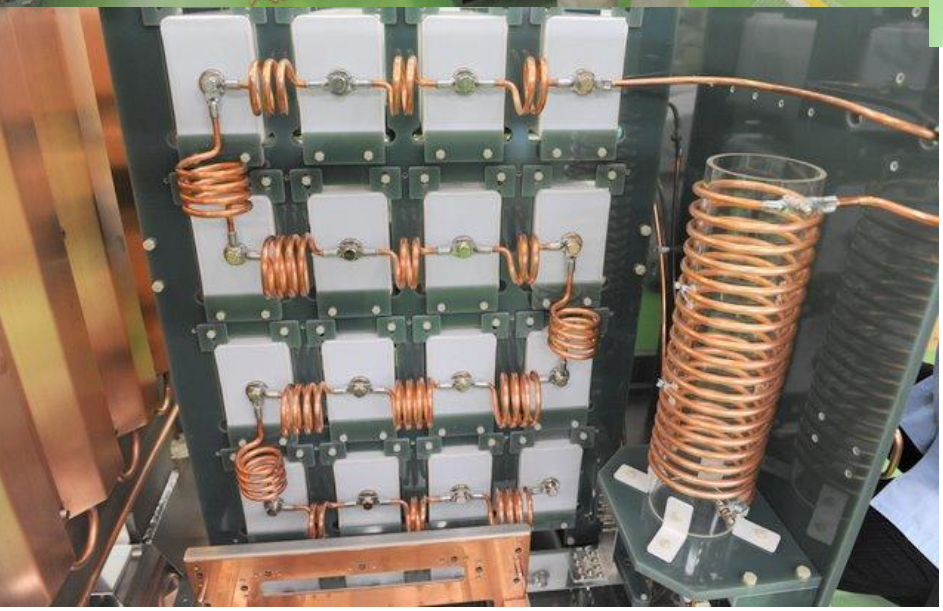
Modulator Tank Fabrication



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Modulators are Arriving to XFEL/SPring-8

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All modulator are tested at high power at 50 kV, 60 pps, 8 hour before installation.

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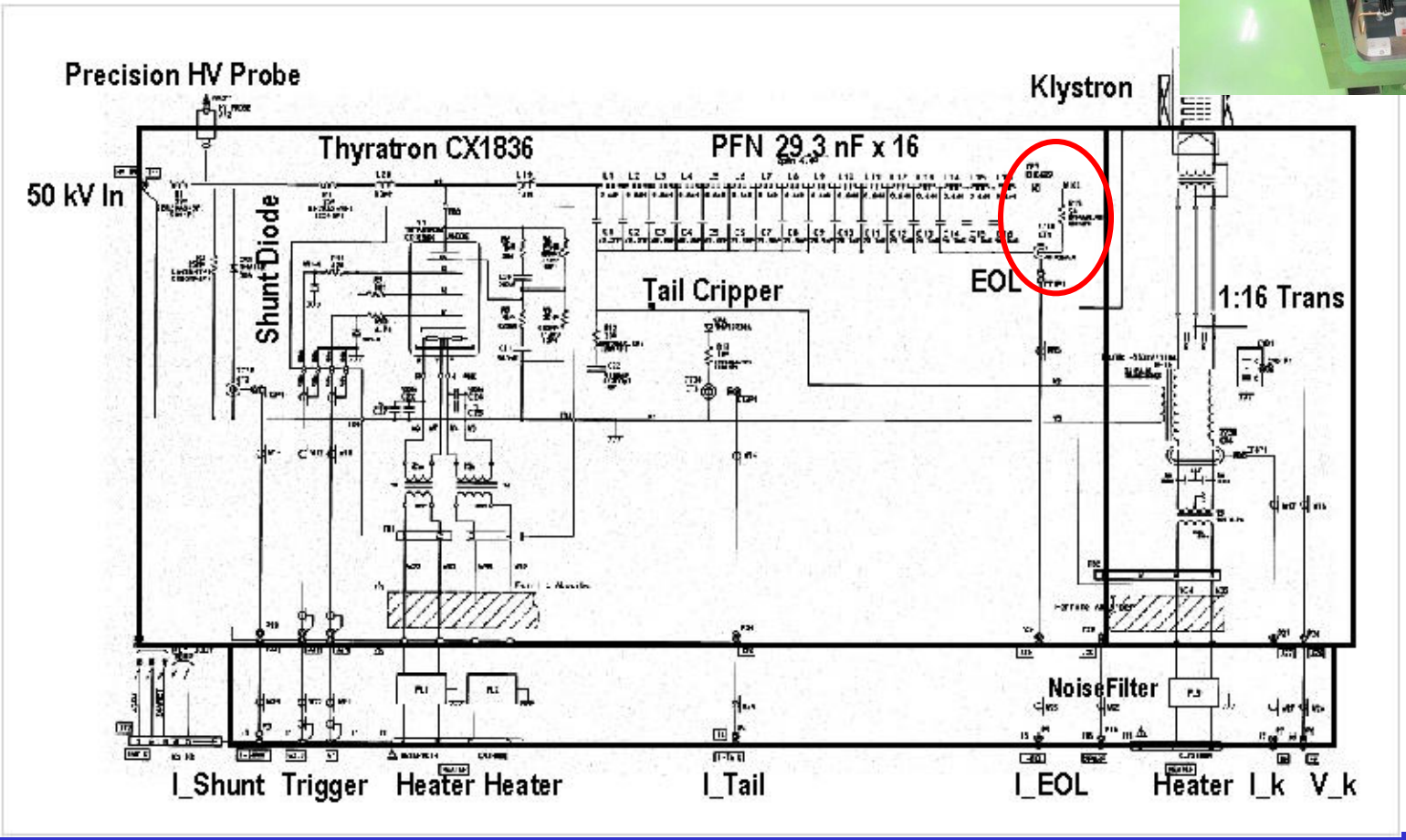
EOL Diode Failure Problem

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



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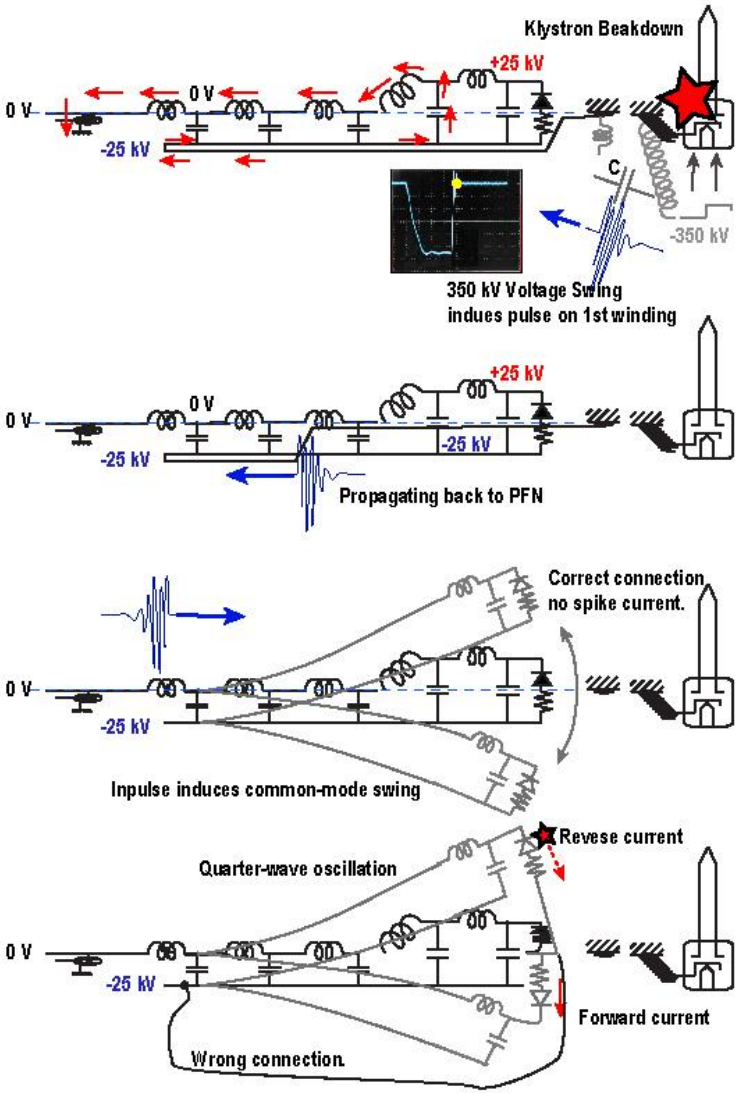
Cause was wrong connection of ground line.



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

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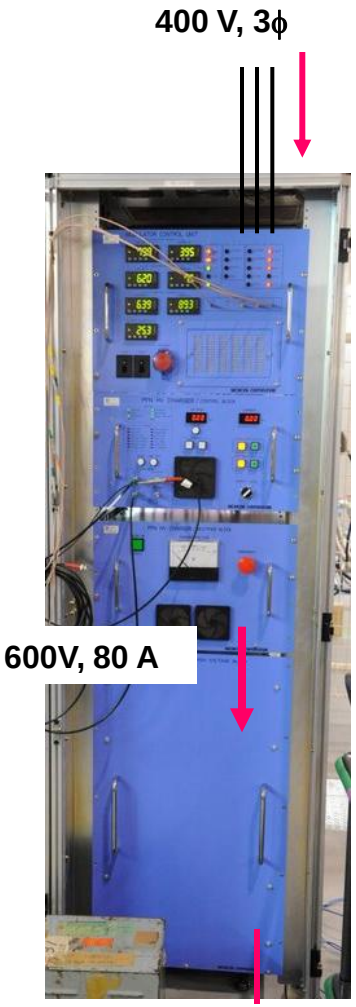
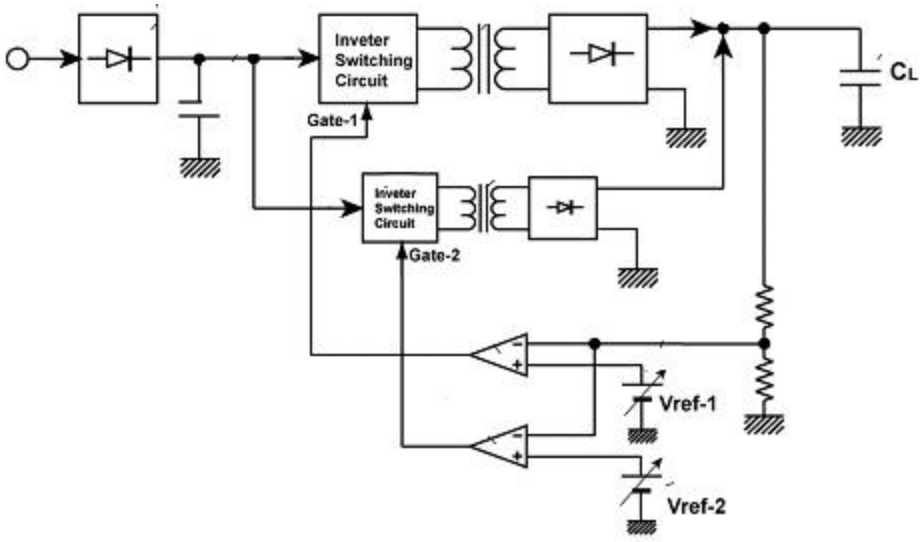
Highly Stable Inverter Type PFN Charger for stable operation of XFEL.



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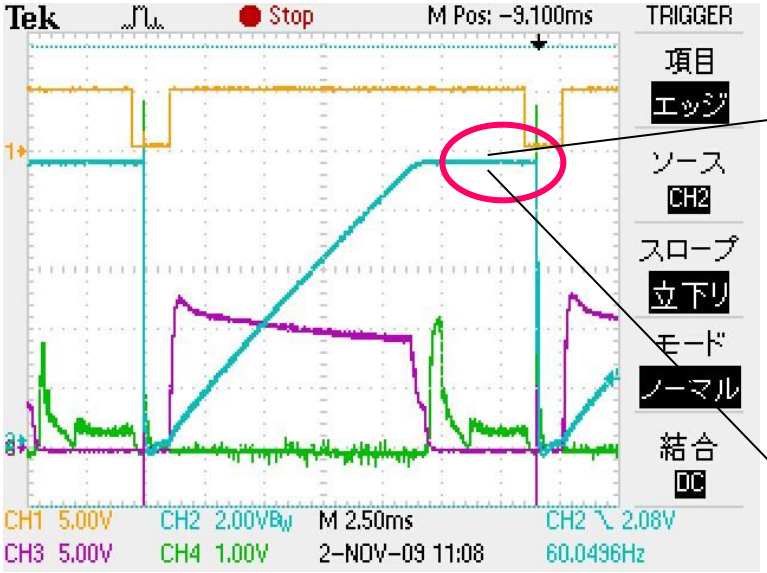
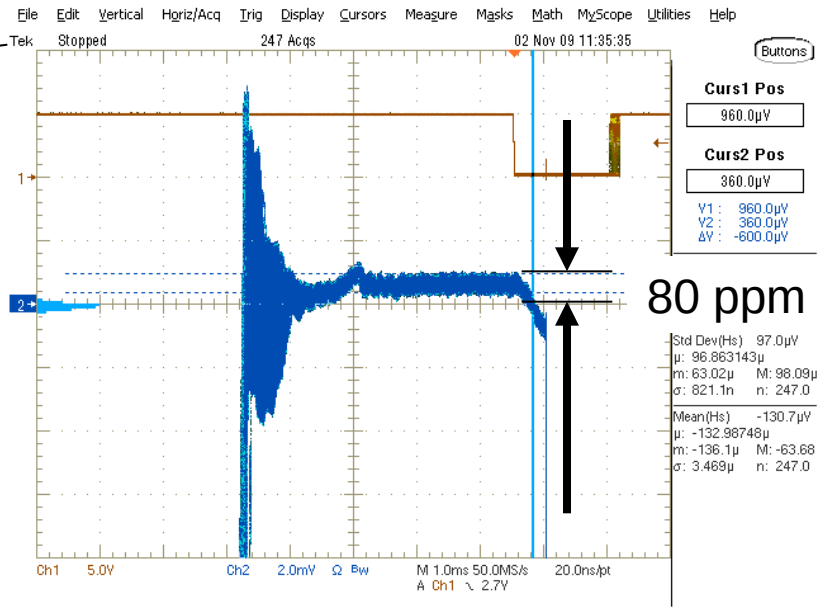
When voltage approaches to target, sub-inverter controls the voltage in fine mode.





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

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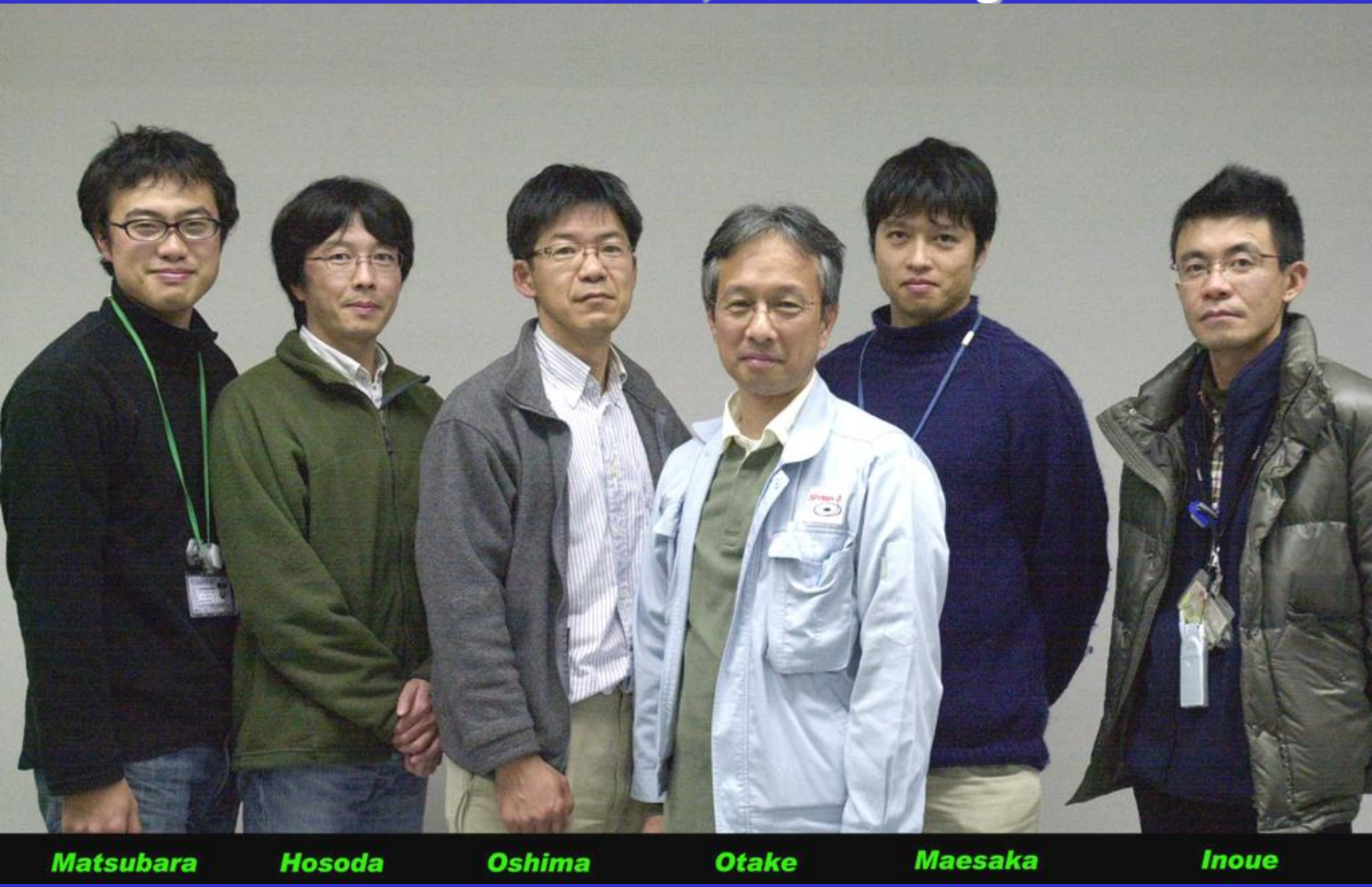
Otake's Team: LLRF, Beam Diagnostics



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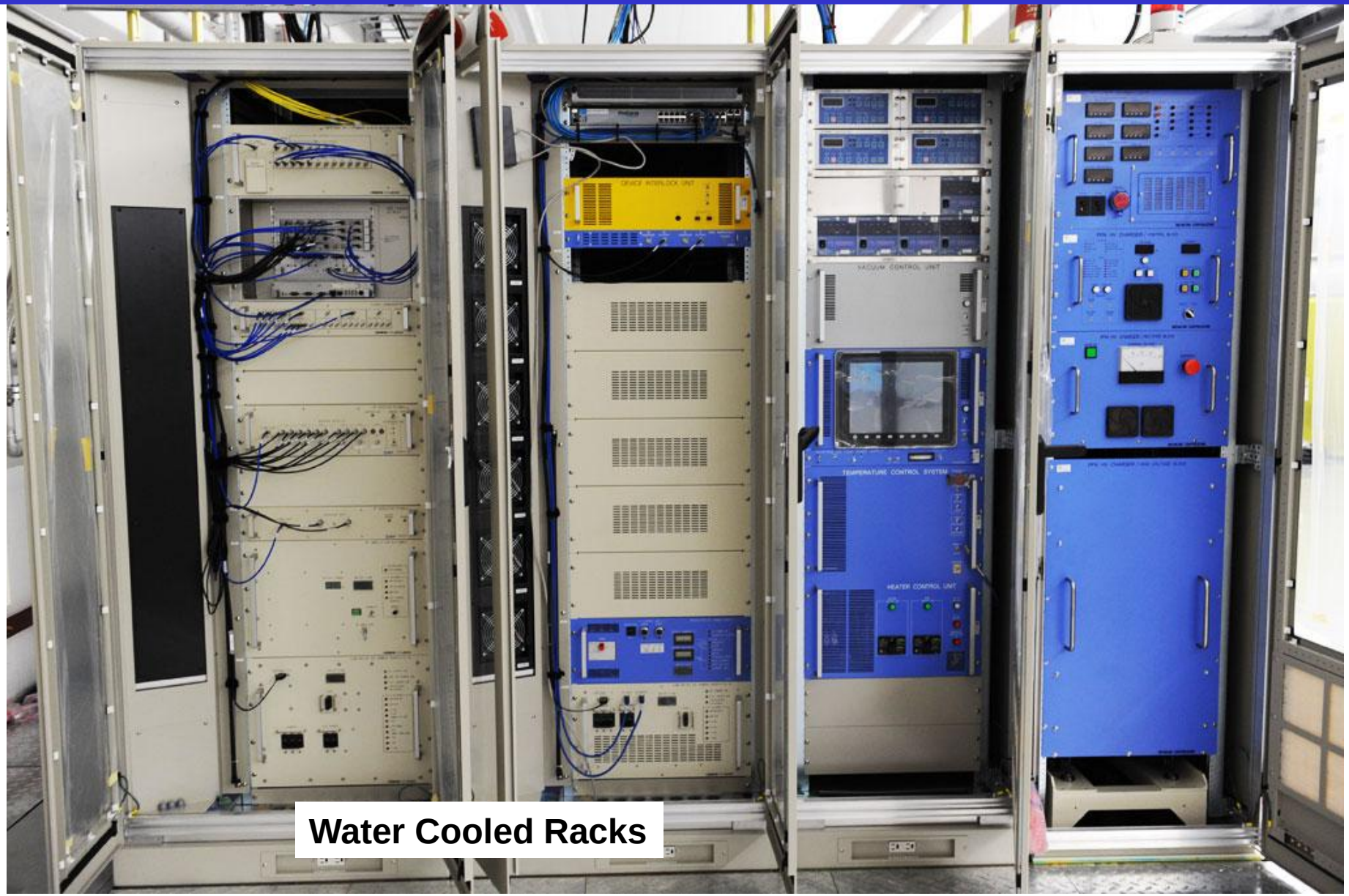
MADOCA Controls, LLRF, Temp Feedback, PFN Charger



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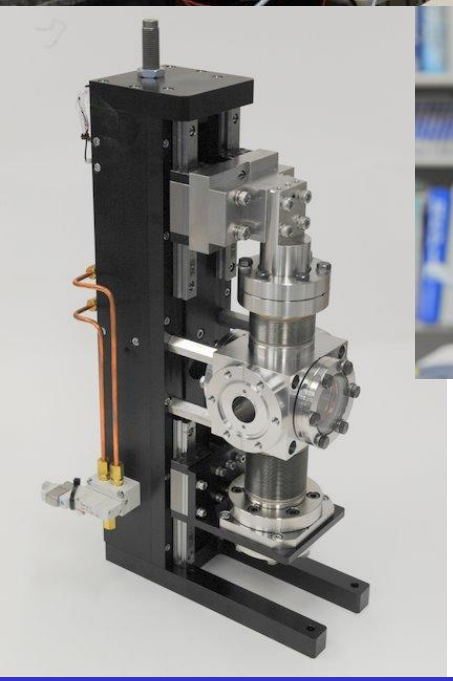
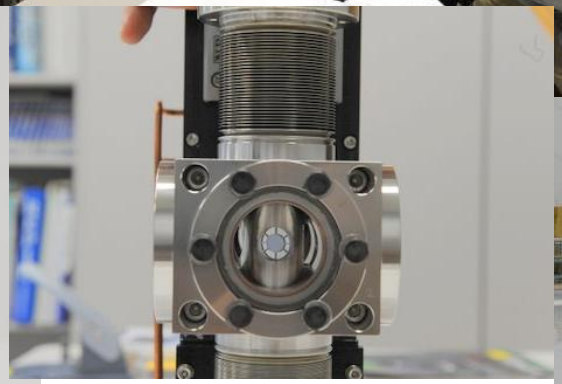
Beam Monitor Devices

By Y. Otake team.

BPM Calibration

Cavity BPMs
0.2 μm resolution was confirmed with beam





OTR Screen Monitor

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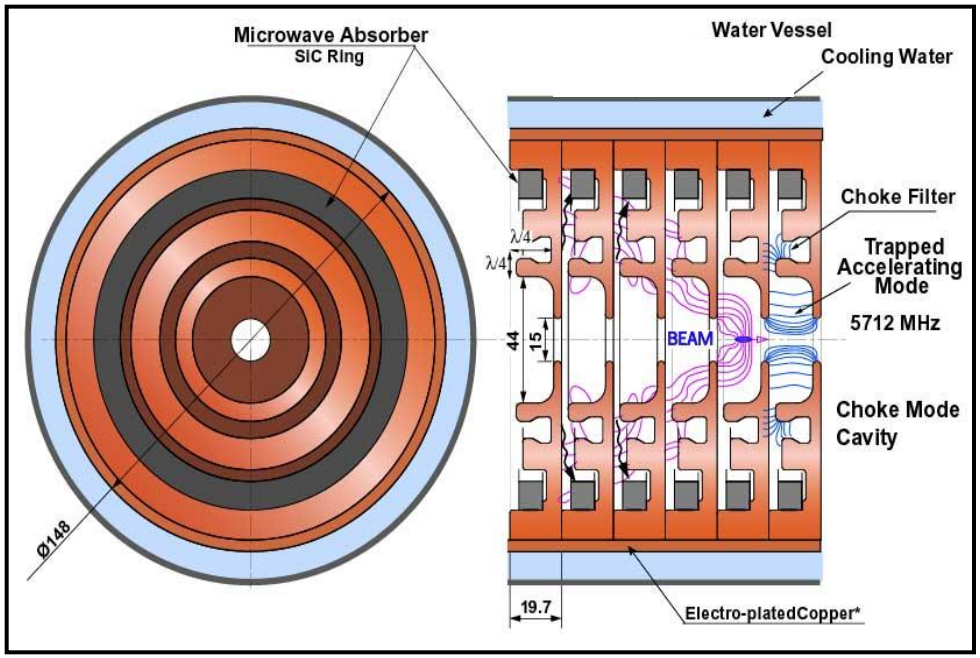
C-band Accelerator for Multi-bunch Option



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

13,000 cells are under mass production.

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.

HITACHI Cable Co. completed mass production of C-band cell. June 2009

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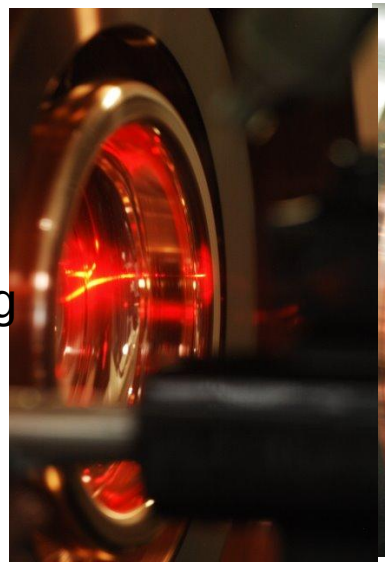
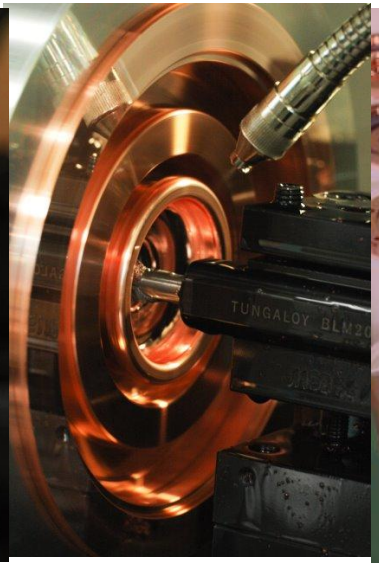
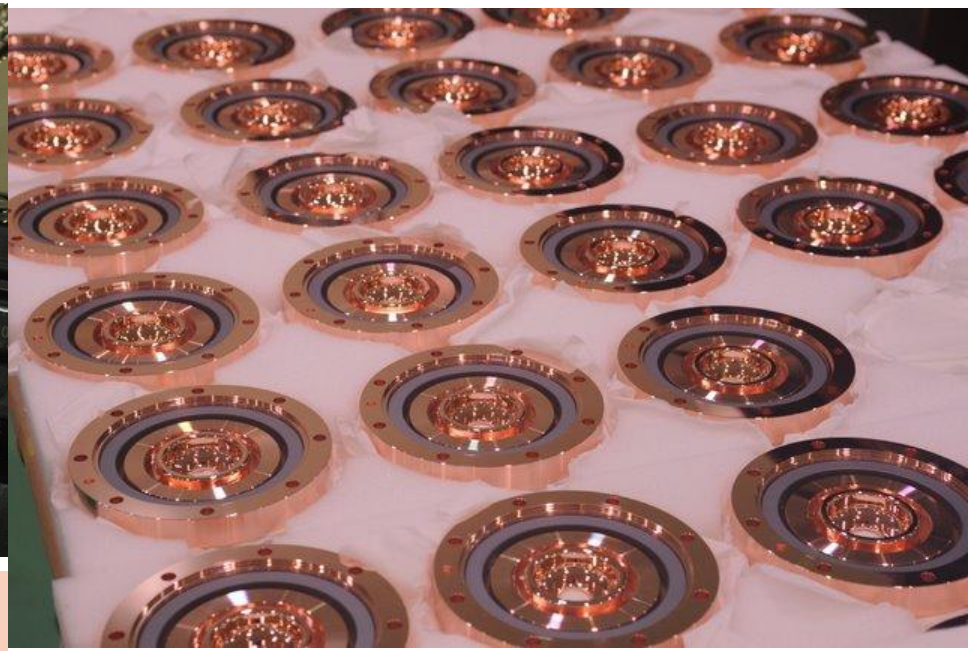
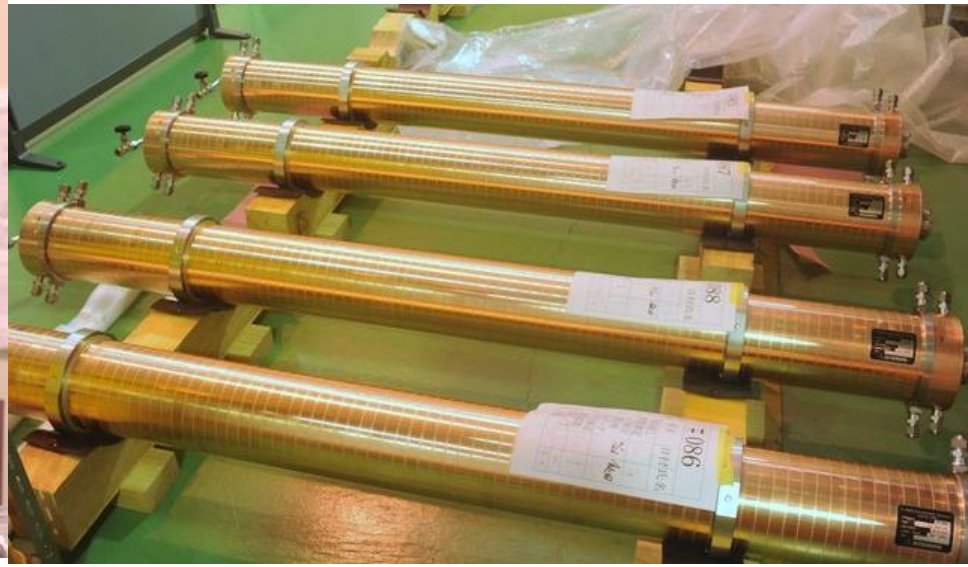
Mass Production of C-band Accelerator at MITSUBISHI Heavy Ind. 2007 ~ 2009

Laser
Guided
Precision
Machining









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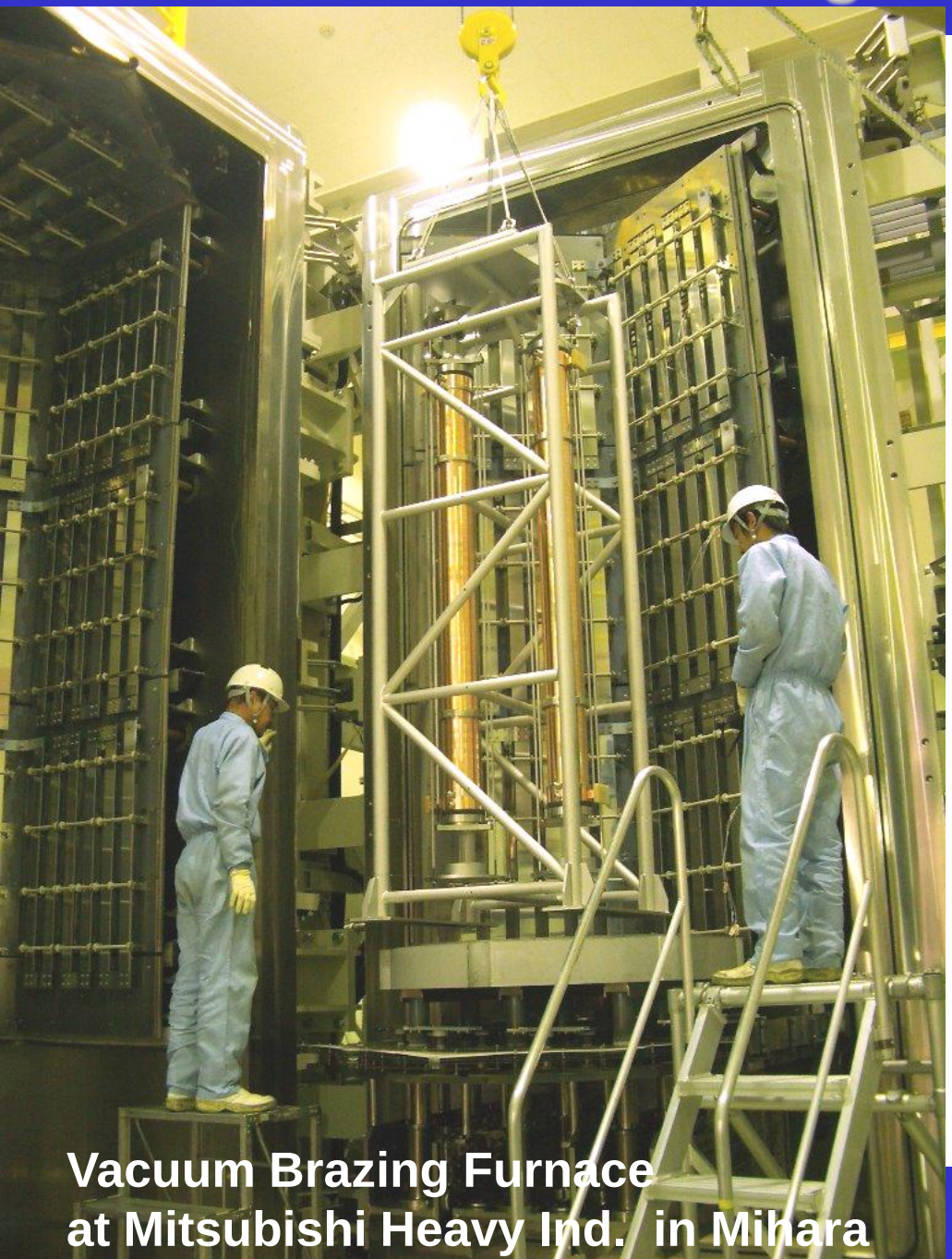
Brazing of C-band Accelerators



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

Tsumoru Shintake
shintake@spring8.or.jp

Routinely Operation: C-band High Gradient Test

T. Sakurai, IPAC2010

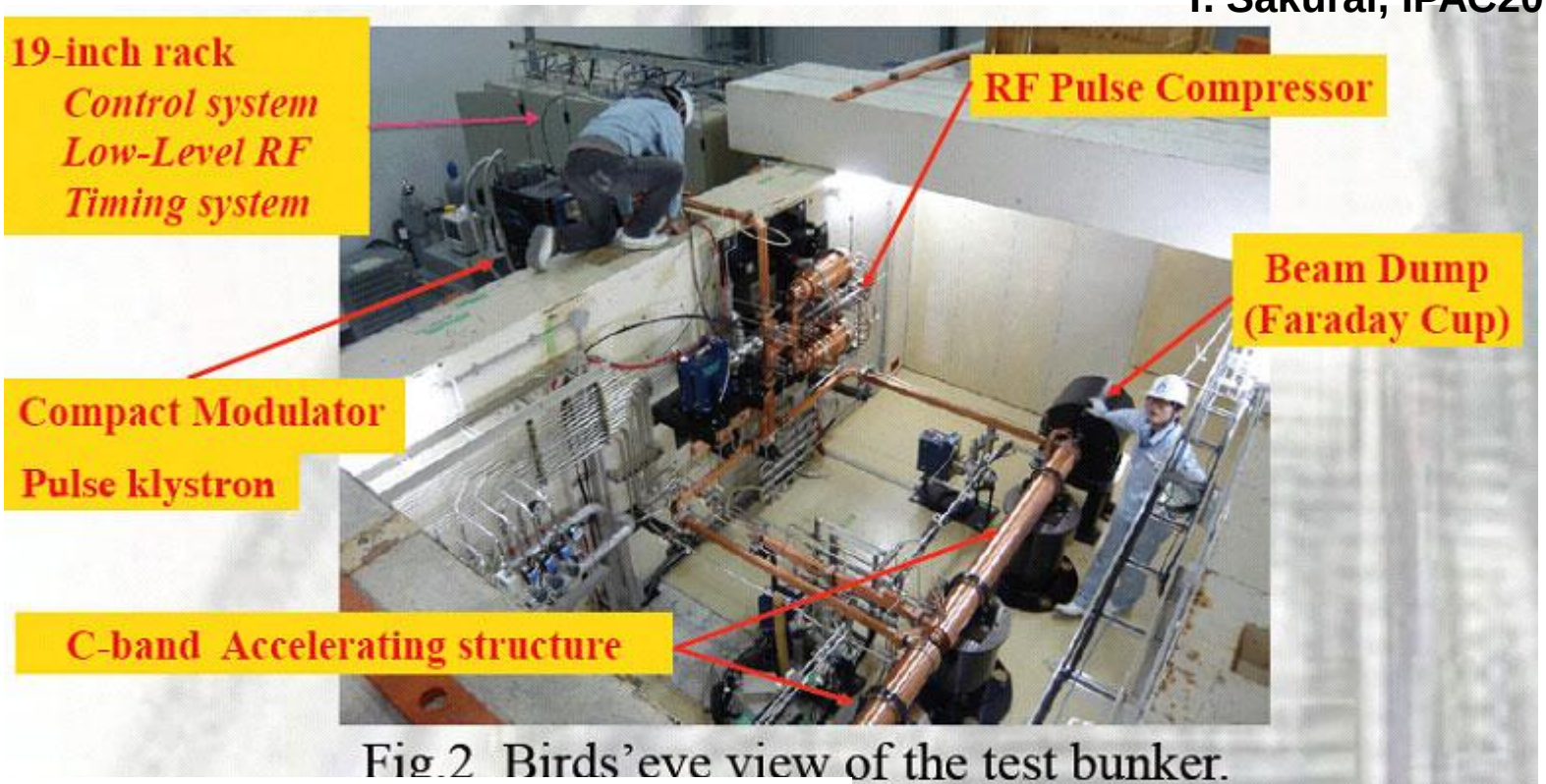

Fig.2 Birds'eye view of the test bunker.

- 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

Tsumoru Shintake
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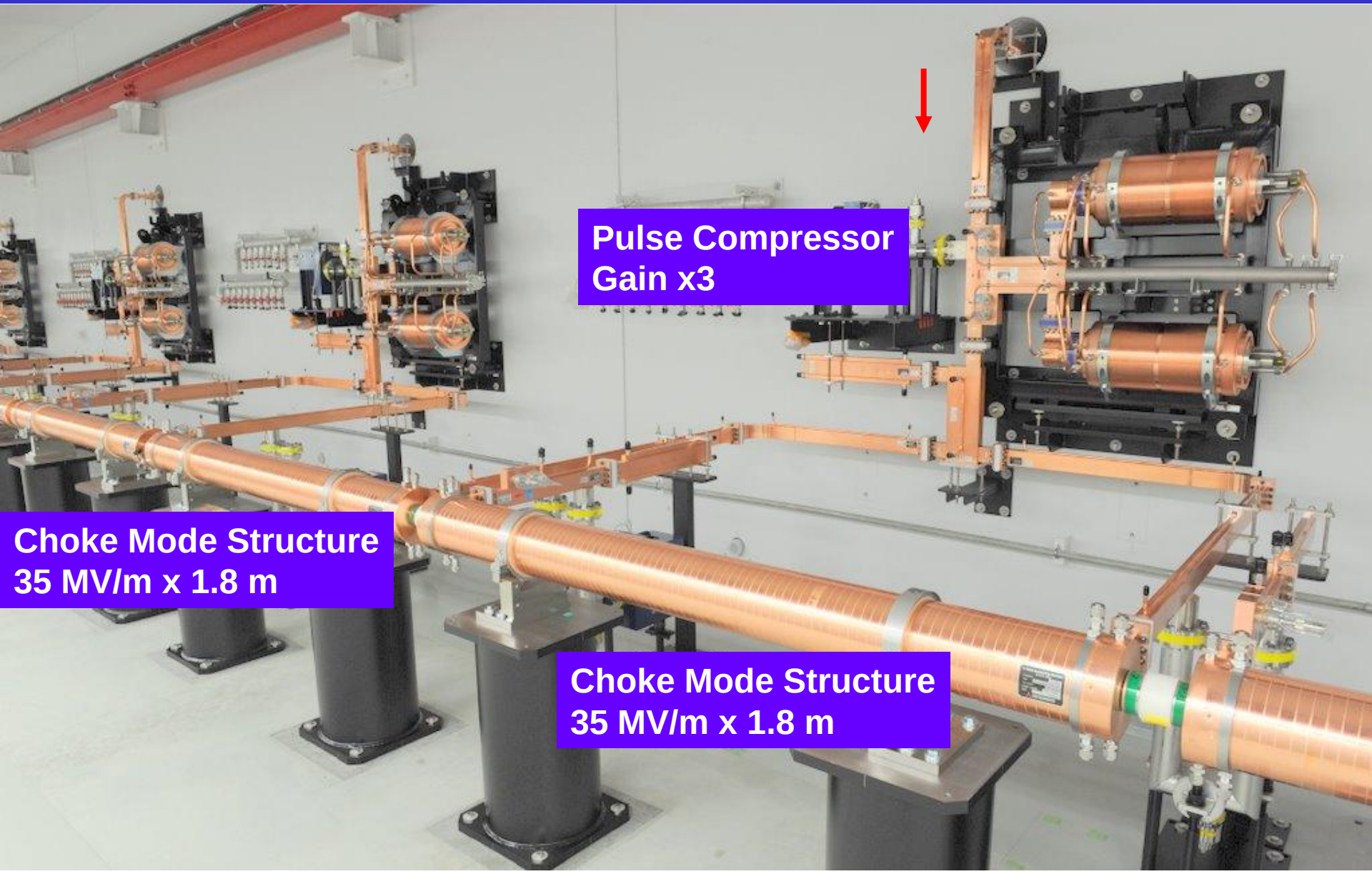
C-band Accelerator



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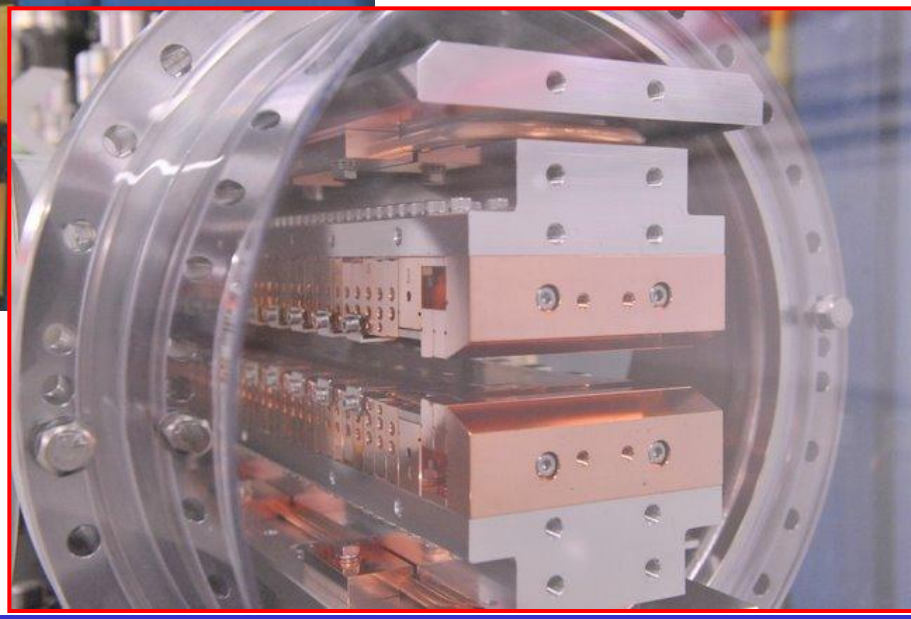
In Vacuum Undulator



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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

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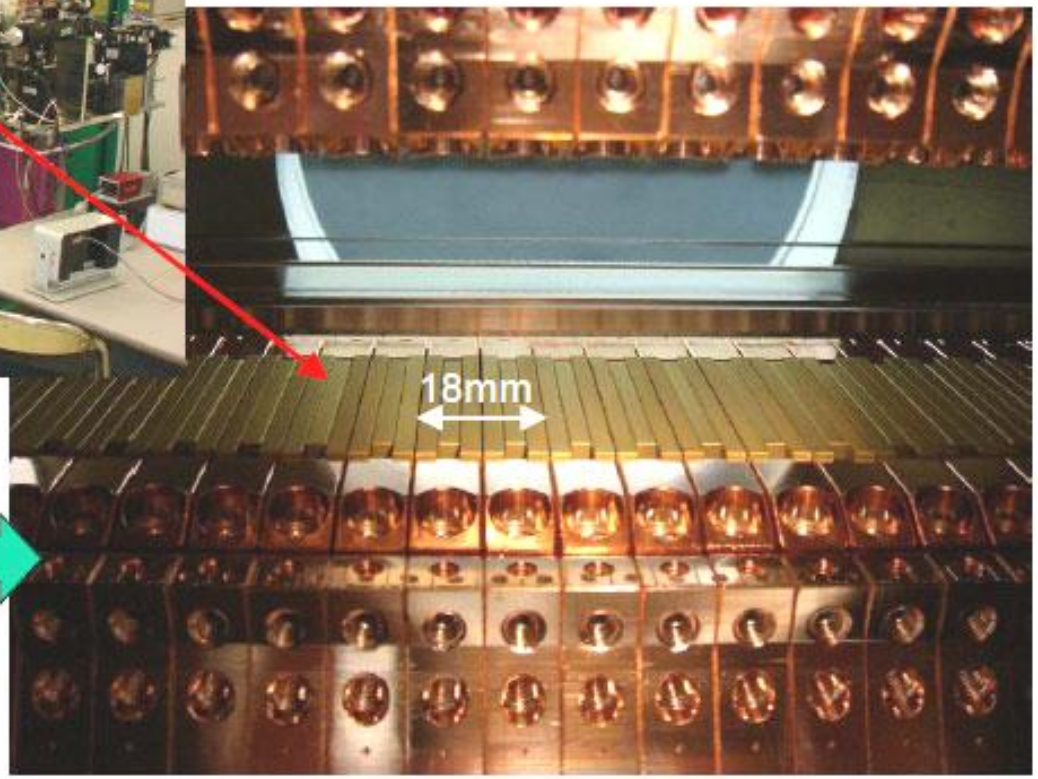
Undulator for XFEL/SPring-8

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

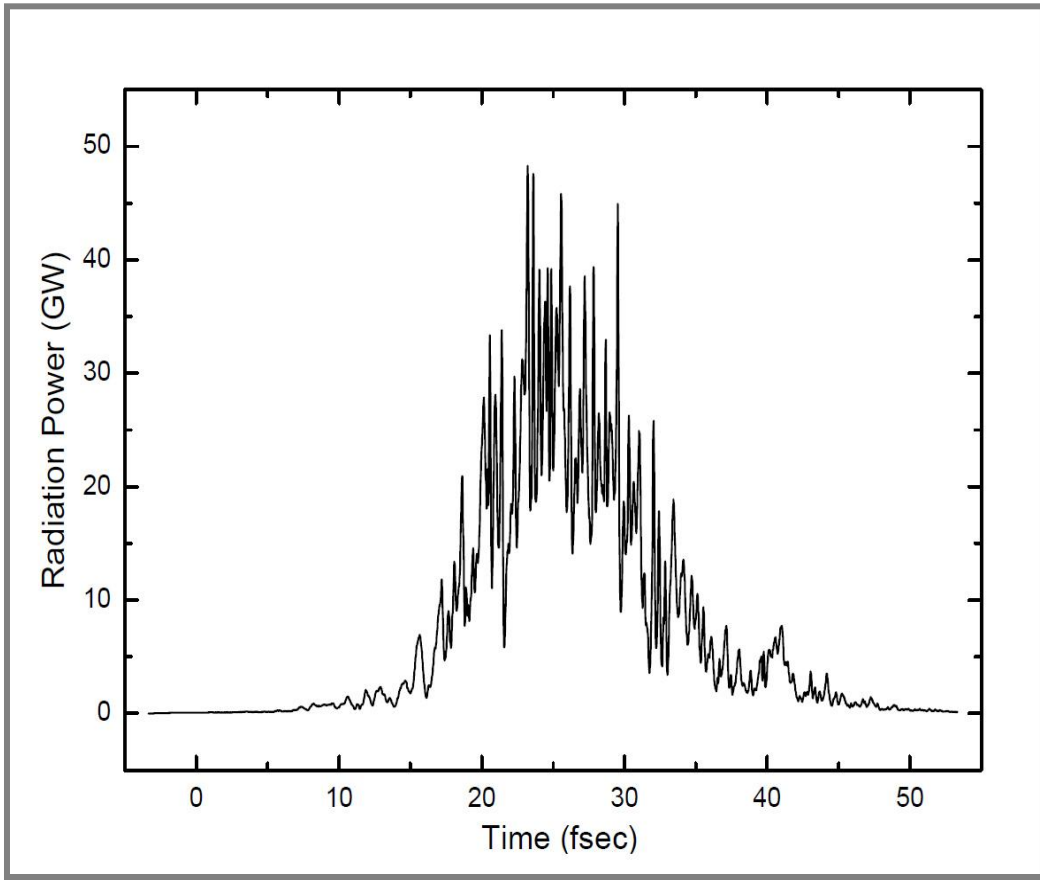
Outlook of 5 m long in-vacuum undulator for X-ray FEL.



NeFeB magnet array, undulator period is 18 mm.

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)

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?

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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.

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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.

Installed Modulator in XFEL Klystron Gallery

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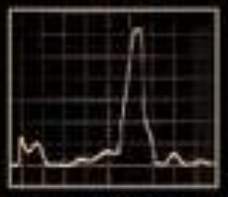
C-band R&D Summary @ 2000

C-band Klystron	Klystron Modulator	RF Pulse Compressor	Accelerating Structure
50 MW, OK 2.5 sec, 47 %	110 MW OK 100 pps	Flat Pulse Gain 3.3	1.8 m OK Choke-Mode
Life test >5000 hour, OK.	Smart modulator using inverter HV charger. Running for klystron life test.	Three-cell cavity.	Beam acceleration at 50 MV/m was done at ATF-KEK, with S-band model. HOM damping performance was proved by ASSET-SLAC test, 1998.



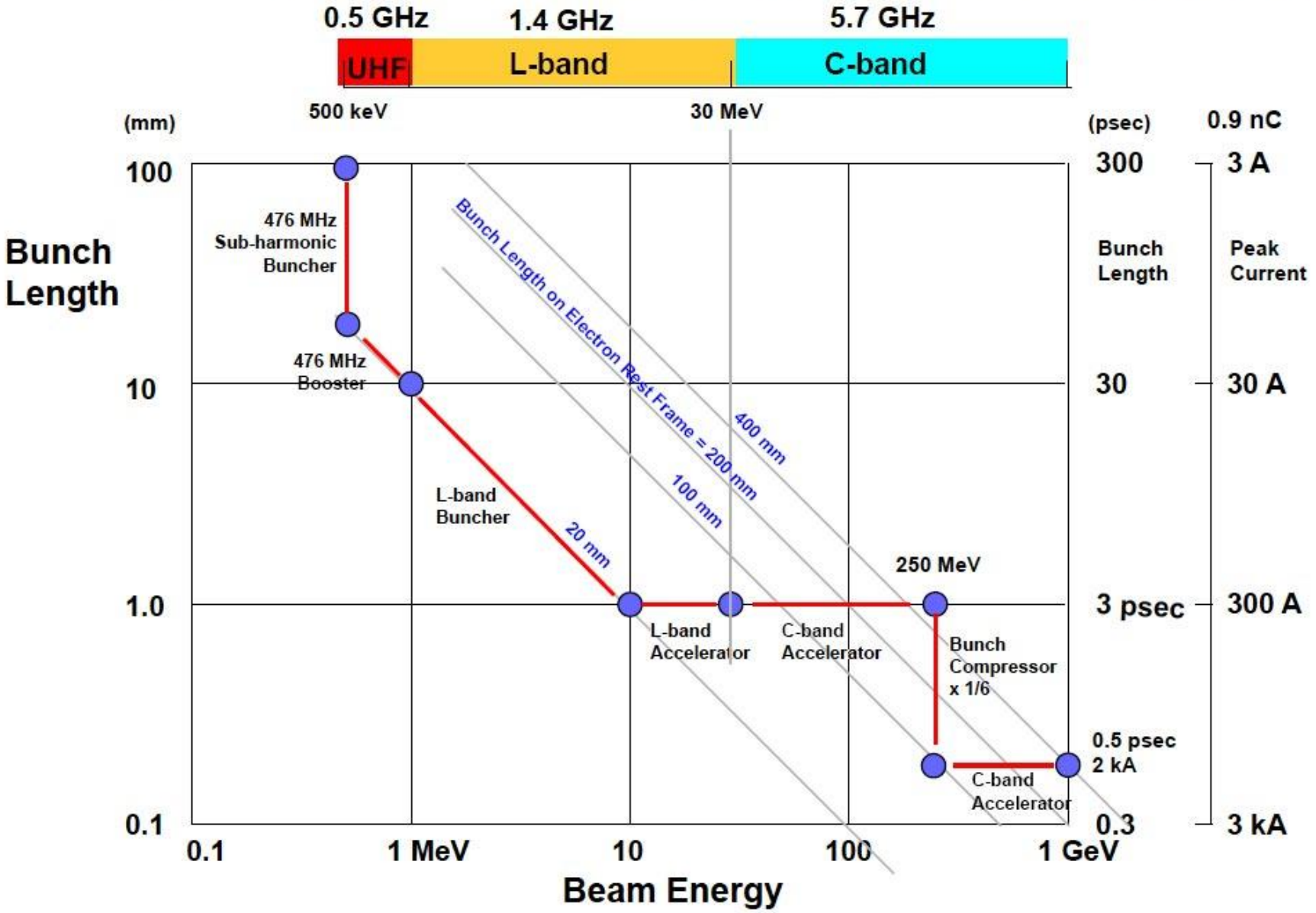
m long cold model.

ed High
wer Test

Contribution to XFEL Construction

Bunch Compression after the Gun

Maintain bunch-length on the electron rest-fram being constant.



Mitsubishi Heavy Ind. made Accelerating Tubes

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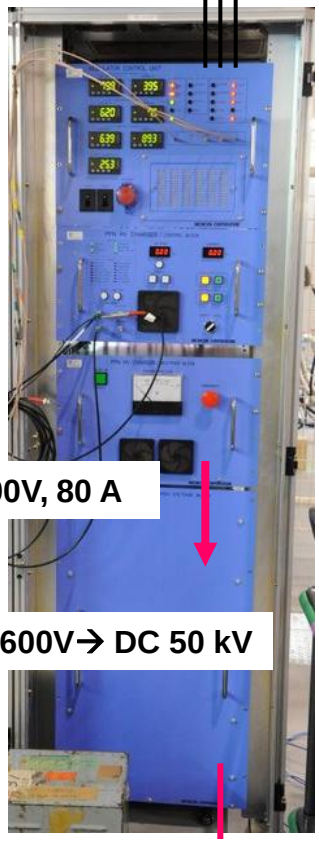
C-band System Configuration

400 V, 3ϕ



600V, 80 A

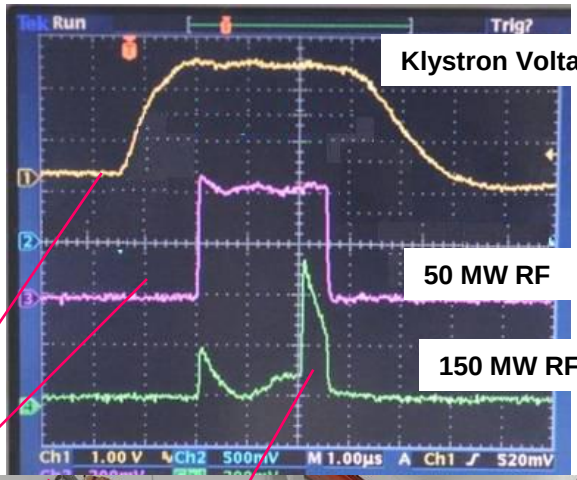
DC 600V→ DC 50 kV

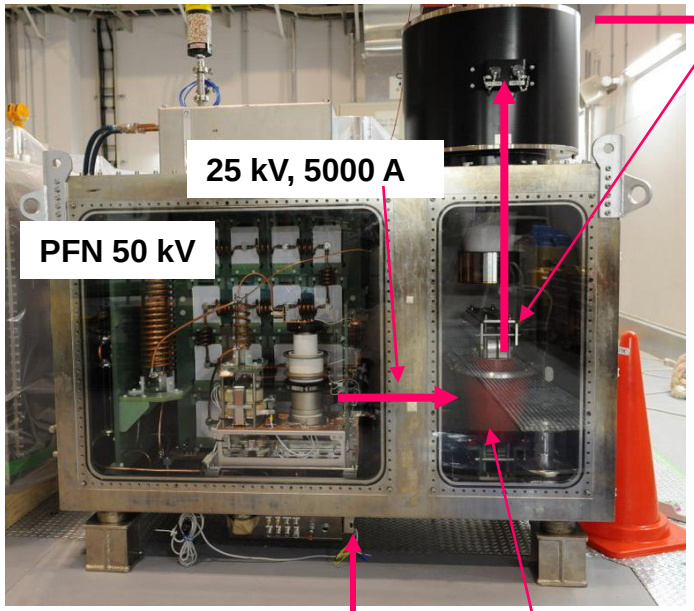
Highly stable
PFN charger
< 100 PPMp-p

Klystron Modulator

C-band
Klystron

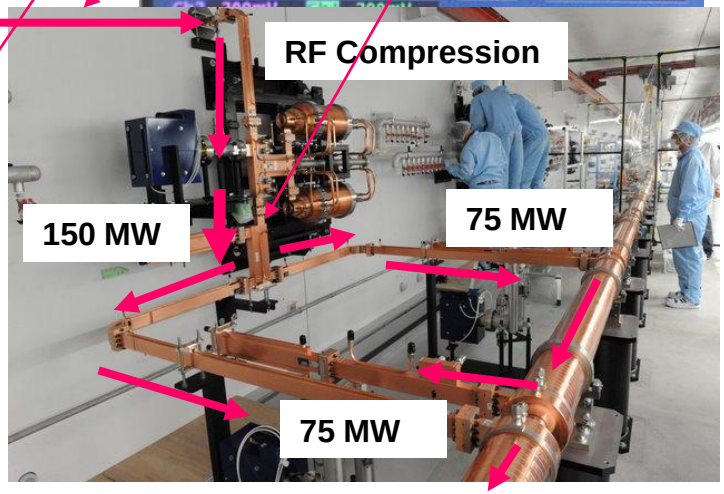
50 MW, 3 usec
RF 5712MHz





50 kV, 1 A

25 kV→ 350 kV



C-band Accelerator
35 MV/m

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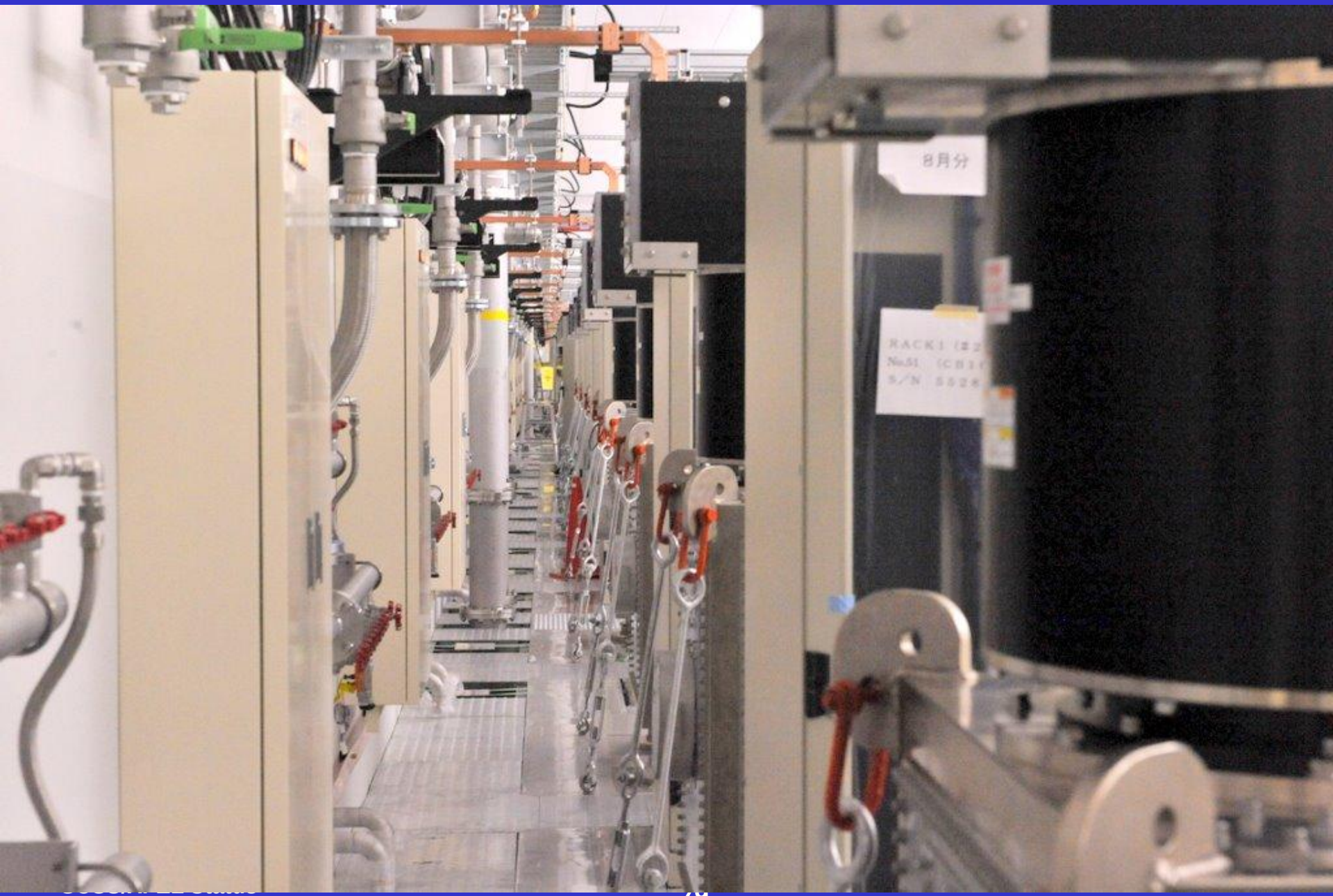
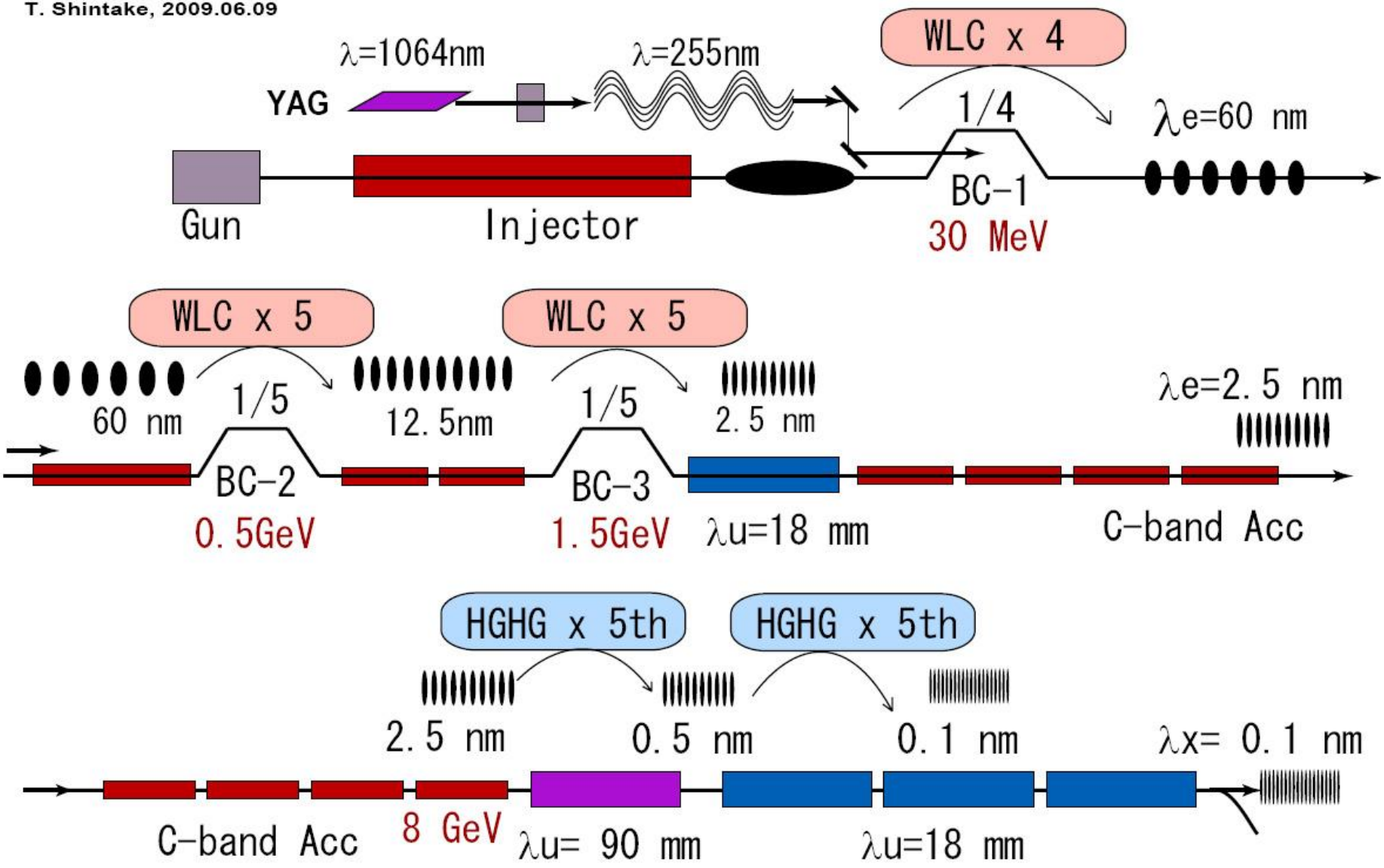
Installed modulator in the klystron gallery, WG connections.



Seeded FEL at X-ray Wavelength

T. Shintake, 2009.06.09



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C-band R&D Team at KEK (1996~2000)

Remained Troubles

- Feb. 2010: We found some of film capacitors were breakdown in February this year. Resonant charging circuit uses 200 pieces of 1.5 kV, 1 uF capacitor. Case is identified to be a side effect due to vacuum oil sintering process of HV circuit and un-balanced voltage distributions in series connection

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