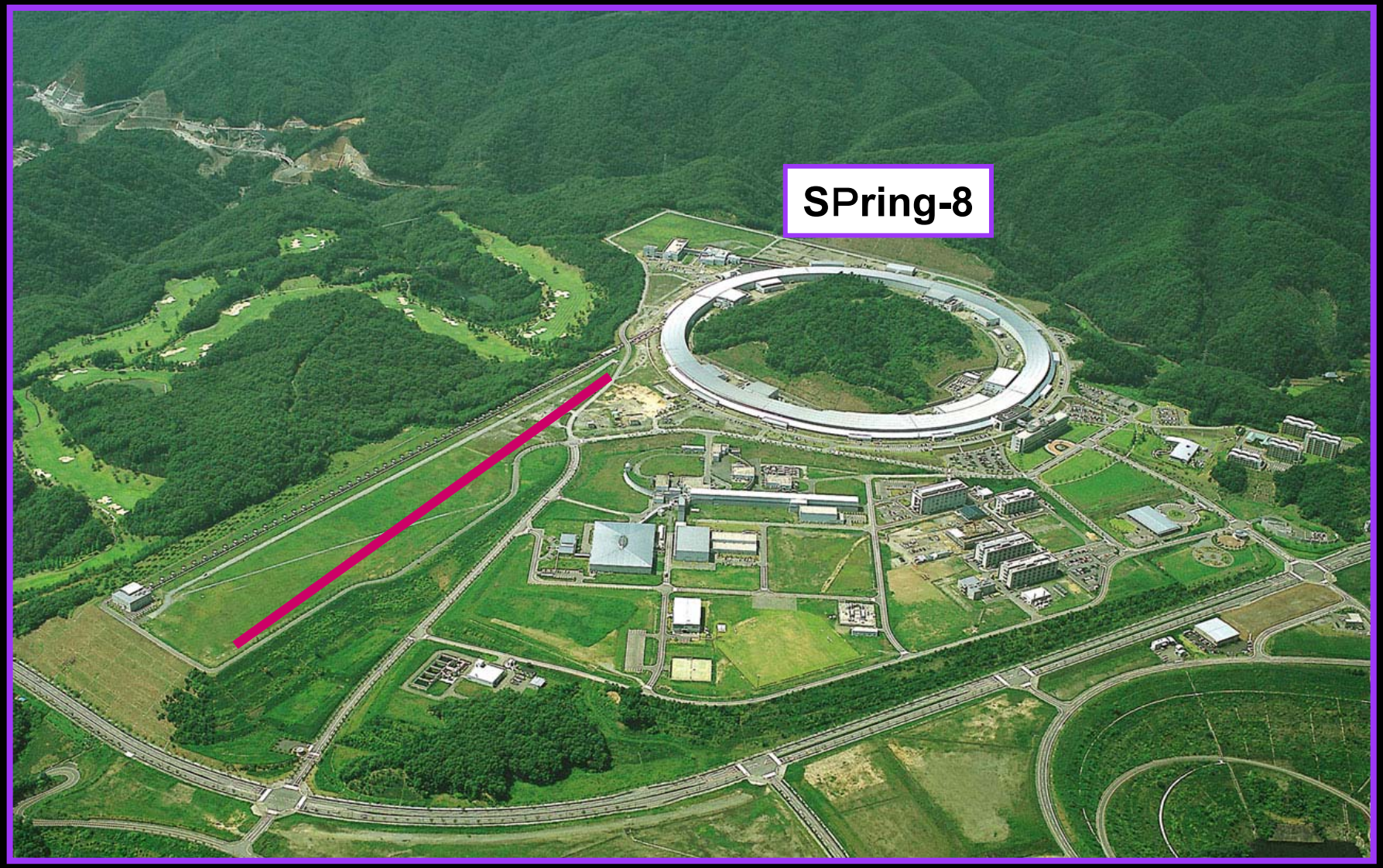
# Existing 1 km Beam Line Space

X-ray FEL



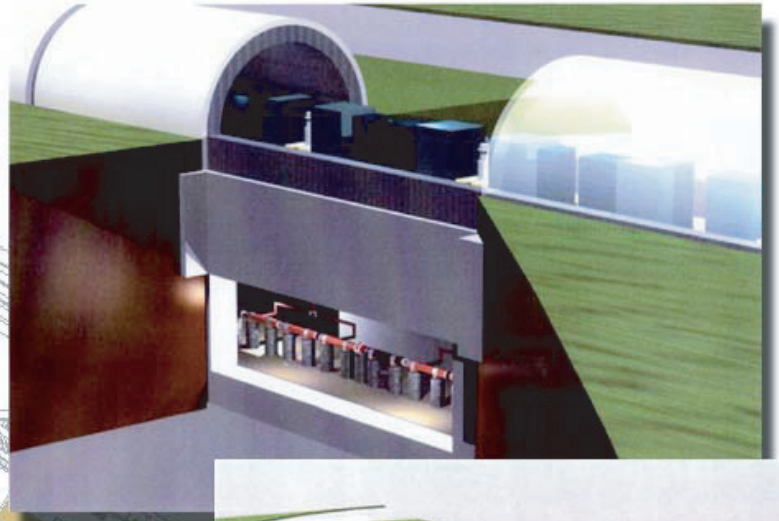
## Future X-ray FEL at SPring-8

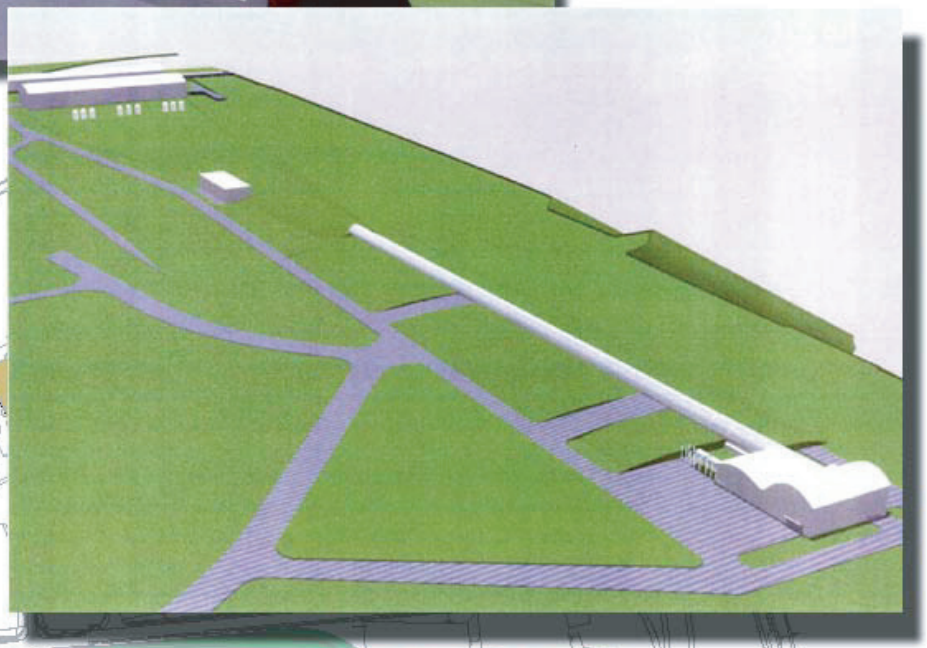
*Target Wavelength 1 A*

*6 GeV C-band Accelerator*

*1 km Site Length*

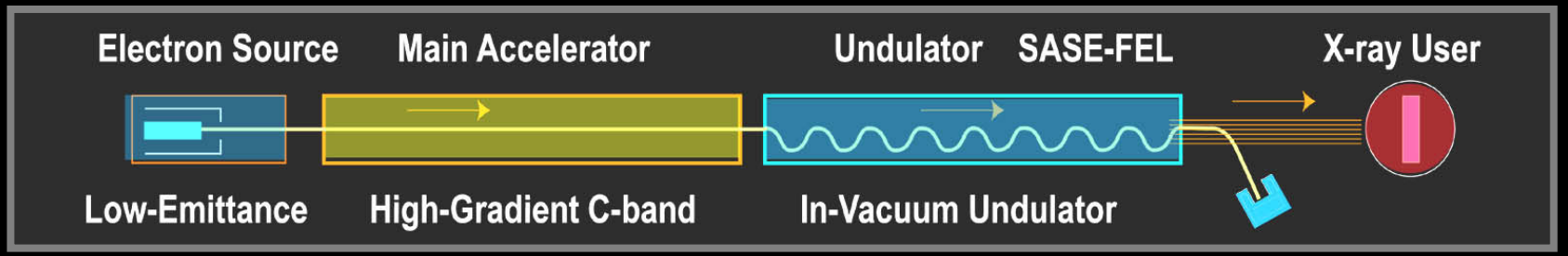
*Multiple User Beam Lines*





# SCSS:SPring-8 Compact SASE Source

X-ray FEL




- Low Emittance Injector → Short Saturation Length
- High Gradient Accelerator → Short Accelerator Length

KEK C-band 35 MV/m x 30 m = 1 GeV

- Short Period Undulator → Lower Beam Energy, Short Saturation Length

Kitamura's In-Vacuum Undulator : E = 1GeV, $\lambda u$ = 15 mm, $\lambda x$ = 3.6 nm

# SCSS group

X-ray FEL



**SPring-8 (RIKEN, JASRI)**
H. Kitamura (Chief, Undulator)
T. Shintake (Chief, Accelerator)
T. Ishikawa (Chief, Experiment)

**KEK C-band**
H. Matsumoto
M. Yoshida

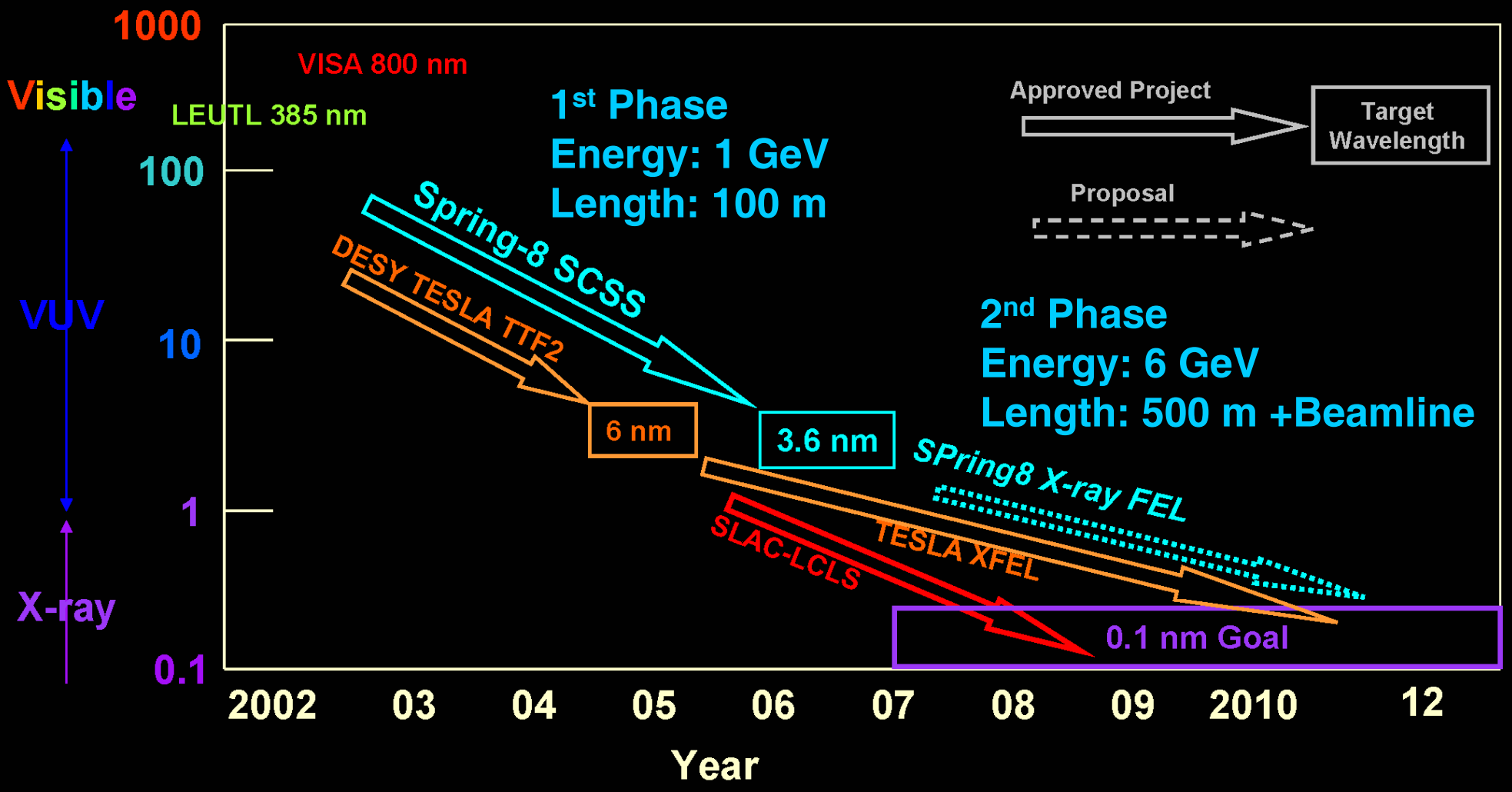
**Accerelator**
H. Baba
Z. Chao
H. Ego
T. Inagaki
Y. Kawashima
S. Matsui
F. Nakata
K. Onoe
T. Saeki
S. Takahashi
T. Takashima

**Undulator**
K. Togawa
T. Bizen
T. Hara
X. Marechal
T. Seike

**Experiments/Utilities**
T. Tanaka
T. Kudo
K. Saino
K. Sezaki
K. Takeshita
K. Tamasaku

# Milestone of SPring-8 X-FEL

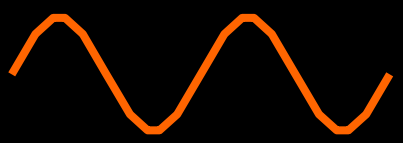
X-ray FEL



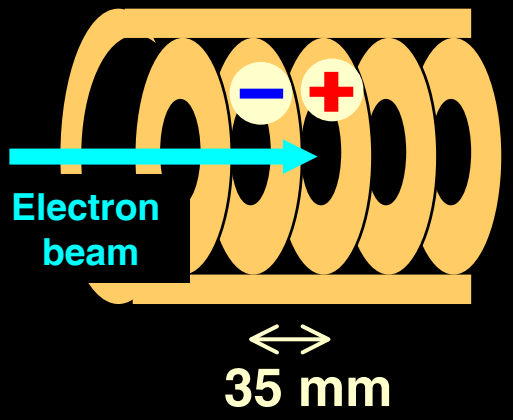
# Main Accelerator : C-band LINAC

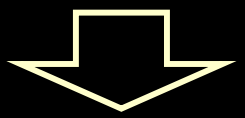


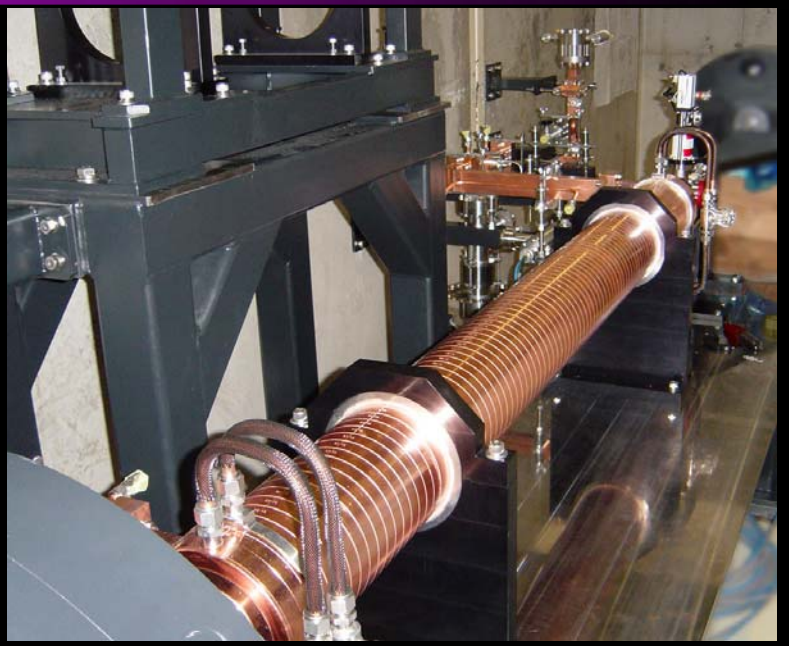
## Conventional: S-band（f= 2.9 GHz）



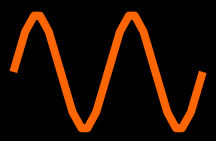
RF (Radio Frequency)
Supply to accelerator



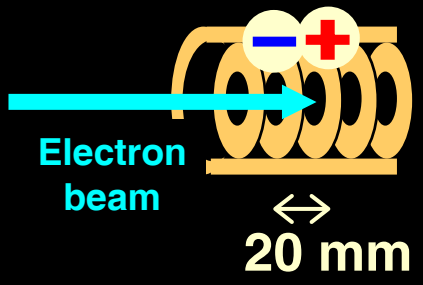





## C-band（f= 5.7 GHz）



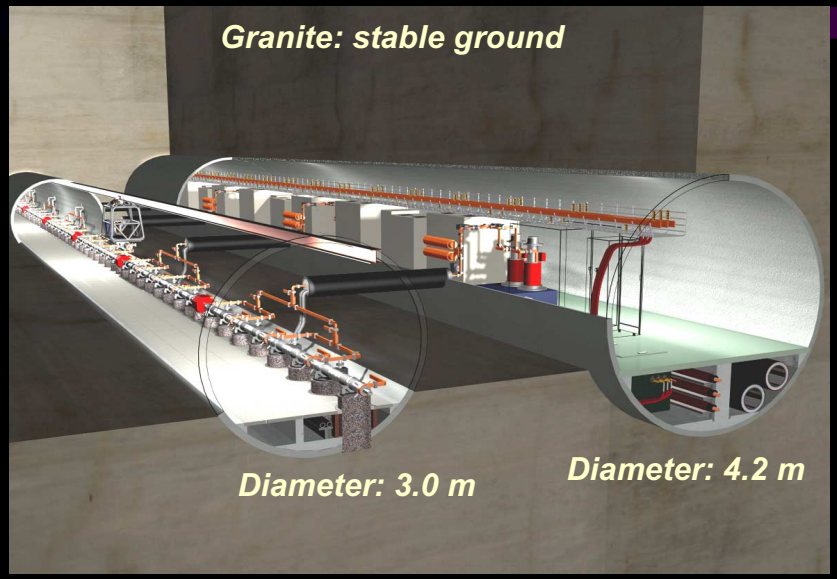
Half wavelength

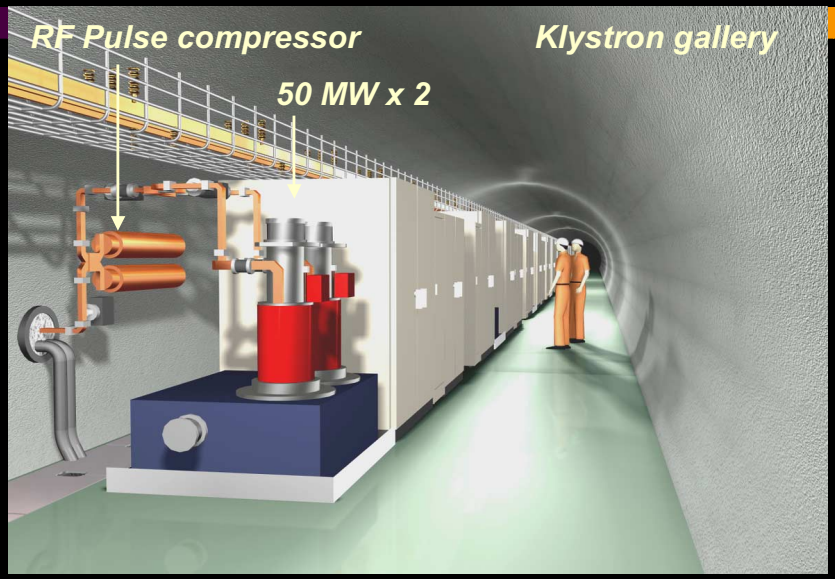


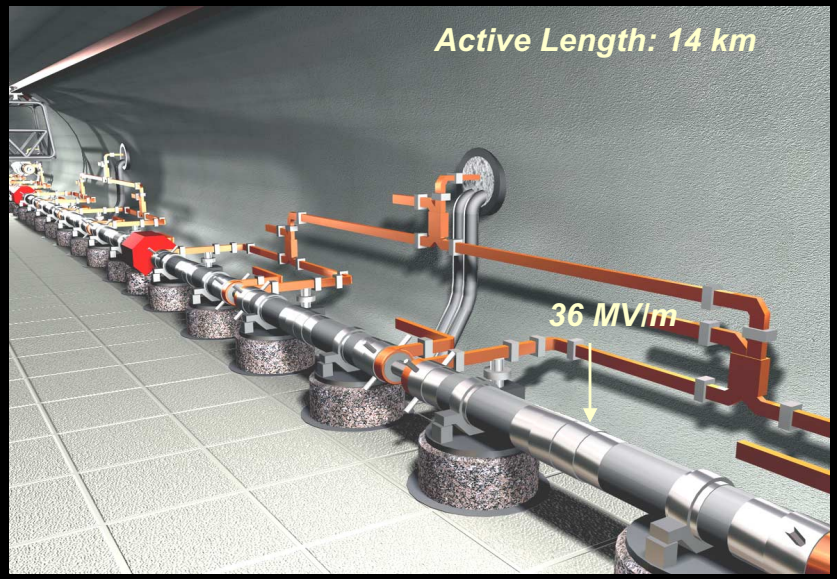

**First** Practical use of C-band LINAC

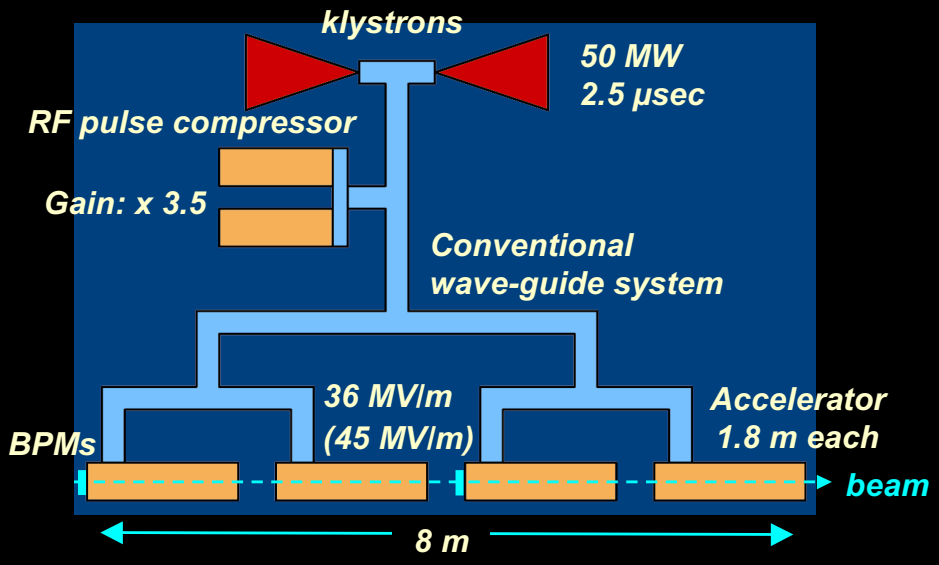
- Compact
- High accelerating gradient

# JLC C-band (5712 MHz) Main Linac Tunnel



# *High Accelerating Gradient → Compact Accelerator*

X-ray FEL

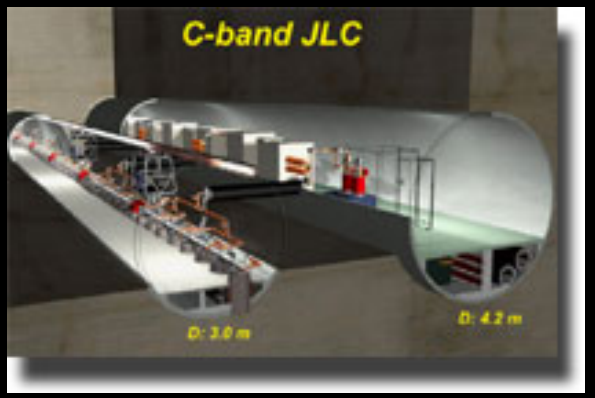
## S-band LINAC

**KEK-PF**
**8 GeV / 460 m**
**= 17 MV/m**

**Spring-8**
**1 GeV / 80 m**
**= 13 MV/m**

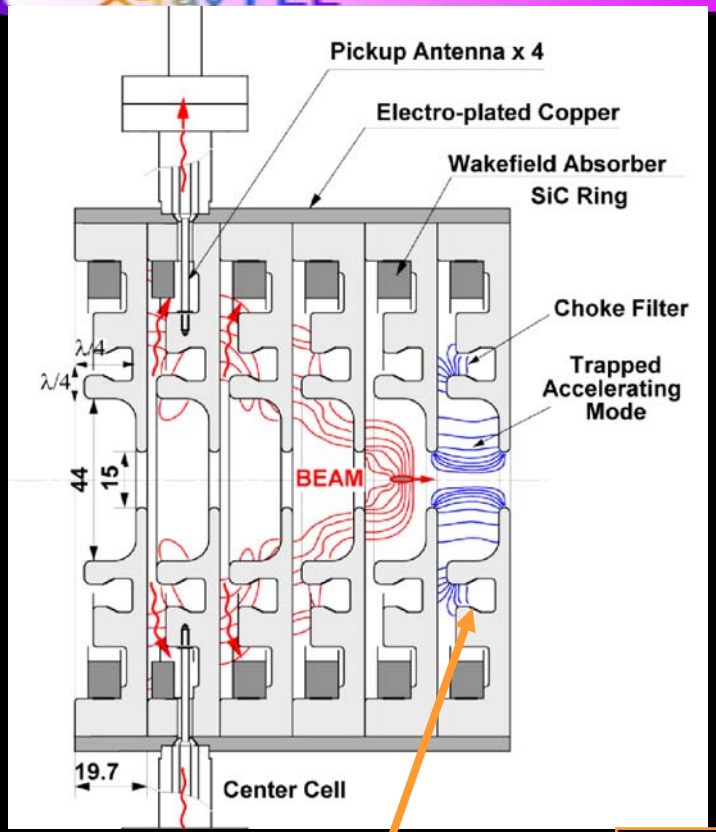
## C-band LINAC

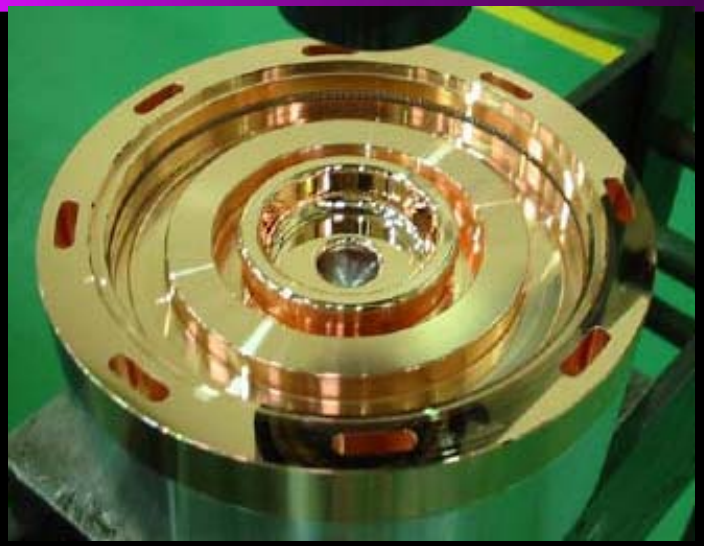
**Linear Collider**
**500 GeV / 13 km**
**= 39 MV/m**

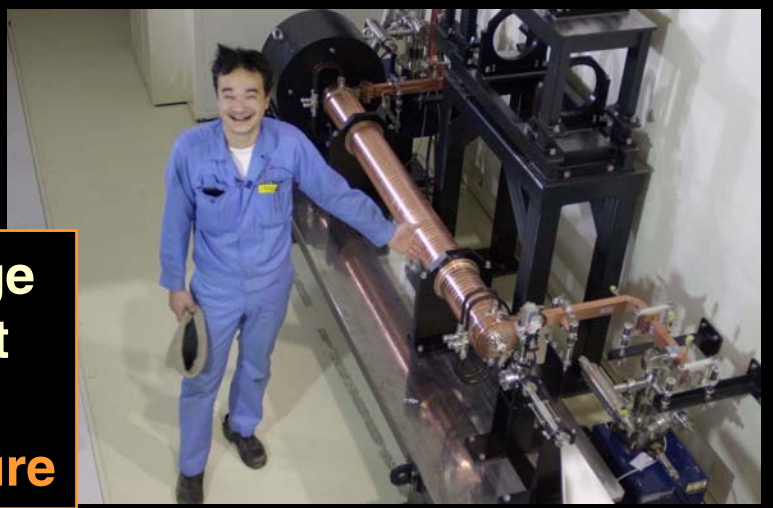



**SCSS**
**1 GeV / 29 m**
**= 34 MV/m**

# C-band Accelerating Structure





**Choke Filter**
- Trap accel. RF
- Remove wakefield

**Avoid** - HV discharge
- Dark current

$O_2$-free copper
Hot Isotropic Pressure

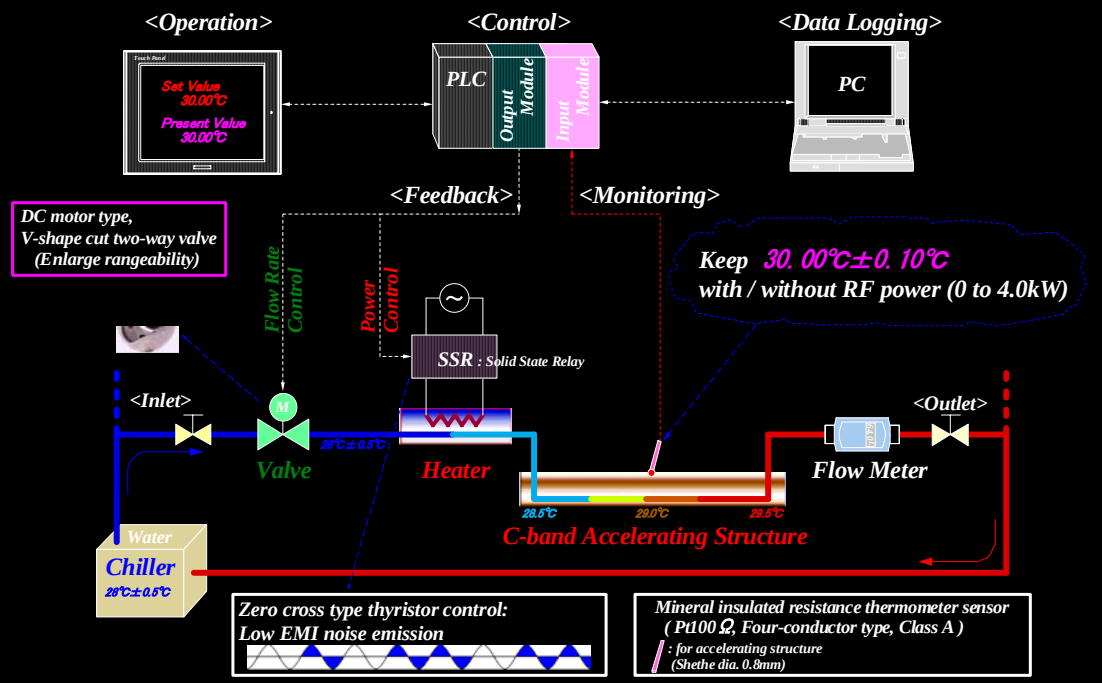
# Resonant frequency adjustment



5.7 GHz ±200 kHz
↓
15 mm ±0.5 μm
**Super-precise lathe**
**（超精密旋盤）**

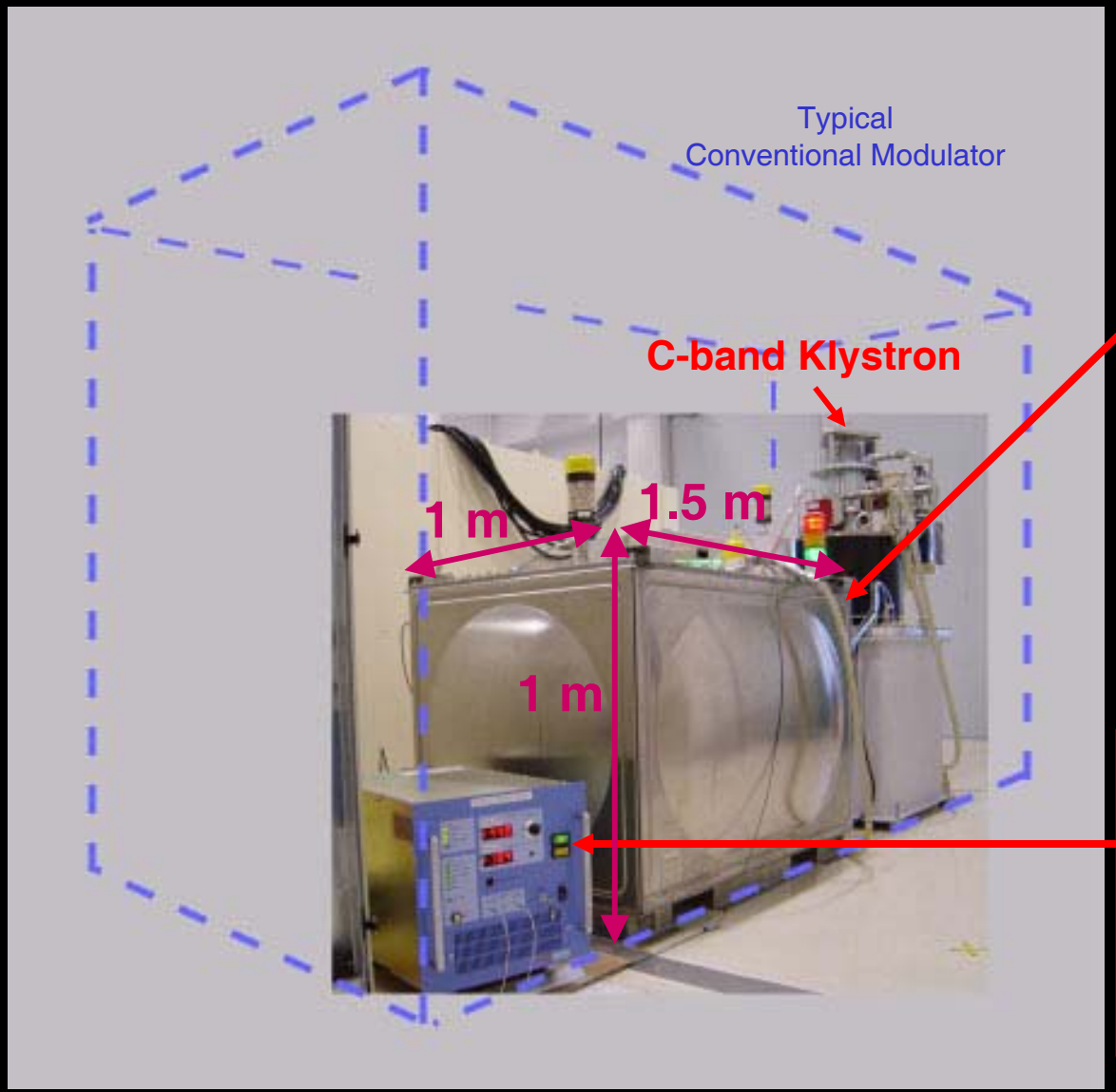
Using heat extension of Cu
100 kHz per 1 ℃
↓
Target temperature ± 0.1 ℃
**Precise Water Control System**

SCSS



# “Compact” Modulator Power Supply

X-ray FEL




## Modulator

- Insulating Oil（絶縁オイル）
  - Compact
  - Air-tight
- Stainless Tank
  - Electric noise shield
  - Movable

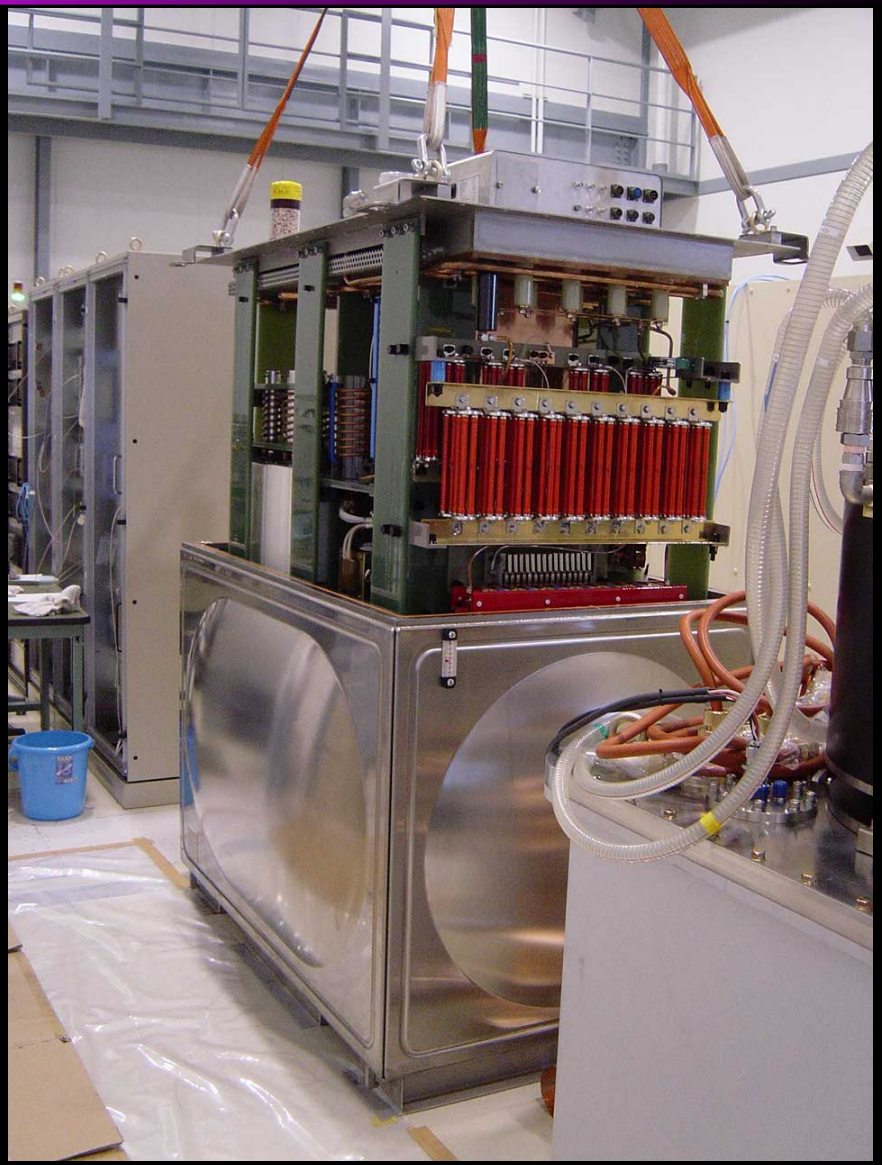
## Inverter Power Supply

Output : 50 kV, 30 kW
Voltage Stability : < ±0.25 %

19-inch rack mounted

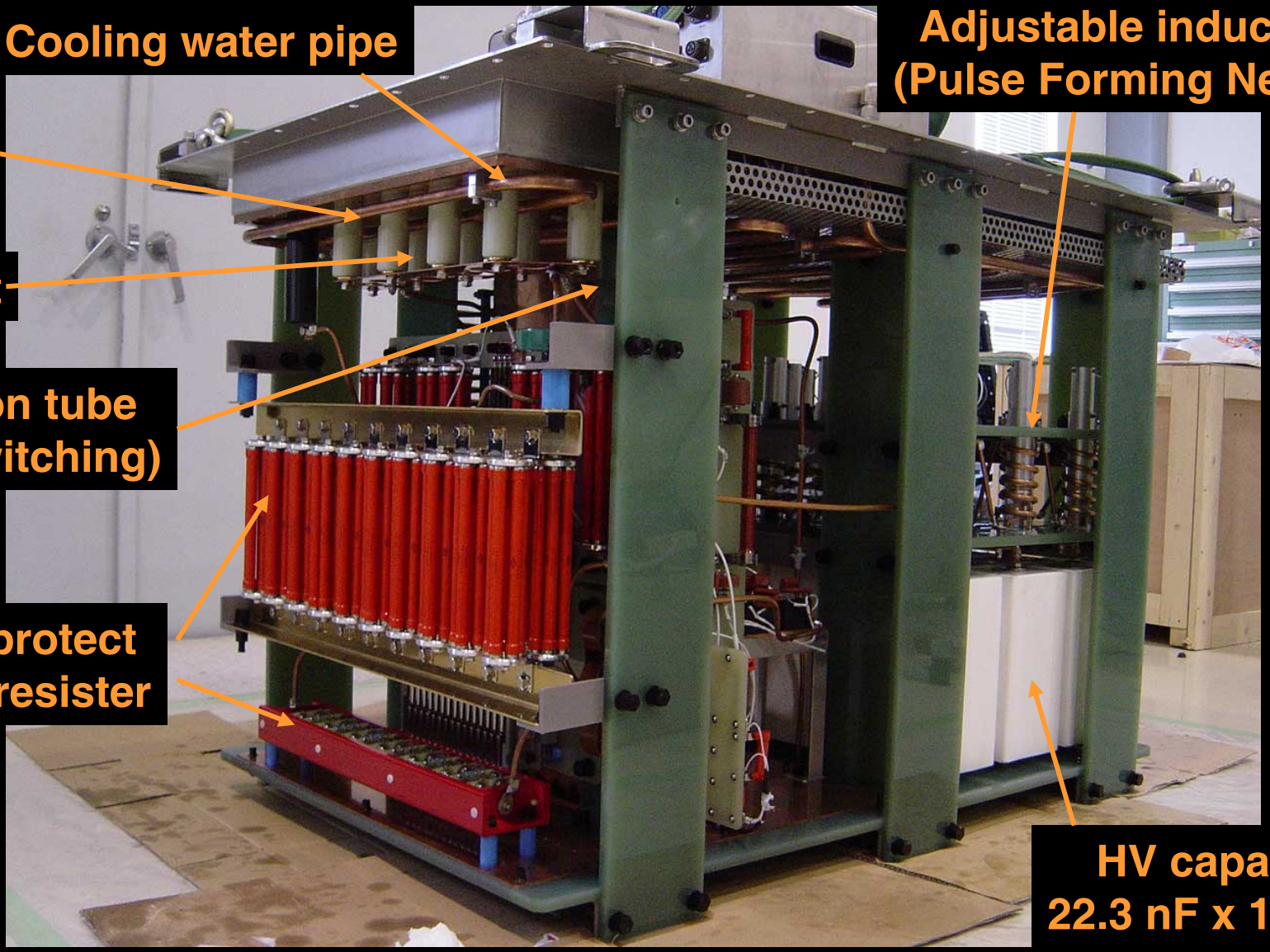
# When the maintenance …





# *Inside of the Modulator*





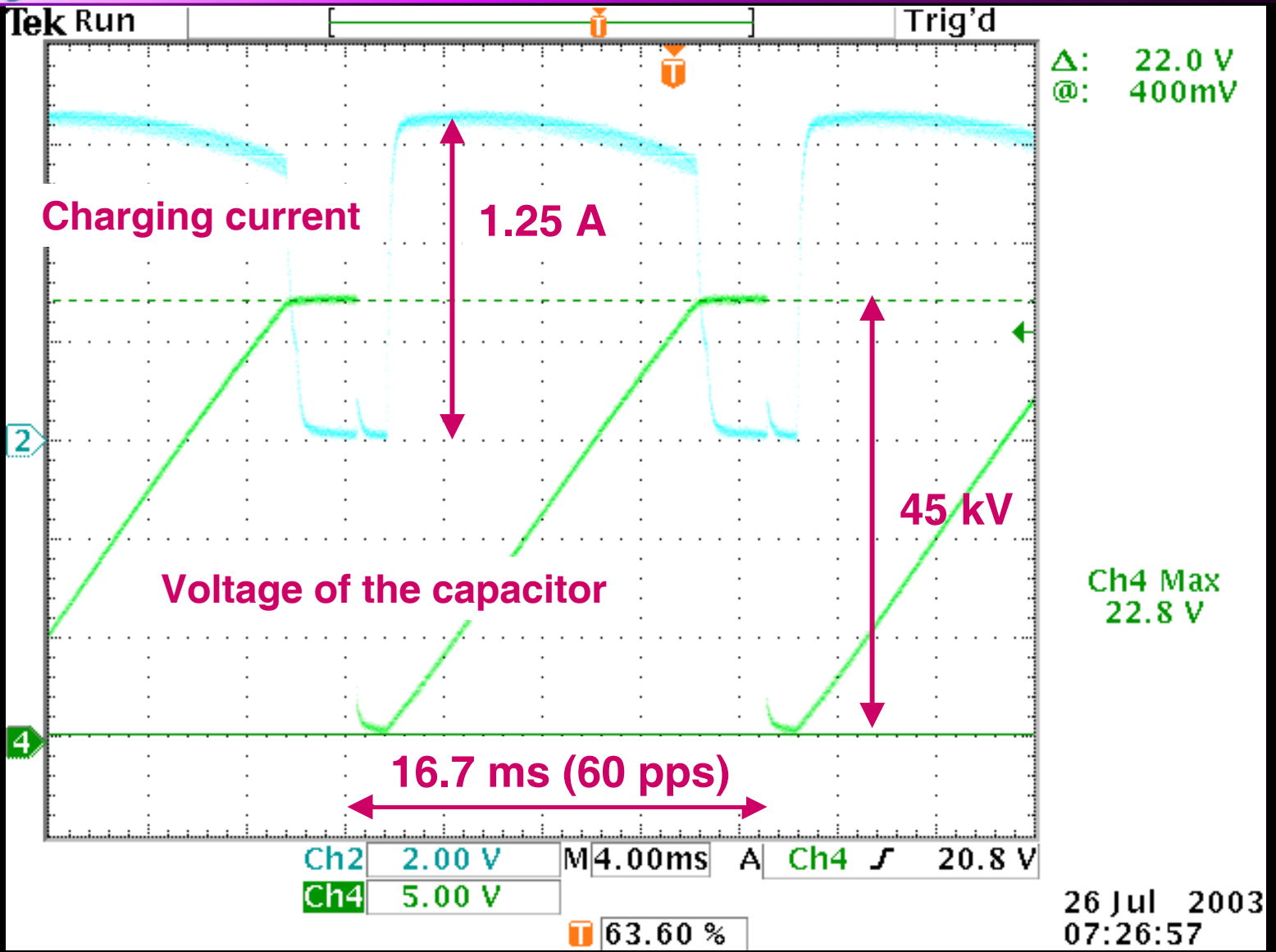
# High Power Operation Test

X-ray FEL

| | |
|---|---|
| 2003 March | Constructed |
| 2003 July | Long run test |
| 2004 January | Klystron RF test |

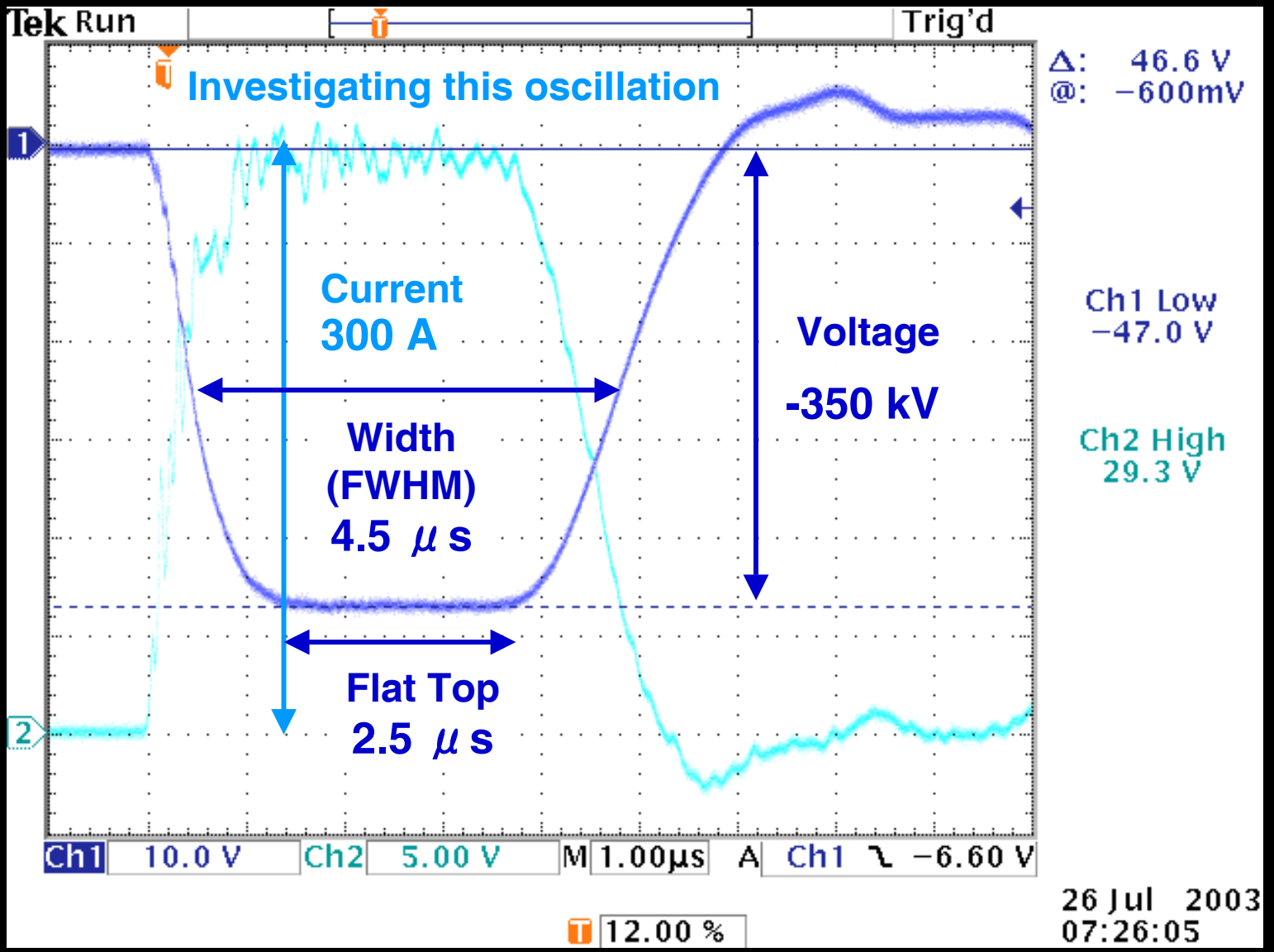
# *Inverter Power Supply → Charging to Modulator Capacitor*





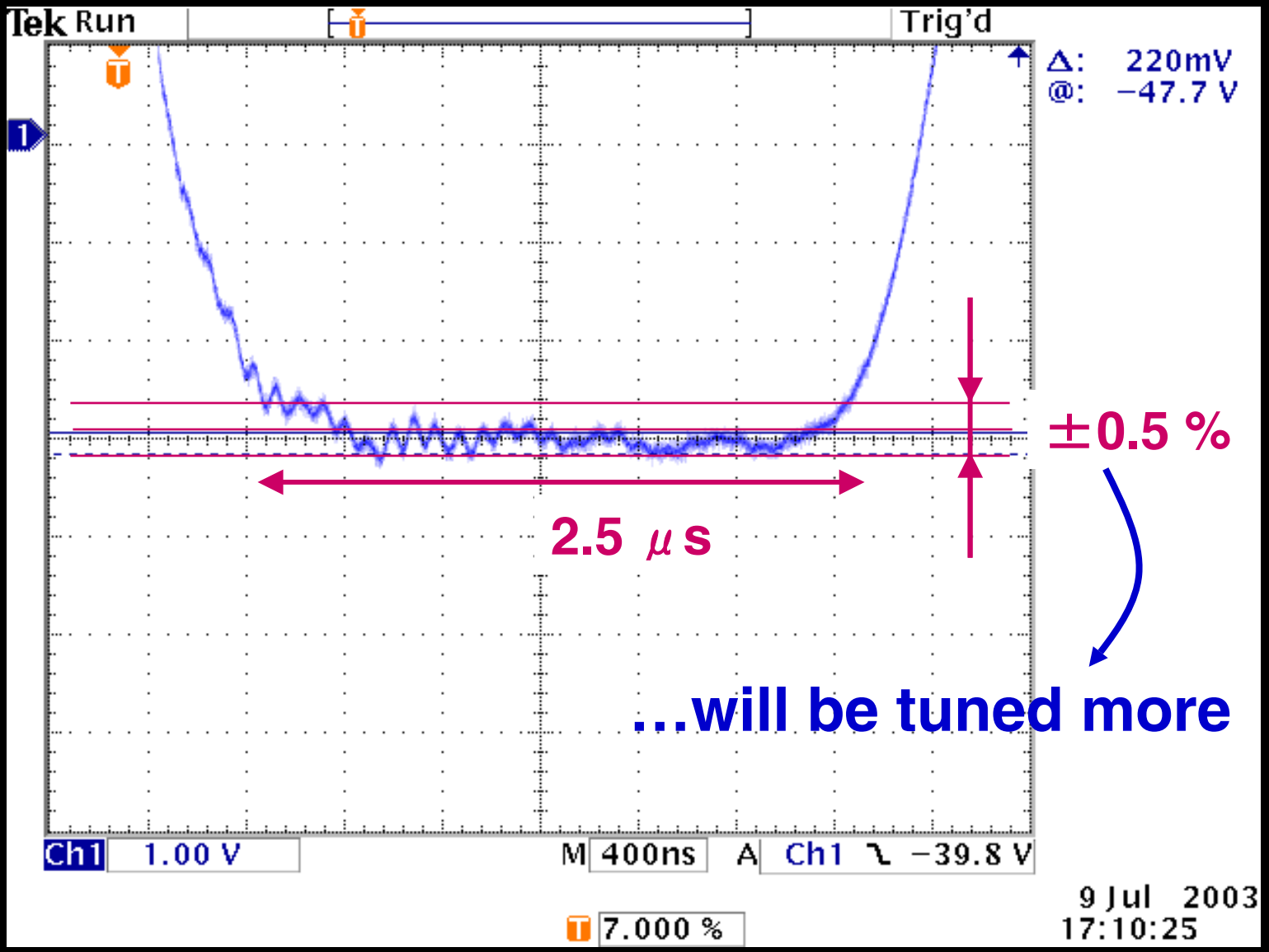
# Modulator → HV Pulse at Klystron Cathode





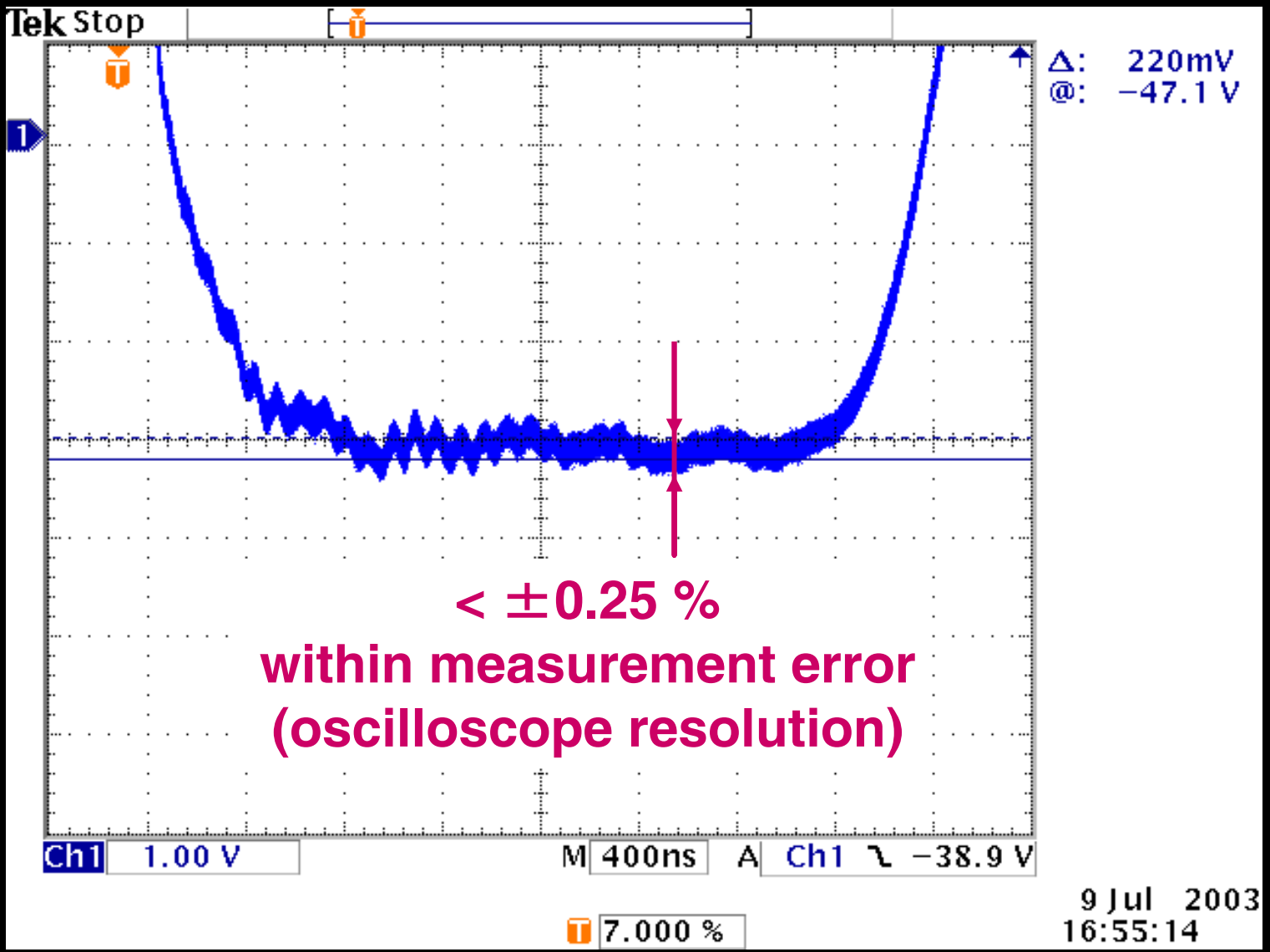
# Flatness of the Flat Top



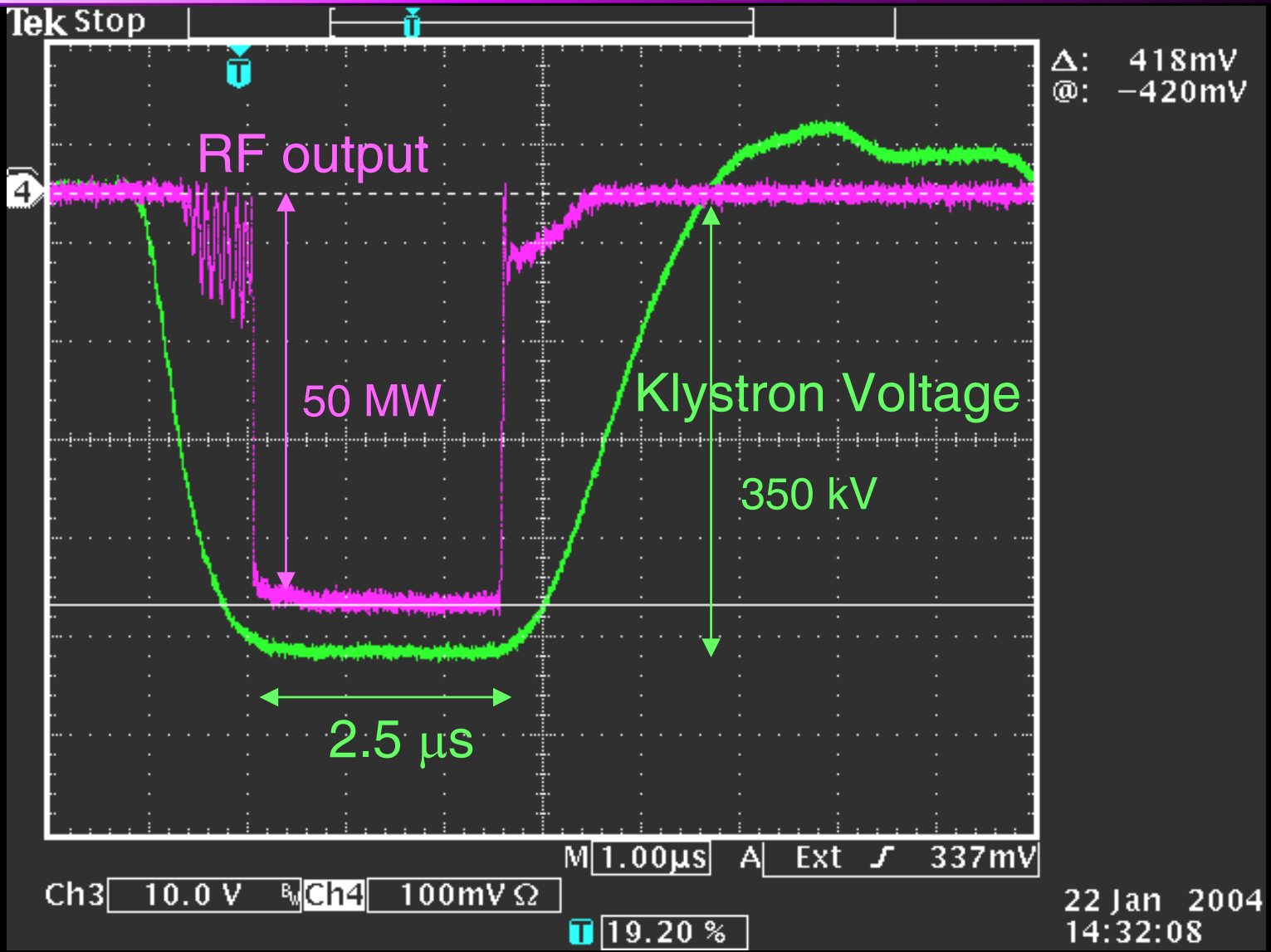


# Stability of the Voltage



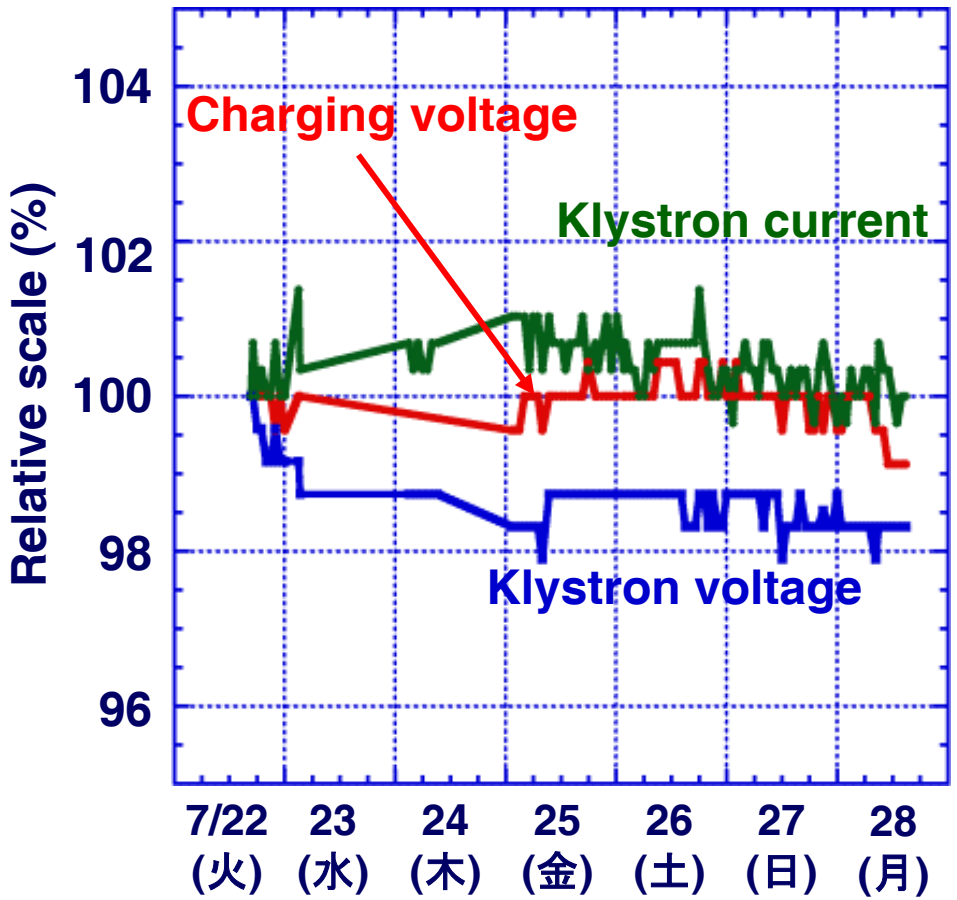


# RF Output of the Klystron



# Continuous Operation Test

X-ray FEL




**Total Operation: 140 hour**
**($3 \times 10^7$ pulse)**

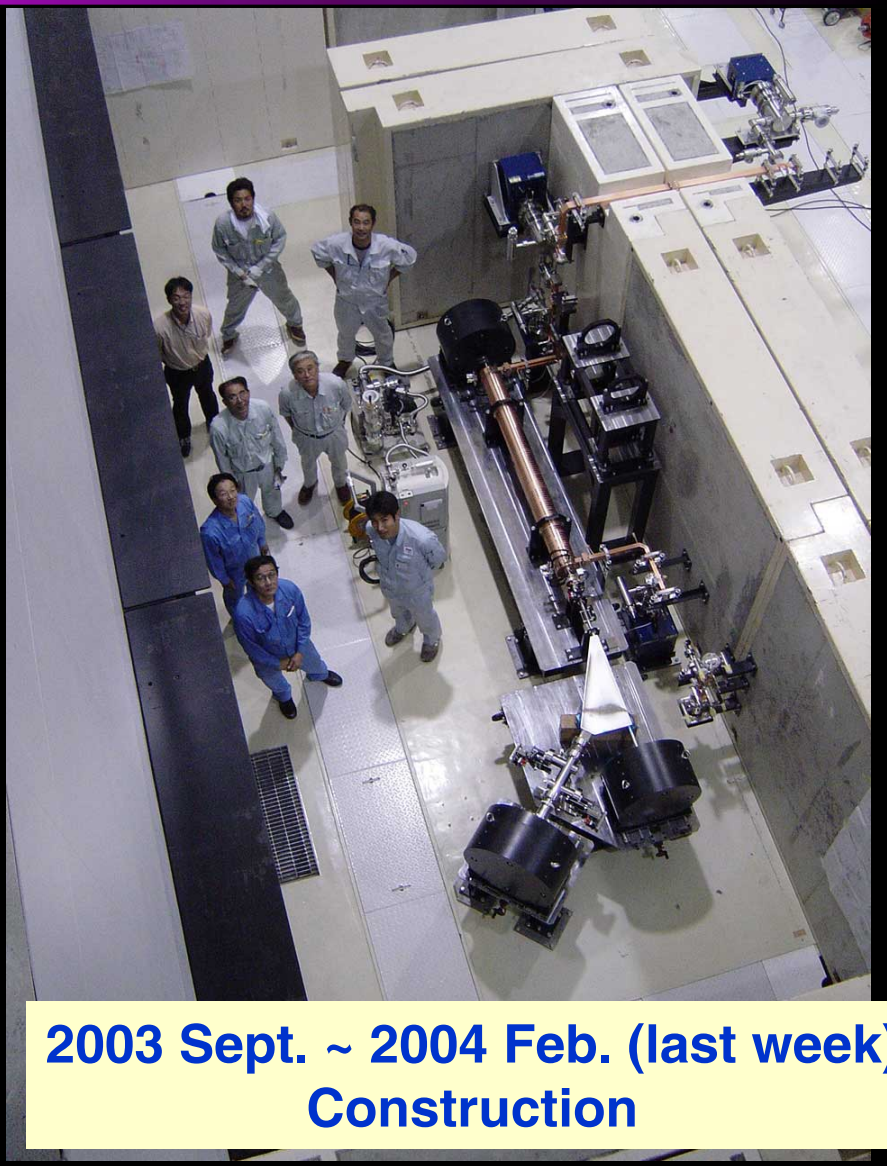
**Interlock stop: 5**

- Klystron discharge 1
- Thyratron miss-fire 2

**→reasonable rate**

**Reset and re-started soon**

# *High Power RF Test (2004 April ~)*



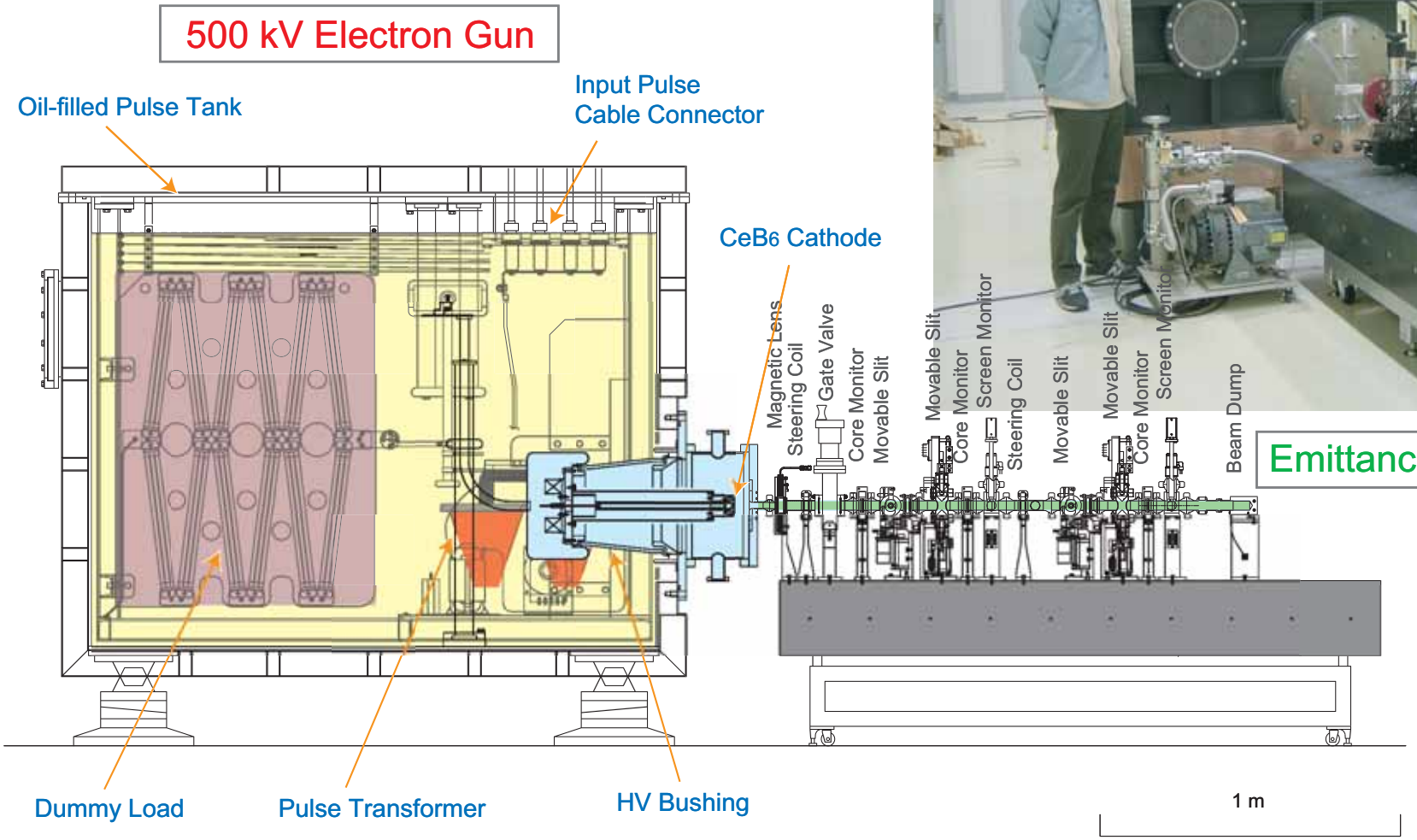
**First trial of**
**High Power RF (50 MW)**
**from Klystron**
**to Accelerating Structure**

- Electrical field (=Accelerating gradient)
  (Nominal: 35 MV/m, Max: 70 MV/m)
- Dark current emission

**2003 Sept. ~ 2004 Feb. (last week)**
**Construction**

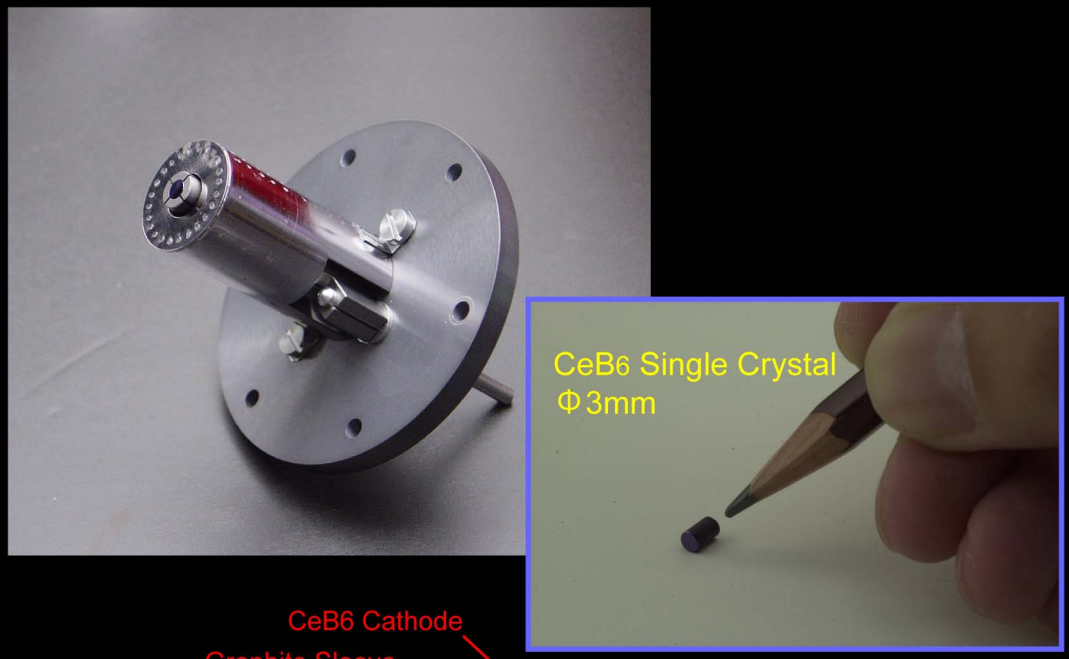
# 500kV Electron Gun Test Stand

Emittance Measurement System

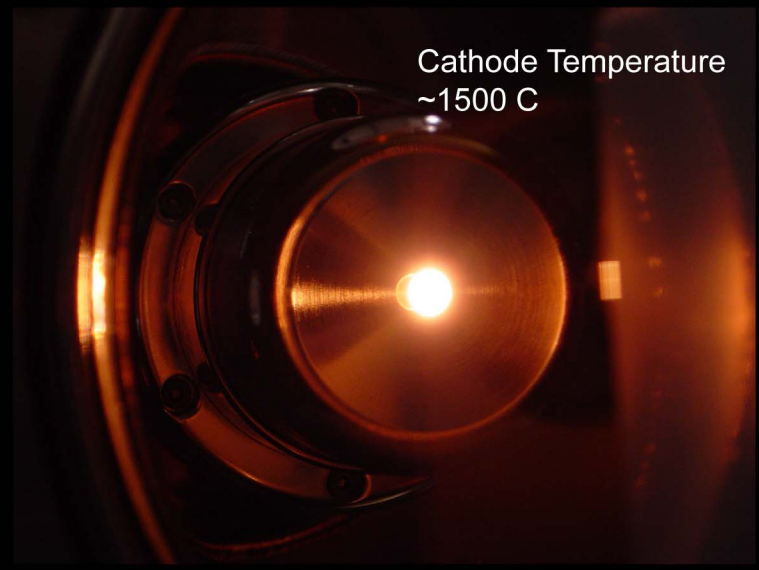


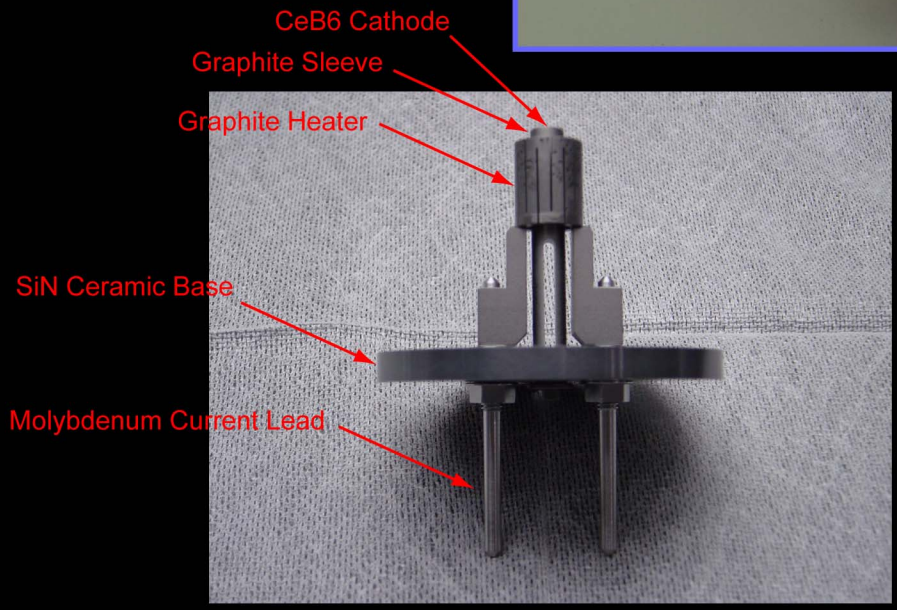
# $CeB_6$ Cathode Assembly for SCSS Gun

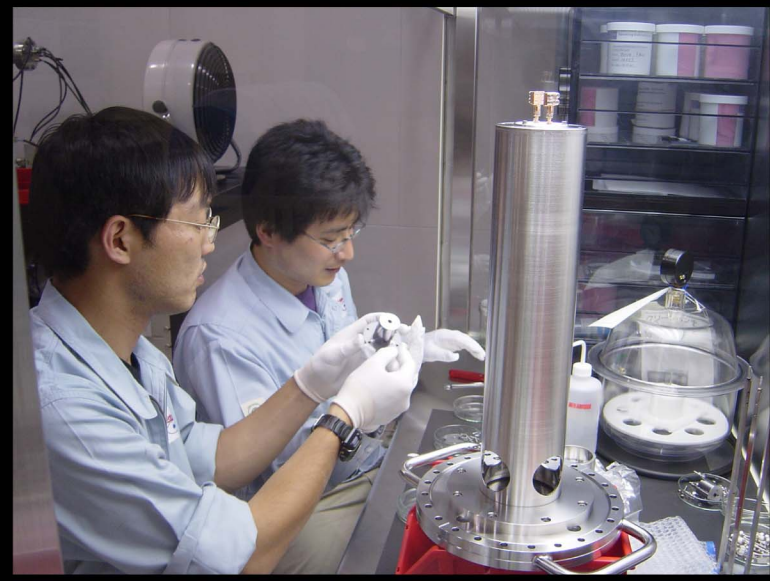
Cathode Assembly




Heated Cathode in Stem

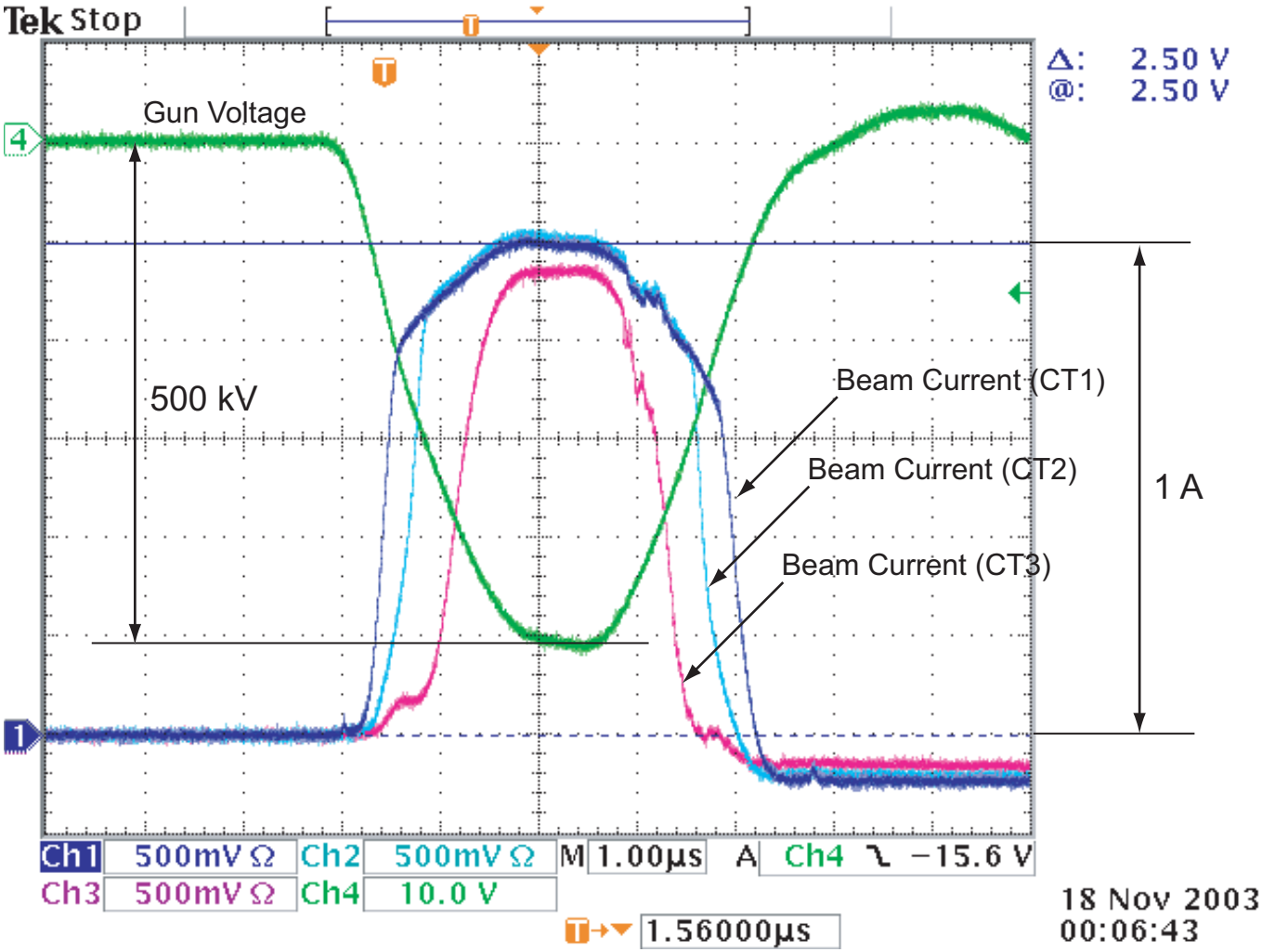


# 500 keV Beam Production

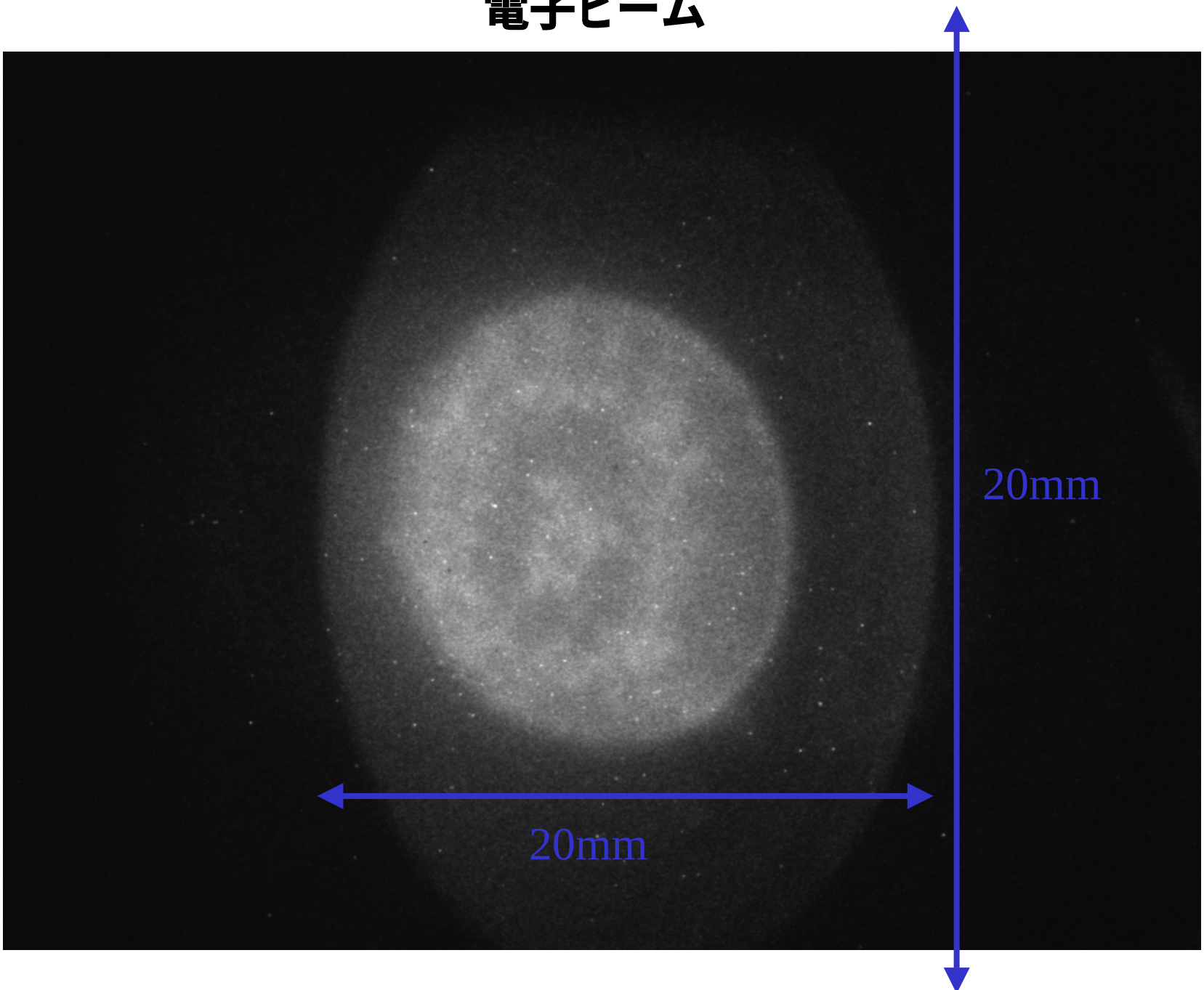
Nov. 19, 2003




Cathode Sleeve Temp
: 1523 deg.-C

Repetition Rate : 1 Hz

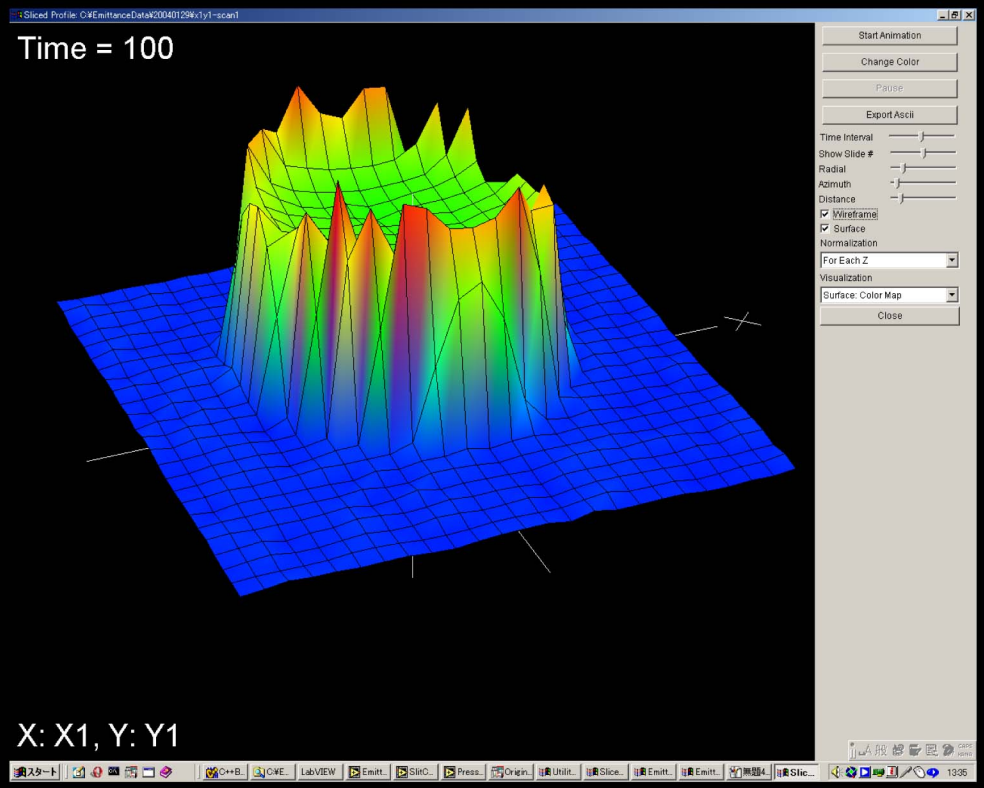
# 電子ビーム



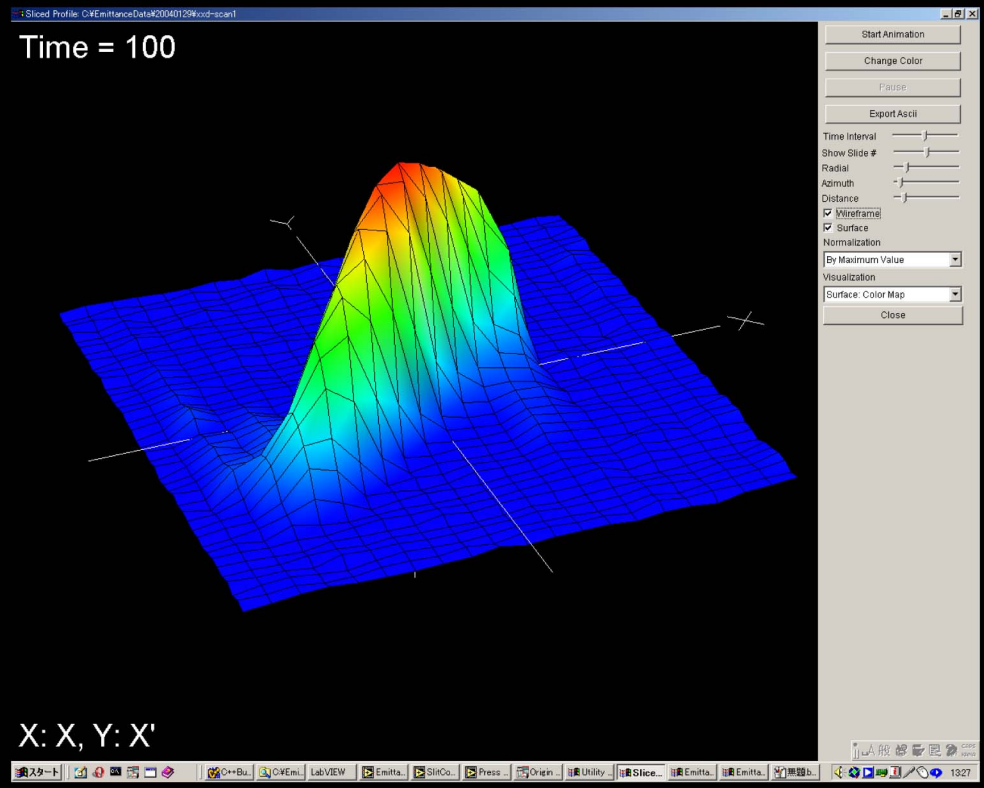
# Emittance Measurement on SCSS Gun

K.Togawa, T.Tanaka, T.Ohata

## Beam Profile




## Emittance Profile




Beam Energy : 200 keV
Peak Current : 0.5 A
Pulse Width : 3 μs
Repetition Rate : 10 Hz

Emittance ($\varepsilon_{n,RMS}$)

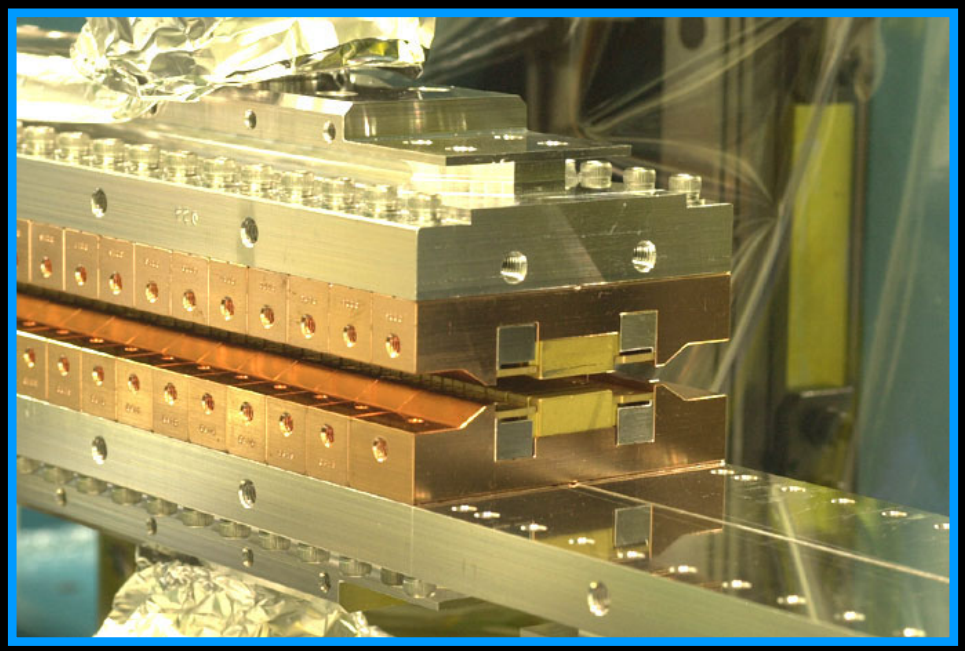
Requirement : 2 π.mm.mrad @Undulator

Experiment : 0.9 π.mm.mrad @Gun (preliminary)

# SCSS Undulator In-Vacuum Type

X-ray FEL

- Segment length 4.5 m
- N=300/segment, $\lambda_u$=15mm
- Mechanical minimum gap = 2mm
- Nominal gap ~ 3.5mm (K~1.3)
- 45-deg. tilted Halbach type
- More compact than ordinary ones



First prototype model arrived, Sep. 2002

# *Summary*

X-ray FEL

- **C-band Accelerator**
  - **Modulator:** operation test
  - **High power test:** 2004 April ~
- **Gun:**
  - **First beam extraction**
  - **Emittance = 0.9π mm･mrad (Preliminary)**
- **Undulator:** 1st model

**Going advanced**
**step-by-step**
**day-by-day**

**R&D ⇒ Construction & Mass-production 2005 ~ (Hope)**

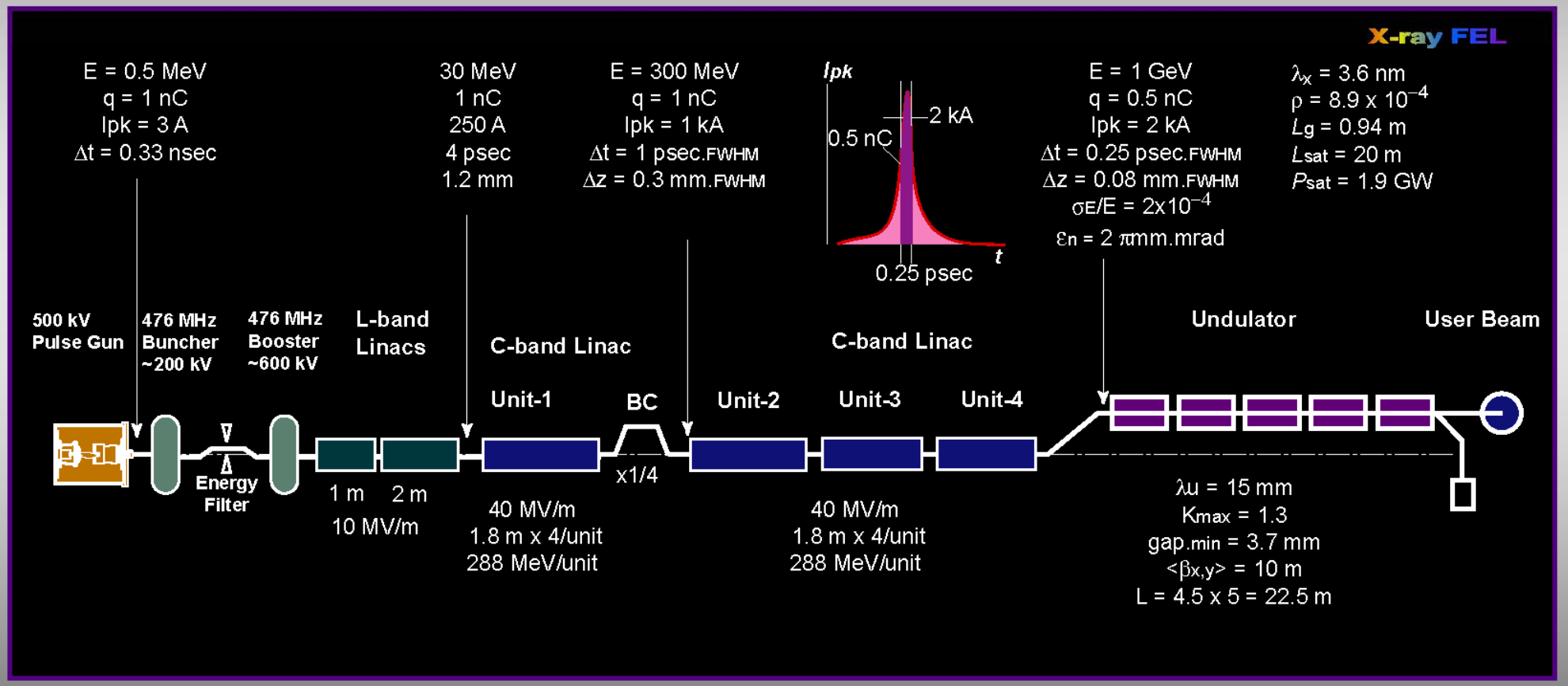
第2回　SCSS技術会議　2003年11月

# *Spare*

# *Technical data*

# SPring-8 Compact SASE Source (SCSS)

*Beam line layout at 1 GeV, 3.6 nm*



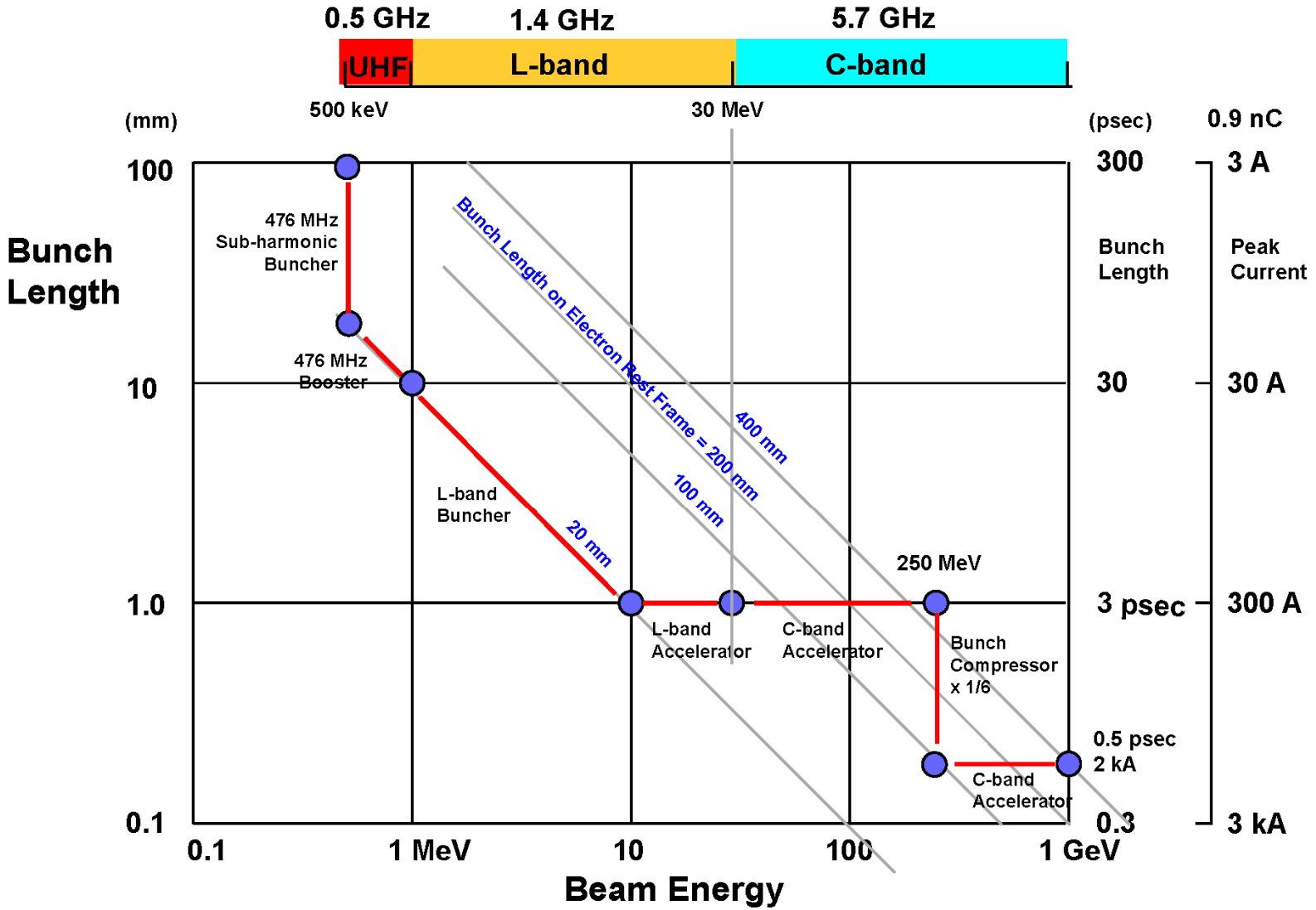
# SCSS & X-ray FEL Beam Parameter

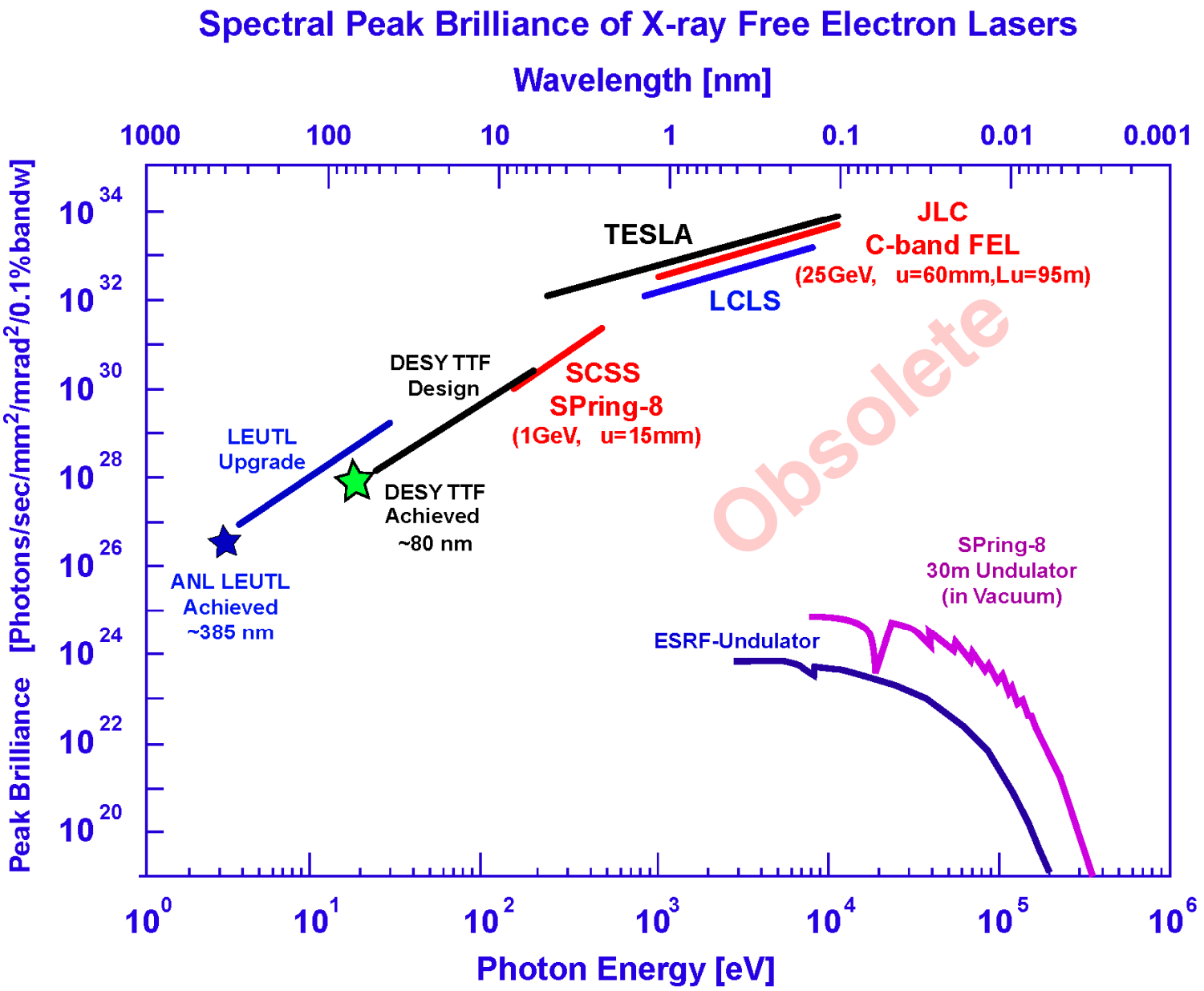
at undulator section

| | | SCSS | X-ray FEL | |
|---|---|---|---|---|
| Beam Energy | $E$ | 1.0 | 6.0 | GeV |
| X-ray Wavelength | $\lambda$ | 3.6 | 0.1 | nm |
| Beam Emittance | $\varepsilon_n$ | 2 | 0.5 | $\pi$mm.mrad |
| Bunch Length | $\Delta z$ | 150 | 75 | $\mu$m |
| | FWMH | 0.5 | 0.25 | psec |
| Transverse Beam Size | $\sigma_{x,y}$ | 100 | 25 | $\mu$m |
| Peak Current | $I_p$ | 2 | 4 | kA |
| Charge per bunch | $q$ | 1 | 1 | nC |
| Undulator Parameter | $\lambda u$ | 15 | 15 | mm |
| | $K$ | 1.3 | 1.3 | |
| Length | $L$ | 22.5 | 50 | m |
| FEL Saturation Length | $L_{sat}$ | 20 | 40 | m |

# *Bunch Compression after the Gun*

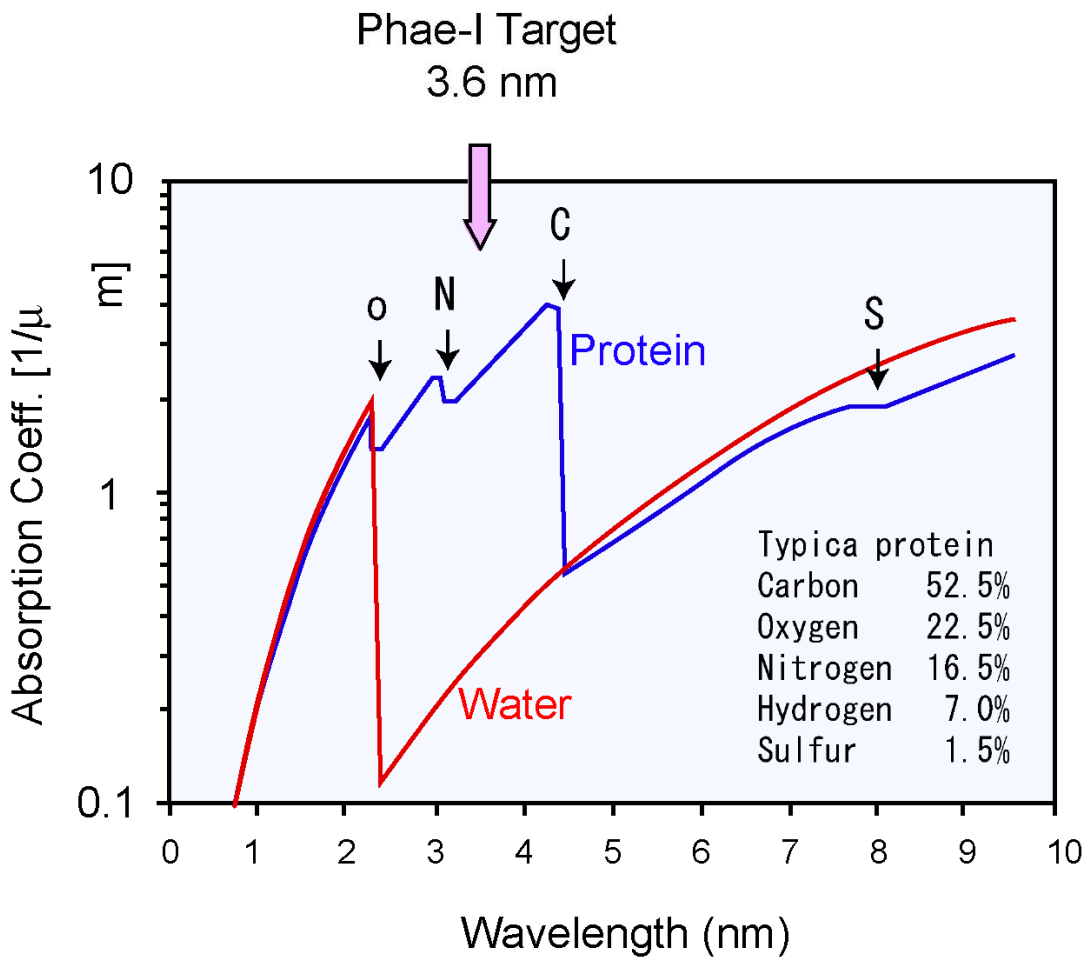
*Maintain bunch-length on the electron rest-fram being constant.*




Spectral Peak Brilliance of X-ray Free Electron Lasers
Wavelength [nm]
1000
100
10
1
0.1
0.01
0.001
Peak Brilliance [Photons/sec/mm²/mrad²/0.1%bandw]
10 34
10 32
10 30
10 28
10 26
10 24
10 22
10 20
TESLA
JLC
C-band FEL
(25GeV, u=60mm,Lu=95m)
LCLS
DESY TTF
Design
SCSS
SPring-8
(1GeV, u=15mm)
LEUTL
Upgrade
DESY TTF
Achieved
~80 nm
ANL LEUTL
Achieved
~385 nm
Obsolete
SPring-8
30m Undulator
(in Vacuum)
ESRF-Undulator
10 0
10 1
10 2
10 3
10 4
10 5
10 6
Photon Energy [eV]

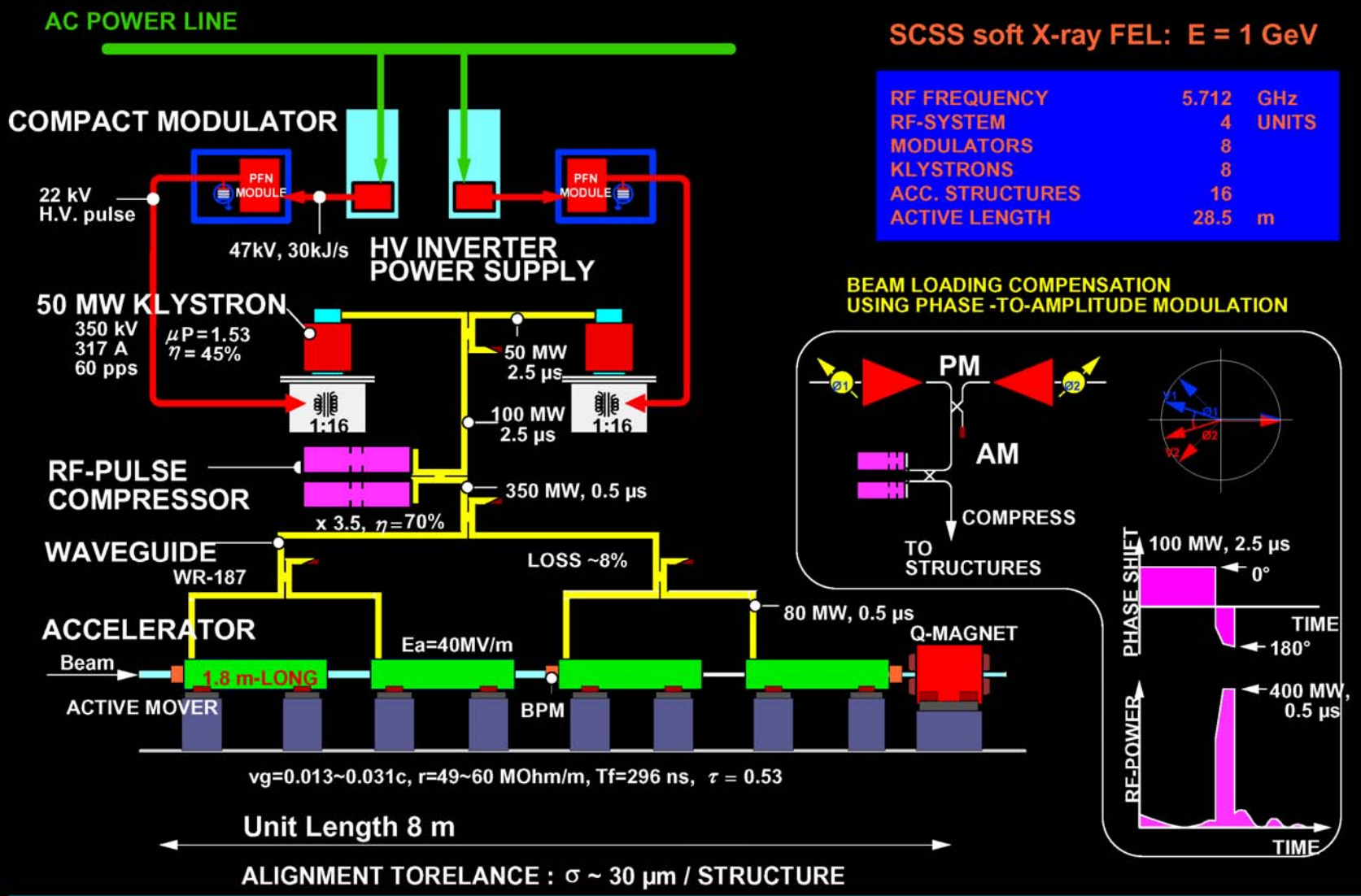
# Phase-I Target Wavelength






Living protein imaging
Nanostructure imaging
Soft X-ray spectroscopy
Femotosecond pump-probe
etc

# C-band LINAC RF SYSTEM




**SCSS soft X-ray FEL: E = 1 GeV**

| | | |
|---|---|---|
| RF FREQUENCY | 5.712 | GHz |
| RF-SYSTEM | 4 | UNITS |
| MODULATORS | 8 | |
| KLYSTRONS | 8 | |
| ACC. STRUCTURES | 16 | |
| ACTIVE LENGTH | 28.5 | m |

**BEAM LOADING COMPENSATION USING PHASE -TO-AMPLITUDE MODULATION**

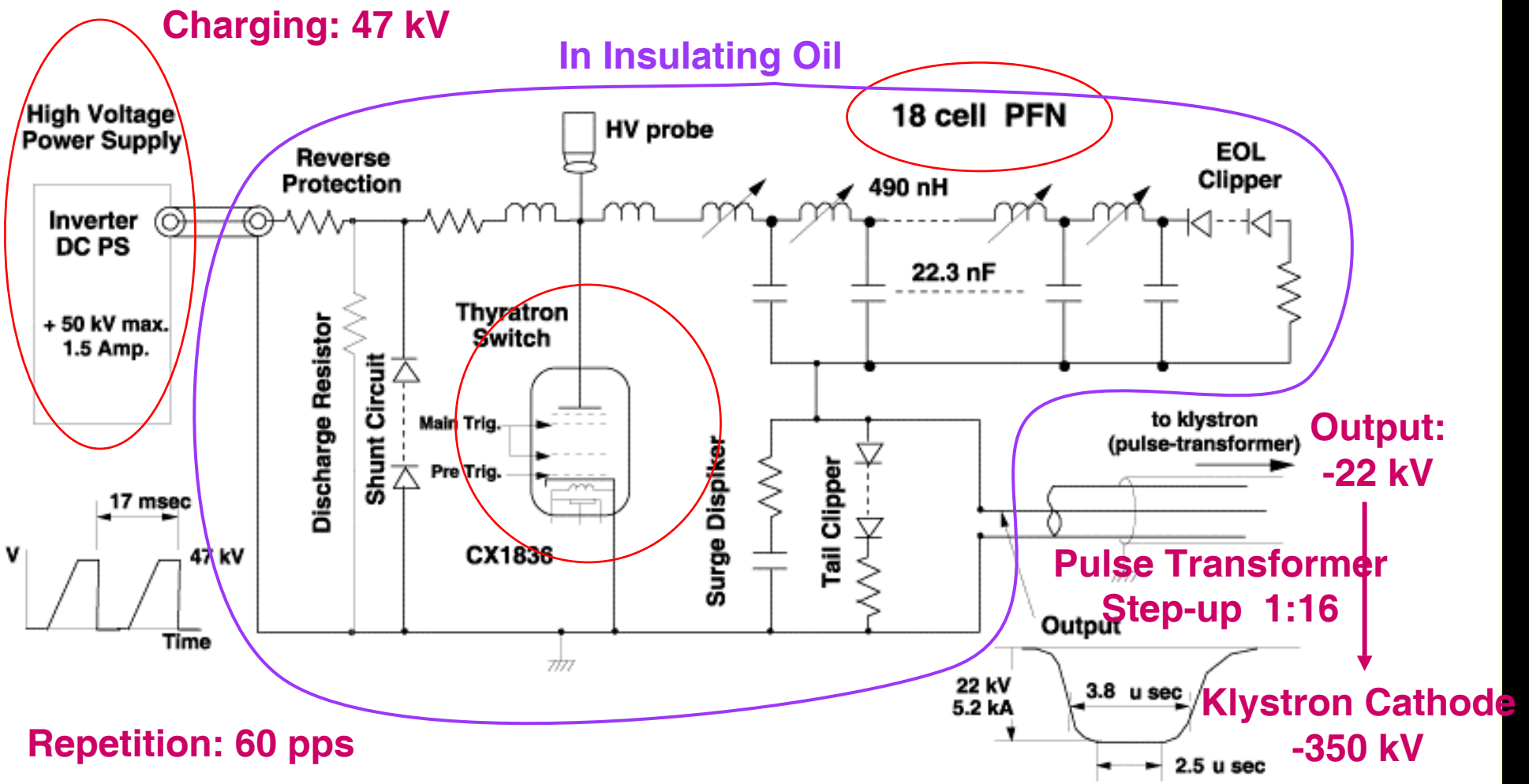



*SCSS SPring-8 Compact SASE Source*

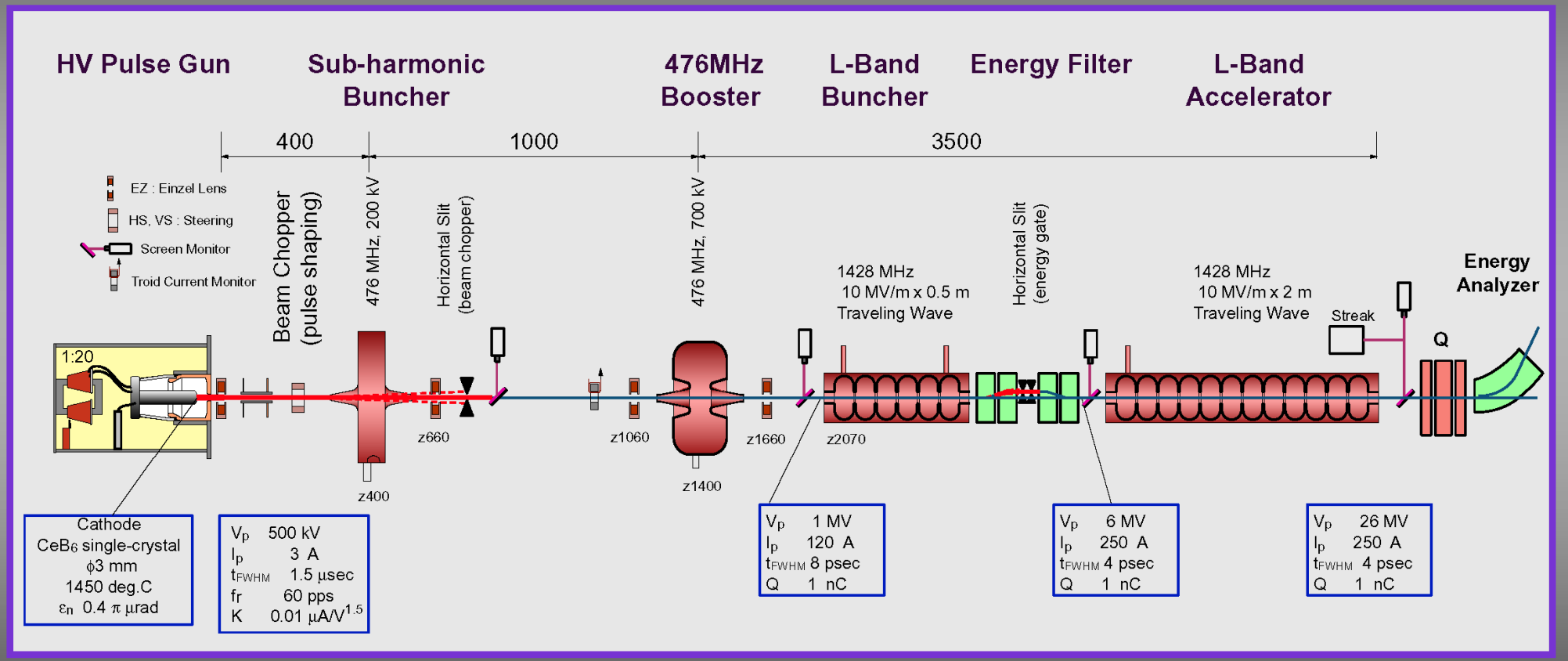
March, 1998, H. MATSUMOTO & T. SHINTAKE, KEK, Novemver, 2003, Updated by T. Inagaki, SPring-8/RIKEN

# Modulator: Electrical Circuit



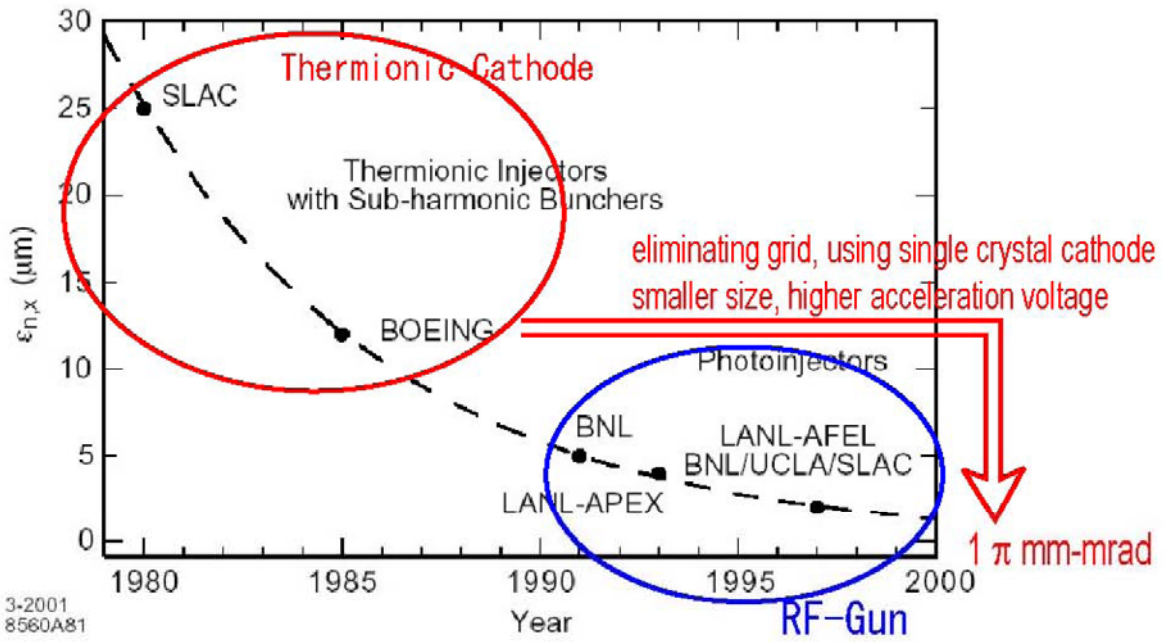


# Low Emittance Injector for SCSS



# *Technical Challenge of Thermionic Injectors to 1 π mm-mrad emittance*

this picture is copied from LCLS "Conceptual Design Report", SLAC-R-593 UC-414




Normalized rms transverse emittance measured by the leading thermoionic (SLAC, BOEING) and rf photocathode injectors [16]. All data are for bunched beams with approximately 1 nC of charge.

- *Eliminating control grid from cathode.*
- *Smaller size cathode, from 8 mm to 3 mm diameter.*
- *Higher gun voltage, 150 kV to 500 kV.*
- *Using single crystal CeB6 cathode.*

# *Other R&D Components*

# Ceramic base stand



# Cavity BPM Design

- Absolute Position Accuracy
  < 10 micron meter
- Resolution ~30 nm for 1nC.
- x, y read out in one cavity.
- COM Free slot design.
- Laser-slit will be integrated for alignment.

# C-band Klystron Development

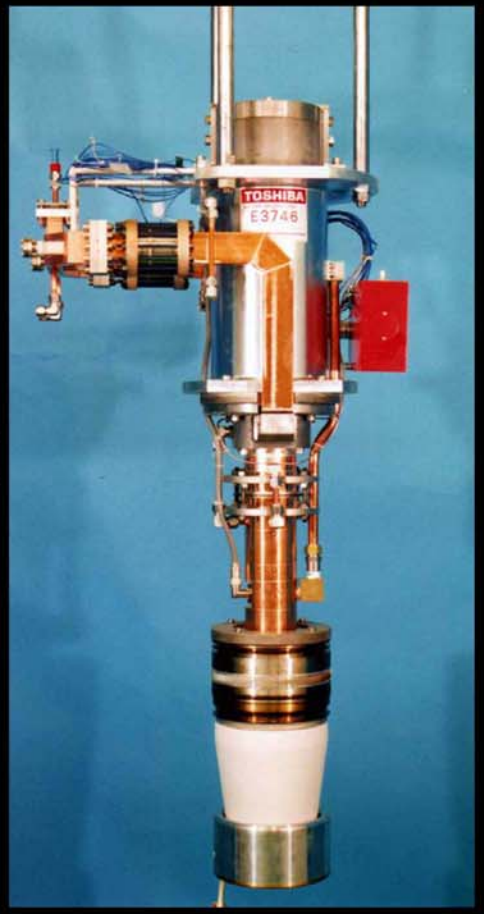
## Under life test since April 1999

Traveling-wave output structure

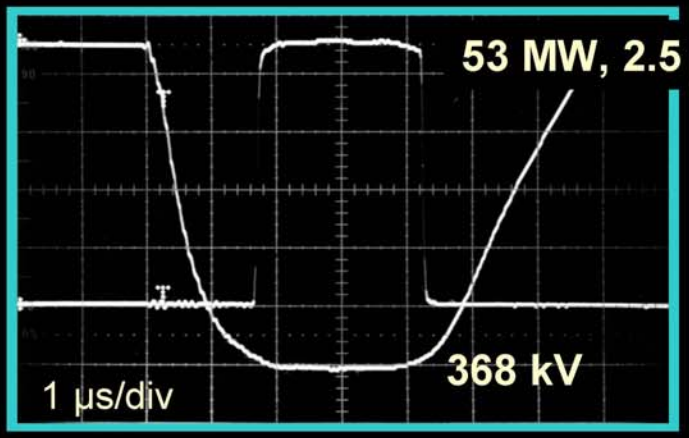
Solenoid Focus (4.6kW)

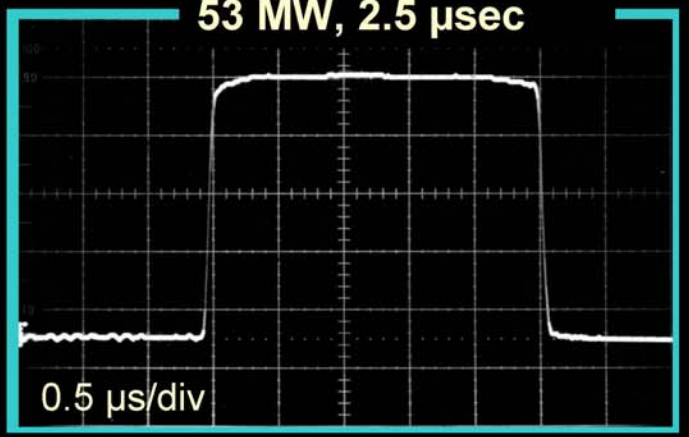
1.5 μP

Dispenser Cathode (D74.5mm,6.3A/cm²)



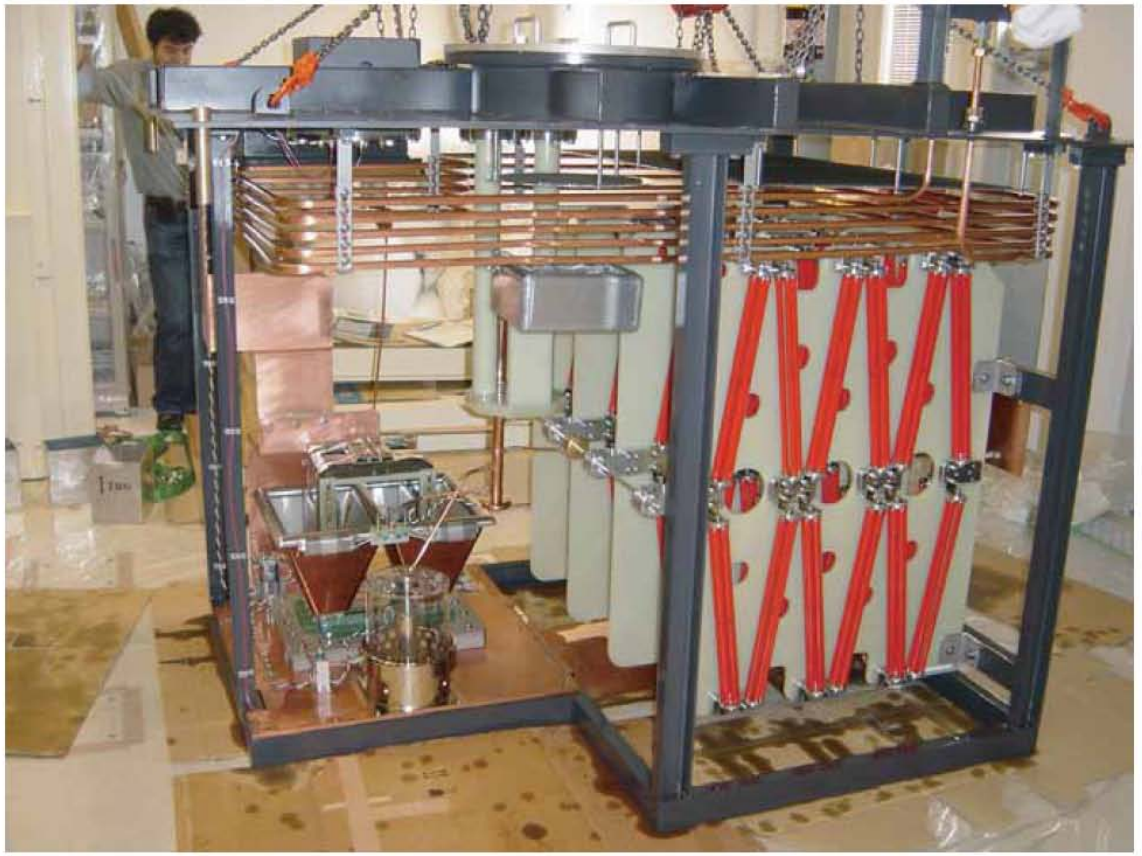

TOSHIBA E3746 No.3



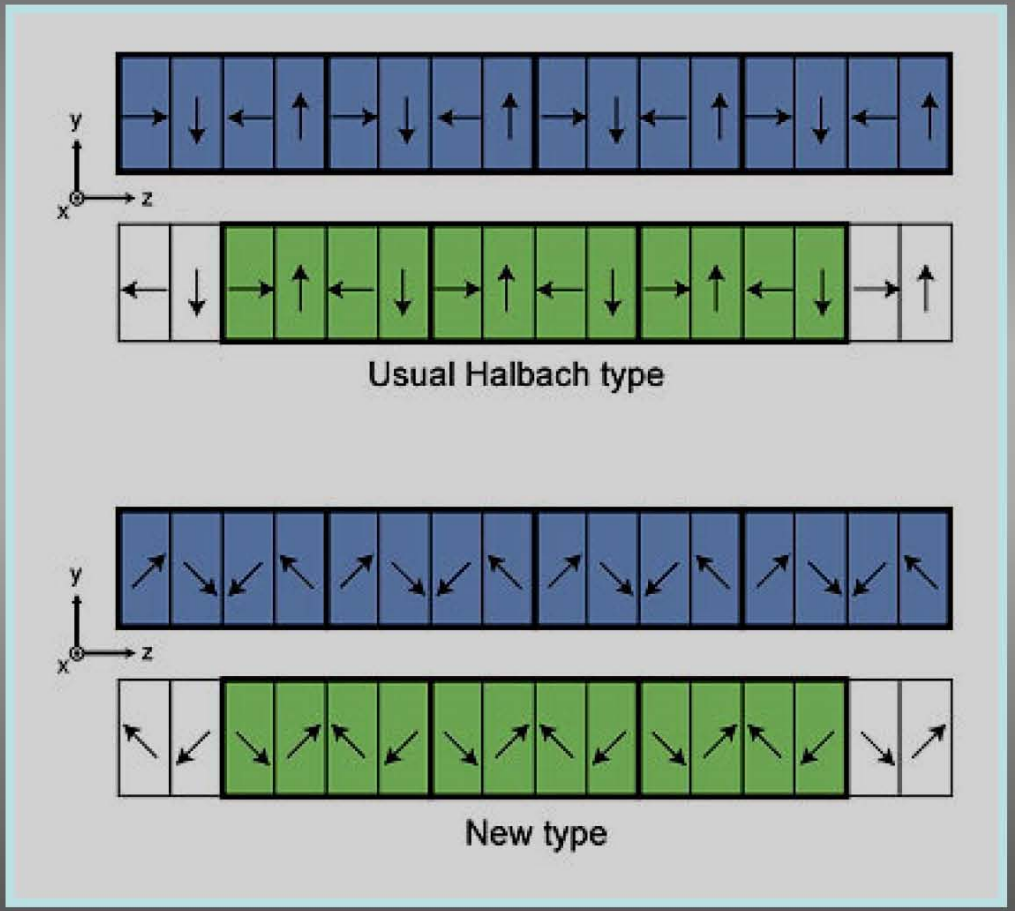




**53 MW, 2.5 μsec, 50 pps, 47%**

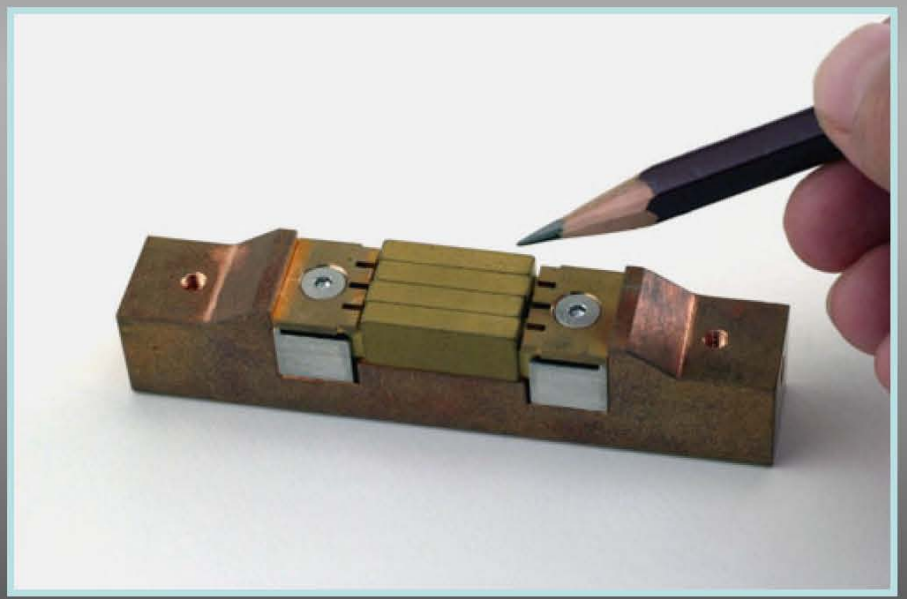
# HV Tank of SCSS Gun



# New Magnet Array



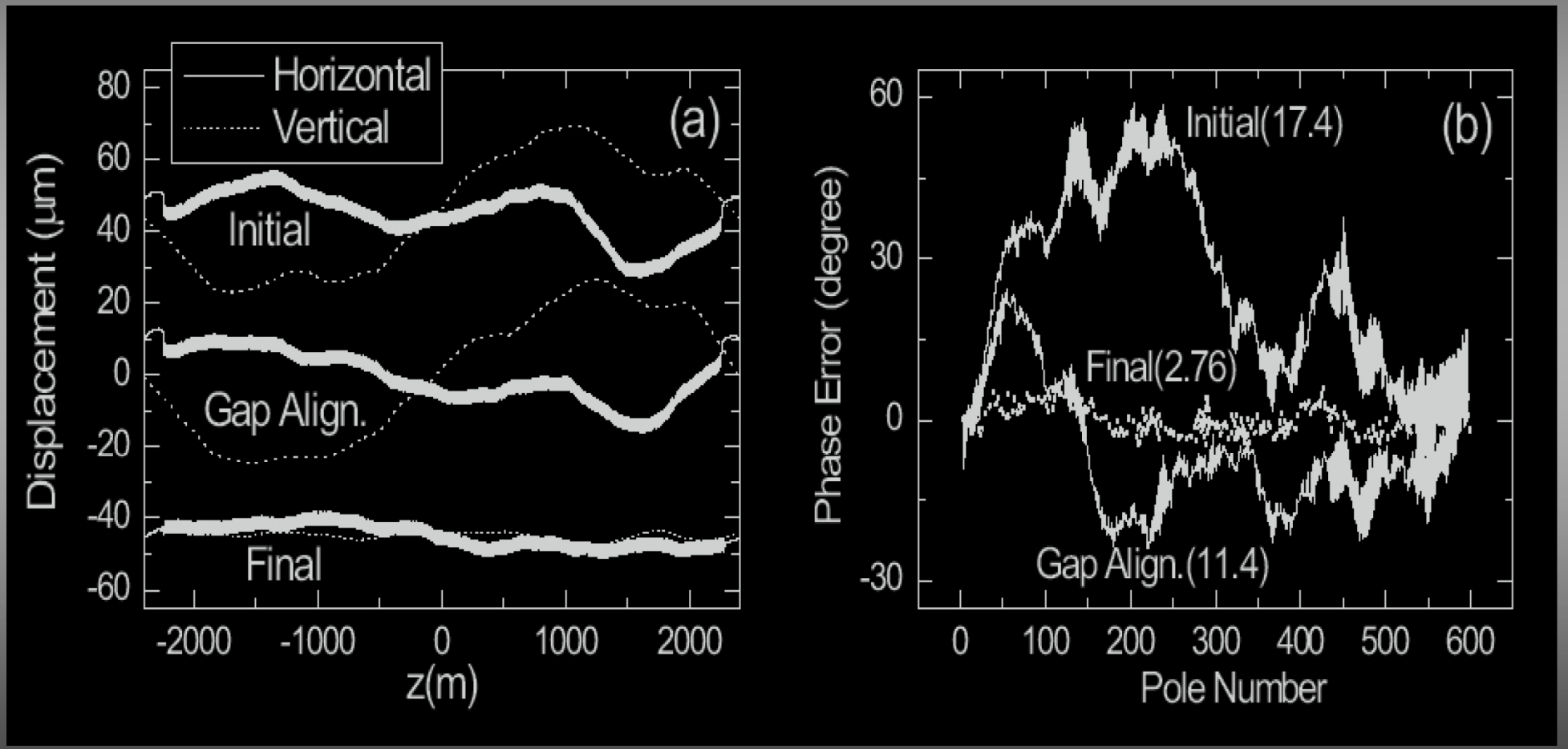

- Four magnets in one block
- 45-deg. tilted array
  - More freedom for in-situ sorting (field correction)



Magnet piece: thickness 3.75, pole face width 20, h 8 mm
NdFeB with TiN coating

# Field Performance of SCSS Undulator

*by T. Tanaka and T. Seike*



# Summary

- Electron gun system has been completed in 2003 Dec., and delivers stable beam in daily experiment. The measured emittance is 0.9 $\pi$.mm.mrad, which is obtained routinely.
- C-band accelerator system: RF components have been developed, and high power test will be started in March 2004.
- Prototype SCSS undulator has been developed and tuned.
- Alignment system using HeNe laser: preliminary test demonstrated capability of a few micrometer transverse alignment. Stable support table using ceramic has been developed.

# Next Step

## Move R&D phase to construction phase, 2005~

- **Need accelerator tunnel, about 80 m long for Phase-I SCSS: 1 GeV, 3.6 nm X-ray FEL.**

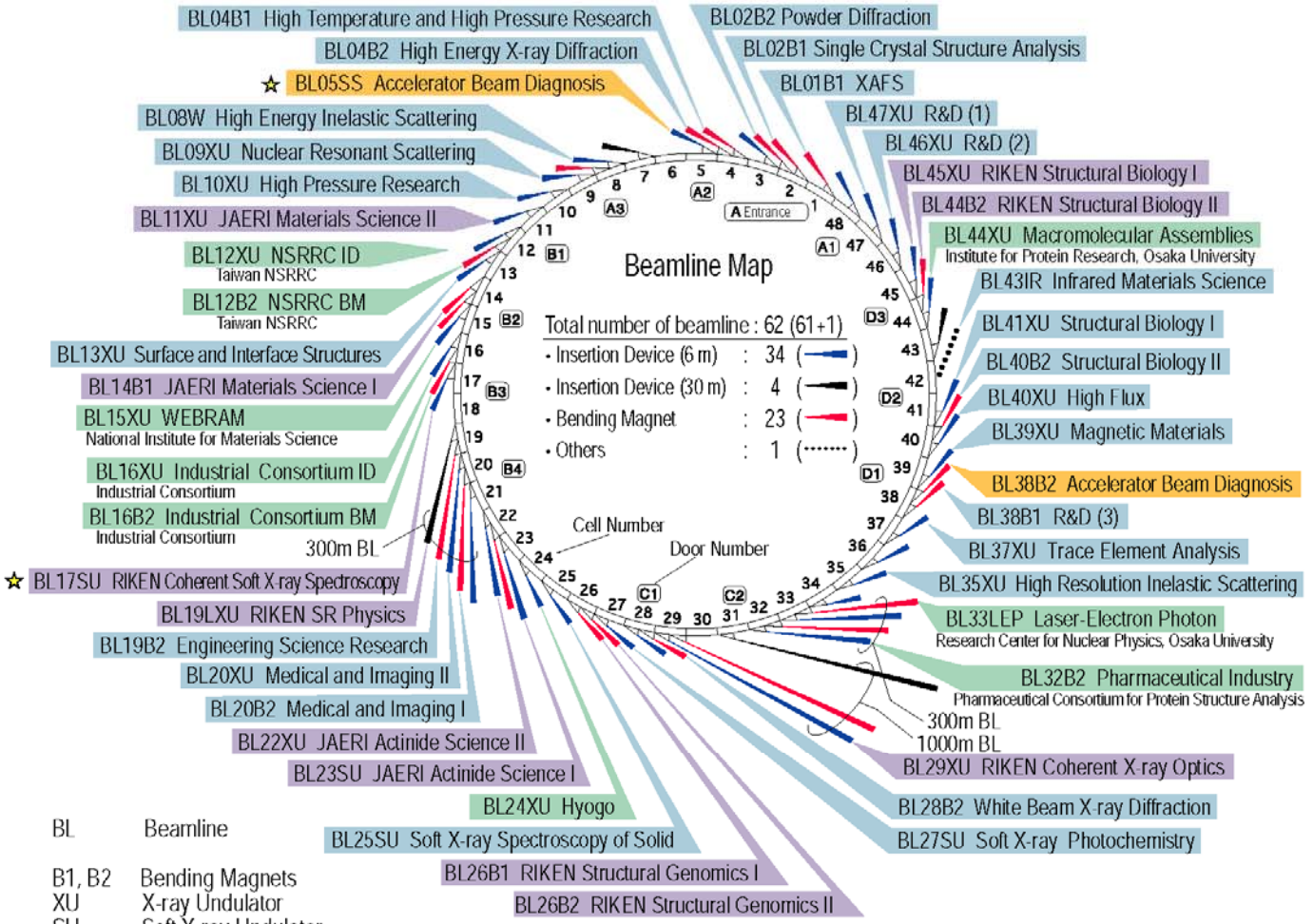
**Building 12 M$**

**(beam tunnel shielding, power supply housing, water cooling system, etc.)**

**Accelerator + X-ray Beam Line = 20 M$**

**(injector 2M$, C-band 3M$/unit x 4 , undulator x4, etc)**

# *X-ray Experiment at SPring-8*


BL04B1 High Temperature and High Pressure Research
BL04B2 High Energy X-ray Diffraction
☆ BL05SS Accelerator Beam Diagnosis
BL08W High Energy Inelastic Scattering
BL09XU Nuclear Resonant Scattering
BL10XU High Pressure Research
BL11XU JAERI Materials Science II
BL12XU NSRRC ID
Taiwan NSRRC
BL12B2 NSRRC BM
Taiwan NSRRC
BL13XU Surface and Interface Structures
BL14B1 JAERI Materials Science I
BL15XU WEBRAM
National Institute for Materials Science
BL16XU Industrial Consortium ID
Industrial Consortium
BL16B2 Industrial Consortium BM
Industrial Consortium
300m BL
☆ BL17SU RIKEN Coherent Soft X-ray Spectroscopy
BL19LXU RIKEN SR Physics
BL19B2 Engineering Science Research
BL20XU Medical and Imaging II
BL20B2 Medical and Imaging I
BL22XU JAERI Actinide Science II
BL23SU JAERI Actinide Science I
BL24XU Hyogo
BL25SU Soft X-ray Spectroscopy of Solid
BL26B1 RIKEN Structural Genomics I
BL26B2 RIKEN Structural Genomics II
BL27SU Soft X-ray Photochemistry
BL28B2 White Beam X-ray Diffraction
BL29XU RIKEN Coherent X-ray Optics
300m BL
1000m BL
BL32B2 Pharmaceutical Industry
Pharmaceutical Consortium for Protein Structure Analysis
BL33LEP Laser-Electron Photon
Research Center for Nuclear Physics, Osaka University
BL35XU High Resolution Inelastic Scattering
BL37XU Trace Element Analysis
BL38B1 R&D (3)
BL38B2 Accelerator Beam Diagnosis
BL39XU Magnetic Materials
BL40XU High Flux
BL40B2 Structural Biology II
BL41XU Structural Biology I
BL43IR Infrared Materials Science
BL44XU Macromolecular Assemblies
Institute for Protein Research, Osaka University
BL44B2 RIKEN Structural Biology II
BL45XU RIKEN Structural Biology I
BL46XU R&D (2)
BL47XU R&D (1)
BL01B1 XAFS
BL02B1 Single Crystal Structure Analysis
BL02B2 Powder Diffraction
Beamline Map
Total number of beamline : 62 (61+1)
• Insertion Device (6 m) : 34
• Insertion Device (30 m) : 4
• Bending Magnet : 23
• Others : 1
Cell Number
Door Number
A Entrance
A1
A2
A3
B1
B2
B3
B4
C1
C2
D1
D2
D3
BL Beamline
B1, B2 Bending Magnets
XU X-ray Undulator
SU Soft X-ray Undulator
W Wiggler
IR Infrared Radiation
LEP Laser-Electron Photon
LXU Long-length Undulator
SS Straight Section
WEBRAM : Wide Energy range Beamline for Research in Advanced Materials
NSRRC : National Synchrotron Radiation Research Center
N
Public Beamline
Contract Beamline
JAERI or RIKEN Beamline
Accelerator Beam Diagnosis Beamline
☆ : Planned or under construction

# X ray / soft-X ray Experiment

X-ray FEL

Experiment room

| | |
|---|---|
| $e^-$ beam energy: | 8 GeV |
| Storage ring: | 1436 m |
| Photon beam line: | 62 |

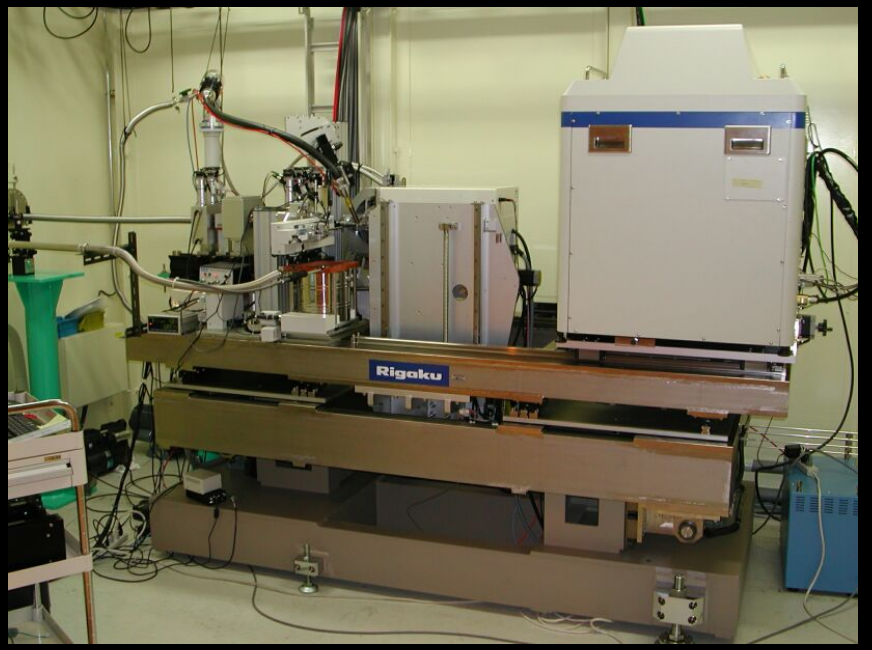
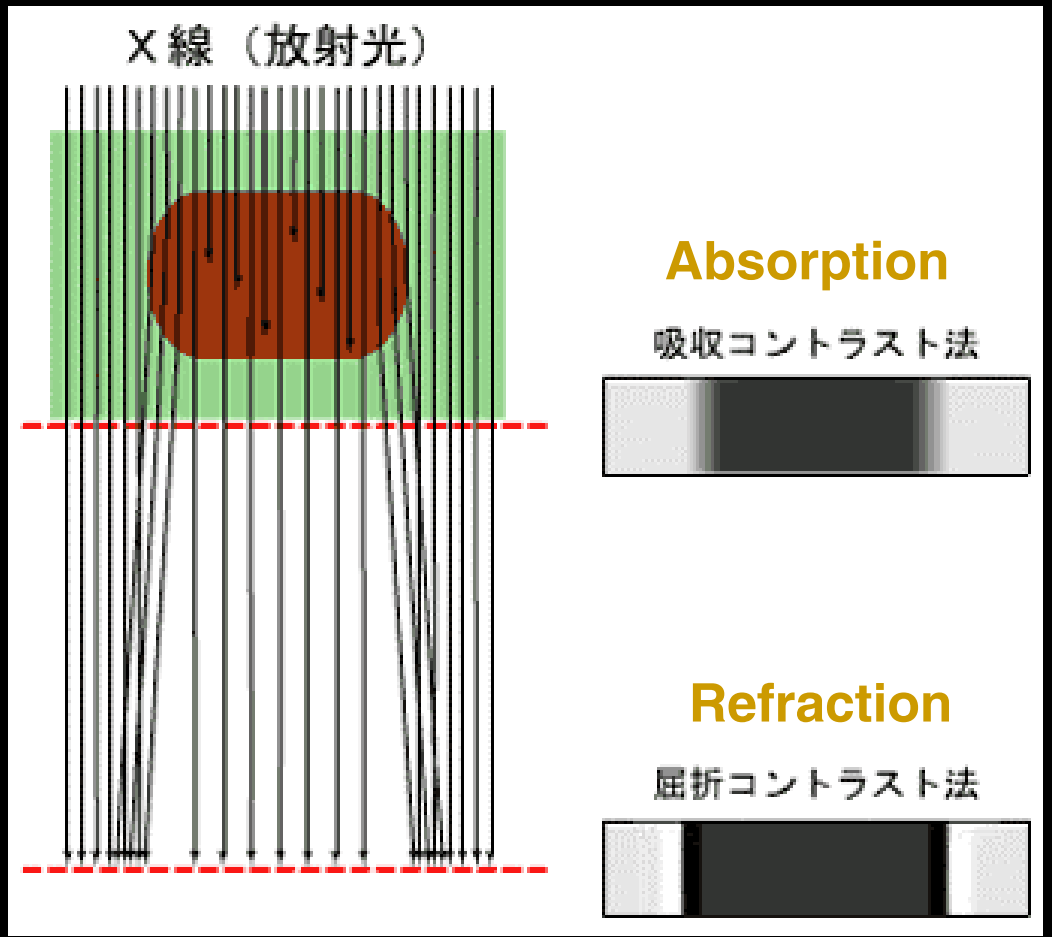


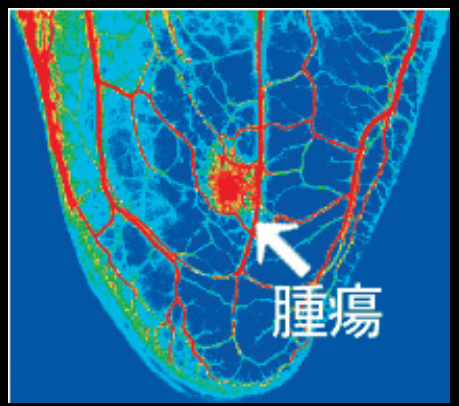

Photo detector
CCD & Imaging plate

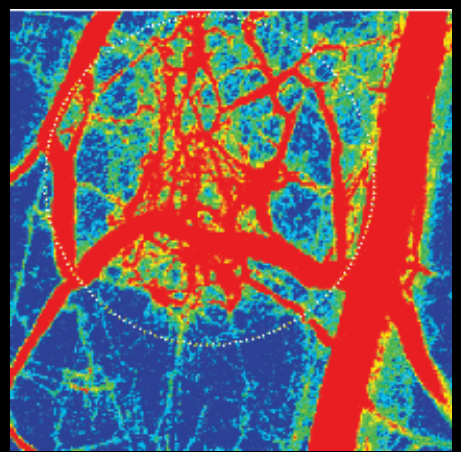
From… http://www.spring8.or.jp

# Imaging





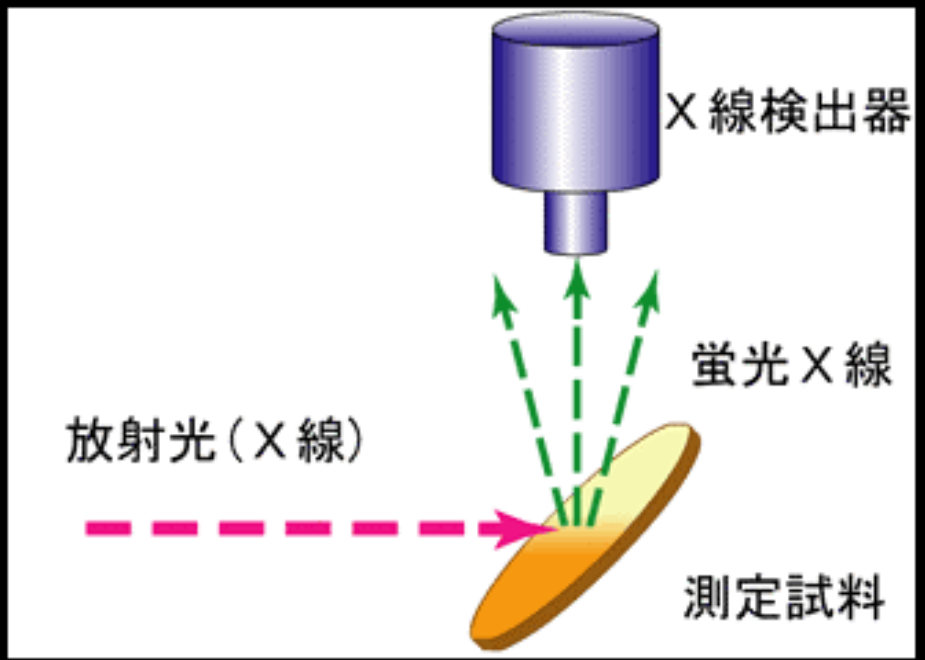



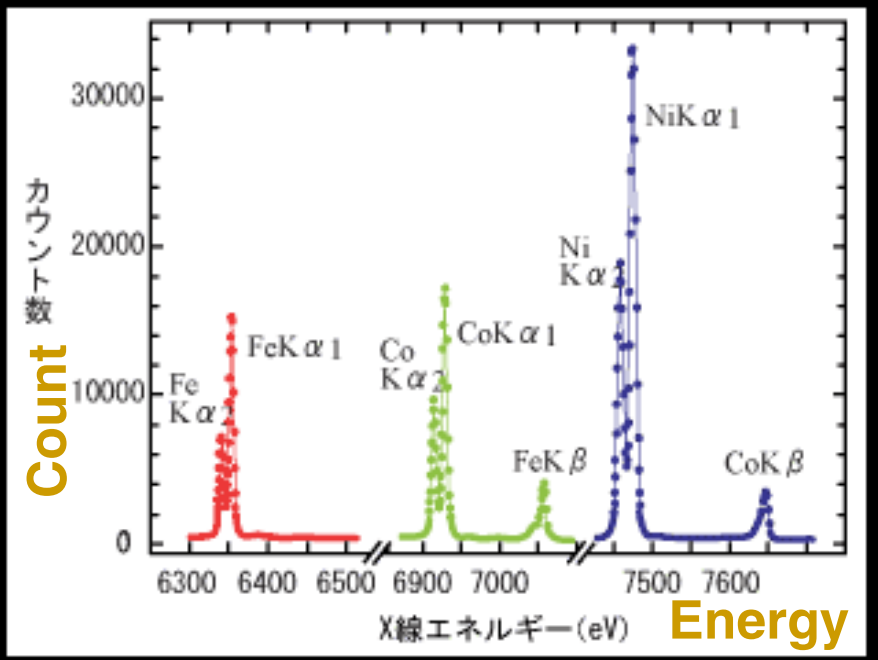
Cancer at ear of the rabbit

From… http://www.spring8.or.jp

# Fluorescence X-ray





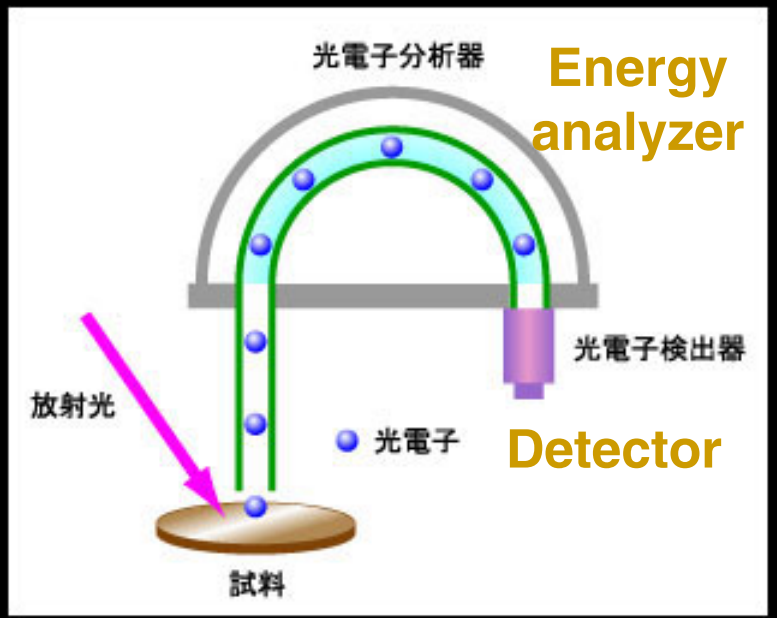



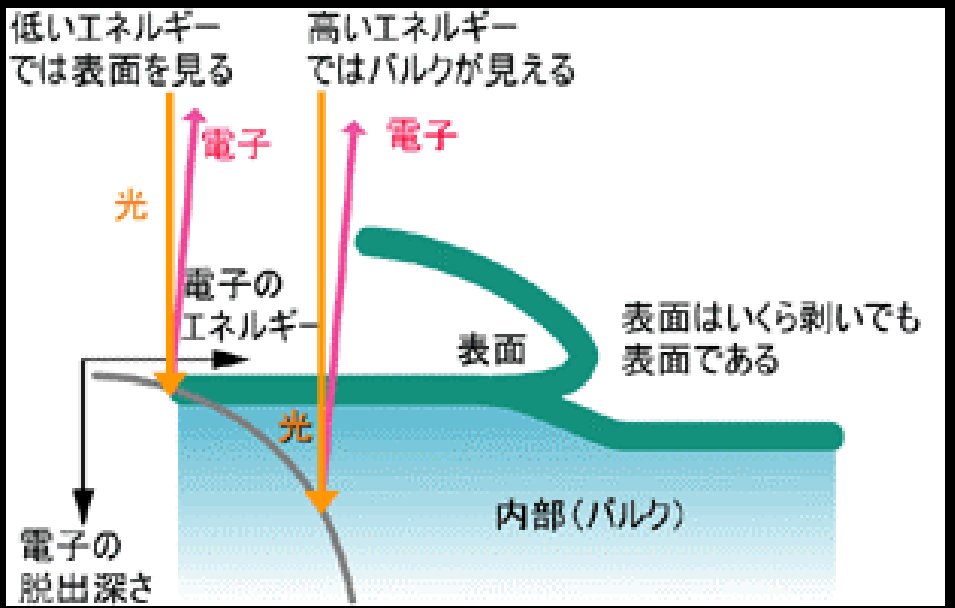

- Science: microanalysis（微量分析）
- Archaeology（考古学）
- Crime detection（犯罪捜査）

From… http://www.spring8.or.jp

# Photo Electron






- Material science

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# X-ray Diffraction



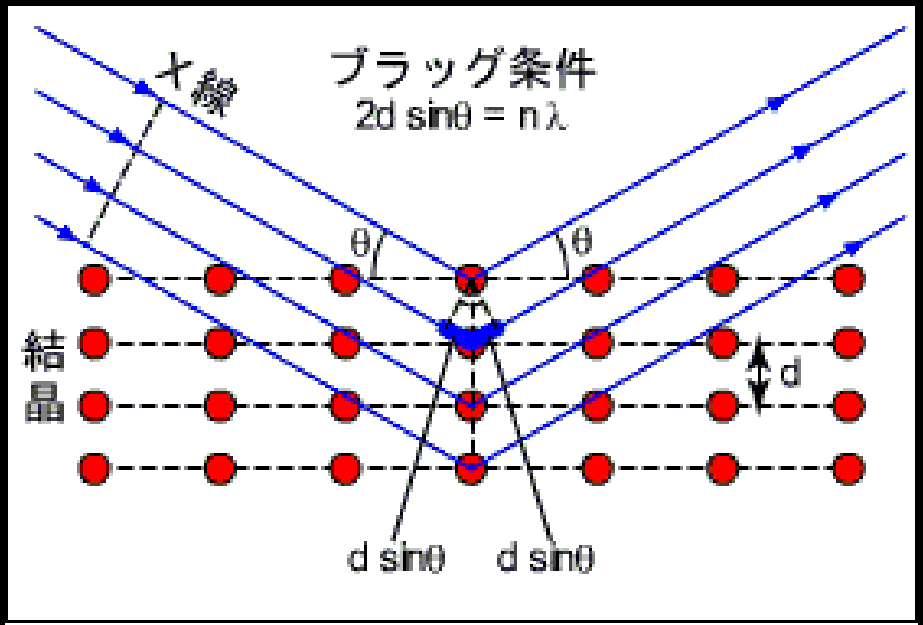
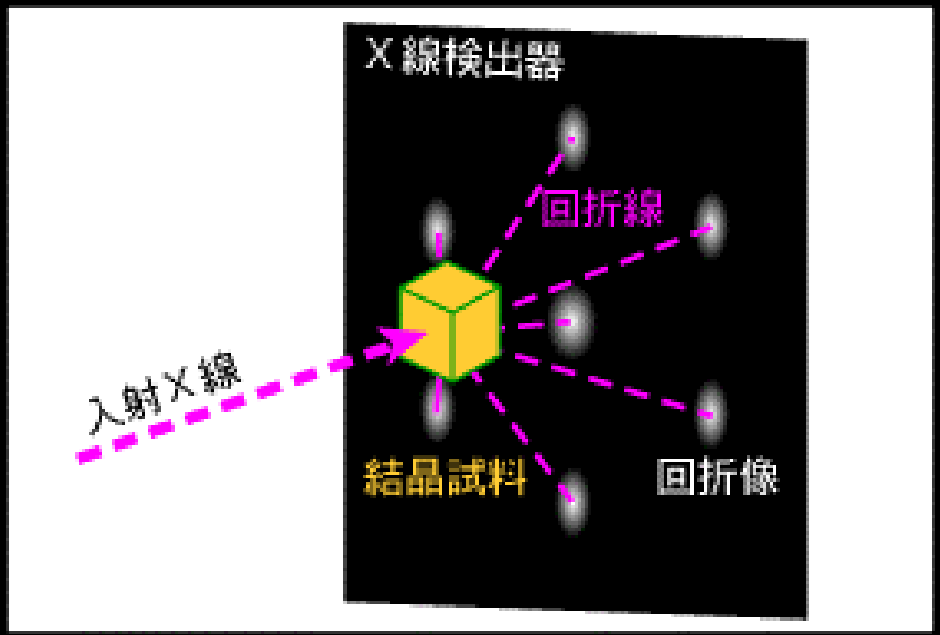



図1　X線の回折とブラッグ条件
d:結晶格子面の間隔、θ:X線の入射の角度、
n:正の整数、λ:X線の波長




- Material science
- Biological science
- Medical science

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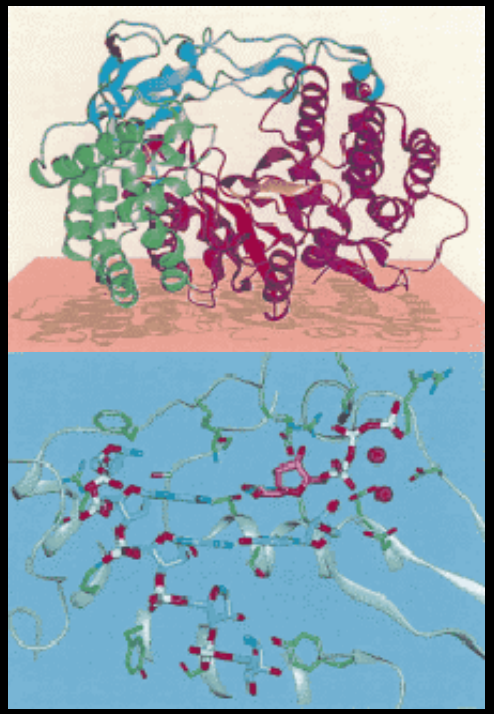
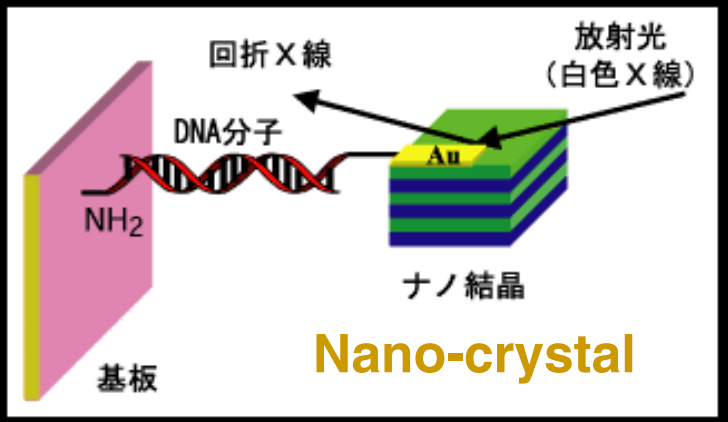
# Biological Application

X-ray FEL



Ferment（酵素）of
HCV（C型肝炎）virus RNA




Brown motion of DNA

“Protein 3000 project”
High-throughput Factory

From… http://www.spring8.or.jp

# LEPS: Inverse-Compton gamma ray

X-ray FEL

## クォーク5個から出来ている新しい粒子発見

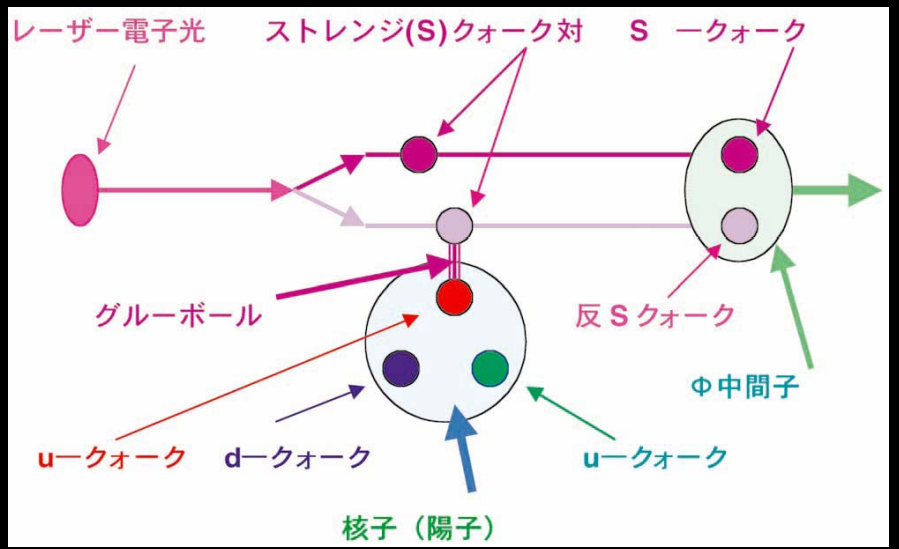
大阪大学核物理研究センター
教授　中野　貴志

**1. クォークとその複合粒子**

クォークは、物質を構成する最小の基本粒子で、アップ(u)、ダウン(d)、ストレンジ(s)、チャーム(c)、ボトム(b)、トップ(t)の6種類があります。地球上で安定な粒子は最も軽いクォー

しても）存在できるということになります。

そのような白色に中和されたクォークの複合粒子をハドロンと呼んでいます。ハドロンには、3個のクォーク（$qqq$）からなるバリオンとクォーク・反クォーク対（$q\bar{q}$）からなるメソンがあ

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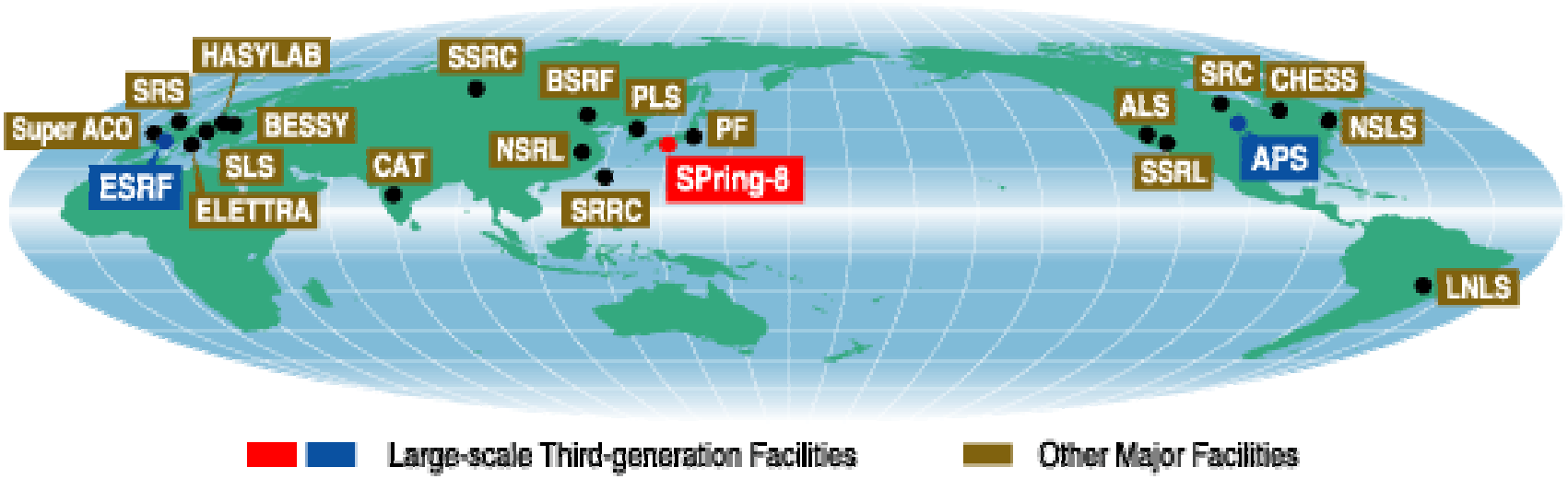
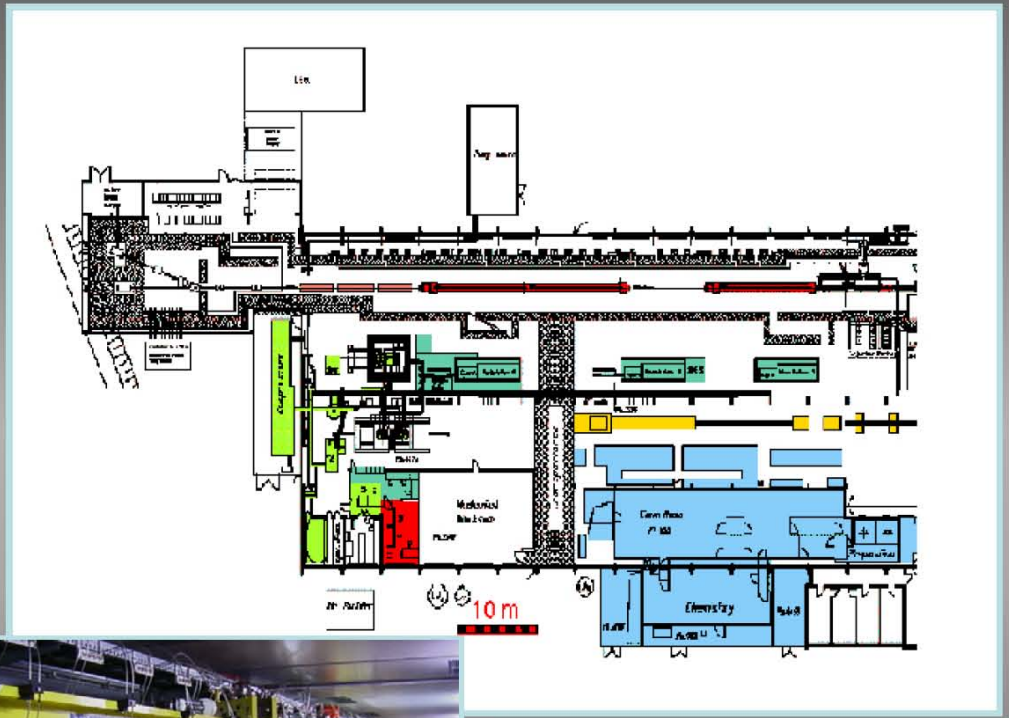
# Synchrotron Radiation in the world

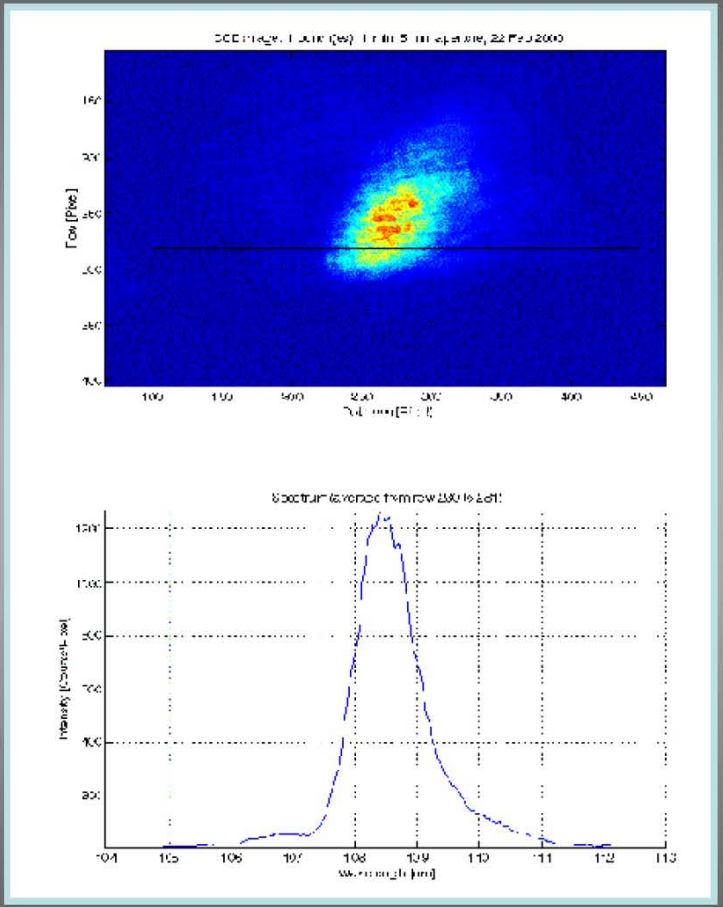
X-ray FEL



# TESLA-TTF at DESY

*First lasing Feb.22.2000*



**Wavelength record is 80 nm at TTF.**

*T. Shintake, Advanced Electron Beam Physics Laboratory*

# LCLS project at SLAC

- *Design 1.5 Å radiation with 14 GeV beam.*
- *Starting beam commissioning in Sep. 2008*

15 GeV Electrons **LCLS** 1.5 Å X-Ray

Linac Coherent Light Source