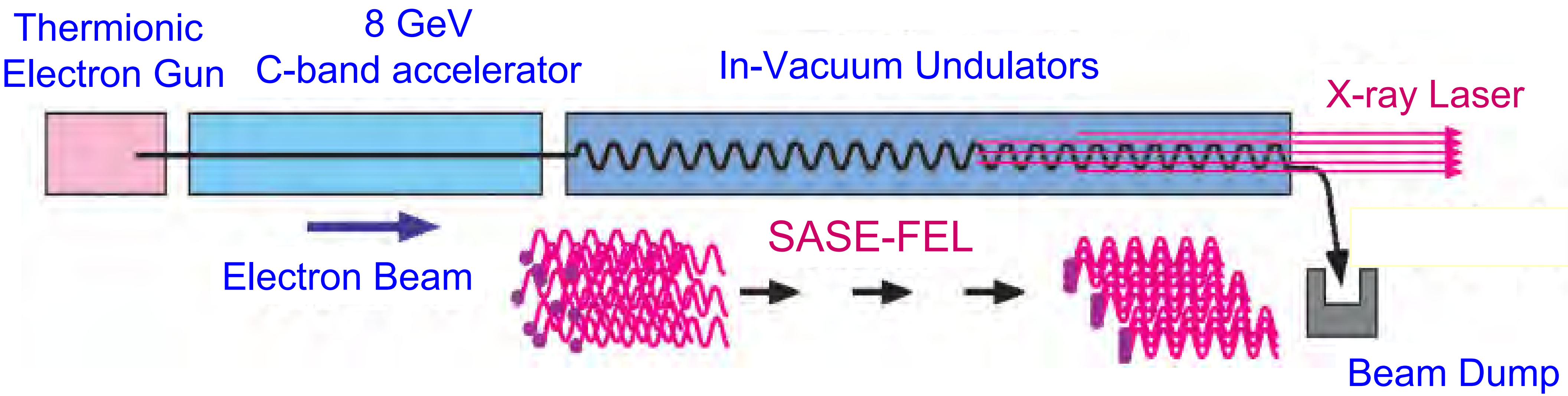
Current Status of X-ray FEL Project at SPring-8

Tsumoru Shintake

For Joint XFEL/SPring-8 Team


May 09 2009
SPring-8
Operating ten years
XFEL/SPring-8
Building construction
completed March 2009
SCSS Test Accelerator
Since 2006, EVU user facility

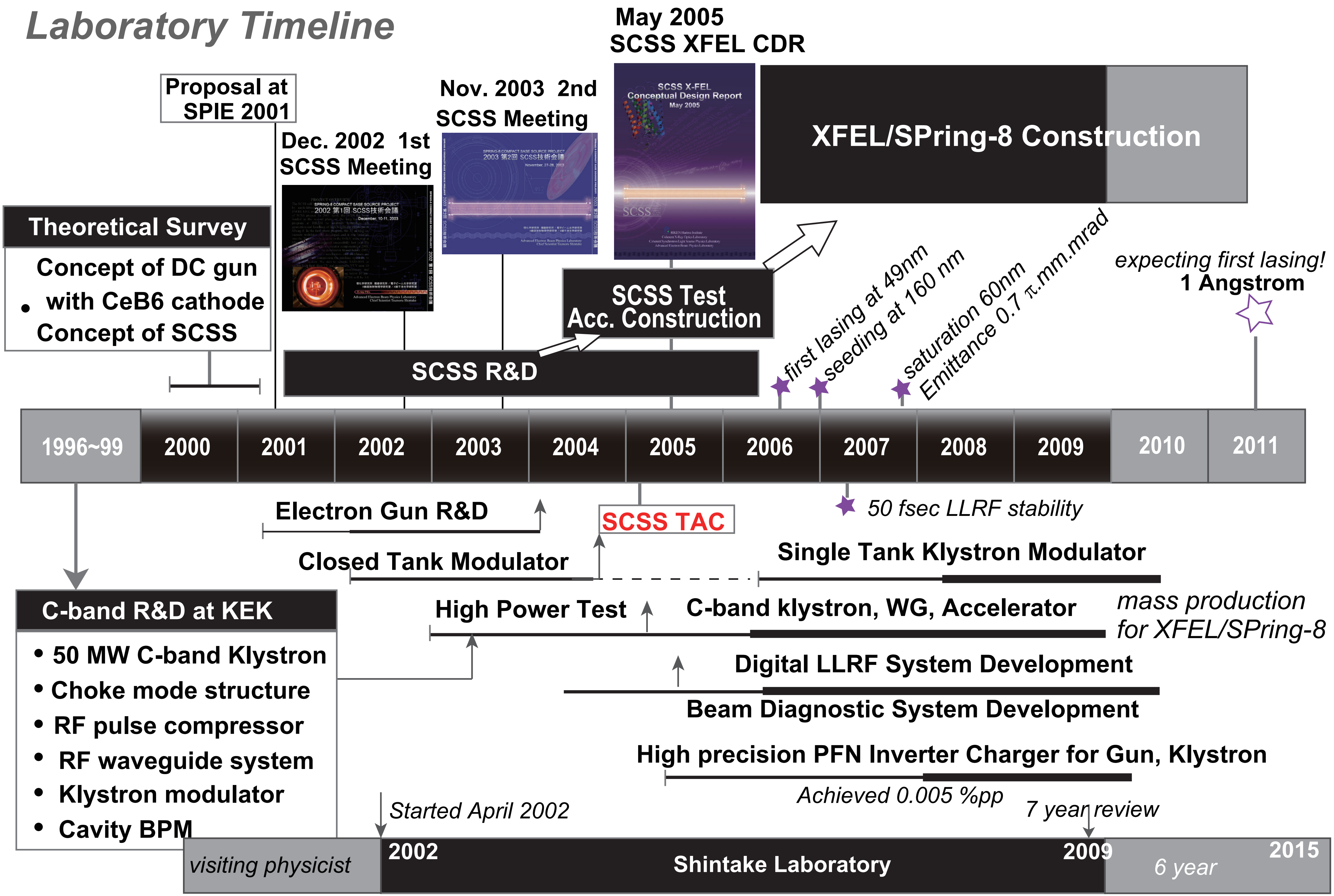
Concept of XFEL/SPring-8



1) **Electron gun** — **Low emittance** ($\varepsilon_N \sim 0.7\pi$ mm*mrad)
Higher electron density at the undulator.

2) **C-band accelerator** — **High gradient** ($E_a \sim 35$ MV/m)
Compact accelerator.

3) **In-vacuum undulator** — **Short period** ($\lambda_u \sim 18$ mm)
Shorter wavelength with lower electron energy.


Laboratory Timeline
Proposal at SPIE 2001
Dec. 2002 1st SCSS Meeting
Nov. 2003 2nd SCSS Meeting
May 2005 SCSS XFEL CDR
SCSS X-FEL
Conceptual Design Report
May 2005
SCSS
XFEL/SPring-8 Construction
Theoretical Survey
Concept of DC gun
with CeB6 cathode
Concept of SCSS
SCSS Test Acc. Construction
SCSS R&D
first lasing at 49nm
seeding at 160 nm
saturation 60nm
Emittance 0.7 π.mm.mrad
expecting first lasing!
1 Angstrom
1996~99
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
Electron Gun R&D
SCSS TAC
50 fsec LLRF stability
Closed Tank Modulator
Single Tank Klystron Modulator
C-band R&D at KEK
50 MW C-band Klystron
Choke mode structure
RF pulse compressor
RF waveguide system
Klystron modulator
Cavity BPM
High Power Test
C-band klystron, WG, Accelerator
mass production for XFEL/SPring-8
Digital LLRF System Development
Beam Diagnostic System Development
High precision PFN Inverter Charger for Gun, Klystron
Achieved 0.005 %pp
Started April 2002
7 year review
visiting physicist
2002
Shintake Laboratory
2009
6 year
2015

SCSS to XFEL/SPring-8 Timeline

- 2001~2003 SCSS R&D CeB$_6$ thermionic gun
- 2004~2005 **SCSS Test Accelerator** Construction
- **2006 June** **First Lasing 49 nm at test accelerator.**
- 2007 Oct. **Saturation at 50~ 60 nm**

0.6 π.mm.mrad @ 1 A DC, 500 kV

X 300 Compression

0.7 π.mm.mrad @ 300 A, 0.7 psec, 250 MeV, 0.3 nC

- 2006 April **XFEL/SPring-8 Construction** was funded.
  Beam optics design. Technical design.
  2007 Technical design, contract.
- 2008 Mass-production of hardware components.
- 2009 March. Linac, Undulator hall building completed.
  Hardware installation.
- 2010 Oct. High power processing 8 GeV accelerator.
- **2011 April**~ Beam commissioning. First lasing at 1 A.

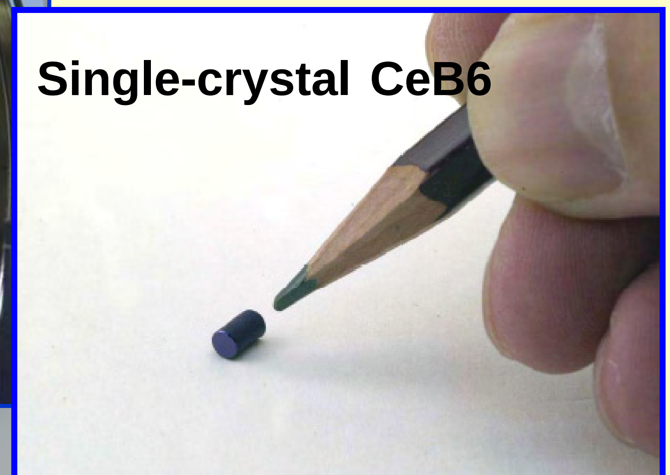
X 10 Compression

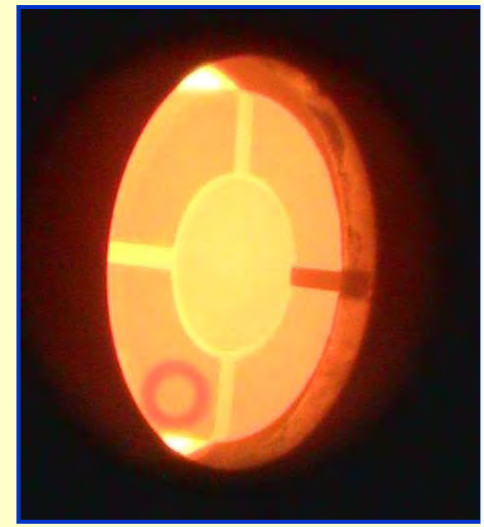
0.8 π.mm.mrad @ 3k A, 8GeV

Single-crystal CeB_6 Cathode for the SCSS Low-emittance Injector

No HV breakdown
for 4 years daily operation

After 20,000 hours operation
1 crystal changed.





Heating Cathode

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

Use Small Size Cathode

…First Strategy for smaller thermal emittance

- *Thermionic cathode*

3*mm* *diameter cathode (CeB6) is used in a low emittance injector. (SCSS SPring-8/RIKEN)*

Operating Temperature 1450°C

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

Thermal Emittance

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

0.28 π mm-mrad/mm

- *RF photo-cathode injector.*

Today's RF photo injectors use ~ 1 mm spot radius.

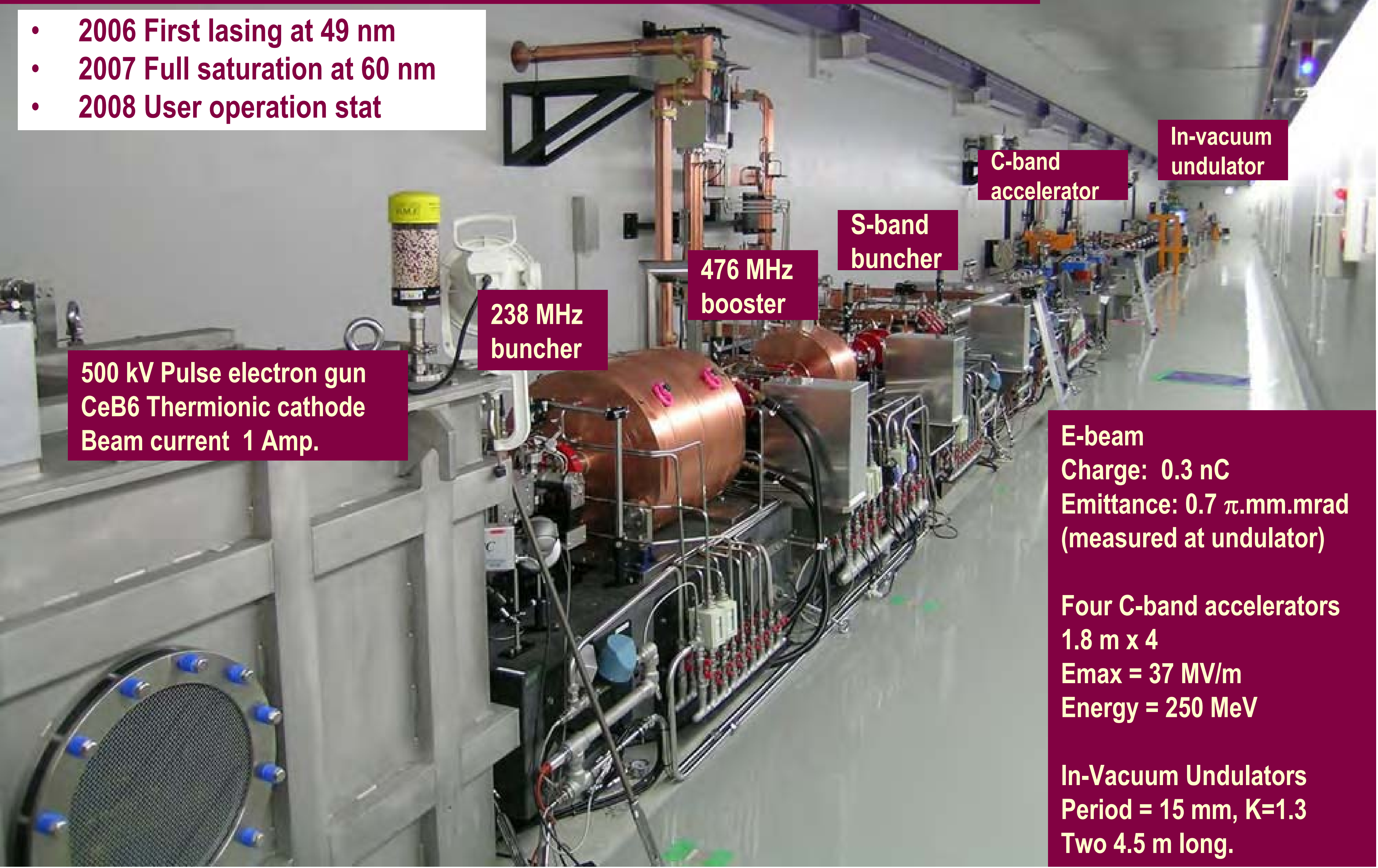
$$\varepsilon_{xN} = \frac{\gamma r_c}{2} \sqrt{\frac{k_B T_e}{m_0 c^2}} = 0.35\ \pi \text{ mm-mrad}$$

Same order!

T_e is "measured" effective electron temperature of copper cathode using 266 nm laser (ref. 2). k T_e = 0.27 eV (2360°C).

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)

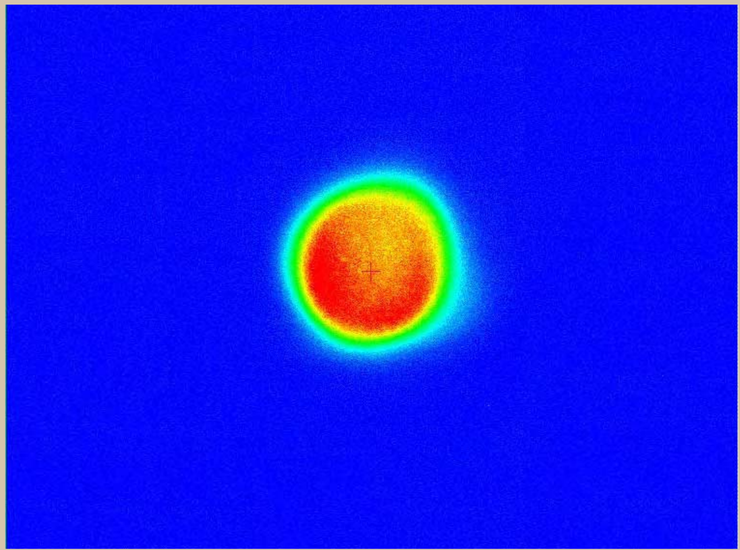
Four C-band accelerators
1.8 m x 4
Emax = 37 MV/m
Energy = 250 MeV

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

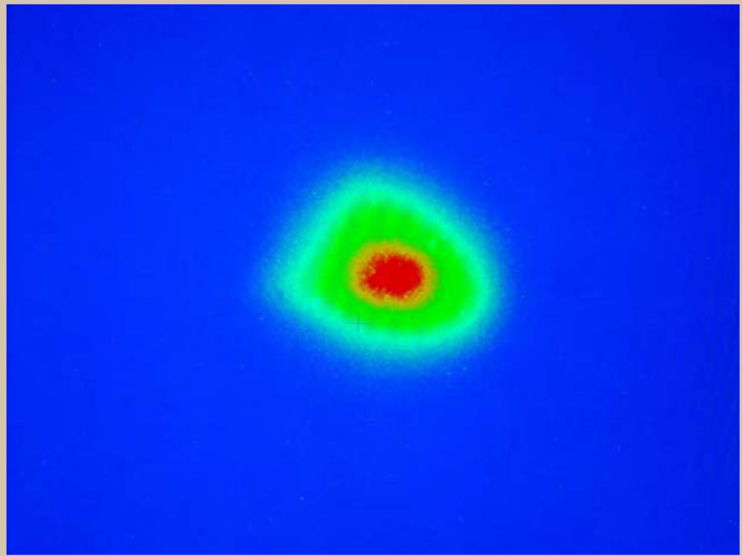
T. Shintake, FEL06

CeB_6 Thermionic Gun provides stable beam.

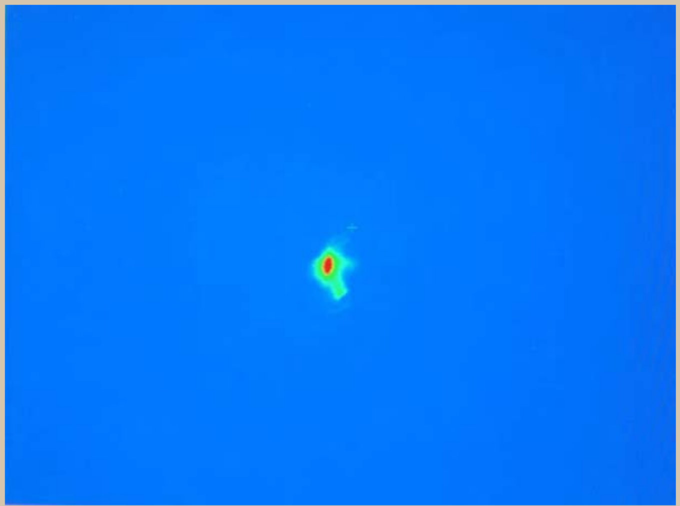
Beam Profile
CCD Image
Scale 10 mm



500 kV Gun

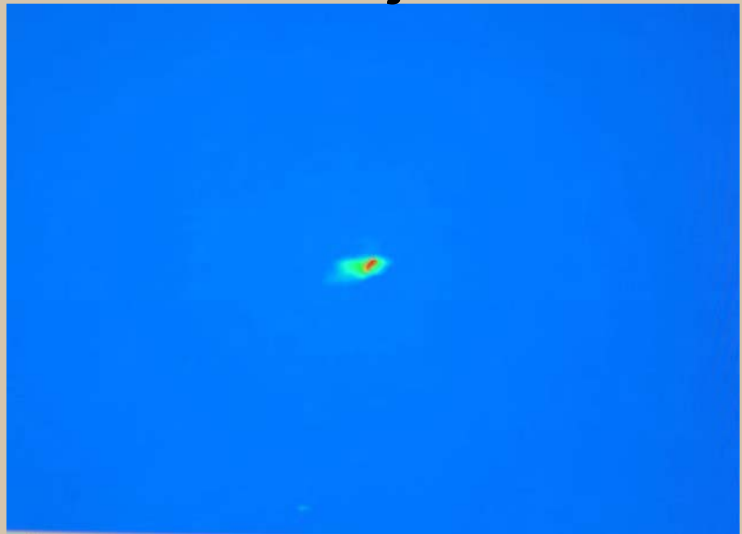


50 MeV Injector Out



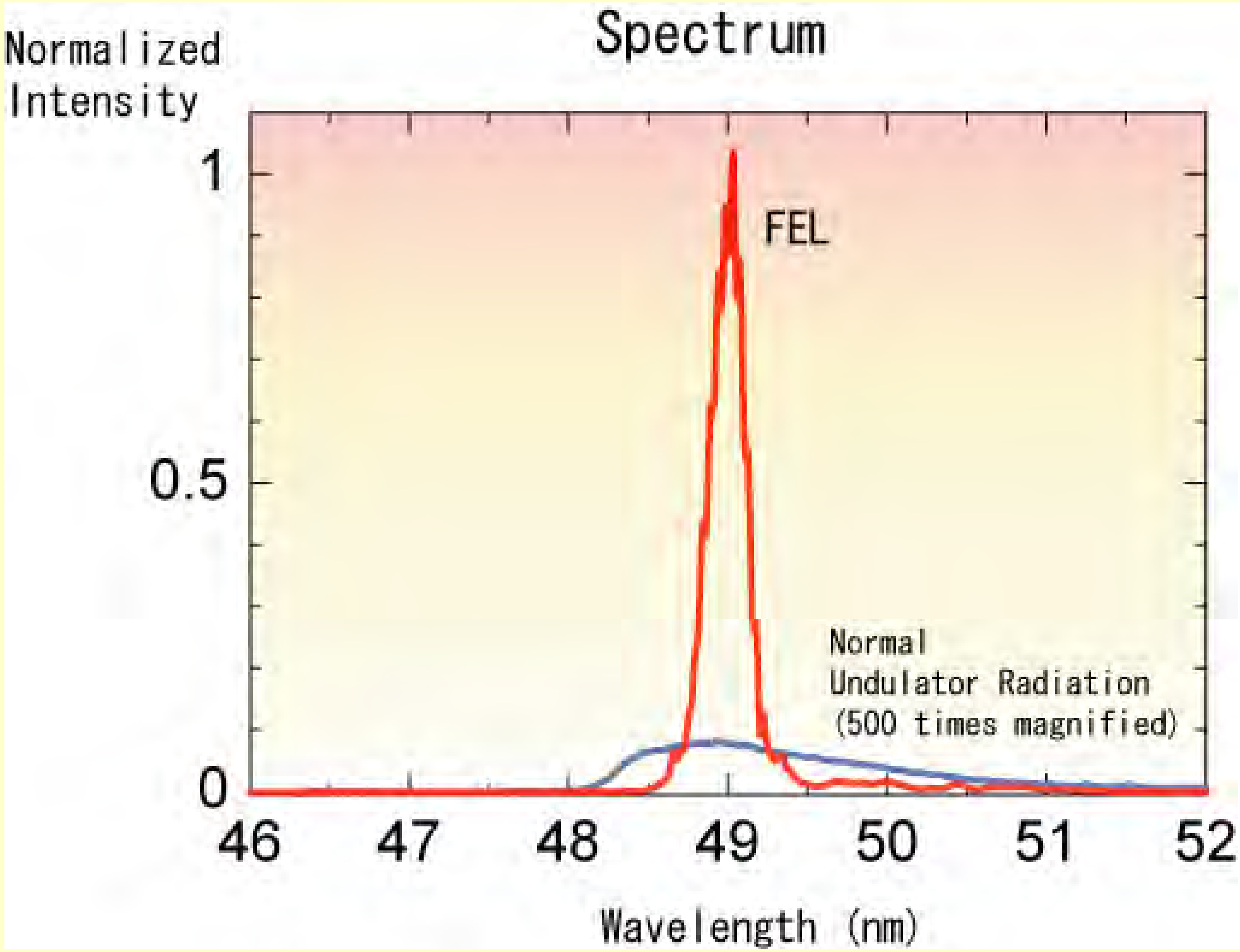
250 MeV Compressor

Undulator Input



Undulator Output

First Lasing at SCSS Prototype Accelerator.



- **The first lasing: 49 nm**
- **E-beam energy : 250 MeV**
- **Bunch charge: 0.25 nC**
- **Bunch length: (< 1 pse)**
- **Peak Current (> 300 A)**

- **At moment spectrum width 0.5 nm is dominated by e-beam energy fluctuation ~ 0.2%.**

First Lasing at SCSS Prototype Accelerator.

June 15, 2006

Thinking big. Tsumoro Shintake with a prototype XFEL at SPring-8.

MATERIALS SCIENCE

Japanese Latecomer Joins Race To Build a Hard X-ray Laser

X-ray free-electron lasers are the next big thing in high-energy probes of matter. With U.S. and European machines in the works, Japan wants into the club

SAYO, HYOGO PREFECTURE, JAPAN—It's the scientific version of keeping up with the Joneses. Once researchers in one region plan a big, new experimental device, researchers everywhere want their own. The latest example: x-ray free-electron lasers (XFELs), which promise beams that are vastly brighter and with higher energy and shorter pulses than today's workhorse synchrotron x-rays.

These "hard" x-ray wavelengths—down to 0.1 nanometer—promise to reveal the struc-

broad interest for science, it is no surprise that [researchers] in three regions of the world want to have a facility of their own," says Reinhard Brinkmann, who leads the European effort based at the German Electron Synchrotron (DESY) research center in Hamburg. "Free-electron lasers are amazing things which herald a new era in photon science," says Janos Hajdu, a synchrotron radiation specialist at Uppsala University in Sweden.

XFELs rely on new approaches to gener-

or oscillating in lockstep—a quality missing from synchrotron light.

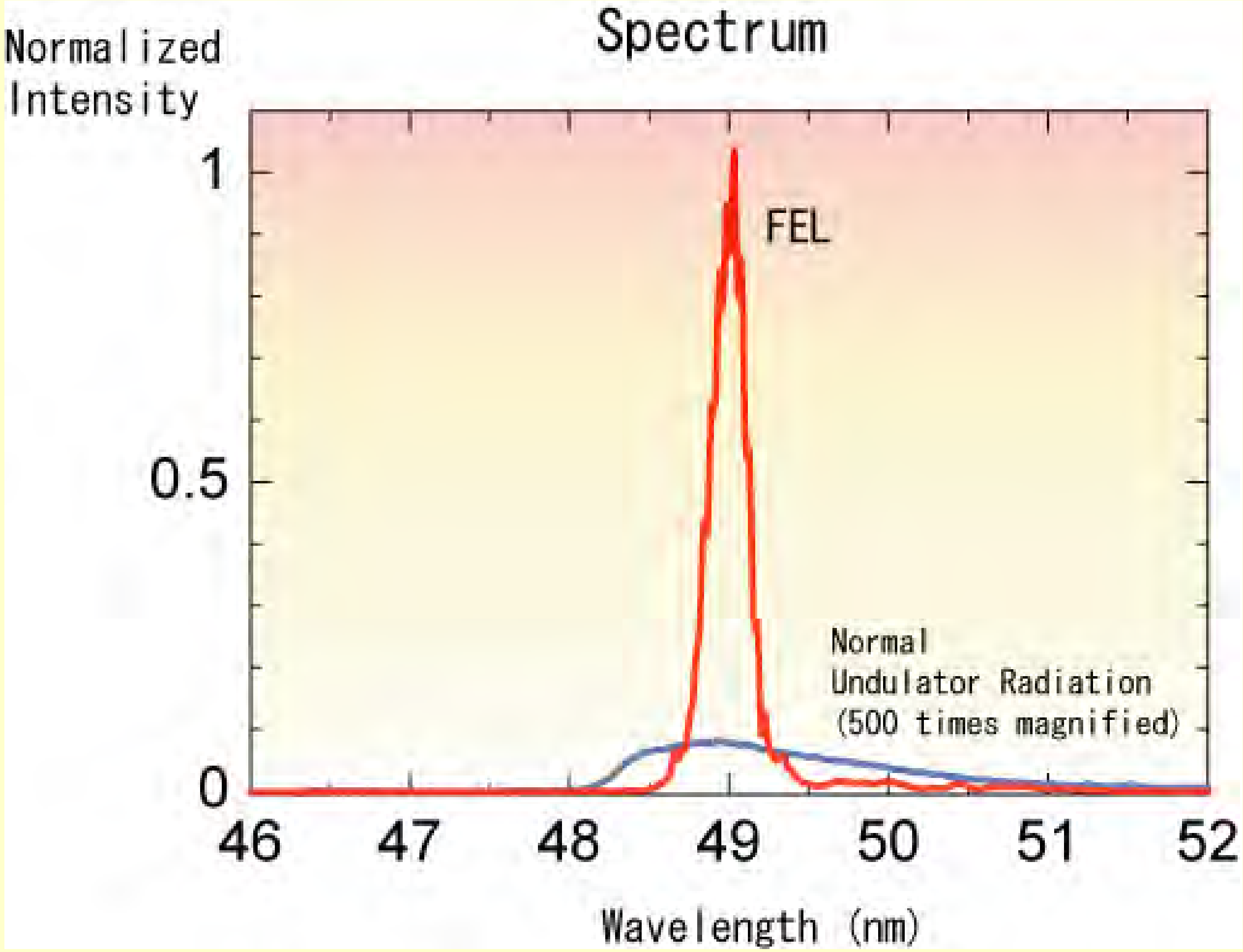
Although all three planned systems share the same basic setup, subtle differences give each of them strengths and weaknesses. "The final targets of the XFEL projects are the same, but the means are different," says Tsumoru Shintake, who heads accelerator development for Japan's XFEL.

The first project to come online will be Stanford's LCLS. Much of the key research underpinning XFELs was done at SLAC beginning in the early 1990s. And SLAC got a head start by using a 1-kilometer stretch of its now-idled linear accelerator, or linac. The SLAC group estimates that reusing its linac has saved more than $300 million, giving a total construction cost of $379 million. LCLS will have one undulator providing hard and soft x-rays to up to six experimental stations. Galayda says the group expects to generate its first x-rays by July 2008 and to start experiments by March 2009.

Japan's entry is the SPring-8 Compact SASE Source (SCSS), just now getting under construction here. Latecomers to the field, the team is using some homegrown technology to cut cost and size. "We're taking the first step toward making XFELs smaller and cheaper so more [institutions] can consider developing their own," boasts SCSS project leader Tetsuya Ishikawa. Whereas the other two machines will generate electrons by firing a laser at a metal target, the SCSS heats a cathode to produce electrons. Eliminating the laser simplifies the system but requires careful compression of the cloud of electrons before they go into the linac.

The wavelength of the output x-rays is a tradeoff between the energy of the electrons

First Lasing at SCSS Prototype Accelerator.



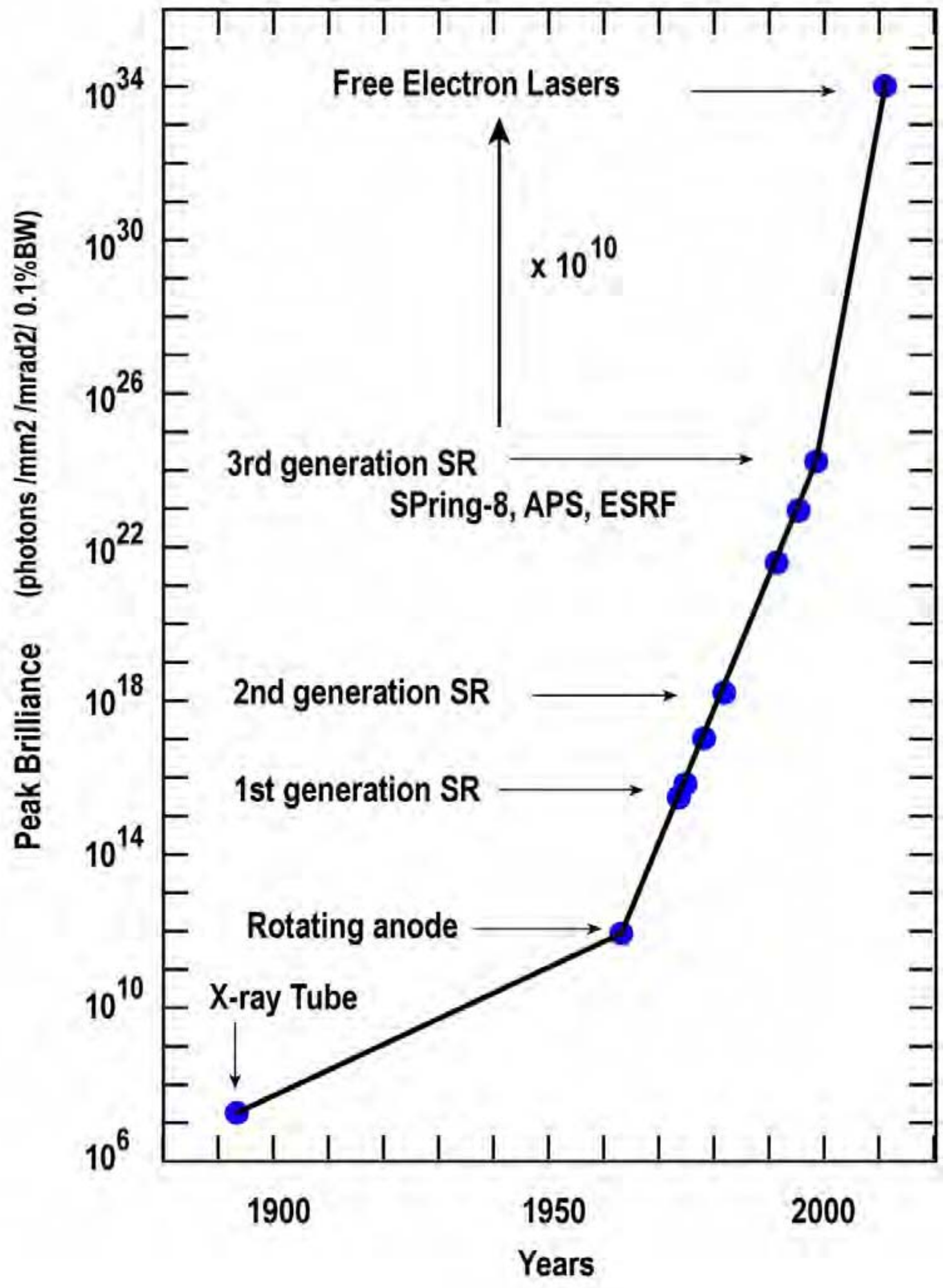
- **The first lasing: 49 nm**
- **E-beam energy : 250 MeV**
- **Bunch charge: 0.25 nC**
- **Bunch length: (< 1 pse)**
- **Peak Current (> 300 A)**

- **At moment spectrum width 0.5 nm is dominated by e-beam energy fluctuation ~ 0.2%.**

SCSS Test Accelerator User Run Has been Started in 2008

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

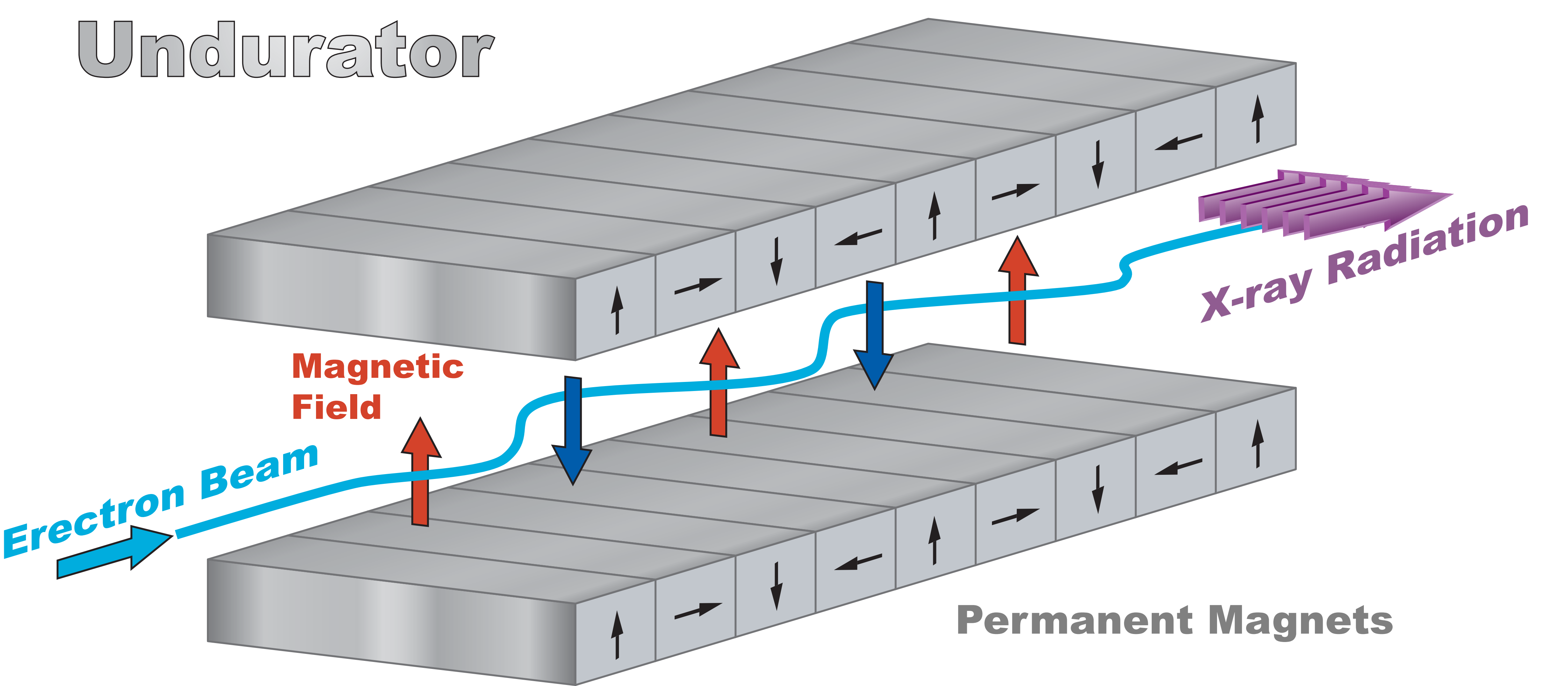
Peak Brilliance Evolution



- Peak brilliance will be enhanced by factor of 10^{10} from 3rd generation SR to XFEL.

- $10^{10} = 10^1 \times 10^1 \times 10^1 \times 10^7$

  = peak current by factor 10
  x lowered emittance by 10
  x energy spread lowered by 10
  x interference effect 10^7 by micro-bunching formation.

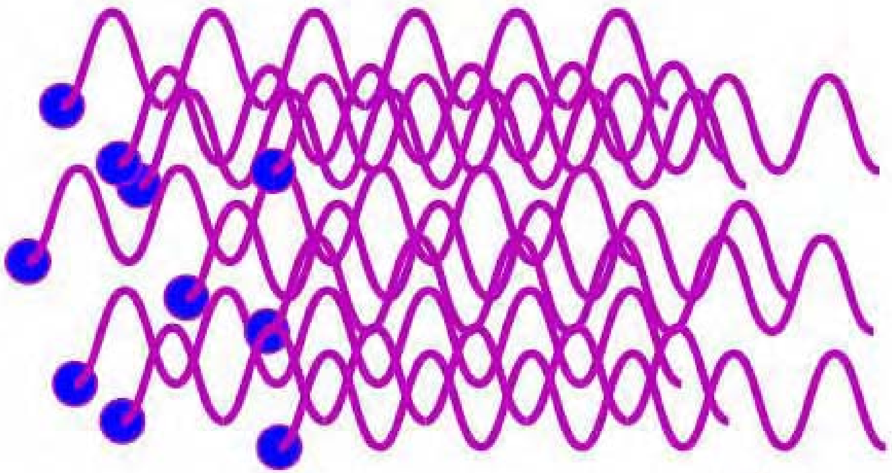

Undurator
Magnetic
Field
Erectron Beam
X-ray Radiation
Permanent Magnets

Freeware Radiation2D is available at http://ShintakeLab.com

From SR to FEL

SR or ERL

Spontaneous Radiation



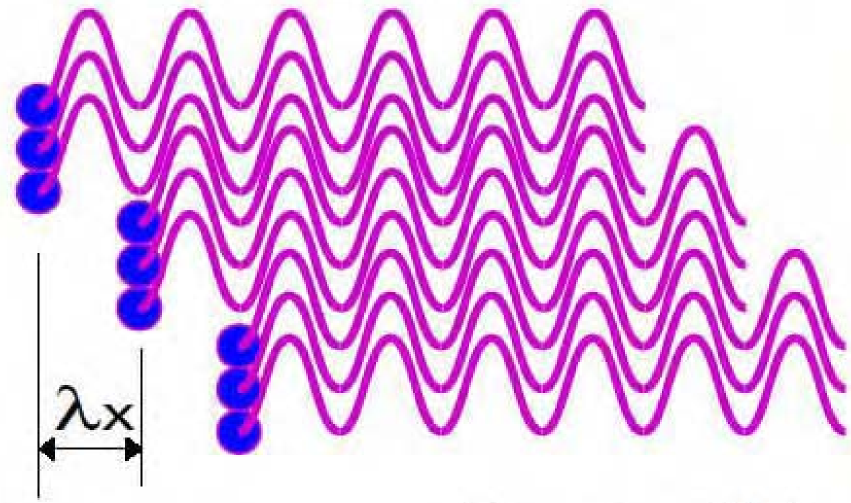
***N*-electrons**
random distribution

$E_{spt} \sim \sqrt{N}\, E_1$

$P_{spt} \sim N\, P_1$

FEL: Free Electron Laser

Coherent Radiation



***N*-electrons**
micro-bunched

$E_{coherent} \sim N\, E_1$

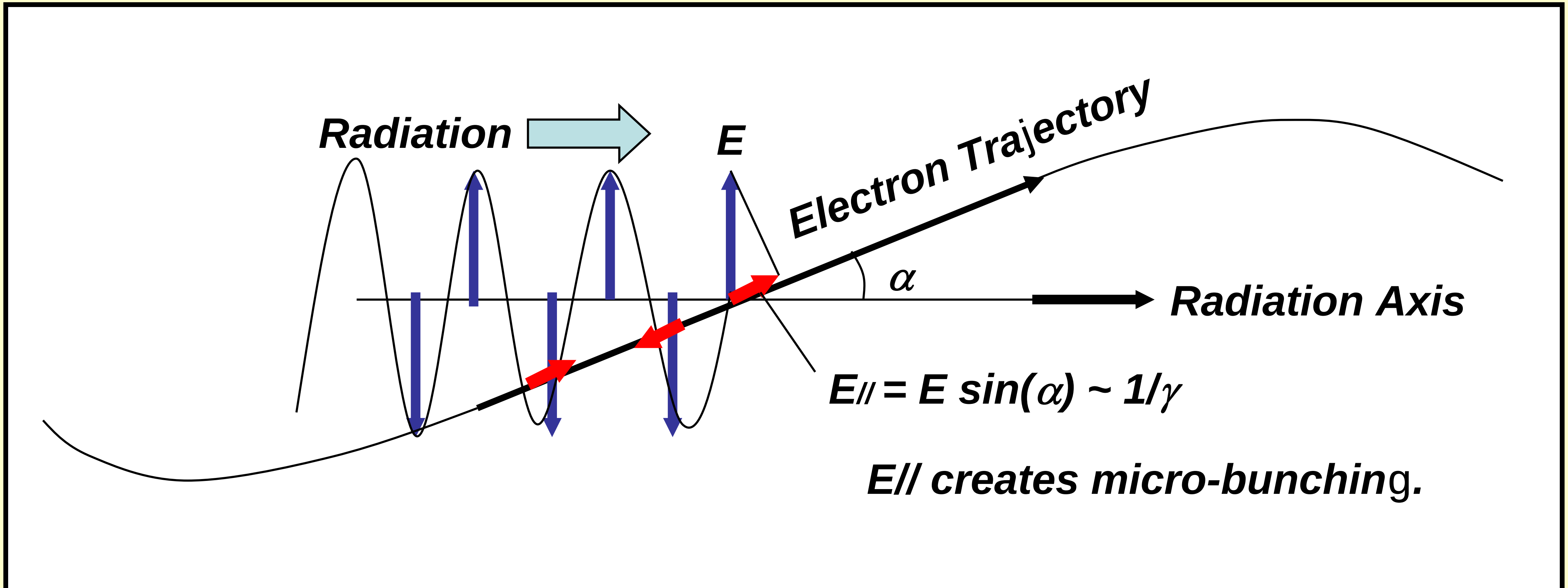
$P_{coherent} \sim N^2 P_1$

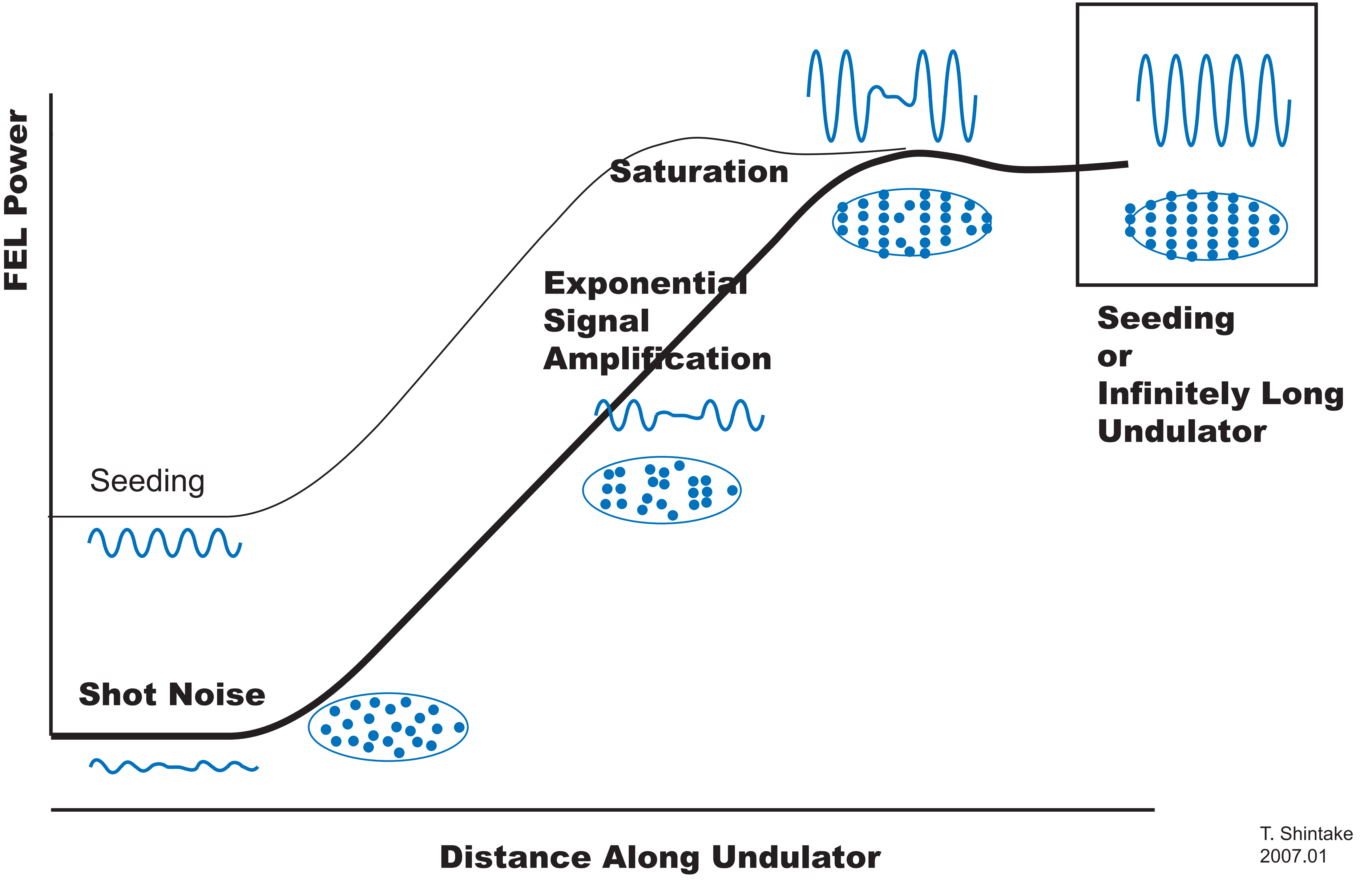
Optical Power Enhancement

$\times 10^5 \sim 10^8$

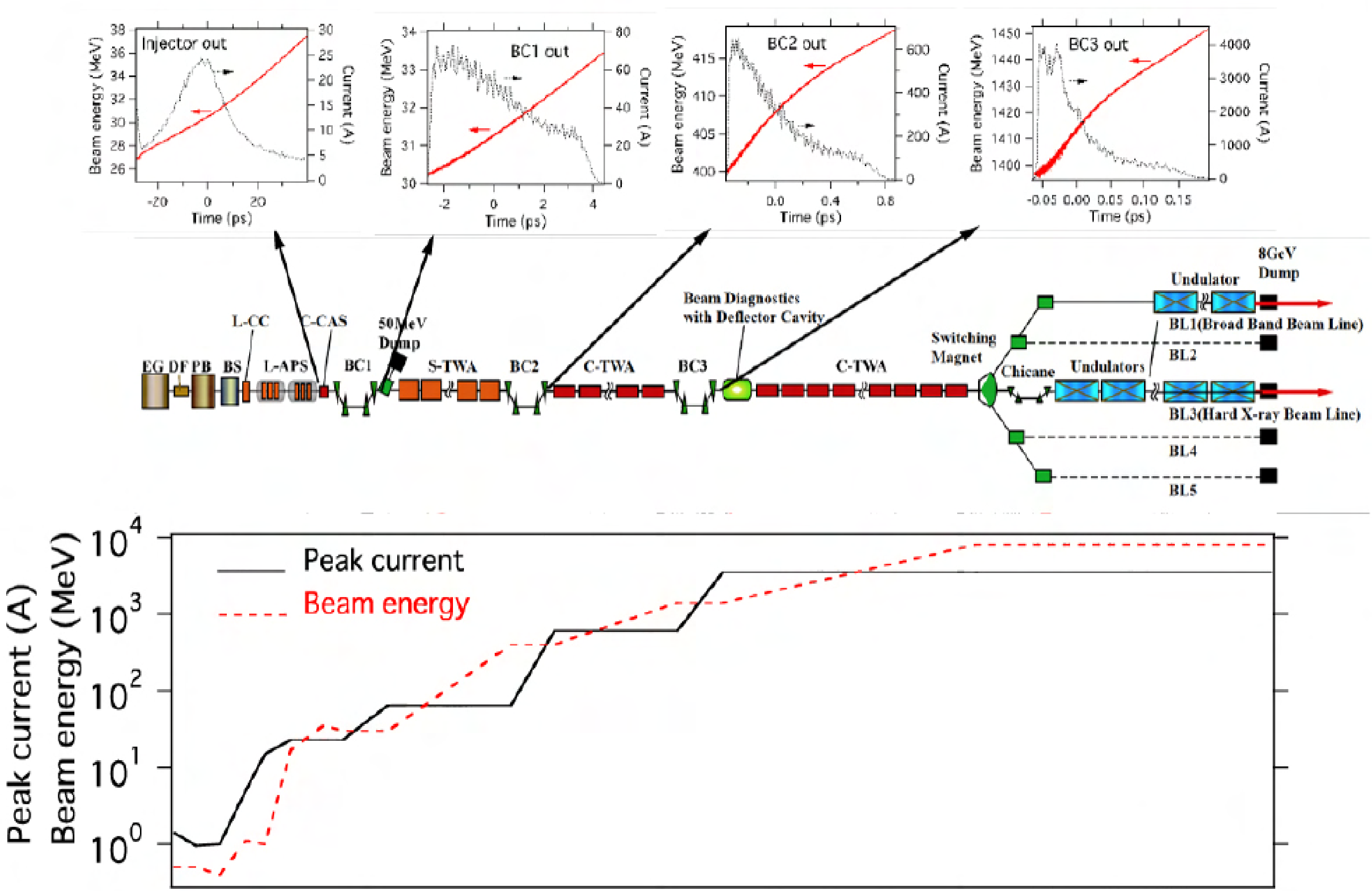
Physical Origin of Micro-bunching (FEL Action)

- Undulator field produces curved trajectory. From this slope, the tangential component of EM wave creates longitudinal field.



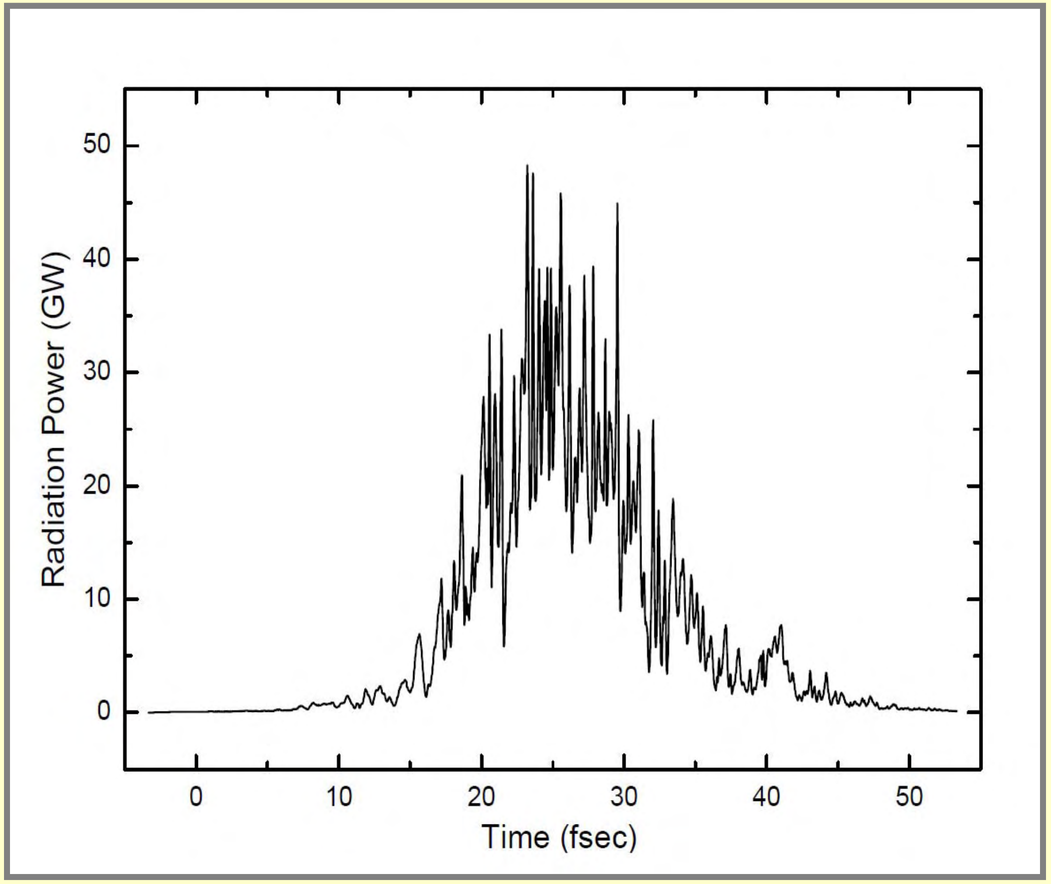

FEL Power
Saturation
Exponential
Signal
Amplification
Seeding
or
Infinitely Long
Undulator
Seeding
Shot Noise
Distance Along Undulator
T. Shintake
2007.01

Basic Machine Layout of XFEL/SPring-8



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**

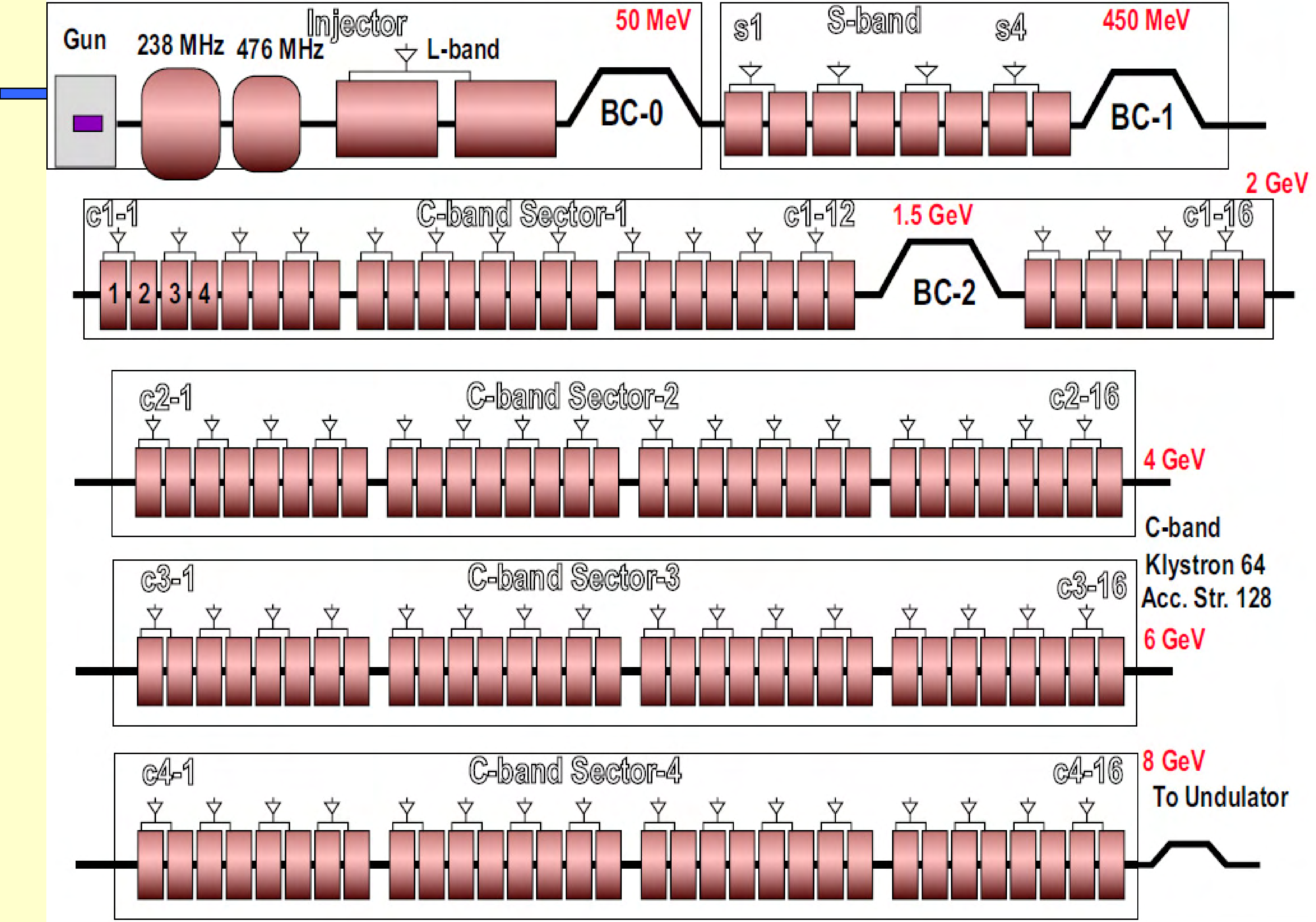


Expected X-ray pulse of 0.1 nm
(SIMPLEX simulation)


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

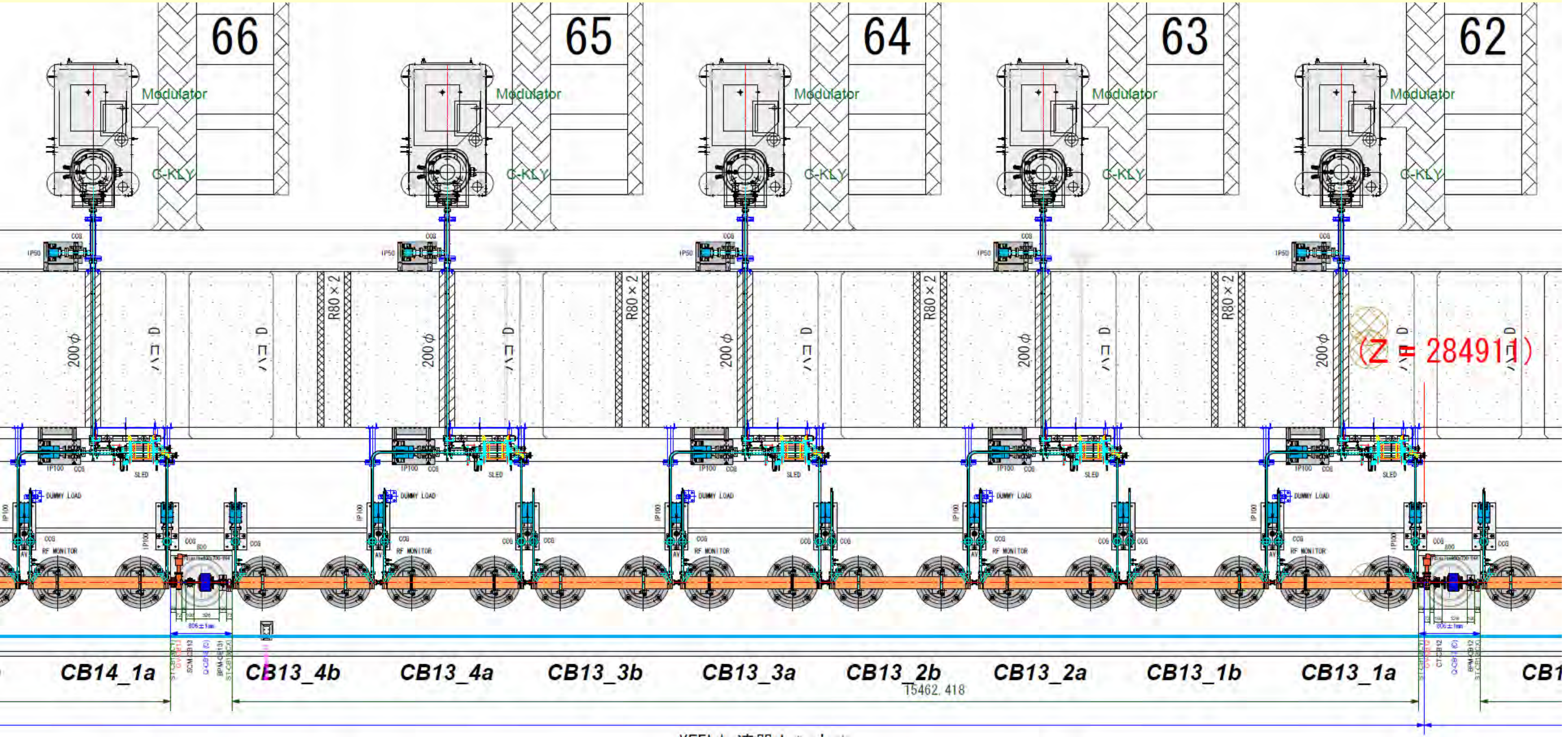
RF Acceleration System in 8 GeV SPring-8 XFEL

T.Shintake 2007 March

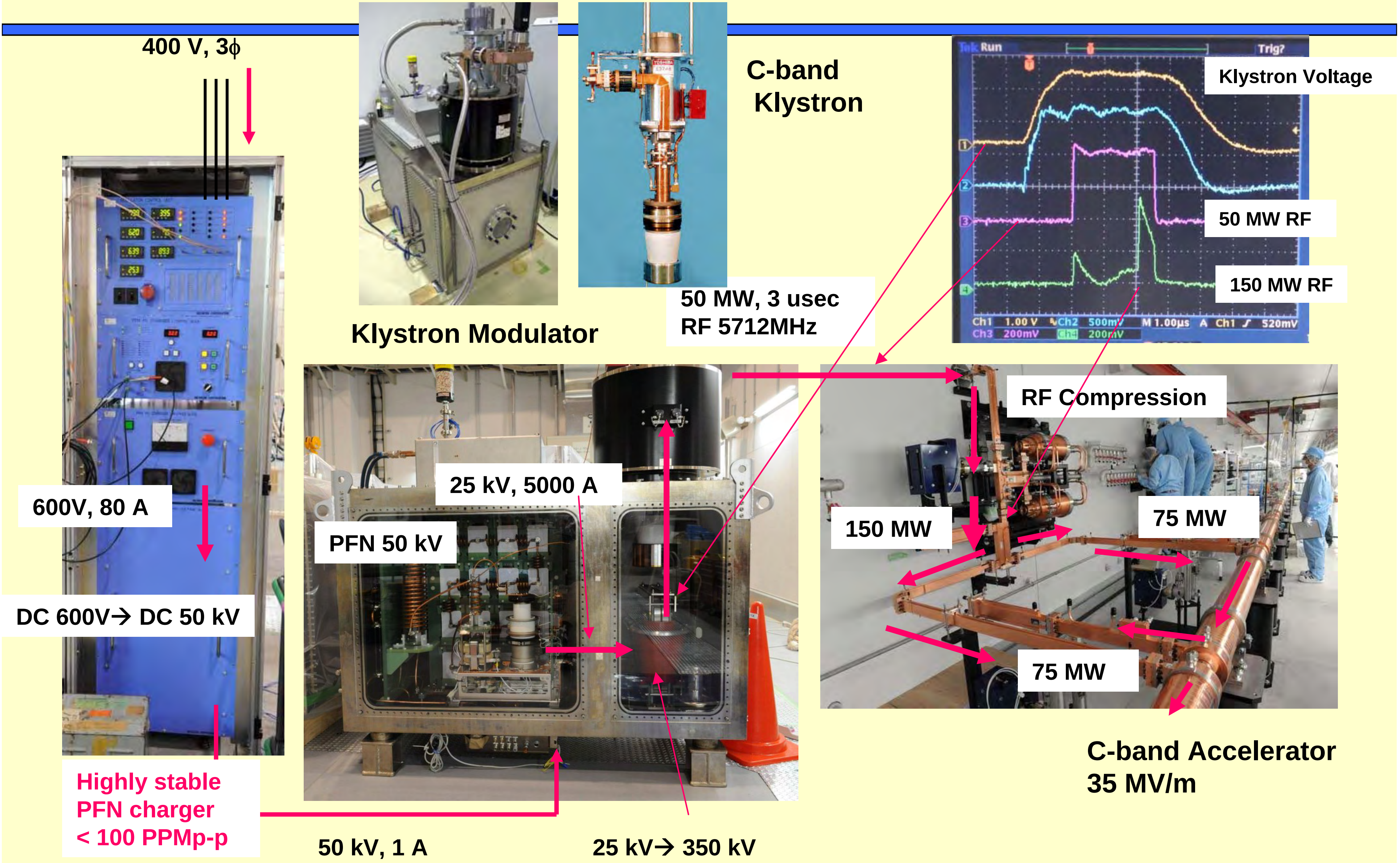


C-band is High Gradient (35 MV/m, max 40 MV/m)

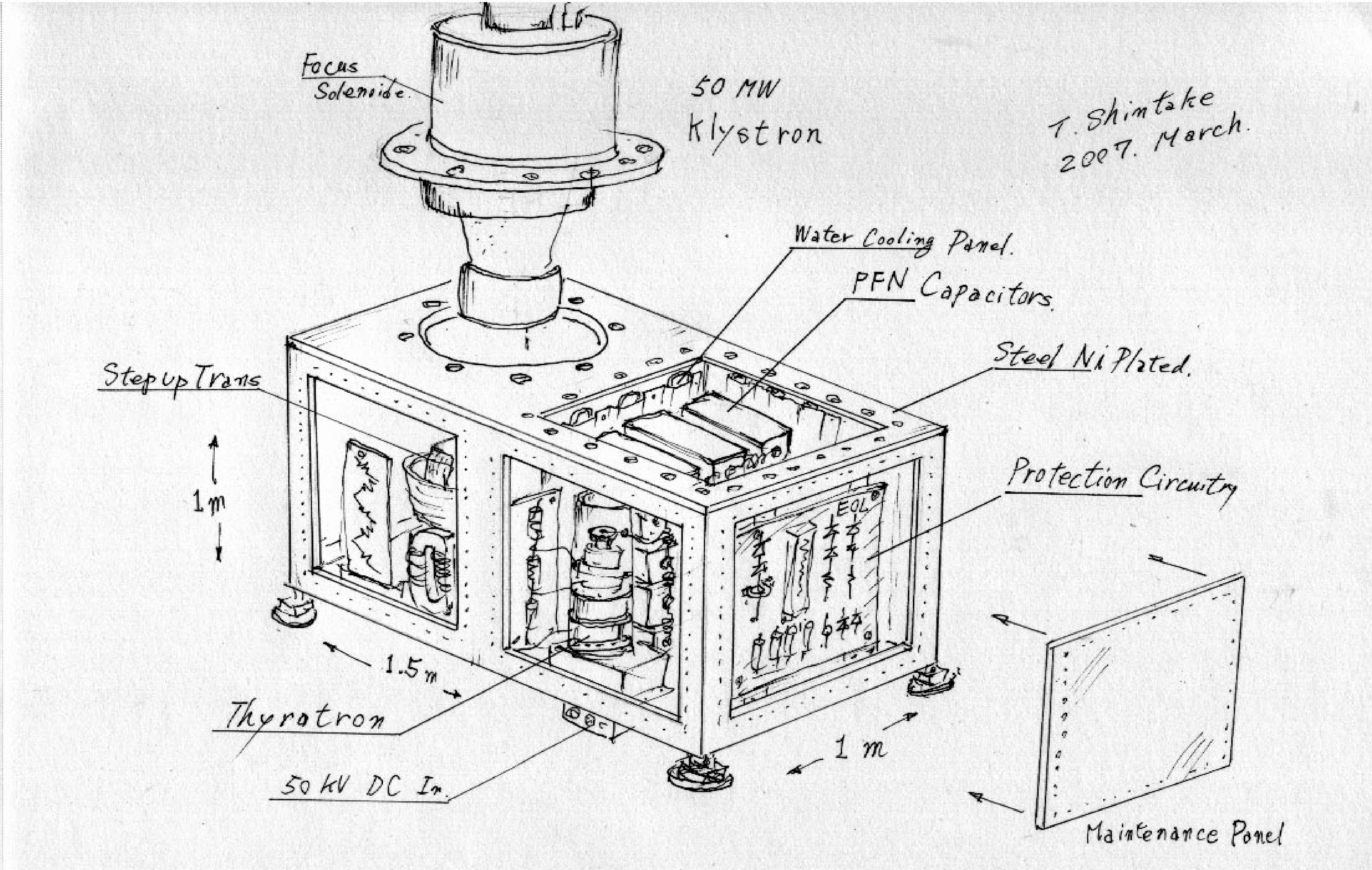
- **Modulator + Control Cabinet have to fit within 3.9 m each.**
  → Need to make "Compact Modulator"
- **High packing efficiency = Active Length/ Actual Length**
  =(1791 x 8) / (15462+806) = 0.88 (Active 35 MV/m -> Average 30 MV/m)



C-band System Configuration

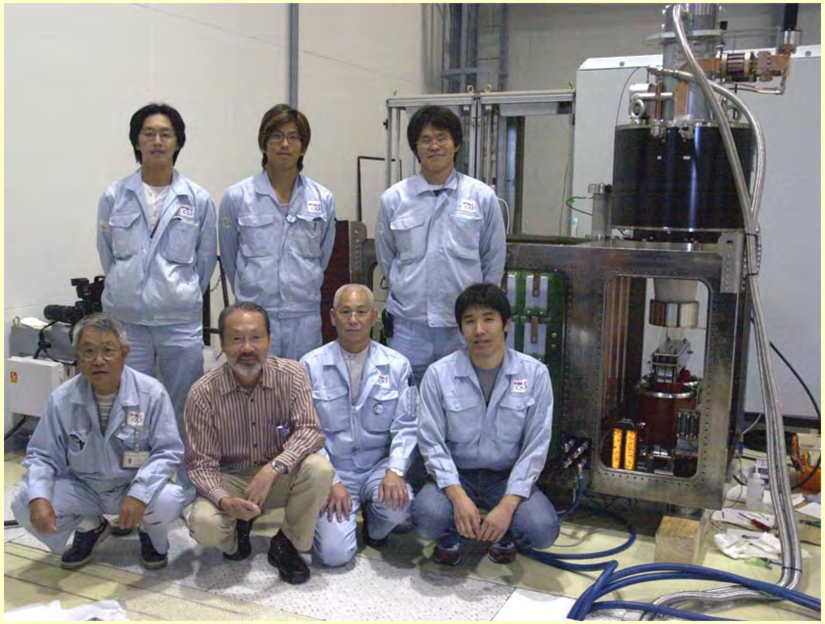


Single Tank Modulator (PFN circuit + Transformer)



Compact Modulator for 50 MW Klystrons

- Output Power 50 MW RF x 60 pps
- 50 kV PFN, 1:16 Trans, 350 kV klystron.
- Compact 1 m x 1 m x 1.5 m,
- Very low noise
  (<10 Vpp on 200 V heater line)
- Water cooled. Max surface temp 45 deg.



Modulator Mass Production at NICHICON

70 modulators

Mass-production of 70 Modulators for Klystron at NICHICON

Modulators are Arriving to XFEL/SPring-8

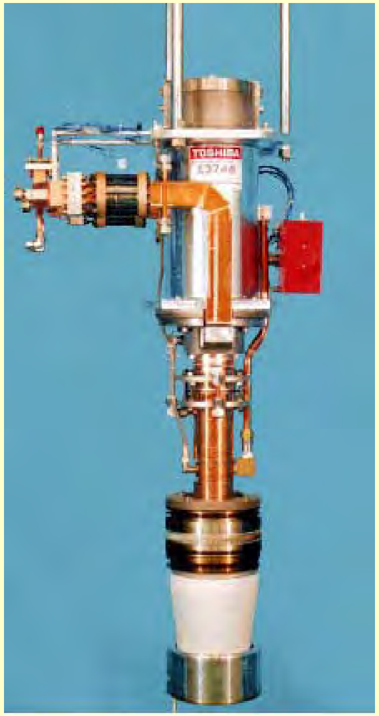
All modulator are tested with high power
at 50 kV, 60 pps, 8 hour before installation.

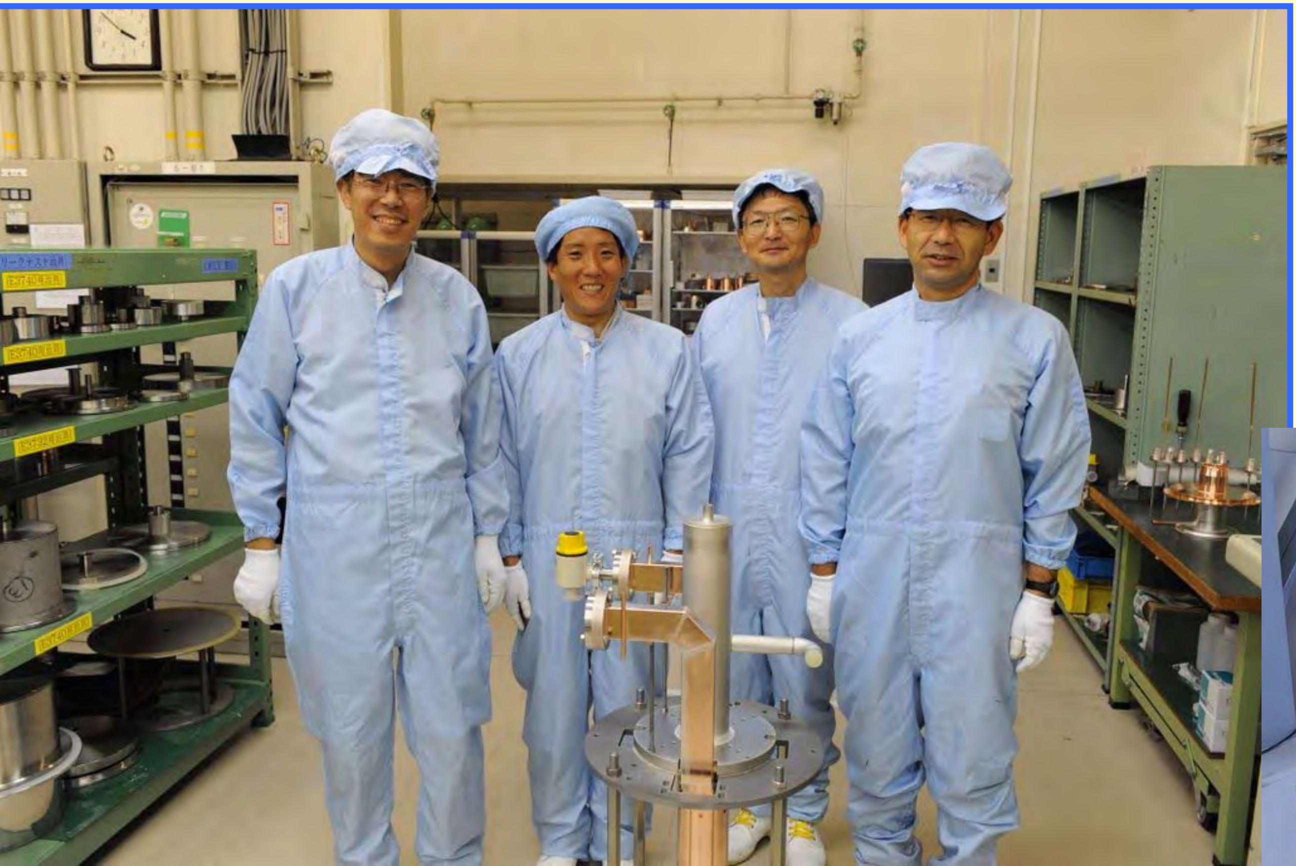
Installed modulator to klystron gallery, waiting WG connection.

Mass Production of Klystrons at TOSHIBA

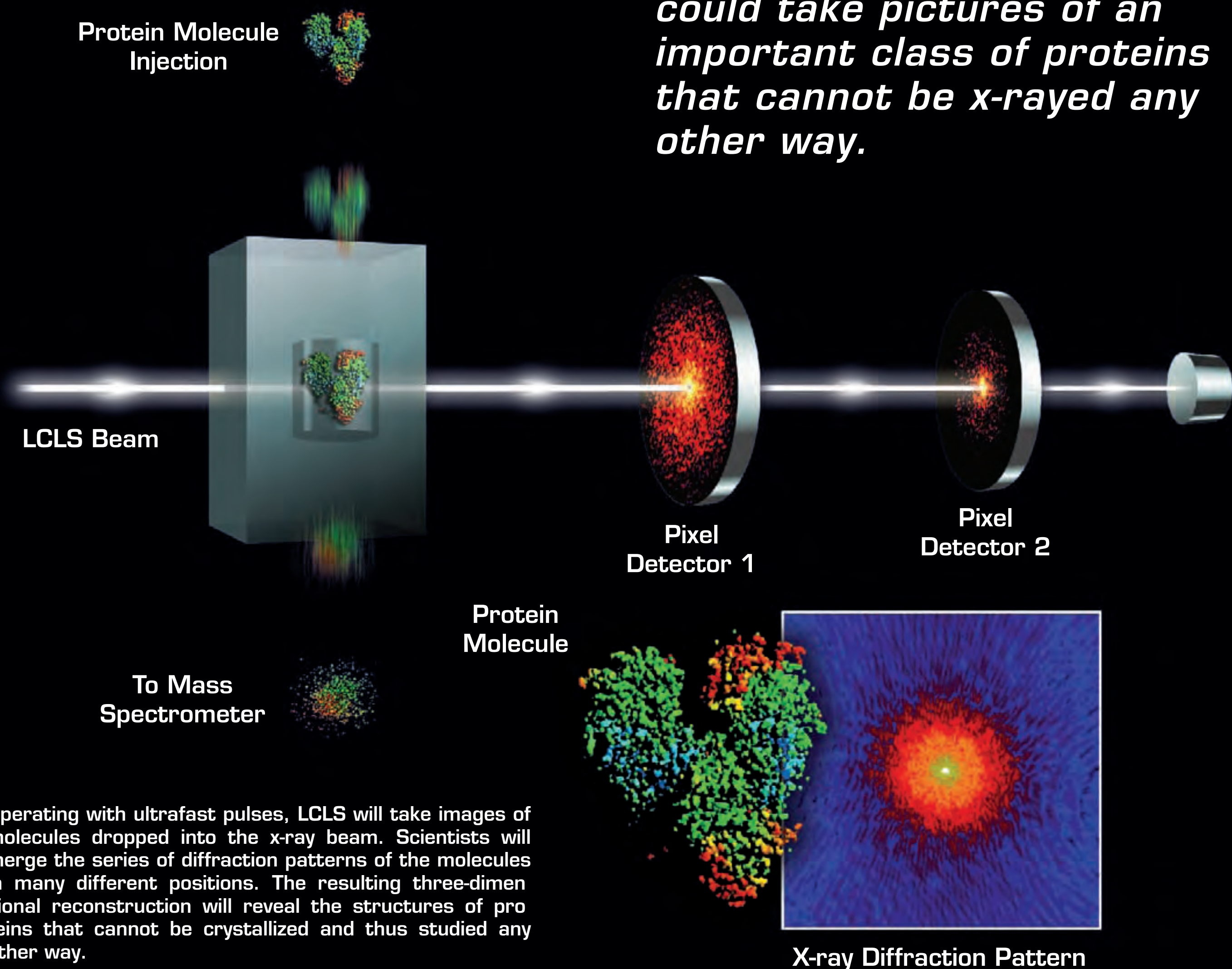
- 64 C-band klystron
- 4 S-band klystron
- 1 L-band klystron

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



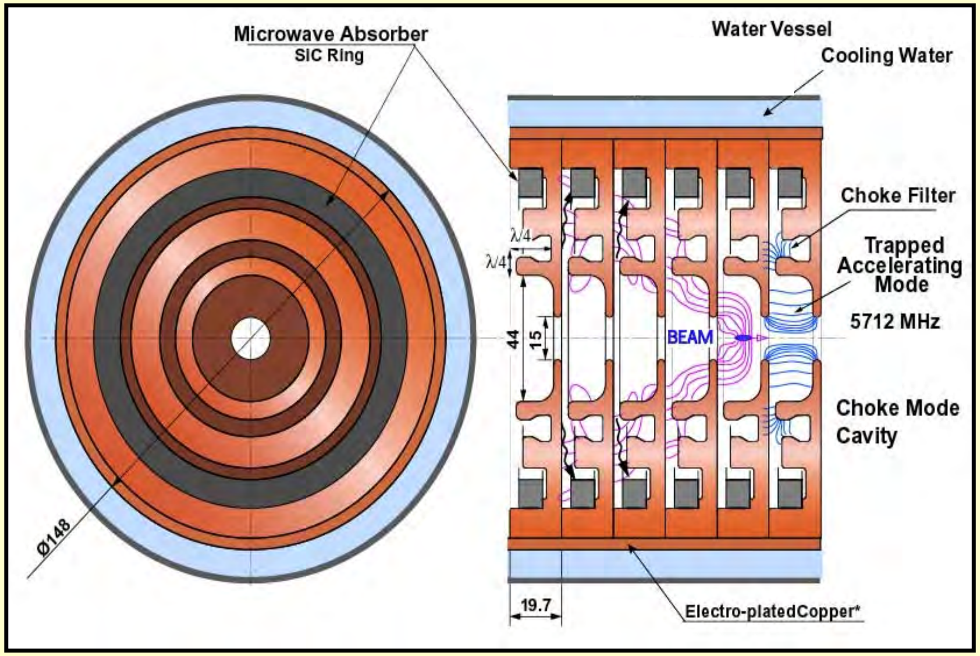


With its fast "shutter" speed and super brightness, LCLS could take pictures of an important class of proteins that cannot be x-rayed any other way.



Operating with ultrafast pulses, LCLS will take images of molecules dropped into the x-ray beam. Scientists will merge the series of diffraction patterns of the molecules in many different positions. The resulting three-dimensional reconstruction will reveal the structures of proteins that cannot be crystallized and thus studied any other way.

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

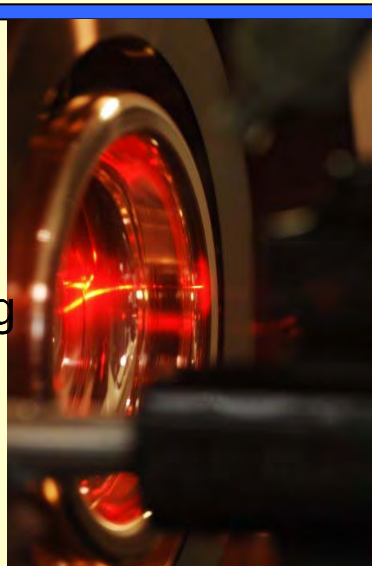
X-ray 4.2 nsec x 50 bunches will be key for
Single bio-molecule imaging to improve Luminosity.

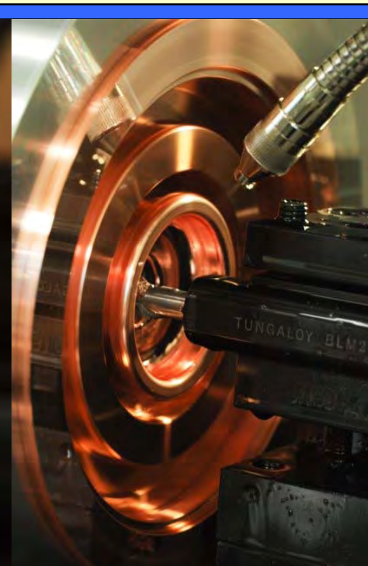
HITACHI Cable Co. completed mass production of C-band cell. June 2009

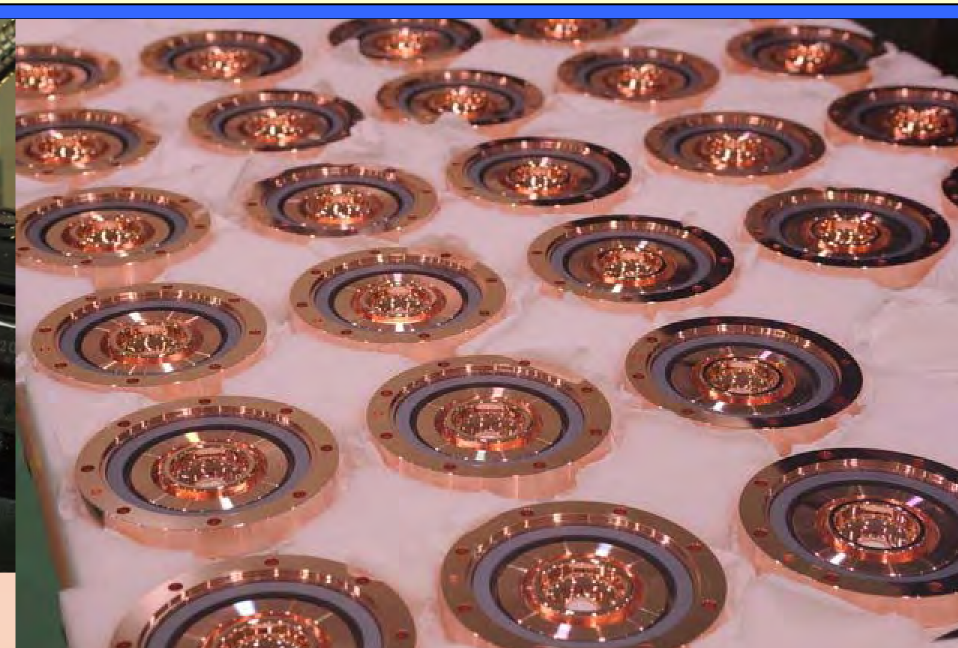
We made 13,000 pieces of C-band accelerator cell.

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

Laser
Guided
Precision
Machining





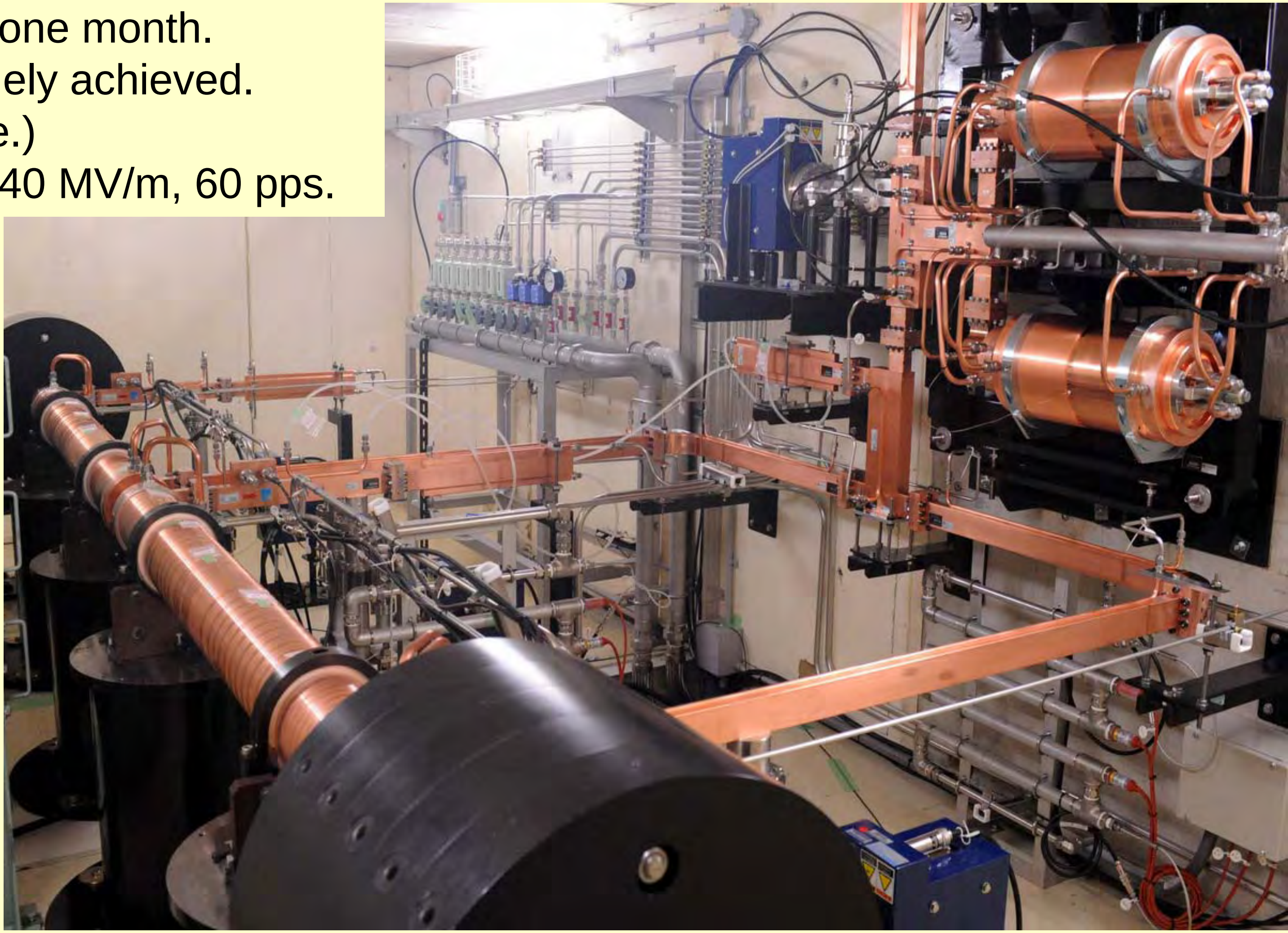


MITSUBISHI-Team completed 100 tubes (out of 128)
C-band Accelerator. Photo March 2009

Routinely Operation: C-band High Gradient Test

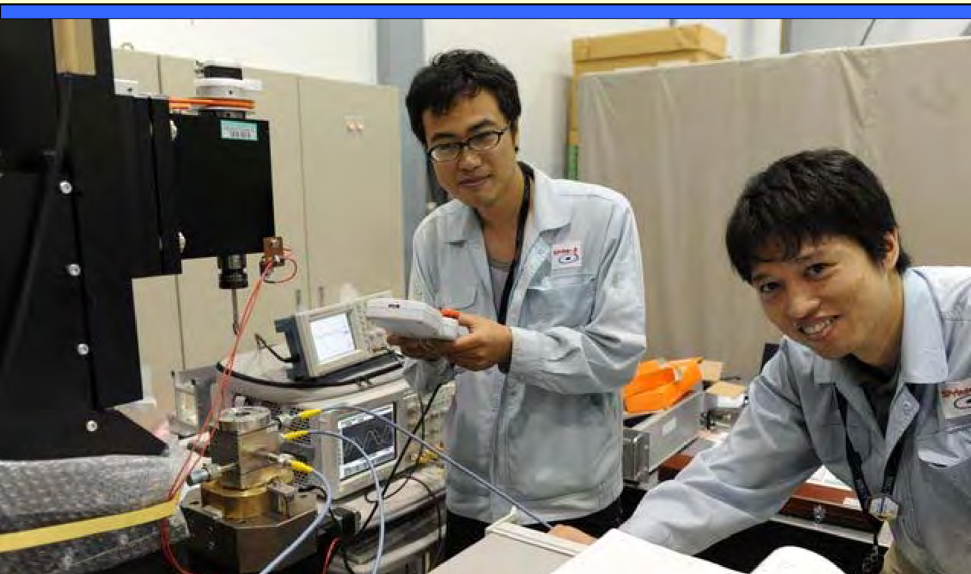
- Sample test from mass production.
- C-band 1 unit for one month.
- **35 MV/m** is routinely achieved.
  (Very low trip rate.)
- Processing up to 40 MV/m, 60 pps.

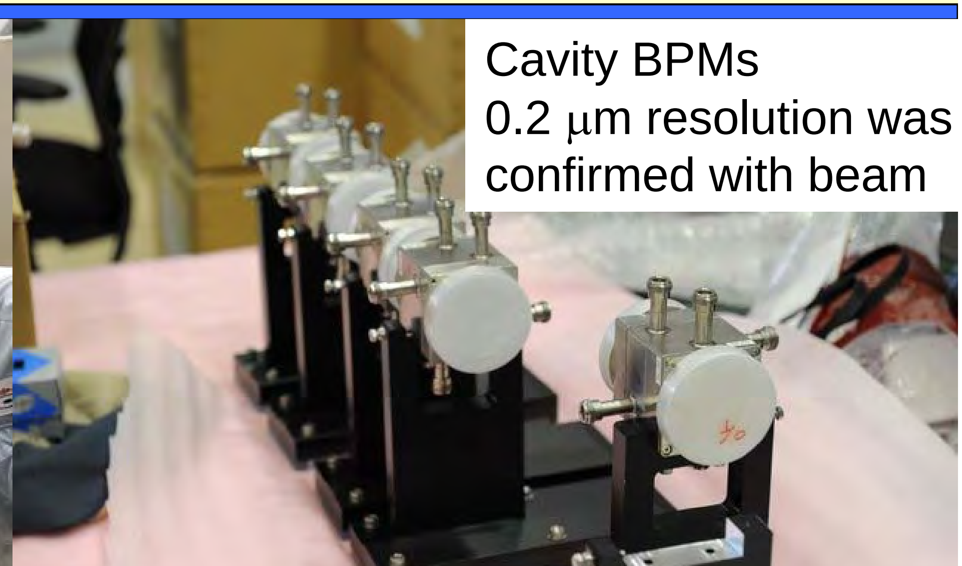
T. Sakurai, PAC2009



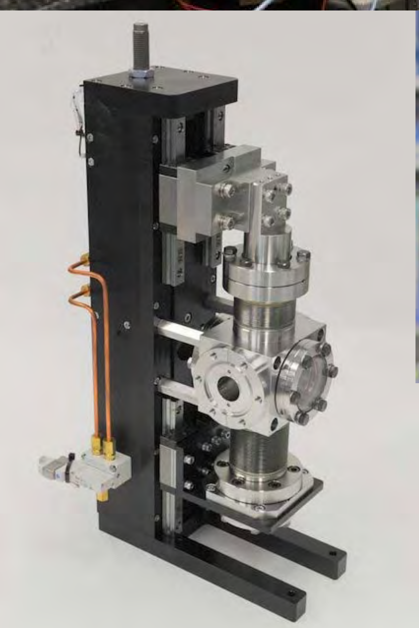
Beam Monitor Devices

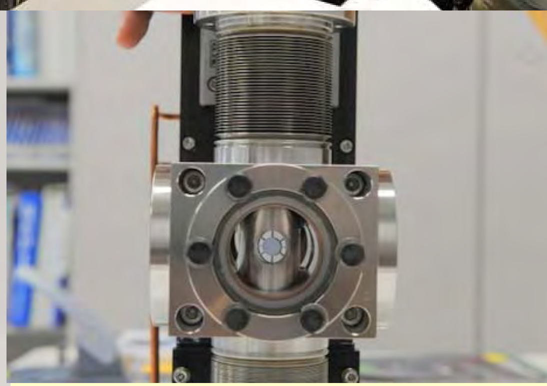
By Y. Otake team.





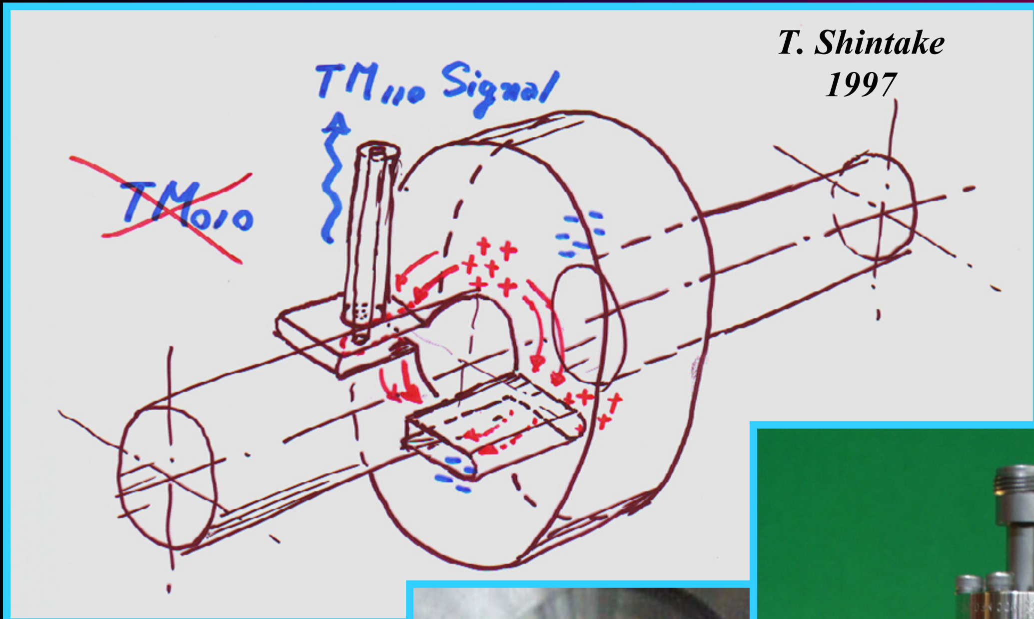
Cavity BPMs
0.2 μm resolution was confirmed with beam

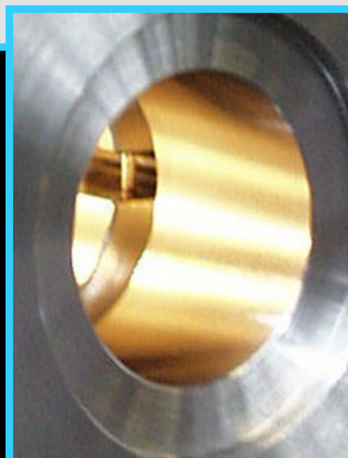


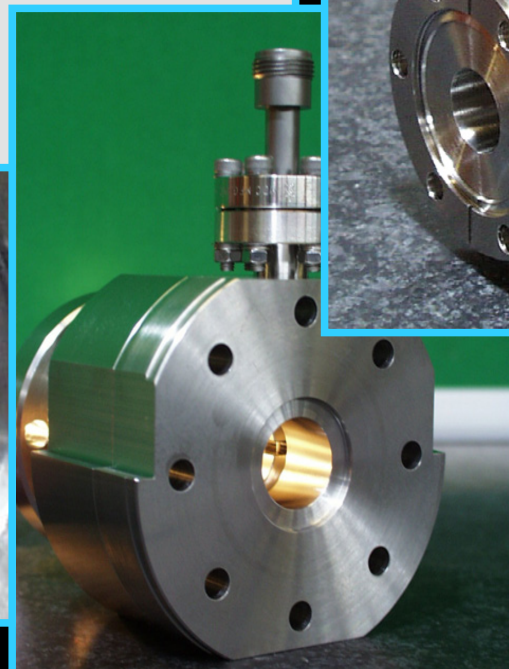


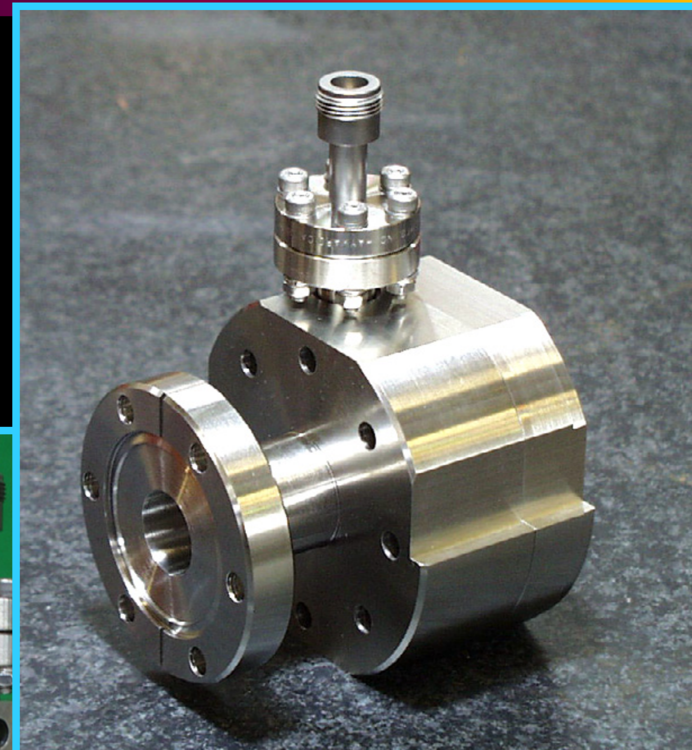
OTR Radiator

COM-Free BPM





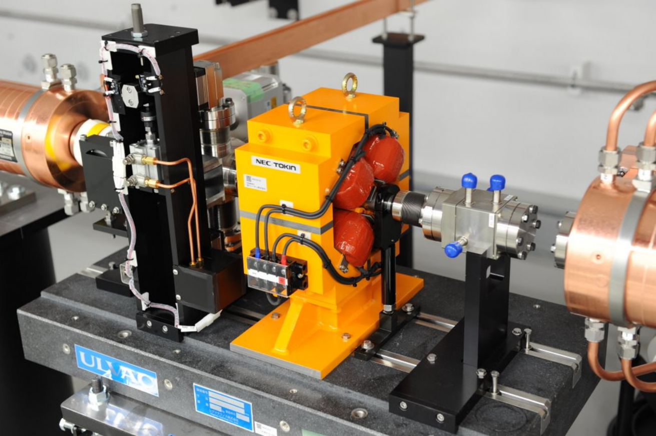


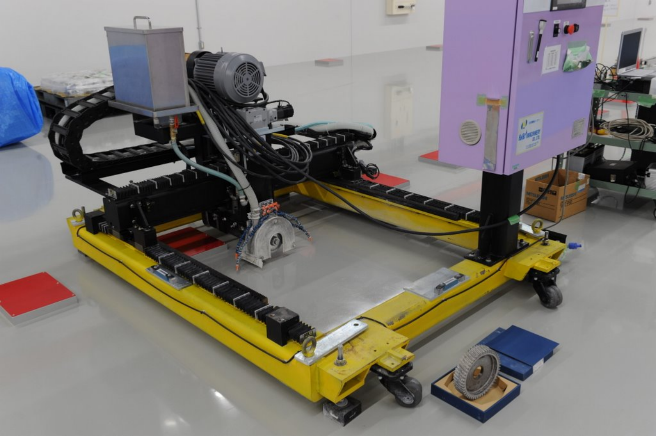


TM010 mode does not couple out to pickup antenna.

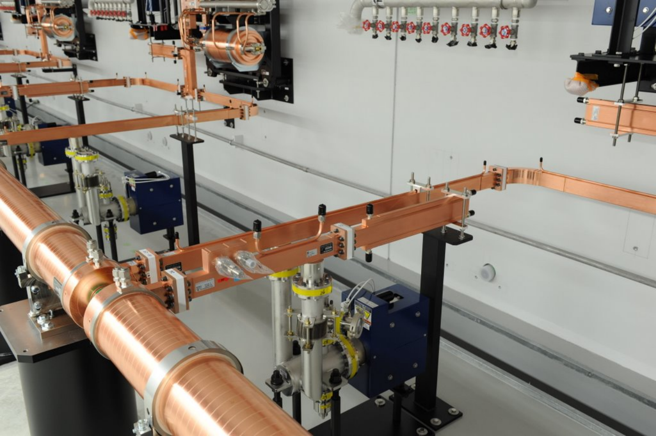
will be used for C-band Accelerator Alignment

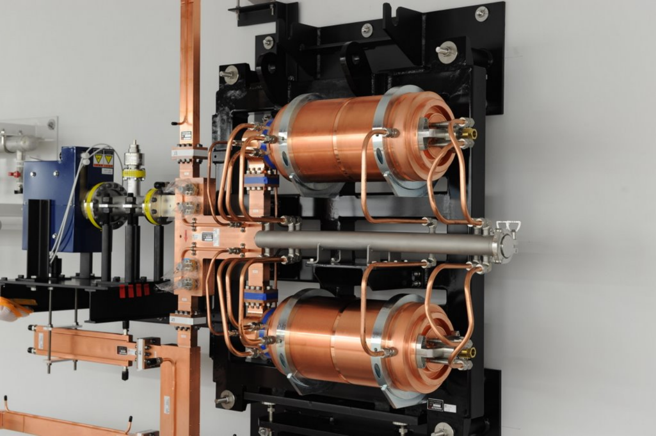

RF-BPM (ø4.5)

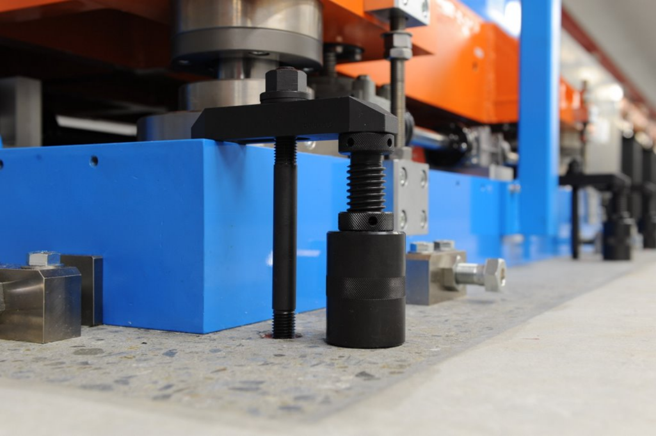

NEC TOKIN
ULVAC

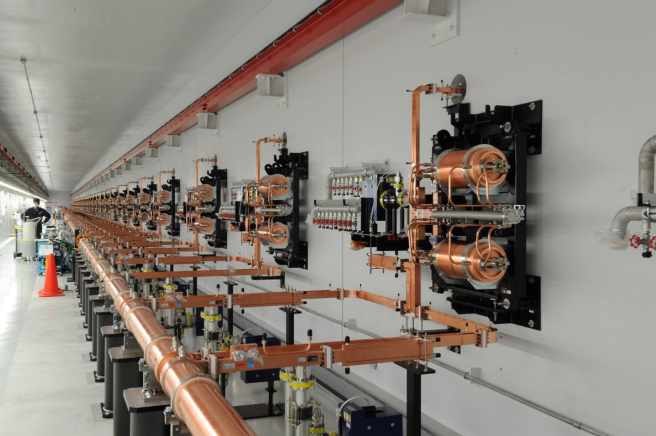



Asahi Diamond Industrial Co., Ltd.
ドラムホイール
3
規格
8D−50W−5U−48ヘリカル
ボンド
チョウアラ#30/40-DZ8
製品No
8828775



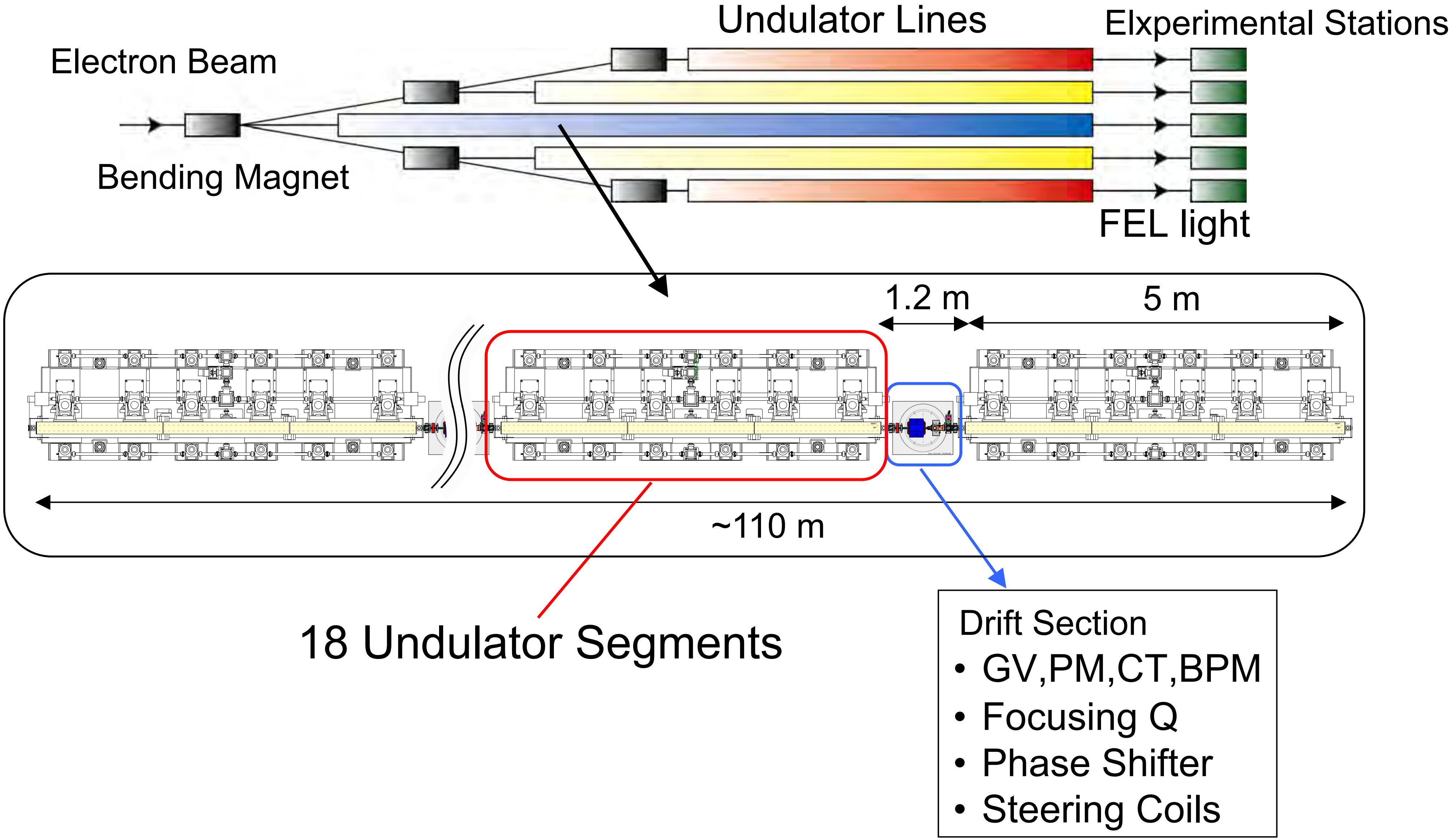






Control rack installation started, from downstream.
VME MADCA control, Digital RF, C-band driver amp., water temp control.
Thanks to extensive effort by Mitsubishi Electric TOKKI System, etc.

SP-8 XFEL Undulator Line



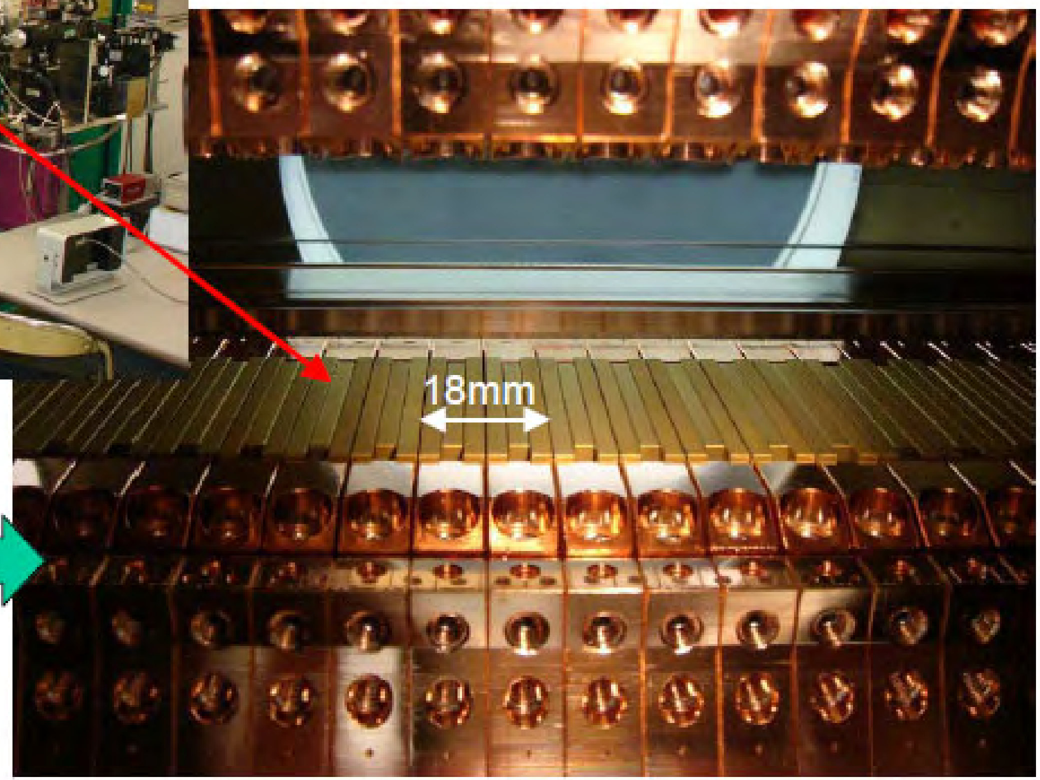
Undulator is ready for mass production.

Undulator Parameter

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

Undulator for XFEL/SPring-8

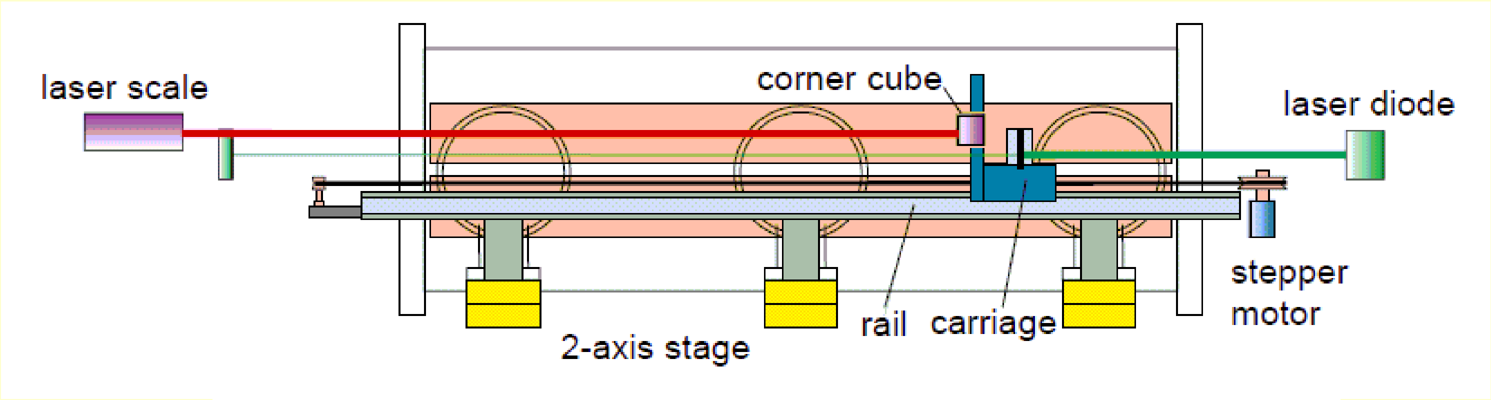
Outlook of 5 m long in-vacuum undulator for X-ray FEL.

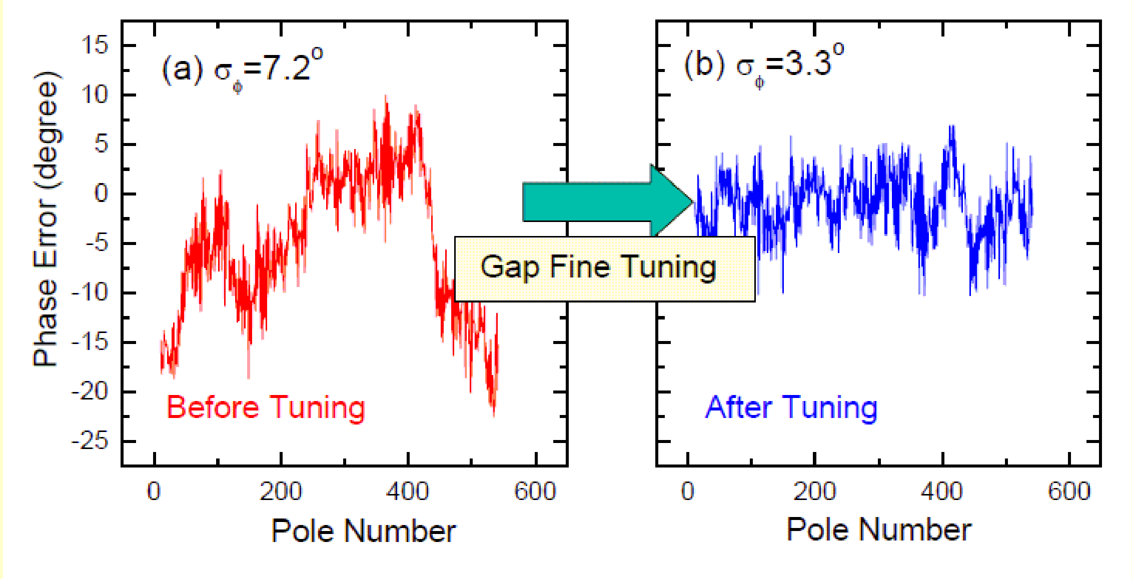


NeFeB magnet array, undulator period is 18 mm.

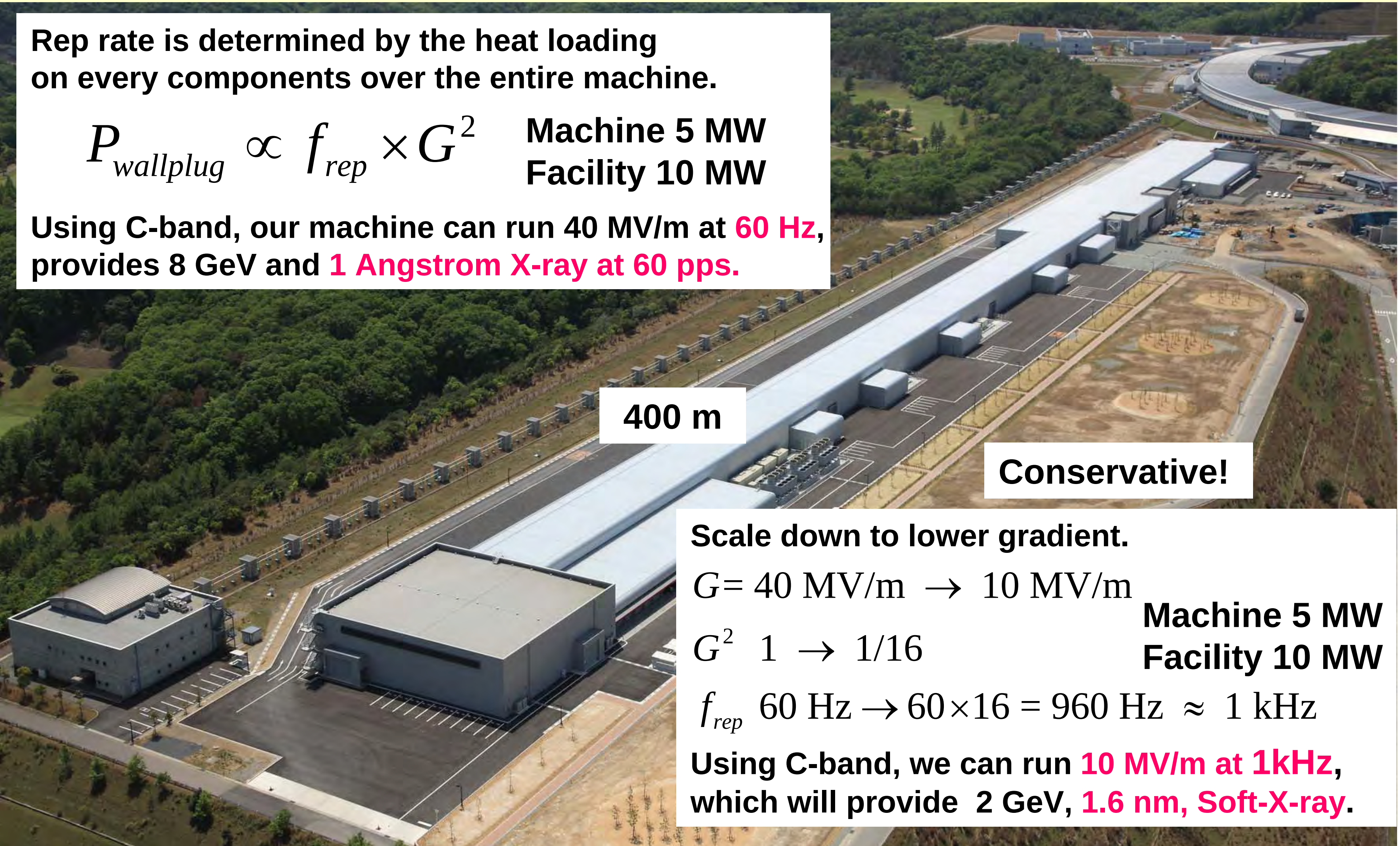
Field Measurement System: SAFALI

- SAFALI: Self-Aligned Field Analyzer with Laser Instrumentation
- Laser guiding positioning system in the vacuum chamber, which carries hole probe for magnetic field measurement.





Can we run our XFEL/SPring-8 at **1 kHz repetition**?



Rep rate is determined by the heat loading on every components over the entire machine.

$$P_{wallplug} \propto f_{rep} \times G^2$$

Machine 5 MW
Facility 10 MW

Using C-band, our machine can run 40 MV/m at 60 Hz, provides 8 GeV and 1 Angstrom X-ray at 60 pps.

400 m

Conservative!

Scale down to lower gradient.

$$G = 40\ \text{MV/m} \rightarrow 10\ \text{MV/m}$$

$$G^2 \quad 1 \rightarrow 1/16$$

$$f_{rep} \quad 60\ \text{Hz} \rightarrow 60 \times 16 = 960\ \text{Hz} \approx 1\ \text{kHz}$$

Machine 5 MW
Facility 10 MW

Using C-band, we can run 10 MV/m at 1kHz, which will provide 2 GeV, 1.6 nm, Soft-X-ray.

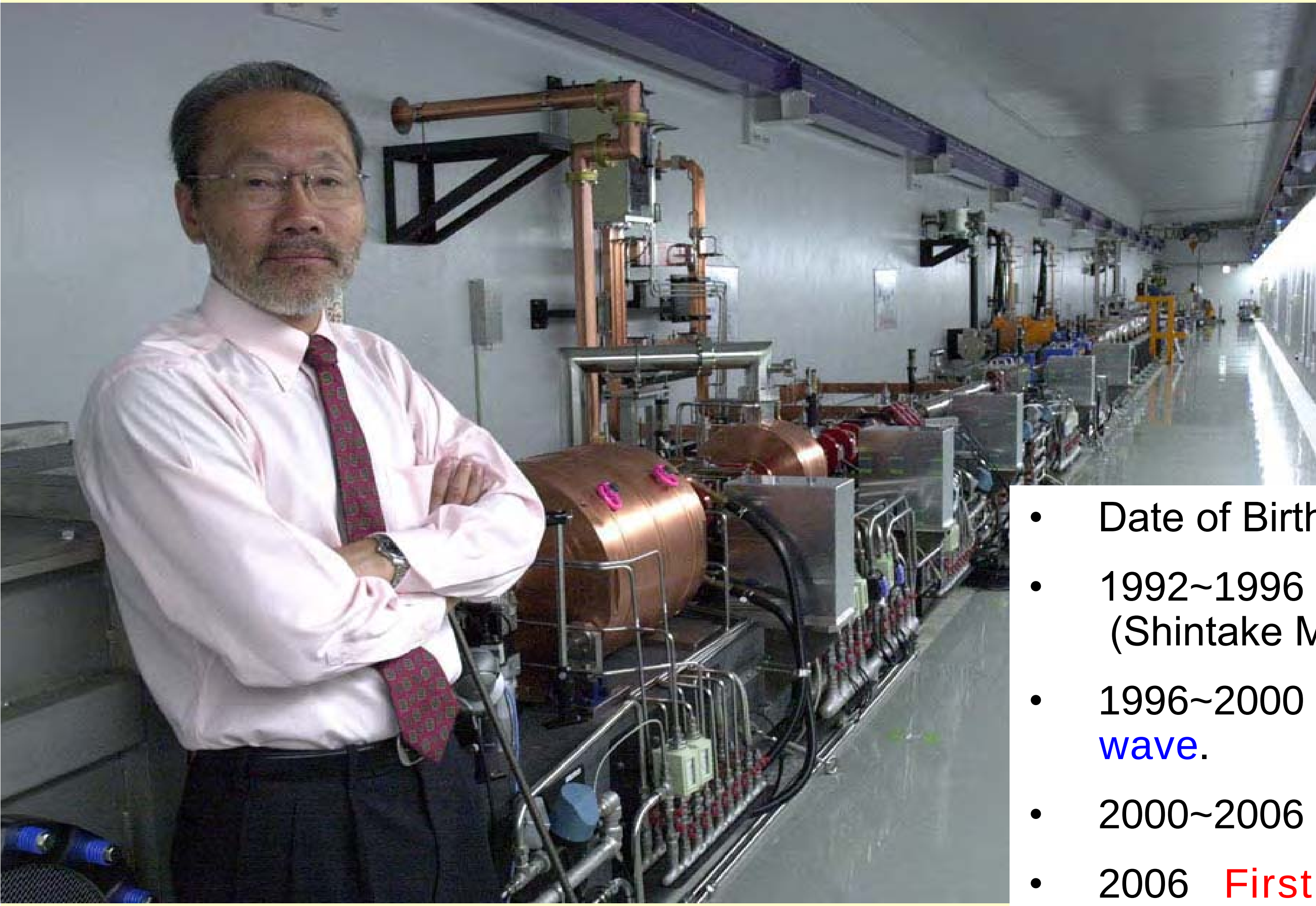
Summary

- So many different efforts are coherently contributing to the project. They are almost on the time schedule.

- Building construction has been completed.
- Accelerator component installation has been started.
~ 1 year installation.

- October 2010, We start high power operation of accelerator.
- Spring 2011, we start beam commissioning.

Who is Shintake?



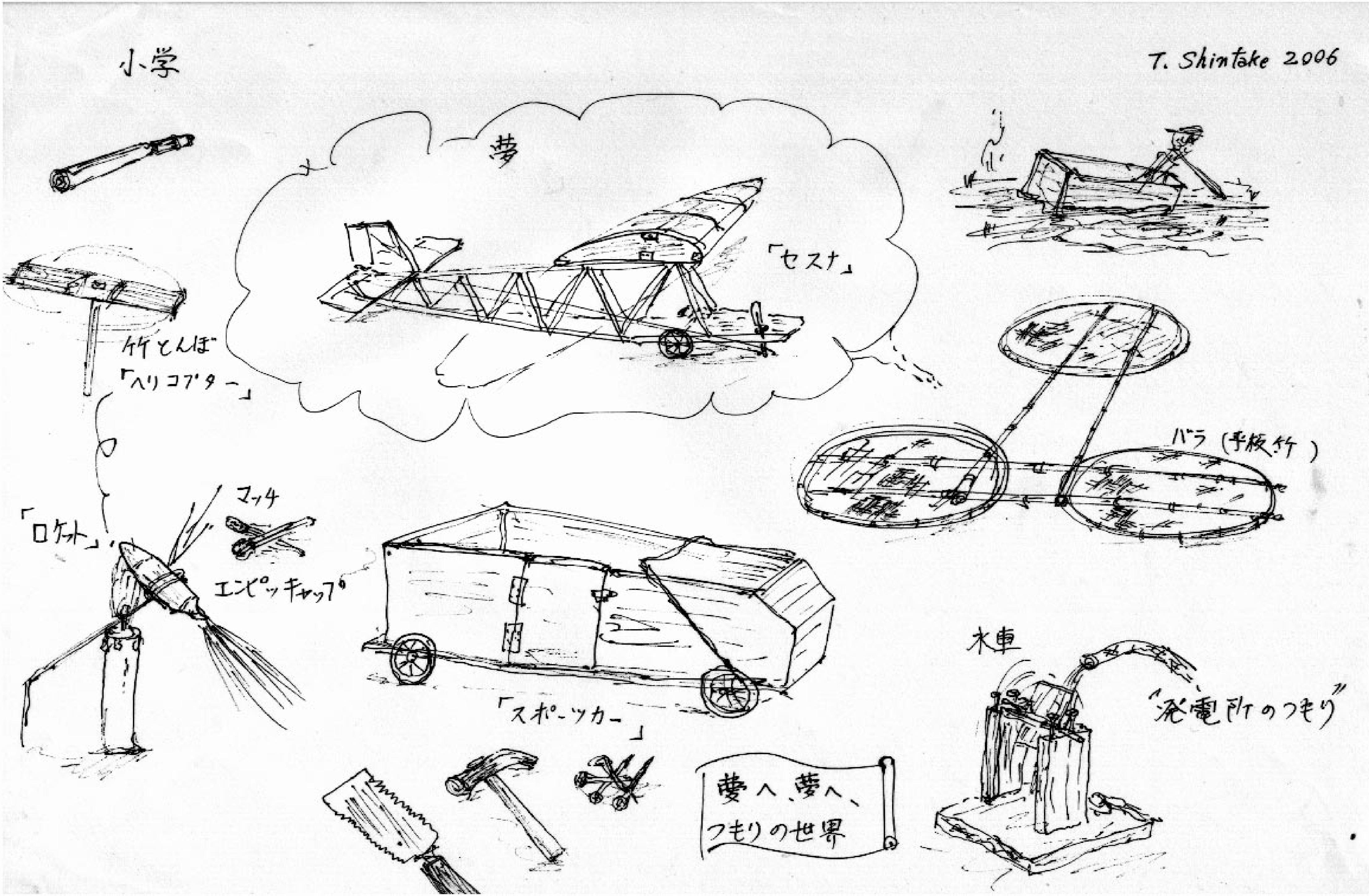
@ SCSS tunnel
Test Accelerator for XFEL

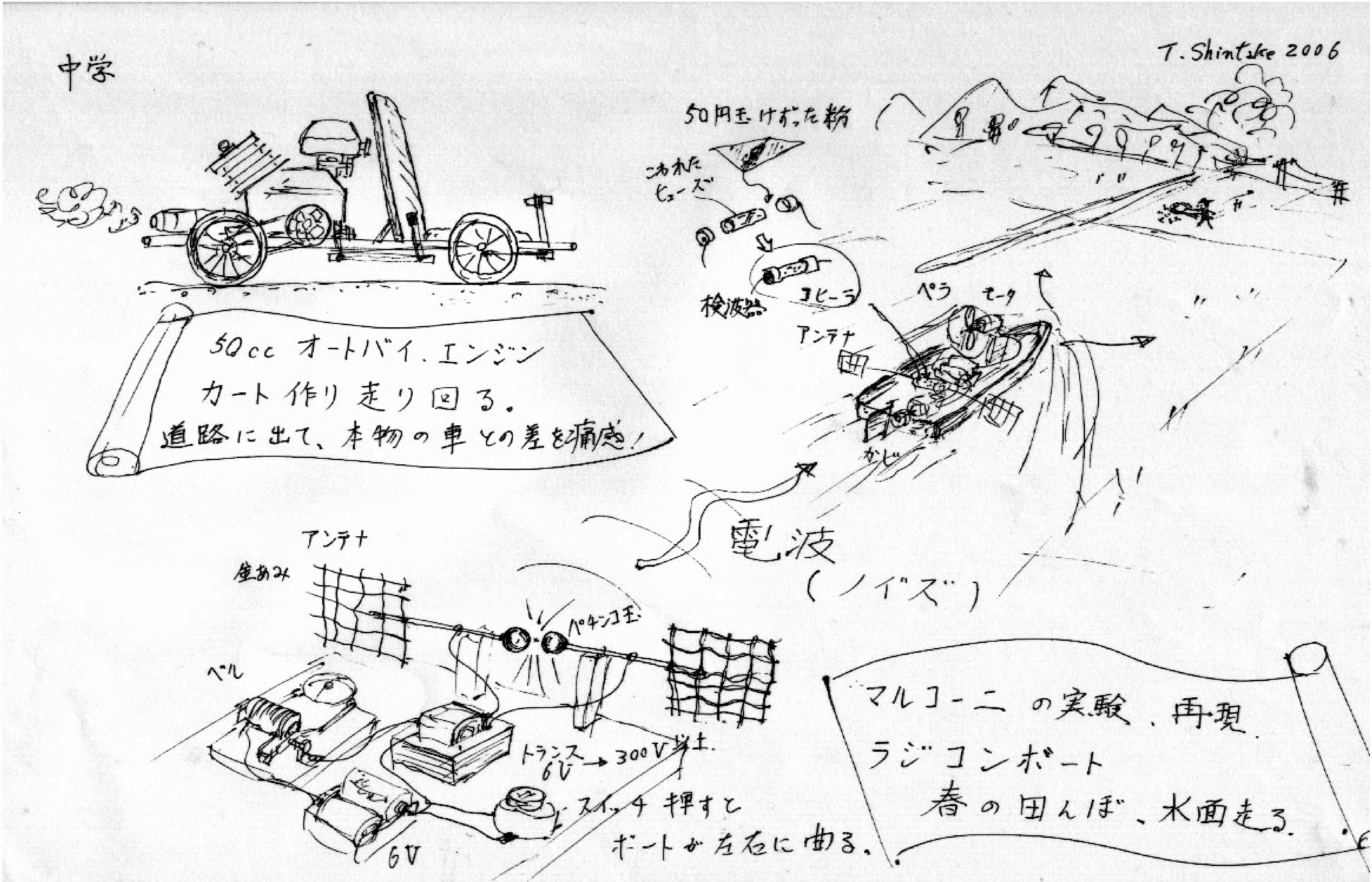
- Date of Birth 1955, Miyazaki, Kyushu Japan
- 1992~1996 FFTB – SLAC "Spot Size Monitor" (Shintake Monitor) 60 nm e with 1 μm wave
- 1996~2000 "C-band R&D" for LC at KEK 5 cm wave.
- 2000~2006 SCSS R&D Leader e- beam
- 2006 First Lasing at SCSS Prototype Accelerator 49 nm wave
- 2006~ Now constructing 8 GeV XFEL/SPring-8 for 0..1 nmm wave

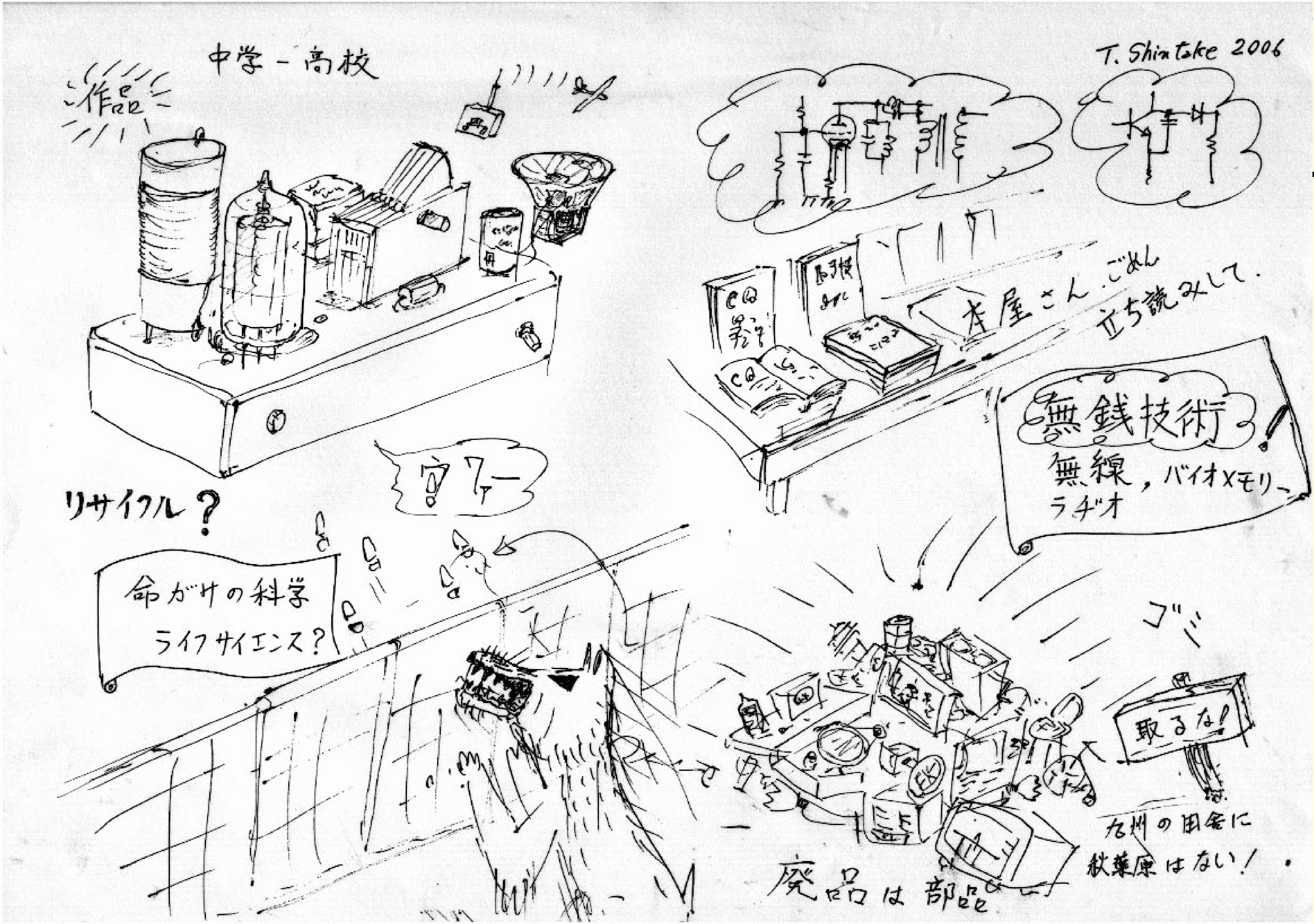
KYUSHU

MIYAZAKI

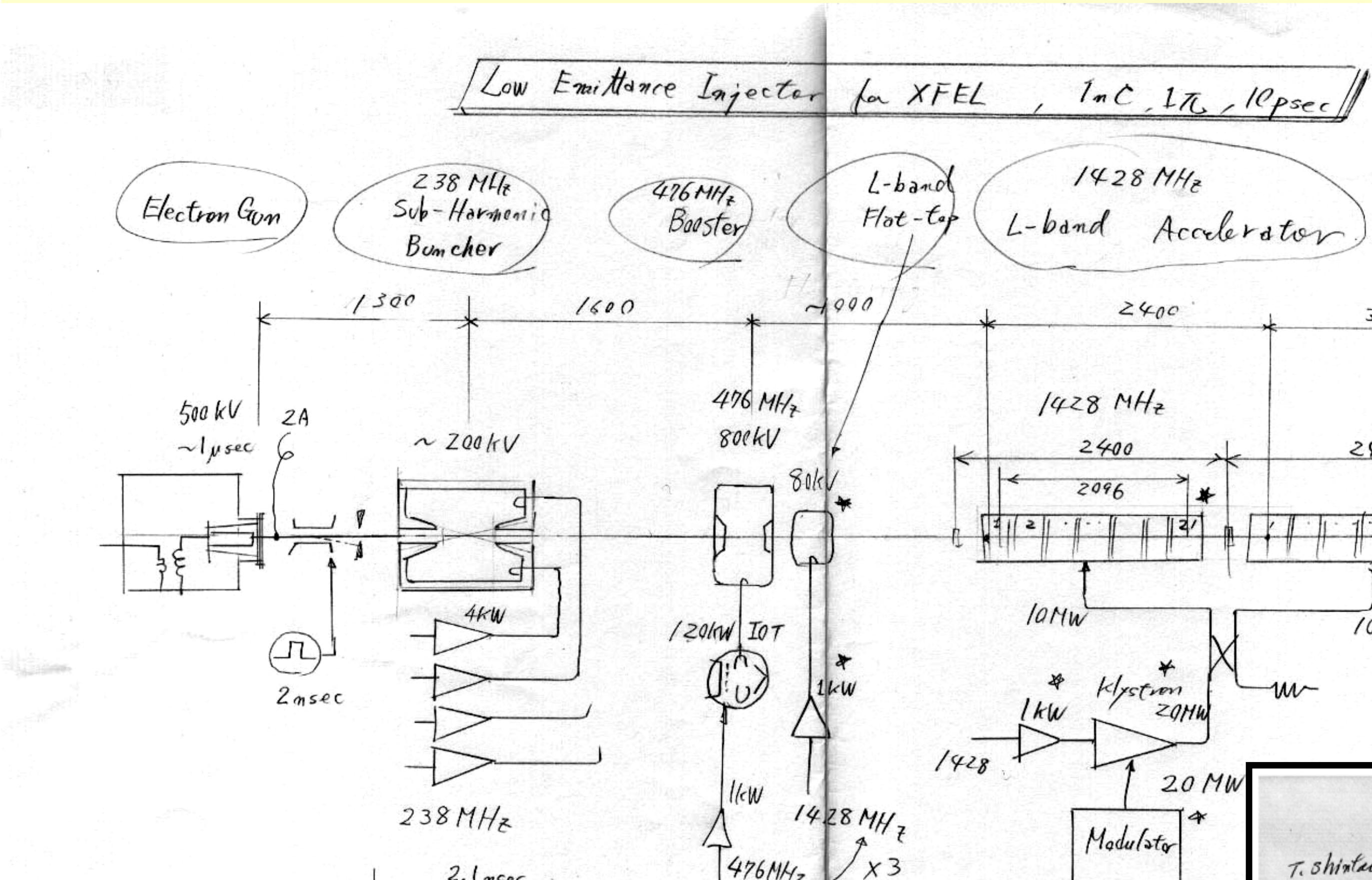

T. Shinoake
農機具
エンジン
朝
夕
昼
人間テスター
スパーク
プラグ点火テスト
ボール紙
パッキン
親父の弟子
電通試験器
5~6才

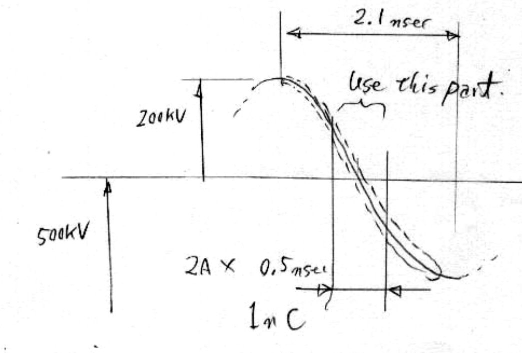

小学
T. Shintake 2006
夢
「セスナ」
竹とんぼ
「ヘリコプター」
「ロケット」
マッチ
エンピツキャップ
「スポーツカー」
バラ（手板竹）
水車
"発電所のつもり"
夢へ、夢へ、
つもりの世界

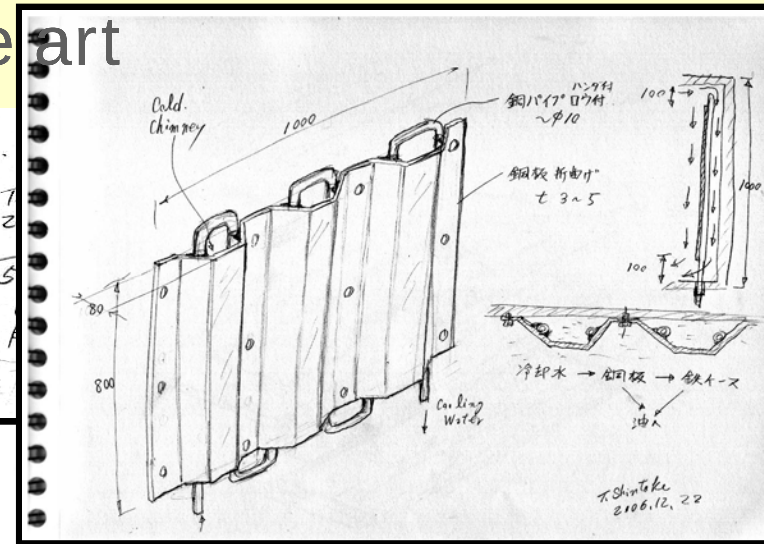

中学
T. Shintake 2006
50円玉けずった粉
こわれたヒューズ
検波器
コヒーラ
ペラ
モータ
アンテナ
かじ
50cc オートバイ. エンジン
カート作り 走り回る。
道路に出て、本物の車との差を痛感！
電波
（ノイズ）
アンテナ
金あみ
パチンコ玉
ベル
トランス 6V → 300V 以上.
6V
スイッチ押すと
ボートが左右に曲る。
マルコーニの実験、再現
ラジコンボート
春の田んぼ、水面走る。

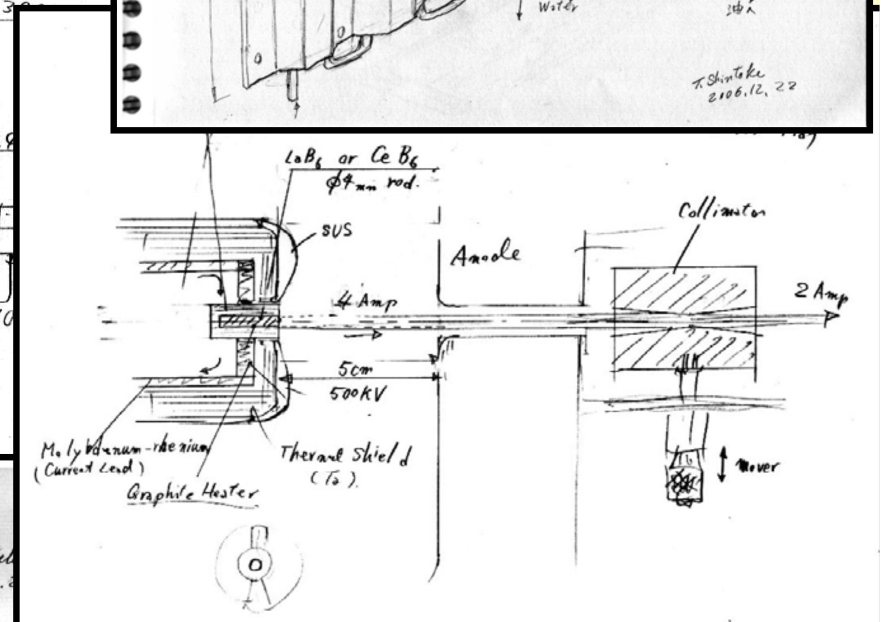

中学－高校
作品
T. Shintake 2006
本屋さん ごめん
立ち読みして.
無銭技術!
無線，バイオメモリー
ラヂオ
リサイクル？
ファー
命がけの科学
ライフサイエンス？
ゴミ
取るな!
九州の田舎に
秋葉原はない！
廃品は部品

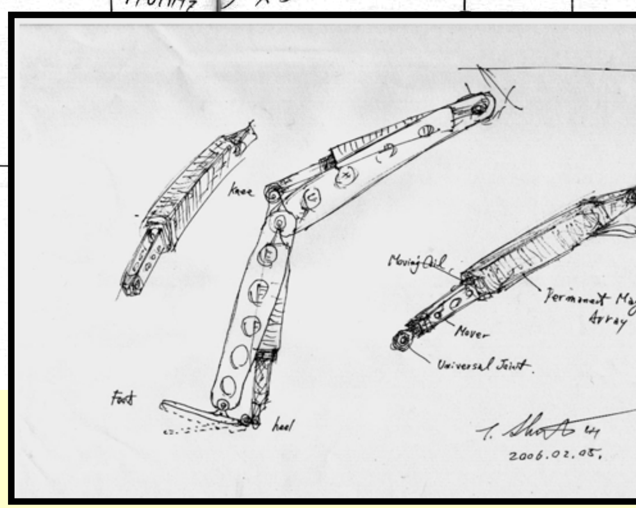
Design accelerator as creating images like art

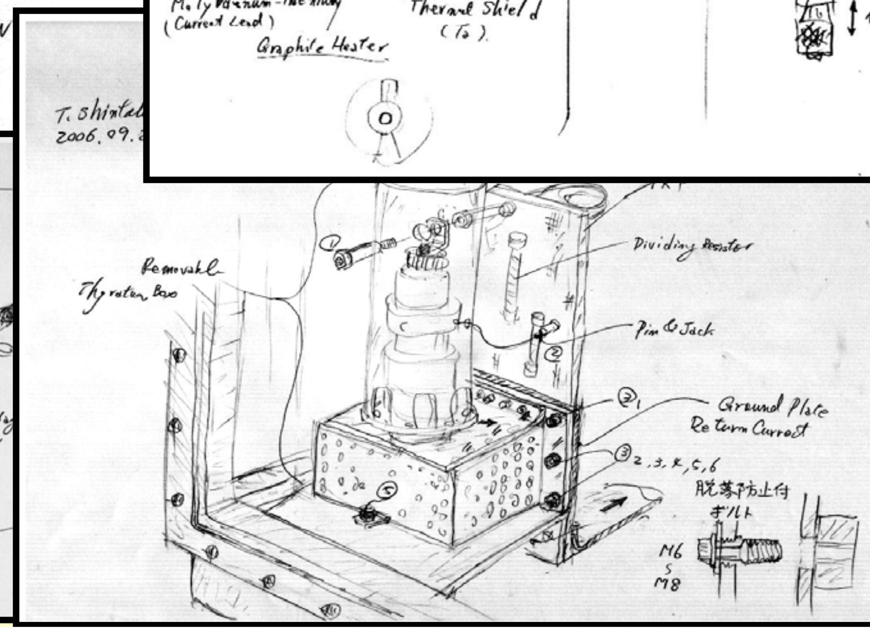




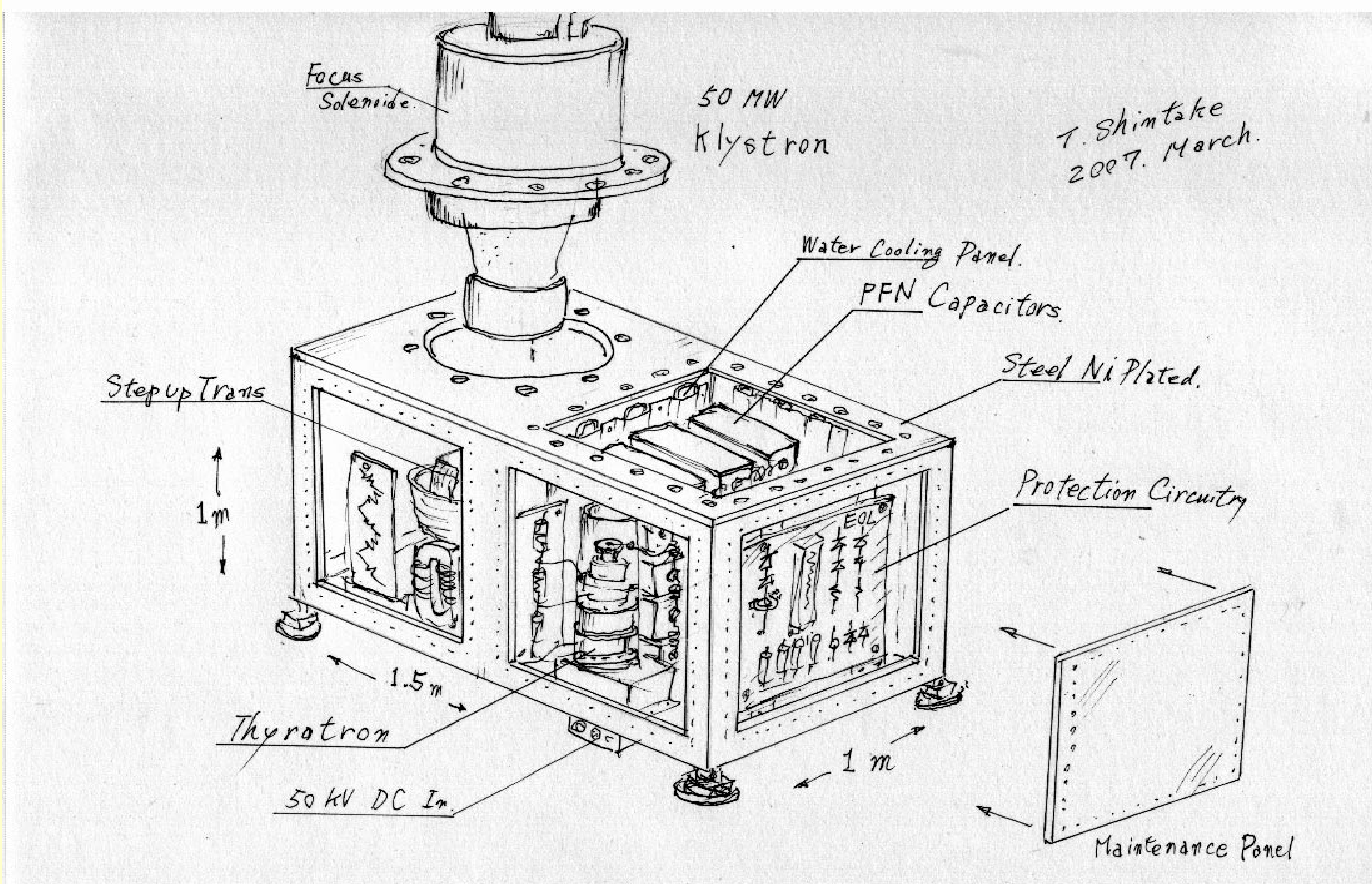








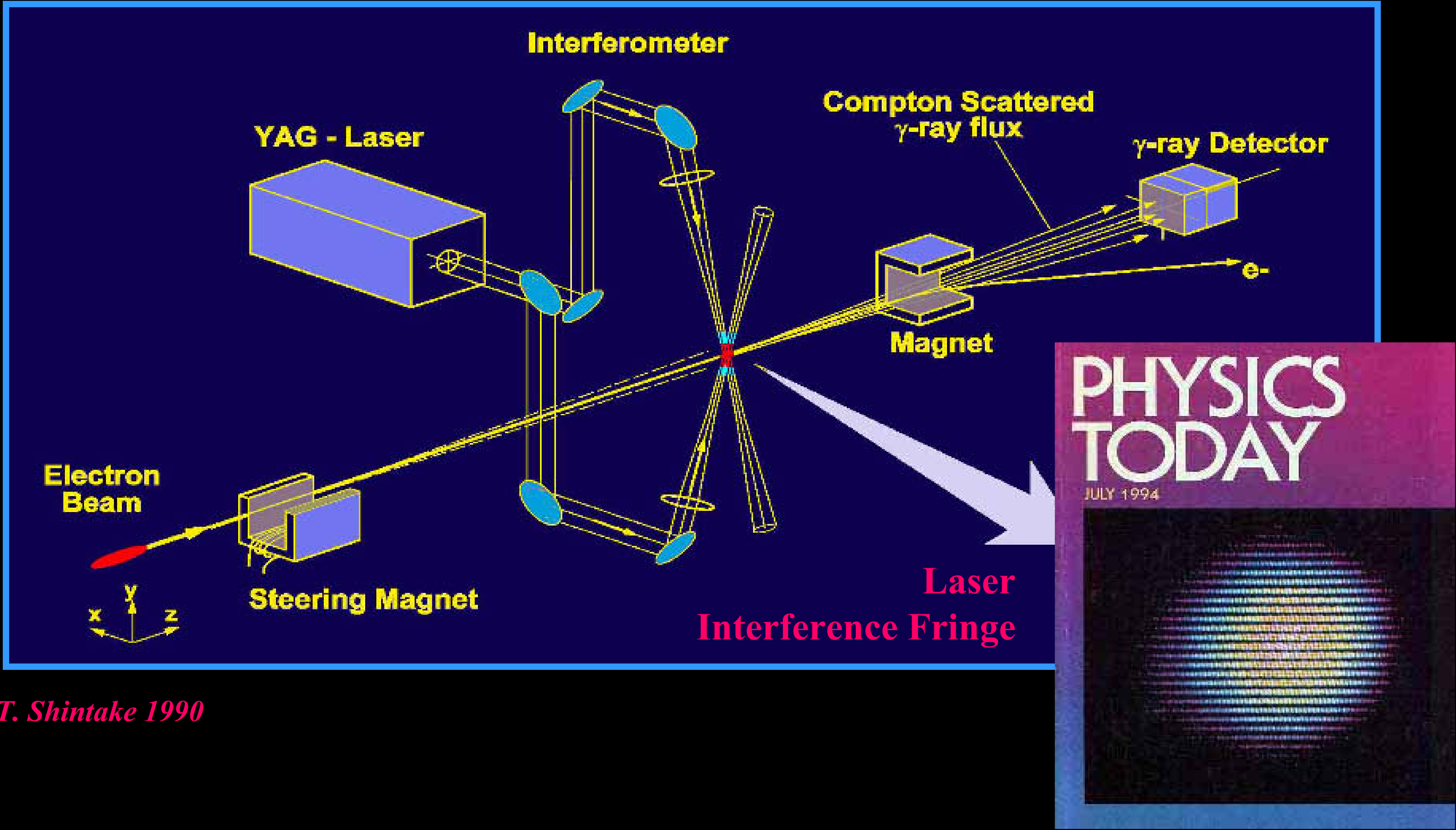
Klystron Modulator for C-band, S-band 50 MW Klystrons



Nanometer Beam Size Measurement

e+e- Linear Collider R&D

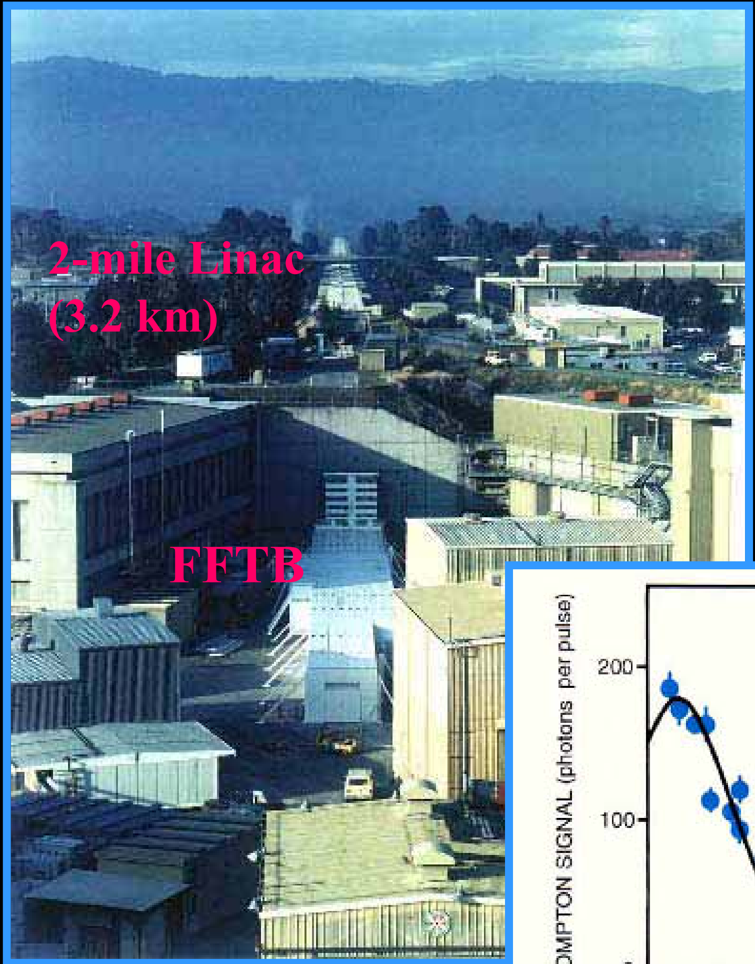
Spot-size Monitor based on Laser Interferometry



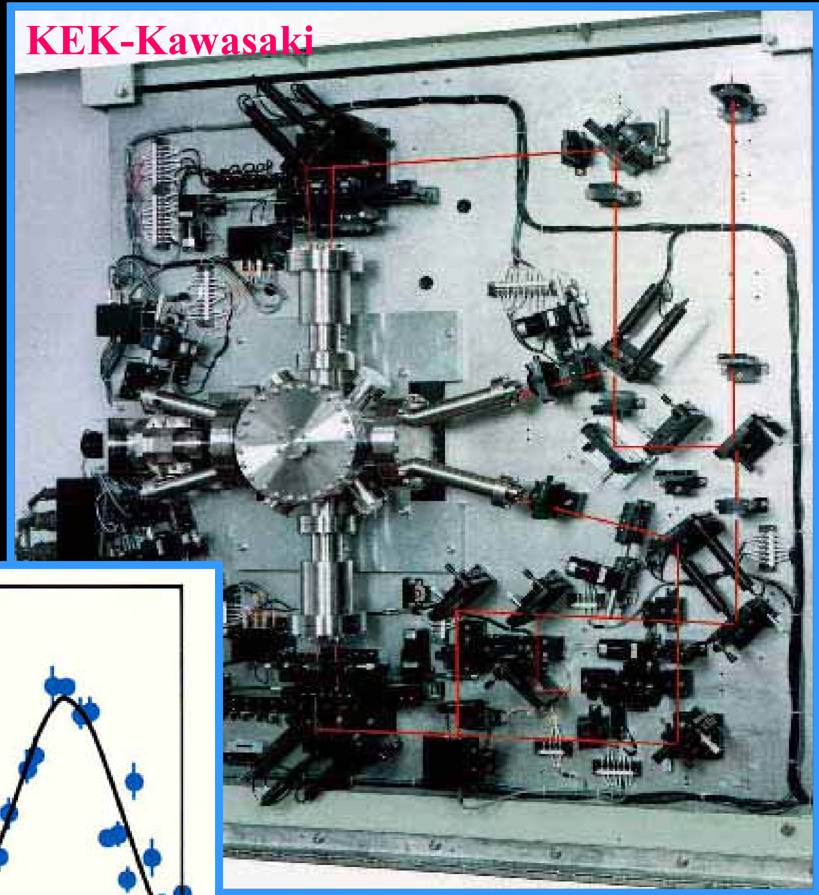
T. Shintake 1990

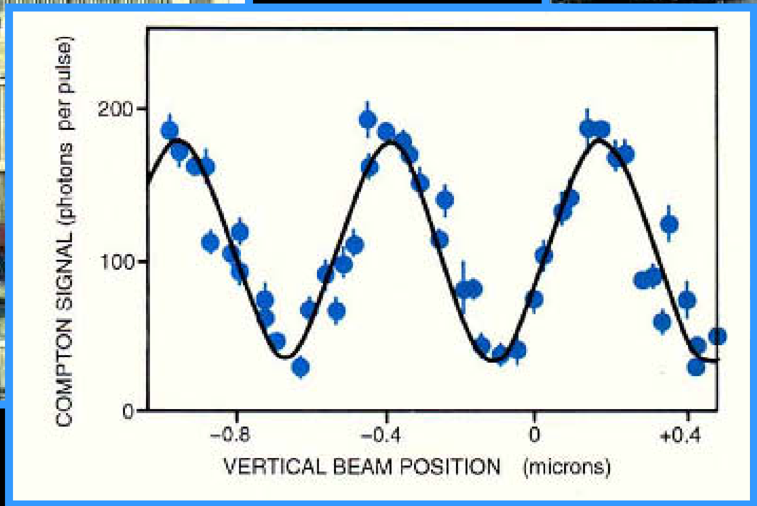
Experimental Test at FFTB

SLAC Two-mile Accelerator & FFTB

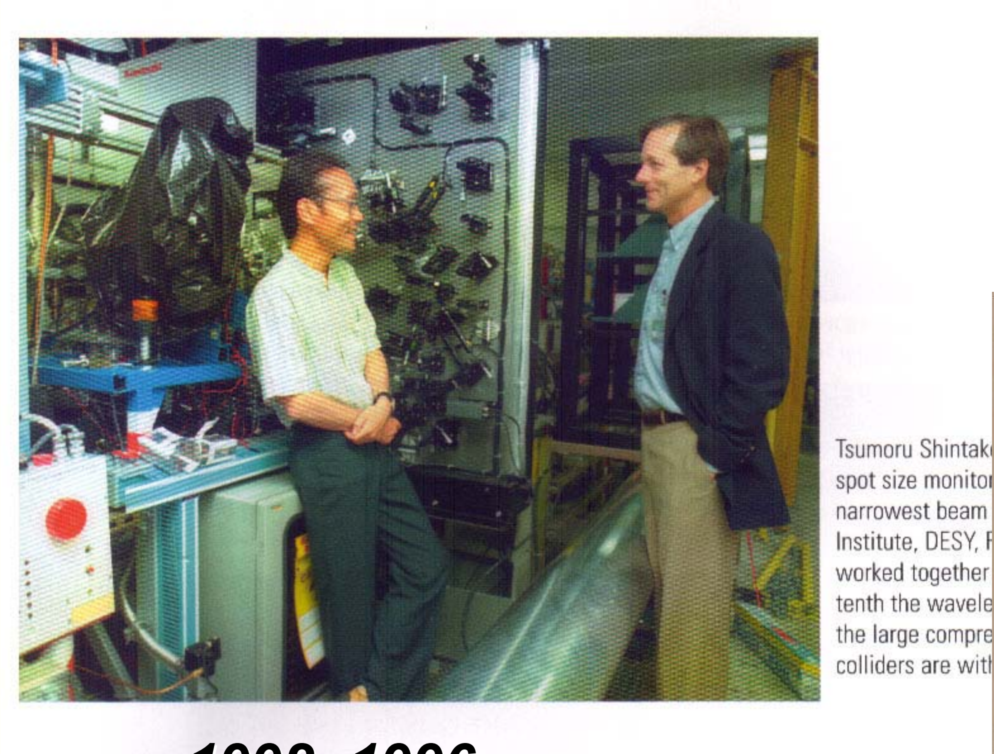


Laser Interferometer Table





Before XFEL

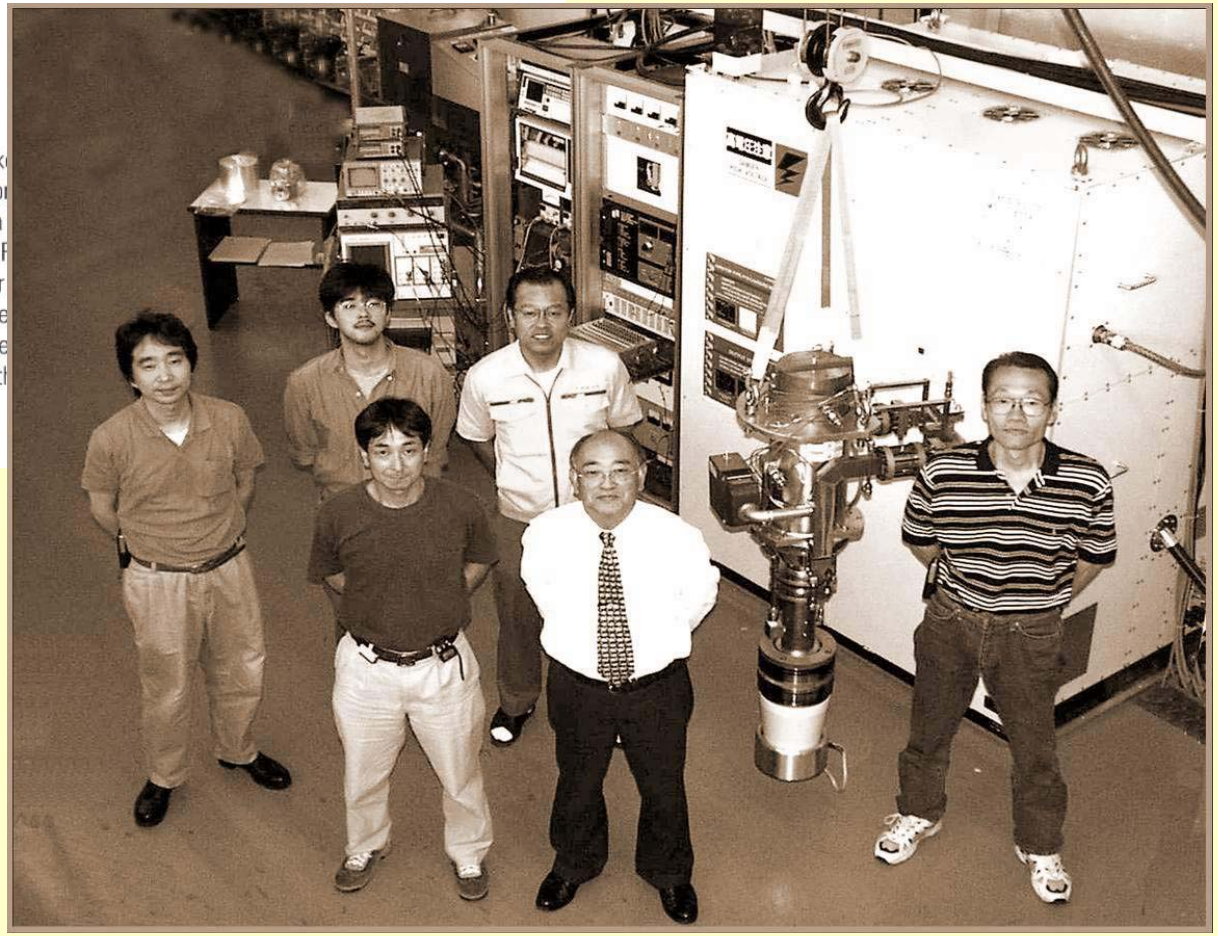


1992~1996
FFTB at SLAC

Laser interferometer for Spot size measurement.

1996~2000 C-band R&D at KEK

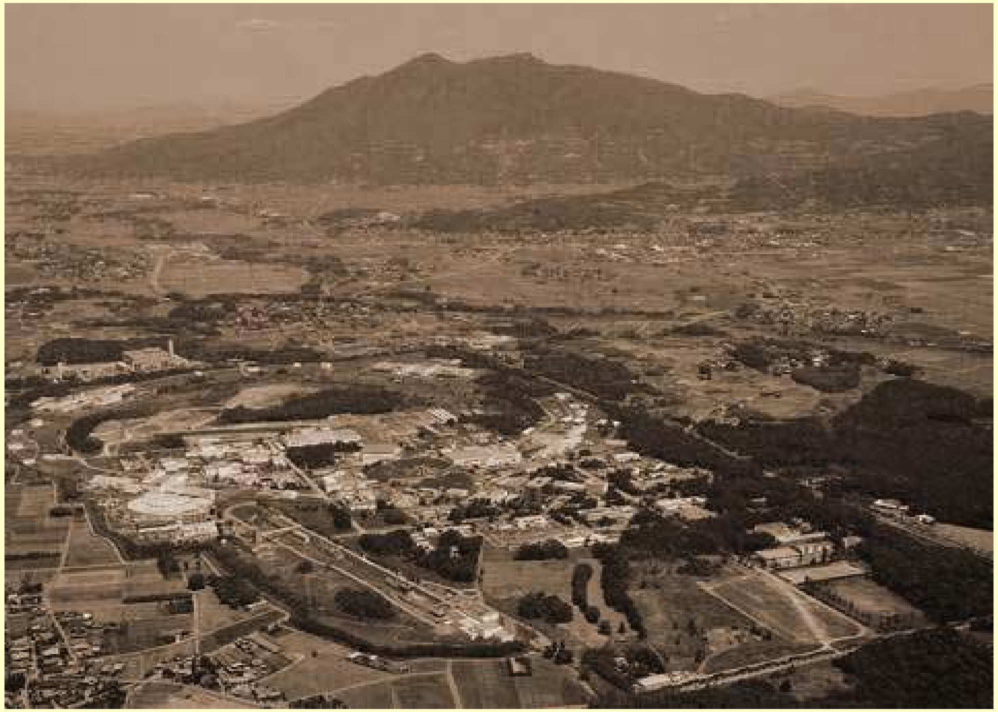
C-band accelerator runs at 37 MV/m



Technology transfer

Year of 2000 ~

KEK C-band



High energy e+e- collider

SPring-8 XFEL

Photon Science