Introduction to XFEL project in Japan

Accelerator Based X-ray Laser

for single molecular structural analysis

and

Femtosecond time resolution

Tsumoru Shintake

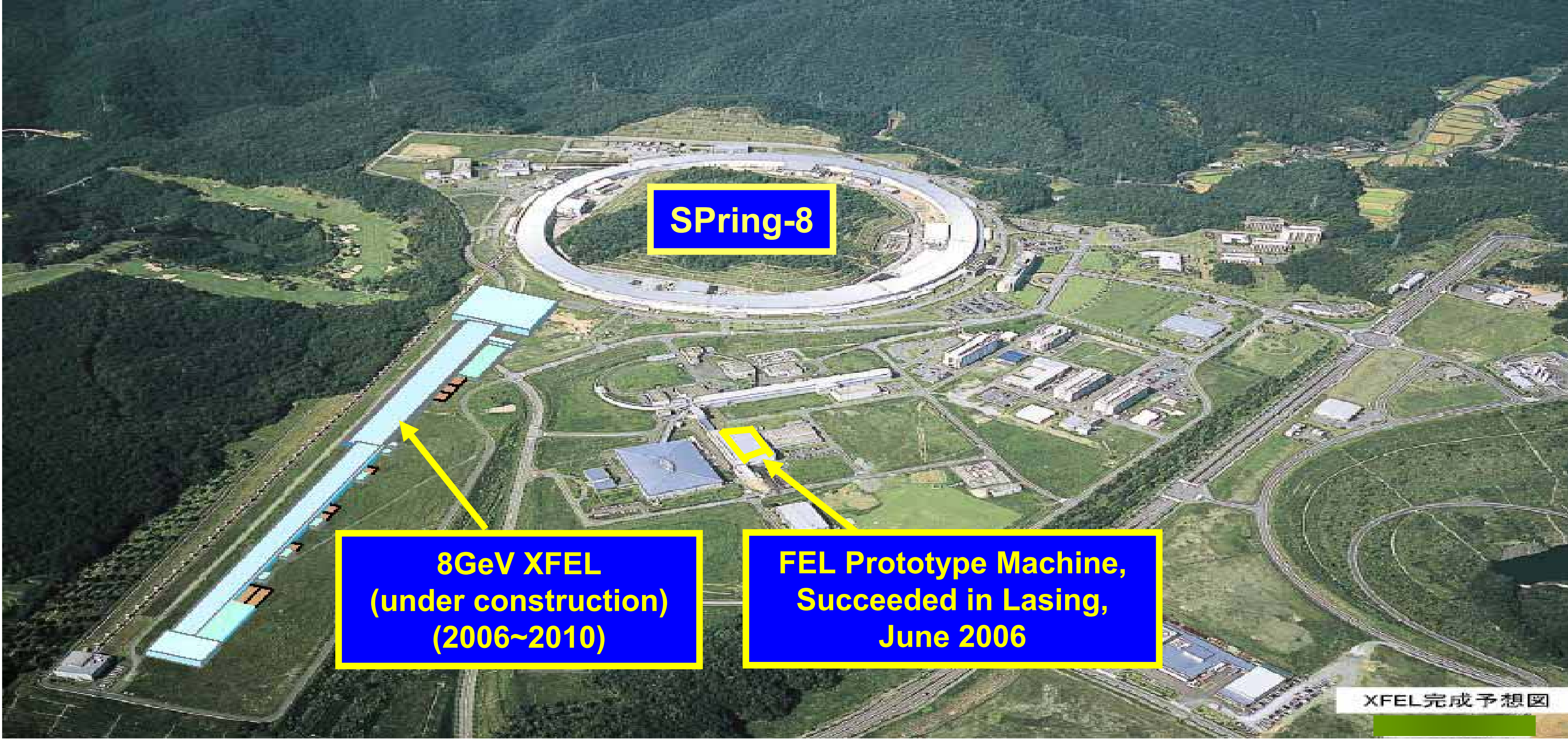
representing all XFEL contributors

RIKEN/SPring-8

Current status

and

Future

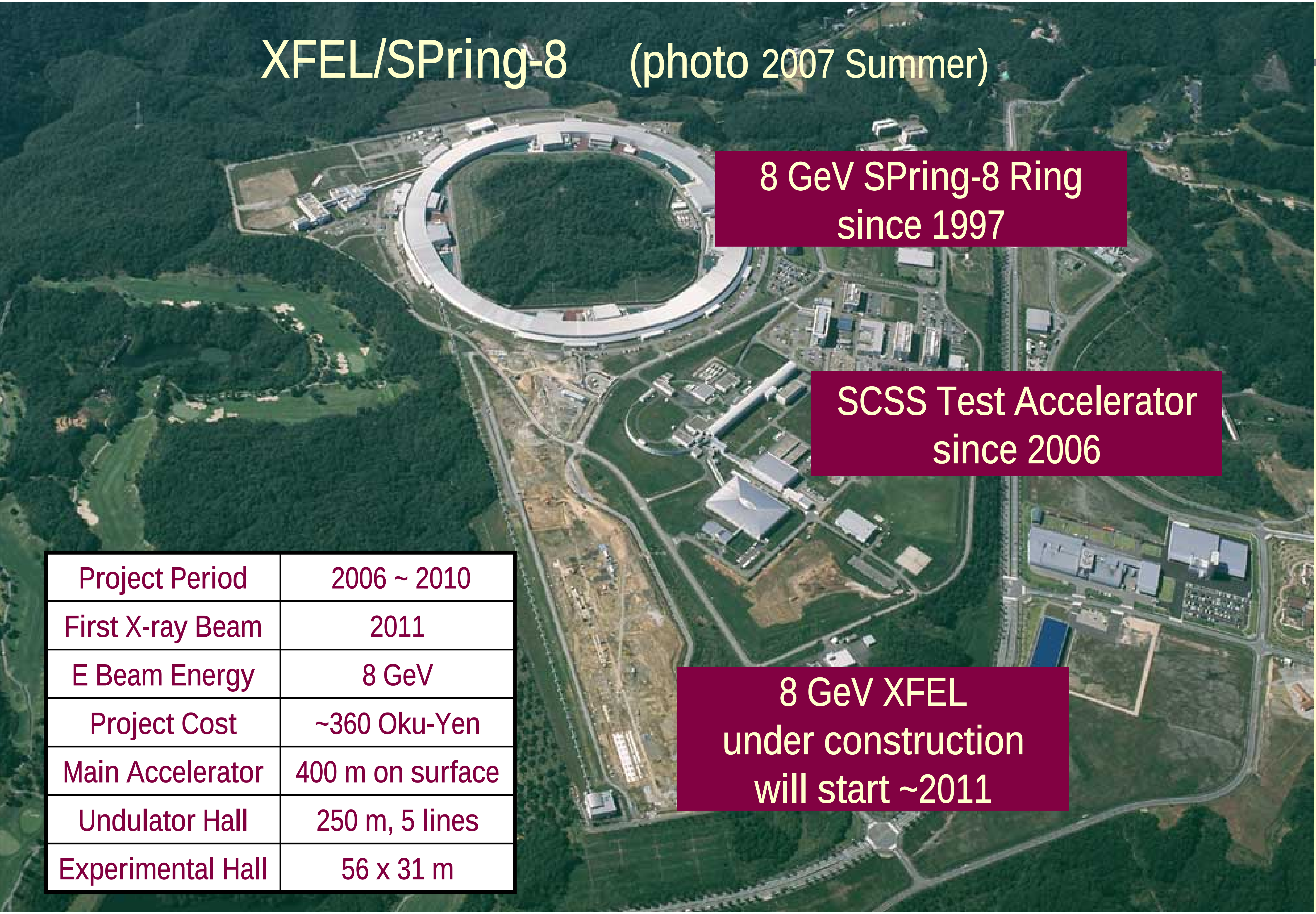


"X-ray Free Electron Laser, XFEL"

National Project of Next-Generation Light Source

RIKEN-JASRI Joint-Project Team for
SPring-8 XFEL Construction

XFEL/SPring-8 (photo 2007 Summer)



Project Period	2006 ~ 2010
First X-ray Beam	2011
E Beam Energy	8 GeV
Project Cost	~360 Oku-Yen
Main Accelerator	400 m on surface
Undulator Hall	250 m, 5 lines
Experimental Hall	56 x 31 m

8 GeV XFEL Construction 2008 January

Undulator area has been excavated to replace soft soil to hard basement.

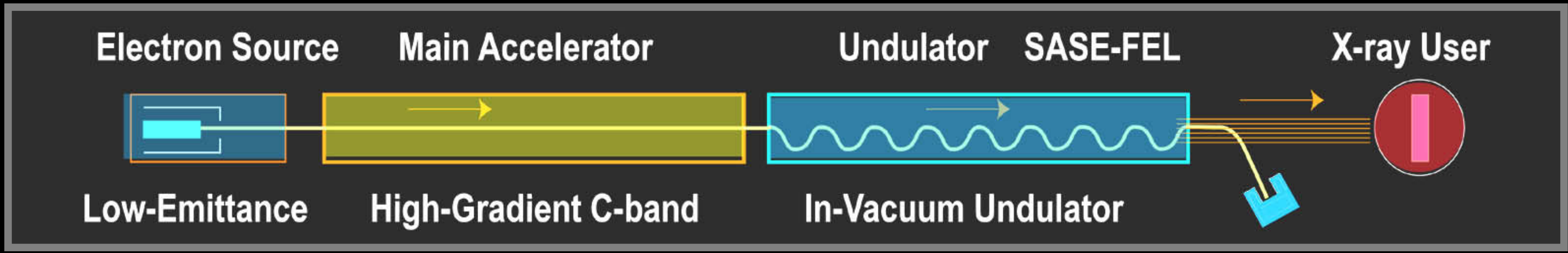
8 GeV XFEL Construction 2008 May

Comparison of X-ray FELs

Projects	Euro-XFEL	LCLS	XFEL/SPring8 (SCSS)
Wavelength	6 – 0.085 nm	1.5 – 0.15 nm	6 – 0.08 nm
Beam Energy	10 - 20 GeV	14.3 GeV	2 - 8 GeV
Main Accelerator	Super Conducting	S-band Normal Conducting	C-band Normal Conducting
Accelerator Length Gradient x Active Length	2.1 km 23.5 MV/m x 900 m	1 km 19 MV/m x 800 m	400 m 35 MV/m x 230 m
Undulator Period Total undulator Length	26 mm 133 m	30 mm 113 m	18 mm 90 m
Total Length Undulator Lines (X-ray)	3.4 km 3 (5)	1.6 km 1 (5)	700 m 1 (3), max 5
Construction Cost	850 M-Euro	380 M$	300 M$

SCSS:SPring-8 Compact SASE Source

X-ray FEL



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

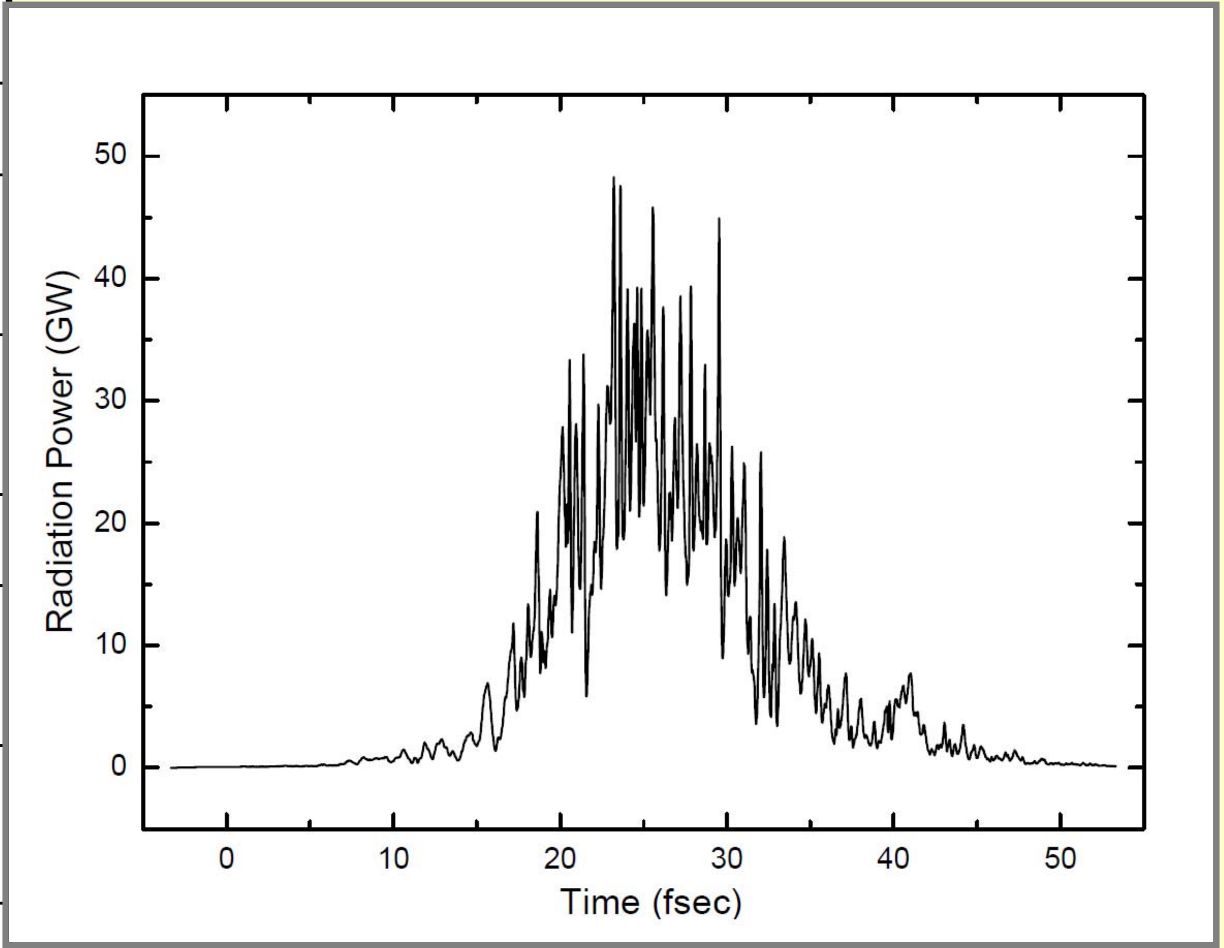
KEK C-band 35 MV/m x 30 m = 1 GeV

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

Kitamura's In-Vacuum Undulator : E = 1GeV, λu = 15 mm, λx = 3.6 nm

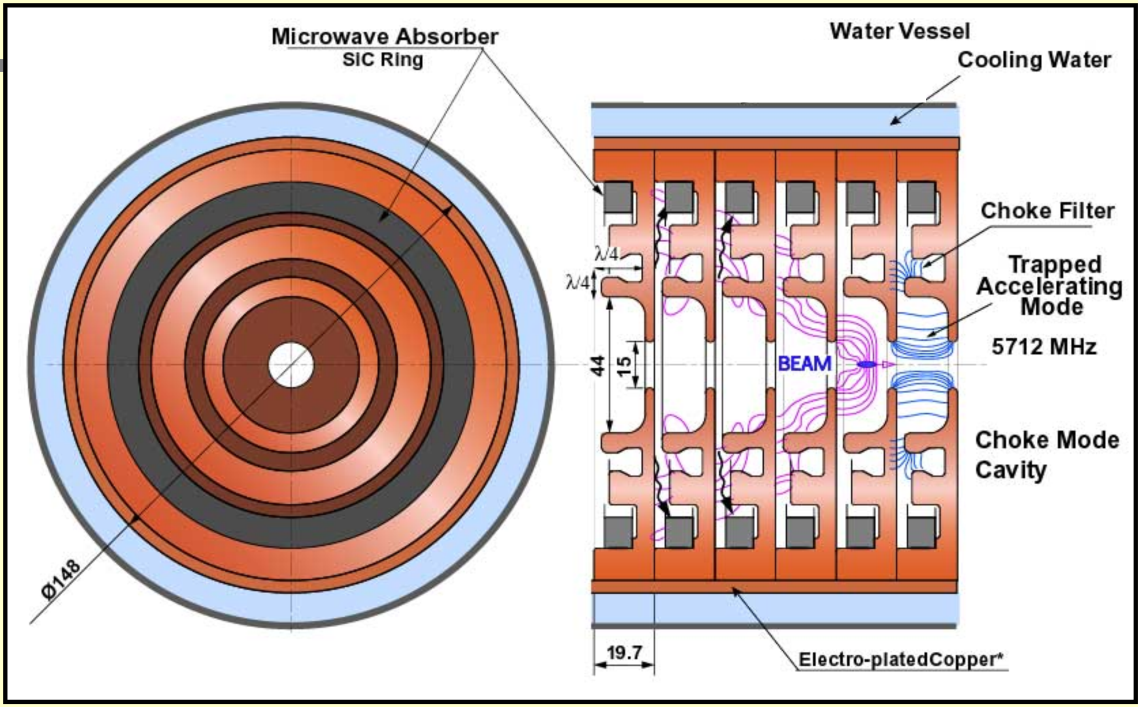
Expected Performance of XFEL/SPring-8

Wavelength	< 0.1 nm
Peak Power	~ 20 GW
X-ray Pulse Length	~ 20 fs
X-ray Pulse Energy	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)

C-band Accelerator for Multi-bunch Option



T. Shintake, "Choke Mode Cavity",
Jpn. J. Appl. Phys. Vol. 31 pp. L1567-L1570, November 1992

13,000 cells are under mass production.

Sadao Miura, MITSUBISHI Heavy Ind, April 2008

Higher Order Mode Damping for
Multi-bunch operation.
Maximum 50 bunches x 1 nC, at 4.2 nsec spacing
3000 X-ray pulses / sec.

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

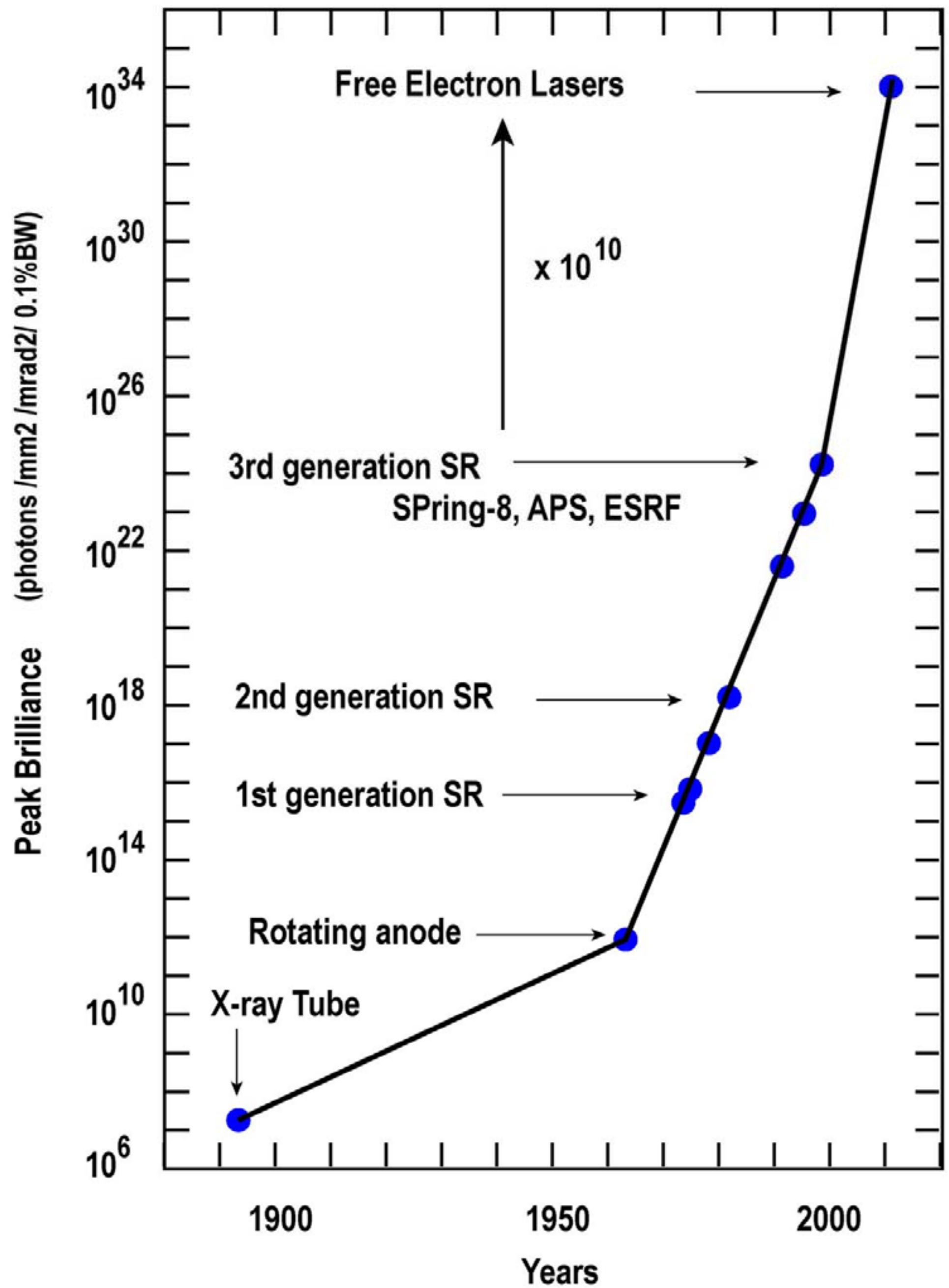
Normal conducting v.s. super-conducting machine

- (1) Super conducting accelerator is three or four times more expensive than normal conducting accelerator.
- (2) FEL is basically pulse machine, and there is no reason to make it CW machine. If you have CW FEL at X-ray, it becomes a weapon, and not useful for scientific research tool, it average power is strong enough to burn verything.
- (3) CCD cameras for X-ray detector has certaing limit of reading time, it slow. For example, 4k x 4k format CCD takes more than one minutes for one frame reading time.
- (4) In the super conducting machie, the beam loading effect dominates beam dynamics,thus in the bunch train the front part has dynamic change before coming to the steady state, thus off energy particle irradiate undulators.

MOVIE !

SPring-8 XFEL Accelerator and Undulator

Peak Brilliance Evolution

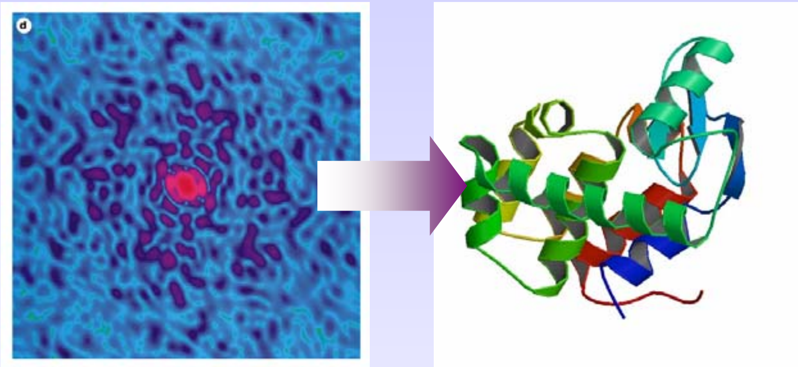


- Peak brilliance will be enhanced by factor of 10^{10} from 3rd generation SR to XFEL.

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

  = 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.

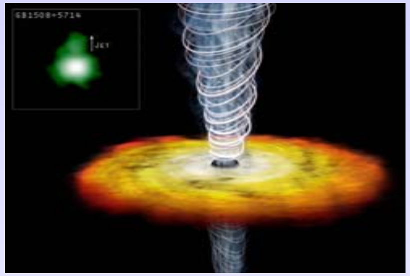
Science with X-ray Free Electron Laser



Atomically-resolved imaging for non-crystalline objects

High brilliance
x10^{9}

Generation of extreme state

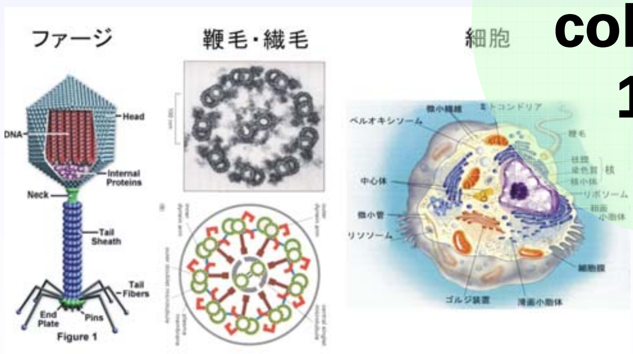


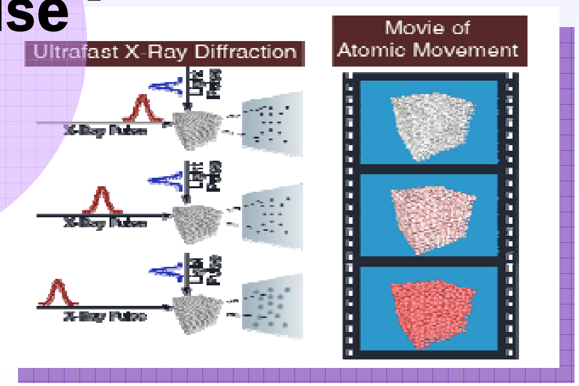
XFEL

Probing of ultrafast chemical reaction & phase transition

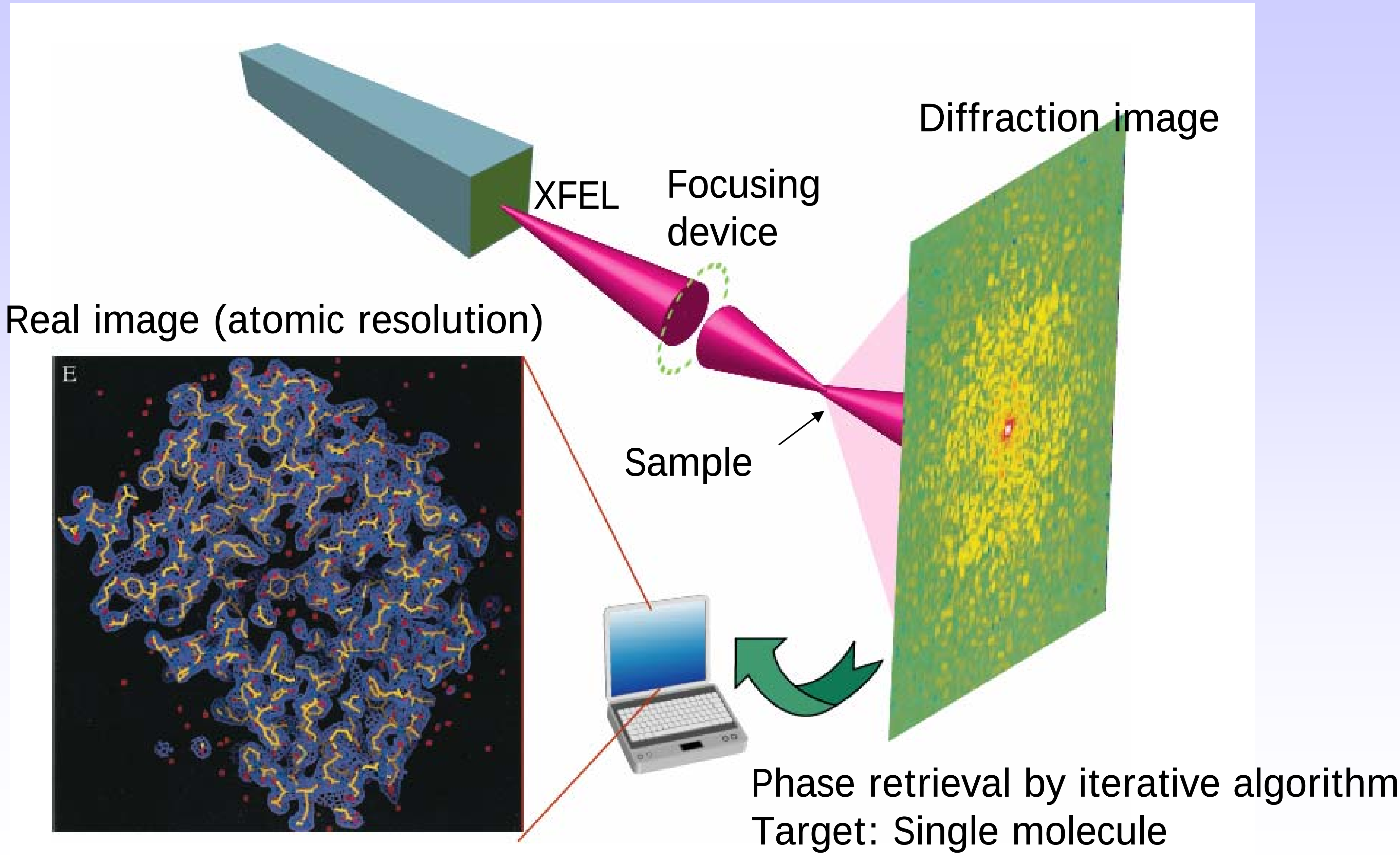
Spatial coherence
100%

Ultrafast pulse
< 100 fs

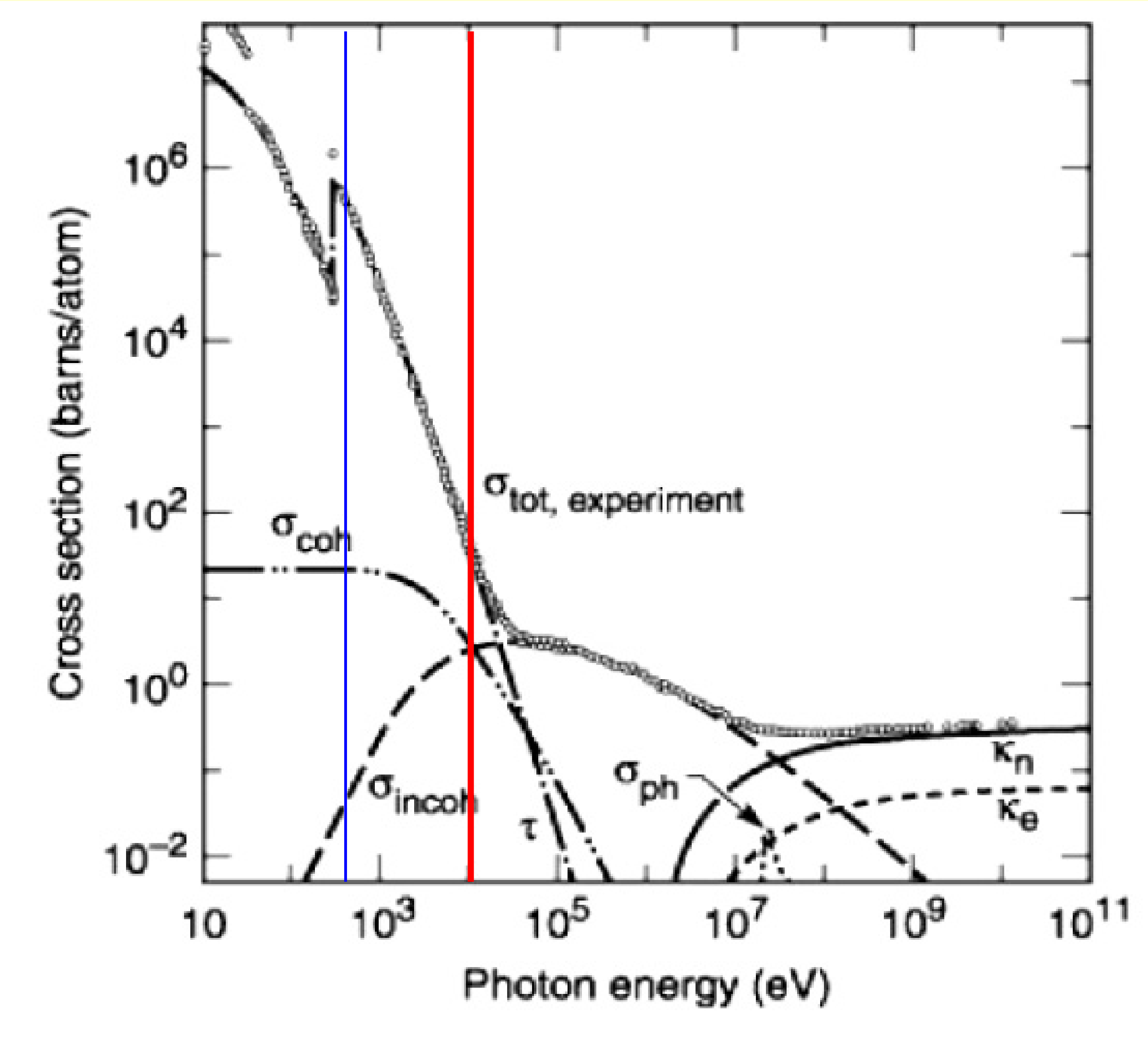




Coherent diffraction imaging



Why 1 Angstrom?



Cross-section of X-ray with Carbon

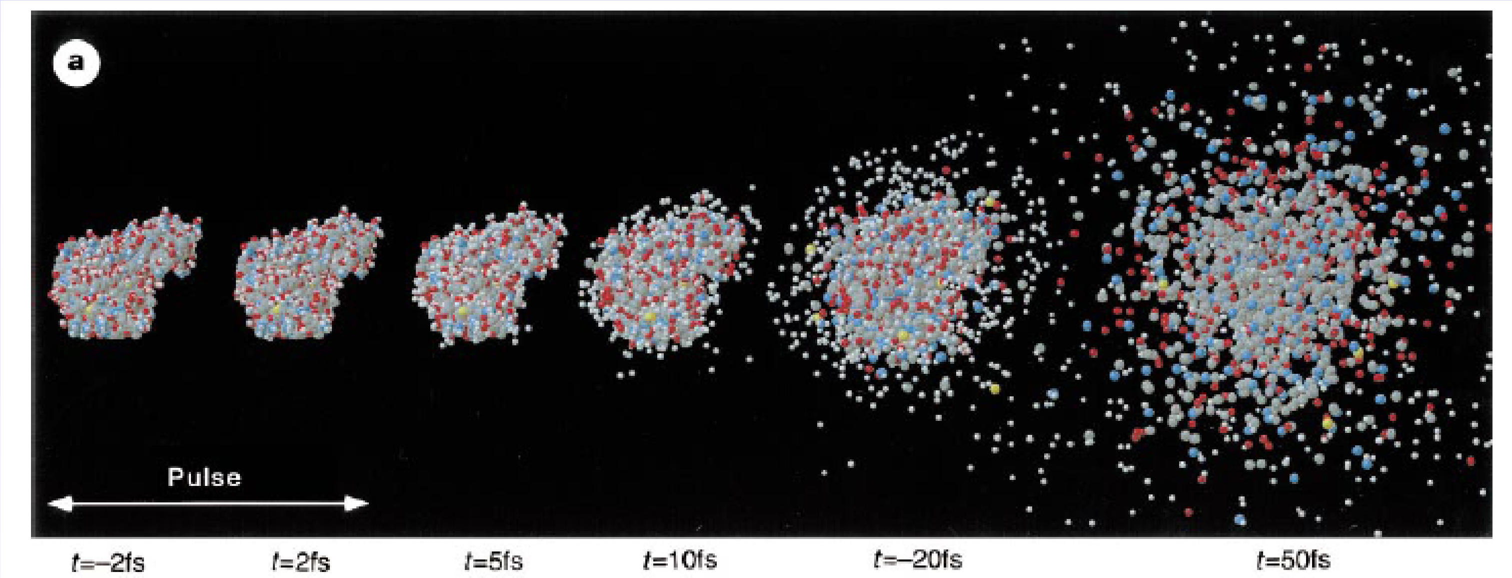
- Photo-ionization becomes lower as X-ray energy.
- Around 1 A, 8 keV, photo-ionization becomes low enough to see coherent scattering.
- Spatial resolution becomes a few Angstrom, which resolves macromolecular crystal in biology.

  → Imaging, crystallography

- **water window** (2.3-4.4nm light) is also another candidate.

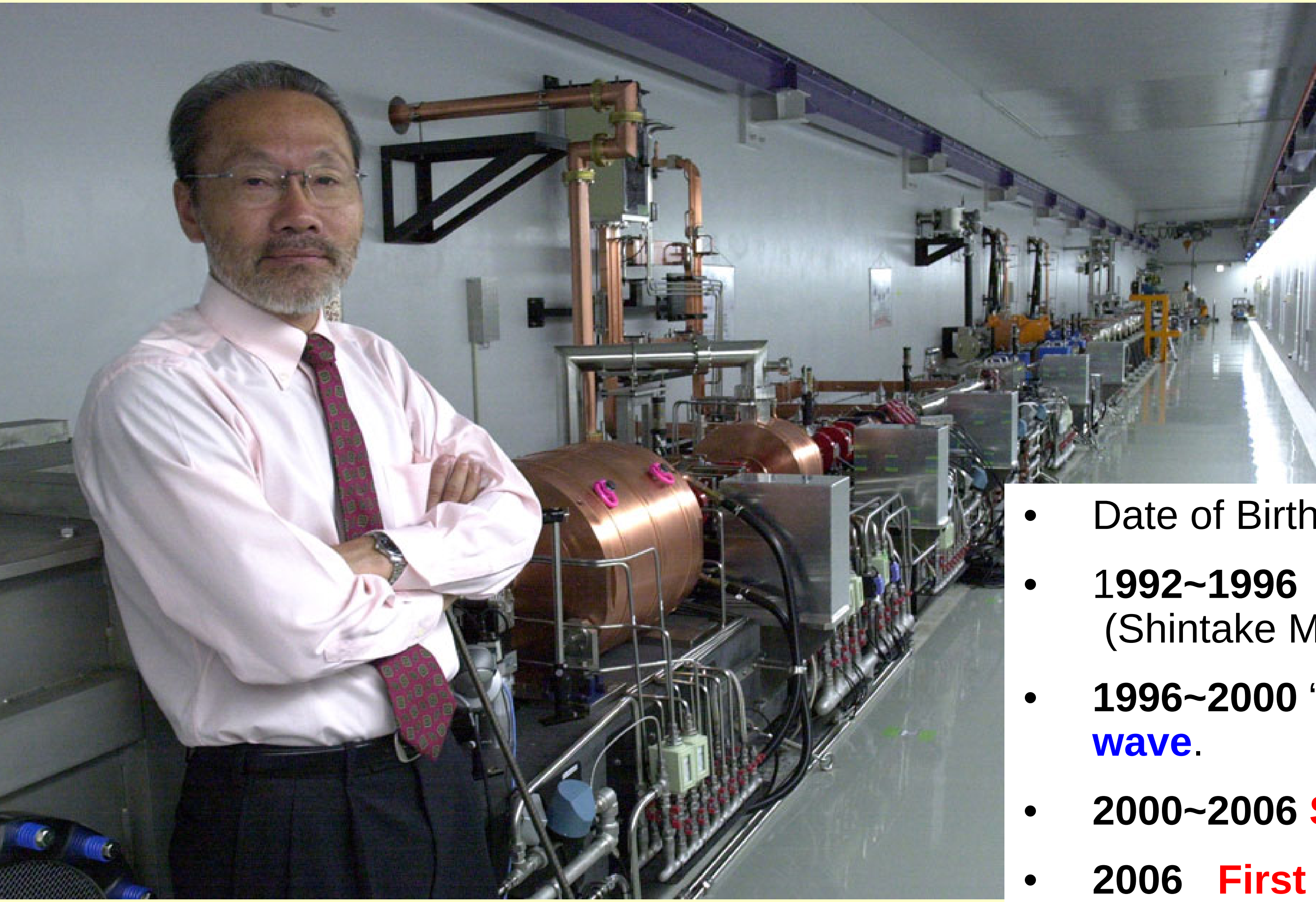
(a few micron-meter thick water)

Sample damage with XFEL irradiation



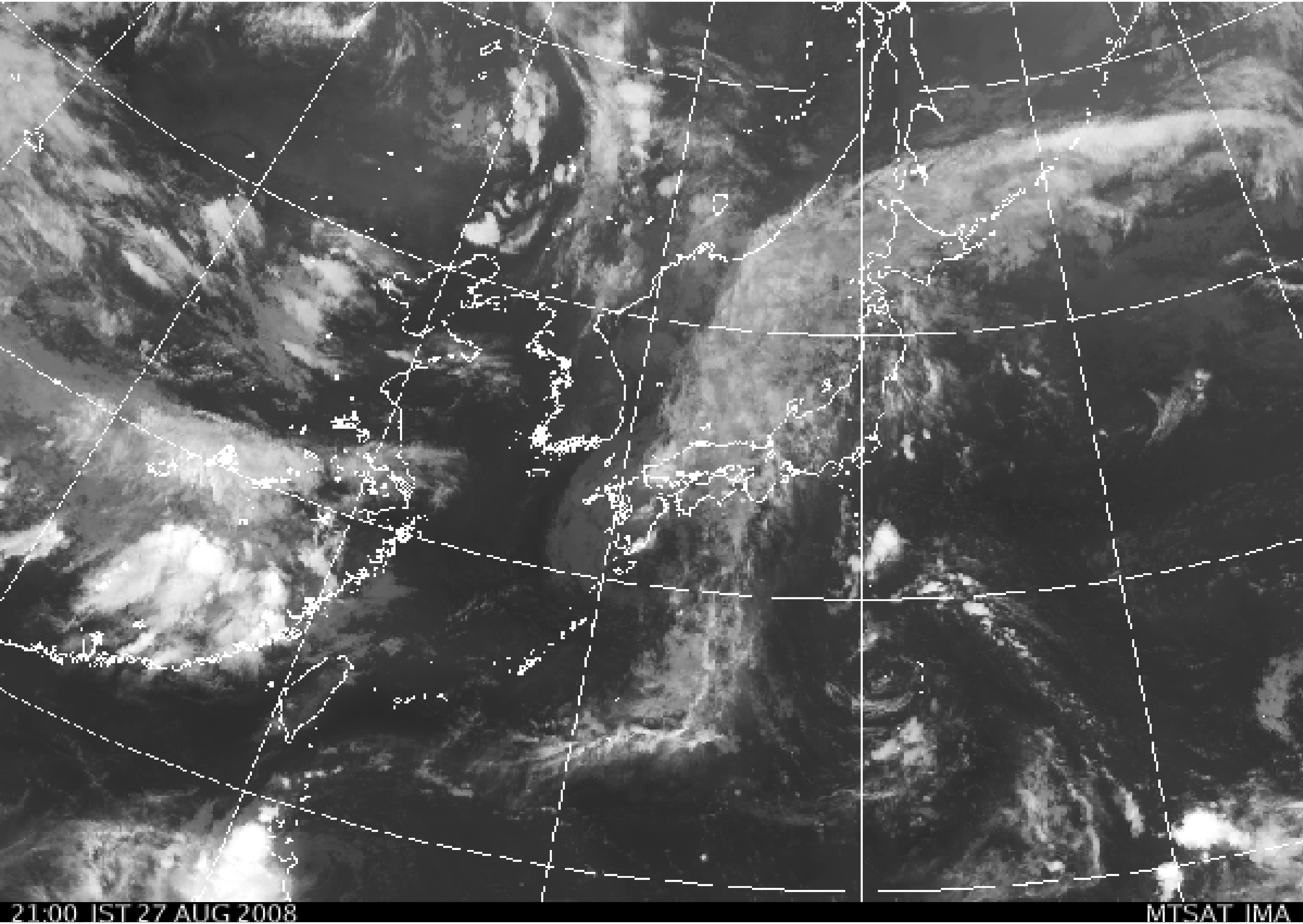
Neutze et al, Nature, 2000

Who is Shintake?



@ SCSS tunnel
Test Accelerator for XFEL

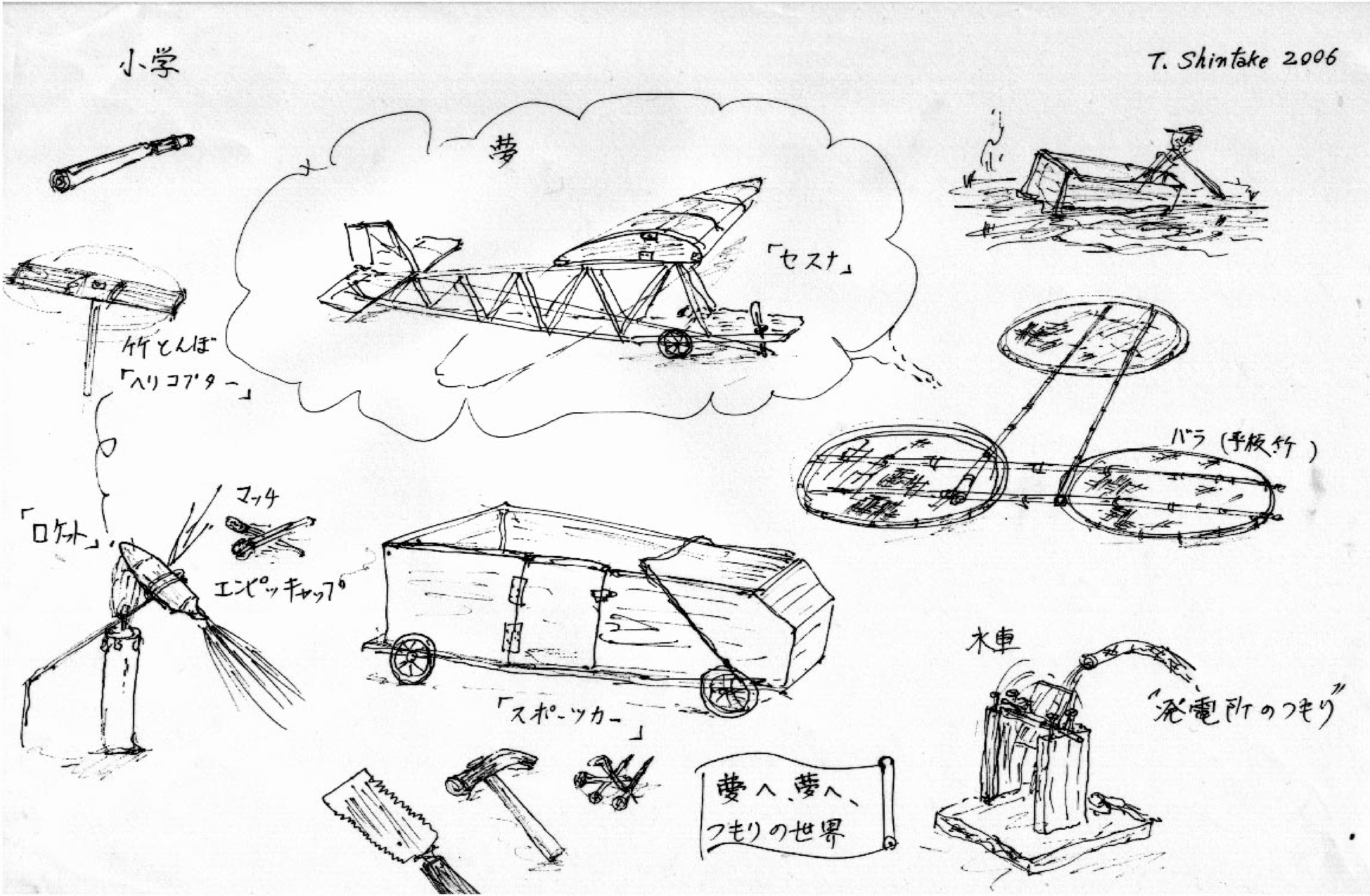
- Date of Birth **1955**,   Miyazaki, Kyushu Japan
- 1**992~1996** FFTB – SLAC "**Spot Size Monitor**" (Shintake Monitor) **60 nm e with 1 μm wave**
- **1996~2000** "**C-band R&D**" for LC at KEK **5 cm wave**.
- **2000~2006** **SCSS R&D** Leader **e- beam**
- **2006**   **First Lasing** at SCSS Prototype Accelerator **49 nm wave**
- **2006~ Now** constructing 8 GeV **XFEL/SPring-8 for 0..1 nmm wave**


21:00 JST 27 AUG 2008
MTSAT JMA

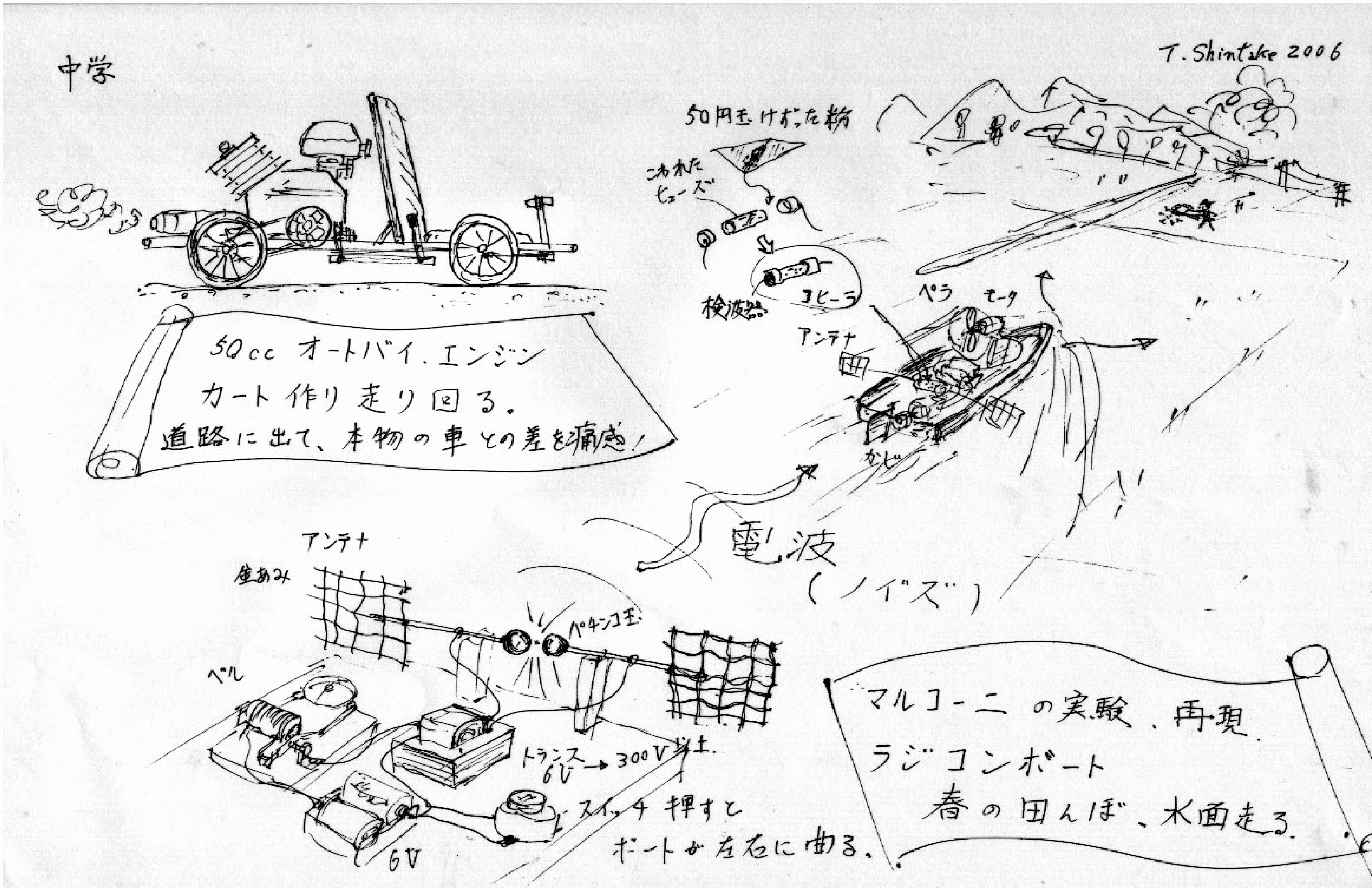

KYUSHU

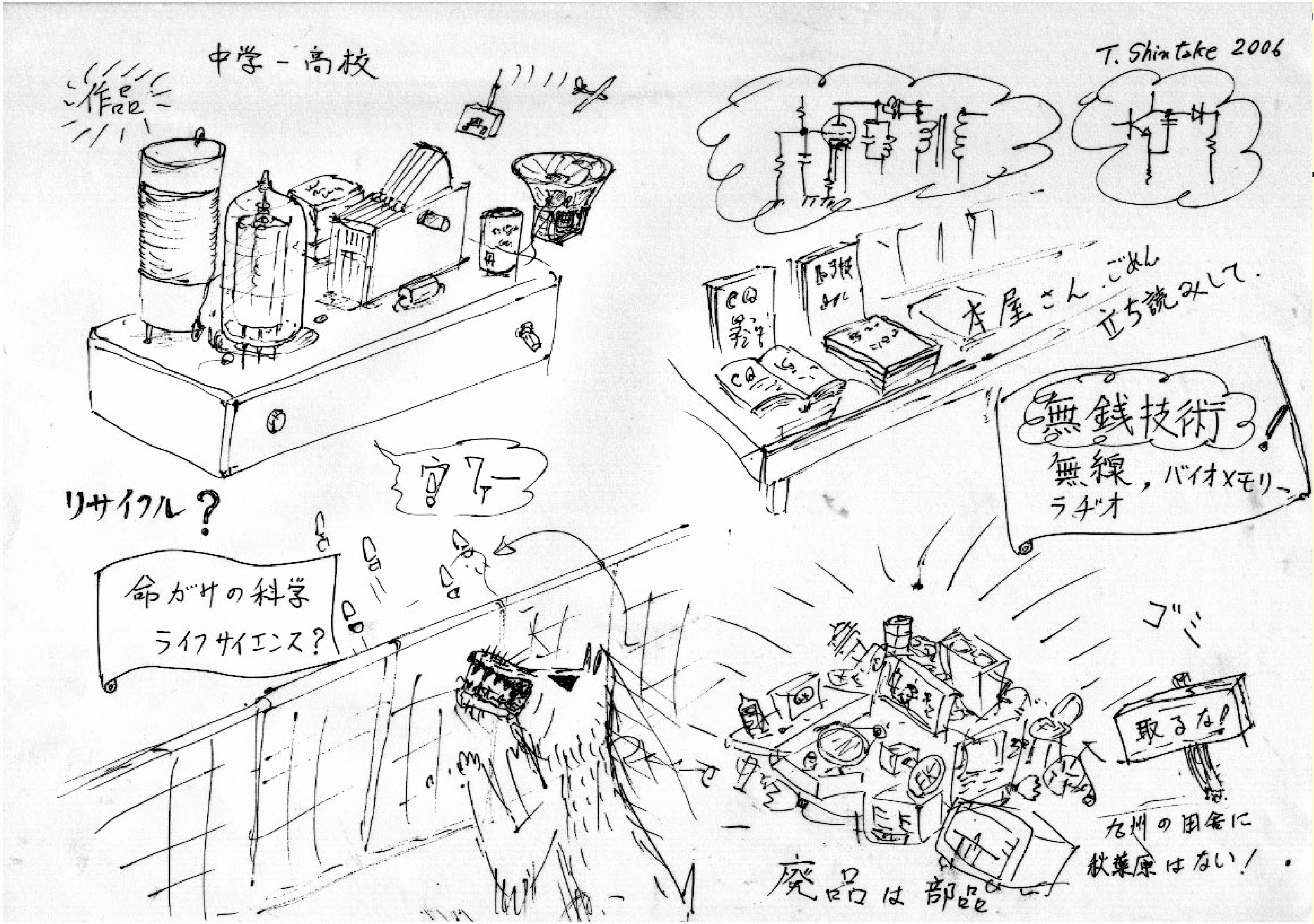
MIYAZAKI

T. Shiutake
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

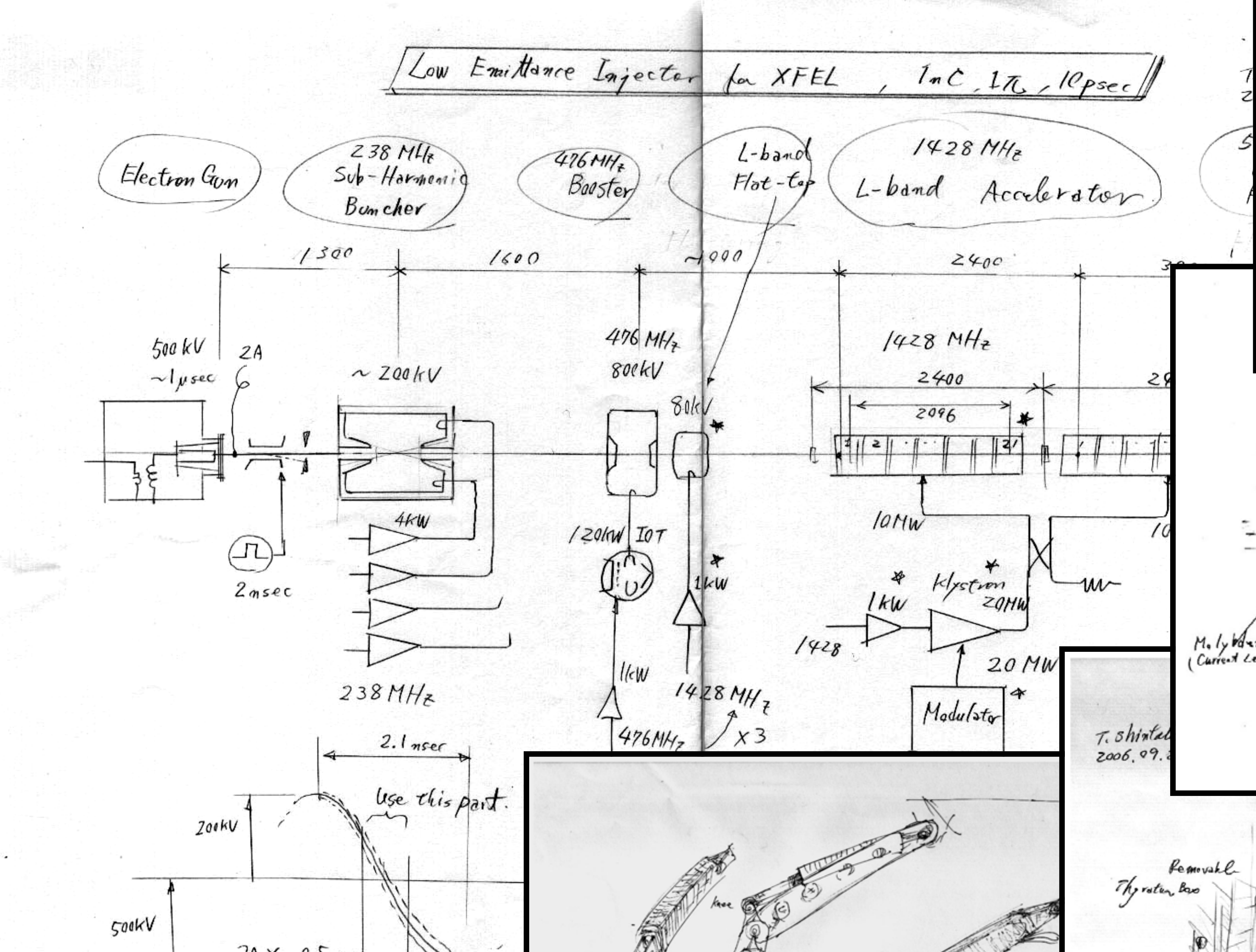


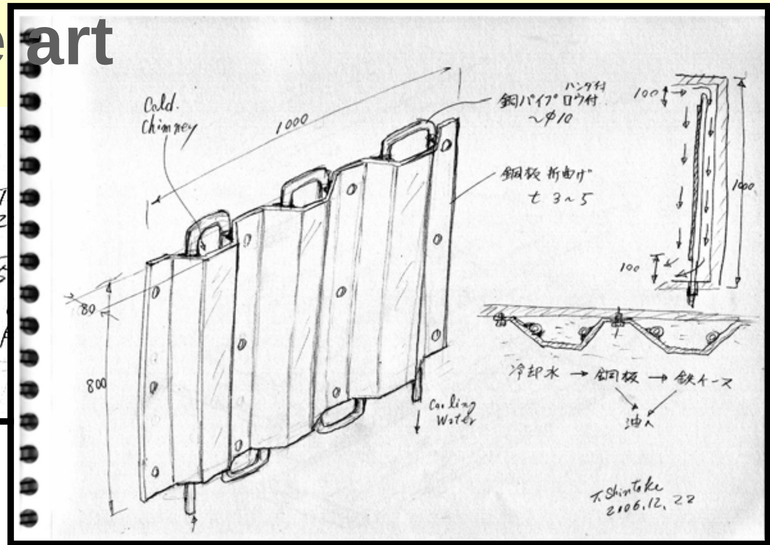
小学
T. Shintake 2006
夢
「セスナ」
竹とんぼ
「ヘリコプター」
「ロケット」
マッチ
エンピツキャップ
「スポーツカー」
バラ (手板竹)
水車
"発電所のつもり"
夢へ、夢へ、
つもりの世界

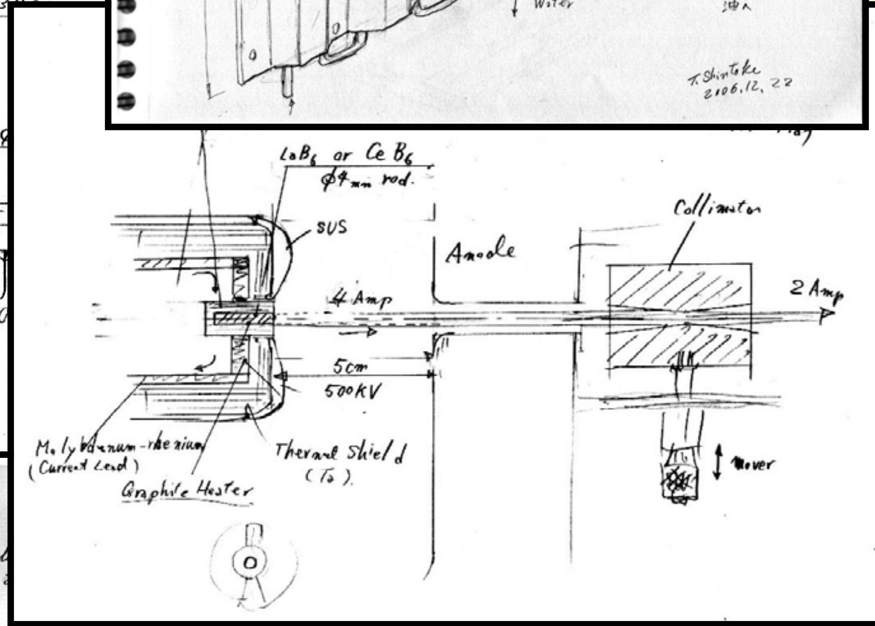

中学
T. Shintake 2006
50cc オートバイ.エンジン
カート作り 走り回る。
道路に出て、本物の車との差を痛感!
50円玉けずった粉
こわれたヒューズ
検波器
ヒーター
ペラ
モータ
アンテナ
かじ
電波
（ノイズ）
アンテナ
金あみ
パチンコ玉
ベル
トランス
6V → 300V以上.
6V
スイッチ押すと
ボートが左右に曲る。
マルコーニの実験.再現
ラジコンボート
春の田んぼ、水面走る。

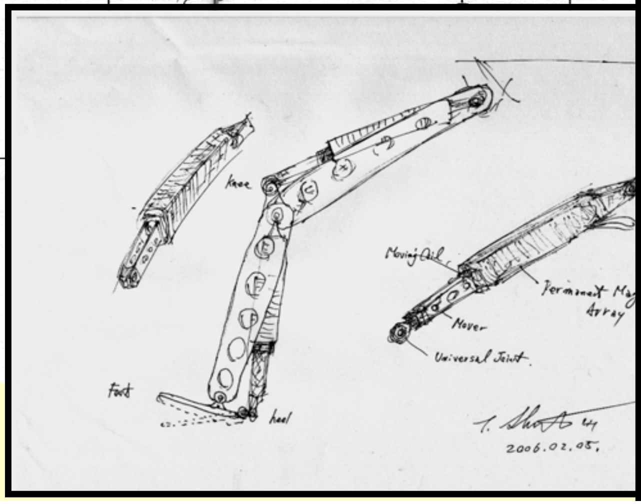

中学－高校
作品
T. Shintake 2006
本屋さん ごめん
立ち読みして.
無銭技術!
無線, バイオメモリー
ラヂオ
リサイクル?
ワァー
命がけの科学
ライフサイエンス?
ゴミ
取るな!
九州の田舎に
秋葉原はない!
廃品は部品

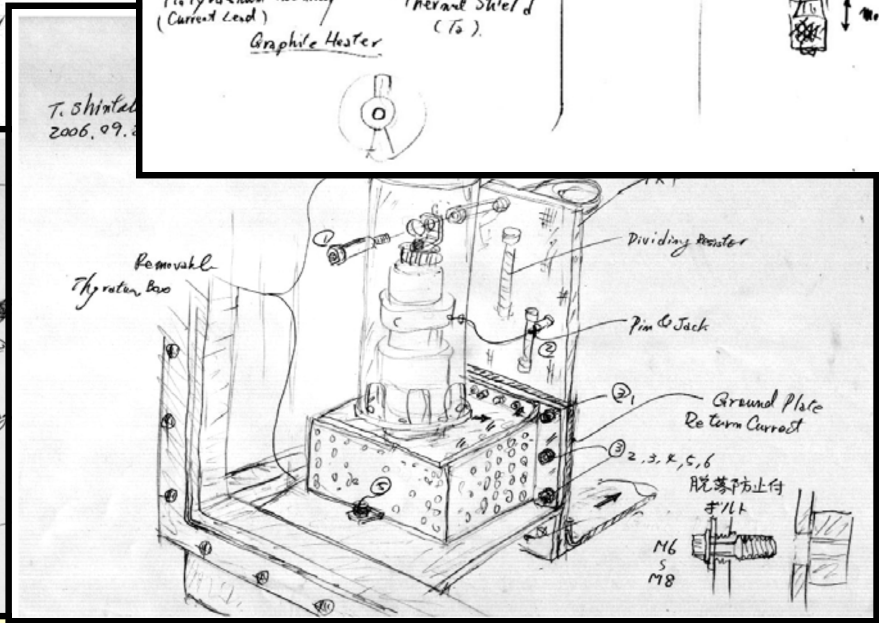
Design accelerator as creating images like art



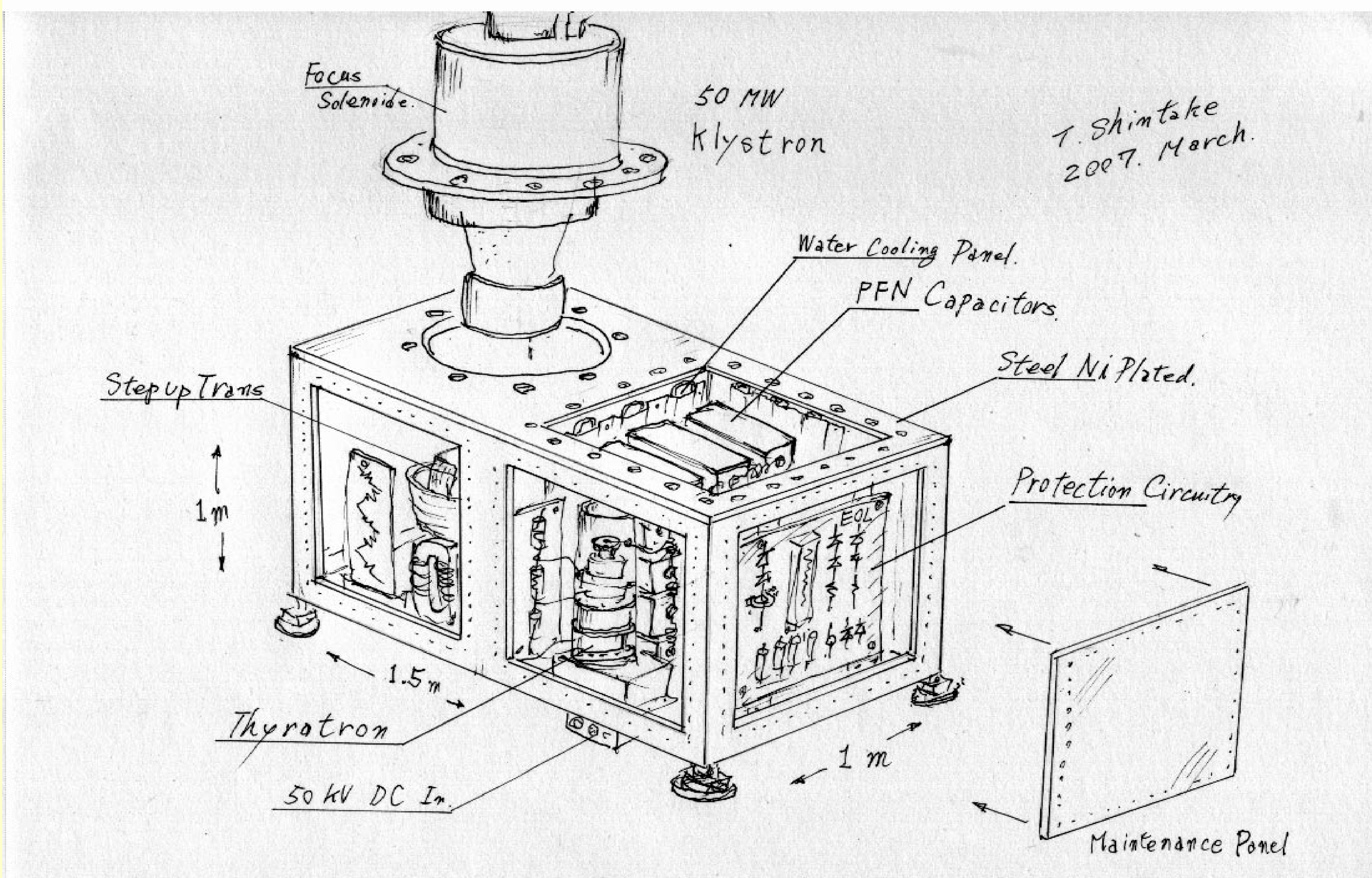








Klystron Modulator for C-band, S-band 50 MW Klystrons



50 MW Klystron and Modulator for XFEL

Max RF power : 50 MW
@C-band and S-band

Max Pulse Power: 110 MW
Max Rep Rate : 60 pps
Size : 1m x 1m x 1.7 m
Total Weight : 4.5 ton
Insulation oil filled.
Water cooled.
Perfect EM noise shield.

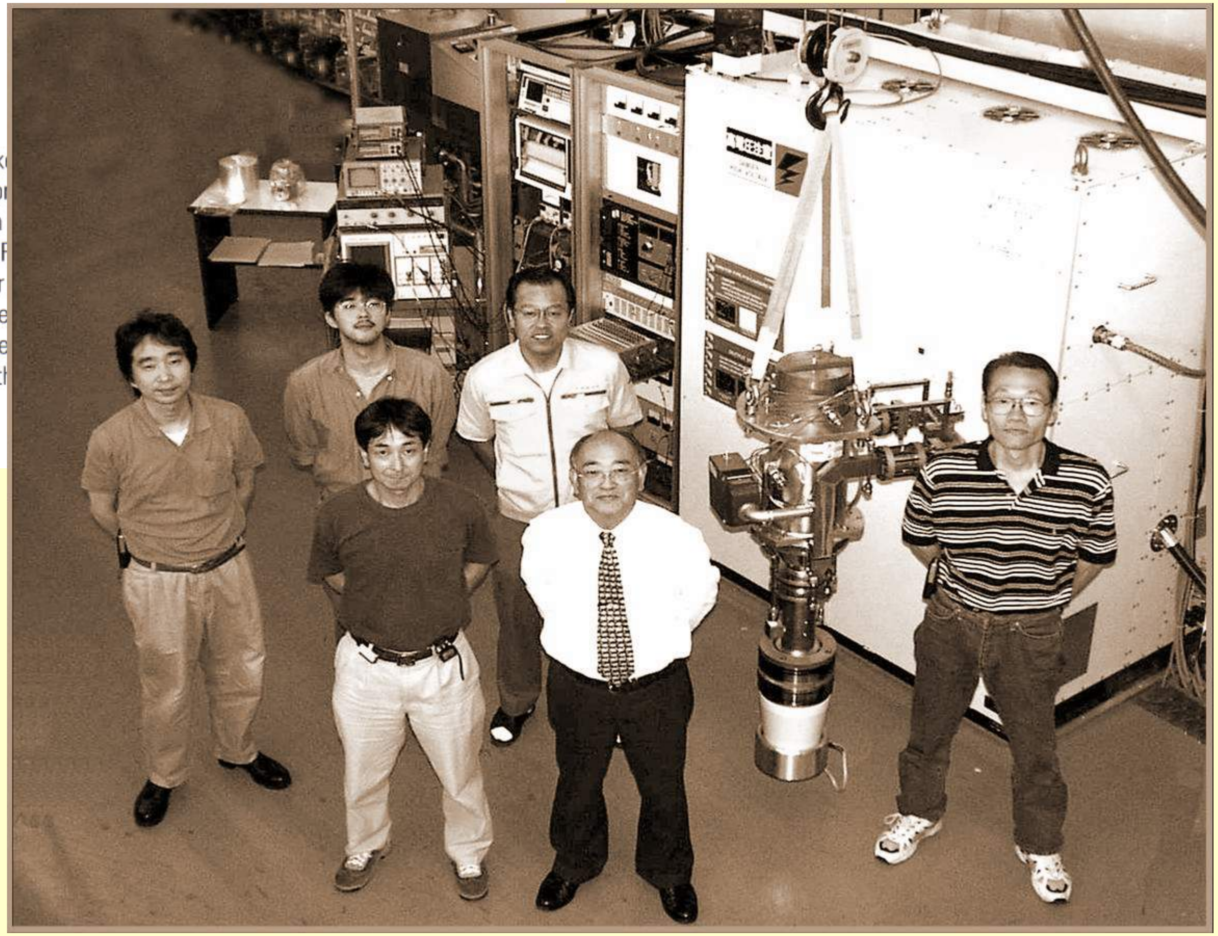
Ready for mass production of 70 units.

Before XFEL

Tsumoru Shintak
spot size monitor
narrowest beam
Institute, DESY, F
worked together
tenth the wavele
the large compre
colliders are with

1996~2000   C-band R&D at KEK

C-band accelerator runs at 37 MV/m



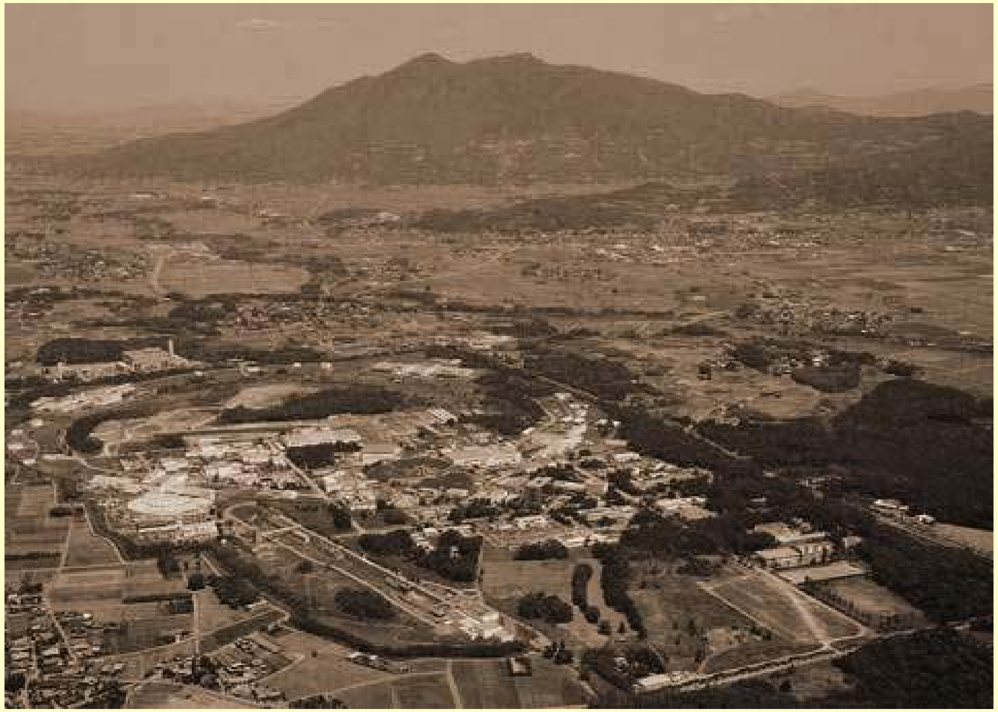
1992~1996
FFTB at SLAC

Laser interferometer for
Spot size measurement.

Technology transfer

Year of 2000 ~

KEK C-band



High energy e+e- collider

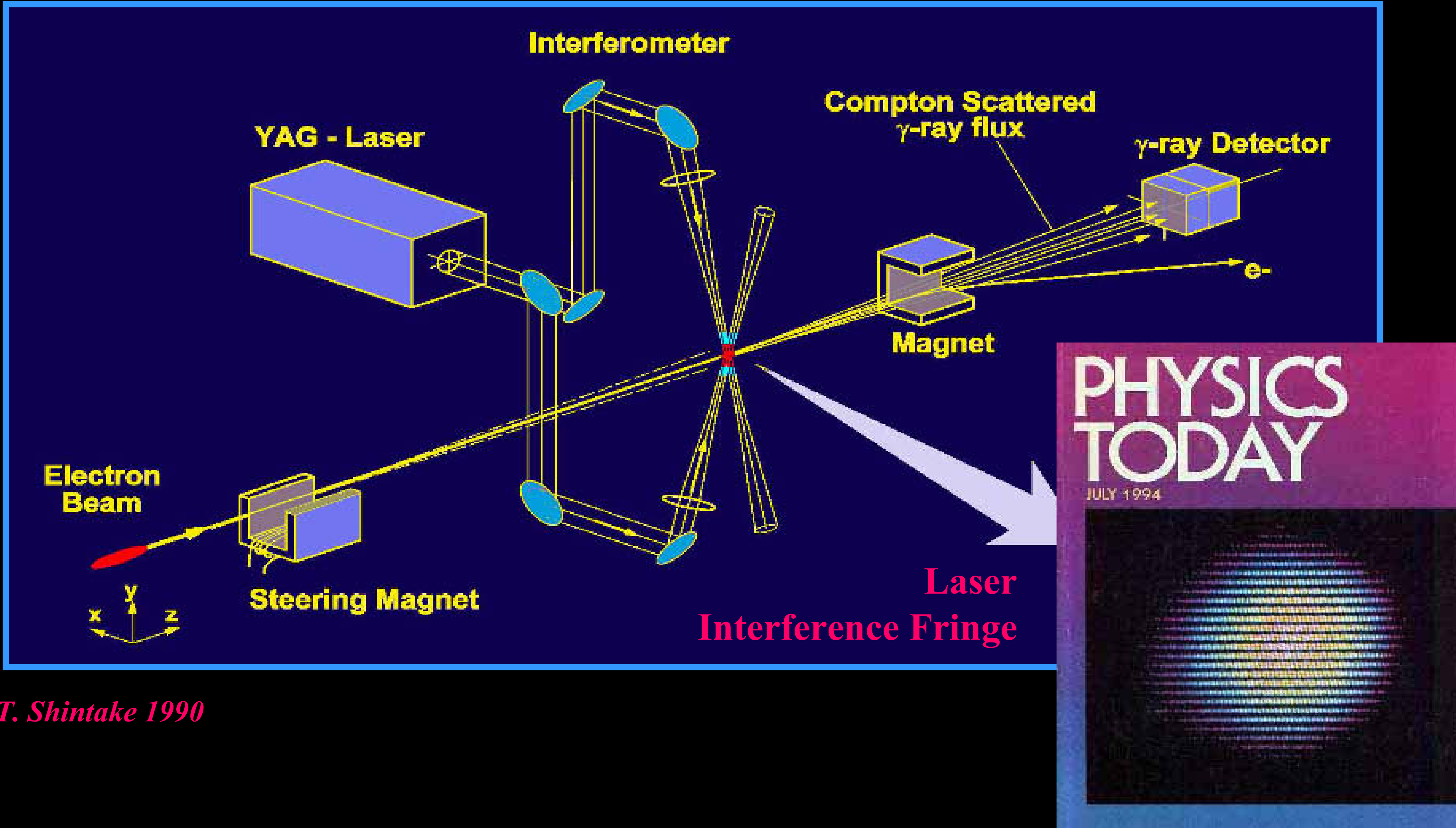
SPring-8 XFEL

Photon Science

Nanometer Beam Size Measurement

e+e- Linear Collider R&D

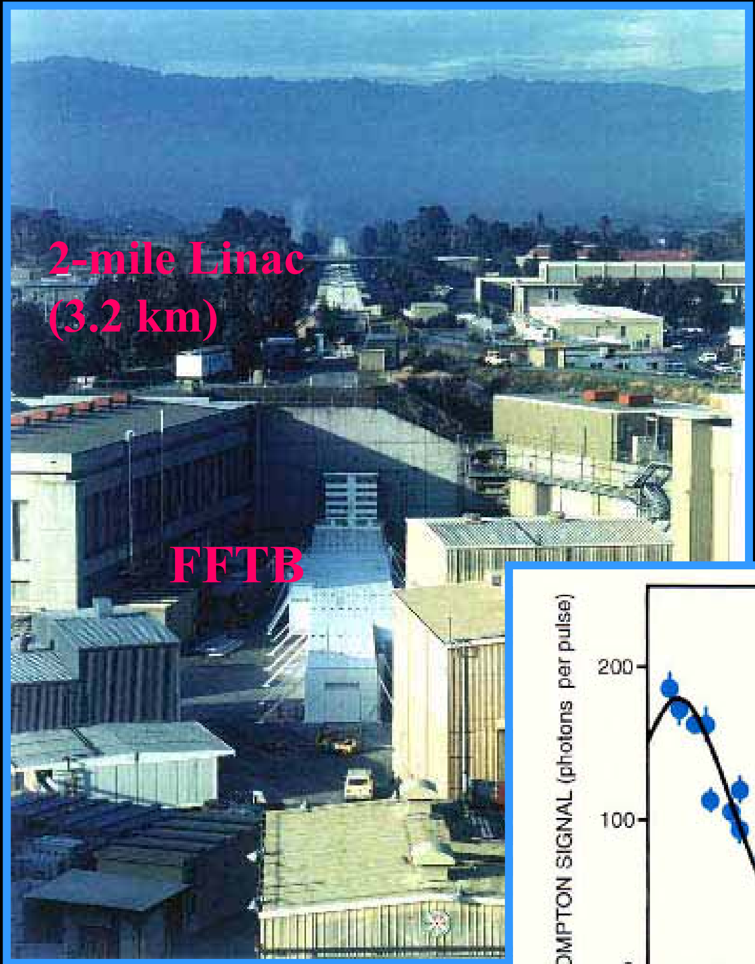
Spot-size Monitor based on Laser Interferometry



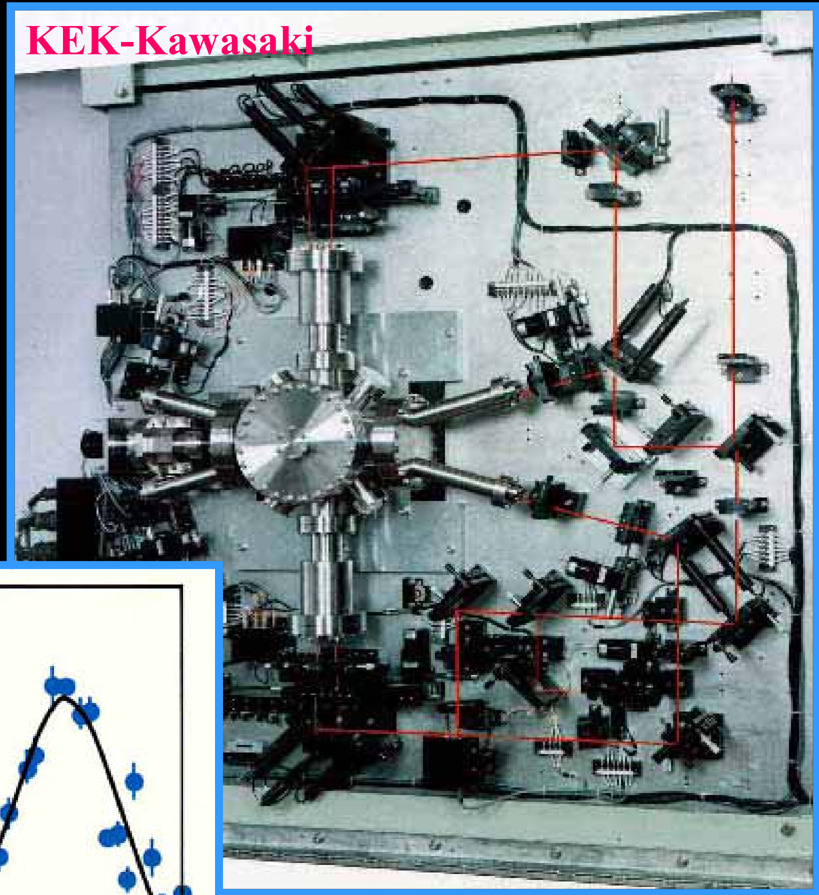
T. Shintake 1990

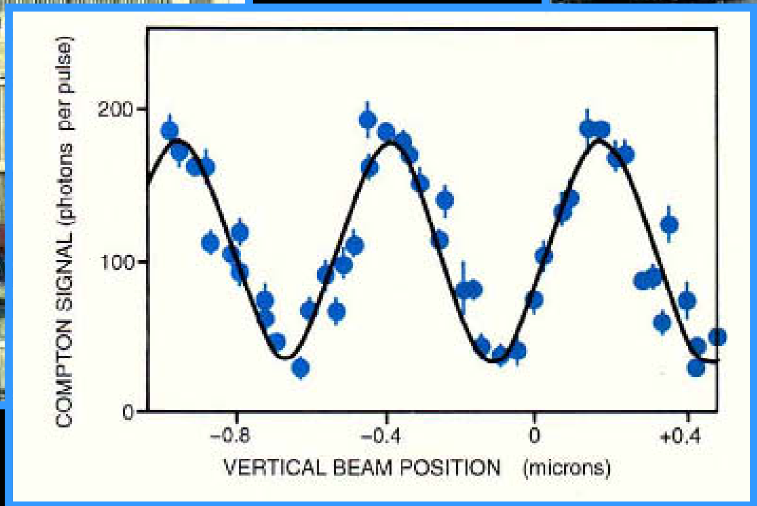
Experimental Test at FFTB

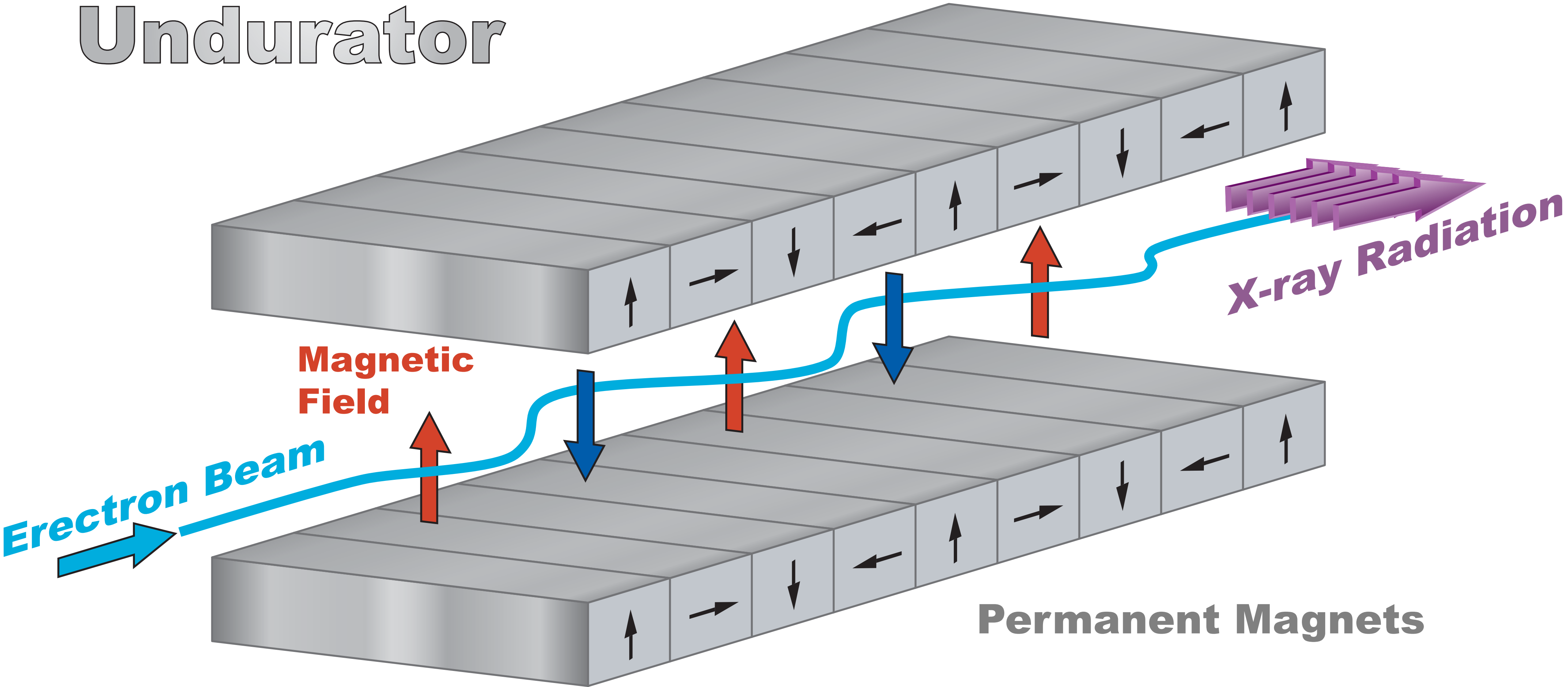
SLAC Two-mile Accelerator & FFTB



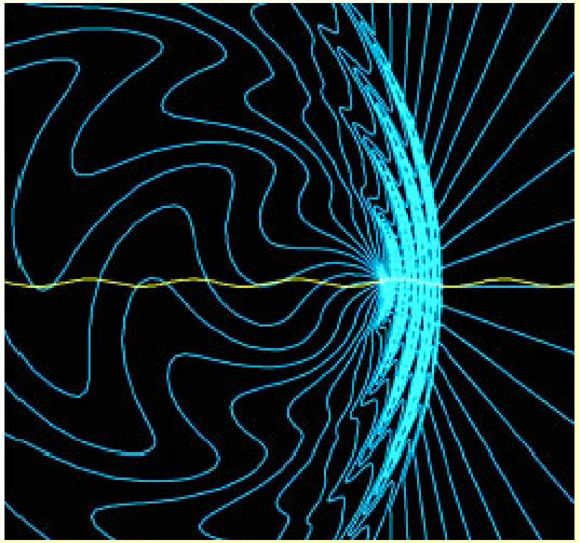
Laser Interferometer Table



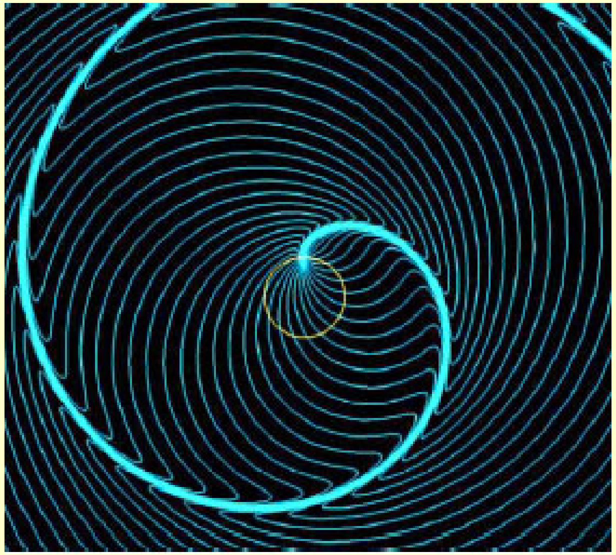



Undurator
Magnetic
Field
Erectron Beam
X-ray Radiation
Permanent Magnets

Feeling & Experience are very important in science.



Radiation2D simulator gives you reality as if you are in front of running noisy electron.



Radiation2d,
available from (freeware)

http://ShintakeLab.com

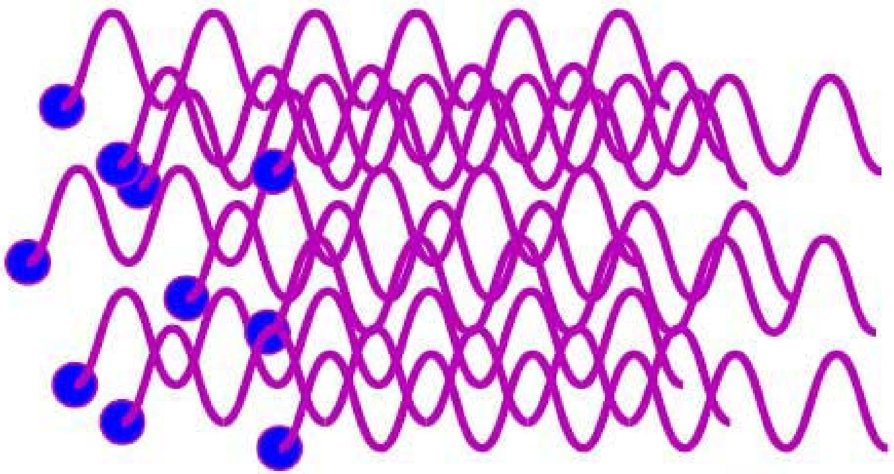
Freeware Radiation2D is available at

http://ShintakeLab.com

From SR to FEL

SR or ERL

Spontaneous Radiation



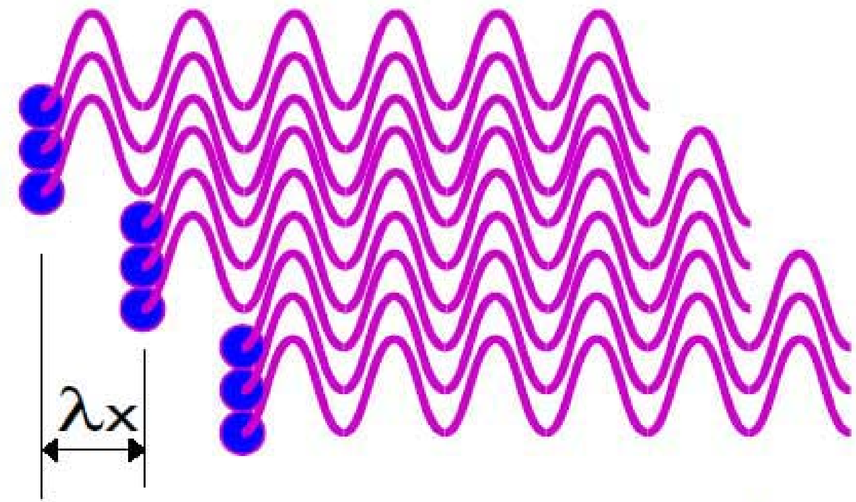
***N*-electrons**
random distribution

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

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

FEL: Free Electron Laser

Coherent Radiation



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

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

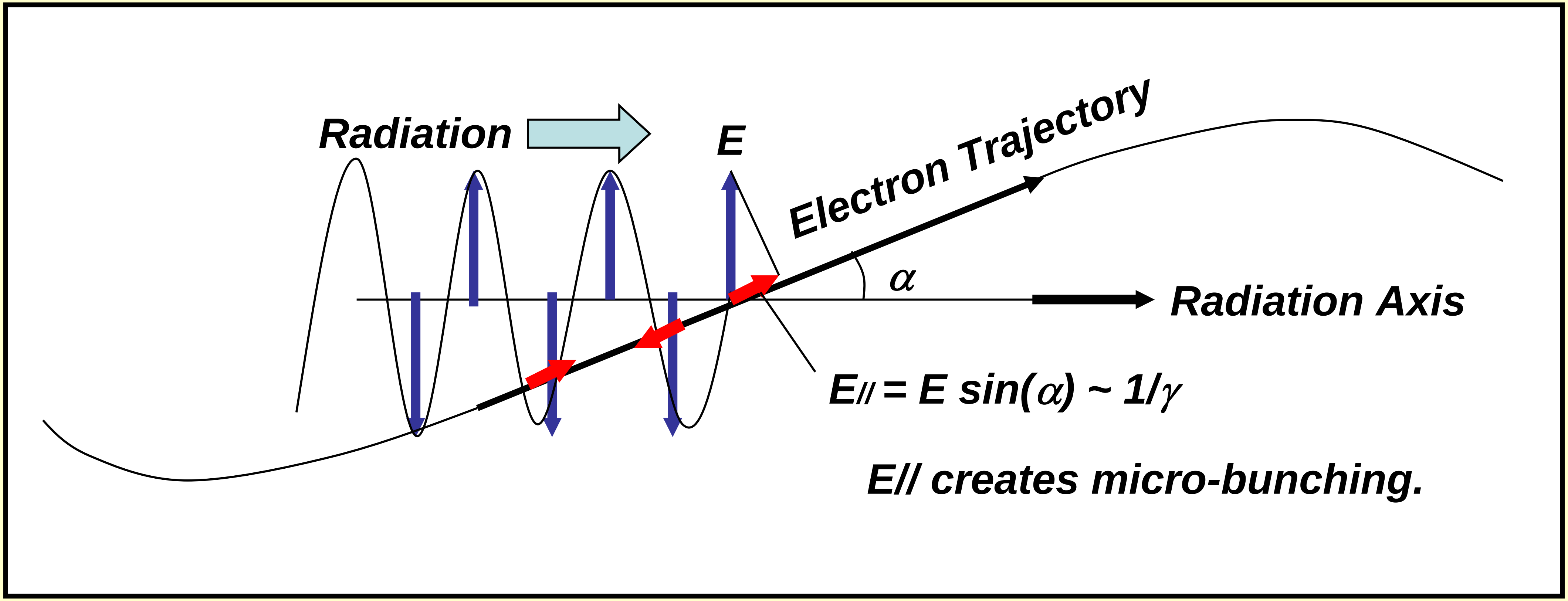
$P_{coherent} \sim N^2\, P_1$

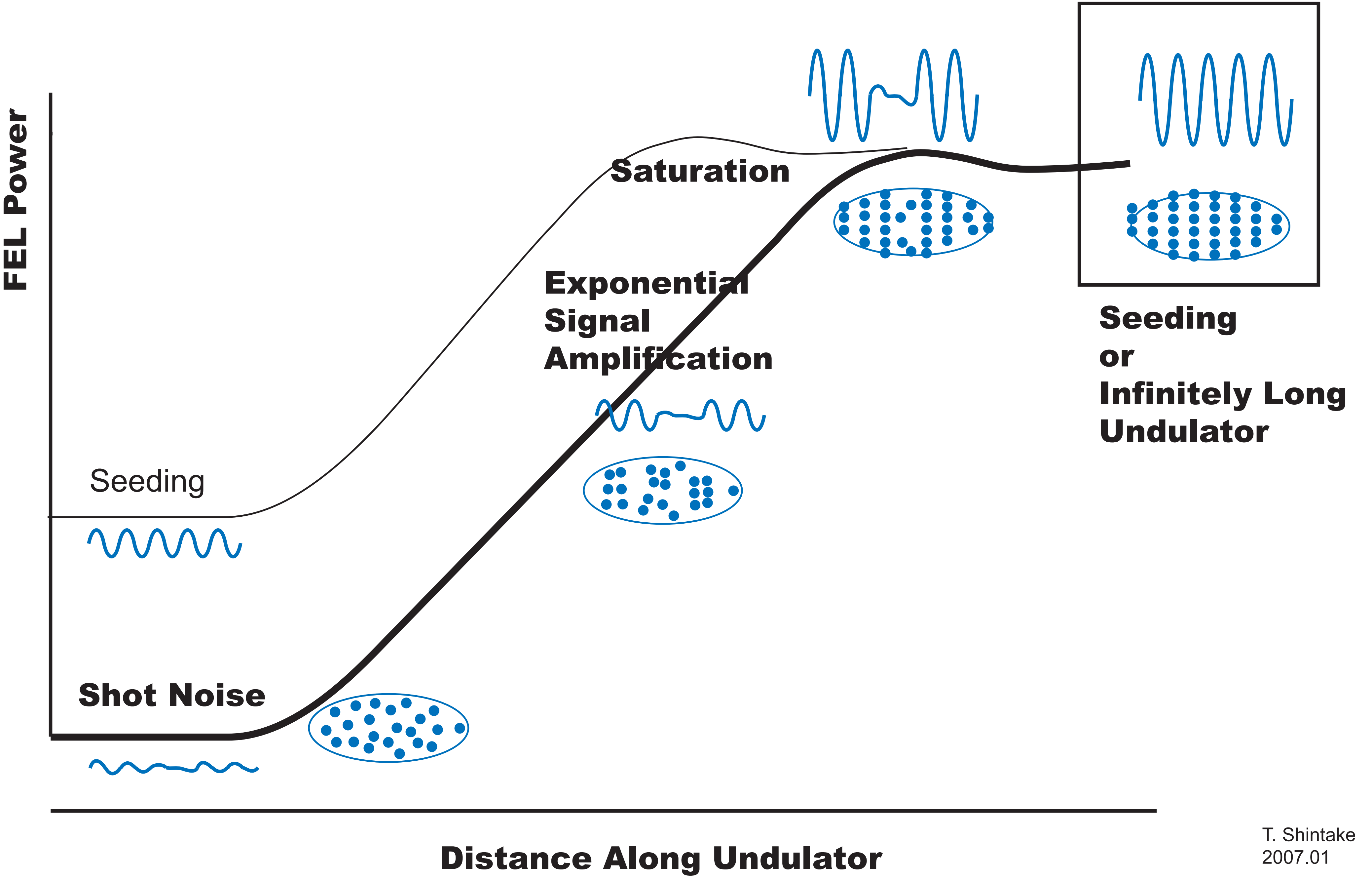
Optical Power Enhancement

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

Physical Origin of Micro-bunching (FEL Action)

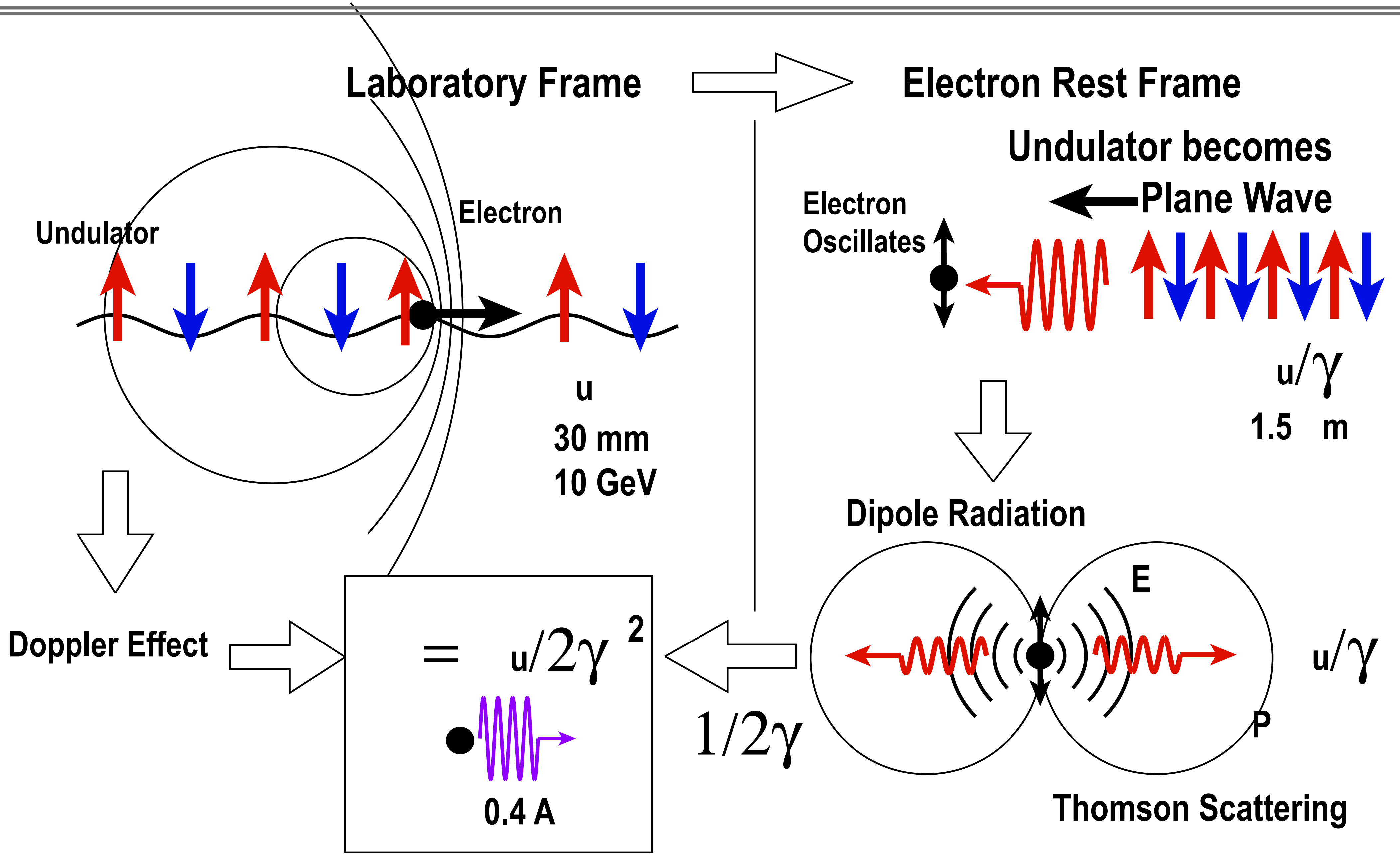
- Undulator field produces curved trajectory. From this slope, the tangential component of EM wave creates longitudinal field.




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

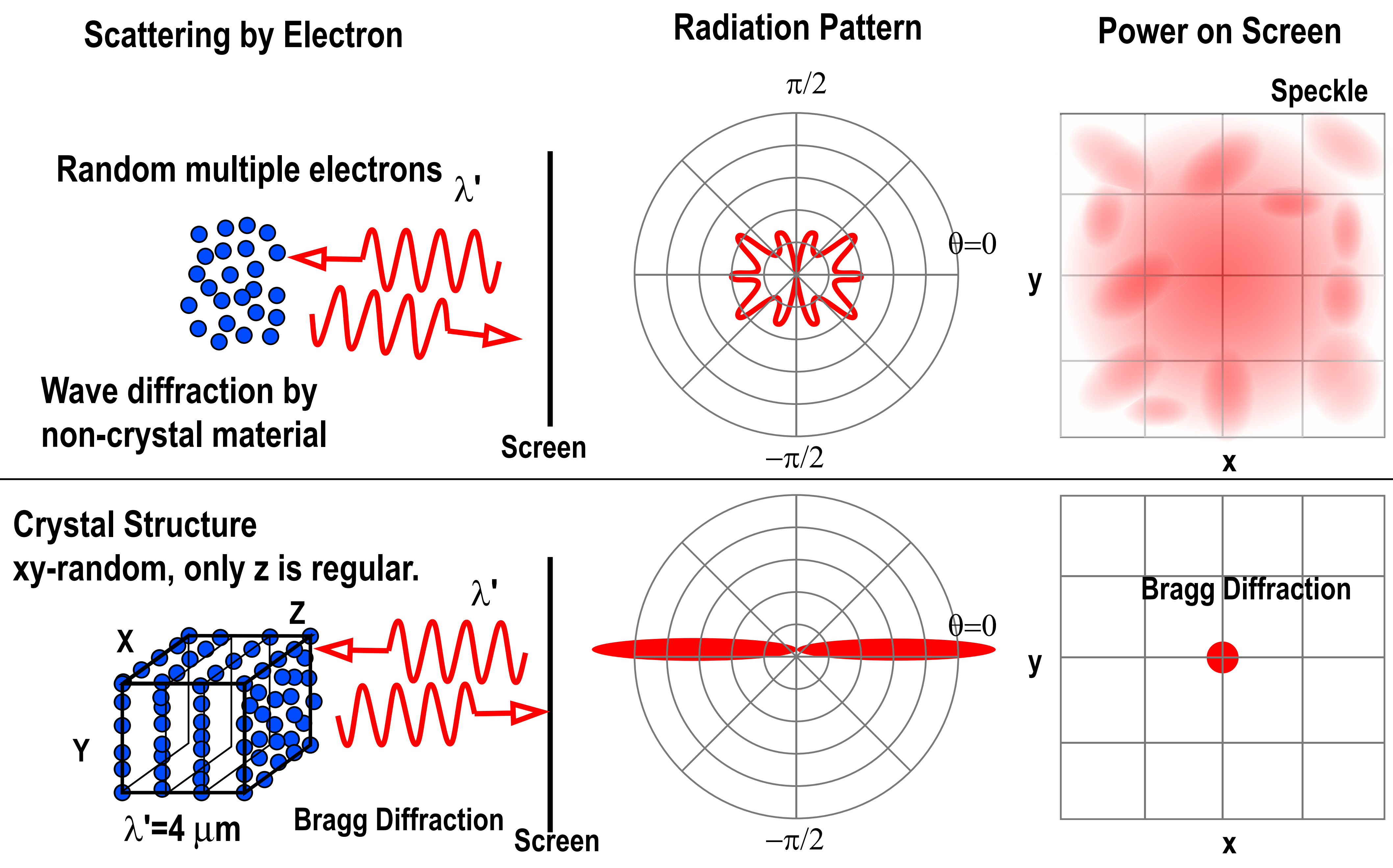
What Undulator does? Scattering Undulator Wave

T. Shintake, 2006

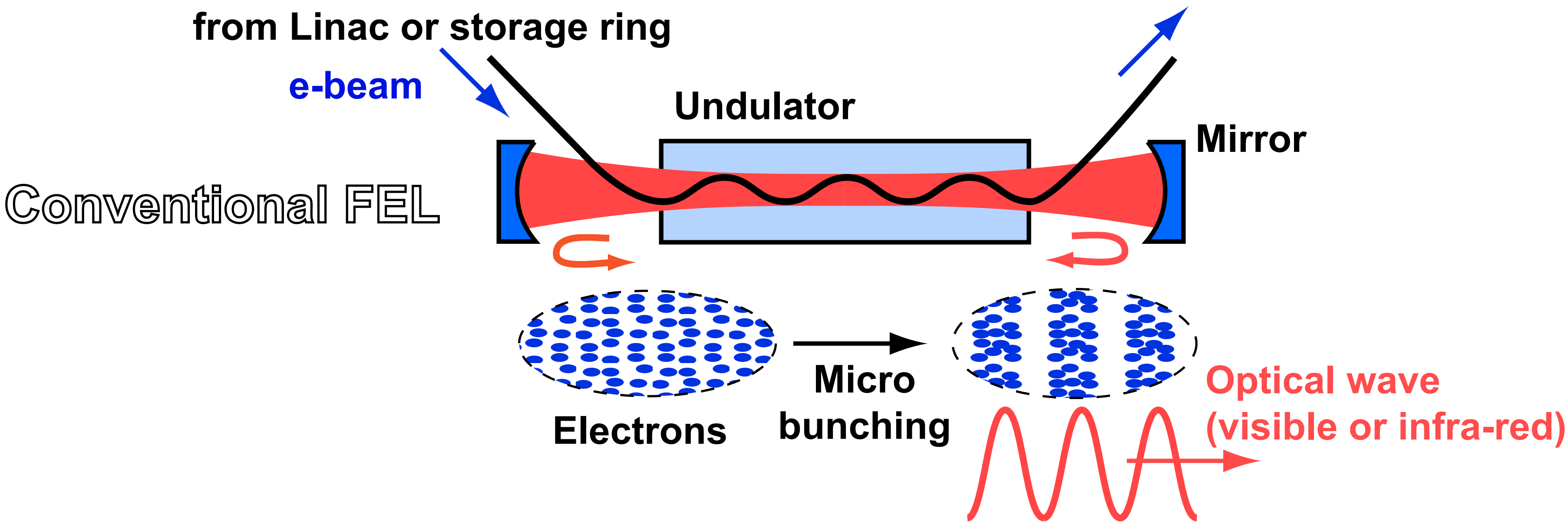


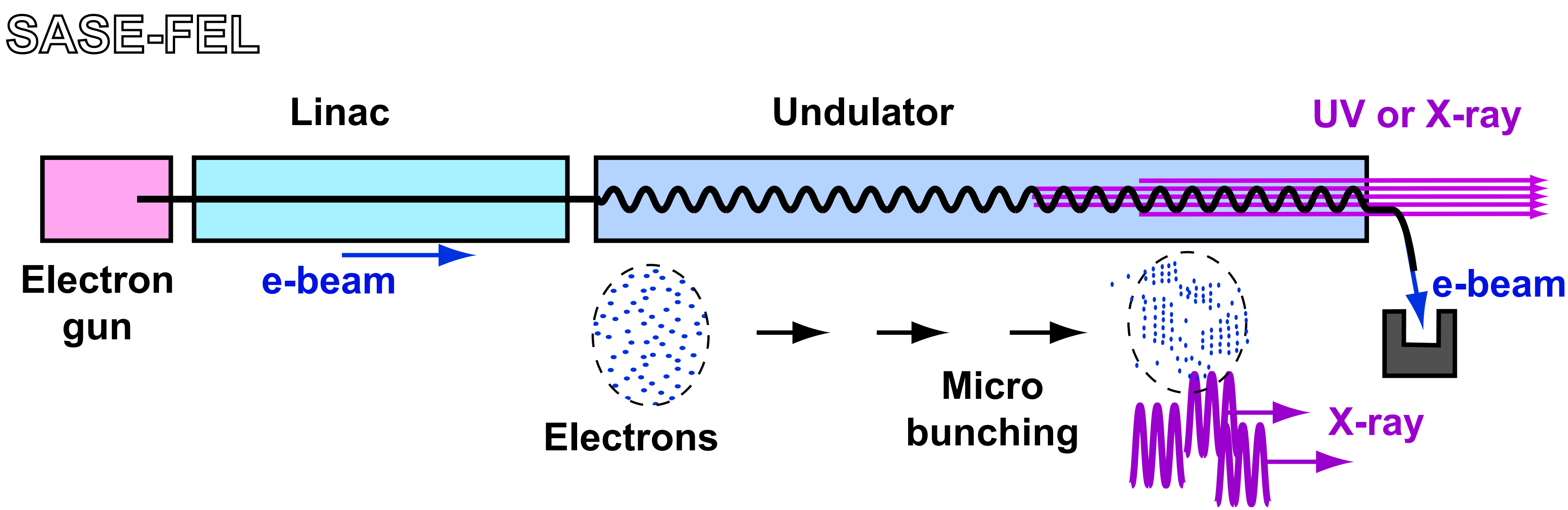
Crystal Diffraction Analogy

T. Shintake, 2006



From Cavity Type FEL to SASE-FEL





We need low emittance beam and high peak current

$$L_g = 1.67\left(\frac{I_A}{I}\right)^{1/2} \frac{(\varepsilon_n \lambda_u)^{5/6}}{\lambda^{2/3}} \frac{(1+K_{rms}^2)^{1/3}}{K_{rms} A_{JJ}} (1+\delta),$$

E. L. Saldim, E. A. Schneidmiller and M. V. Yurkov, Opt. Commun. 235 (2004) 415

- For 0.1 nm, and L =< 10 m (Saturation ~100 m)
- Beam emittance ~ **1 π.mm.mrad** (normalized, slice)
- Peak current ~ **a few kilo Amp**.

before the "emittance" Such Beam Source Should be

- ***Stable*** *………charge, energy, pointing,*
  - *important for the machine tuning and performance.*
  - *stable X-ray beam delivery to the user.*

    (SASE fluctuation can be reduced by seeding)
- ***Clean*** *………no halo, no dark current*

  (high field on cathode such as 100 MV/m will not be good).
  - *important for*
    - *undulator protection*
    - *accurate beam position monitoring*
- ***Uniform*** *………current density*
  - *eliminate gain variation due to local lasing.*
  - *deliver an uniform and stable X-ray beam to the user.*
- ***Maintenance Free***

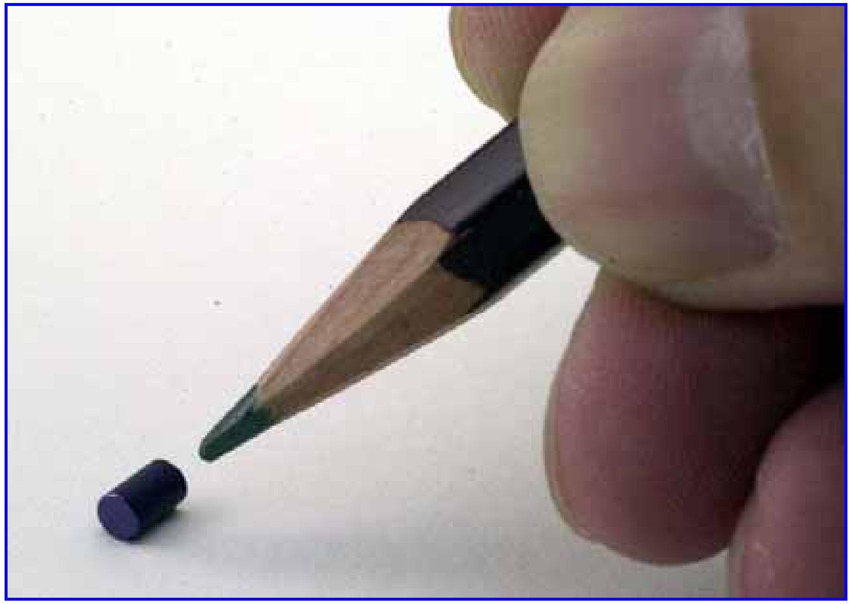
Like a Full Moon
(stable and clean)

「月待図」『江戸年中行事図聚』より

Use Small Size Cathode

…First Strategy for smaller thermal emittance

- *Thermionic cathode*



3mm 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.

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

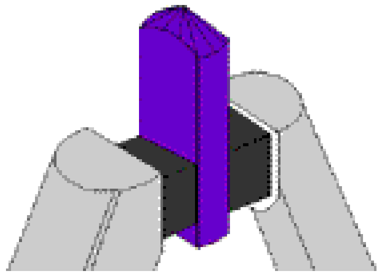
Same order!

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

FEI COMPANY

LaB_6 / Cebix Cathodes

FEI Beam Technology Division is th
LaB_6 and CeBix cathodes and mate
partnership with each electron bean
to ensure our cathodes meet the rec

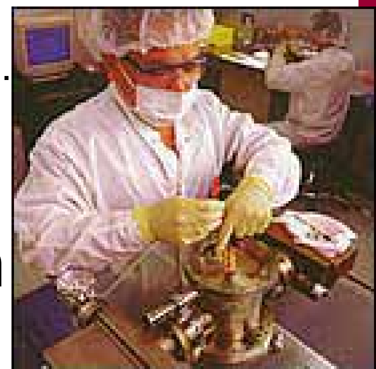


equipment and application. Included with each cathode is
handling and operating guideline for the specific instrument. FEI maintains a la
inventory of cathodes, and orders are typically shipped the next day.

FEI Mini Vogel Mount (MVM) cathodes provide stable, high-brightness, long-lifetime operation for all major electron beam instruments. View FEI's standard parts for all major electron beam instruments in use worldwide on our Applications Chart.

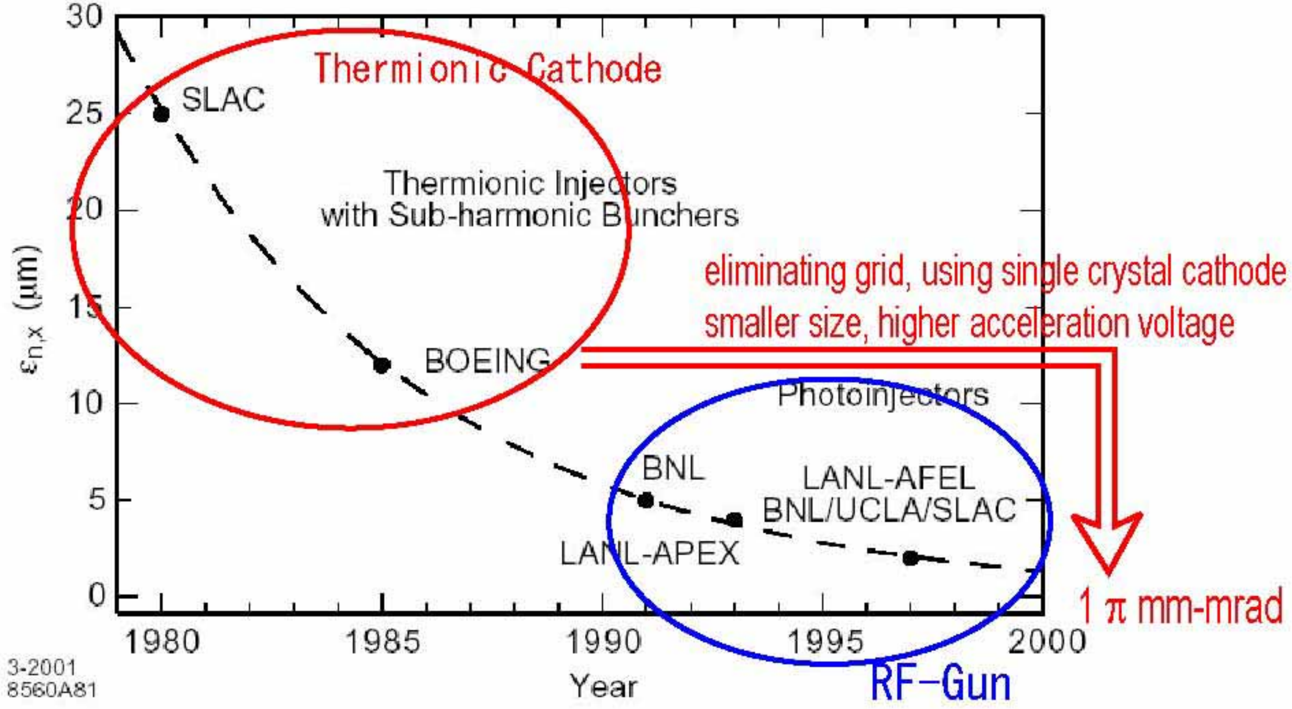
The superiority of the MVM comes from the simplicity of its design.

http://www.feibeamtech.com



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.*

FEL Map

copied from M. Ferrario, "OVERVIEW OF FEL INJECTORS", EPAC06

Figure 1: IV generation synchrotron light sources based on short wavelength FEL world distribution. Red and blue lables: FEL projects based on normal conducting or superconducting technology respectively. White circles: first SASE demonstrative experiments.

How to obtain such high quality beam

- **RF-photocathode gun + magnetic bunch compression**

RF-Photocathode gun 0.5 nC, 10 psec, 50 A

→ Chicane Compression 1/100 → 100 fsec, 5 kA

- **Thermionic gun + velocity bunching + magnetic bunch compression**

Thermionic gun 0.5 nC, 500 psec, 1 A

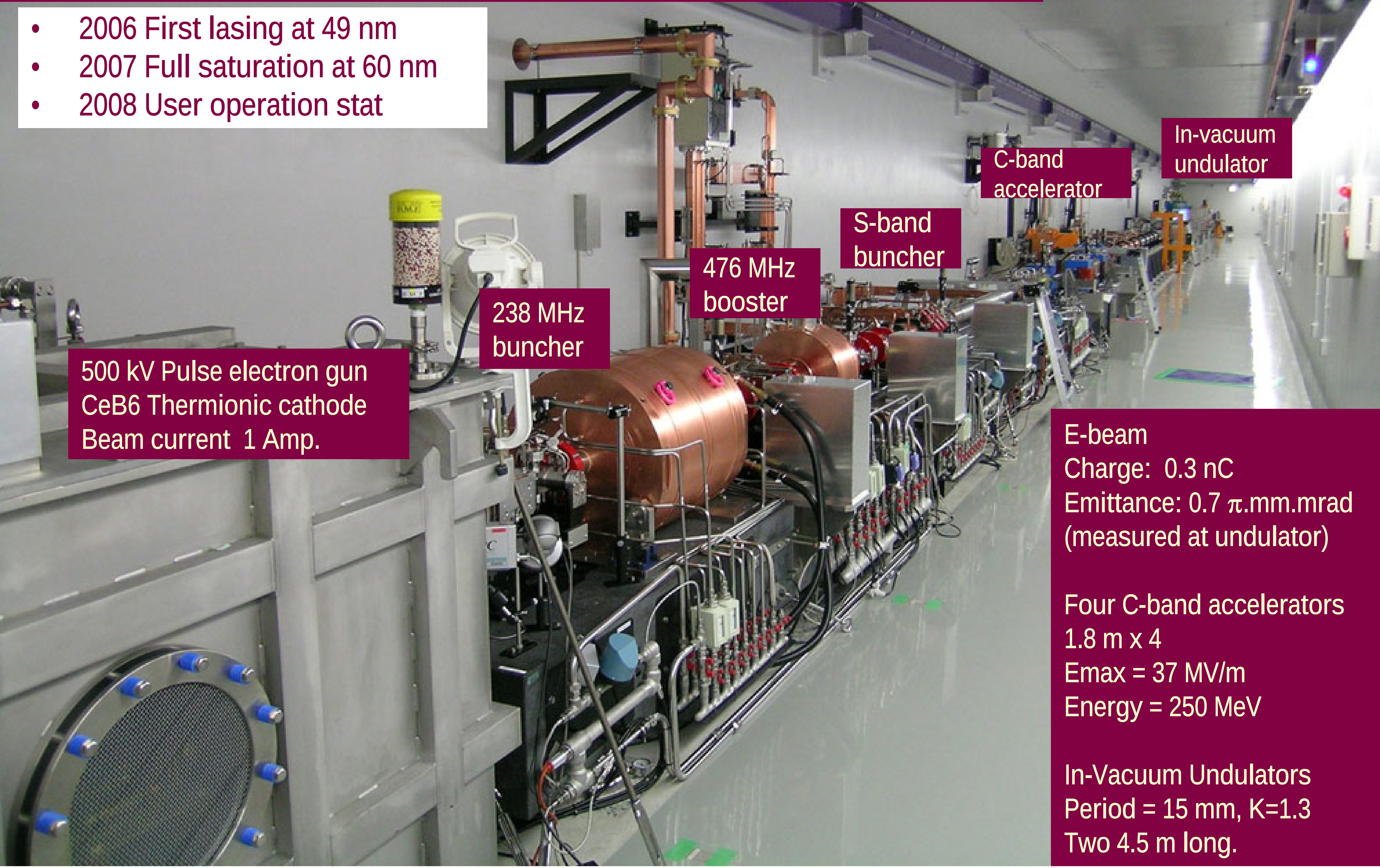
→ Velocity Bunching 1/20 → 20 psec, 20 A

→ Chicane Compression 1/150 → 150 fsec, 3 kA

Big technical challenge!

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

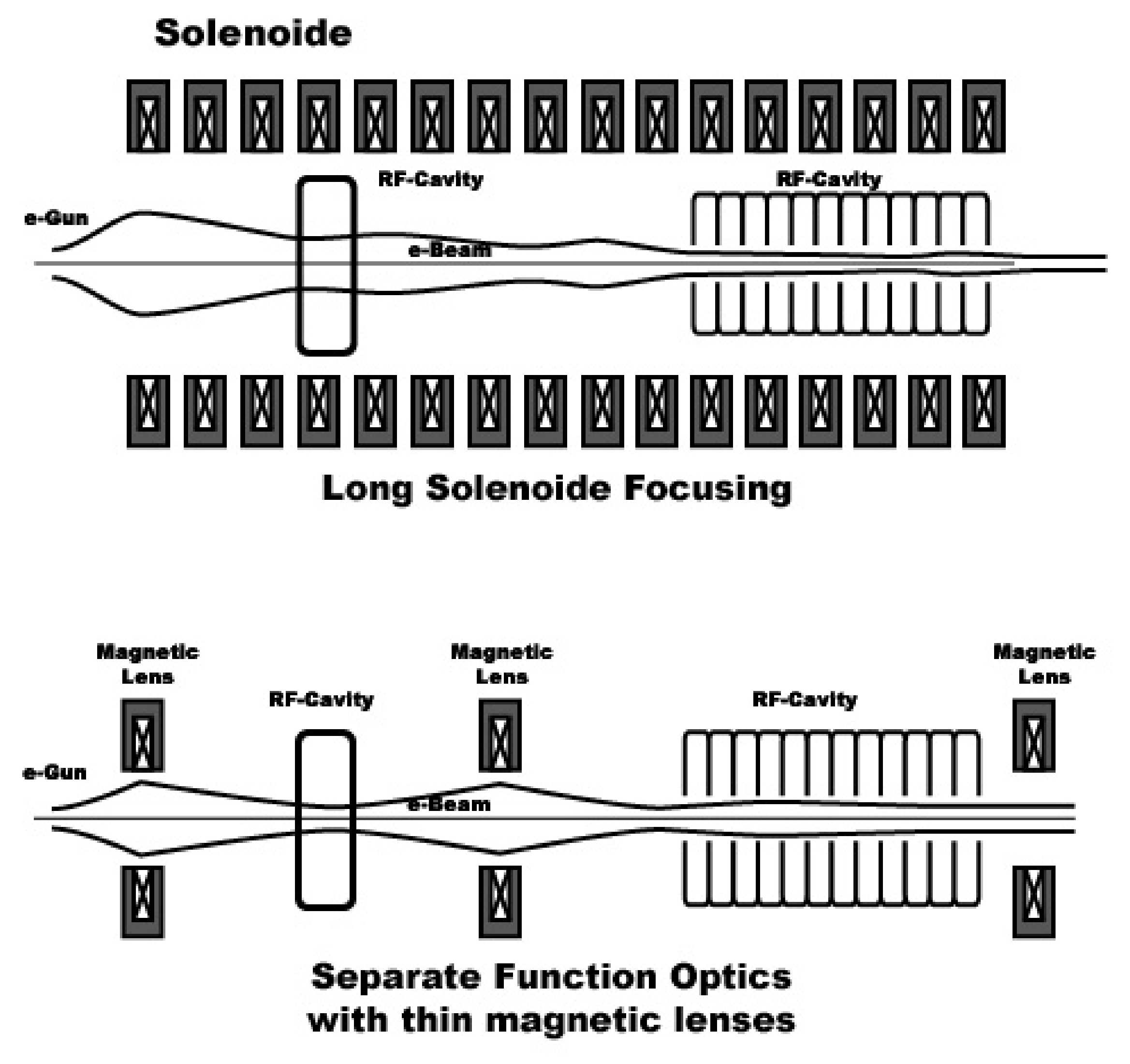
In-Vacuum Undulators
Period = 15 mm, K=1.3
Two 4.5 m long.

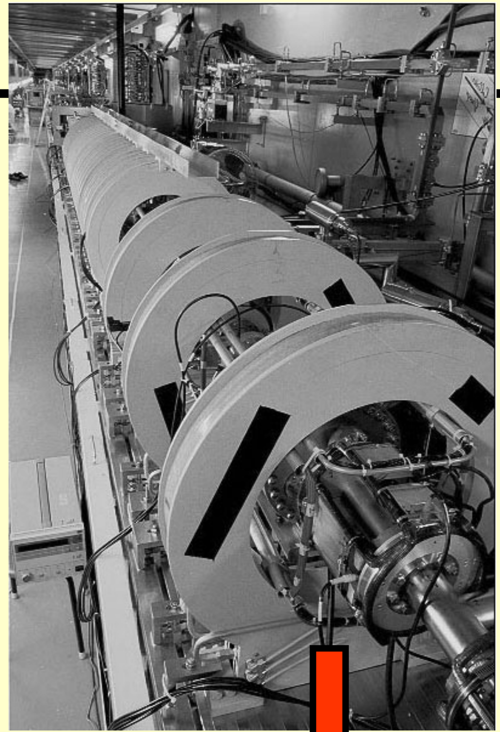
About our SCSS & XFEL/SPring-8

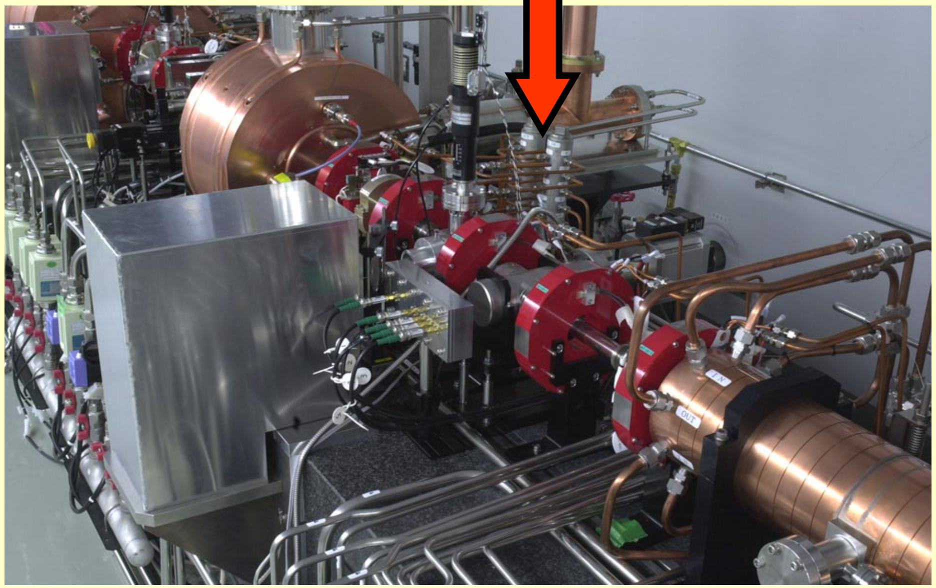
All home made technology

- The thermionic electron gun
- Low emittance injector based on “Adiabatic Bunch Compression”
- C-band high gradient accelerator (35 MV/m)
- In-vacuum undulator

Remove Solenoid → Separate Function Machine



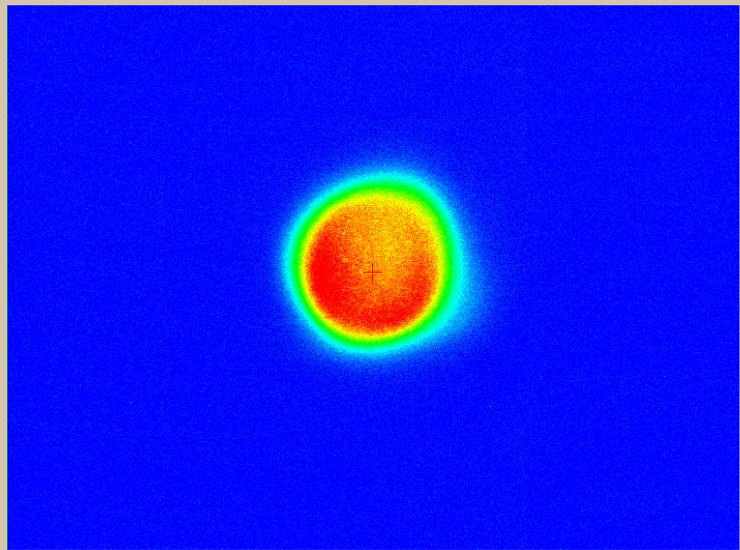




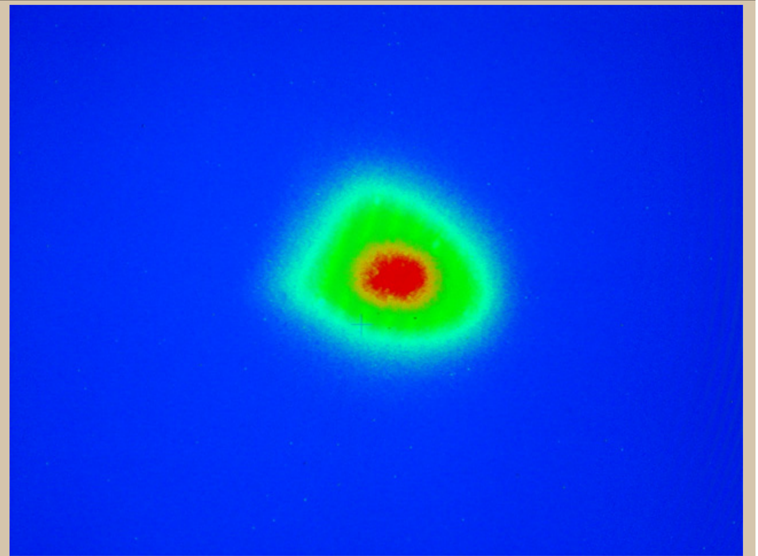
T. Shintake, FEL06

CeB_6 Thermionic Gun provides stable beam.

Beam Profile
CCD Image
Scale 10 mm



500 kV Gun



50 MeV Injector Out

250 MeV Compressor

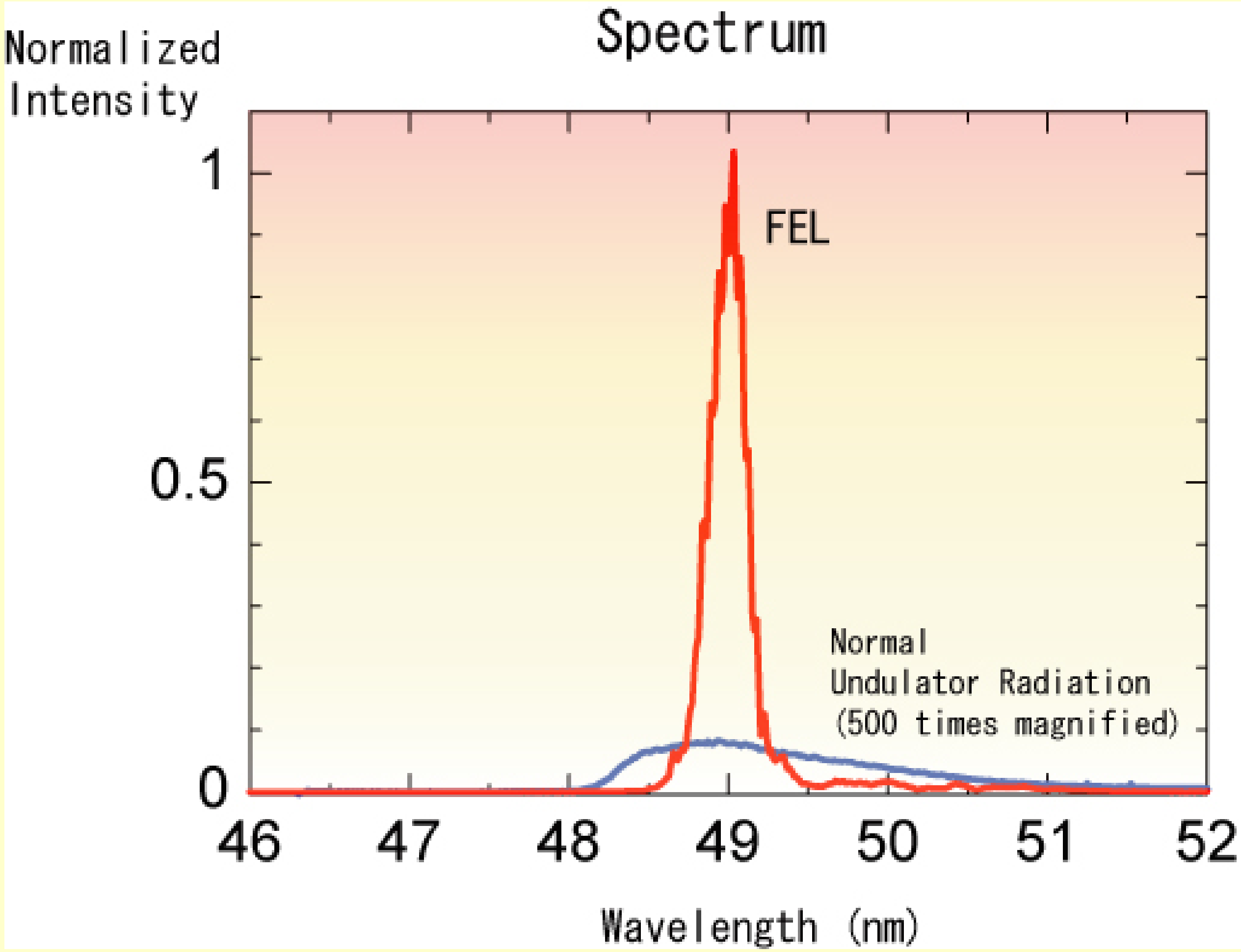
Undulator Input

Undulator Output

First Lasing at SCSS Prototype Accelerator.

June 15, 2006

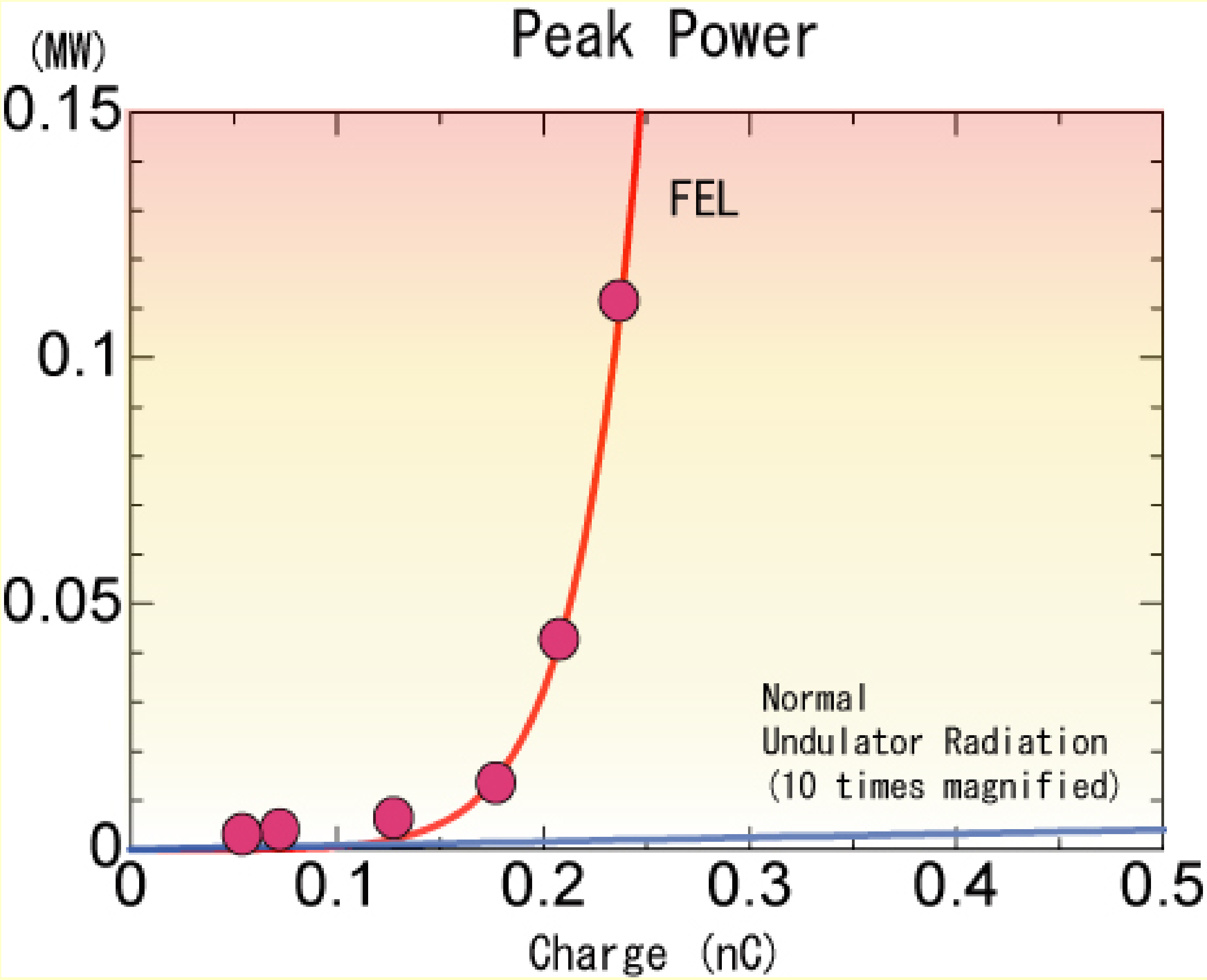
First Lasing at SCSS Prototype Accelerator.



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

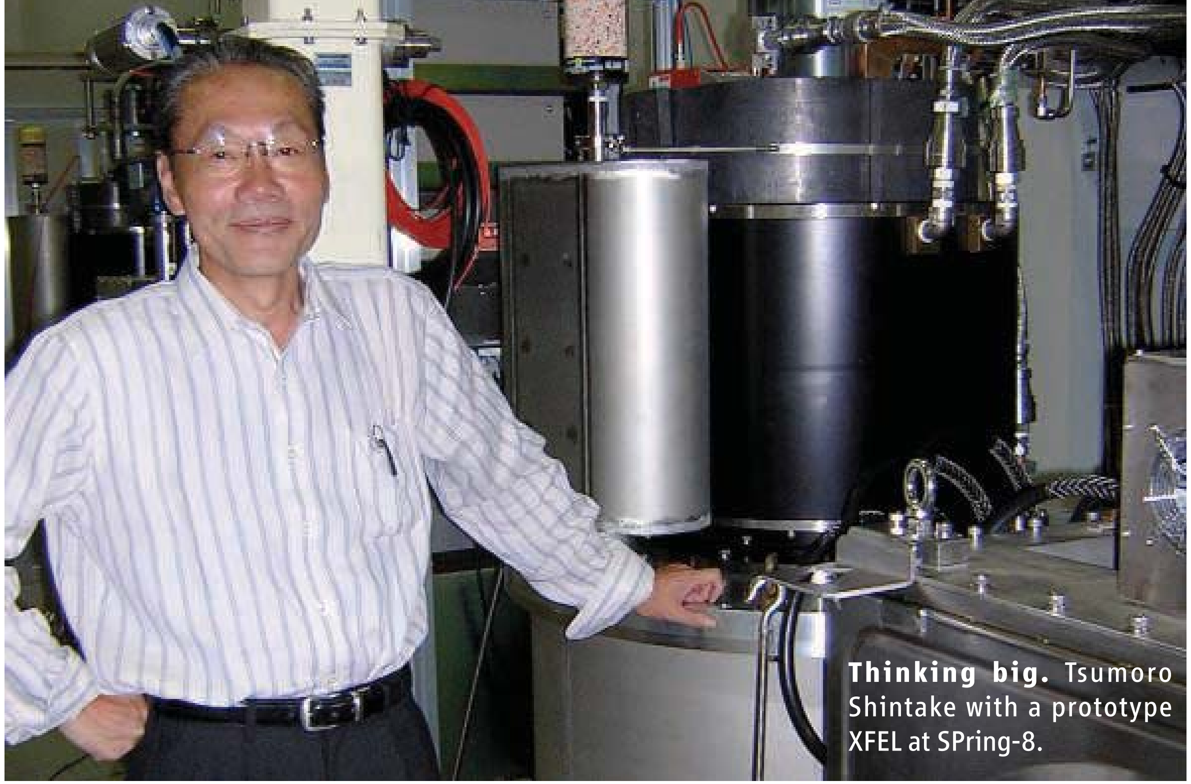
- **At moment spectrum width 0.5 nm is dominated by e-beam energy fluctuation ~ 0.2%.**

First Lasing at SCSS Prototype Accelerator.



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

- Laser pulse length has not yet measured, (will be ~ 100 fsec).
- Peak power estimation assumed 1 psec width.



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-

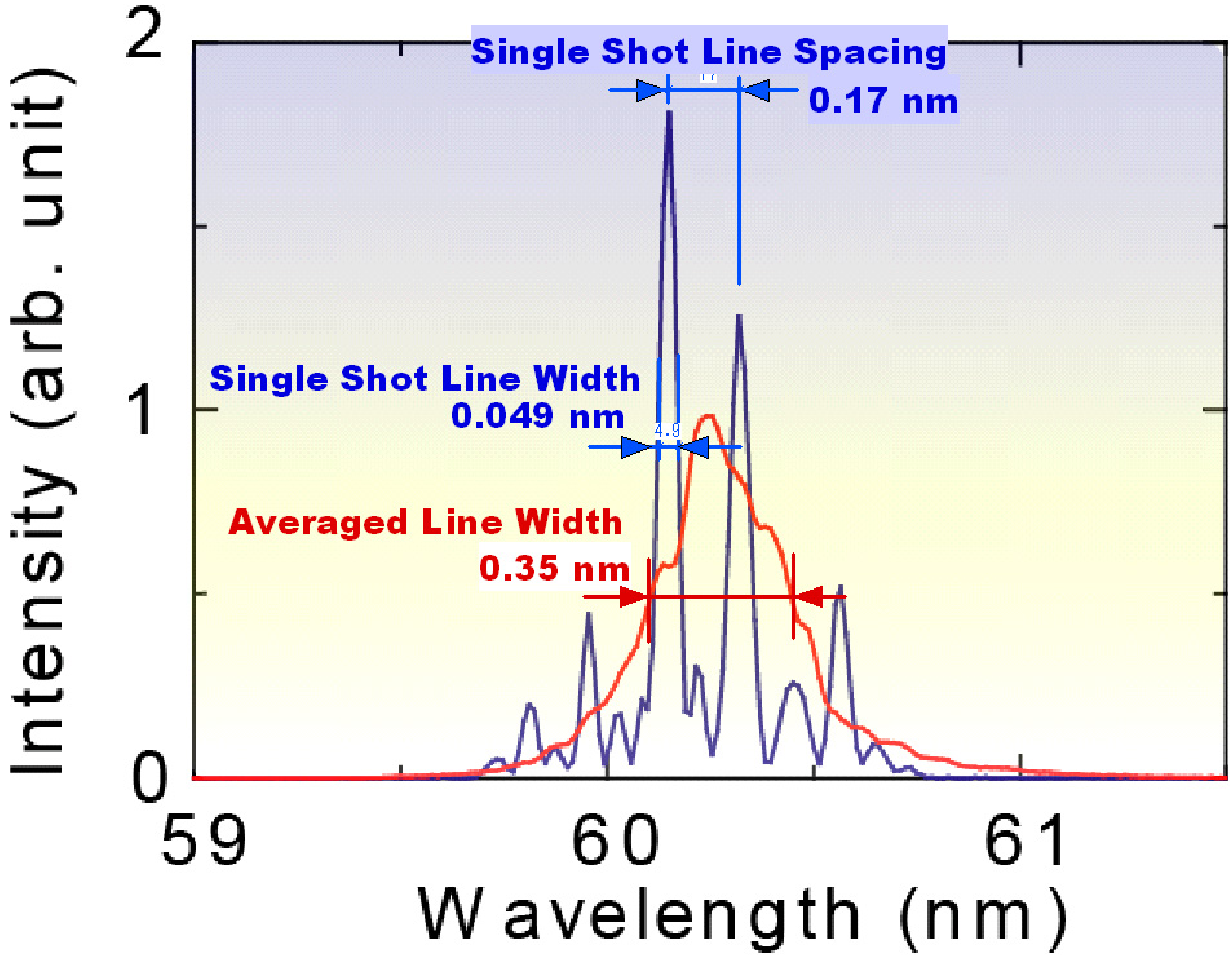
or oscillating in lockstep—a quality missing from synchrotron light.

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.

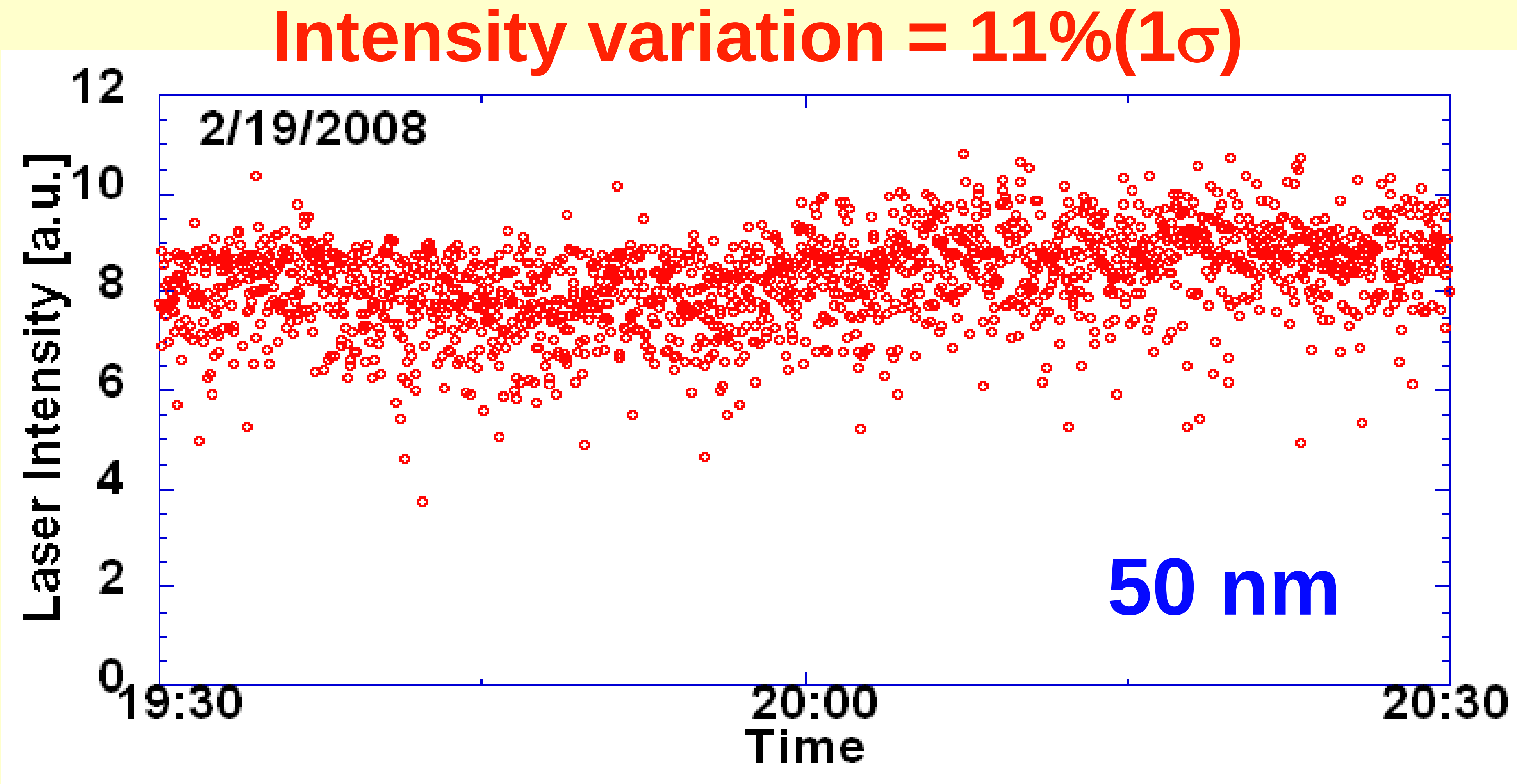
The first project to come online will be Stanford's LCLS. Much of the key research underpinning XFELs was done at SLAC beginning in the early 1990s. And SLAC got a head start by using a 1-kilometer stretch of its now-idled linear accelerator, or linac. The SLAC group estimates that reusing its linac 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


Single Shot Line Spacing
0.17 nm
Single Shot Line Width
0.049 nm
Averaged Line Width
0.35 nm
2
1
0
59
60
61
Intensity (arb. unit)
Wavelength (nm)

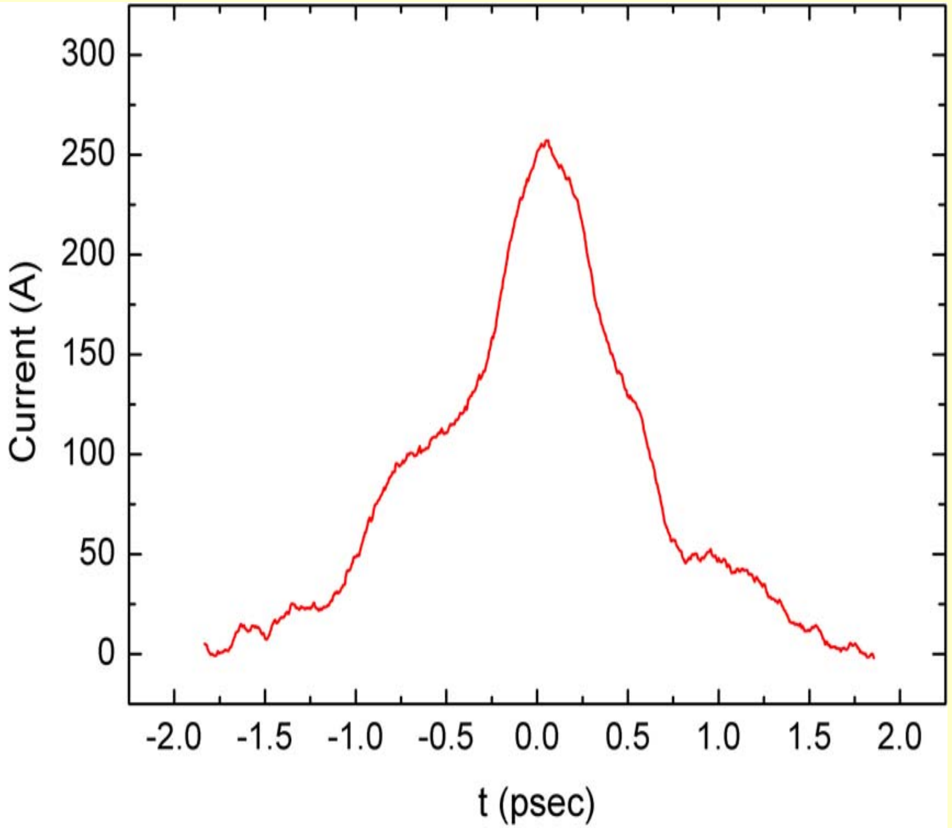
Stability of SASE Intensity

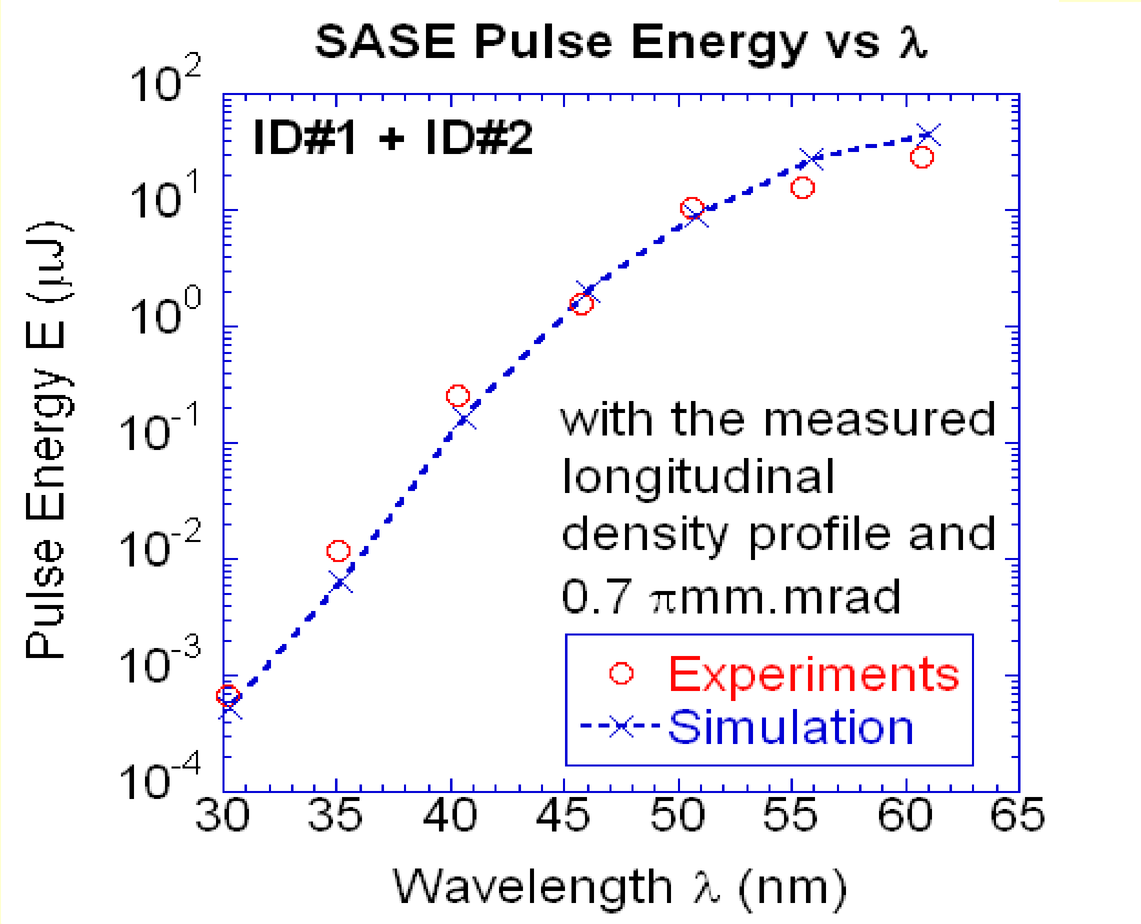


Evaluation of Slice Emittance

The normalized emittance at the lasing slice is estimated to be 0.7πmm.mrad !

Measured Density Profile





SCSS Test Accelerator Performance

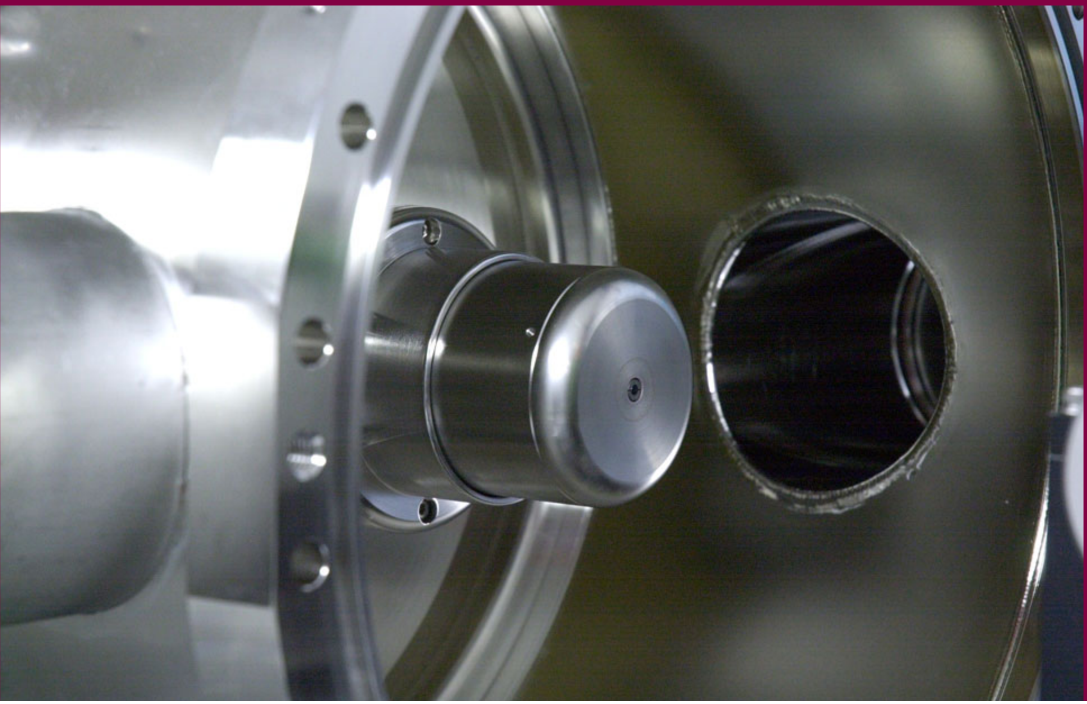
- Running Always in Saturation Mode
  - 50~60 nm (wavelength is limited by accelerator energy)
  - 30 uJ/pulse energy
  - 200 fs pulse length

  - E-beam 250 MeV, 250 A peak, 0.3 nC, < 1 psecFWHM, 20 pps

- E-beam Emittance in the undulator is 0.7 π.mm.mrad
  - Determined from FEL gain measurement.

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).

SCSS Test Accelerator User Run Has been Started in 2008

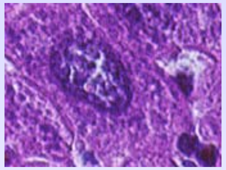
- 50~60 nm, 30 μJ/pulse
- Multi-photon absorption
- Coherent diffraction imaging
- etc.

Experimental proposals at SCSS

XFEL

High-contrast "coherent" imaging for biological samples & nano-materials

Biology & Medicine



Plasma physics

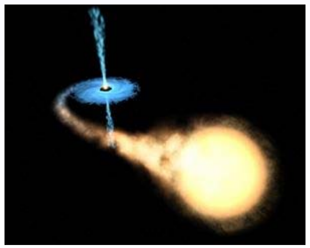
EUV-FEL

R&D of XFEL experimental technologies (timing, DAQ, etc..)

Physics

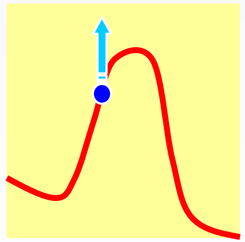
Chemistry

Creation of "extreme" conditions in molecules &clusters



Nonlinear spectroscopy

"Snap-shot" probing of chemical reaction

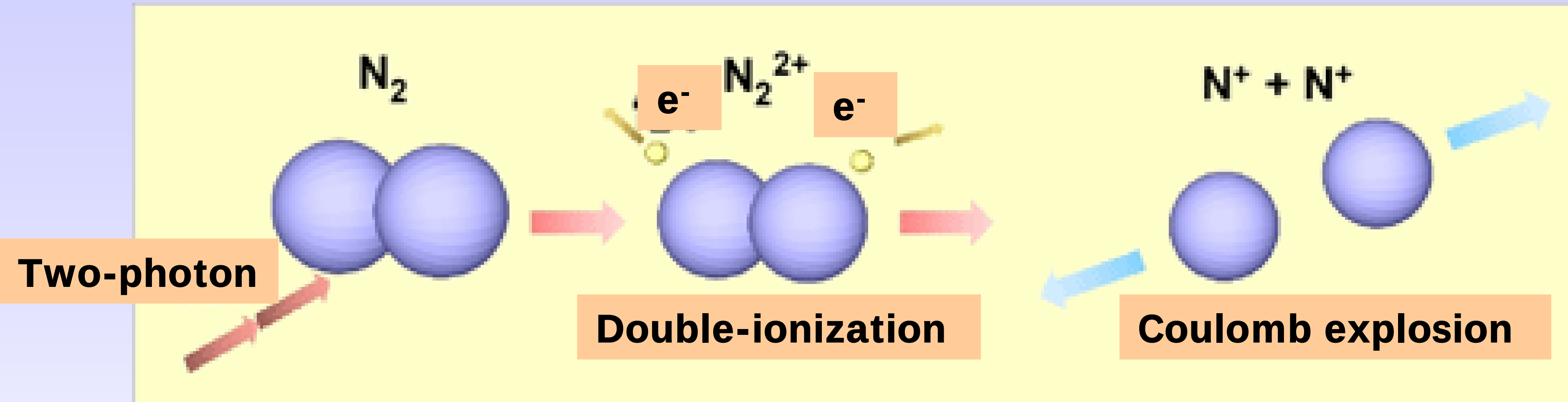


MEXT XFEL user application programs

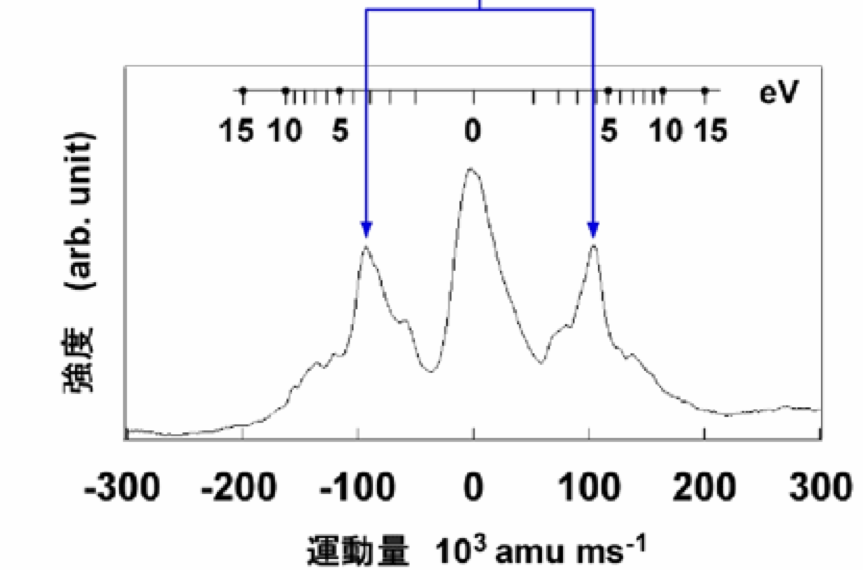
First experimental results from SCSS

Sato et al, Applied Physics Letters, April 2008

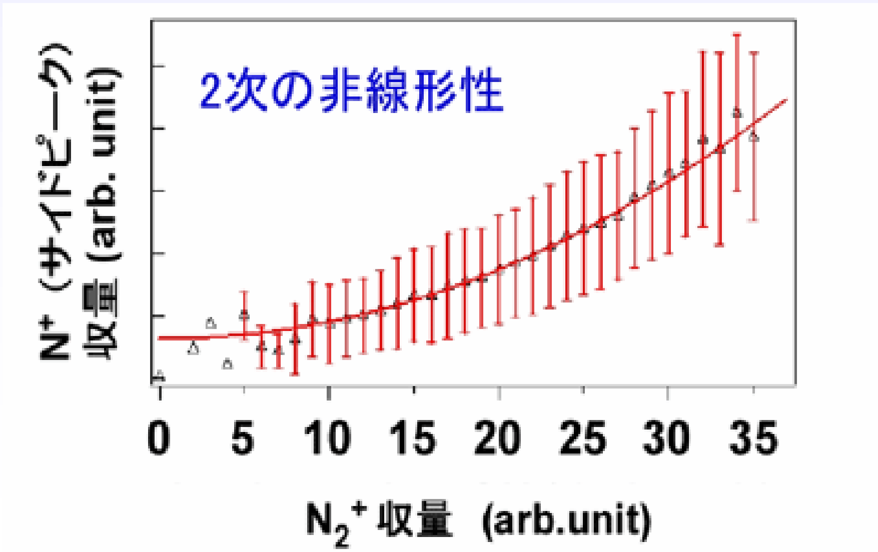
Strong EUV-FEL radiation produced Coulomb explosion of nitrogen molecules



Nitrogen ions after Coulomb explosion



Quadratic dependence on radiation intensity



Status of 8 GeV XFEL/SPring-8 Construction

- 2008 Summer, on schedule.
  30% mass-production has done.
- 2009 April ~ , Accelerator tunnel construction will be completed. We start machine installation
- 2010 October. Accelerator construction complete.
- 2011 March, first e-beam to undulator
- 2011 First lasing at < 1 nm
  → start XFEL in operation.

Thank you!