Future Light Source based on Energy Recovery Linac

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ERL Project Office, High Energy Accelerator Research Organization
Photon Factory, High Energy Accelerator Research Organization

Outline

1) **Present status of the PF and PF-AR**
2) **What is the requirement for the future light source?**
3) **Scientific cases at the ERL**
4) **Present status of the R&D for the ERL project**

- ERL計画推進室 河田先生:

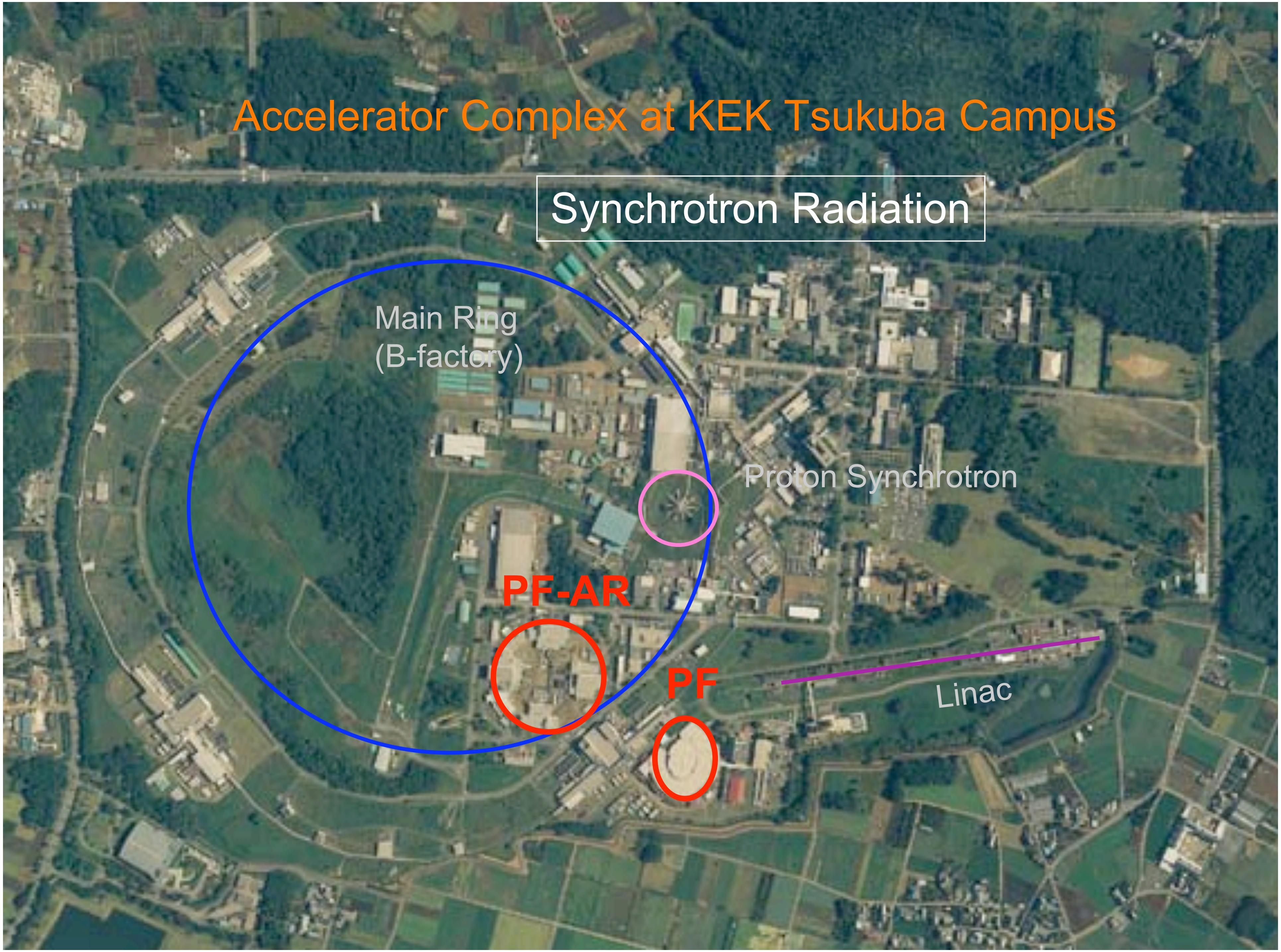
素核研の小松原です。

本日 10/05(金) 17:00-- の金茶会で引き続き
「次期放射光光源としてのERL計画の現状 II」ということで
セミナーをお願いします。

前回同様、途中でいろいろと質問がでると思いますが
18:00 になったらいったん会は終了にして
その後はお茶やお菓子といっしょに歓談ということにしたいと思います。
(話をそのようにまとめていただければと思います。)

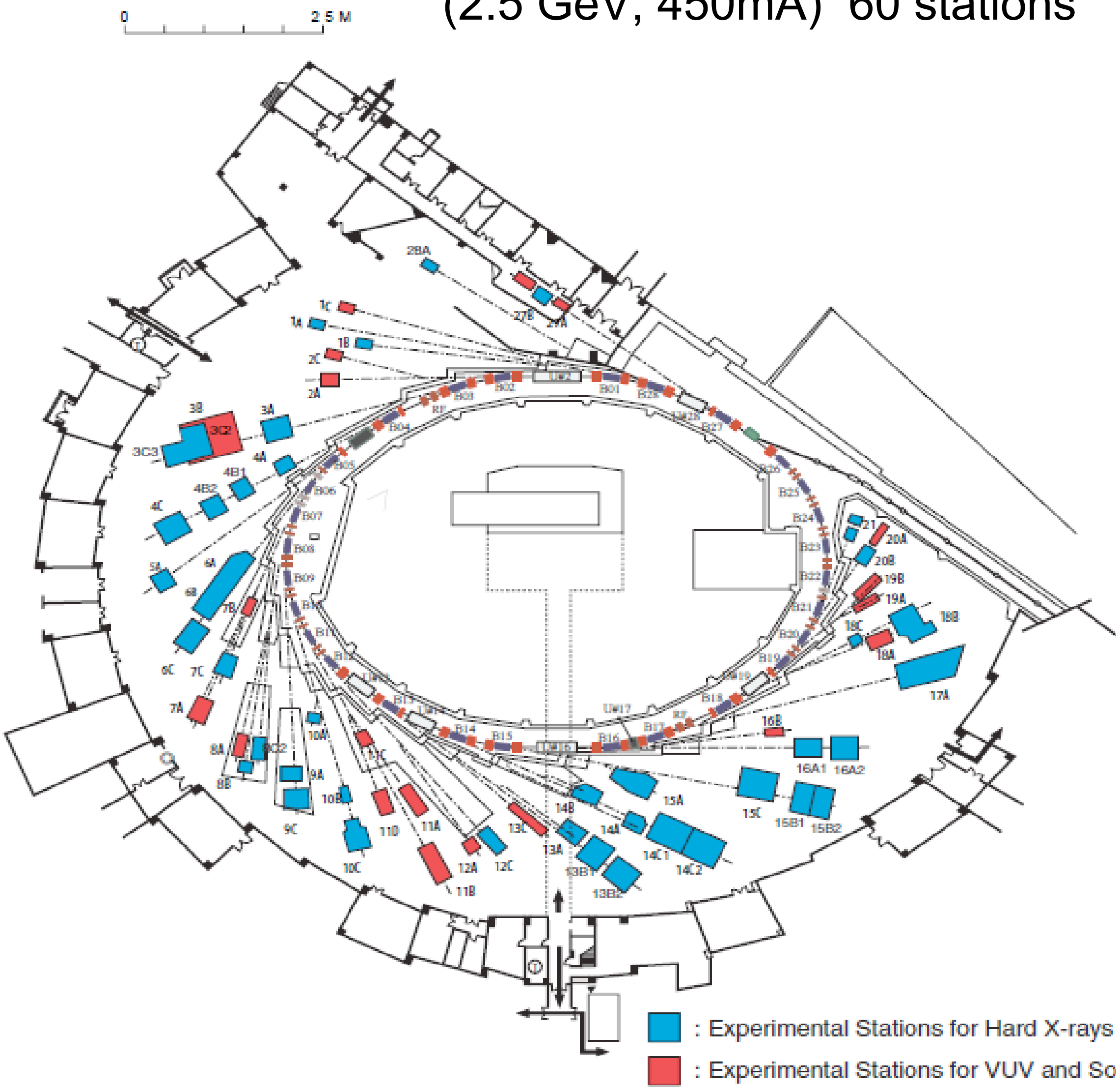
よろしく御願い申し上げます。

今回はリターンマッチはご勘弁ください!


Accelerator Complex at KEK Tsukuba Campus
Synchrotron Radiation
Main Ring
(B-factory)
Proton Synchrotron
PF-AR
PF
Linac

Plan view of PF

Photon **F**actory
(2.5 GeV, 450mA) 60 stations



Constructed in 1982
(the 2nd generation source)

Major improvements
1987 400 →130 nm rad
1997 130 → 36 nm rad
2005 Straight section upgrade

C=186.6 m, ε = 36 nmrad
E=2.5GeV,I = 450 mA,
τ = ~ 60 hrs

23 BLs (incl. 8 IDs)
60stations

Plan view of PF-AR

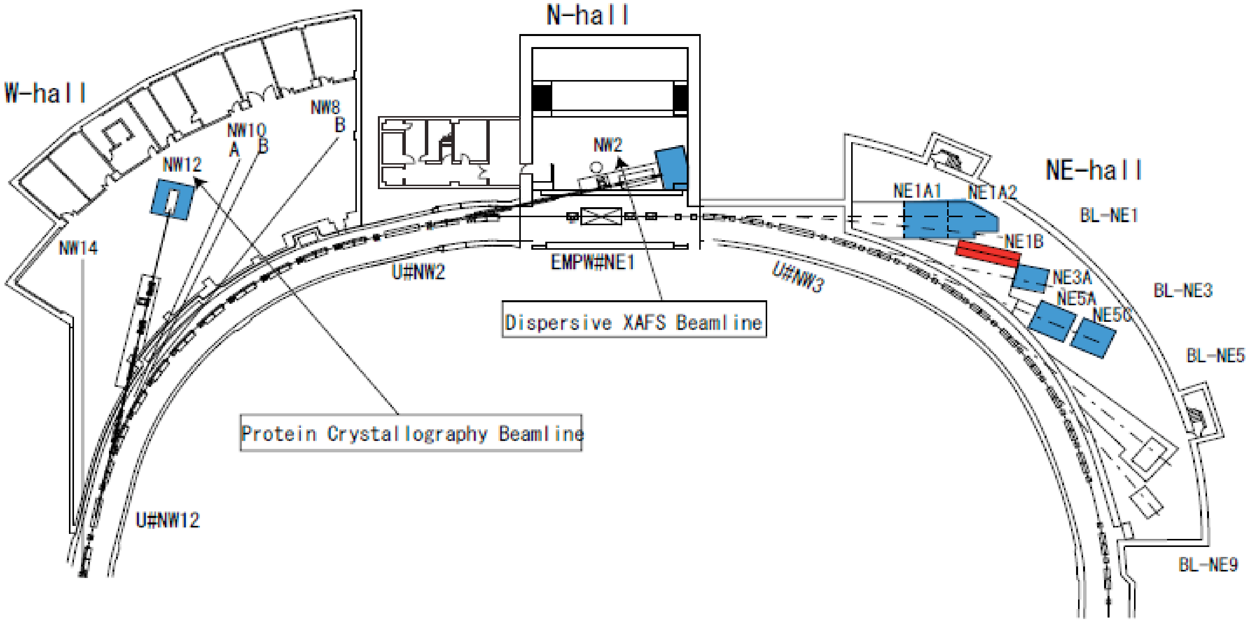
Photon **F**actory - **A**dvanced **R**ing
(6.5 GeV, 60mA, SB) 10 stations

AR : Constructed in 1984 as the injector of the 30 GeV TRISTAN main ring

synchrotron radiation program
parasitic : since 1986
dedicated : since 1997
vacuum upgrade : 2002
new experimental hall: 2002

C = 377m, ε = 294nmrad
E=6.5 GeV ,I = 60mA
τ = 15~20hrs
Single bunch

10 experimental stations
5 ID operational



Upgrade of PF Beamlines

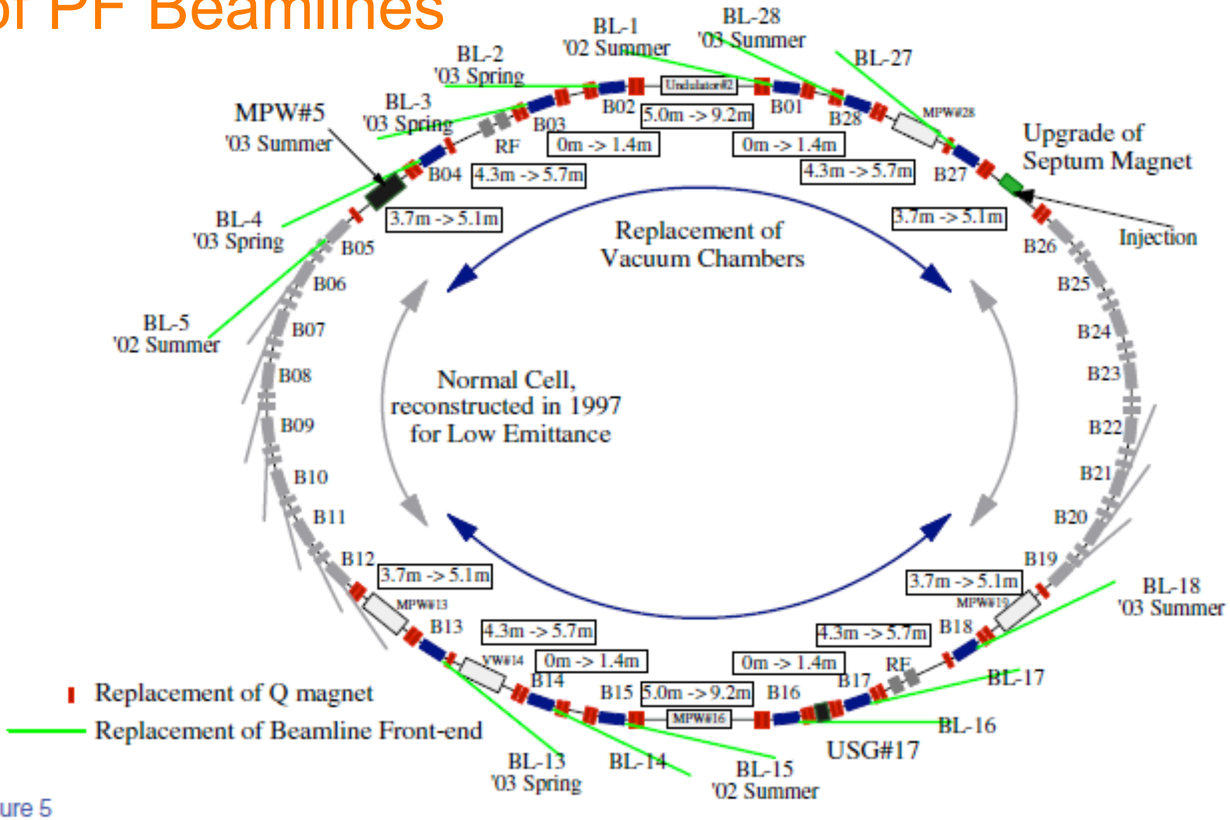


Figure 5
Outline of the upgrade project.

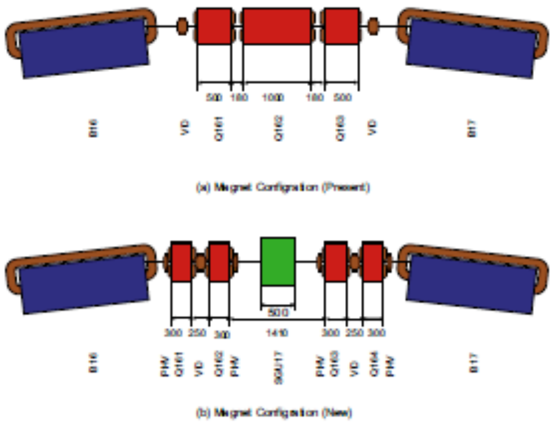


Figure 6
Creation of the short straight section.

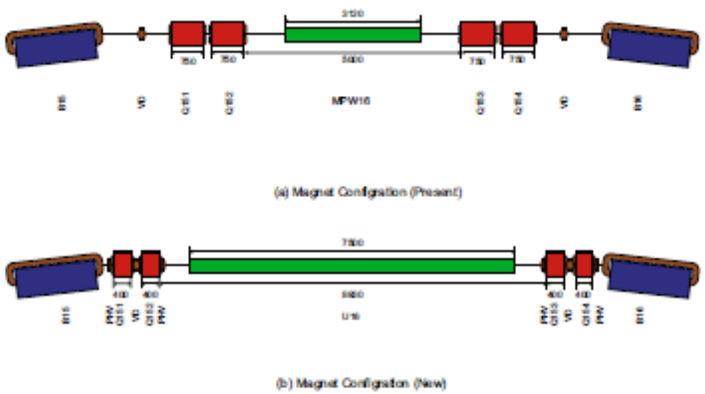
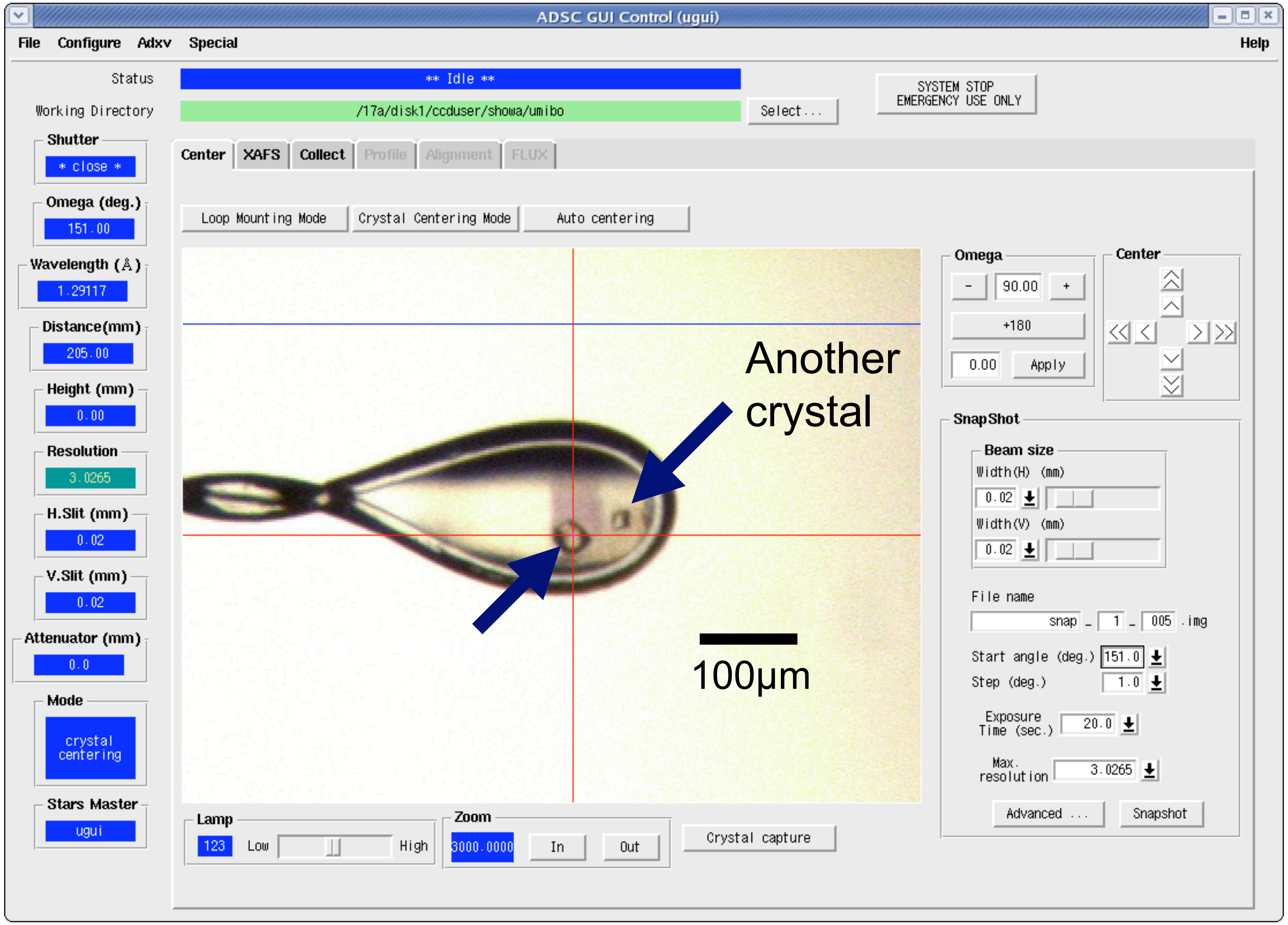


Figure 7
Extension of the longest straight section.

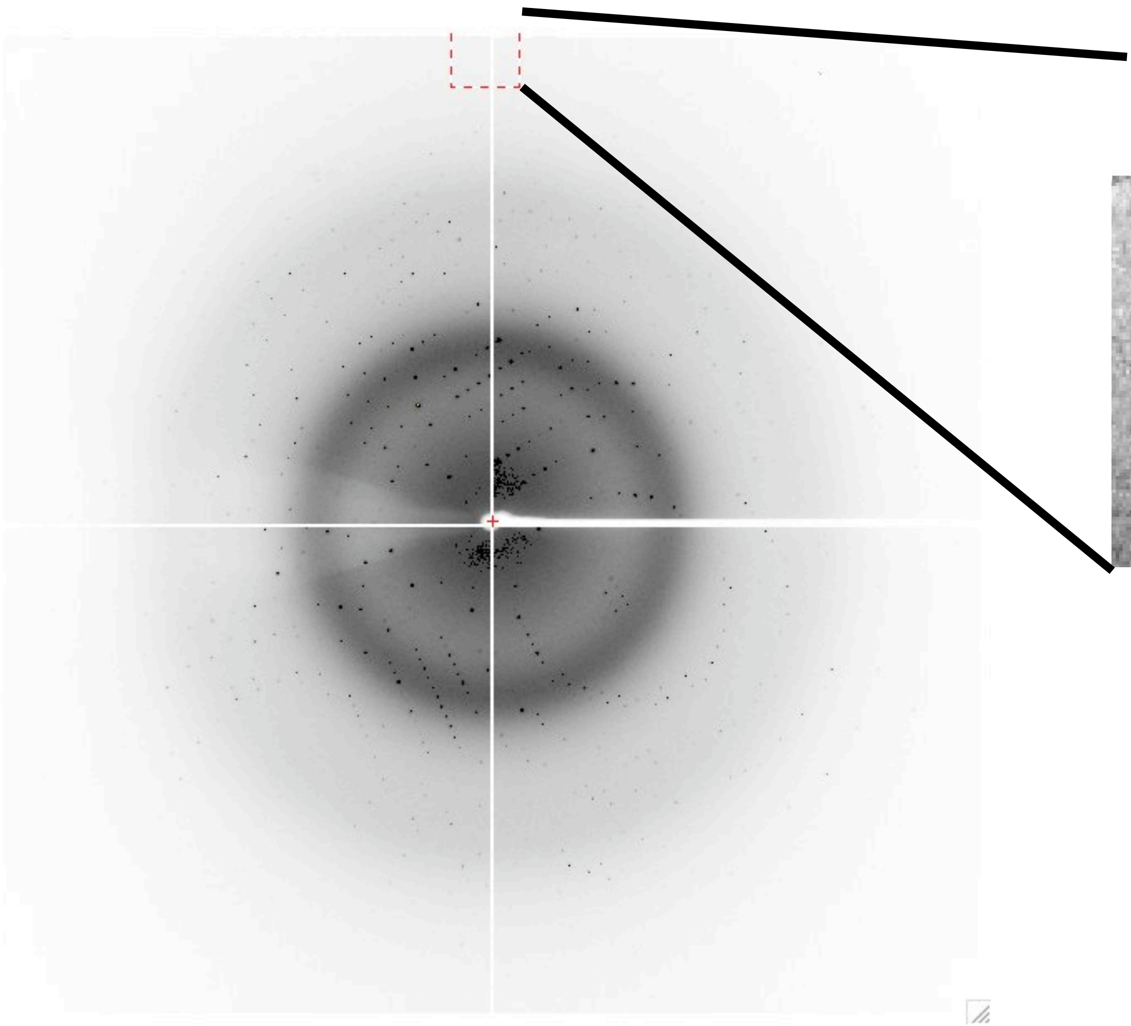
Small crystal (20μm x 20μm)

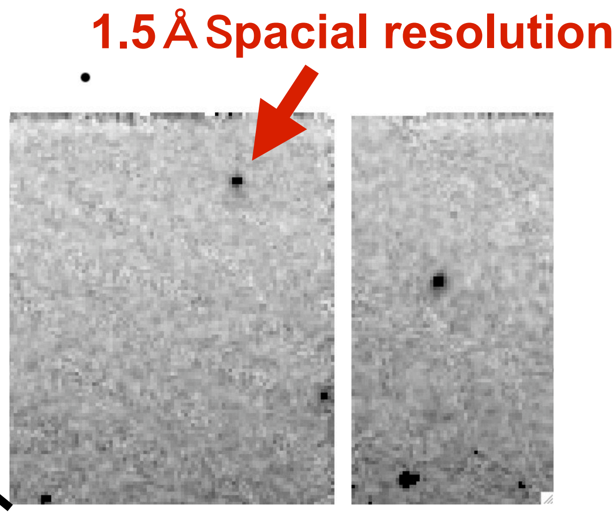
With courtesy of Dr. N. Tanaka, M. Tsunoda



Small crystal experiment

N. Tanaka, M. Tsunoda (Showa Univ.)

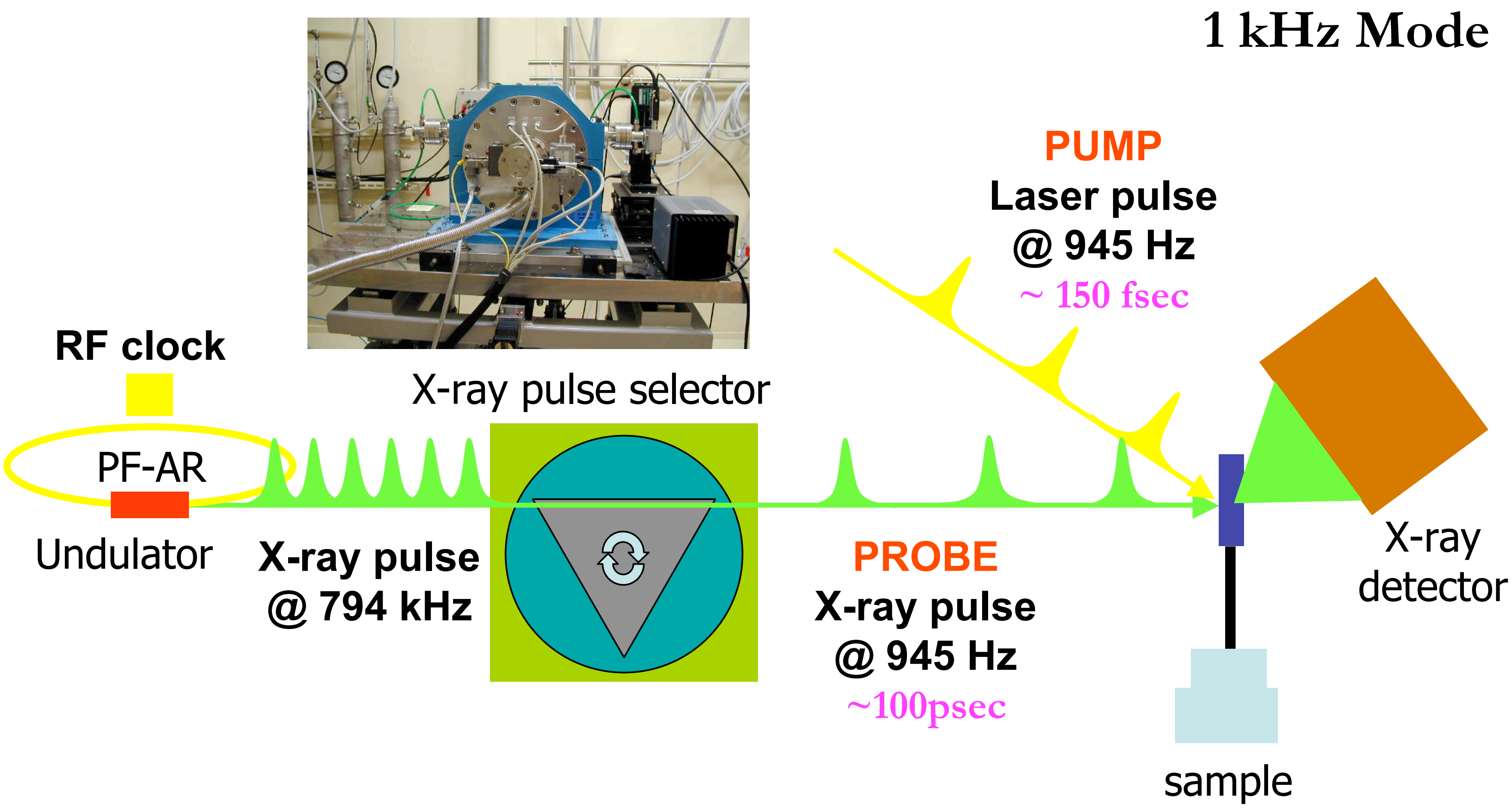




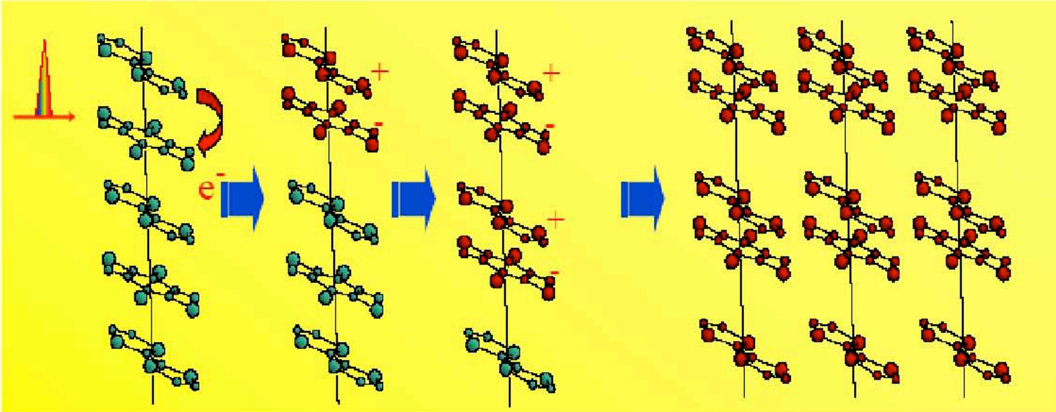
Sample 2

Wavelength : 1.291 Å
Slit size : 20 μm × 20 μm
Exp. Time : 20 sec

TR-Experiment at PF-AR NW14A
Schematic View (Pump-Probe experiment)



Time resolved diffuse scattering from Photo-induced Phase Transition material (TTF-CA)

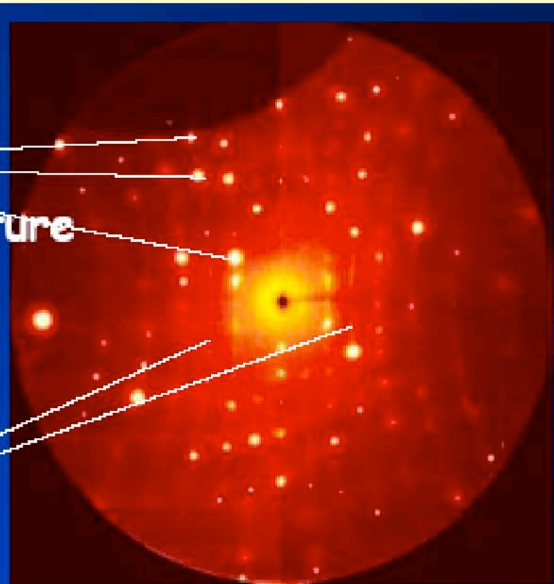


Bragg peaks : Diffraction

position : average lattice

shape : domain size

intensity : atoms and average structure



Diffuse scattering :

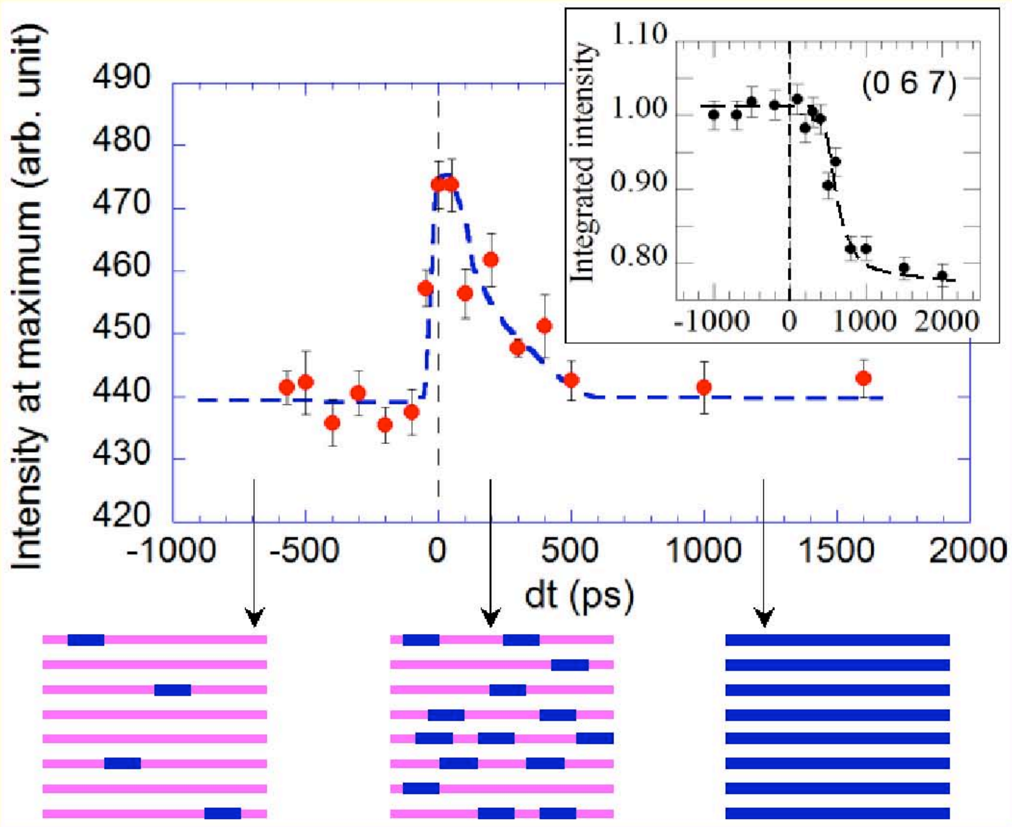
position : local periodic structure

shape : correlation of local order

intensity : deviation from the average structure

100-ps Time-resolved Diffuse Scattering of TTF-CA at 105 K (March 2006)

Eric Collet, Marylise Buron-Le Cointe, Johan Herbert (Univ. Rennes 1)
Laurent Guérin (ERATO JST)

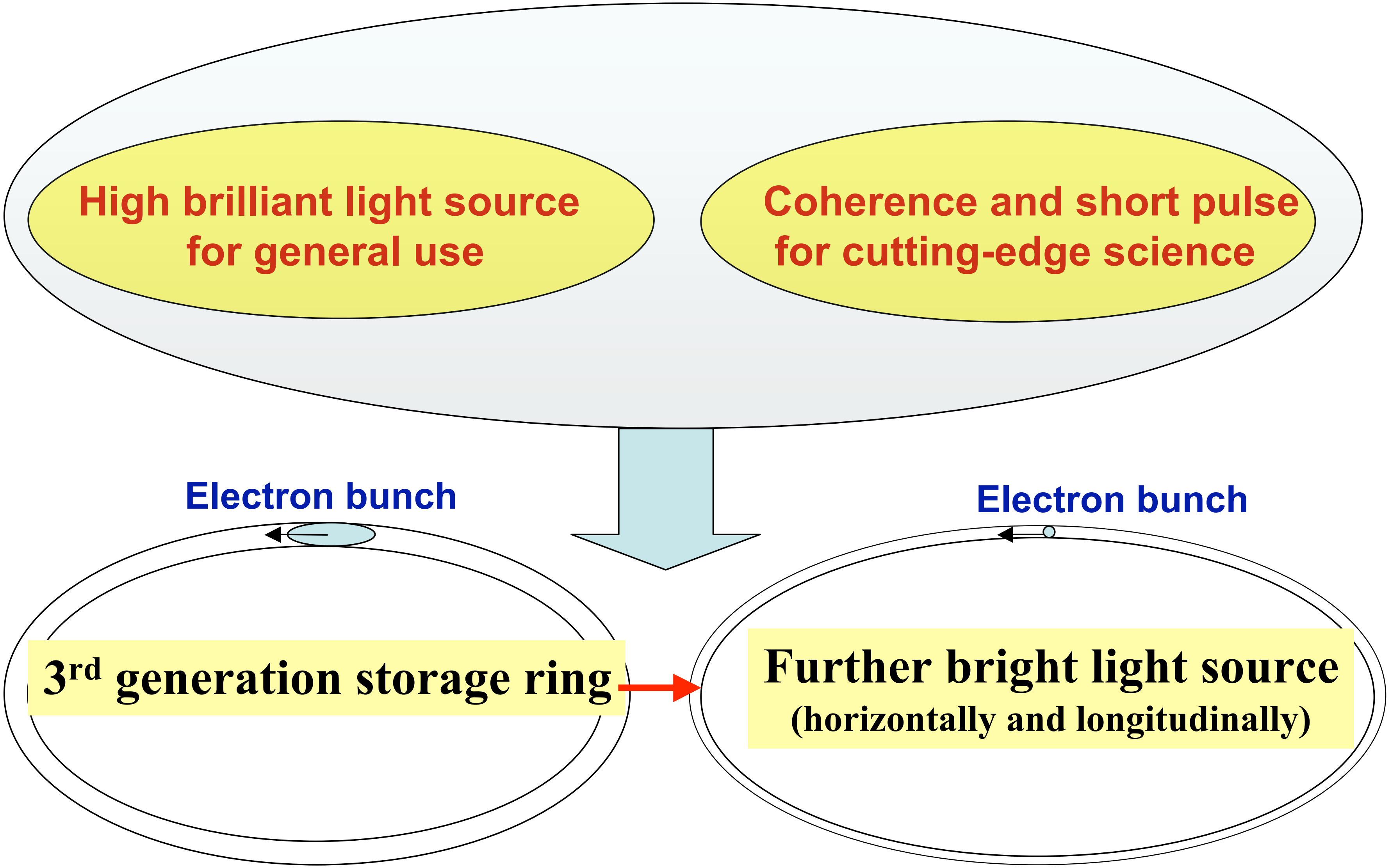


Plan for Future Light Source

Scientific requirement

Continuation (precise analysis)	Jump (cutting-edge science)
1) nano-structure	**3) non-crystalline materials**
beam size : μm → nm	**coherency**
2) electronic states	**4) non-equilibrium states**
ΔE : 1meV → 0.1meV	**sub-pico second pulse**
High brilliant light source	**Coherence and short pulse**

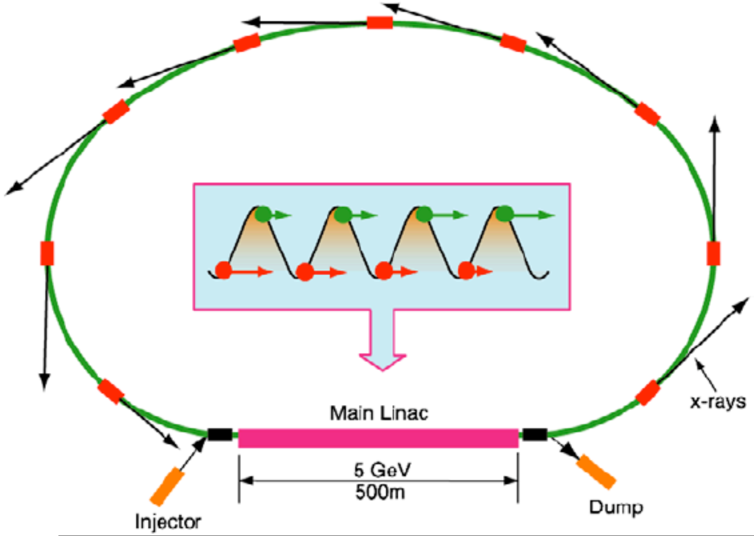
What kinds of accelerator are needed?



Specification of the synchrotron radiation from the future light source

Energy region :VUV-X (30eV-30keV)
Brilliance: 10^{21}-10^{23}
photons/sec/mrad^2/mm^2/0.1%B.W. @1~10 keV
Coherent fraction: 10~20%@ 10keV

Emittance: 10pmrad~ $\lambda/4\pi$ @ 10keV
Short pulse: ~100 fs
Number of ID beamlines: ~30 lines



Energy Recovery Linac(ERL)

ERL is promising for future light source

#) Linac based light source:

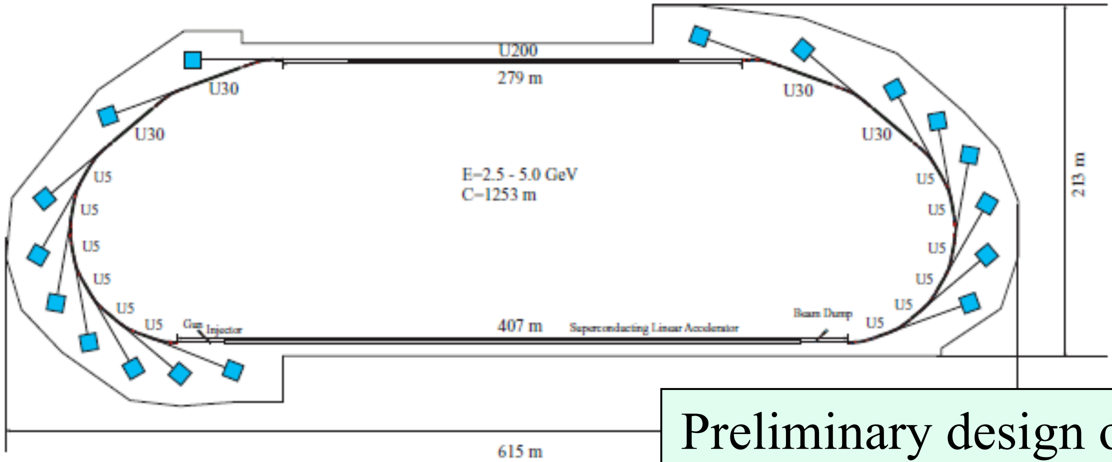
1) Emittance can be improved by a factor of 1/γ from a natural emmitance .

2) Short purse of the order of 0.1~1 pico-second can be available.

#) A great numbers of ID-beamlines can be available.

#) ERL will not provide extremely high peak brilliance, but high averaged brilliance. This feature will be suitable to keep a character for the proving light source as an usual synchrotron radiation experiments.

PF - ERL

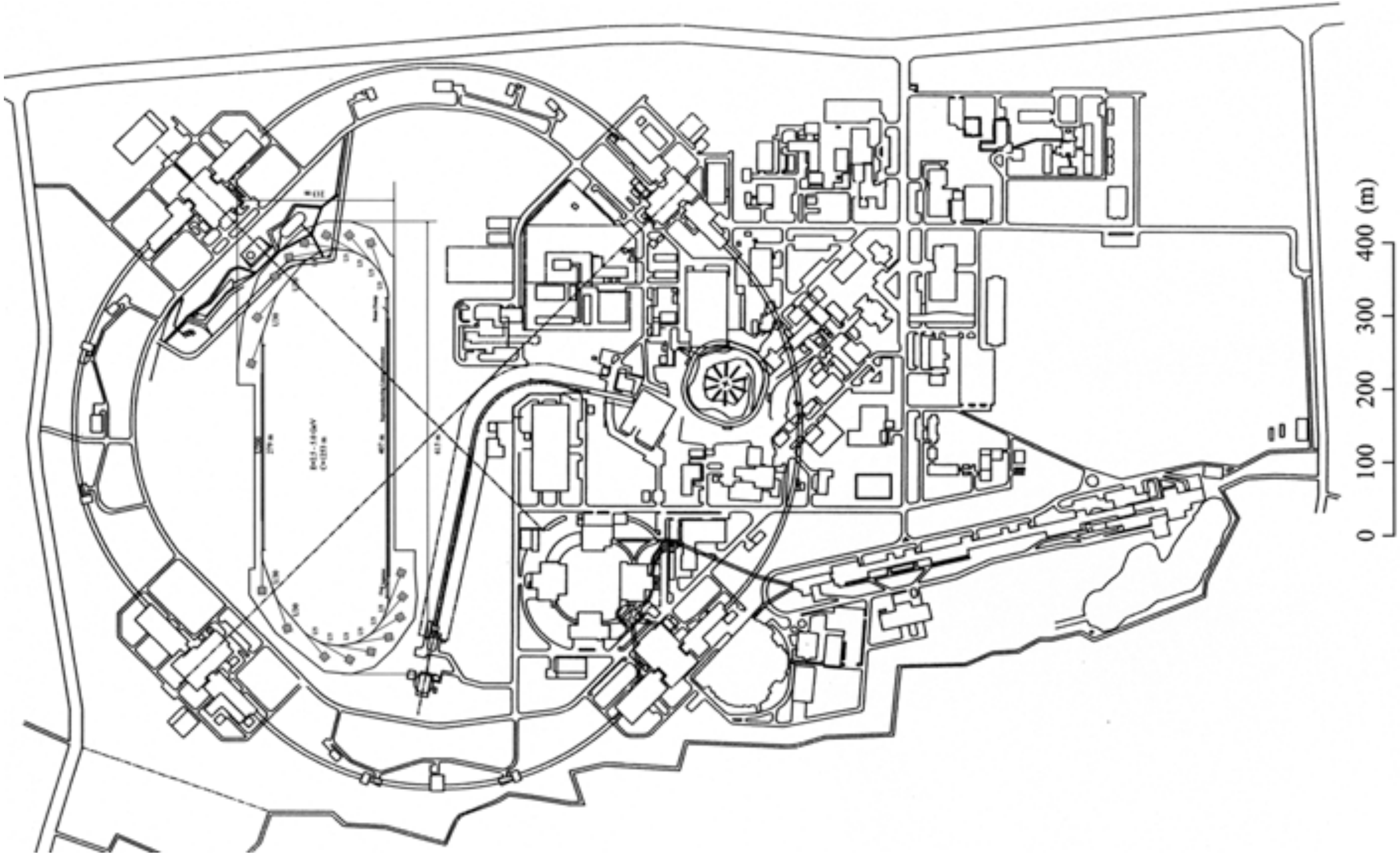


Preliminary design of PF-ERL at 2002

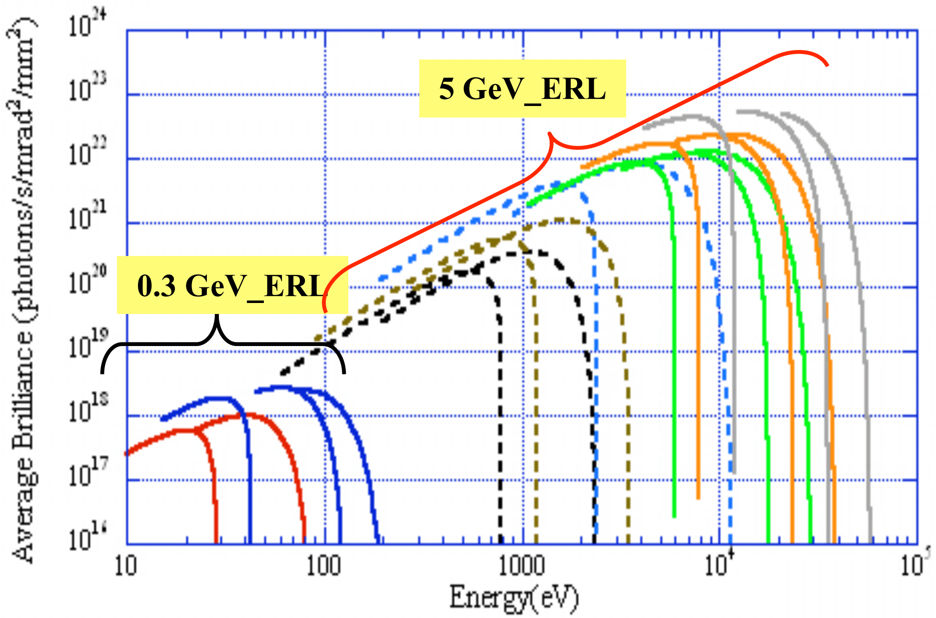
		PF-ERL undulator @ 5 GeV		SPring-8 undulator @ 8 GeV	
Beam current		100 mA	100 mA	100 mA	100 mA
Undulator length		30 m	5 m	25 m	5 m
Source size (μm)	horizontal	37.8	18.2	892	892
	vertical	37.8	18.2	22.8	10.6
Source div. (μrad)	horizontal	4.1	9.8	37.4	38.4
	vertical	4.1	9.8	4.3	10
Beam size @ 50 m (μm)	horizontal	244	510	2761	2813
	vertical	244	510	236	509
Average brilliance(ph/s/0.1%/mm^2/mr^2)		6.0×10^{23}	7.6×10^{22}	2.2×10^{21}	5.0×10^{20}
% beam coherence		19	15	0.14	0.13

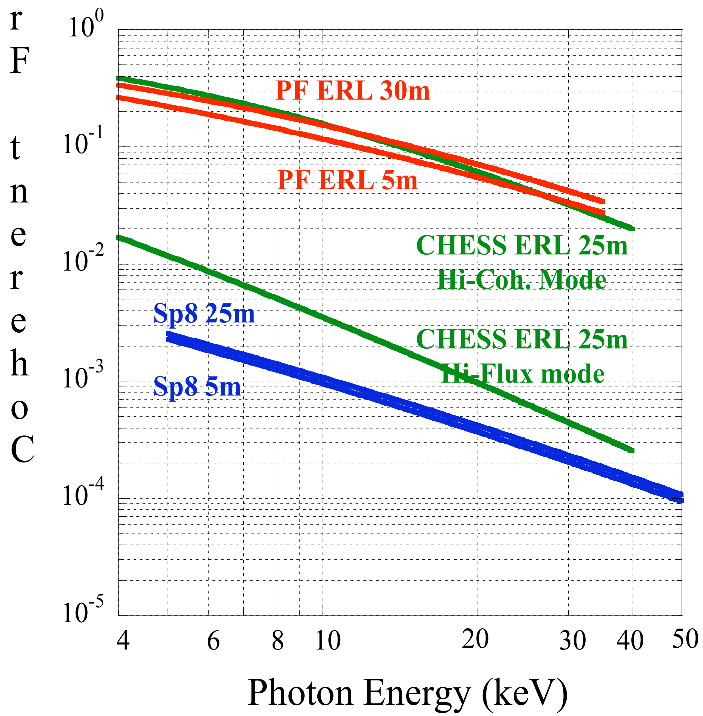
At the case of 8 keV photon energy

Size of 5-GeV class ERL



Brilliance and coherent fraction spectra from ERL(5GeV, 0.3GeV)





It is possible to cover the energy range from VUV to X-ray by using 5GeV ERL and 0.3GeV ERL.

Coherent fraction expected from ERL. It is possible to achieve the values of 10-20% at the energy range of 10keV.

Scientific cases at PF-ERL

- **Scientific subject opened by coherent X-rays**

  #Structural analysis of non-crystalline materials

  #Phase contrast imaging

  #Investigation at the fluctuation of several domains by means of X-ray photon correlation spectroscopy

- **Scientific subjects opened by short pulses (sub-pico second)**

  #Investigation of non-equilibrium dynamics.

  #Study of spin dynamics in material.

  #Chemical reaction.

  #Photo-induced phase transition and related materials

  #Reaction process at protein (life science)

- **Scientific cases opened by nano beam**

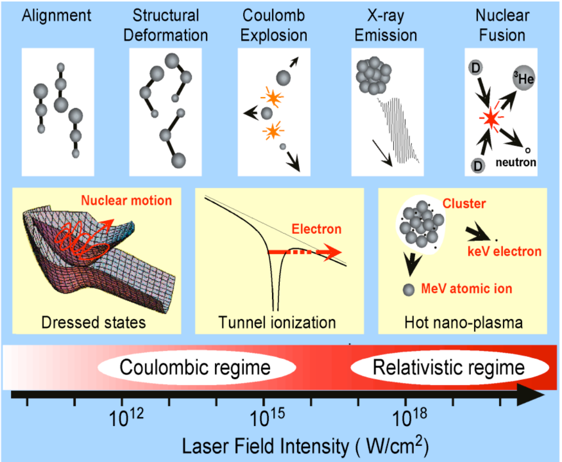
  #Combination with the other general experimental method.

↓

Local structural analysis, Local electronic state, Microscopic studies, Structural analysis of small crystals (~100 nm), etc.

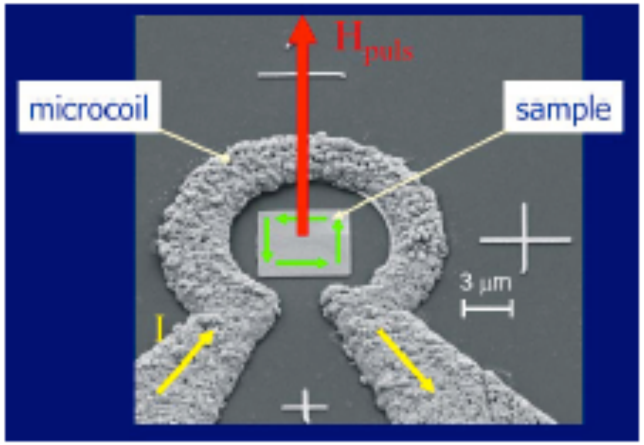
Time Domain Science with SR

Atomic physics



Yamanouchi (2002) Science 295, 1659.

XMCD, PEEM



Fischer et al. (SRI2003)

XAFS

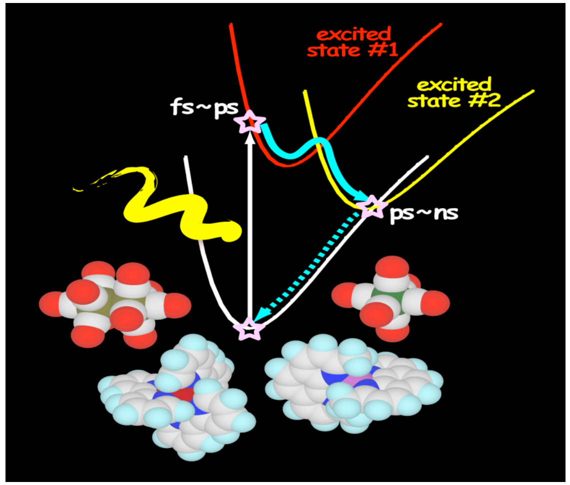
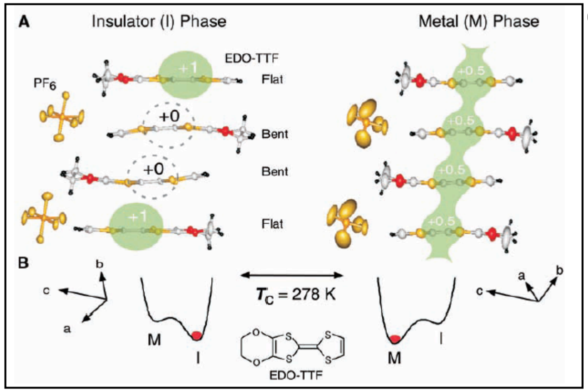
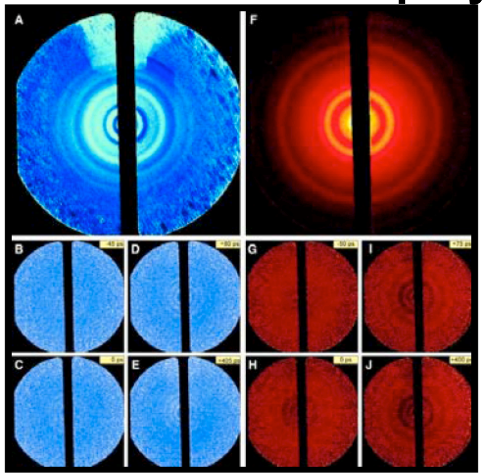


Photo-induced materials



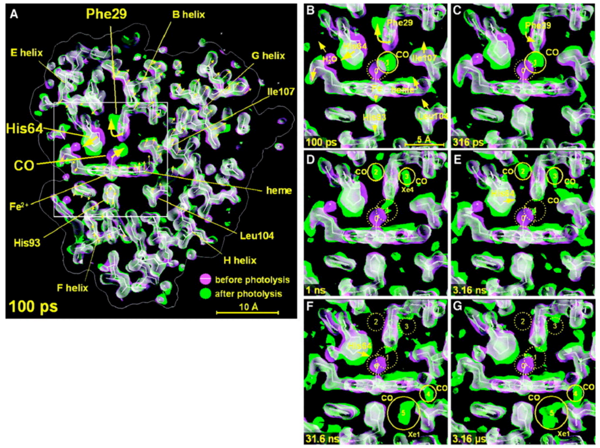
Collet et al. (2005) Science 307, 86

Chemical reaction at polymer



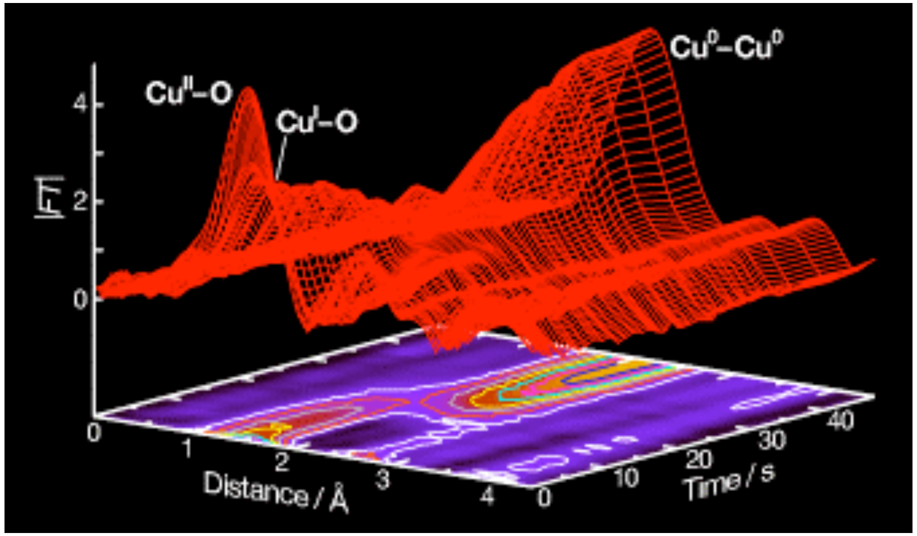
Ihee et al., (2001) Science 291, 458

Life science

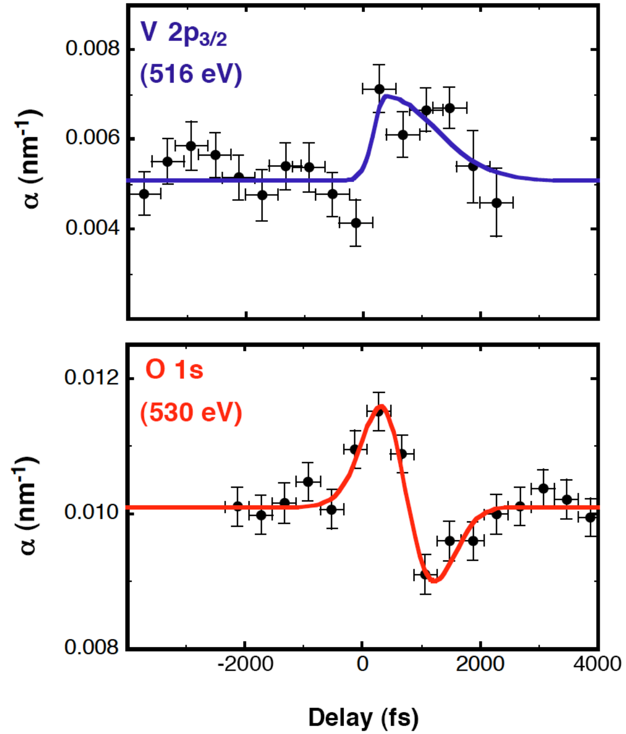


Schotte et al. (2003) Science 300, 1944

Time resolved XAFS experiments (Dynamics of the chemical reaction)



Yasuhiro Inada (Photon Factory, KEK) msec order

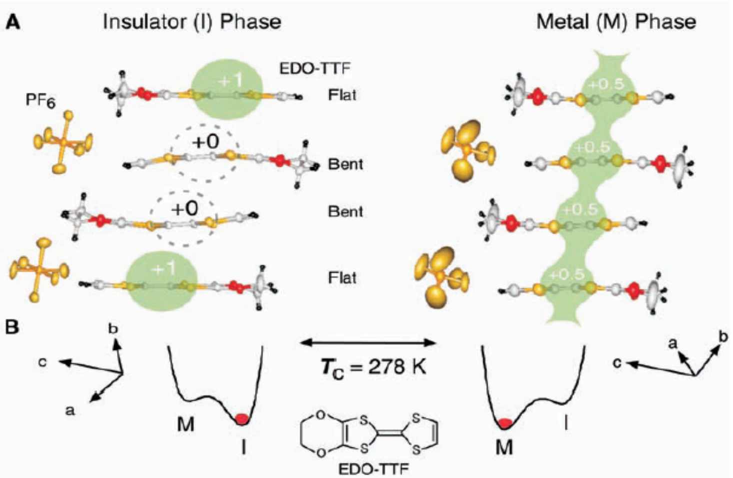


ERL provides us complete XAFS spectra with a good statistics, so that it will be possible to get much more detailed information about the electronic states, charge transfer and local atomic structure during a chemical reaction.

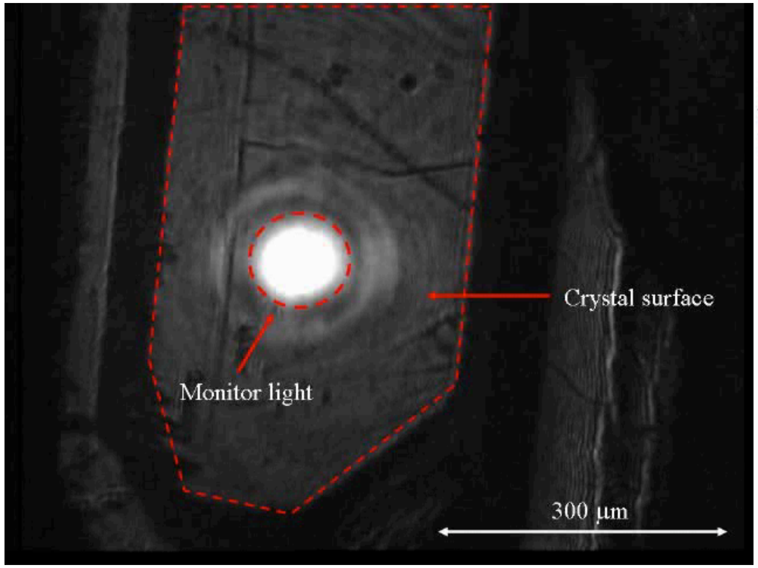
A.Cavalleri et.al., Phys.Rev.Lett. 95, 067405 (2005)

Femtosecond electronic rearrangement measurement during Photo induced I-M phase transition in $V0_2$ by using synchrotron radiation from "laser-sliced" electron bunches at ALS. 100fsec order

Photo-induced phase transition
(Strongly-Correlated Electron Systems)



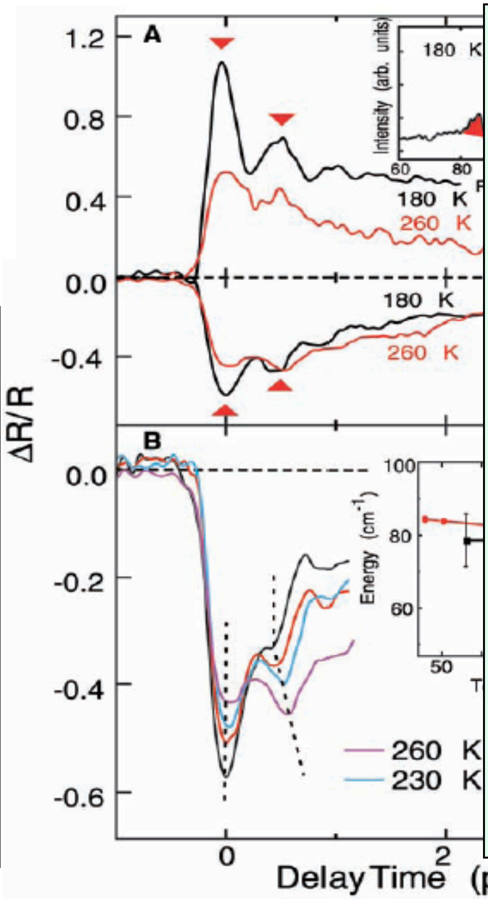
Collet et al. (2005) Science 307, 86



Koshihara et.al. (Tokyo Institute of Tech.)

Sub-pico second Photo-induced metal-insulator phase transition

- Application for a THz-switching device -



ERL will provide us following information!!

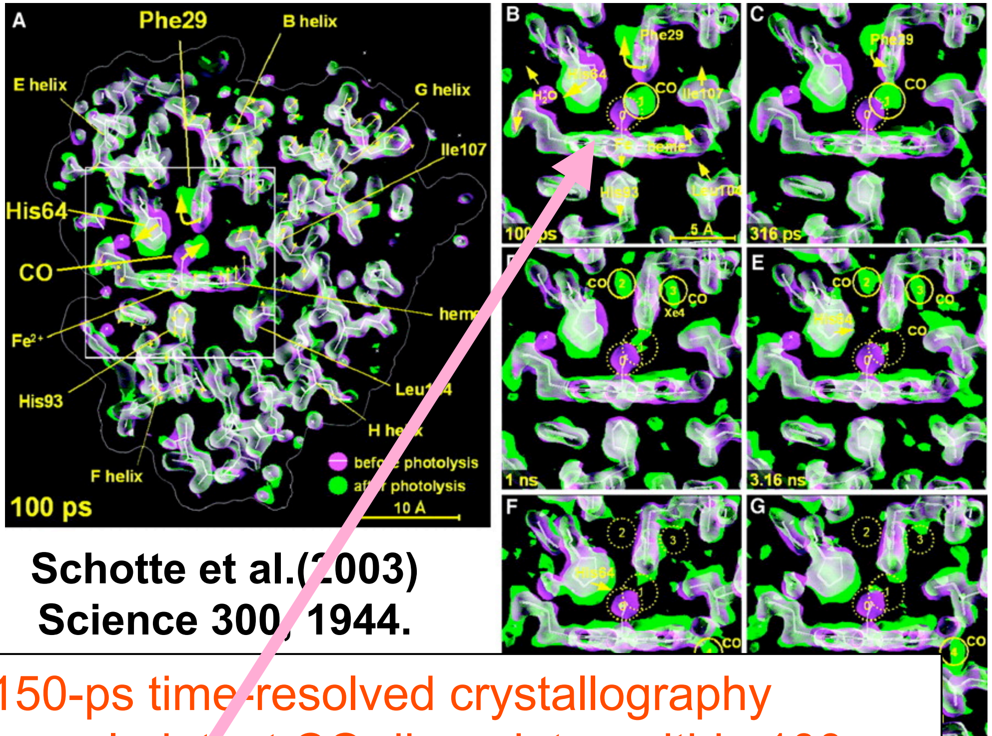
Structure?
(X-ray diffraction)

Electronic state?
(Photo-emission spectroscopy)

Domain formation?
(X-ray Photon Correlation Spectroscopy)

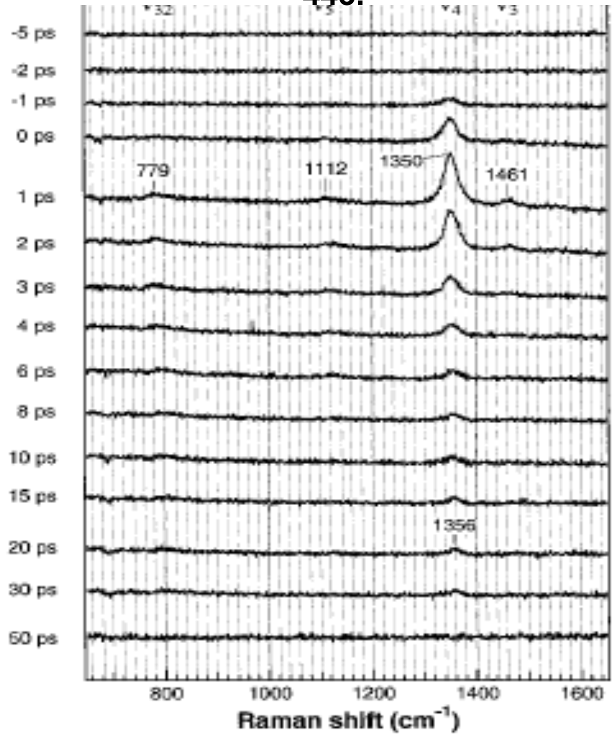
Structural Biology

myoglobin-CO



Schotte et al.(2003) Science 300, 1944.

Mizutani and Kitagawa (1997) Science 278, 443.



150-ps time-resolved crystallography revealed that CO dissociates within 100 ps.

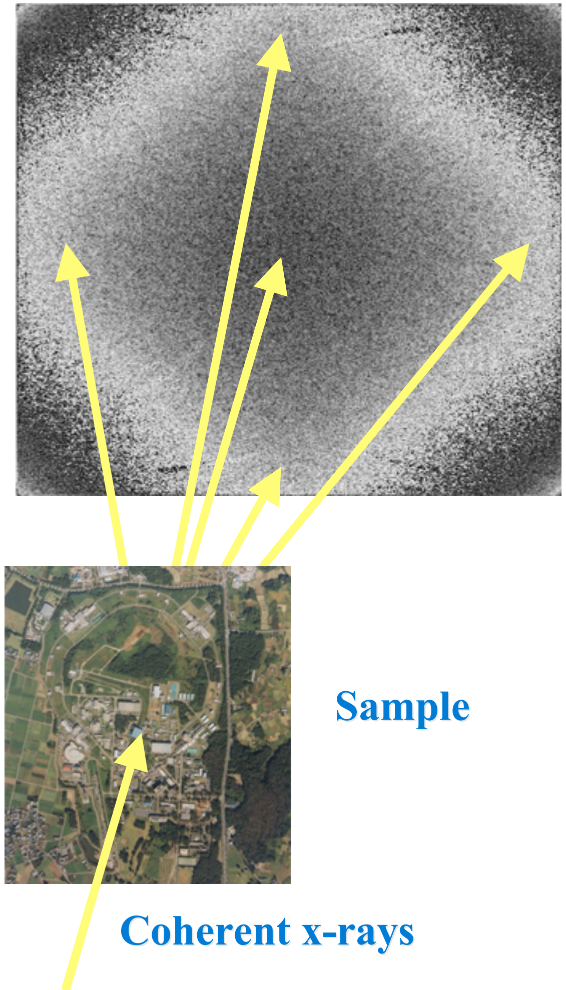
150-fs time-resolved resonance Raman revealed cooling of excited heme ends within 50 ps.

Something happens during 0-100 psec.

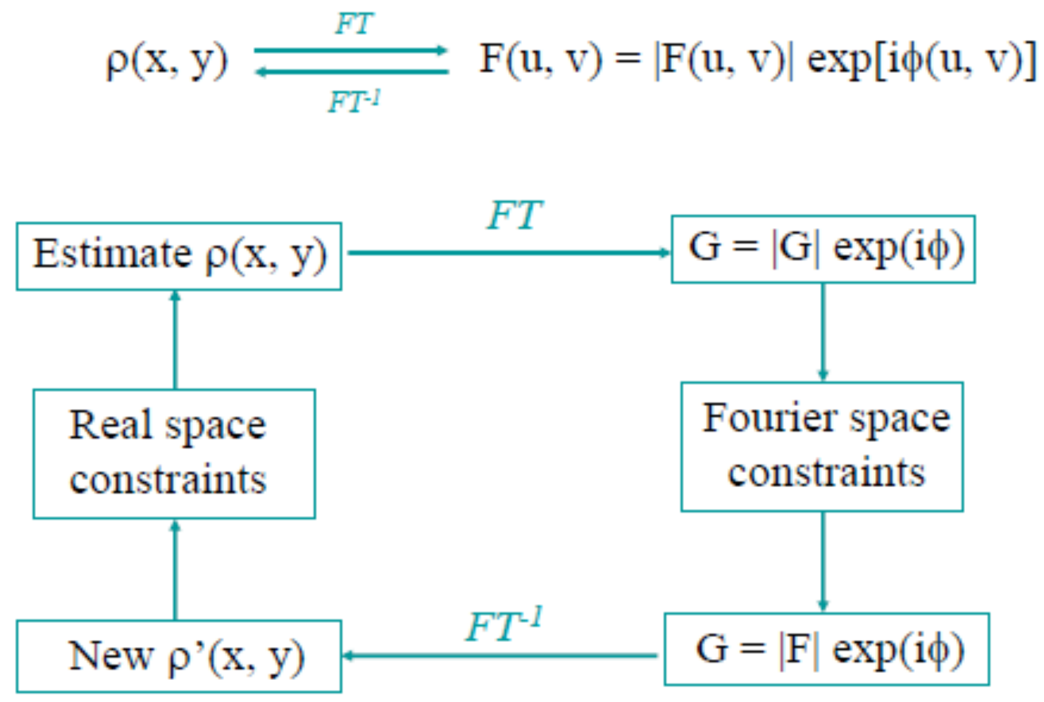
ERL: Sub-pico second time resolved structural analysis will give us information about the initial stage of structural changes.

X-ray Coherent Diffraction Microscopy

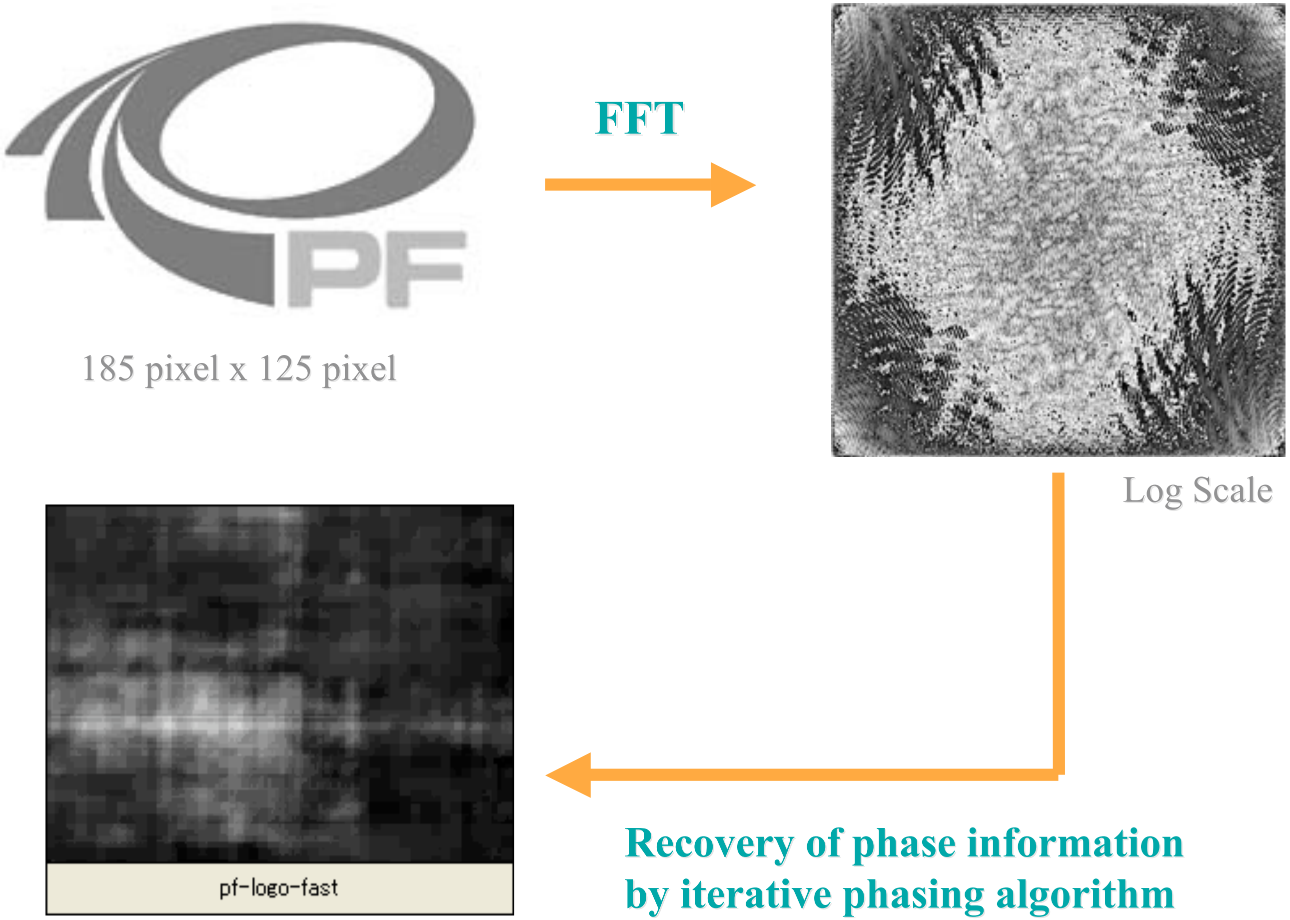
Fraunhofer diffraction pattern (Log scale)



Far-field diffraction → (oversampling / iterative phasing algorithm) → **Real-space imaging !!!**



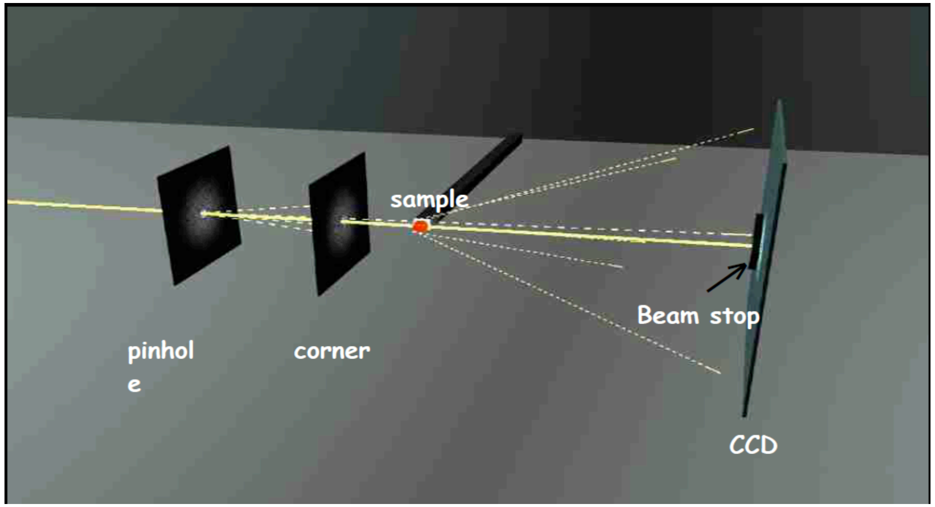
1) R. W. Gerchberg and W. O. Saxton, *Optik*, **35**, 237-246 (1972).
2) J. R. Fineup, *Appl. Opt.*, **21**, 2758-2769 (1982).



CPU: AMD Athlon XP 2400+
3000 iterations, 20 min

By K. Hirano (Photon Factory, KEK)

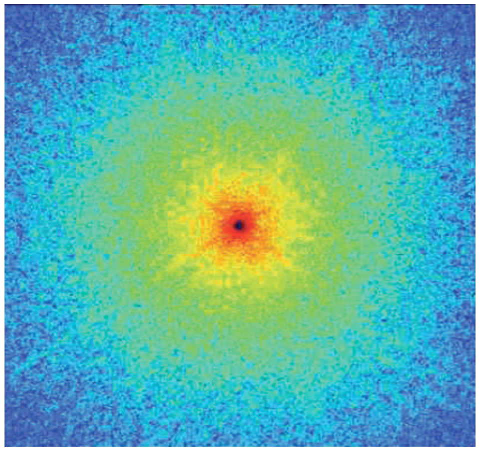
ERL cellular and sub-cellular imaging combined with high resolution structures from crystallography, EM and SAXS

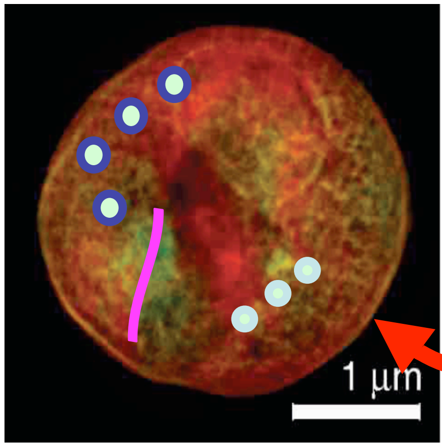


Experimental setup

- **ERL would improve spatial resolution up to a few nm.**
- **Use of anomalous dispersion for elemental mapping inside the cell**

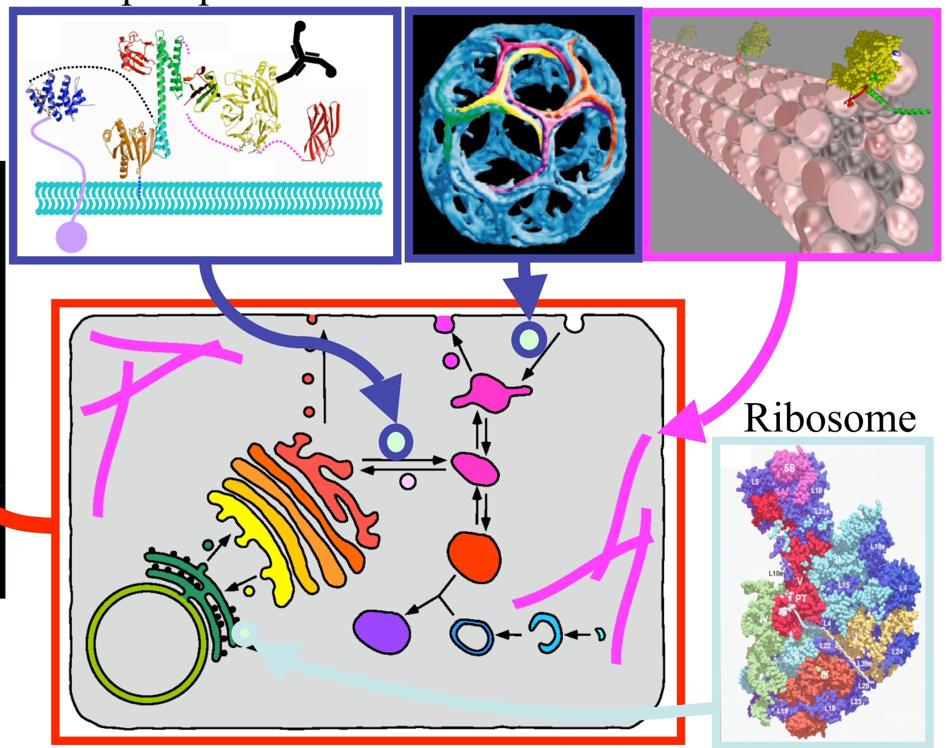
(K. Hirano: Trans. MRS-J 28 (2003) 43.)





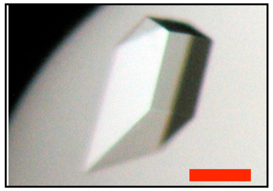
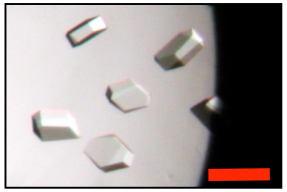
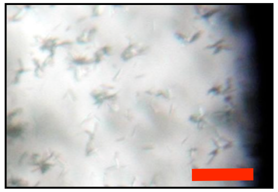
Diffraction from a yeast cell　　Reconstructed image

(Left hand side figures prepared from those by C. Jacobsen, Stony Brook)



Need of even stronger beam for structural analyses of large complexes and membrane proteins

Typical crystals	Current limit	Submicron crystals
100 μm	10 μm	1 μm ~ 0.1 μm
(10^{12} molecules)	10^9 molecules	10^6～10^3 molecules

bar：50μm

Towards the limit of the synchrotron based X-ray beam:

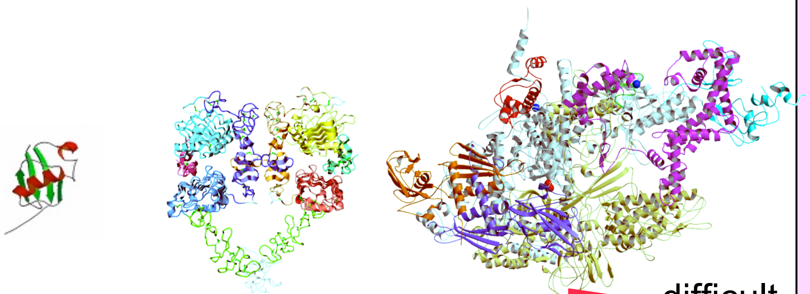
Nano meter size

About 100 protein molecules

And highly parallel beam

easy ⟷ difficult

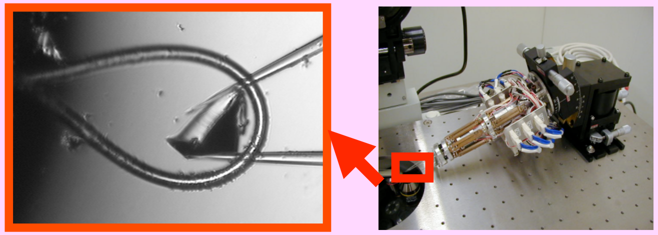
Molecular weight



easy ⟷ difficult

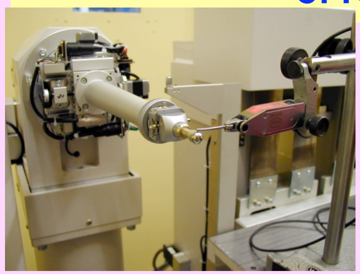
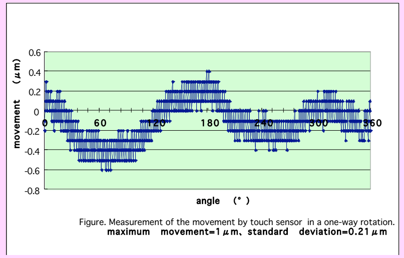
Handling techniques

Micro-hand / laser tweezer



Tamio Tanikawa (AIST)

Super diffractometer with 100 nm error of rotation

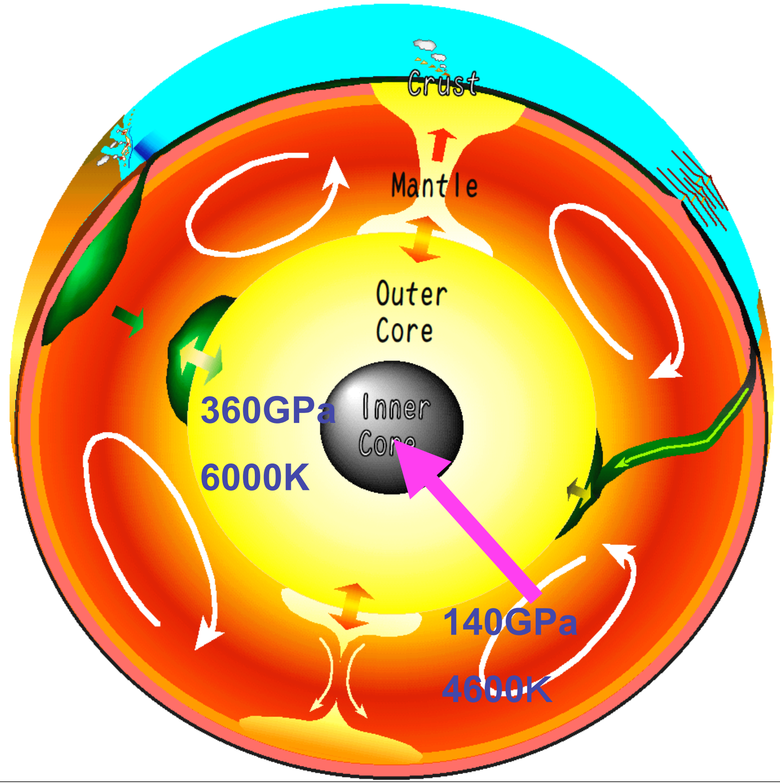



Nano beam for extremely small crystals

	Now	Future goals	
・Beamsize	100 × 100	0.1 × 0.1	μ m^2
・Intensity	10^{13}–10^{14}	10^{16}–10^{14}	photons/s/mm^2

Application to the Earth & Planetary Science

Exploration of Earth's Core



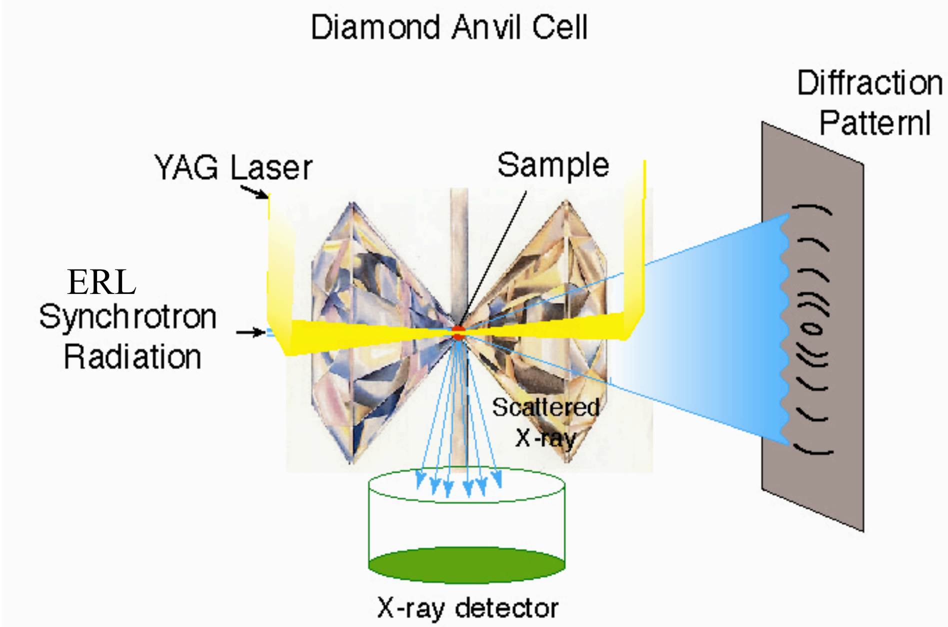
The Earth's interior consists of several geologic layers; an outer solid crust, a highly viscous mantle, a liquid outer core and a solid inner core. The core is largely composed of iron (80%).

Lower mantle: 140GPa and 4600K

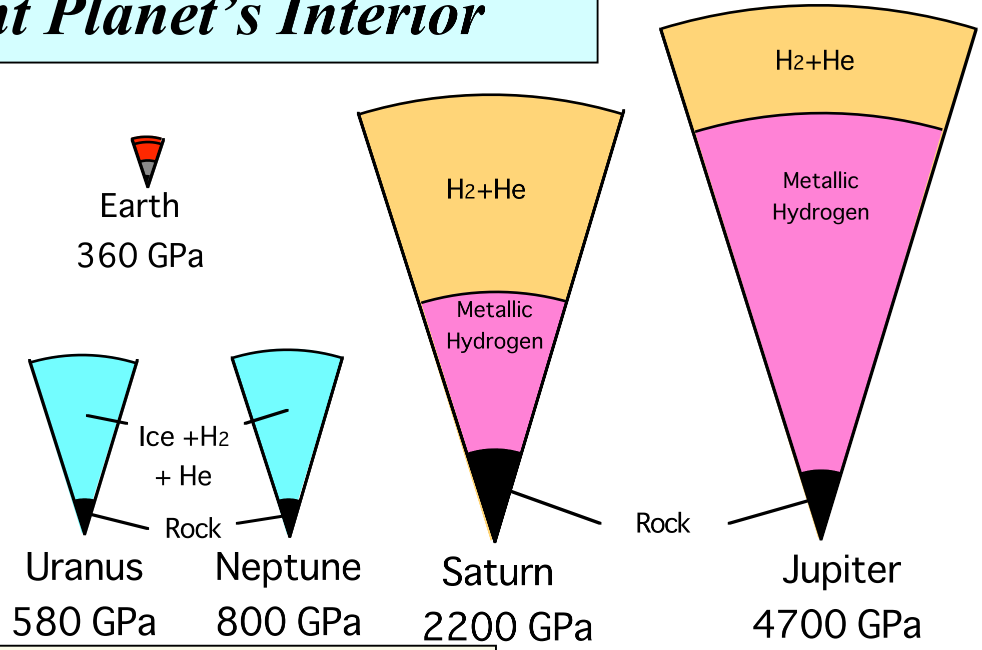
Present 3rd generation synchrotron radiation light sources have brought information about lower mantle.

Center of the earth: 360GPa and 6000 K

High intense sub-micron focused beam from ERL will give us information about center of the earth. Combination of X-ray diffraction and scattering will give us information about both of atomic, electronic and magnetic structures.



Investigation of the Giant Planet's Interior



#Gas Giant's (Jupiter and Saturn) interiors consist of liquid metallic hydrogen.

⇕

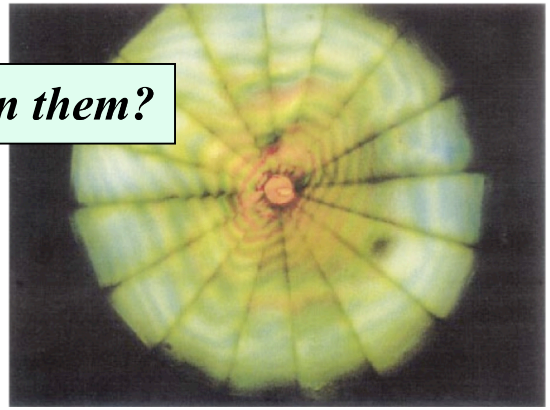
Is there any relationship between them?

Both planets have a giant heat flow, a strong magnetosphere and dynamics of atmosphere.

#The metallic hydrogen itself is theoretically predicted to be a room-temperature superconductor.

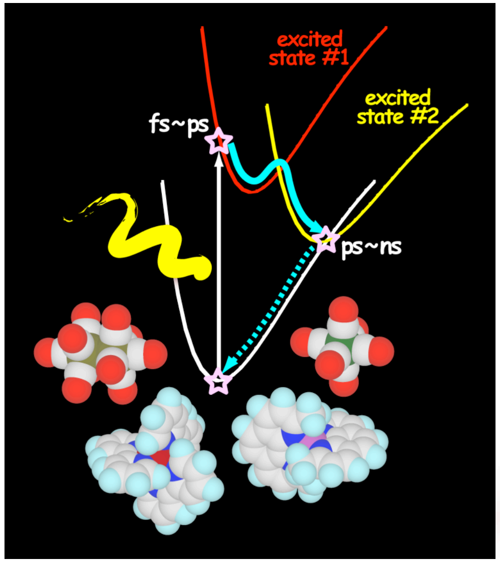
⇓

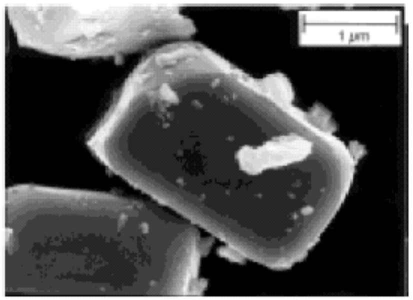
Studies of structure and magnetic property of Hydrogen under ultra-high pressure are important.

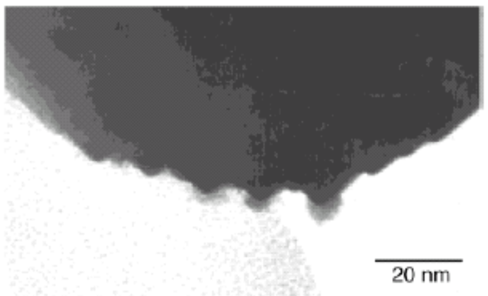


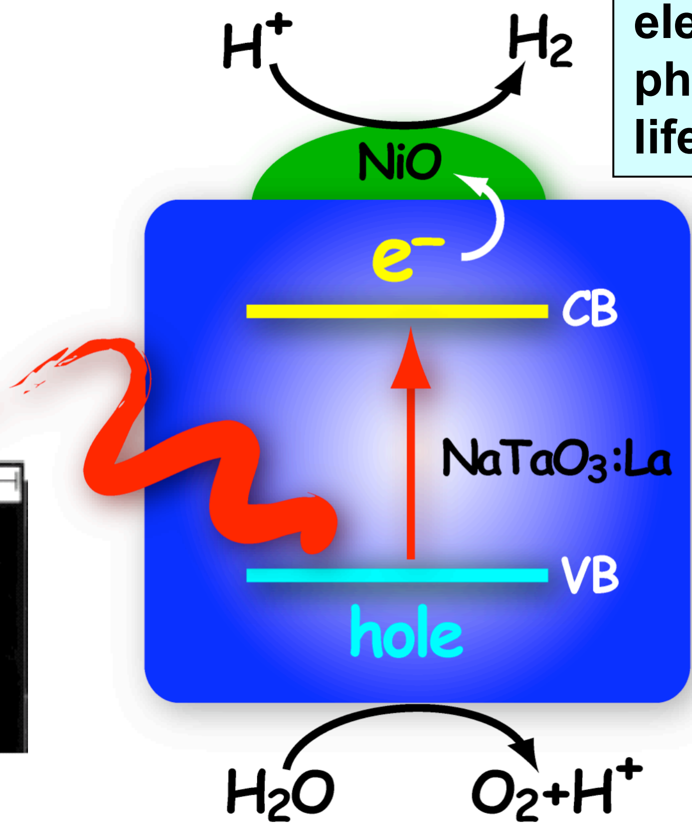
A tiny oval shape shows hydrogen at 330 GPa squeezed between diamond anvils whose culet size is only ϕ20μm.

Mechanistic Interpretation of Photocatalysis Functions









Analyses of structure and electronic states for photoexcited states with the lifetime of ps order

other applications

photocatalyst for
fixation of carbon dioxide
$Re(bpy)(PR_3)_2(CO)\ _2$

dehydration catalyst
for alcohols and alkanes
$RhCl(CO)(PR_3)_2$

etc …

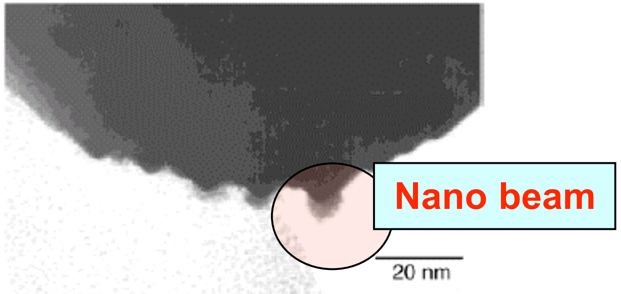
highly active **water decomposition** catalyst
$NaTaO_3$:La + NiO and its reaction model

A. Kudo, *et al. J. Am. Chem. Soc.* (2003), *J. Phys. Chem.* (1986)

Catalysis Chemistry

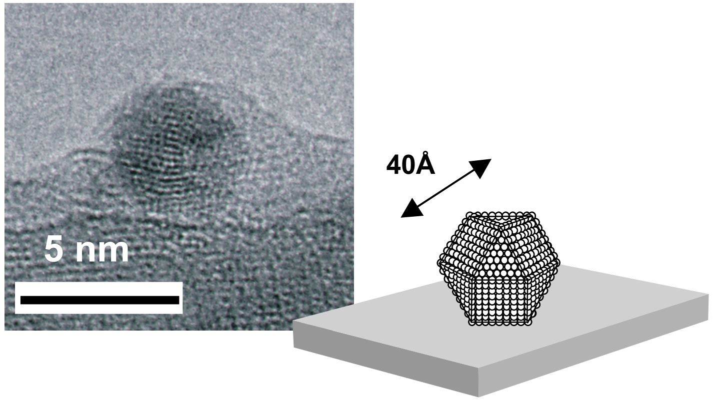
in situ observation of active site (species) itself using nano beam

active site (species) of catalysts



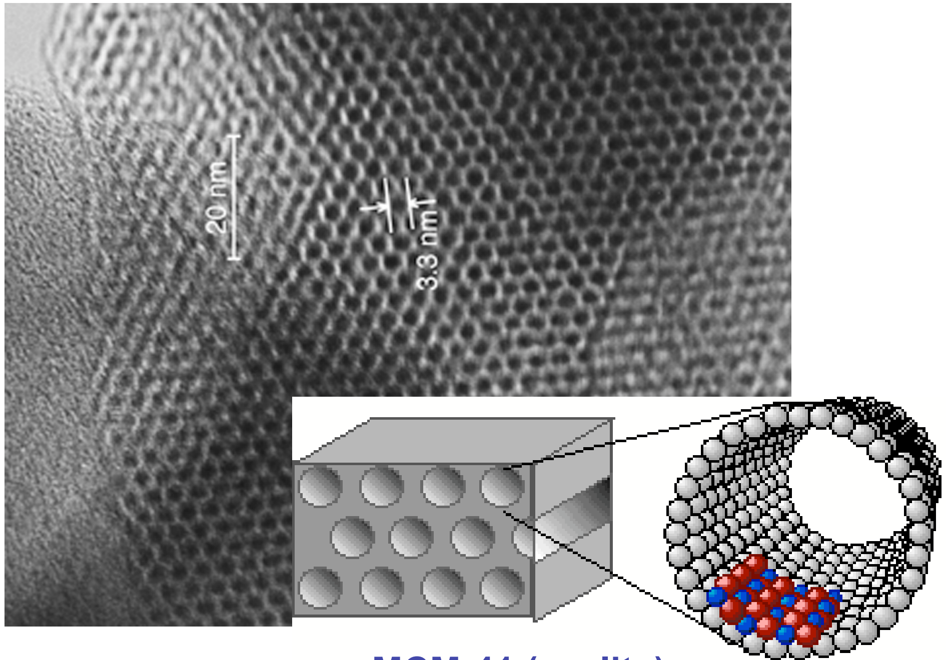
$NaTaO_3$:La + NiO catalyst

A. Kudo, *et al. J. Am. Chem. Soc.* (2003)



Pd nanocluster

K. Kaneda, *et al. J. Am. Chem. Soc.* (2002)
J. Am. Chem. Soc. (2004)



MCM-41 (zeolite)

N. *Ichikuni et al.* (2005)

nano beam will evaluate
local structure
electronic state
of active site (species) for various catalysts which is operating in the nanometer space

R&D Plan towards the ERL Light Source

Development of key components

- DC photocathode gun
- 1.3GHz CW laser
- Superconducting cavities
- Beam dynamics

Compact ERL

- Testing critical components under beam operations
- Generation and acceleration of ultra-low emittance beams
- Investigation of accelerator physics issues (CSR, beam losses etc.)
- **Scientific applications**

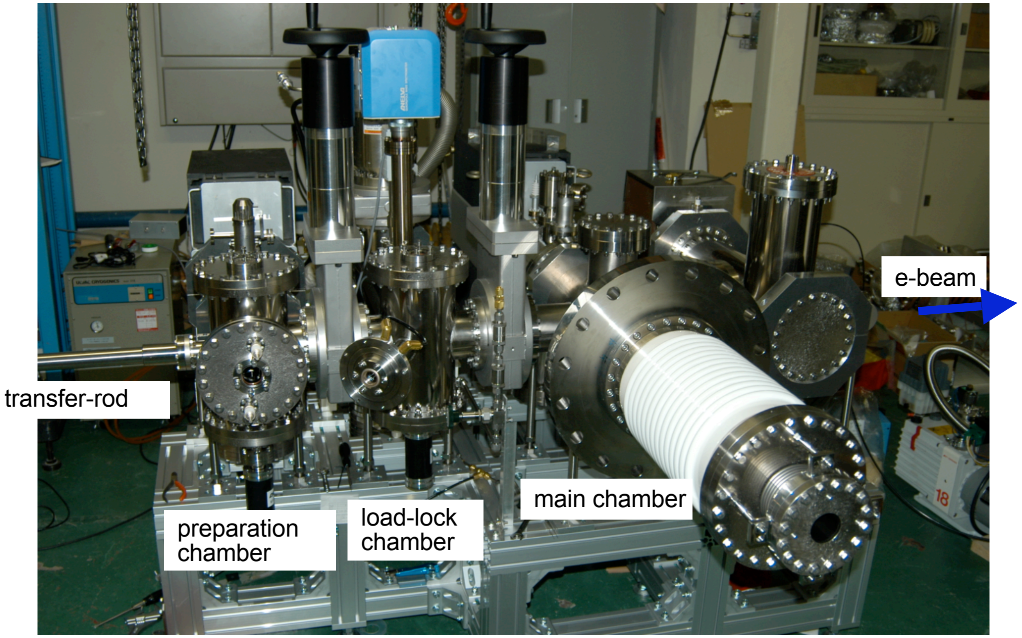
  High intense THz CSR

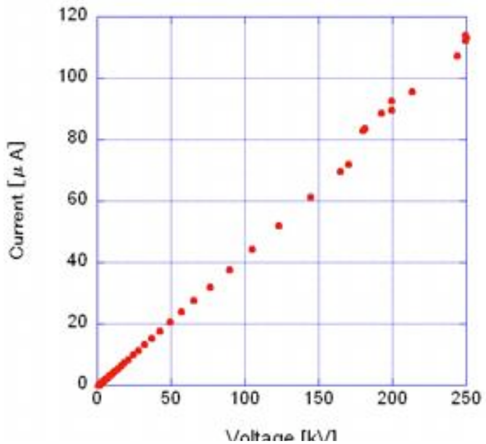
  Laser-Compton X-ray source for fs-Science and X-ray imaging

加速器要素技術の検討･開発の進捗状況

(PACでの発表を基にして）

Development of a photocathode DC gun (JAEA group)

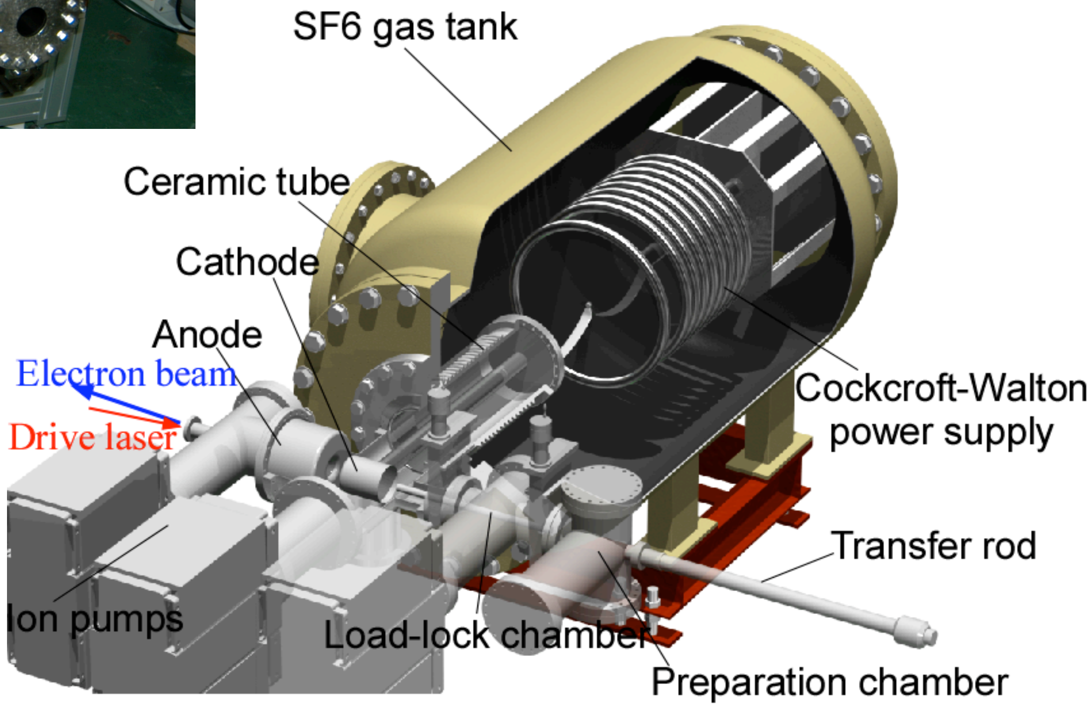




high voltage test without beam loading

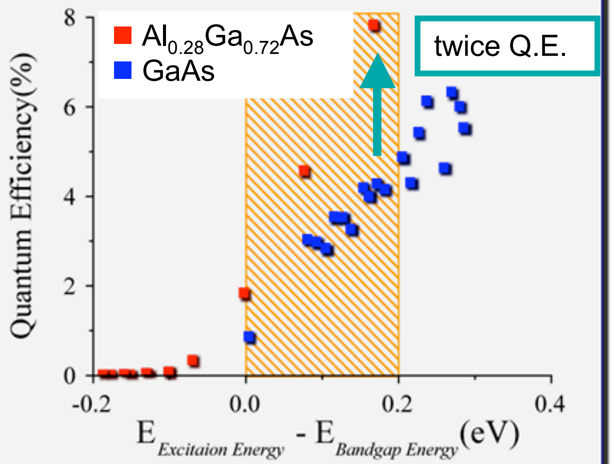
A 250 kV-50 mA DC gun is under development.

- ✓ A high-voltage test has been completed without beam loading.
- ✓ All the chambers have been assembled and a vacuum test is under way.
- ✓ We hope to see the first beam in this summer.



Photocathode for higher-QE and longer life (JAEA group)

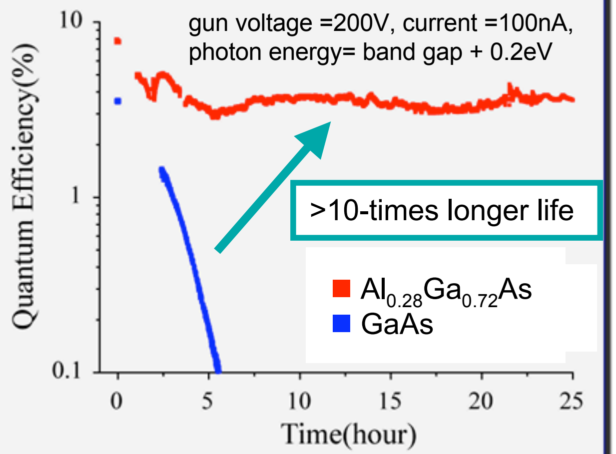
Quantum Efficiency



Bulk-AlGaAs shows higher QE than bulk-GaAs

Larger band gap and higher JDOS
→ more efficient excitation of electrons

Cathode Lifetime



Bulk-AlGaAs shows longer life than bulk-GaAs

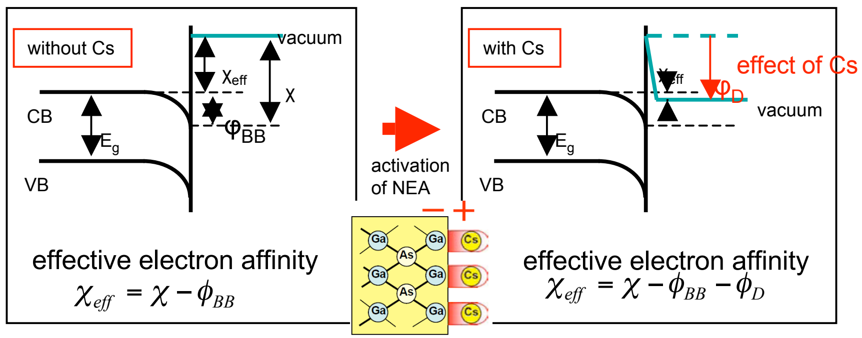
electron affinity
GaAs = 4.1 eV
$Al_{0.28}Ga_{0.72}As$ = 3.8 eV

We propose AlGaAs as a photocathode material

From the measurements at a test bench,

✓ AlGaAs shows 10-times longer life than GaAs

✓ AlGaAs shows 2-times higher QE than GaAs



Drive laser

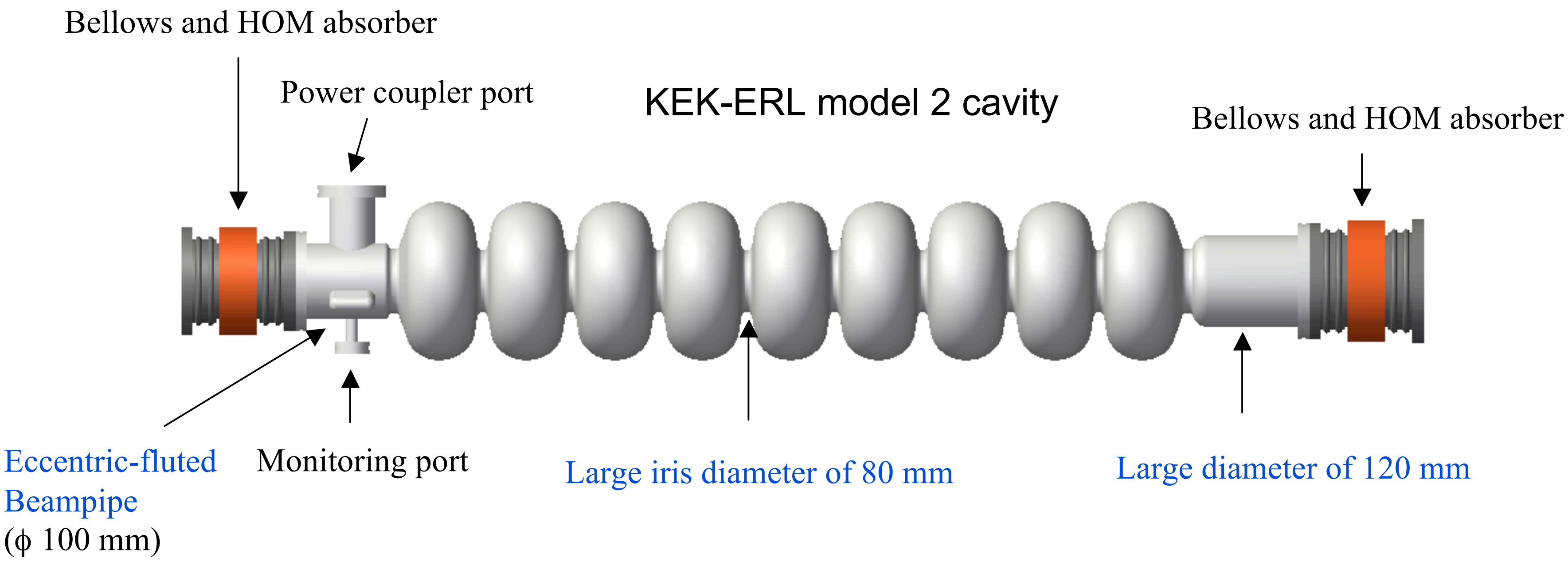
We plan to develop a drive laser system using Yb-doped fiber laser and NOPA.
→ wavelength tunability to minimize the thermal emittance.

Superconducting Cavity for the Main Linac (Furuya group)

1) **Cavity cell shape**
   - **Iris diameter 80mm, elliptical shape at equator**
   - **Cavity diameter 206.6mm**
2) **Large beampipe with microwave absorbers**
   - **Beampipe diameter 120mm & 100mm**
3) **Eccentric fluted beampipe**
   - **Damp quadrupole HOMs**

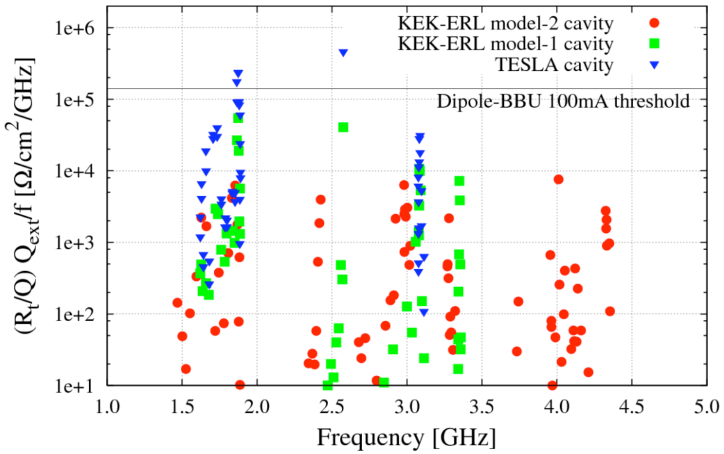
Parameters for accelerating mode

Frequency	1300 MHz
Coupling	3.8 %
R_{sh}/Q	897 Ω
$Q_o \times R_s$	289 Ω
E_p/E_{acc}	3.0
H_p/E_{acc}	42.5 Oe/(MV/m)

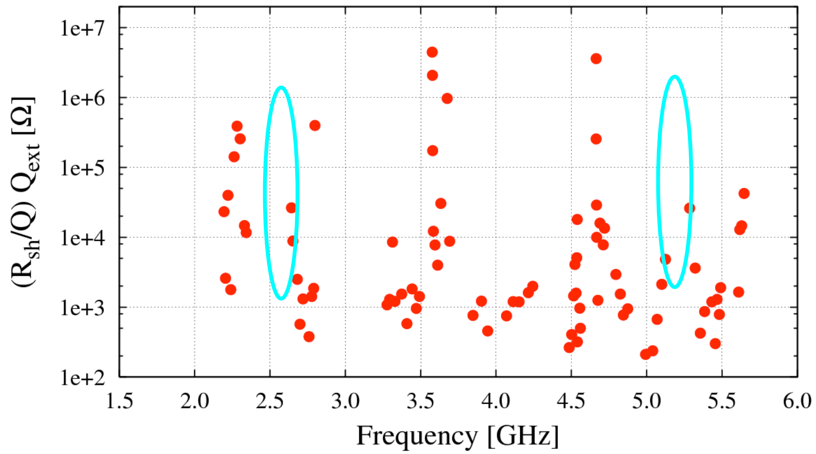


Performance of HOMs (main linac)(Furuya group)

Dipole modes



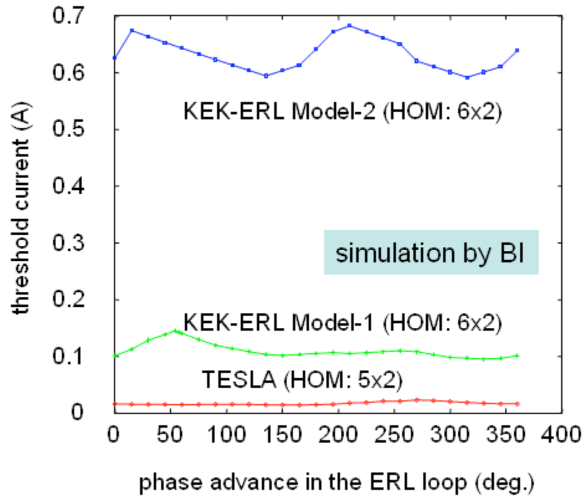
Monopole modes

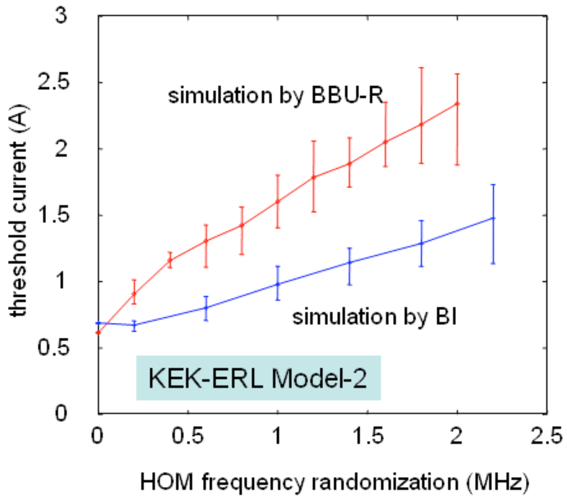


HOM-BBU threshold current

E_{inj} = 10 MeV, E_{loop} = 5 GeV, E_{acc} = 20 MV/m

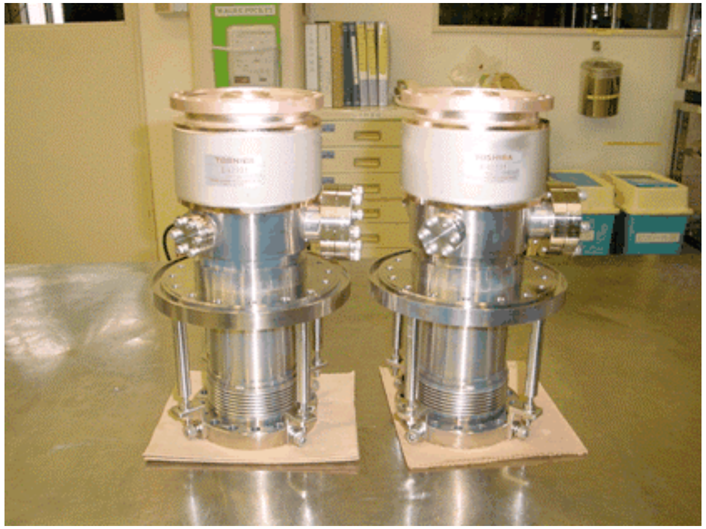
BI : developed at Cornell
BBU-R : developed at JAEA





Injector Cavities (Noguchi group)

- Total rf power of 0.5 - 1 MW should be delivered to the beams. We consider using three or four 2-cell cavities. Double couplers per cavity.
- Key component is an input coupler.
- Coaxial antenna coupler with a warm ceramic disk supplies the RF of 250 kW.
- Conceptual design of the cavity, an input coupler, and HOM couplers, started.
- We are going to use much R&D results from the International Linear Collider.

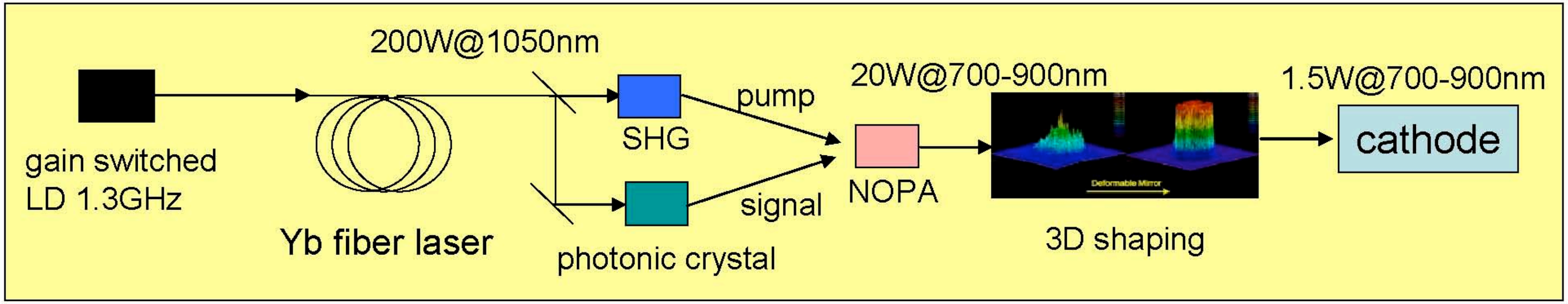


1.3 GHz power coupler for KEK-ILC.
Water-cooled coupler with warm ceramic disk is used.

Action Plan for Drive laser

1.5 W, 1.3 GHz, 700-900 nm (tunable)

fund bidding - MEXT-KAKENHI, 2007-2010, ~1M USD for the laser.



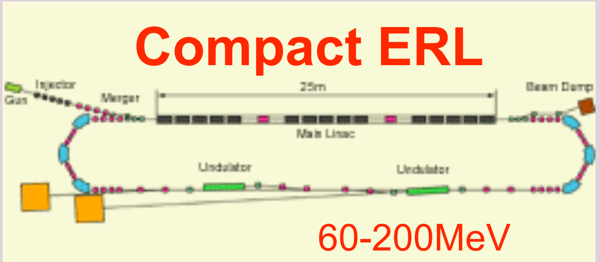
NOPA = non-collinear optical parametric amplifier
3D shaping = deformable mirror (transverse) + pulse stacker (longitudinal)

gain-switched LD will be replaced by Yb solid-state oscillator in due time.

related description is found in ERL-REPORT-003 (Aug. 17, 2006)
http://pfwww.kek.jp/ERLoffice/info/index.html

Evolution of ERL

Development of key components

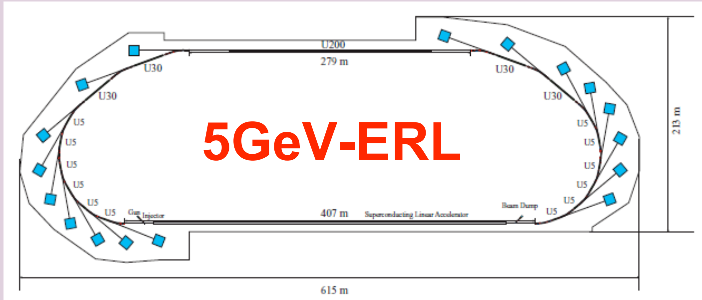


～2013

Coherent SR at THz region

Hard X-ray (-10keV) by Laser-Compton scattering

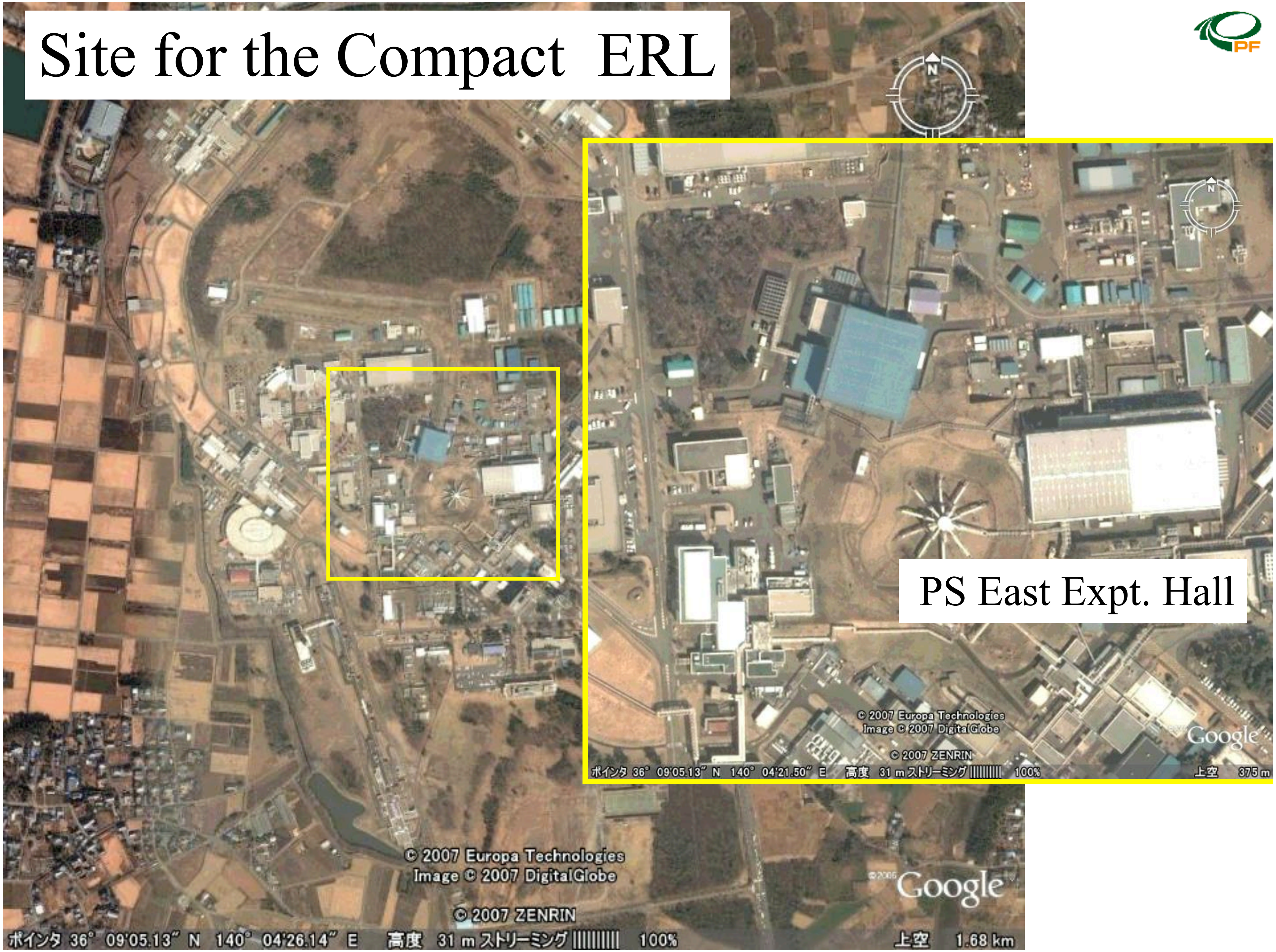
Future light source



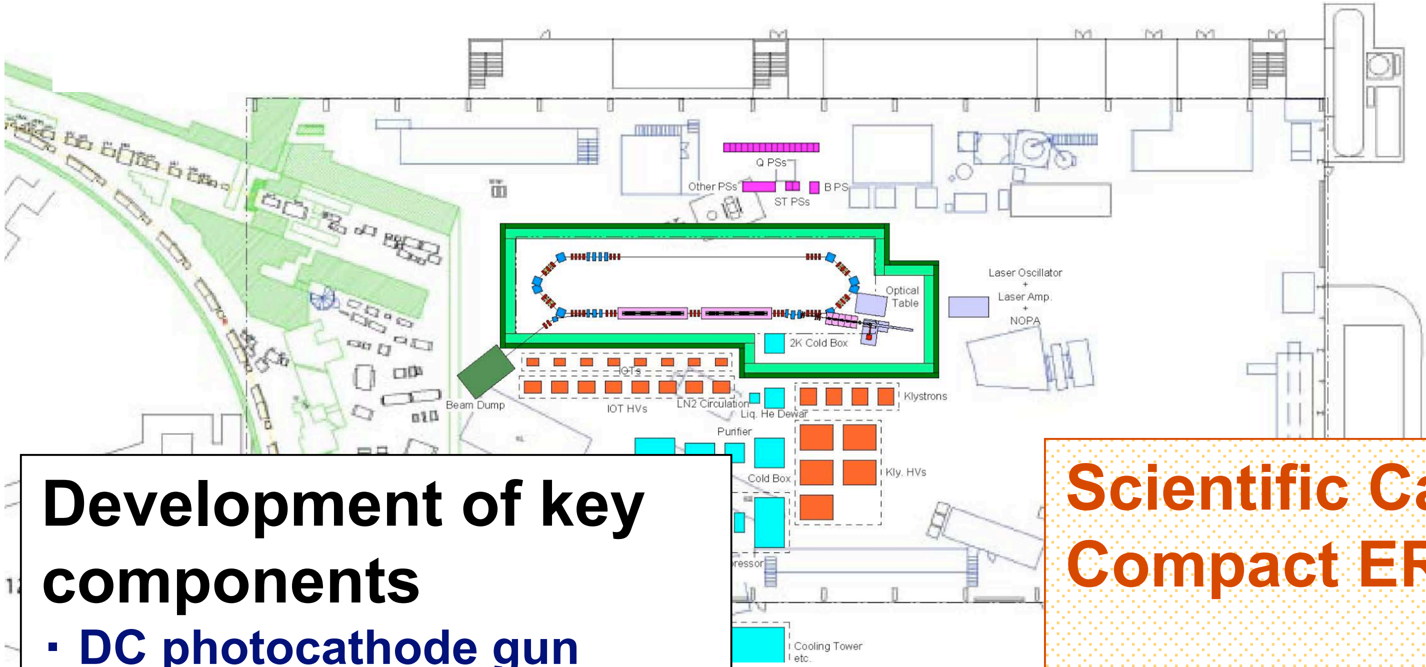
2013～

Spread of the advanced compact X-ray imaging source

Site for the Compact ERL

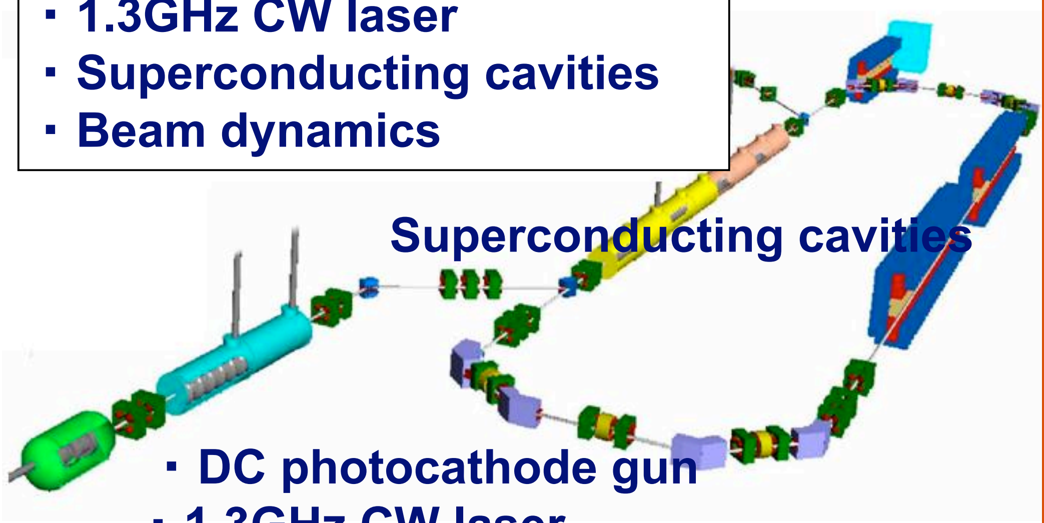


Compact ERL(60-200MeV) (~2013



Development of key components

- DC photocathode gun
- 1.3GHz CW laser
- Superconducting cavities
- Beam dynamics



Scientific Case on Compact ERL

Coherent SR at THz region
high intensity by order of 6-7 compared with conventional source

Hard X-ray (-10keV) by Laser-Compton scattering
- extremely small beam
  -> medical imaging application
- fs science

Time Schedule of the ERL Project

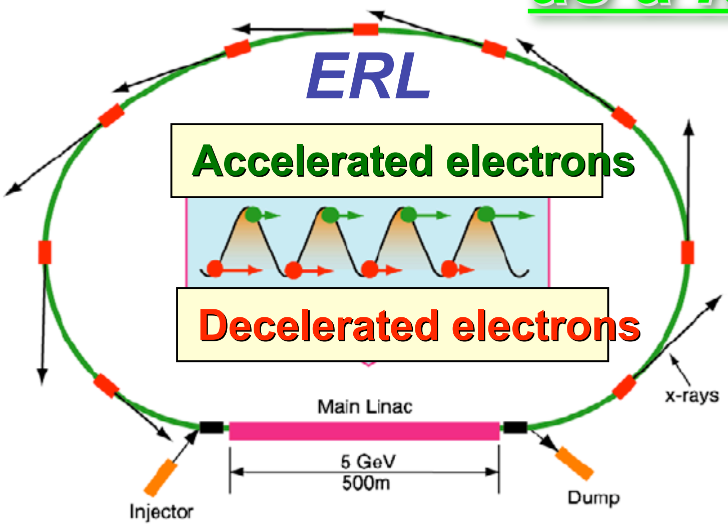
1)Construction of a 60~200MeV class Compact ERL
2) Demonstration of the principle of the ERL until 2012.
3) User operation of the compact ERL will start from 2013
4) Ready to start construction of 5 GeV class ERL from ~2013.

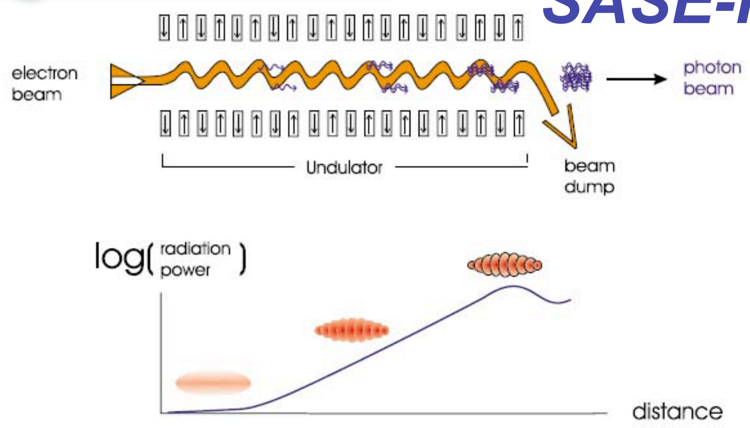
Summary

- ERL is promising for future light source.
- ERL project has been progressed under the collaboration with KEK, JAEA, ISSP, CHESS and other facilities.
- To resolve technical & physical challenges and demonstrate the characteristic scientific cases on ERL, the Compact ERL is under designing.
- The Compact ERL will consist of a 5-MeV injector, 1-2 cryomodules, a return loop and a beam dump. The energy will be 60 – 200 MeV.
- R&D for the DC photocathode gun (at JAEA) and for the SC cavities (at KEK) have been started.

Thank you for your attention!

Comparison between ERL and SASE-FEL as a future light source





	average brilliance	peak brilliance	repetition rate (Hz)	coherent fraction	bunch width (ps)	# of BLs	Remark
ERL	$\sim 10^{23}$	$\sim 10^{26}$	1.3G	~20%	0.1~1	~30	Non-perturbed measurement
XFEL	$\sim 10^{22\sim 23}$	$\sim 10^{33}$	100~1K	100%	0.1	~1	One-shot measurement

(brilliance : photons/mm^2/mrad^2/0.1%/s @ 10 keV)