ERL2011
October 16-21, 2011
KEK, Tsukuba, Japan

Ultrafast Science with ERL

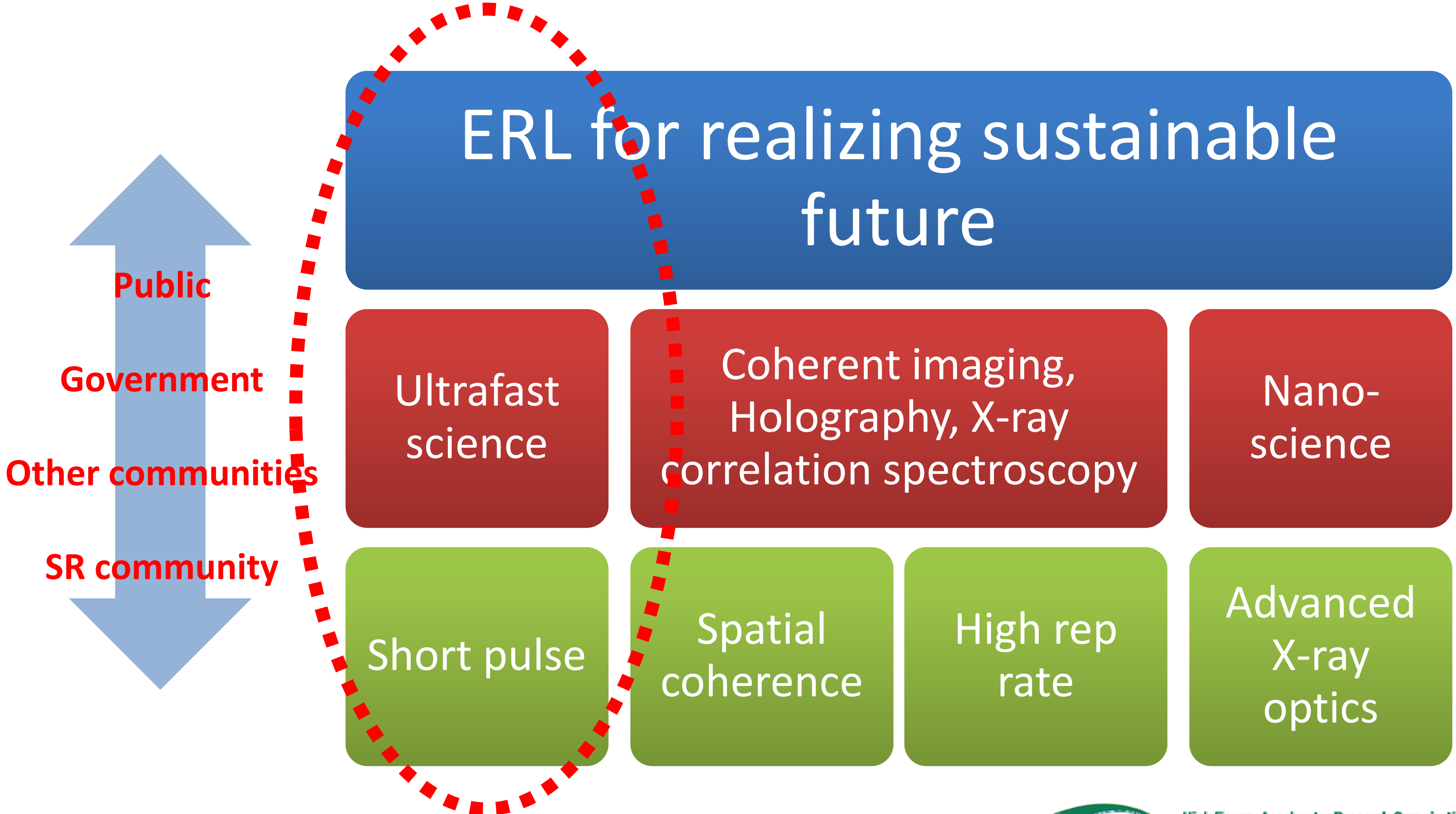
Shin-ichi Adachi
Photon Factory, KEK

High Energy Accelerator Research Organization (KEK)
Institute of Materials Structure Science (IMSS)
Photon Factory

ERL Science

Who are the targets?

ERL Science
What ERL can do?



High Energy Accelerator Research Organization (KEK)
Institute of Materials Structure Science (IMSS)
Photon Factory

Outline

1. Introduction
2. Current status of picosecond X-ray science at PF-AR, KEK
3. Future challenges of ultrafast X-ray science with ERL
4. Summary

High Energy Accelerator Research Organization (KEK)
Institute of Materials Structure Science (IMSS)
Photon Factory

Spatial features of ERL

(natural emittance, electron beam size, and divergence)

Sources	Natural emittance (nmrad)	σ_x μm	σ_y μm	$\sigma_{x'}$ μrad	$\sigma_{y'}$ μrad
ERL (3GeV)	0.017	7.1	7.1	2.3	2.3
SPring-8 (8GeV)	3.4	298	6.1	12	1.1
Photon Factory (2.5GeV)	36	600	12	88	29

Diffraction limit @ ~7keV

High Energy Accelerator Research Organization (KEK)
Institute of Materials Structure Science (IMSS)
Photon Factory

Temporal features of ERL

(rep rate, photons, and duration)

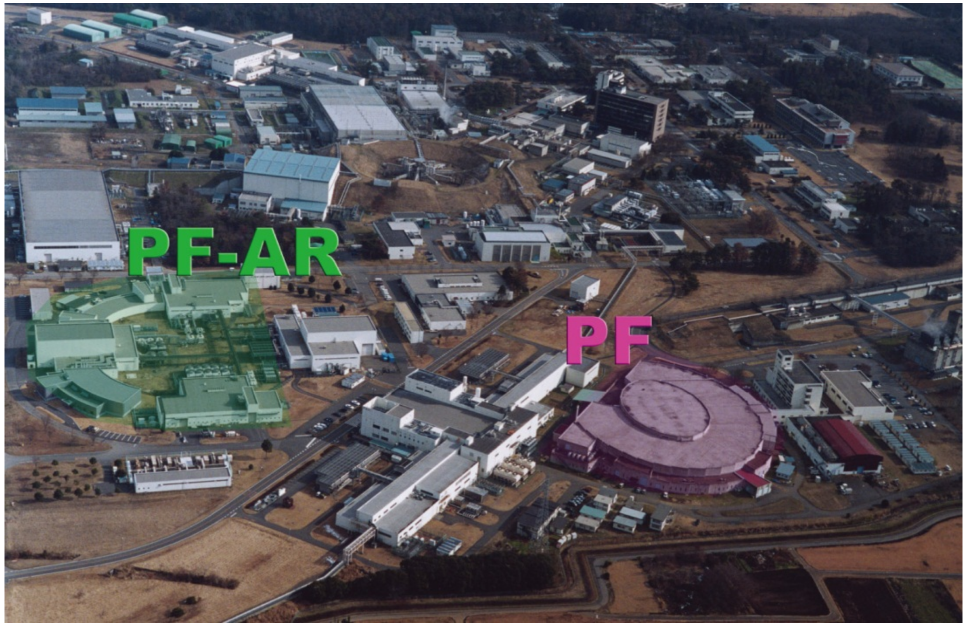
Source	Rep rate	Photons/pulse	Photons/sec	Pulse duration
ERL	1.3GHz	10^3-10^6	10^{12}-10^{15}	100fs-1ps
SASE-XFEL	60-120Hz	~10^{12}	~10^{14}	10-100fs
Storage ring	1MHz-500MHz	10^6-10^9	10^{12}-10^{15}	~100ps

Short pulse, high rep rate

High Energy Accelerator Research Organization (KEK)
Institute of Materials Structure Science (IMSS)
Photon Factory

picosecond X-ray science @ PF-AR, KEK

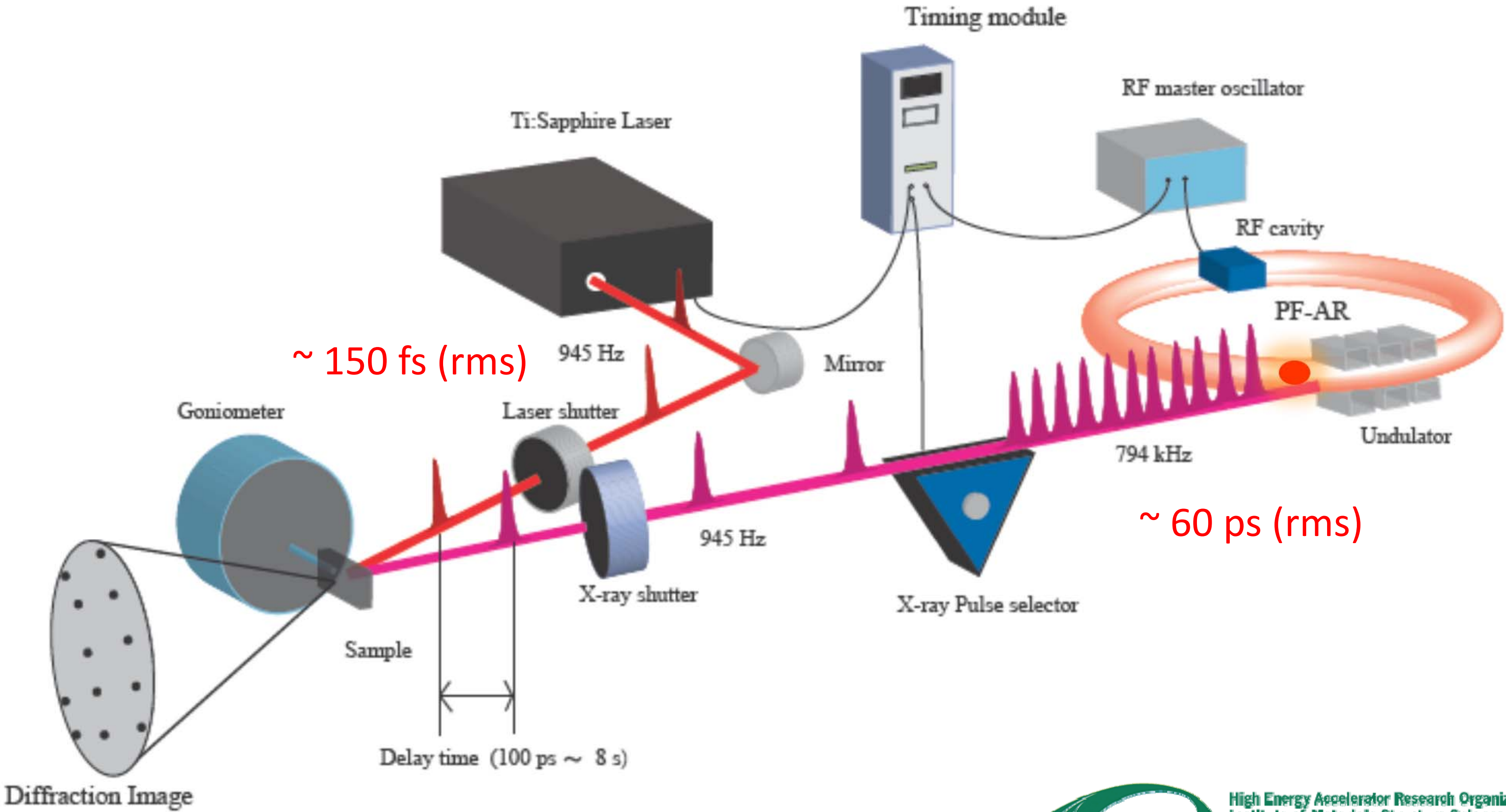
dedicated single-bunch operation



Ring energy: 6.5 GeV
RF frequency: 508.58 MHz
Circumference: 377 m
Harmonic number: 640
Bunch length: 18.6 mm (62 ps)

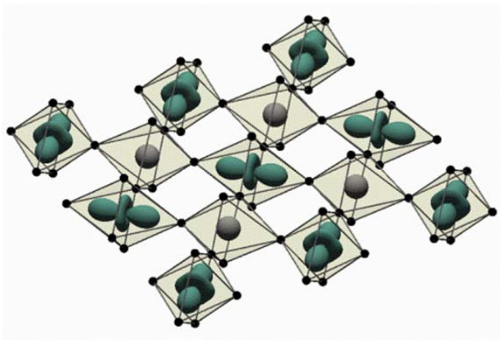
High Energy Accelerator Research Organization (KEK)
Institute of Materials Structure Science (IMSS)
Photon Factory

Schematic layout of time-resolved X-ray beam line (NW14A, PF-AR, KEK)



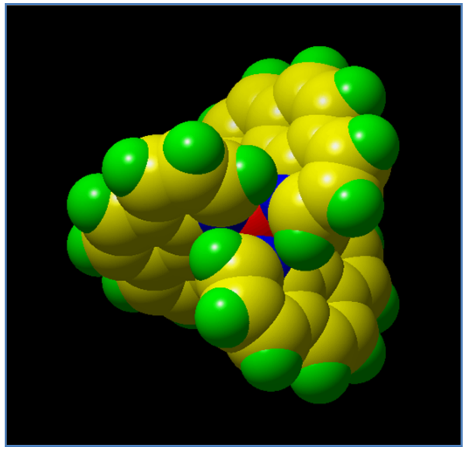
Picosocond X-ray applications at PF-AR

Picosecond photoresponse of perovskite manganite (NSMO) thin film (TR-Diffraction: t~ 50ps ~ 2ns)



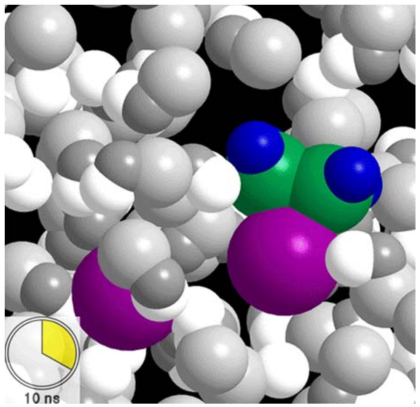
Ichikawa et al. **Nature Materials**, **10**, 101 (2011)

Photo-induced spin-crossover transition of metal complex in solution (TR-XAFS: t ~700ps)

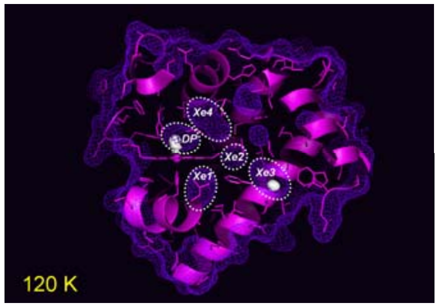


Nozawa *et al.* **J. Am. Chem. Soc., 132**, 61 (2010)

Photochemical reaction in liquid (TR-solution scattering: t~100ps~1ms)

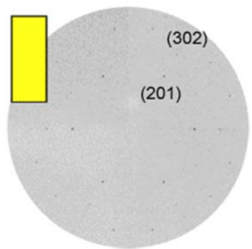


Ligand migration dynamics in protein crystal (TR-protein crystallography: t~800 min)



Tomita et al. **Proc. Natl. Acad. Sci. USA**, **106**, 2612 (2009)

Laser shock-induced lattice deformation of CdS single crystal (TR single-shot Laue diffraction: t~1ns~10ns)



0ns

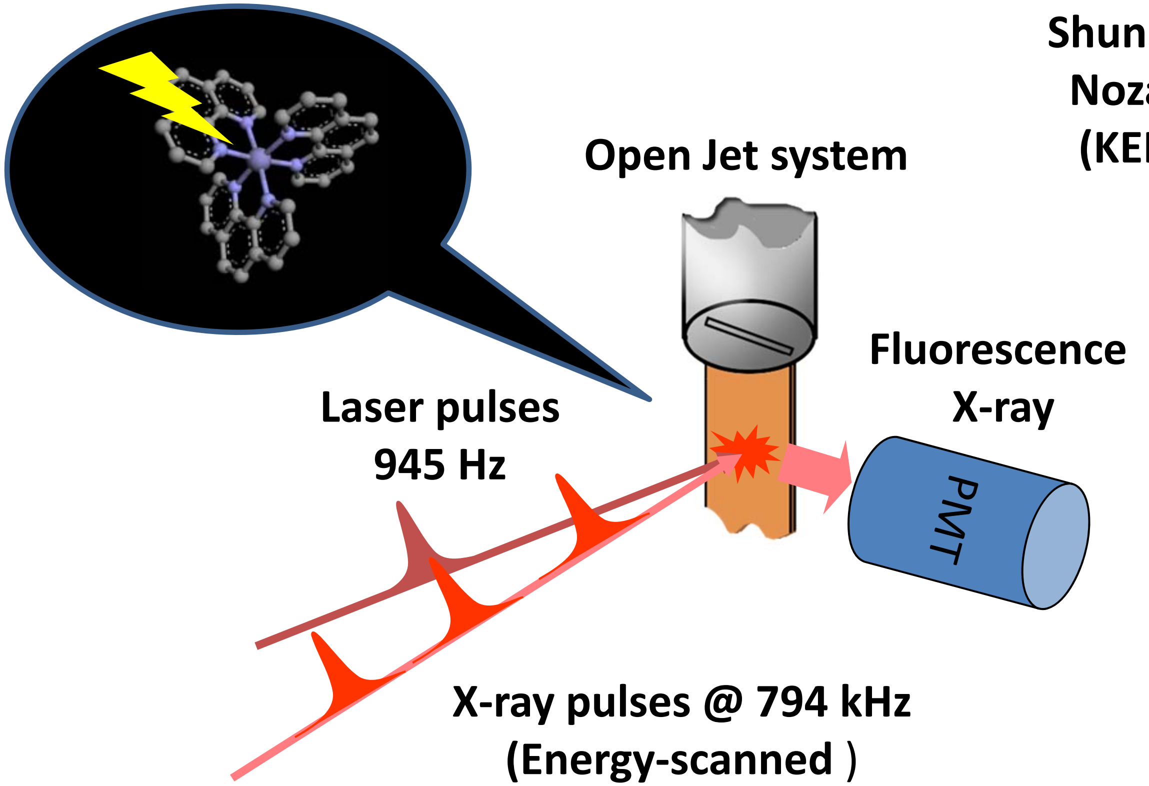
Ichiyanagi et al. **Appl. Phys. Lett. 91**, 231918 (2007)

Nozawa *et al.* **J. Am. Chem. Soc., 132**, 61-63 (2010).

Ultrafast structural dynamics of Fe complex revealed by TR-XAFS

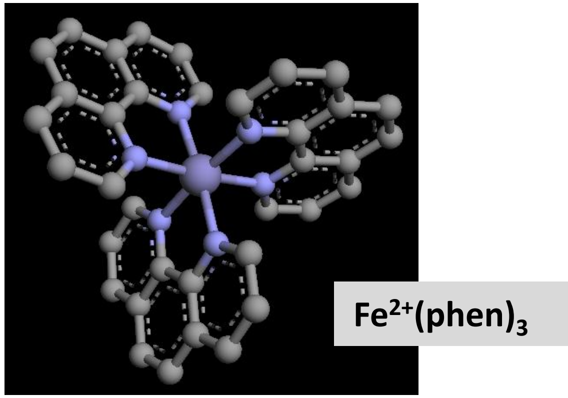
Shunsuke Nozawa (KEK)

Tokushi Sato (KEK)

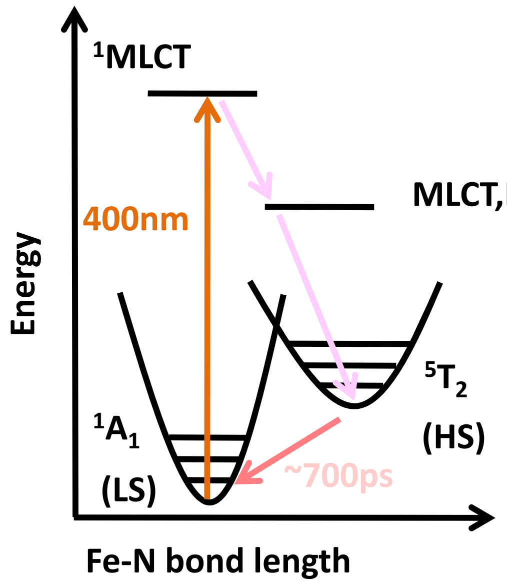


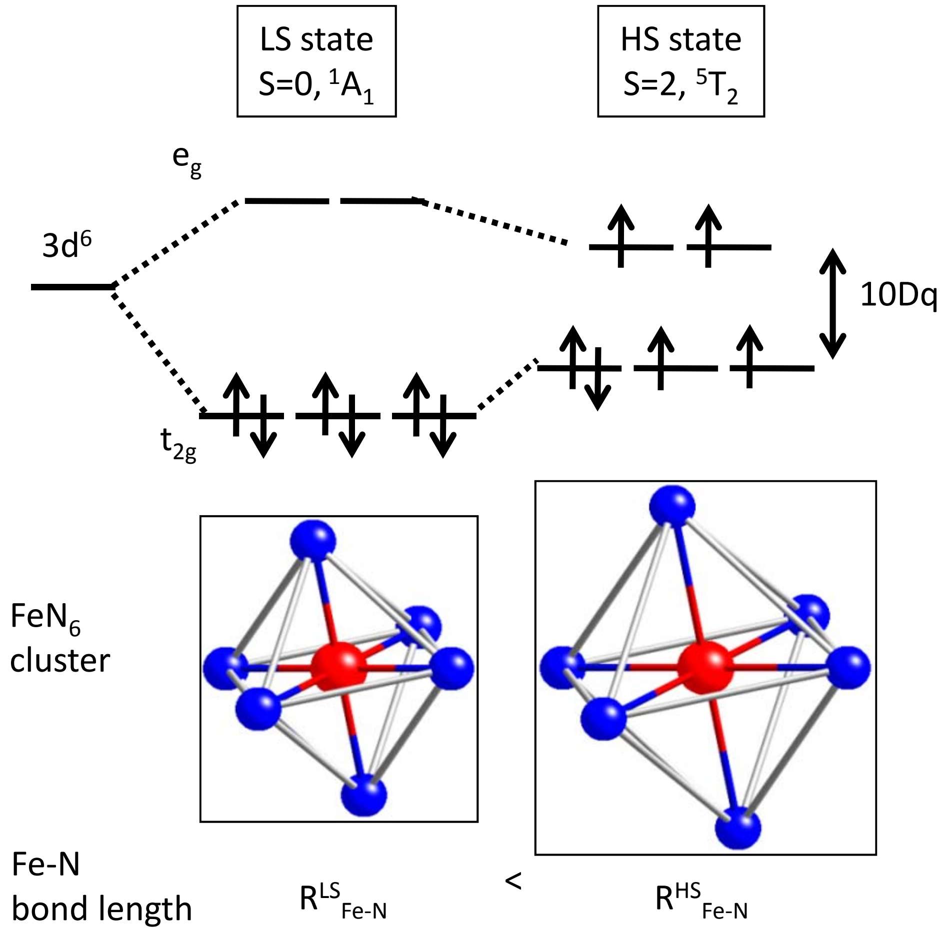
High Energy Accelerator Research Organization (KEK)
Institute of Materials Structure Science (IMSS)
Photon Factory

picosecond spin transition of $Fe^{II}(phen)_3$



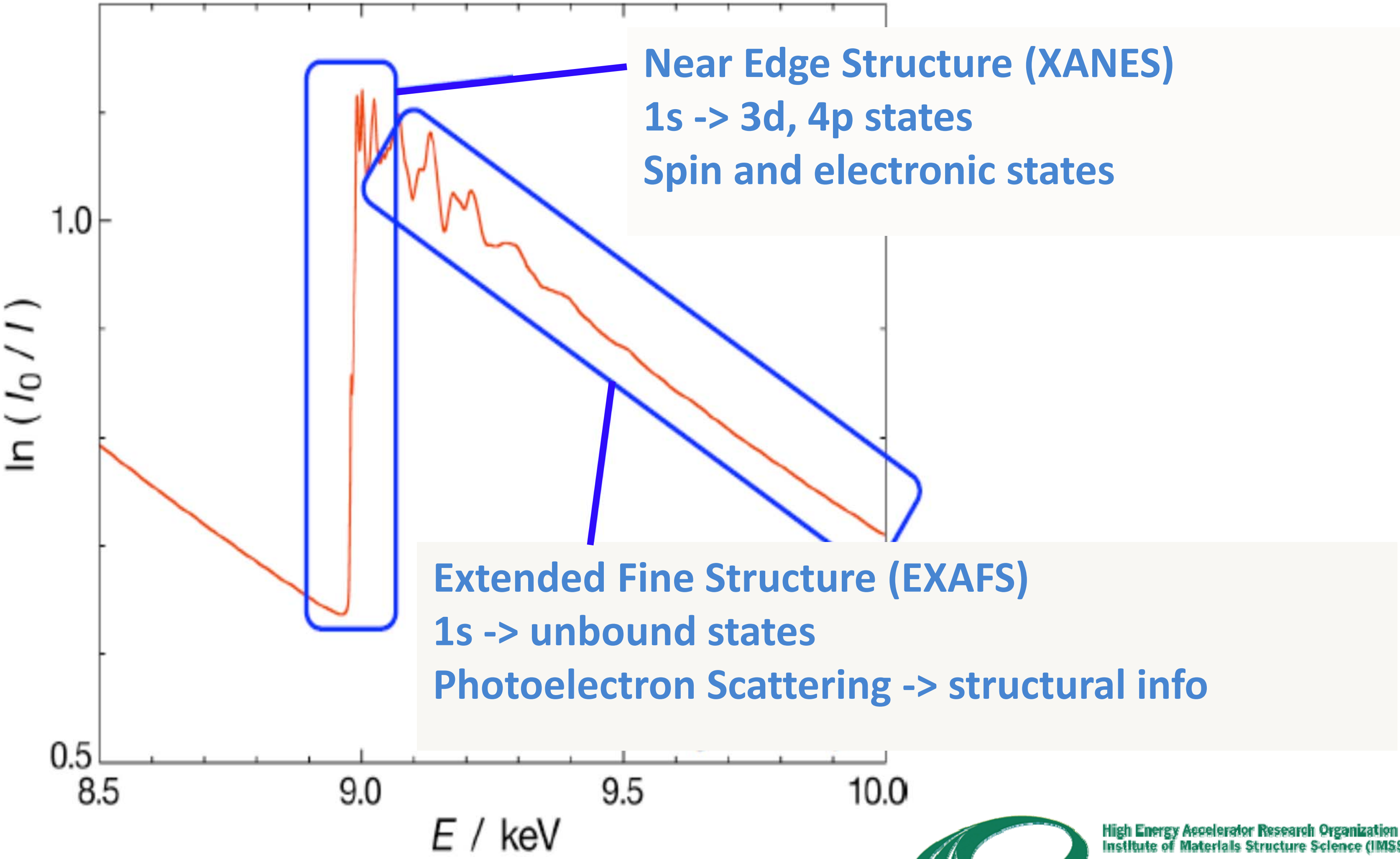
Octahedral FeN_6



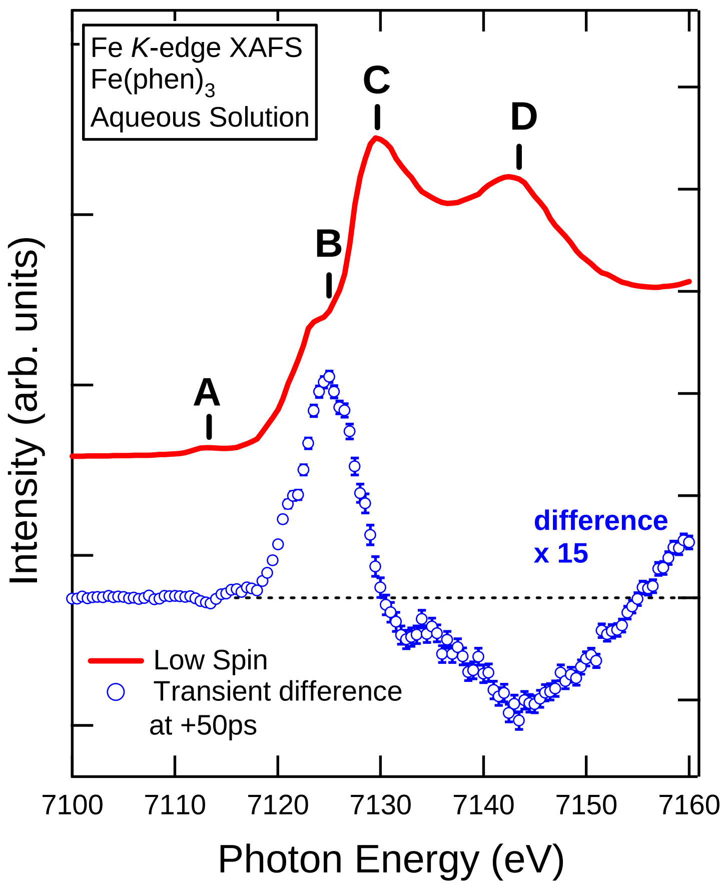


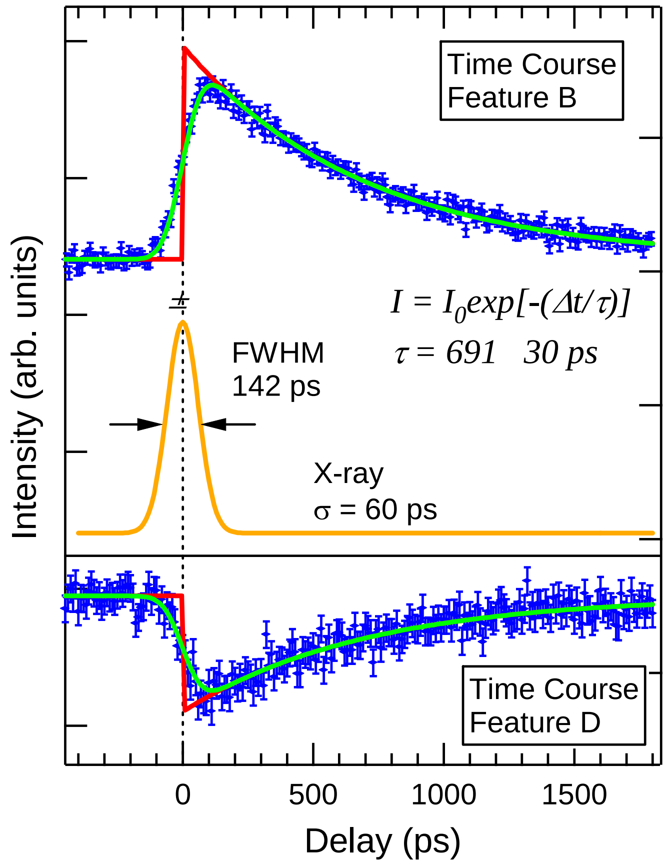
High Energy Accelerator Research Organization (KEK)
Institute of Materials Structure Science (IMSS)
Photon Factory

X-ray Absorption Fine Structure (XAFS)
Cu K-Edge (Cu foil, 5μm thickness)



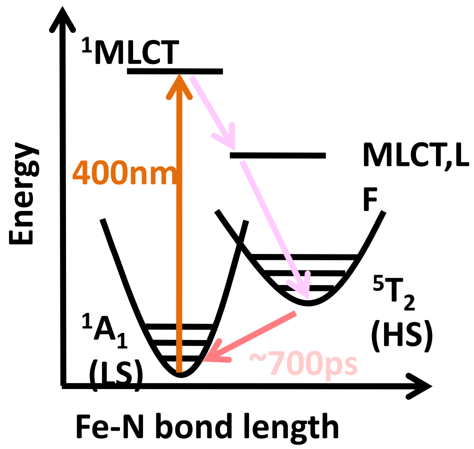
Excite state XANES

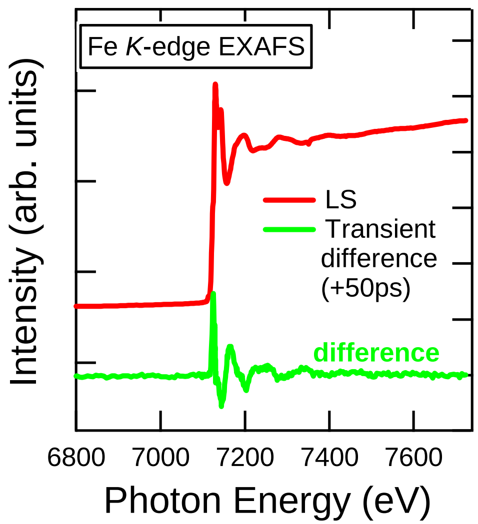


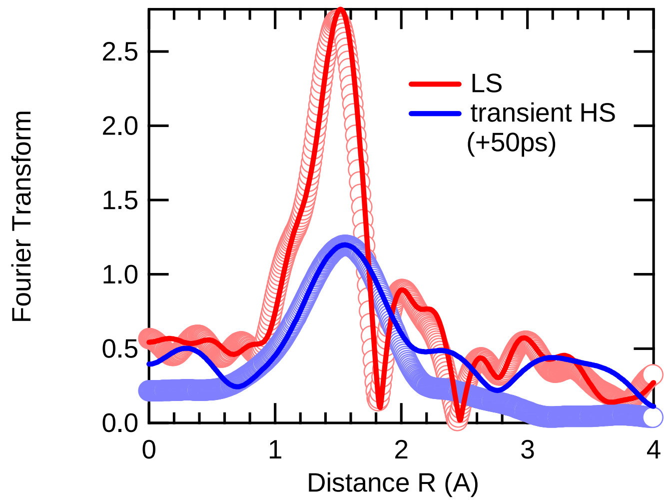


High Energy Accelerator Research Organization (KEK)
Institute of Materials Structure Science (IMSS)
Photon Factory

Excited state EXAFS







EXAFS analysis summary

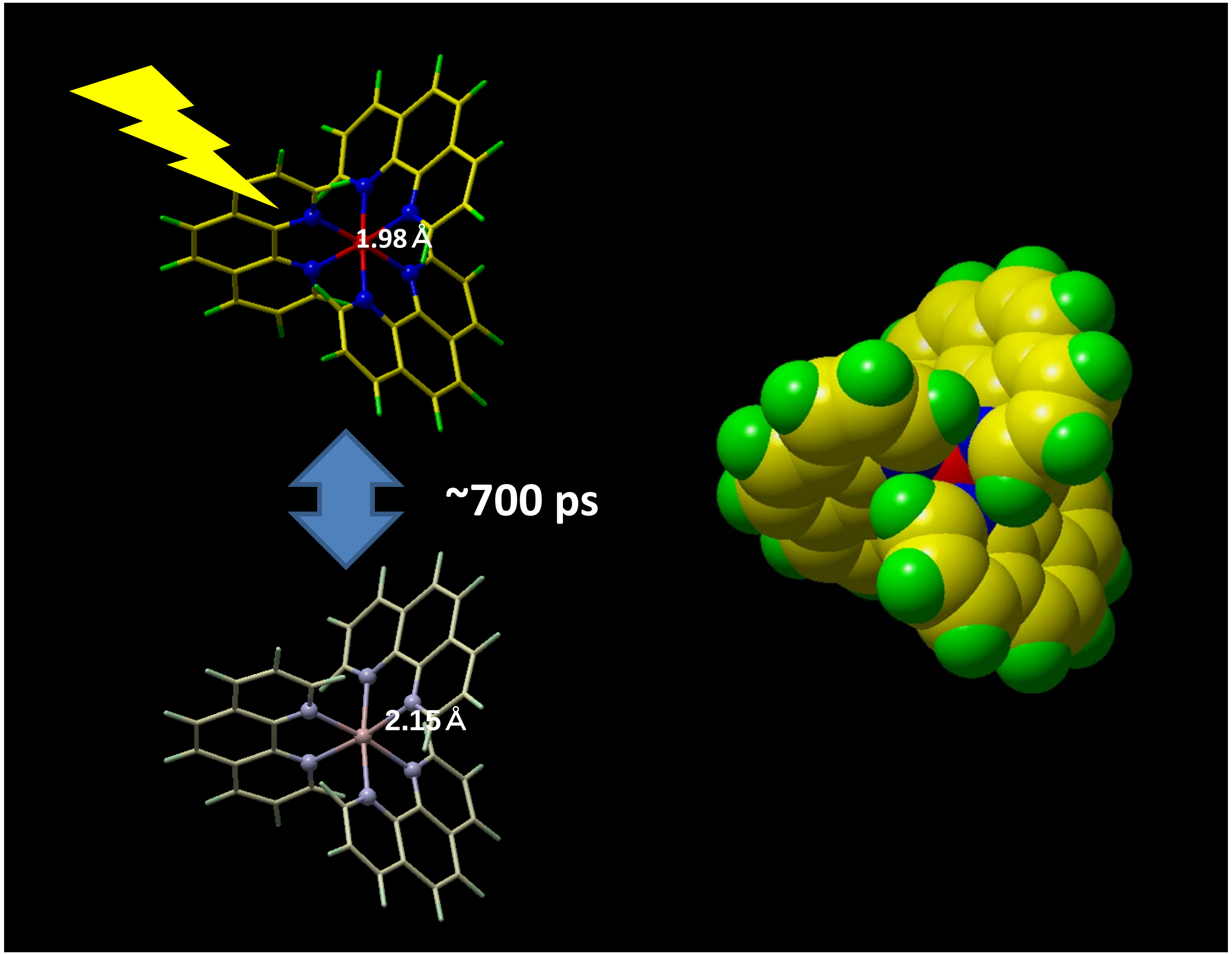
Spectrum	$R_{Fe\text{-}N}$ (Å)	σ^2 (Å^2)
LS	1.98(1)	0.001(1)
Photo-excited HS	2.15(2)	0.011(3)

High Energy Accelerator Research Organization (KEK)
Institute of Materials Structure Science (IMSS)
Photon Factory

Picosecond molecular movie!

Low Spin Ground State ($^1A_1$)

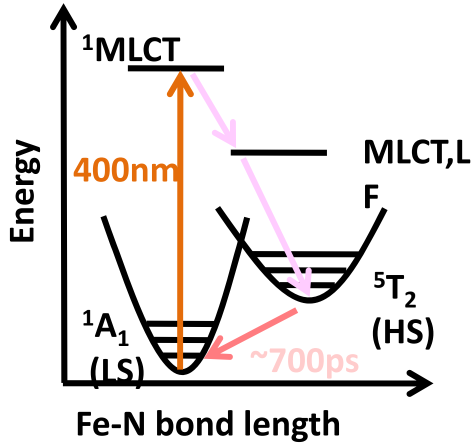
Photo-Excited High Spin State ($^5T_2$)

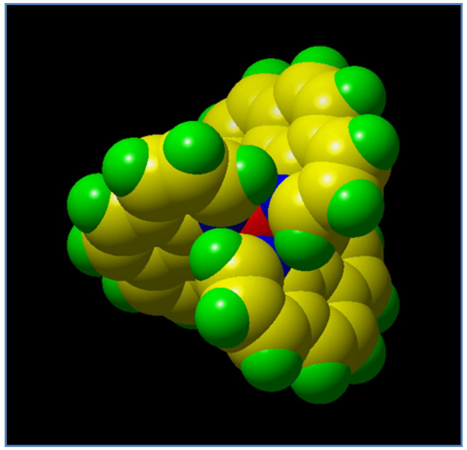


Nozawa *et al.* **J. Am. Chem. Soc., 132**, 61-63 (2010).

High Energy Accelerator Research Organization (KEK)
Institute of Materials Structure Science (IMSS)
Photon Factory

Ultrafast X-ray study @ KEK

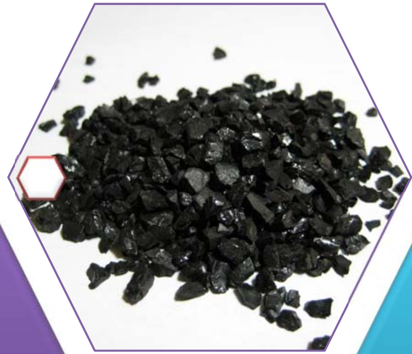




- Ultrafast X-ray study provides dynamic information of **spin, electronic and structural states** of materials

Is ultrafast X-ray also useful to solve problems our society?

Future challenges
ERL for sustainable society



Exhaustion of Fossil fuels

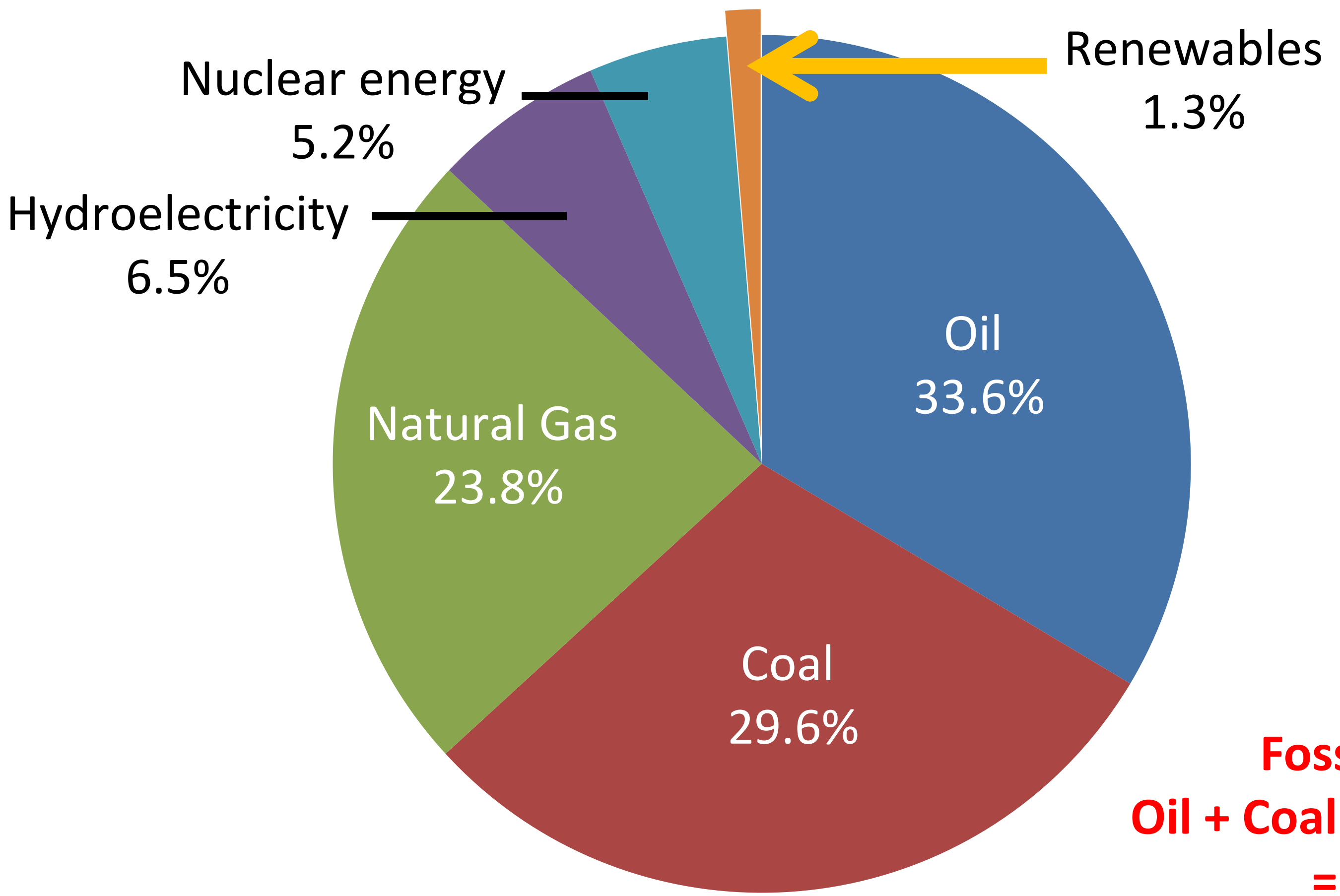
Global heating

Renewable energy source

Safety of Nuclear Energy

High Energy Accelerator Research Organization (KEK)
Institute of Materials Structure Science (IMSS)
Photon Factory

World energy consumption by fuel type in 2010

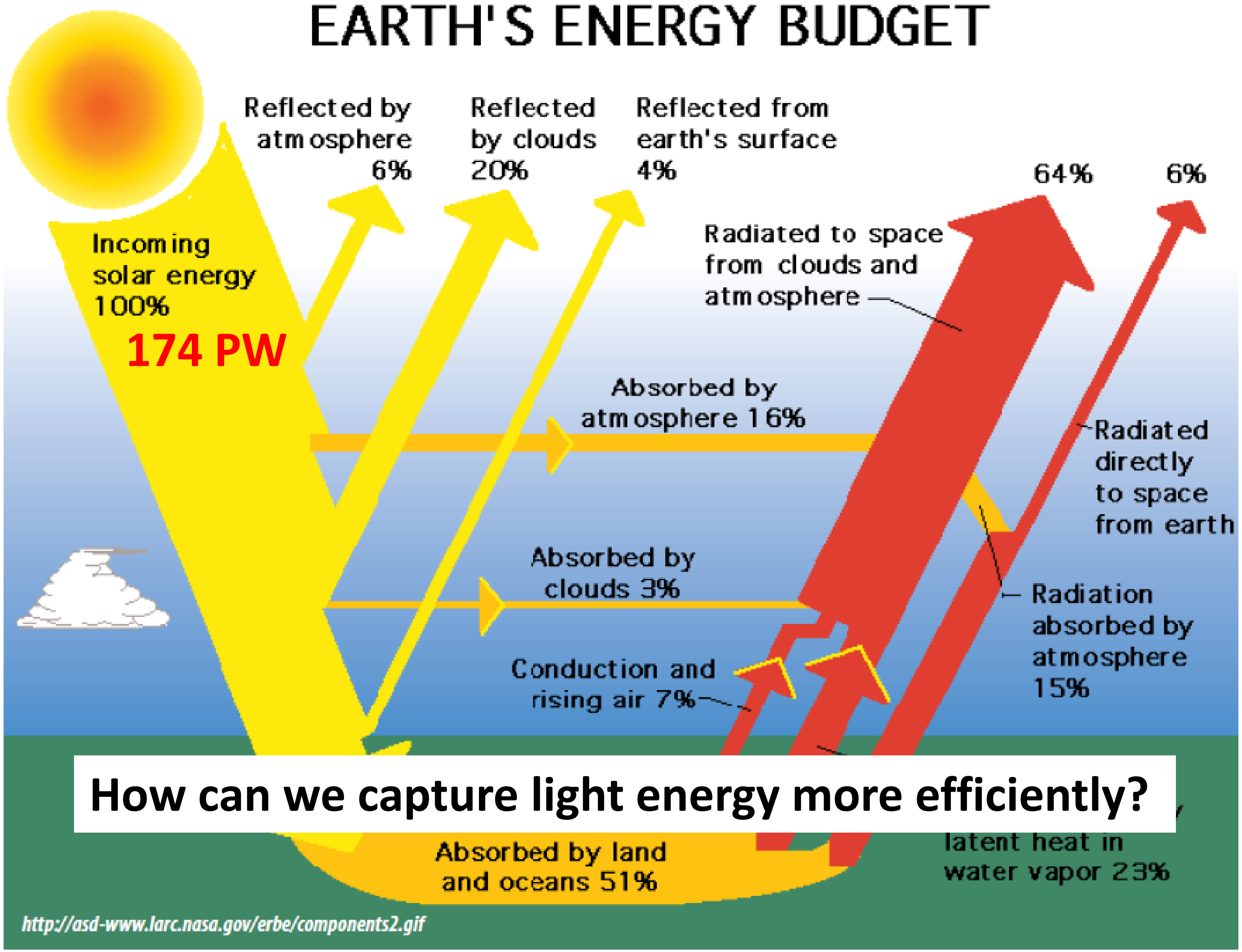


Fossil Fuels
Oil + Coal + Natural gas
= 87 %

BP statistical review of world energy, June 2011
http://www.bp.com/sectionbodycopy.do?categoryId=7500&contentId=7068481

Energy consumption and supply on the earth

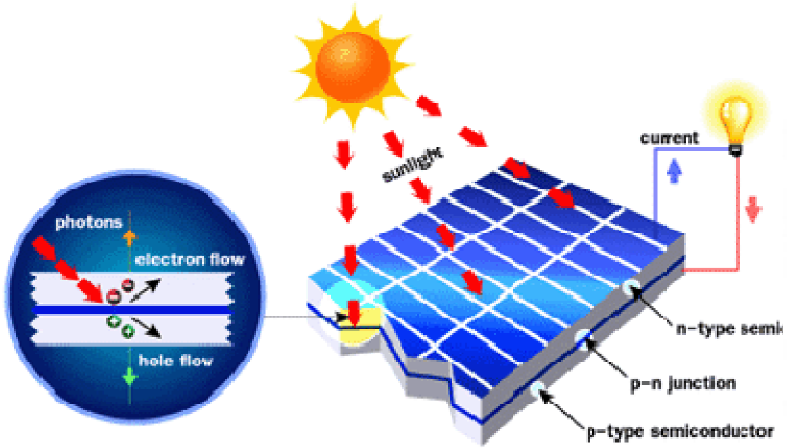
- Incoming solar energy: 5.5×10^{24} (J/year)
- Global energy consumption: 3×10^{20} (J/year)
  - 0.005% (~1 hour) of incoming solar energy
- Global production of photosynthesis: 3×10^{21} (J/year)
  - 0.05% (~10 hours) of incoming solar energy
- Remaining amount of fossil fuels: 9×10^{22} (J)
  - 1.6% of incoming solar energy per year

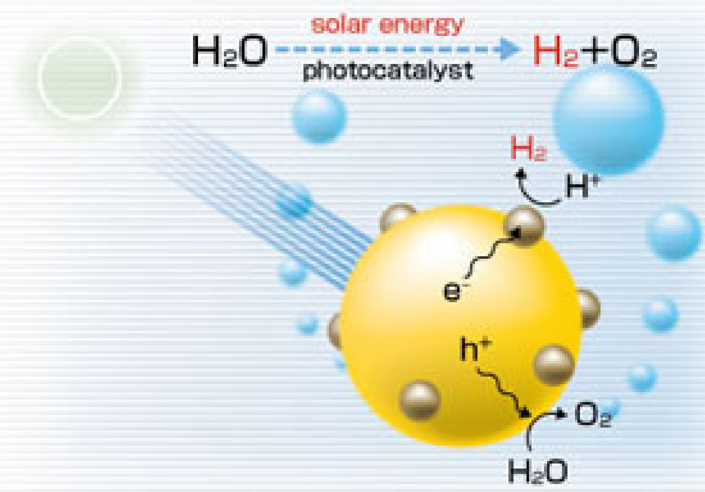


Investigating the Climate System, NASA, June 2003
http://www.nasa.gov/pdf/62319main_ICS_Energy.pdf

High Energy Accelerator Research Organization (KEK)
Institute of Materials Structure Science (IMSS)
Photon Factory

Key players
Solar Cell and Photocatalyst





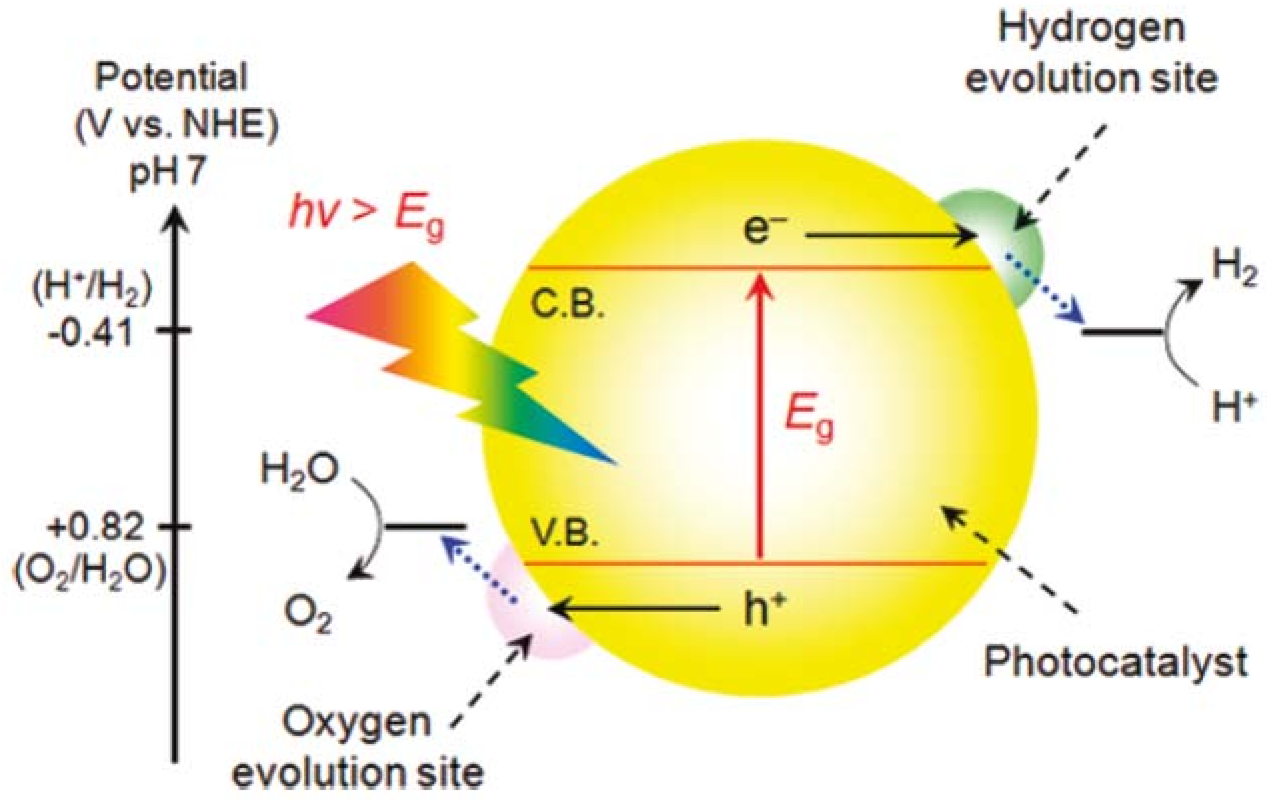
- Converts light energy to electricity
- Large-scale battery is needed for storage
- Quantum efficiency : ~20%

- Converts light energy to chemical energy
- Easily stored as hydrogen or hydrocarbons
- Quantum efficiency: ~5%

High Energy Accelerator Research Organization (KEK)
Institute of Materials Structure Science (IMSS)
Photon Factory

Toward artificial photosynthesis (1)

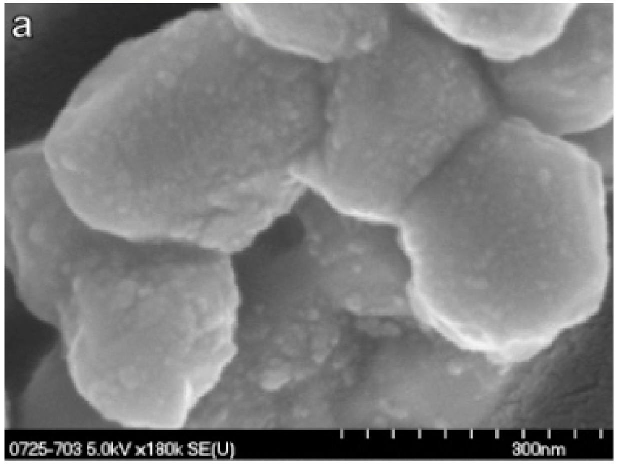
Ultrafast dynamics of photocatalyst



Maeda, K. and Domen K. (2010) *J. Phys. Chem. Lett*. **1**, 2655.

Toward artificial photosynthesis (2)

Hydrogen generation from water by photocatalyst $(Ga_{1-x}Zn_x)(N_{1-x}O_x)$

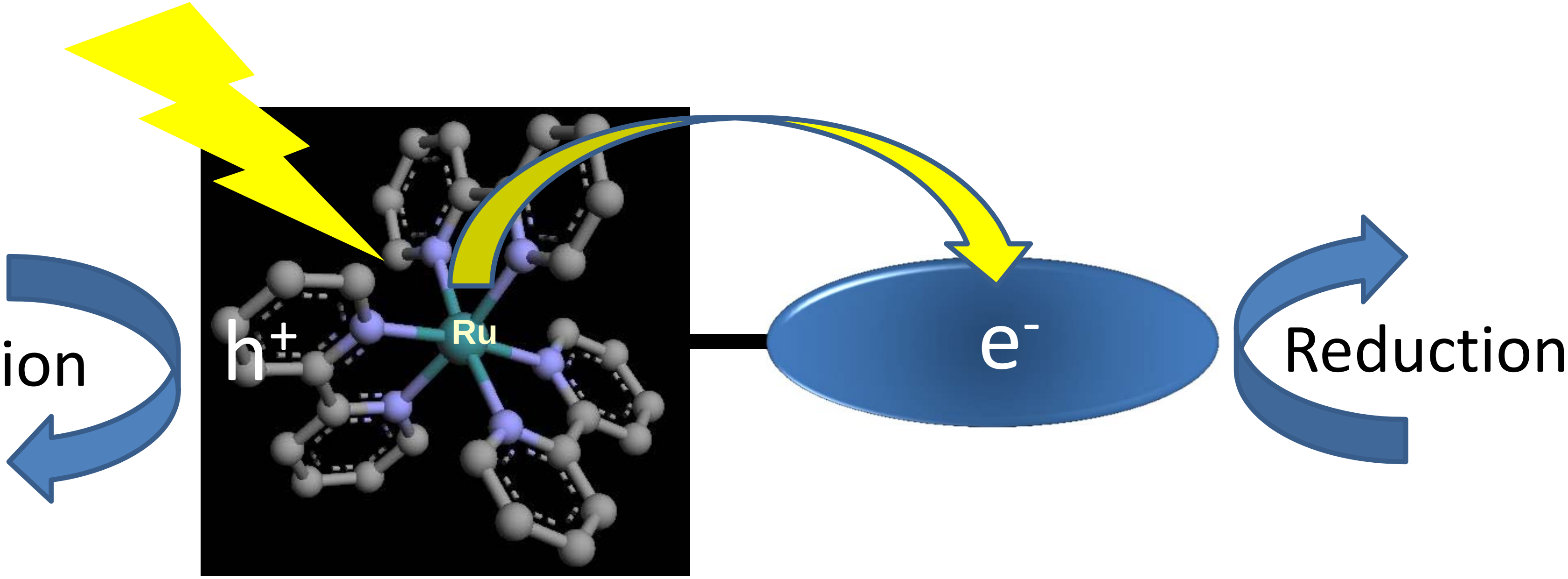


Maeda K. et al. (2006) *Nature* **440**, 295

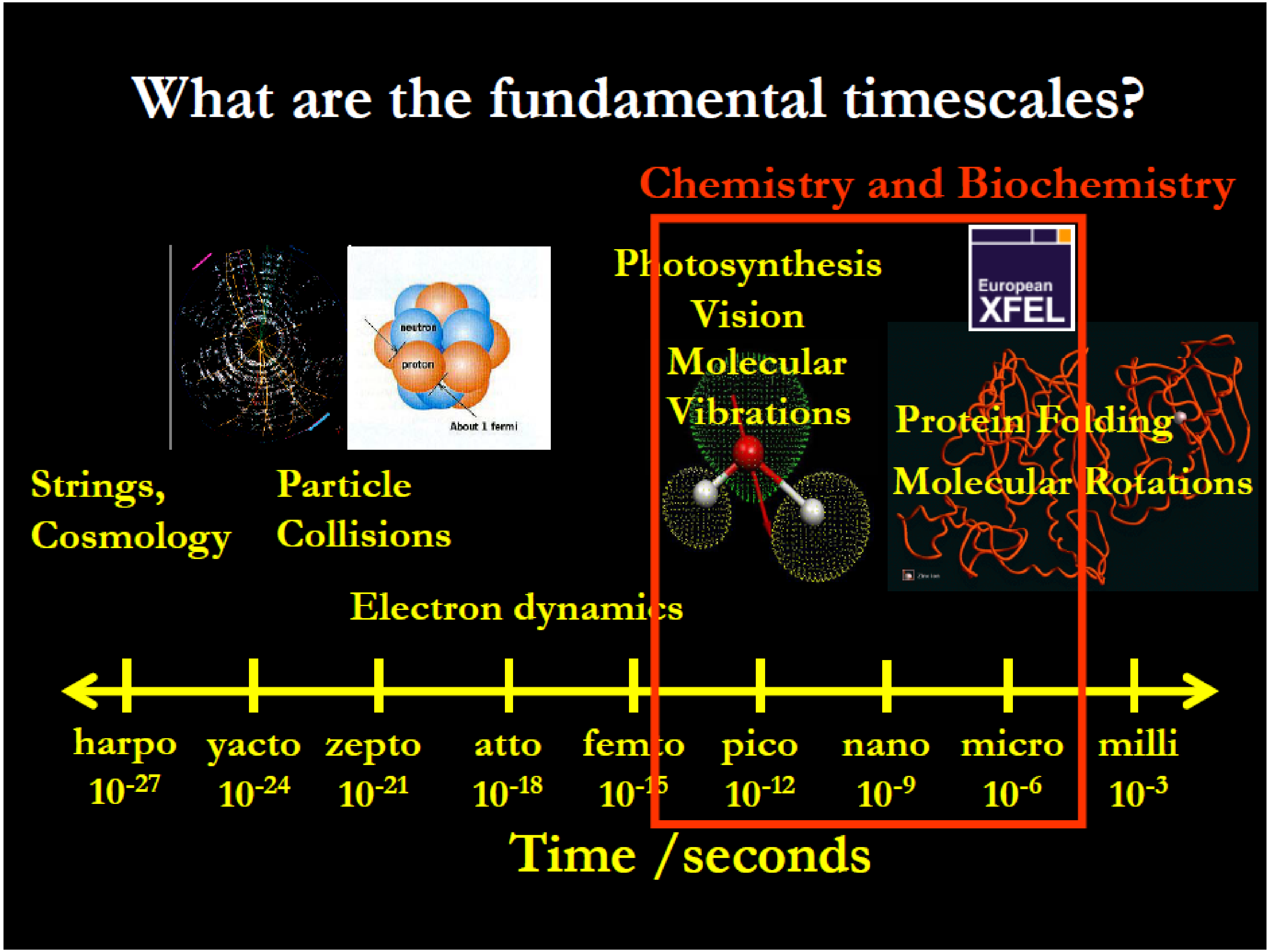
High Energy Accelerator Research Organization (KEK)
Institute of Materials Structure Science (IMSS)
Photon Factory

Toward artificial photosynthesis (3)

Capturing Light Energy by Ruthenium Complex

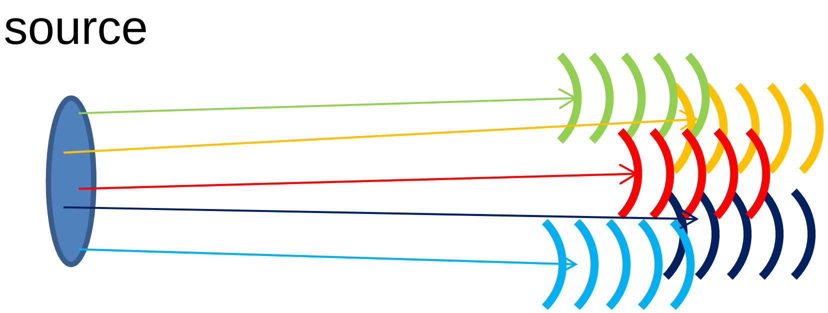


$[Ru(bpy)_3]^{2+}$

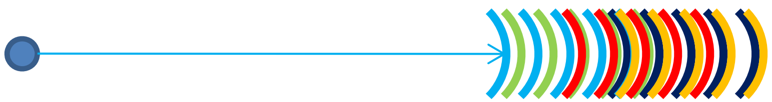


Courtesy of Christian Bressler (European XFEL)

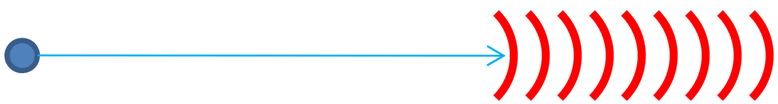
Toward temporal coherence



Case1: 3rd gen. synchrotron sources

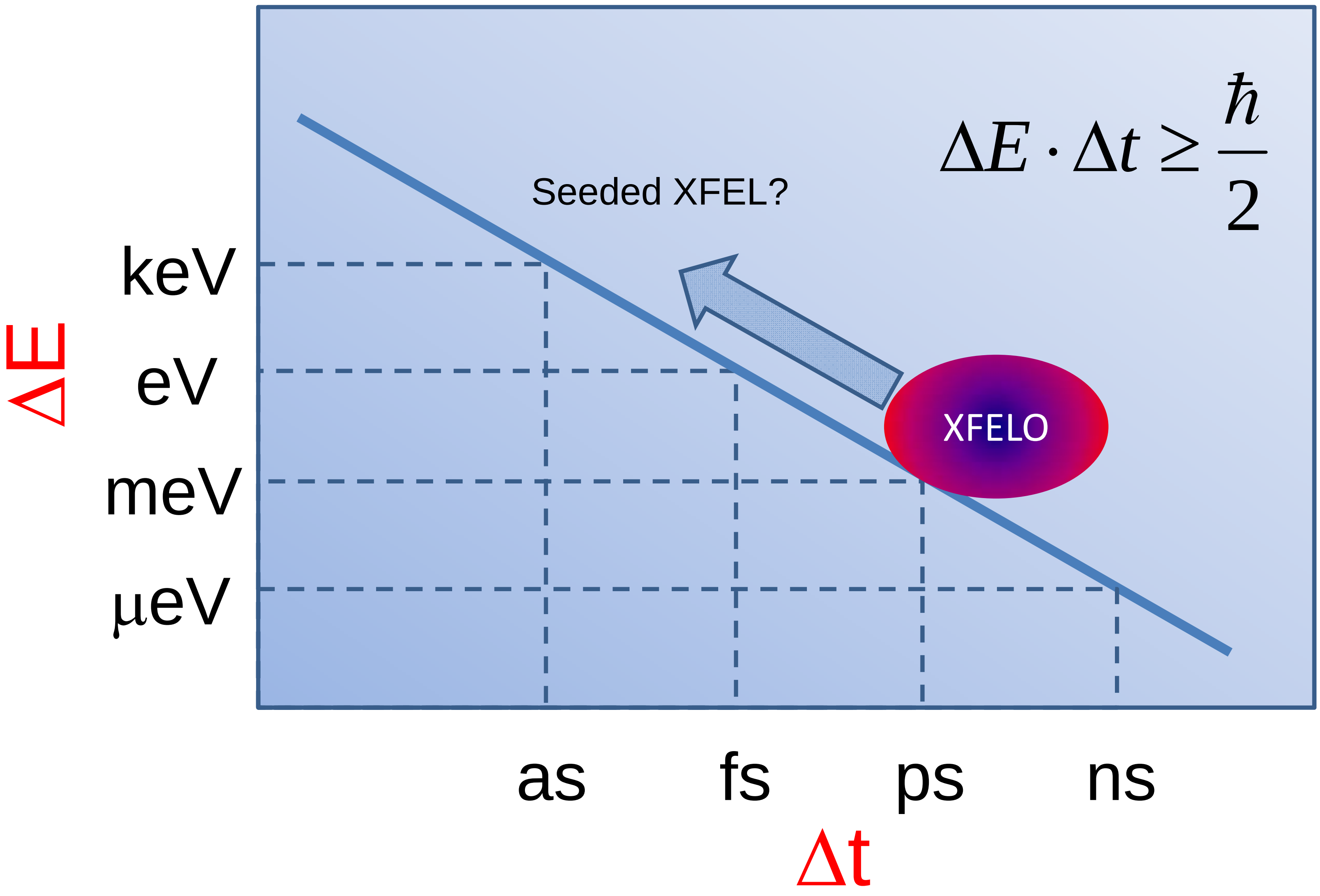


Case2: ERL & SASE-XFEL
(Diffraction limit)



Case3: XFELO & seeded XFEL
(Fourier transform limit)

Fourier-limited X-ray



Ultrafast Science with ERL and XFEL-O

- Sub-picosecond pulse duration
  - Molecular vibration or phonon
  - Electron-phonon coupling: superconductivity
- 1meV energy bandwidth
  - femtosecond time-resolved RIXS, ARPES, EXAFS
- Temporal coherence
  - Nonlinear X-ray optics
  - Two-photon correlation spectroscopy
  - Transient grating

High Energy Accelerator Research Organization (KEK)
Institute of Materials Structure Science (IMSS)
Photon Factory

Summary (1)

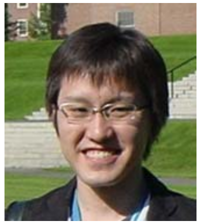
- Ultrafast X-ray study provides dynamic information of **spin, electronic and structural states** of materials
- Powerful tool for **artificial photosynthesis** studies
- Picosecond is not enough. Femtosecond and temporal coherence opens new field.
- **Hopefully, few femtoseconds to attosecond** is needed to capture electronic dynamics
- High rep rate is critically important for pump-probe experiment

High Energy Accelerator Research Organization (KEK)
Institute of Materials Structure Science (IMSS)
Photon Factory

Summary (2)
(by Chi-Chang Kao @ XDL2011, WS3)

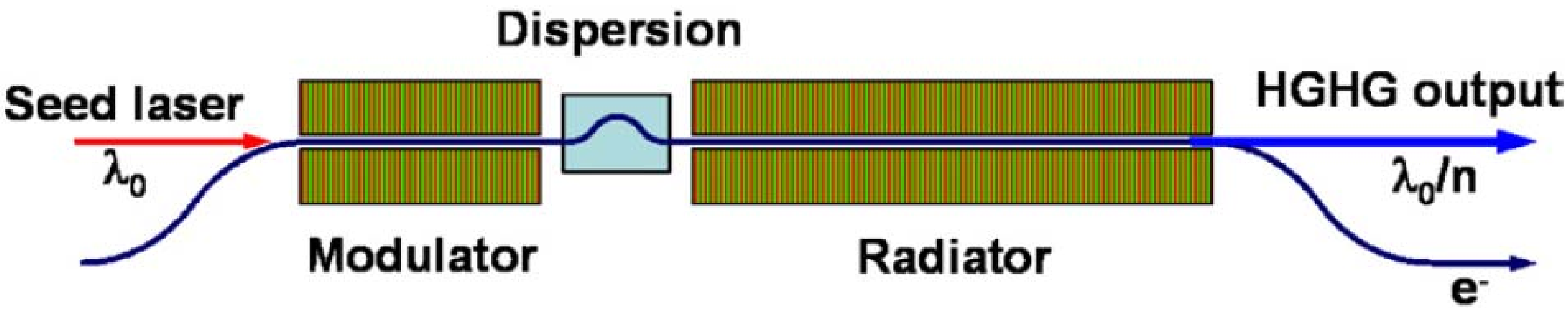
- In order to realize future light source,
  - Identify problems that can capture the imagination of many
  - Organize the community to develop the scientific case, the necessary tools
  - Work with accelerator community to support the R&D effort

members @ Beam Line NW14A, KEK

Shunsuke Nozawa (KEK)		Tokushi Sato (KEK)	
Manabu Hoshino (TITECH, KEK)		Ayana Tomita (KEK)	
Matthieu Chollet (→LCLS)		Laurent Guérin (→Univ. Rennes 1)	
Kouhei Ichiyanagi (→Univ. Tokyo)		Shin-ya Koshihara (TITECH)	

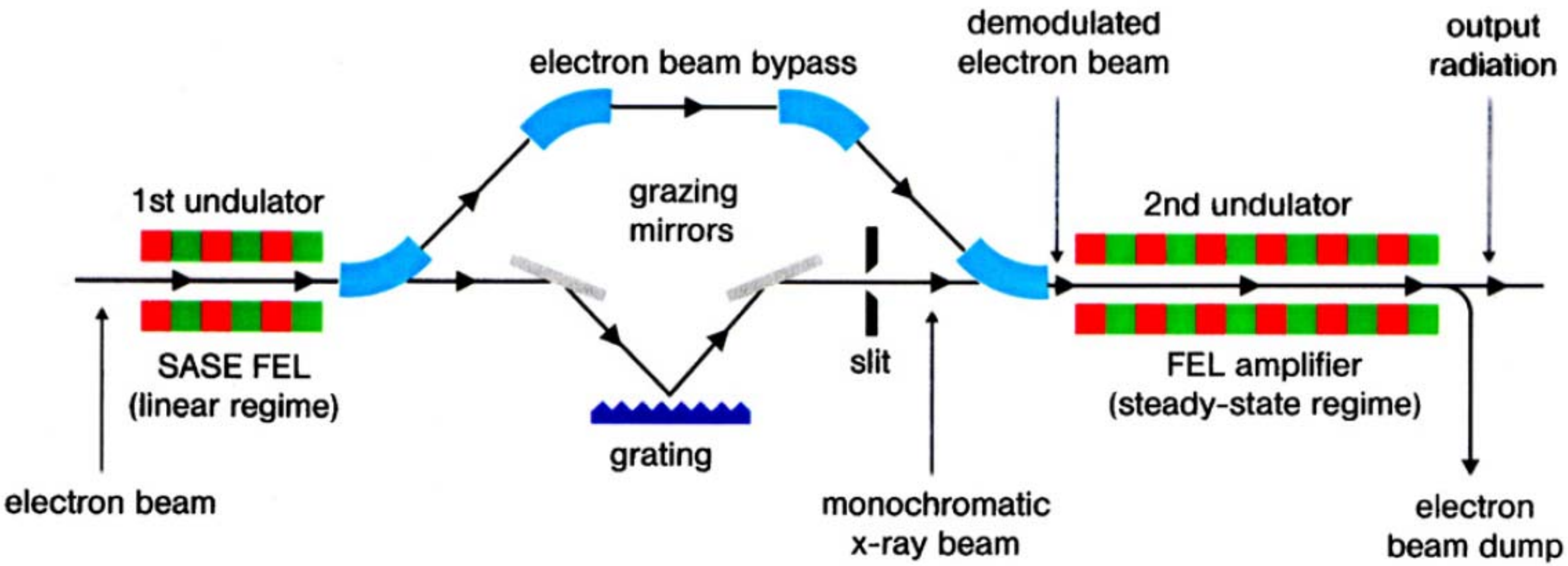
Thank you!

Fully coherent sources
(1) High-Gain Harmonic Generation (HGHG)



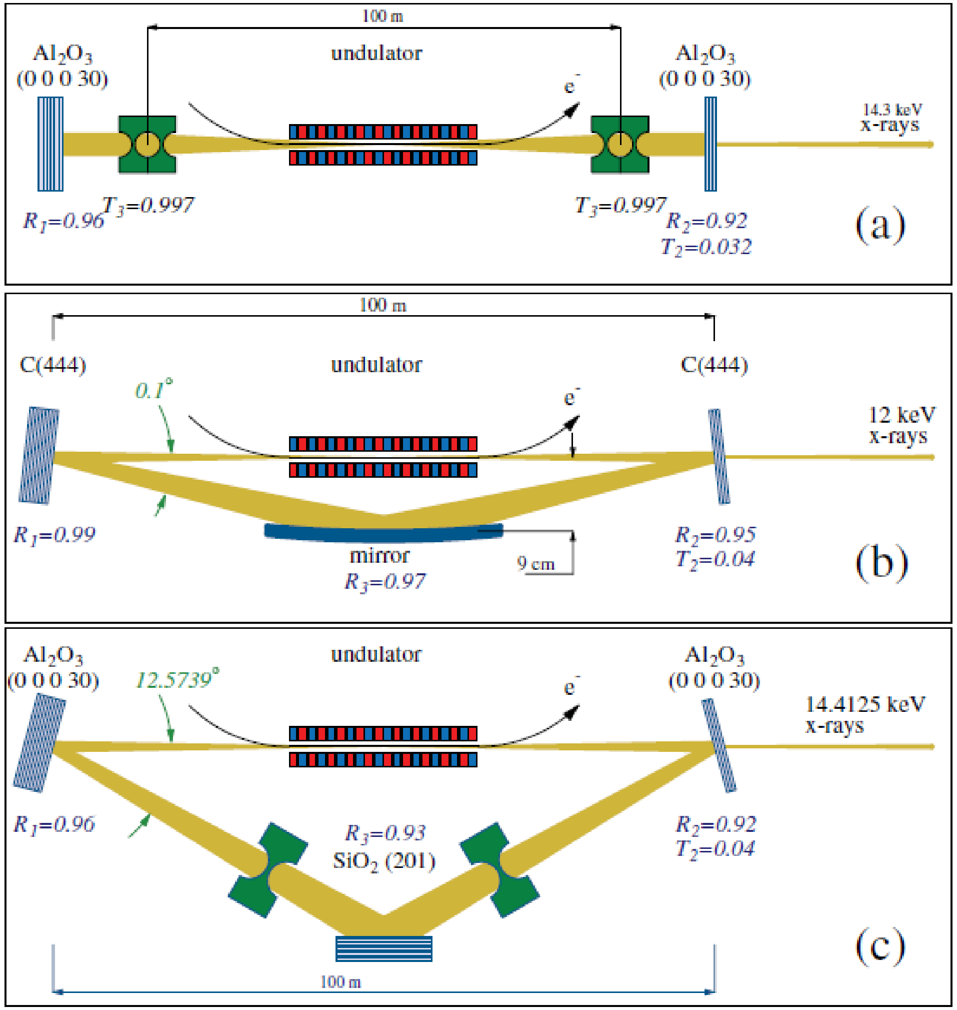
L.-H. Yu *et al, Science* **289** 932–4 (2000).
L.-H. Yu *et al, Phys. Rev. Lett.* **91** 074801 (2003).
T. Togashi *et al, Opt. Exp*. **19**, 317 (2011).

(2) Self-seeded FEL



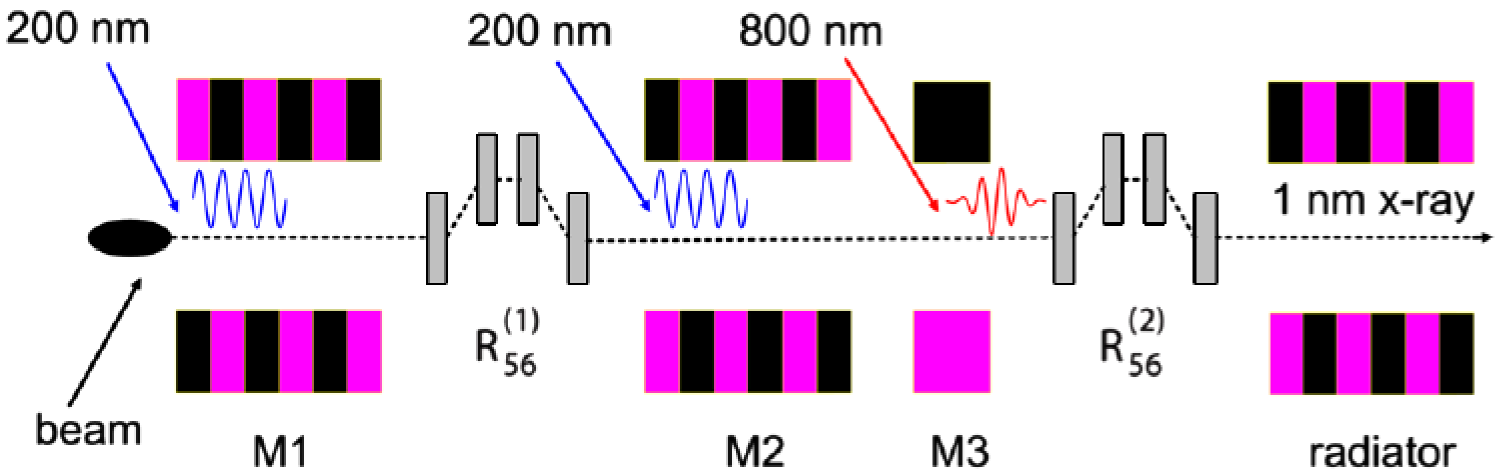
Saldin E L, Schneidmiller E A and Yurkov M V,
Nucl. Instrum. Methods A **445** 178–82 (2000)

(3) XFEL Oscillator



K.-J. Kim, Y. Shvyd'ko, and S. Reiche, PRL **100,** 244802 (2008)

(4) Echo-Enabled Harmonic Generation (EEHG)



Electron beam energy: 3 GeV
Peak current: 1 kA
Normalized emittance: 1 mm mrad
Slice energy spread: 150 keV
Undulator period length in M1 and M2: 25 cm
Number of undulator periods in M1 and M2: 6
Undulator period length in M3: 20 cm
Number of undulator periods in M3: 2

D. Xiang, Z. Huang, and G. Stupakov, Phys. Rev. ST Accel. Beams 12, 060701 (2009)