3rd AOFSRR School: Cheiron School 2009 (Nov. 2-11, 2009)
Spring-8/RIKEN Harima, Hyogo, Japan

Overview of Synchrotron Radiation (SR)

Moonhor Ree

Director, Pohang Accelerator Laboratory (PAL)
Professor, Chemistry Department & Polymer Research Institute
Pohang University of Science & Technology
Pohang 790-784, Korea
Tel: +82-54-279-1001, 2120
Fax: +82-54-279-0999, 3399
E-mail: ree@postech.edu
http://pal.postech.ac.kr
http://www.postech/ac.kr/chem/mree

PAL 포항가속기연구소 POHANG ACCELERATOR LABORATORY

Acknowledgments :

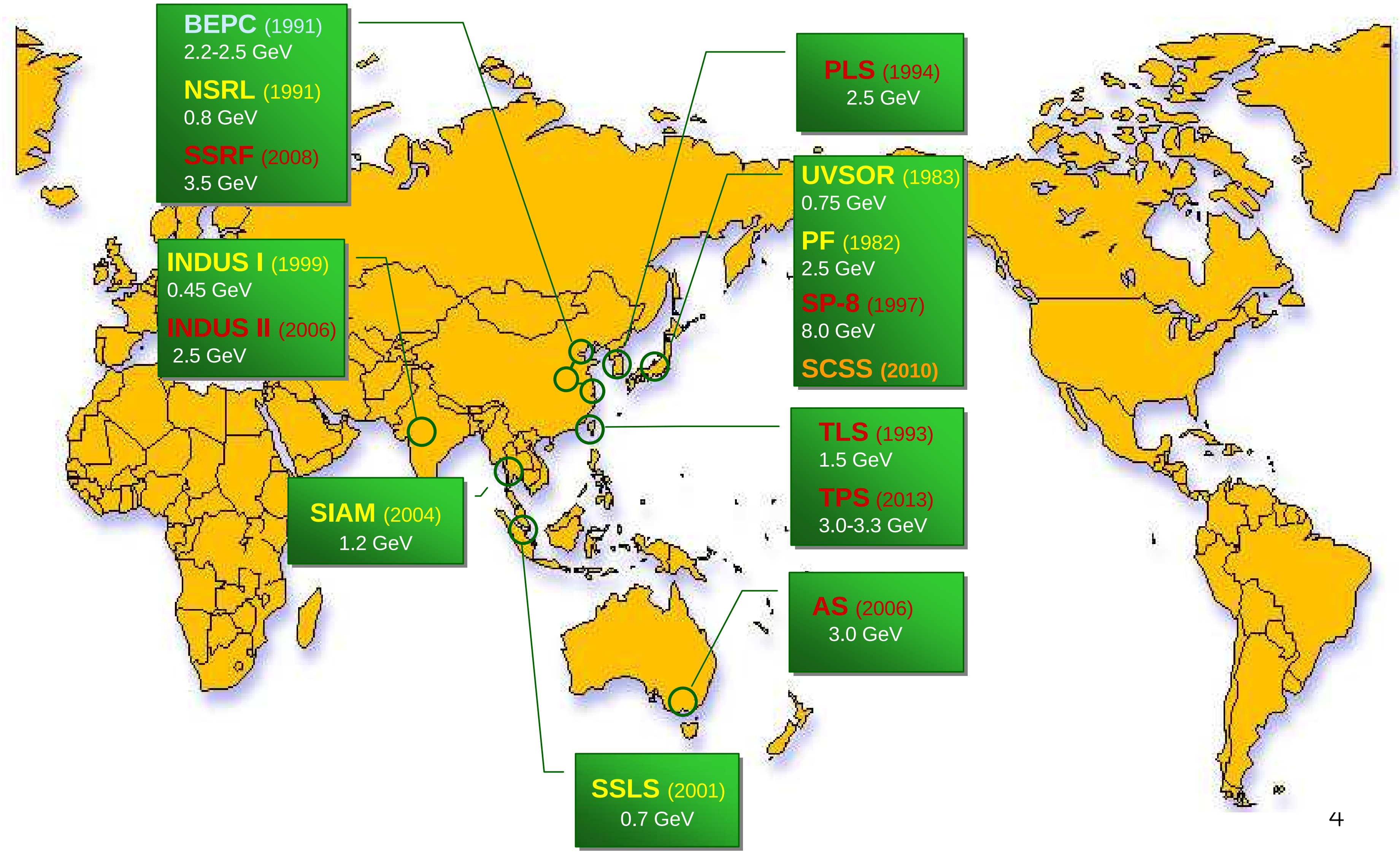
Organizing Committee Members of Cheiron School
Spring-8/JASRI; *Dr. Tetsuhisa Shirakwa*, President
RIKEN Harima Institute
MEXT, Japan; Director *Hiroki Takaya*
AOFSRR

Prof. Keng Liang (NSRRC, Taiwan)
Prof. Zhentang Zhao (SSRF, China)
Prof. Tetsuya Ishikawa (RIKEN/Spring-8, Japan)
Prof. Masaki Takata (RIKEN/Spring-8/U Tokyo, Japan)
ProfProf. Osamu Shimomura (KEK, Japan)
Prof. Hiroshi Kawata (KEK, Japan)
Prof. Won Namkung (PAL, Korea)
Prof. In-Soo Ko (PAL, Korea)

Outline

1. Introduction
   - History of SR
   - SR
2. 1^{st}-2^{nd} Generation SR
3. 3^{rd} Generation SR
   - Current Status of 3^{rd} Generation SR Facilities
   - Applications in Science &Technology
4. 4^{th} Generation SR
   - Current Status of 4^{th} Generation SR Facilities
   - Applications in Science &Technology
5. Summary & Conclusions
6. Acknowledgments

Synchrotron Radiation Facilities in Asia-Oceania



AOFSRR

(Asia–Oceania Forum for Synchrotron Radiation Research)

Objectives:

(1) To establish a general framework of collaboration for the development of science and technology, which mutually benefits advancing the research goals of the Parties

(2) To promote comprehensive cooperation in the Asia Oceania region

(3) To provide education and communication opportunities

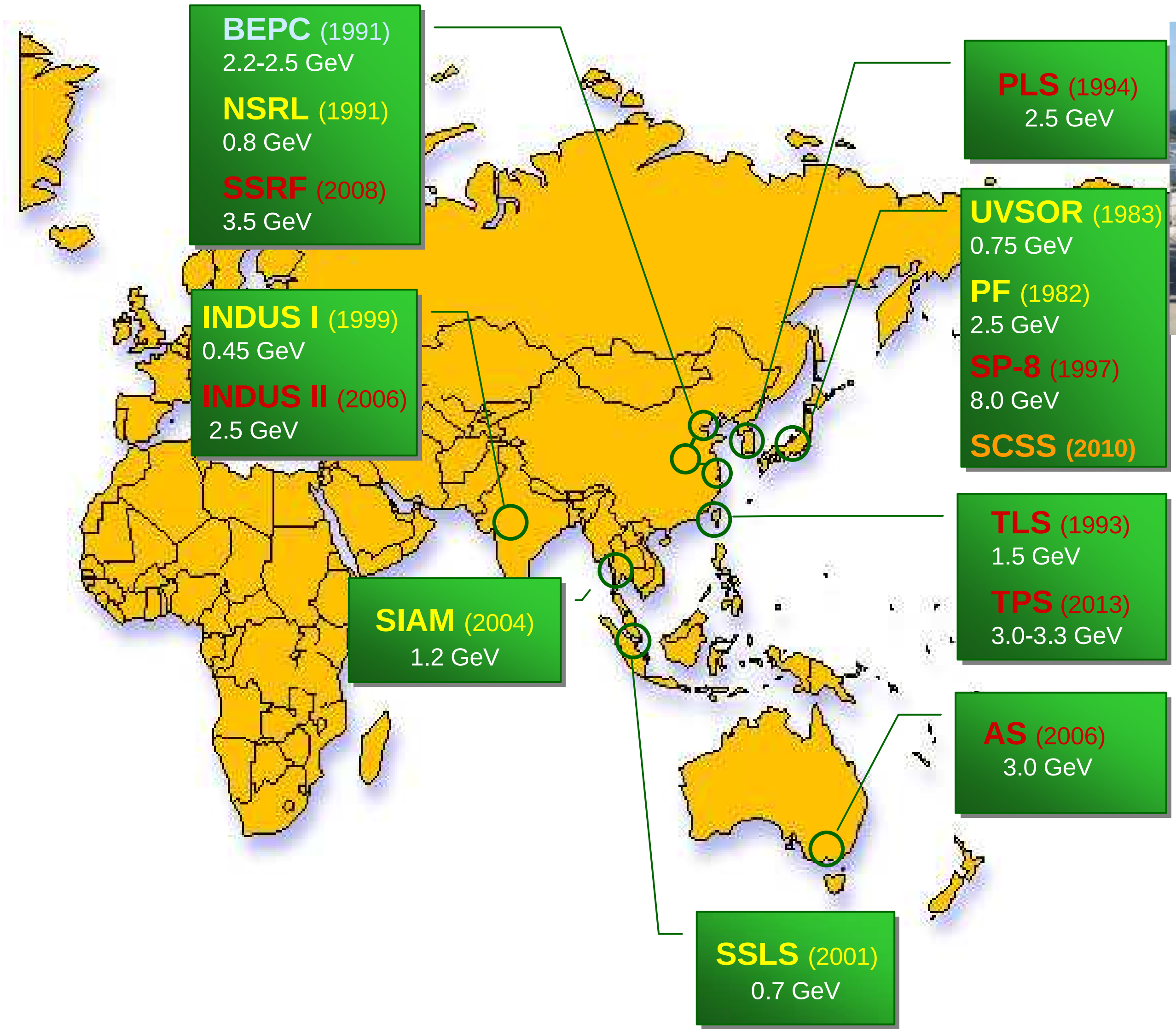
- AOFSRR Conference (per year)

1st, 24-25/11/2006, Tsukuba, Japan
2nd , 31/10-02/11/2007, Shinchu, Taiwan
3rd, 4-5/12/2008, Melbourne, Australia
4th, 31/11-02/12/2009/Shanghai, China
5th, 2010/Pohang, Korea ……..

- Cheiron Summer School

1st, 10-19/09/2007, SPring-8, Japan
2nd, 29/09-08/10/2008, Spring-8
3rd, 02-11/11/2009, Spring-8 …..

Asia-Oceania Forum for SR Research



Dec. 4-5, 2008 @Melbourne

Local Organizing Member – Cheiron School

Masaki Takata (RIKEN/SPring-8)
Masayo Suzuki (JASRI/SPring-8)
Kouki Sorimachi (RIKEN/SPring-8)
Hiroaki Kimura (JASRI/SPring-8)
Haruo Ohkuma (JASRI/SPring-8)
Ryotaro Tanaka (JASRI/SPring-8)
Naoto Yagi (JASRI/SPring-8)
Yoshiharu Sakurai (JASRI/SPring-8)
Shunji Goto (JASRI/SPring-8)

Committee

Principal: Keng Liang (President of AOFSRR, NSRRC/Taiwan)
Vice Principal: Moonhor Ree (Vice President of AOFSRR, PAL/Korea)
Secretary: Masaki Takata (RIKEN/JASRI/SPring-8, Japan)

AOFSRR

Council Member

Keng Liang (NSRRC/Taiwan)
Moonhor Ree (PAL/Korea)
Masaki Takata (RIKEN-JASRI-Spring8/Japan)
Yoshiyuki Amemiya (Univ. of Tokyo/Japan)
Robert Lamb (Australia Synchrotron/Australia)
Herbert O. Moser (SSLS/Singapore)
Masaharu Oshima (President of JSSRR, Univ. of Tokyo/Japan)
Weerapong Pairsuwan (NSRC/Thailand)
V. C. Sahni (INDUS/India)
Hongjie Xu (SSRF/China)
Osamu Shimomura (KEK/Japan)
Richard Garrett (ANSTO/Australia)

International Advisory Board

Tetsuya Ishikawa (RIKEN/Japan)
Hideo Ohno (JASRI/Japan)
J. Murray Gibson (APS/USA)
W. G. "Bill" Stirling (ESRF/France)
Gerhard Materlik (Diamond/UK)
Nobuhiro Kosugi (IMS/Japan)
Shih-Lin Chang (NTHU/Taiwan)

The 3rd AOFSRR School

Cheiron School 2009

SPring-8, Japan — November 2nd (Mon.) - 11th (Wed.) — Organizer: AOFSRR, RIKEN, JASRI, KEK

Time	Nov.2 Mon.
9:00 - 10:00	Registration
10:00 - 10:20	Opening Remarks **K. Liang** (NSRRC) **T. Shirakawa** (JASRI)
10:20 - 11:40	Overview of SR **M. Ree** (PAL/PLS)
11:40 - 12:40	*Lunch*
12:40 - 14:00	Ring Accelerator Physics **H. Tanaka** (RIKEN)
14:00 - 14:20	*Coffee Break*
14:20 - 15:40	Light Source 1 **T. Tanaka** (RIKEN)
15:40 - 16:00	*Coffee Break*
16:00 - 17:00	**Safety Education**
17:00 - 18:00	**Self introduction of participants**
18:00 - 19:30	**Welcome Reception**

Time	Nov.3 Tue.
9:00 - 10:20	Light Source 2 **T. Tanaka** (RIKEN)
10:20 - 10:40	*Coffee Break*
10:40 - 12:00	X-ray physics **Als-Nielsen** (Copenhagen Univ)
12:00 - 13:00	*Lunch*
13:00 - 14:20	VUV & SX Optics **K. Amemiya** (KEK-PF)
14:20 - 14:40	*Coffee Break*
14:40 - 16:00	VUV & SX Beamline Design **K. Amemiya** (KEK-PF)
16:00 - 16:20	*Coffee Break*
16:20 - 17:20	X-ray Beamline Design **S. Goto** (JASRI)
17:20 - 18:30	*Dinner*
18:30 - 20:30	**Site Tour SPring-8**

Time	Nov.4 Wed.
9:00 - 10:20	X-ray monochromator **T. Matsushita** (KEK-PF)
10:20 - 10:40	*Coffee Break*
10:40 - 12:00	XFEL **T. Shintake** (RIKEN)
12:00 - 13:00	*Lunch*
	Site Tour XFEL
13:00 - 20:30	**Excursion Himeji**

Time	Nov.5 Thu.
9:00 - 10:20	Mirror and multilayer **T. Matsushita** (KEK-PF)
10:20 - 10:40	*Coffee Break*
10:40 - 12:00	Diffraction and Scattering **S. Sasaki** (Tokyo Inst. Univ)
12:00 - 13:00	*Lunch*
13:00 - 14:20	Single Crystal Diffraction/Charge Density Study **F. K. Larsen** (Aarhus Univ)
14:20 - 14:30	*Coffee Break*
14:30 - 15:30	Future of SR **T. Ishikawa** (RIKEN)
15:30 - 17:00	"Meet the experts" Part 1
17:00 - 19:30	*Dinner*

Time	Nov.6 Fri.
9:00 - 10:20	Detectors **R. Lewis** (Monash Univ.)
10:20 - 10:40	*Coffee Break*
10:40 - 12:00	EXAFS **I. Watanabe** (Ritsumeikan Univ.)
12:00 - 13:00	*Lunch*
13:00 - 14:20	SX & X Microscopy **Y. Kagoshima** (Univ. of Hyogo)
14:20 - 14:30	*Coffee Break*
14:30 - 15:50	Medical Imaging **R. Lewis** (Monash Univ.)/ Soft X-ray Absorption Spectroscopy and Resonant Scattering **Di-Jing Huang** (NSRRC)
15:50 - 17:20	"Meet the experts" Part 2
17:20 - 18:30	*Dinner*
18:30 - 20:30	**Site Tour SCSS & New SUBARU**

Time	Nov.7 Sat.
7:45 - 21:30	**Excursion Kyoto**

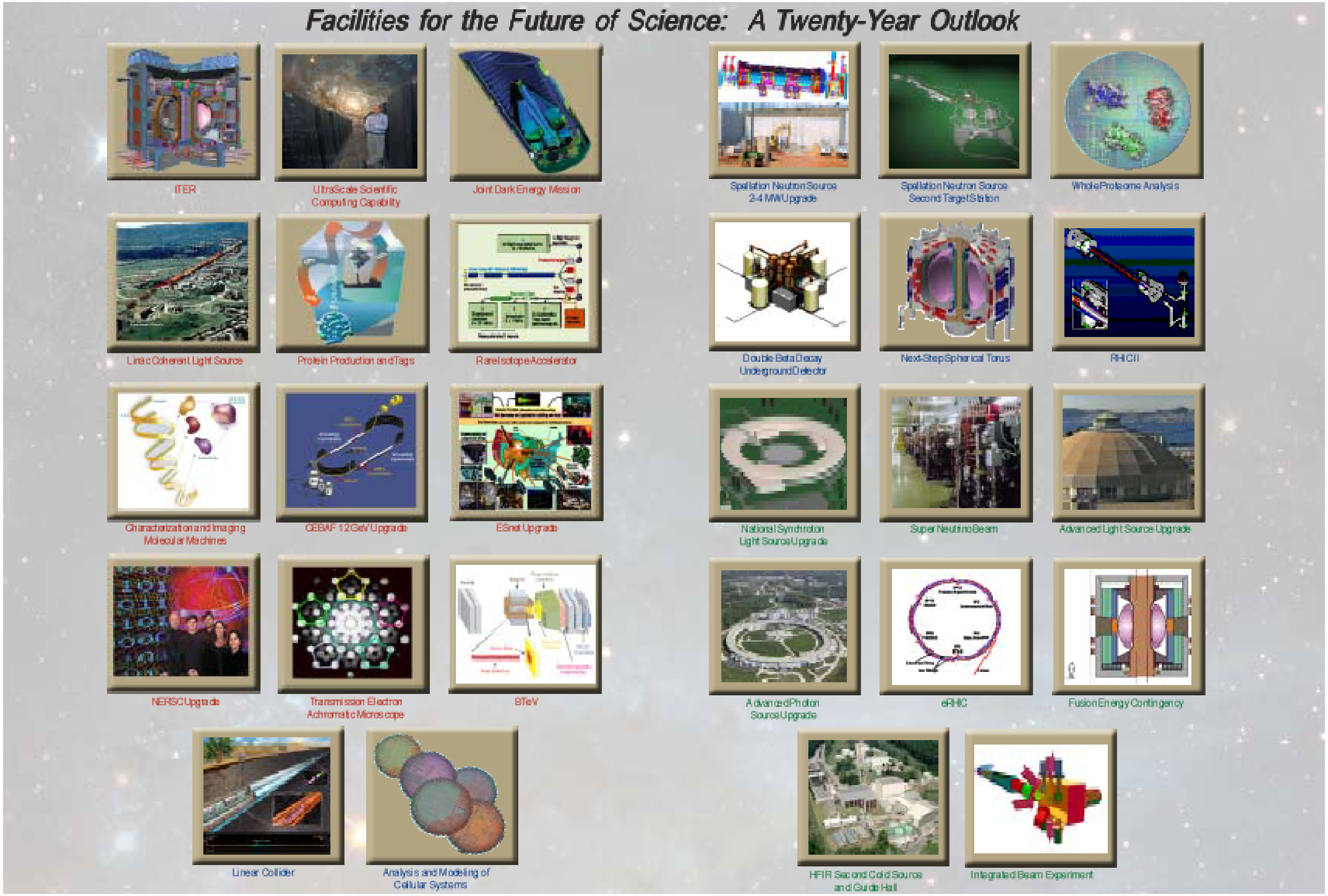
Time	Nov.8 Sun.
9:00 - 10:20	Small-angle Scattering **Y. Amemiya** (Univ. Tokyo)/ Atomic and Molecular Physics **K. Ueda** (Tohoku Univ.)
10:20 - 10:40	*Coffee Break*
10:40 - 12:00	Protein crystallography **S. Wakatsuki** (KEK-PF)/ Photoemission(1): Spectroscopy **Ku-Ding Tsuei** (NSRRC)
12:00 - 13:00	*Lunch*
13:00 - 14:20	X-ray Fluorescence Analysis **I. Nakai** (Tokyo Sci.Univ.)/ Infrared **M. Tobin** (Australian Synchrotron)
14:20 - 14:40	*Coffee Break*
14:40 - 16:00	Powder Diffraction **B. Kennedy** (Univ. of Sydney)/ Photoemission(2): PEEM and nanoscience **A. Tadich** (Australian Synchrotron)
16:00 - 16:20	*Coffee Break*
16:20 - 17:40	Pump-Probe Experiment **M. Wulff** (ESRF)
17:40 - 19:30	*Dinner*

Time	Nov.9 Mon.
9:00 - 17:30	**BL Practical Part 1**
17:30 - 19:30	*Dinner*

Time	Nov.10 Tue.
9:00 - 17:30	**BL Practical Part 2**
18:00 - 19:30	**Farewell Reception**

Time	Nov.11 Wed.
9:00 - 10:20	Inelastic X-ray Scattering **A. Baron** (RIKEN)
10:20 - 10:40	*Coffee Break*
10:40 - 11:20	Coherence **T. Miyahara** (Tokyo Metro. Univ.)
11:20 - 11:40	*Coffee Break*
11:40 - 12:20	New Scientific Possibilities and Directions **J. Mizuki** (JAEA)
12:20 - 12:30	Closing Remarks

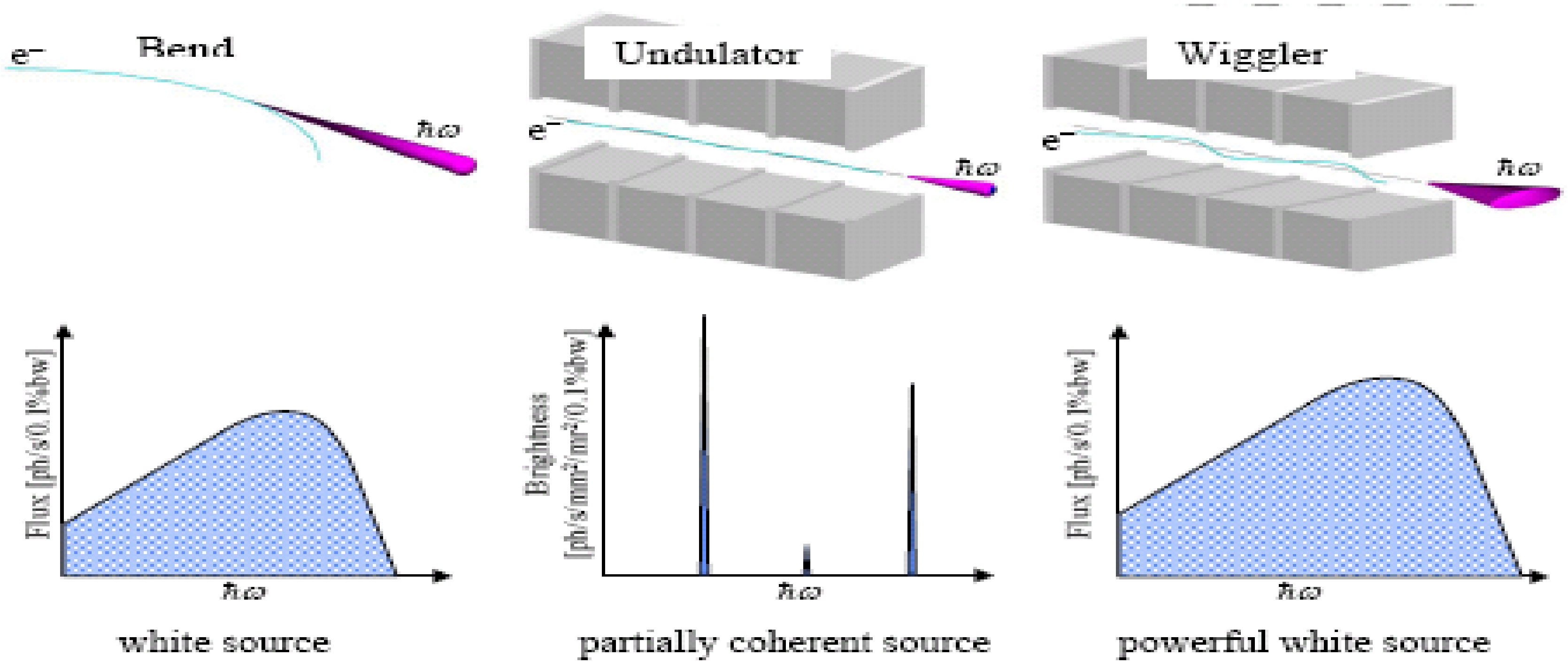
US DOE Plan for 20-years (2003)

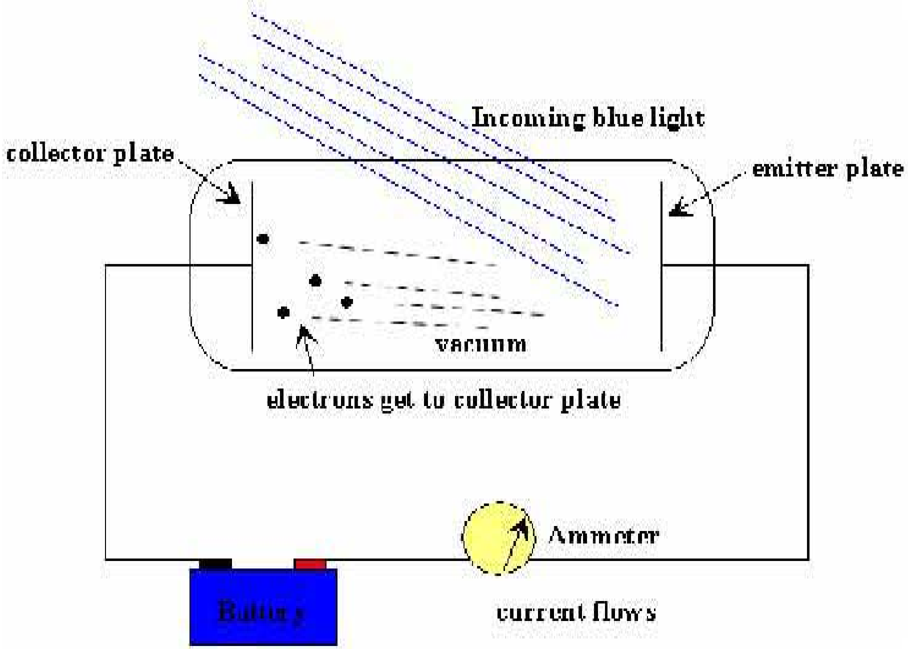


Synchrotron Radiation

- When moving along a curved trajectory in a speed close to that of light, electrons emit electromagnetic radiation in tangential direction.
  This kind of radiation is called synchrotron radiation since it was first observed at a 70 MeV synchrotron radiation machine.

- The curved trajectory can be created by <u>bending magnet</u>, <u>wiggler</u> and <u>undulator</u> magnets in accelerators.

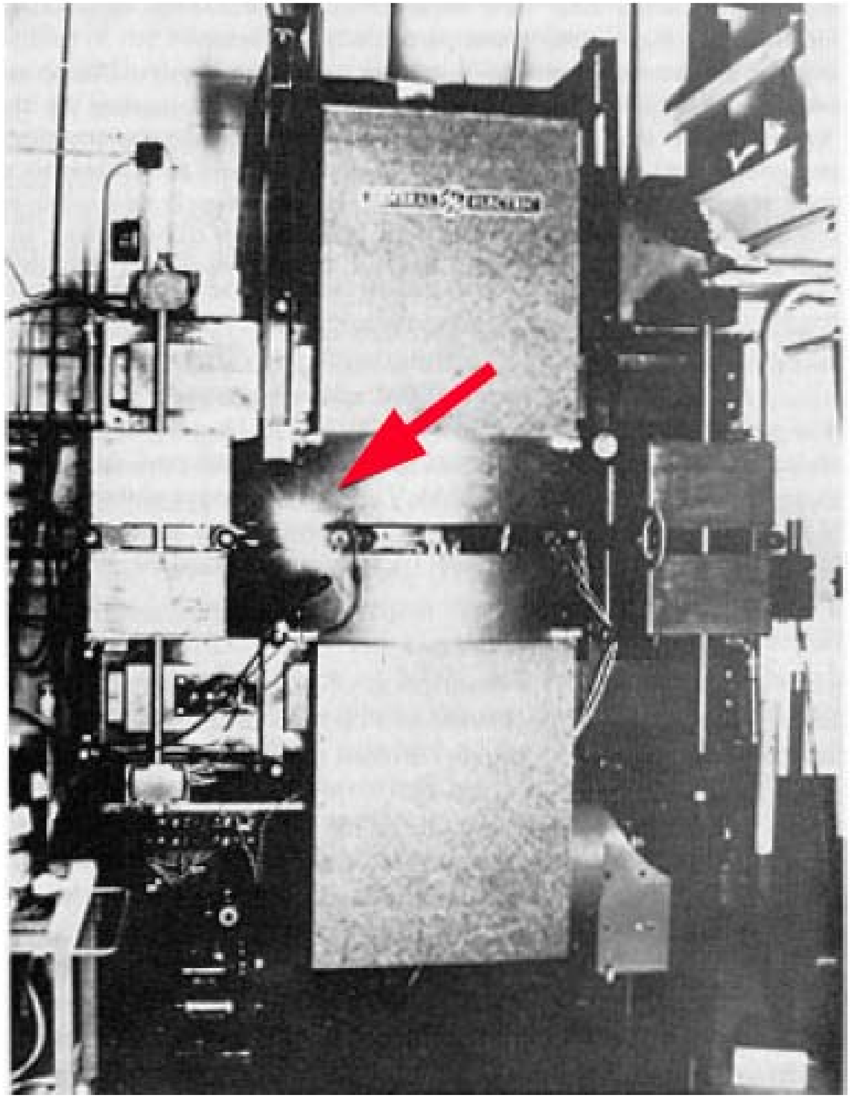




- e/m = $1.76*10^8$ c/g

J.J.Thomson was awarded the 1906 Nobel Prize in Physics for the discovery of the electron and his work on the conduction of electricity in gases.

First Man-Made Synchrotron Radiation Source at GE on Apr. 24, 1947



General Electric betatron built in 1946, the origin of the discovery of Synchrotron radiation.

The radiation was named after its discovery in a General Electric synchrotron accelerator built in 1946 and announced in May 1947 by Frank Elder, Anatole Gurewitsch, Robert Langmuir, and Herb Pollock in a letter entitled "Radiation from Electrons in a Synchrotron." Pollock recounts:

> **"On April 24, Langmuir and I were running the machine and as usual were trying to push the electron gun and its associated pulse transformer to the limit. Some intermittent sparking had occurred and we asked the technician to observe with a mirror around the protective concrete wall. He immediately signaled to turn off the synchrotron as "he saw an arc in the tube." The vacuum was still excellent, so Langmuir and I came to the end of the wall and observed. At first we thought it might be due to Cherenkov radiation, but it soon became clearer that we were seeing Ivanenko and Pomeranchuk radiation."**

First Observation of Synchrotron Radiation from Galaxy (July, 1054)

The supernova was observed by ancient Korean/Japanese/Chinese astronomers in the year 1054. The pulsar (the bright compact emission) produces highly relativistic electrons which themselves produce synchrotron radiation in the magnetic field of the nebula.

How a Synchrotron Works

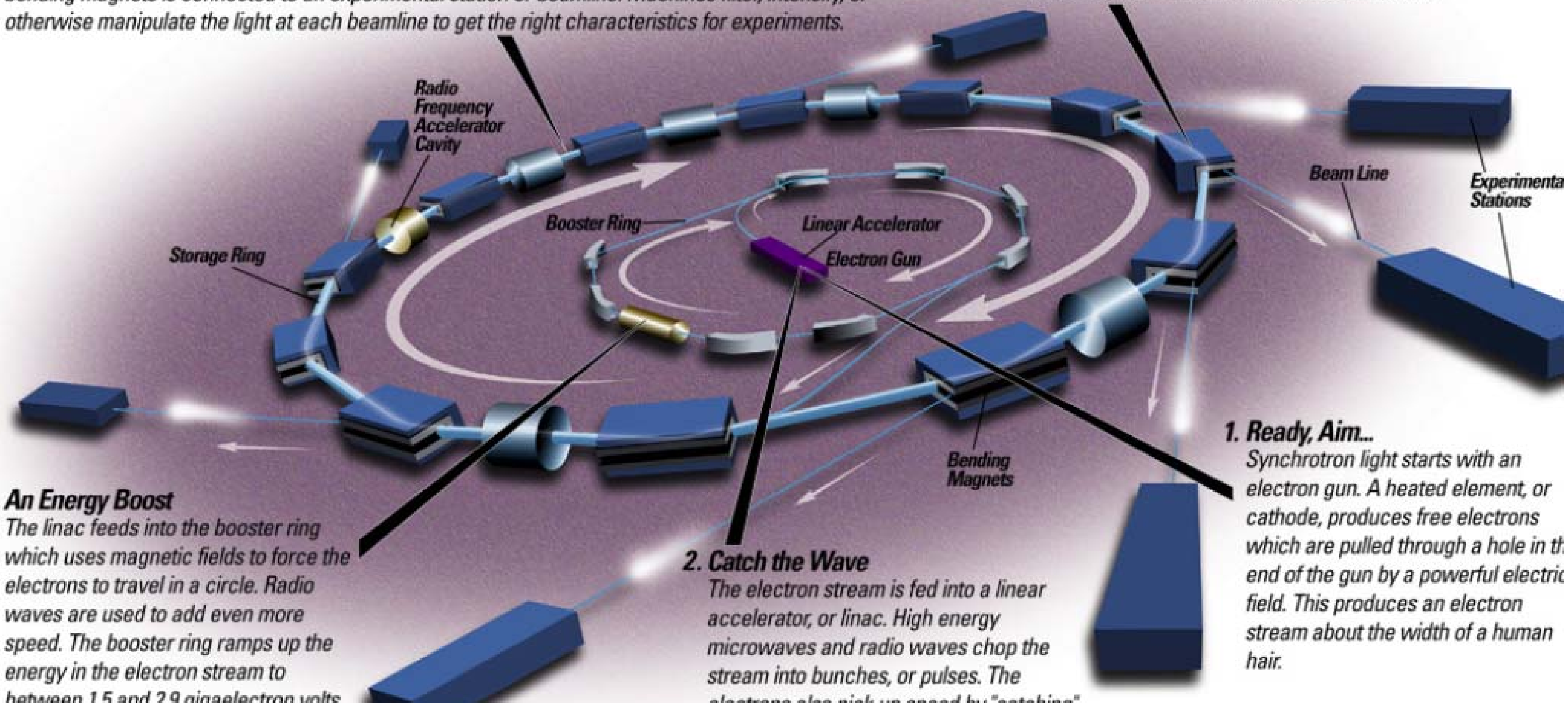
4. Storage Ring

The booster ring feeds electrons into the storage ring, a many-sided donut-shaped tube. The tube is maintained under vacuum, as free as possible of air or other stray atoms that could deflect the electron beam. Computer-controlled magnets keep the beam absolutely true.

Synchrotron light is produced when the bending magnets deflect the electron beam; each set of bending magnets is connected to an experimental station or beamline. Machines filter, intensify, or otherwise manipulate the light at each beamline to get the right characteristics for experiments.

5. Focusing the Beam

Keeping the electron beam absolutely true is vital when the material you're studying is measured in billionths of a metre. This precise control is accomplished with computer-controlled quadrupole (four pole) and sextupole (six pole) magnets. Small adjustments with these magnets act to focus the electron beam.



1. Ready, Aim...

Synchrotron light starts with an electron gun. A heated element, or cathode, produces free electrons which are pulled through a hole in th end of the gun by a powerful electric field. This produces an electron stream about the width of a human hair.

2. Catch the Wave

The electron stream is fed into a linear accelerator, or linac. High energy microwaves and radio waves chop the stream into bunches, or pulses. The electrons also pick up speed by "catching" the microwaves and radio waves. When they exit the linac, the electrons are travelling at 99.99986 per cent of the speed of light and carry about 300 million electron

3. An Energy Boost

The linac feeds into the booster ring which uses magnetic fields to force the electrons to travel in a circle. Radio waves are used to add even more speed. The booster ring ramps up the energy in the electron stream to between 1.5 and 2.9 gigaelectron volts (GeV). This is enough energy to produce synchrotron light in the infrared to hard X-ray range.

Source: University of Saskatchewan
Paradigm Media Group Inc.

Pohang Light Source

2.5 GeV Linac

2.5 GeV Storage Ring

Beamlines and Exp. Stations

Beam energy (GeV)	2.5
Rf (MHz)	2856
Klystron power (MW), max	80
Bunch length (ps)	13
Normalized emittance (nm.mrad)	150
Beam current (A)	30
Energy spread (%), fwhm	0.6
Total length (m)	160

Beam energy (GeV)	2.5
Circumference(m)	280.56
Natural emittance (nm)	18.9
Rf (MHz)	500.082
Rf voltage (MV)	1.6
Tunes	14.28/8.18
Super-periods	12

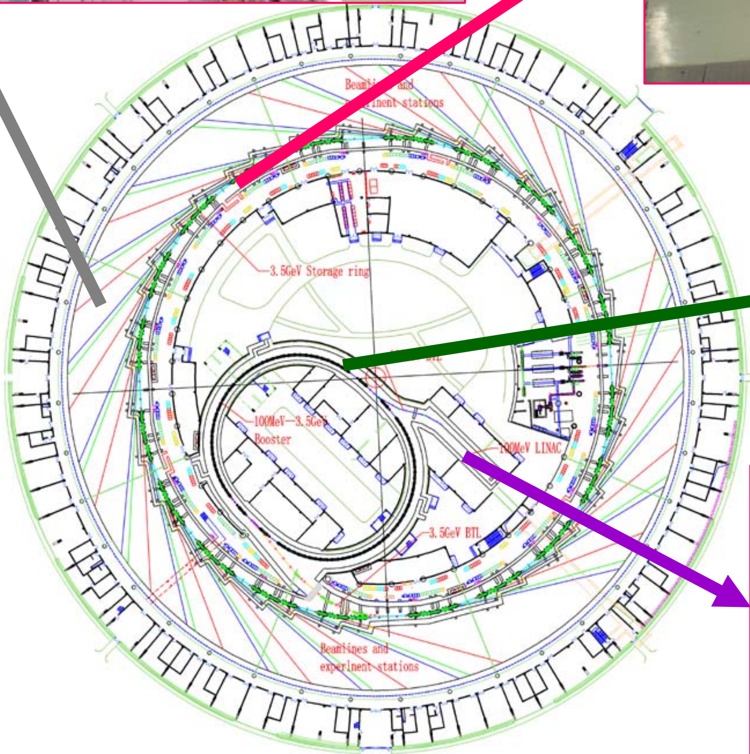
30 B/L (9 IDs)
1 FEL (THz BL)

10 B/L (in plan)

41 (Total)
52 (in full capacity)

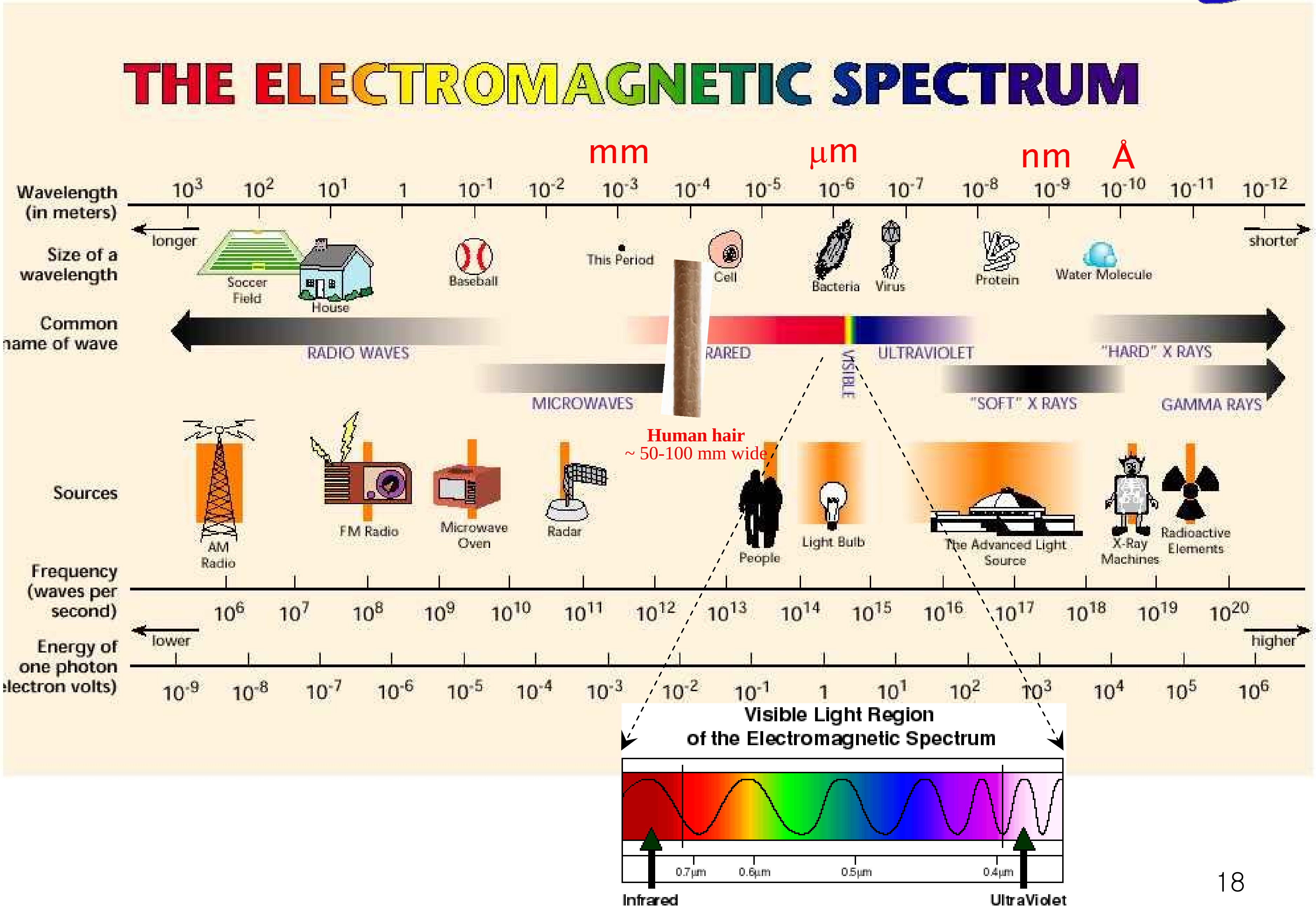
Shanghai Light Source

Storage Ring
3.5GeV, C=432m



Booster
3.5GeV, C=180m

Electron Linac
150MeV



THE ELECTROMAGNETIC SPECTRUM
mm
µm
nm
Å
Wavelength (in meters)
10^3 10^2 10^1 1 10^-1 10^-2 10^-3 10^-4 10^-5 10^-6 10^-7 10^-8 10^-9 10^-10 10^-11 10^-12
longer
shorter
Size of a wavelength
Soccer Field
House
Baseball
This Period
Cell
Bacteria
Virus
Protein
Water Molecule
Common name of wave
RADIO WAVES
MICROWAVES
RARED
VISIBLE
ULTRAVIOLET
"SOFT" X RAYS
"HARD" X RAYS
GAMMA RAYS
Human hair
~ 50-100 mm wide
Sources
AM Radio
FM Radio
Microwave Oven
Radar
People
Light Bulb
The Advanced Light Source
X-Ray Machines
Radioactive Elements
Frequency (waves per second)
10^6 10^7 10^8 10^9 10^10 10^11 10^12 10^13 10^14 10^15 10^16 10^17 10^18 10^19 10^20
lower
higher
Energy of one photon (electron volts)
10^-9 10^-8 10^-7 10^-6 10^-5 10^-4 10^-3 10^-2 10^-1 1 10^1 10^2 10^3 10^4 10^5 10^6
Visible Light Region of the Electromagnetic Spectrum
0.7µm 0.6µm 0.5µm 0.4µm
Infrared
UltraViolet

Properties of Synchrotron Radiation

- Broad spectrum: from infrared to hard X-ray;
- Wide tunability in photon energy (or wavelength) by monochromatization: sub eV up to the MeV Range;
- High Brilliance and high flux: many orders of magnitude higher than that with the conventional X-ray tubes;
- Highly collimated: radiation angular divergence angle proportions inversely to electron beam energy (1/ γ);
- High level of polarizations: linear, circular, elliptical;
- Pulsed time structures: tens of picoseconds pulse;
- …;

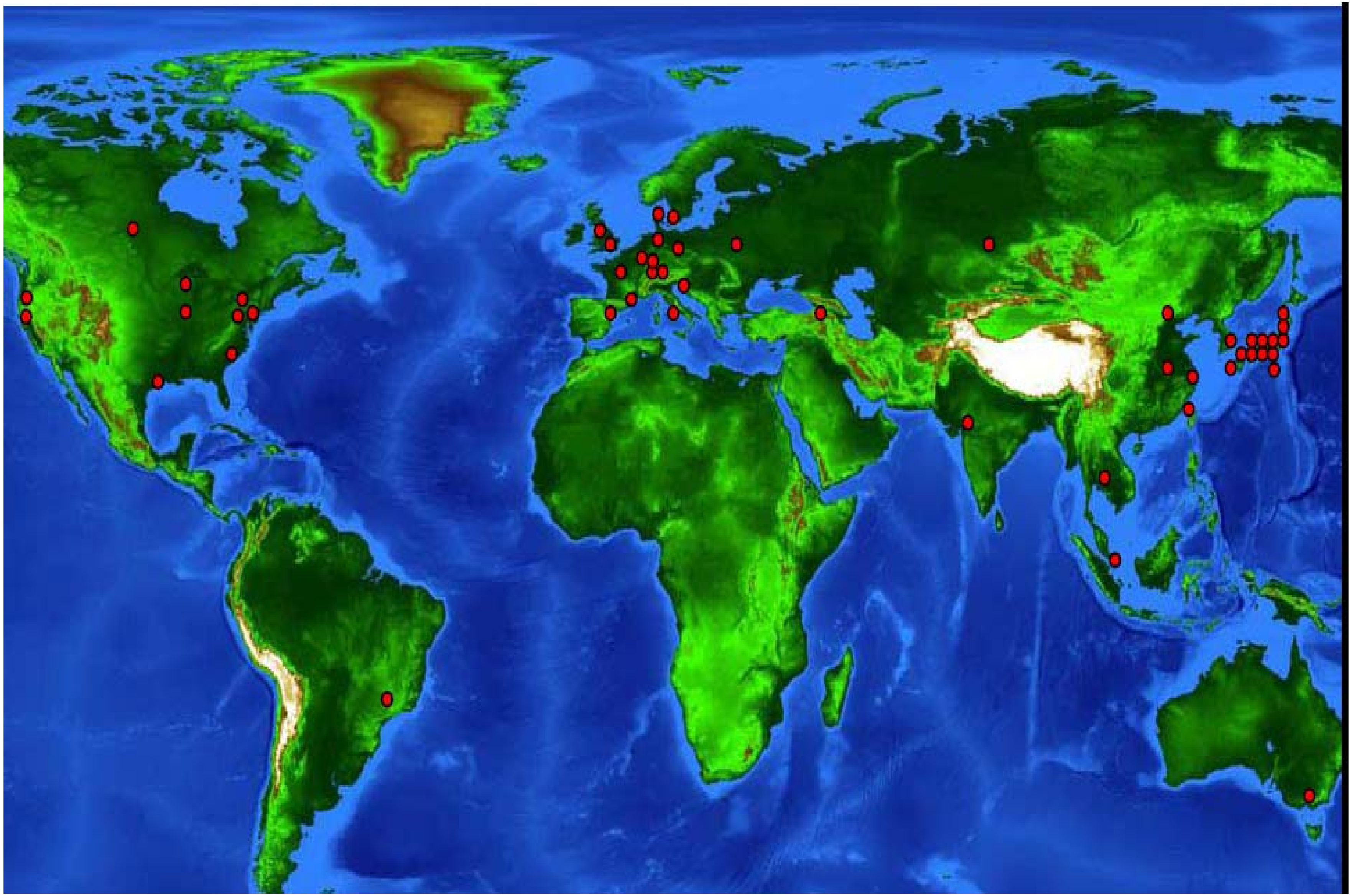
Synchrotron Radiation Facilities

- Over the past 30 years, design and construction of dedicated SR facilities have been continuously carried out all over the world. Currently there are about 50 SR light sources in operation and about 20 of them are third generation light sources;

- Before 1980s, first generation light sources, attached to high energy machines, were parasitically operated;
- From the mid-1970s to the late 1980s, second generation light sources were designed and constructed as dedicated SR user facilities;
- From the mid-1980s, third generation light sources have been designed and constructed with low emittance beam and undulators;
- Since the Mid-1990s, the construction of intermediate energy third generation light sources has been the focus of efforts worldwide;
- Meanwhile compact synchrotron radiation facilities have been designed and constructed.

Synchrotron Radiation Facilities (in operation)

Asia-Oceania : 26 Europe : 25 America : 18



www.lightsources.org

MAX
Lund
ASTRID
Aarhus
HASYLAB Hamburg
BESSY Berlin
DELTA Dortmund
ELSA-II Bonn
ANKA Karlsruhe
SLS Villigen
DIAMOND
Didcot
SRS
Daresbury
ESRF
Grenoble
LURE
Orsay
SOLEIL
Saint-Aubin
LLS
Barcelona
ELETTRA
Trieste
DAFNE
Frascati
CLS
Saskatoon
SRC
Stoughton
ALS
Berkeley
SSRL
Stanford
APS
Argonne
CHESS
Cornell
NSLS
Brookhaven
SURF II
Gaithersburg
CAMD
Baton Rouge
LNLS
Campinas
SSRC
Novosibirsk
INDUS
Indore
BSRF
Beijing
NSRL
Hefei
PLS
Pohang
SPS
HELIOS 2
Singapour
NSRRC
Hsinchu
NANO-HANA
Chiba
PHOTON FACTORY
Tsukuba
VSX
Tokyo
UVSOR
Okazaki
NEW SUBARU
Himeji
SPRING8
Himeji
HSRC
Hiroshima
Australian Synchrotron
Melbourne

1st Generation SR Facilities (1)

1st Generation?

Synchrotron light sources were basically beamlines built onto the existing facilities designed for particle physics studies.

Facility	Location	Energy (GeV)	Operation Year (Status)
SURF-II(NBS)	USA	0.28	1974-1997 (Upgraded)
DAΦNE	Italy	0.51	1999 (Operation)
ASTRID	Denmark	0.6	1990 (Operation)
Accum.Ring(KEK)	Japan	6.5	Partly Ded.
DCI(LURE)	France	1.8	Dedicated
DORIS(DESY)	Germany	3.7-5.2	1974-1993 (Upgraded)
SPEAR-I(SSRL)	USA	3.0-3.5	1972-1992 (Upgraded)
VEPP-3(INP)	Russia	2.2	1979-1985 (Upgraded)
CESR(CHESS)	USA	5.5	1979-2002 (Upgraded)
BEPC(IHEP)	China	1.5-2.8	1989-2004 (Upgraded)
ELSA	Germany	1.5-3.5	1987 (Operation)

1st Generation SR Facilities (2)

Facility	Location	Energy (GeV)	Operation Year (Status)
TSSR	Japan	1.5	Proposed
TRISTAN MR	Japan	6.0-30	1987-1995 (Shutdown)
AmPS	Netherland	0.9	Planned use
EUTERPE	Netherland	0.4	Planned use
VEPP-2M	Russia	0.7	1965-1999 (Upgraded)
VEPP-4	Russia	5.0-7.0	1994 (Operation)
N-100	Russia	2.2	Dedicated
HP-2000	Russia	5.5	Partly Ded.

2nd Generation SR Facilities (1)

2nd Generation?

Synchrotron light sources were dedicated to the production of synchrotron radiation and employed electron storage rings to harness the synchrotron light.

Facility	Location	Energy (GeV)	Operation Year (Status)
SRS(Daresbury)	UK	2.0	1981-2008 (Decommissioned)
NSLS-I	USA	0.75	1982 (Operation)
Aladdin	USA	0.8-1.0	1977 (Operation)
PF(KEK)	Japan	2.5-3.0	1983 (Operation)
BESSY I	Germany	0.8	1987-1999 (Decommissioned)
UVSOR	Japan	0.75	1983-2003 (Upgraded)
SOR-Ring	Japan	0.38	1974-1997 (Shutdown)
INDUS-I	India	0.45	1999 (Operation)
LNLS-I	Brazil	1.15	1997 (Operation)
HESYRL(USTC)	China	0.8	1991 (Operation)
MAX(LTH)	Sweden	0.55	1986 (Operation)
PETRA-II	Germany	7.0-13	1995-2009 (Decommissioned)

2^{nd} Generation SR Facilities (2)

Facility	Location	Energy (GeV)	Operation Year (Status)
TERAS	Japan	0.8	Dedicated
Siberia-I	Russia	0.45	Dedicated
TNK	Russia	1.2-1.6	Dedicated
CAMD	USA	1.2	(Operation)

Third Generation Light Sources

- Third generation light sources, based on advanced undulators and low emittance storage ring, are currently then main working horses. According to the storage ring energy, it can be classified into, low-, high- and intermediate energy light sources;

- High energy third generation light sources (>4GeV)：ESRF, APS, Spring-8;
- Low energy ones (<2.5GeV): ALS, Elettra, TLS, BESSY-II, MAX-II, LNSL, … ;
- Intermediate energy ones (2.5 ~ 4.0GeV): PLS, ANKA, SLS, CLS, SPEAR3, Diamond, SOLEIL, INDUS-II , ASP, SSRF, ALBA, NSLS-II, TPS, MAX-IV, … ;
- In addition, further advanced third generation light sources, diffraction limited or ultimate, are under investigations and studies. Notably, progress is very encouraging in upgrading the high energy physics accelerators into advanced third generation light sources, such as the PETRA-III project under construction at DESY and the PEP-X proposal at SLAC;

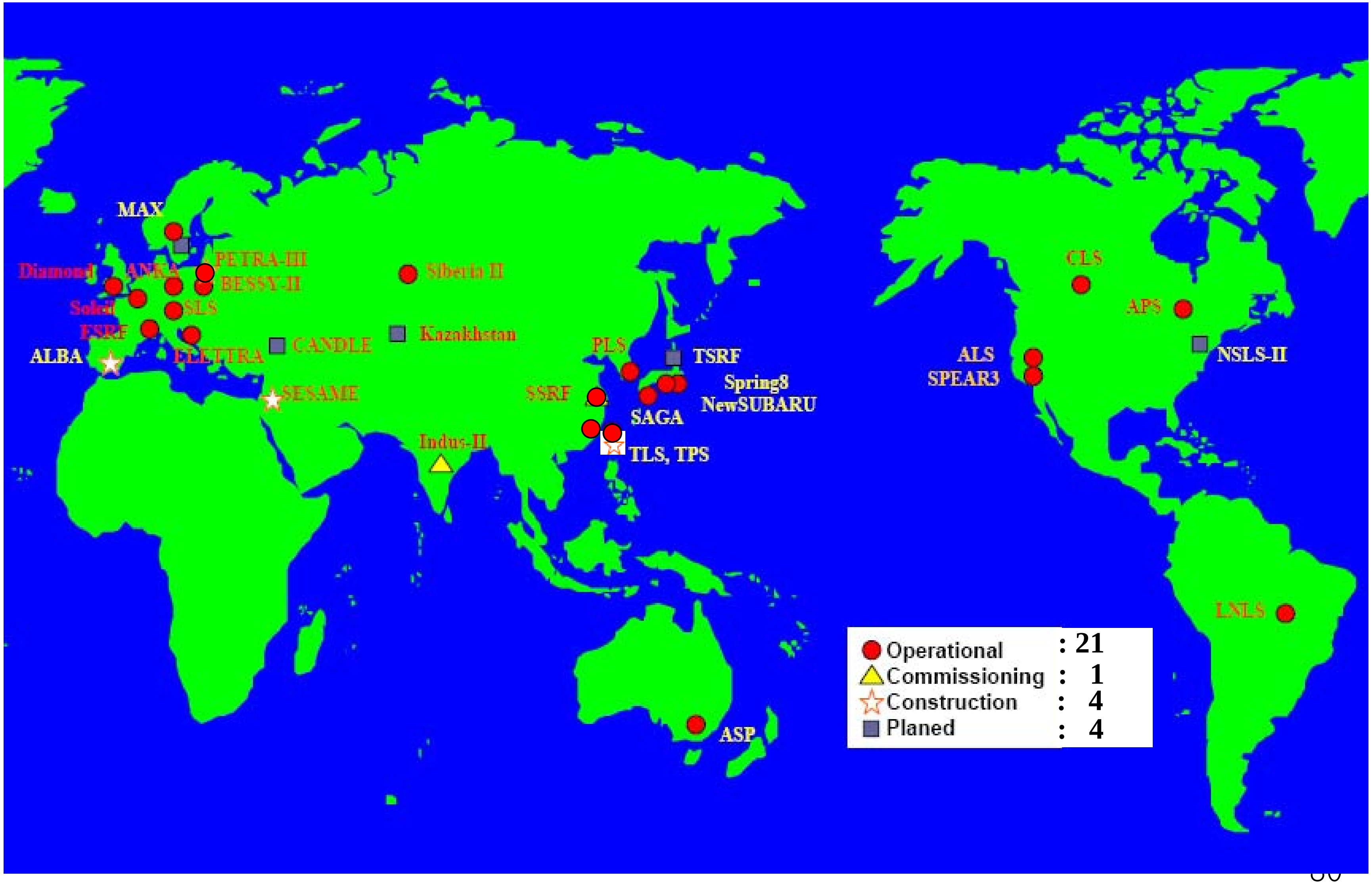
Intermediate Energy Light Sources

- The pioneering third generation light sources generated bright radiation based on fundamental and lowest harmonic spectral line of undulator:
  - High energy machines were optimized at 5-25keV for hard X-ray science;
  - Low energy ones were designed &optimized for VUV and soft X-ray sciences;
- As undulator technology well developed, its theoretical brilliance can be achieved at higher harmonics, this leads to a few of outstanding properties of intermediate energy light sources;
  - The photon beam properties in the 5-25keV range generated with intermediate energy light sources are comparable with those from high energy machines;
  - Up to 11th-15th harmonics are currently used at operating machines;
  - Circumference ranges from 100^{+}m to ~800m depending on budget;
  - Low construction and operation costs make it a cost effective light source right for meeting the regional needs;

Intermediate Energy SR Facilities

- Since the beginning of 21st century, intermediate energy light sources have been being successively put into operation;
  - SLS in 2001, ANKA in 2002, CLS in 2003, SPEAR3 in 2004, SAGA-LS in 2005, and another three, ASP, Diamond and SOLEIL in 2007;
  - Three more will be operational in the coming years, SSRF in 2009, ALBA in 2010 and SESAME probably in 2011;
  - NSLS-II, TPS and MAX-IV may start operation before 2015;
- Other intermediate light source plans are under consideration or R&D in countries including Armenia (CANDLE), Poland and South Africa;
- Some new proposals are still appearing, including a new one in China;

3rd Generation Light Sources around the World



3rd Generation Light Sources in Operation (1)

Light Source	Energy (GeV)	Circumference (m)	Emittance (nm.rad)	Current (mA)	Straight Section	Status
1. ALS	1.9	196.8	6.3	400	12×6.7m	Operation (1993)
2. ESRF	6.0	844.4	3.7	200	32×6.3m	Operation (1993)
3. TLS	1.5	120	25	240	6×6m	Operation (1993)
4. ELETTRA	2.0/2.4	259	7	300	12×6.1m	Operation (1994)
5. PLS	2.5	280.56	18.6	200	12×6.8m	Operation (1995)
6. APS	7.0	1104	3.0	100	40×6.7m	Operation (1996)
7. SPring-8	8.0	1436	2.8	100	44×6.6m, 4×30m	Operation (1997)
8. LNLS	1.37	93.2	70	250	6×3m	Operation (1997)
9. MAX-II	1.5	90	9.0	200	10×3.2m	Operation (1997)
10. BESSY-II	1.7	240	6.1	200	8×5.7m, 8×4.9m	Operation (1999)
11. Siberia-II	2.5	124	65	200	12×3m	Operation (1999)
12. NewSUBARU	1.5	118.7	38	500	2×14m, 4×4m	Operation (2000)

3rd Generation Light Sources in Operation (2)

Light Source	Energy (GeV)	Circumference (m)	Emittance (nm.rad)	Current (mA)	Straight Section	Status
13. SLS	2.4-2.7	288	5	400	3×11.7m, 3×7m, 6×4m	Operation (2001)
14. ANKA	2.5	110.4	50	200	4×5.6m, 4×2.2m	Operation (2002)
15. CLS	2.9	170.88	18.1	500	12×5.2m	Operation (2003)
16. SPEAR-3	3.0	234	12	500	2×7.6m,4×4.8m, 12×3.1m	Operation (2004)
17. SAGA-LS	1.4	75.6	7.5	300	8×2.93m	Operation (2005)
18. ASP	3.0	216	7-16	200	14×5.4m	Operation (2007)
19. DIAMOND	3.0	561.6	2.7	300	6×8m, 18×5m	Operation (2007)
20. SOLEIL	2.75	354.1	3.74	500	4×12m, 12×7m, 8×3.8m	Operation (2007)
21. SSRF	3.0	432	3.9	300	4×12m, 16×6.5 m	Operation (2009)

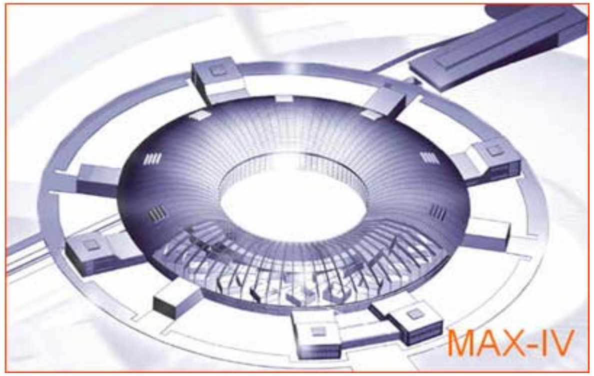
3rd Generation Light Sources in Operation (1)

New 3rd Generation Light Sources in Operation (2)

New 3rd Generation Light Sources
in Commissioning, Construction and Plan

Light Source	Energy (GeV)	Circumference (m)	Emittance (nm.rad)	Current (mA)	Straight Section	Status
22. Indus-2	2.5	172.5	58	300	8×4.5m	Commi.&Opera.
23. PETRA-III	6.0	2304	1.0	100	1×20m, 8×5m	Construction (commissioning in 2010)
24. ALBA	3.0	268.8	4.5	400	4×8m, 12×4.2m, 8×2.6m	Construction
25. SESAME	2.5	133.12	26	400	8×4.44m, 8×2.38 m	Construction
26. TPS	3.0	518.4	1.6	400	6×12m, 18×7m	Construction
27. CANDLE	3.0	216	8.4	350	16×4.8m	Planned
28. NSLS-II	3.0	792	2.1	500	15×9.3m, 15×6.6 m	Planned
29. MAX IV	3.0	287.2	0.8	500	12×4.6m	Planned
30. TSRF	TBD	TBD	TBD	TBD	TBD	Planned

New 3rd Generation Light Sources

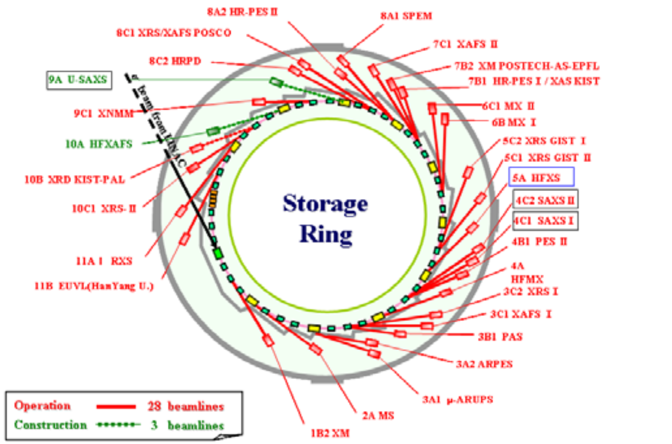


Upgrade Project of PLS Facility
(2009-2011)

(1) Major Upgrade -- (2009-2011) (started in January, 2009)

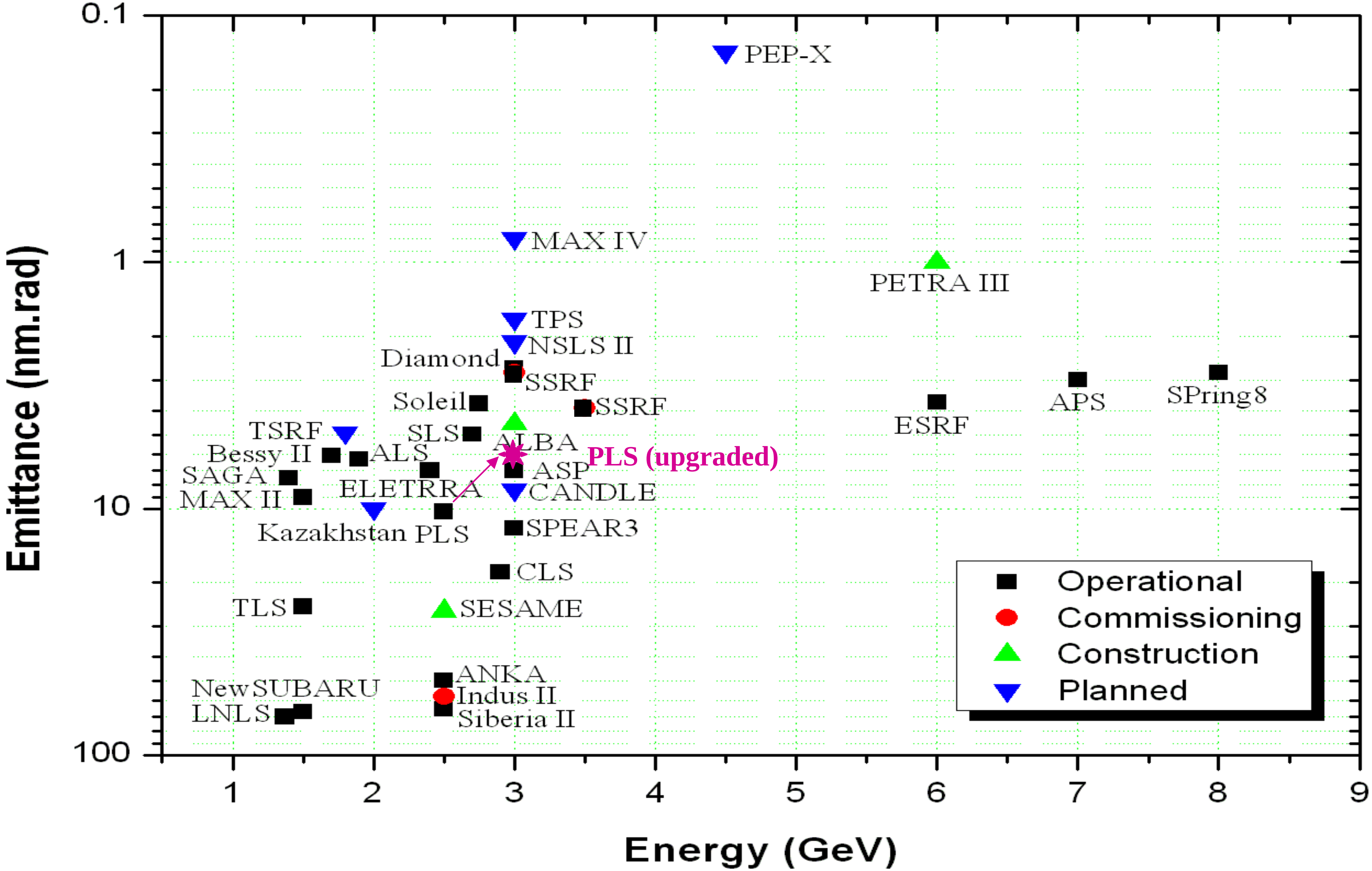
- Higher Energy : 3.0 GeV (← 2.5 GeV)
- Smaller Emittance: 5 nm·rad (←18 nm·rad)
- Higher Beam Flux: 10^2-10^3 higher
- More Insertion Device Beam Lines: 20 (← 10)

(2) Top-Up Mode Operation (2008-2010)

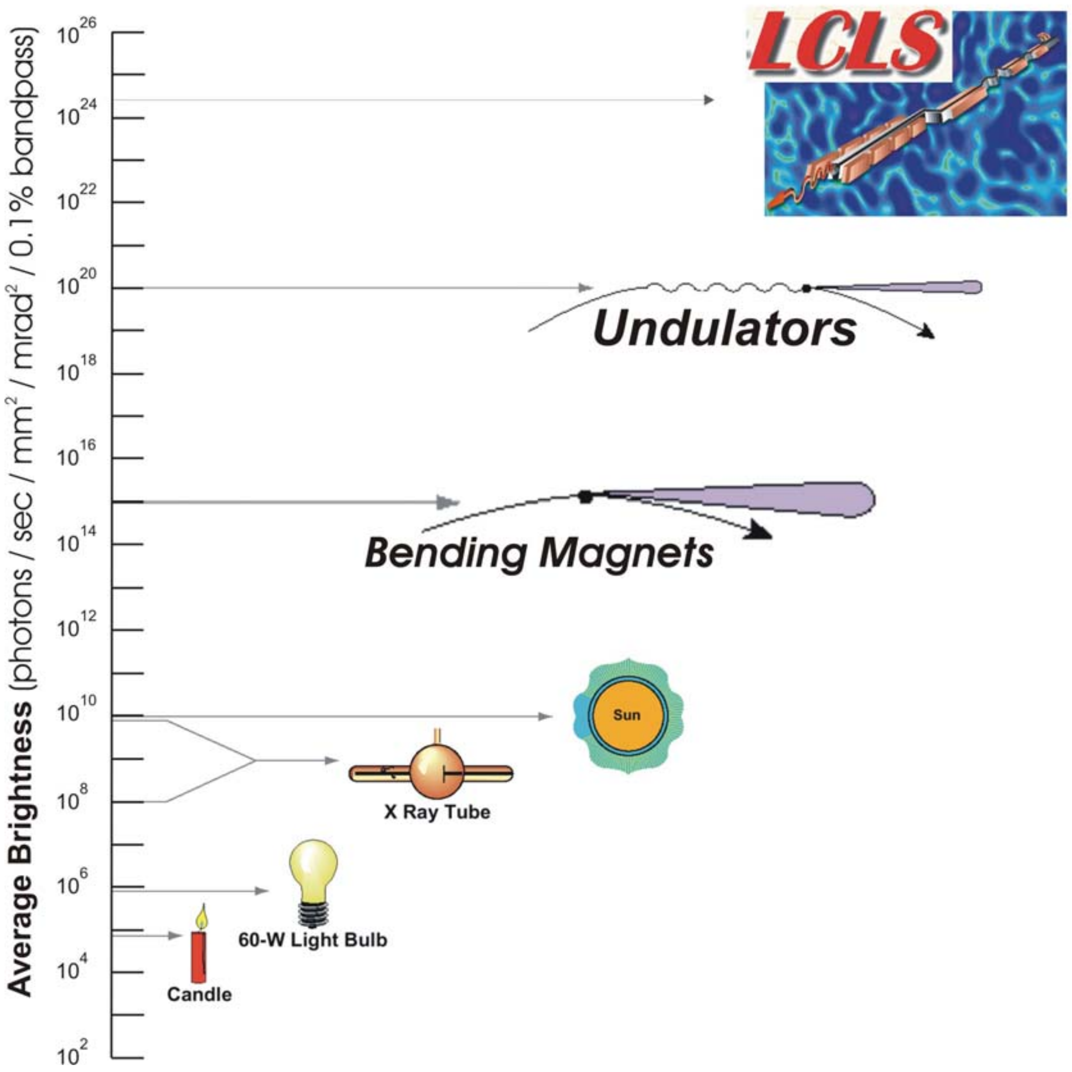


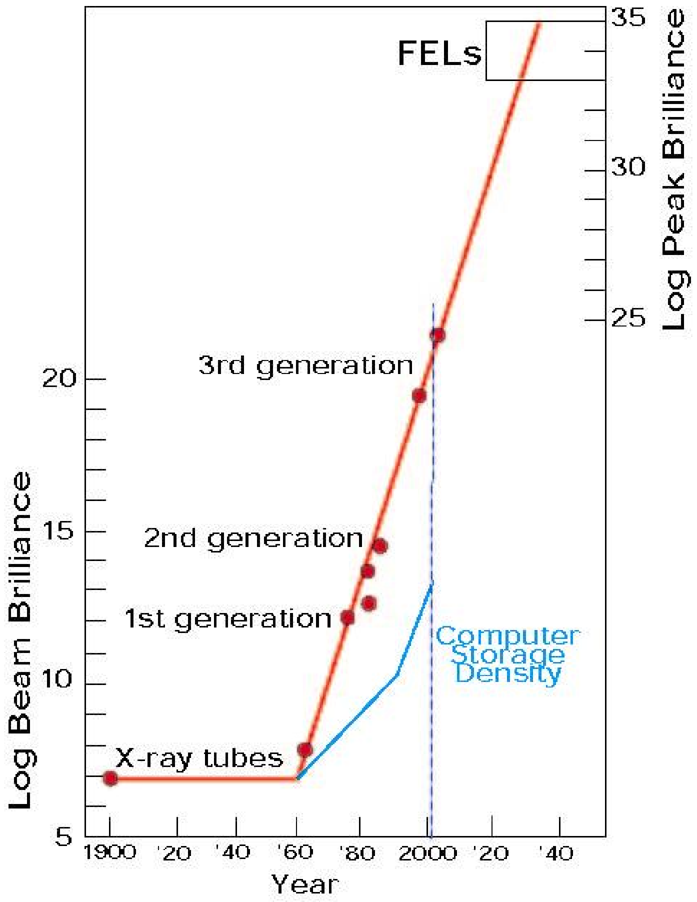
* fs-THz BL (FEL Beamline) : Technical Building II

Third Generation Light Sources



Brilliance Improvement





Main Figures of Merit of Third Generation Light Sources

- Undulator average spectral brilliance
  - Emittance;
  - Beam current;
  - Energy spread;
- Beam quality
  - Beam position stability;
  - Intensity stability;
  - Energy stability;
  - Beam lifetime;
  - Availability, reliability and MTBF
- Time structured and polarized radiation
  - Bunch fill patterns and short bunch schemes;
  - Various ID applications;

Third Generation Light Sources

❑ **Properties of third generation light sources;**

- **Higher brilliance: up to 10^{17}~10^{21}photons/s/mm^2/mrad^2/0.1%BW;**
- **Higher flux: up to 10^{15}~10^{17}photons/s/0.1%BW;**
- **Sub-micro orbit stability: beam position and divergence stability down to submicron and sub-microradian;**
- **Large number and various kinds of insertion devices: EU, PMW, PMU, EPU, HU, INVU, CPMU, SW, SU, …;**
- **Top-up operation: keeping operating current constant at 0.1-1% level;**
- **Partially coherent (vertical direction): vertical diffraction limited;**
- **Short pulse radiation: picoseconds to sub-picoseconds;**
- **High reliability-availability operation: availability is better than 95%;**
- **Ultra-low emittance: pushing for 1 nm-rad emittance by using damping wigglers**

3rd Generation Light Source

- ~ 2.0 GeV is the boarder line for VUV and X-ray machines;

(Note that 800 MeV vs. 2.5 GeV at NSLS)

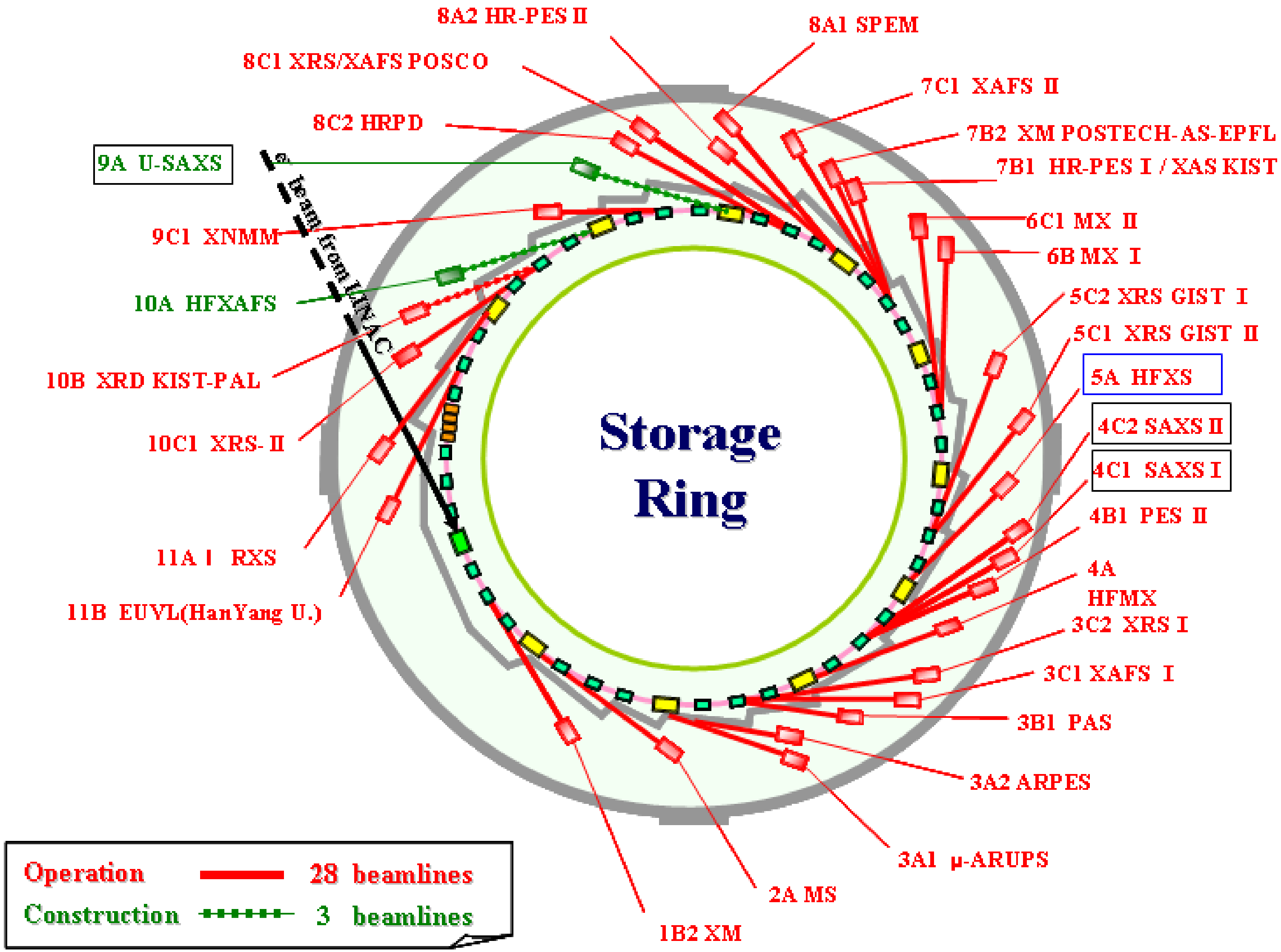
- User number : ~ 20% (VUV) vs. 80% (X-ray)

- Required beam time /Experiment :
  ~ 80 % (VUV) vs. 20 % (X-ray)

Beamines & Science

January 2009

PLS



* fs-THz BL (FEL Beamline) : Technical Building II

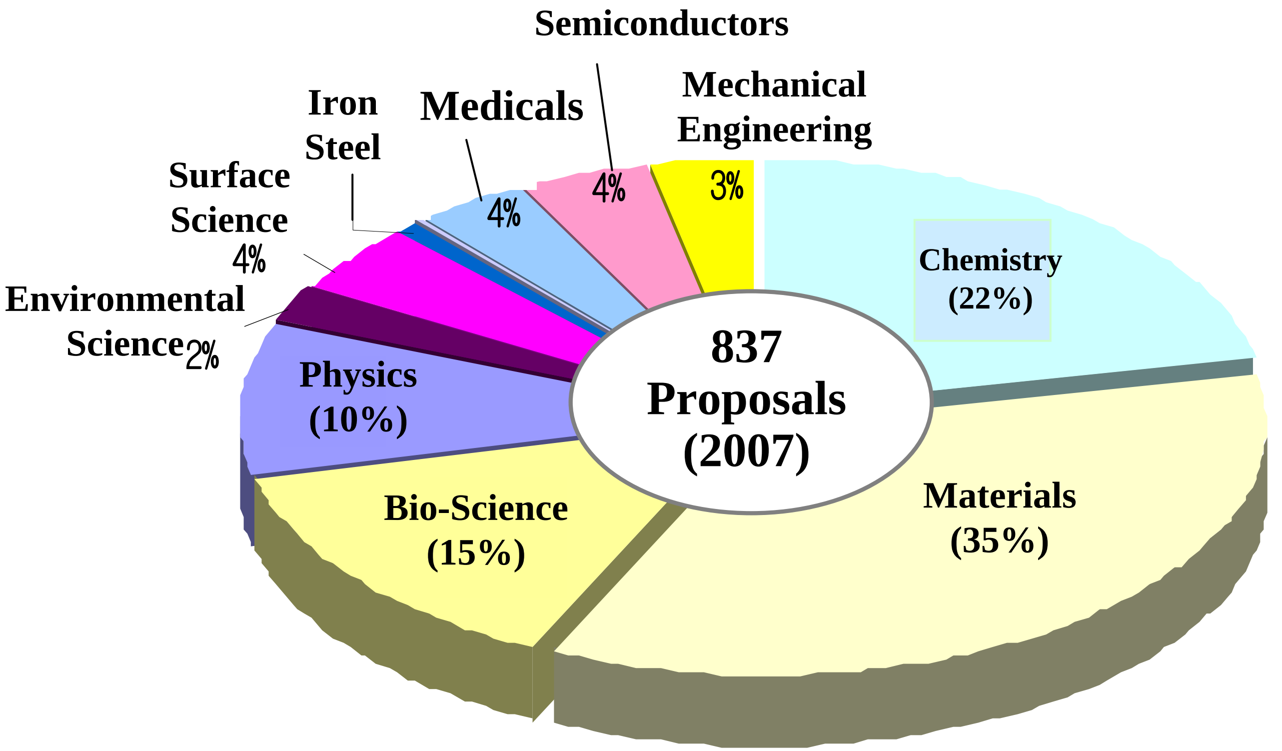
SR Applications in Science

- Spatial Science vs. Time-Domain Science
- Spectroscopy Science
- Scattering Science
- Microscopy (Imaging) Science
- Science & Technology Fields:

Physics, Chemistry, Materials , Biology, Medicine, Pharmaceutics, Environmental, Agriculture, Information Technology, Displays, Mechanical Engineering ……….

(almost all fields of Science and Technology)

Applications of PLS in Science and Industry



Users' publications: ca. 900
Average Impact Factor: 3.8

Accepted Proposals/year: 800-850
Acceptance Rate/year: 50-70%
Users/year: 3,000 (came to PLS for exps.)

- **There are dramatic increased demands from life science research, for example, big three statistics (ESRF, APS, Spring-8) in structural biology.**

- **One may note that cases of PLS and TLS are also outstanding results.**

- **The overall users are about 100,000 in the world.**

ESRF Scientific Output

863 refereed publications in 2000
(registered – > 85% are “real”ESRF publications)

1201 refereed publications in 2001 (registered)

~ 40 papers in NATURE and SCIENCE

~ 50 papers in Physical Review Letters/Europhysics Letters

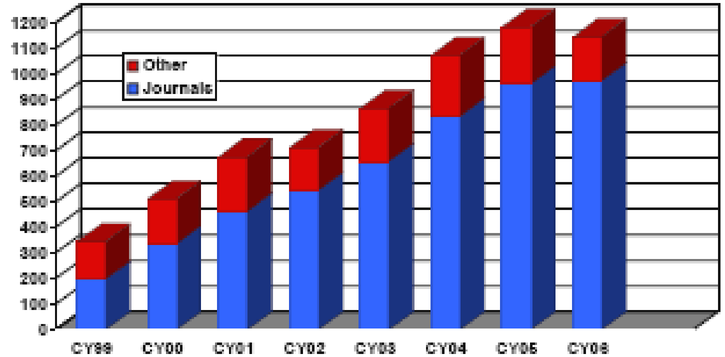
~ 90 papers in Physical Review

1106 refereed publications in 2002 (registered)

1206 refereed publications in 2003 (registered)

APS scientific impact increasing (by the numbers)

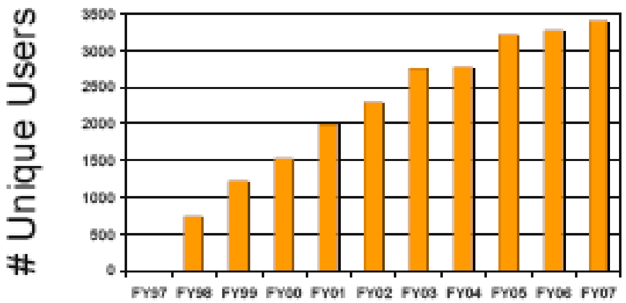
Refereed publications



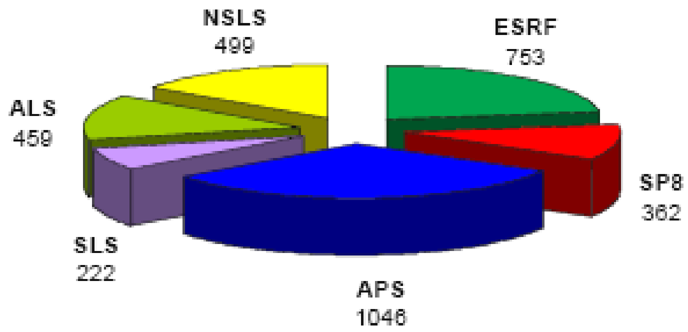
Selected high-impact stats

	2004	2005	2006
Cell	7	6	14
All *Nature*	32	37	37
PRL	21	27	37
Science	11	9	20
PNAS	33	44	43

58% journal papers with impact factor >3.5 (2006)

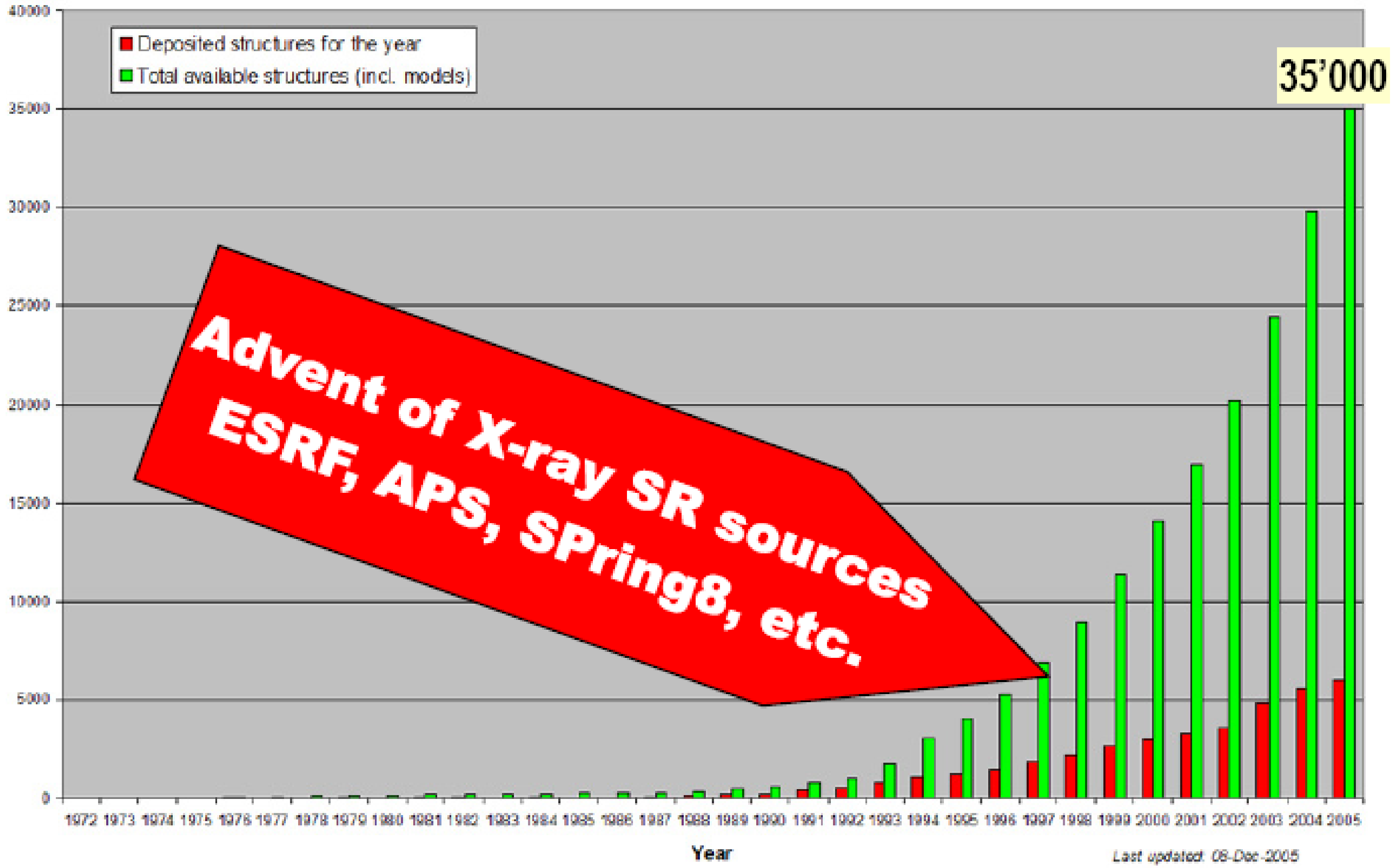


3411 unique users in 2007



2006 Protein Data Bank deposits

Spectacular growth of structural biology



X-ray sources, ICFA Seminar, SNAL, October 2008, L. Rivkin, PSI & EPFL

Scientific Demands

Coherency

Atomic and nanoscale imaging (Cells & Viruses, Nano-materials etc.), Others

Femto-second science

Real-time reaction with high repetition rate

(Chemical reaction, Photo-induced phase transition etc.)

Nano beam

Condensed matter physics under extreme conditions

Performances

Brilliance : brighter by 2 orders

Pulse width : shorter by 2 orders

compared to those of 3rd generation SR

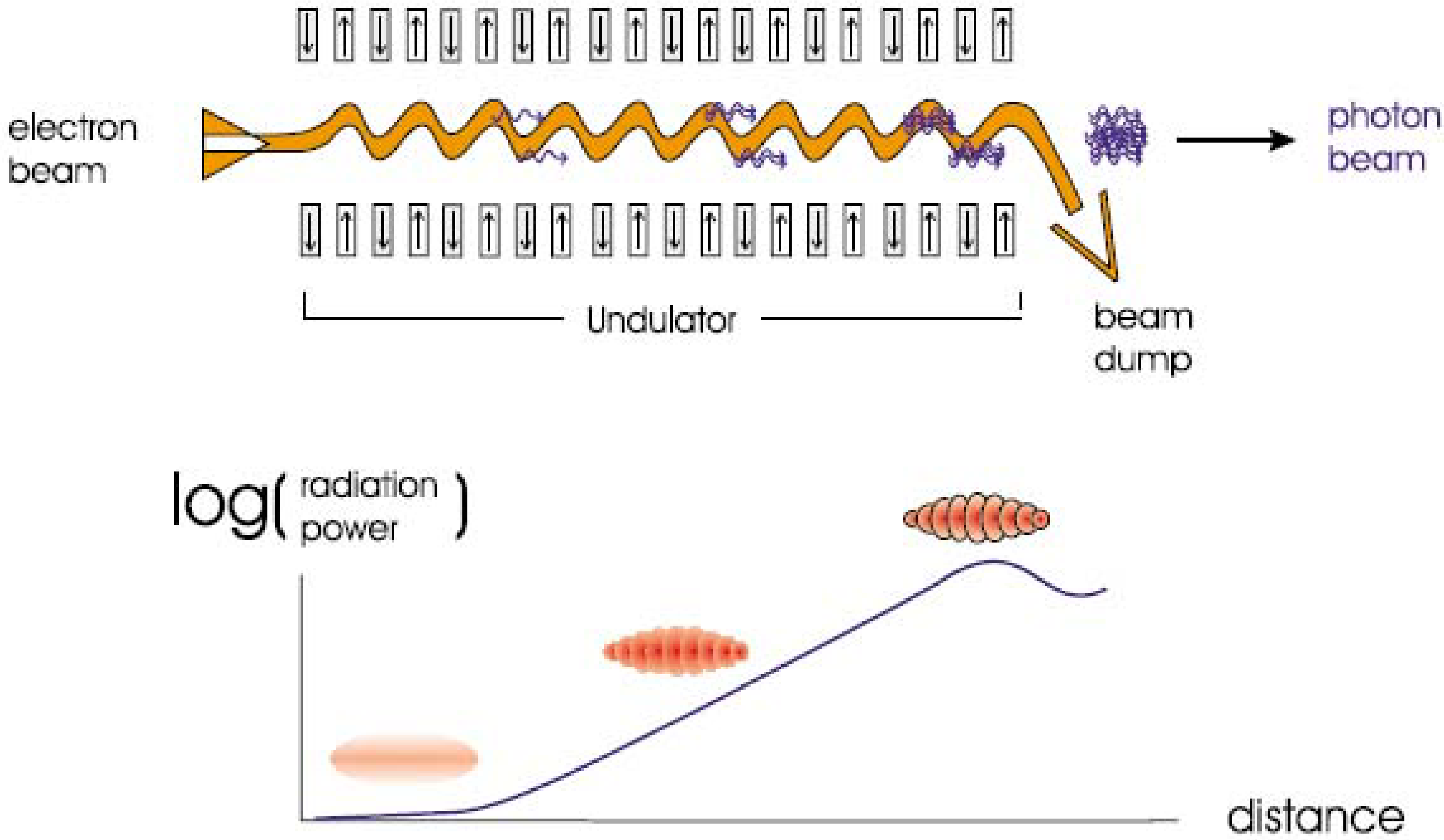
New Light Source

- X-Ray Free Electron Laser (XFEL)
- Energy Recovery Linear-Accelerator (ERL)

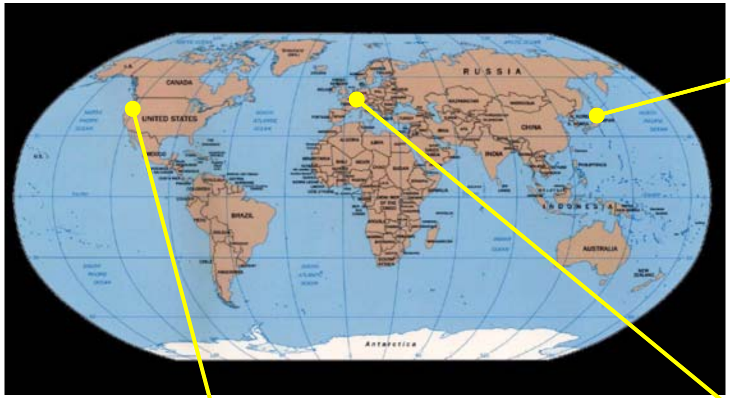
} 4th Generation SR

X-Ray Free Electron Laser (XFEL)

Self Amplification of Spontaneous Emission (SASE)



XFEL Facilities in the World

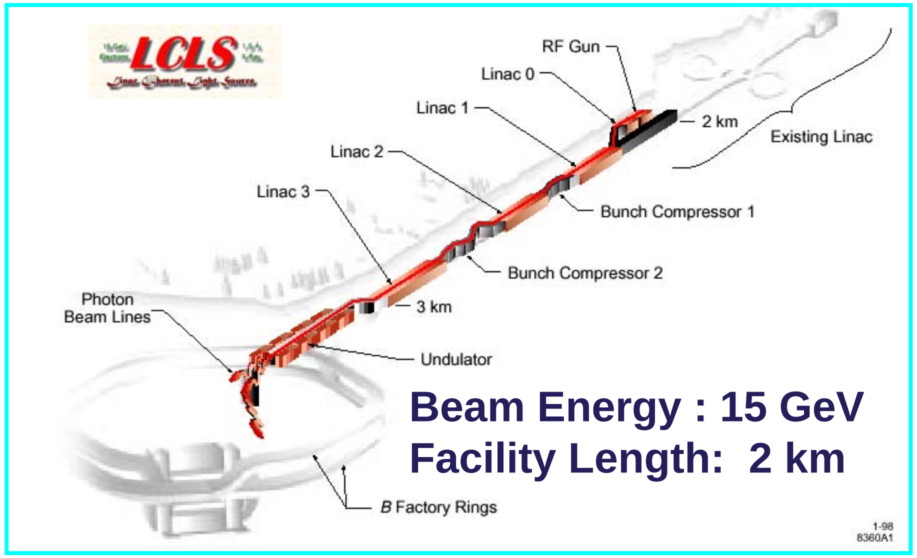


SP8-XFEL
SPring-8
2010

Beam Energy : 8 GeV
Facility Length : 0.7 km, 390 M$

LCLS, Stanford, 2009

(First XFEL demonstration on April 10, 2009)



Beam Energy : 15 GeV
Facility Length: 2 km

E-XFEL, Hamburg, DESY, 2014

Beam Energy : 20 GeV
Facility Length : 3 km, 1500 M$

PAL XFEL (proposed)

PAL XFEL (X-ray Free Electron Laser) Facility (4th Generation)

(1) **Energy:** 10 GeV (0.1 nm λ)

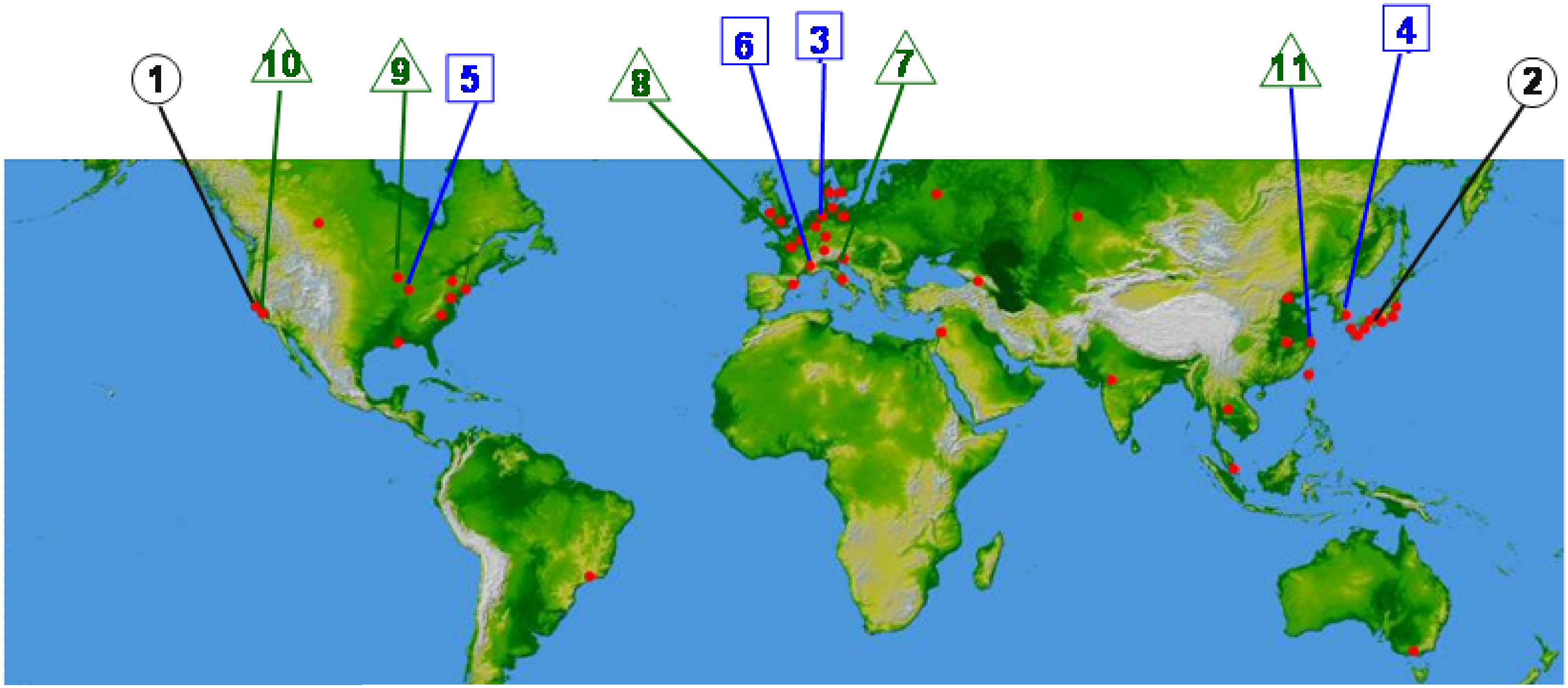
(2) **Beamlines:** 3 X-ray + 3 VUV BLs

(3) **Budget:** 400 M$

(4) **Construction:** 4 yrs (2011-2014)

- **Coherent X-ray Beam**
- **Super-high Beam Flux**
- **Nanoscale Beam Size**
- **Femtosecond Pulse X-ray Beam**

Next (4th) Generation Synchrotron Facilities: XFEL



Current Projects:

1. LCLS – SLAC
   (Stanford, USA)
   (in commissioning, 2009)
2. SCSS – SPring-8
   (Hyogo, Japan) (2006-2011)
   (in construction)
3. Euro-XFEL – DESY
   (Hamburg, Germany) (2009-2014)
   (started construction in 2009)
   FLASH(UV-FEL) in operation

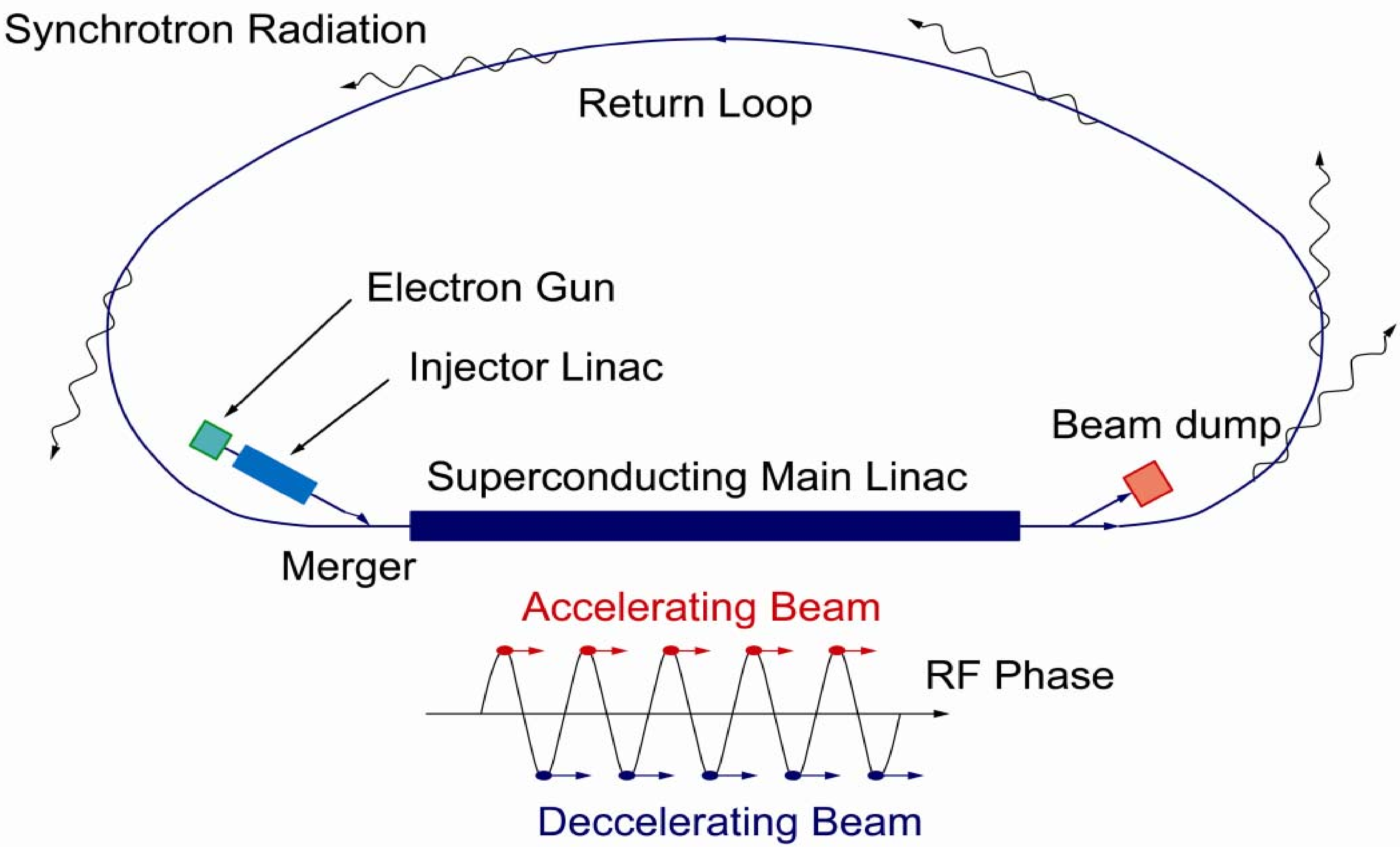
Future Projects:

4. PAL XFEL – PAL, Pohang, Korea (2011-2014)
5. XFELO – Argonne, Illinois, USA

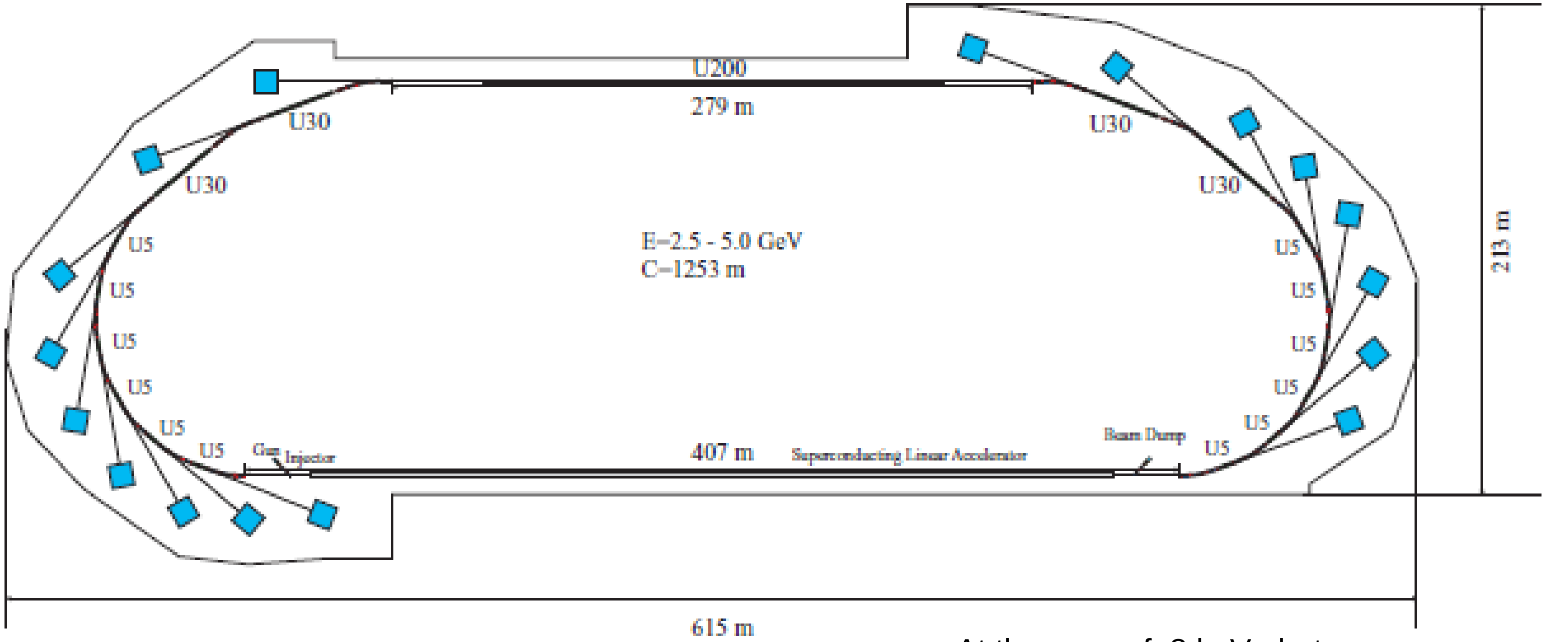
(Small Size/VUV)

6. PSI XFEL – PSI, Villigen, Switzerland
7. FERMI-ELETTRA, Trieste, Italy
8. Arc en Ciel – LAL, Orsay, France
9. WiFEL – Madison, Wisconsin, USA
10. Soft X-Ray – Berkeley, CA, USA
11. SDUV-FEL – Shanghai, PRC

Energy Recovery Linac (ERL)



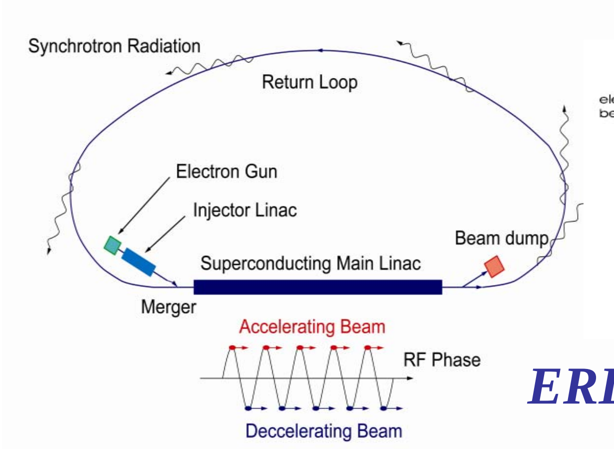
PF(KEK) - ERL



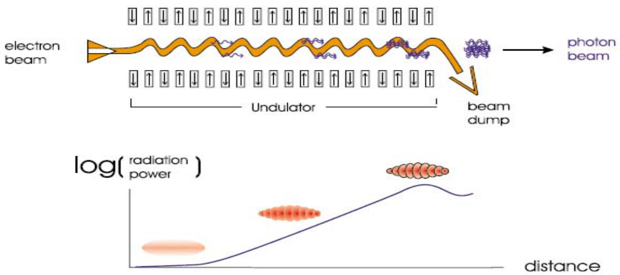
At the case of 8 keV photon energy

		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

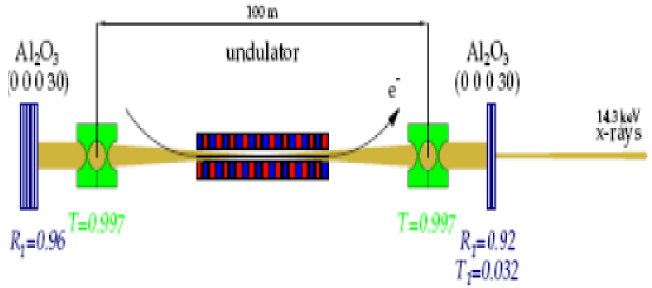
Functions of XFEL(SASE), XFEL-O & ERL



ERL



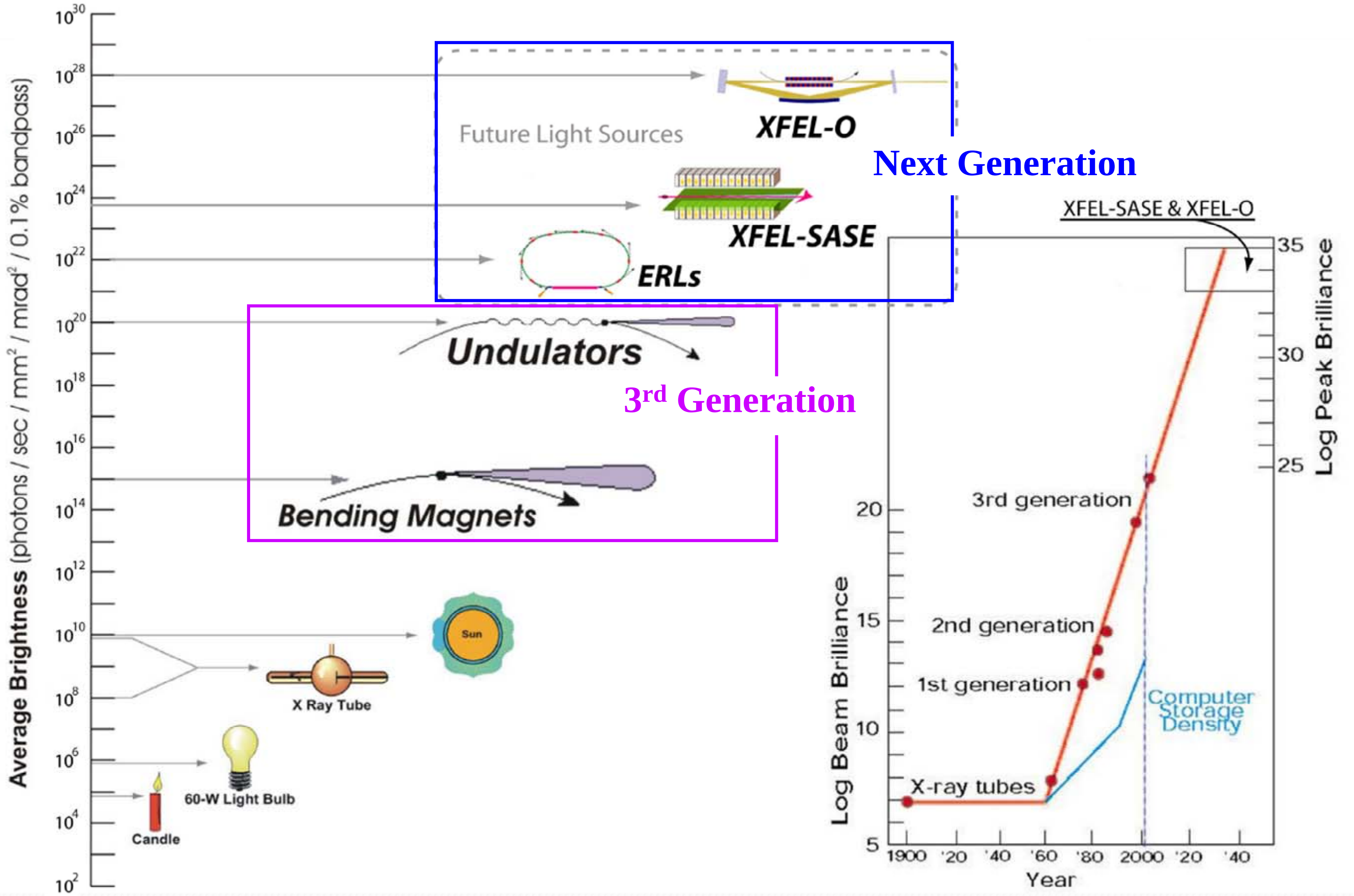
SASE-FEL



XFEL-O

SR	average brilliance	peak brilliance	repetition rate (Hz)	coherent fraction	bunch width(ps)	# of BLs	Remark
XFEL (SASE)	$\sim10^{22\sim24}$	$\sim10^{33}$	100~10K	100%	0.1	few	One-shot measurement
XFEL-O (Option)	$\sim10^{27}$	$\sim10^{33}$	~1M	100%	1	few	Single mode FEL
ERL	$\sim10^{23}$	$\sim10^{26}$	1.3G	~20%	0.1~1	~30	Non-perturbed measurement
3rd-SR	$\sim10^{20\sim21}$	$\sim10^{22}$	~500M	0.1%	10~100	~30	Non-perturbed measurement

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

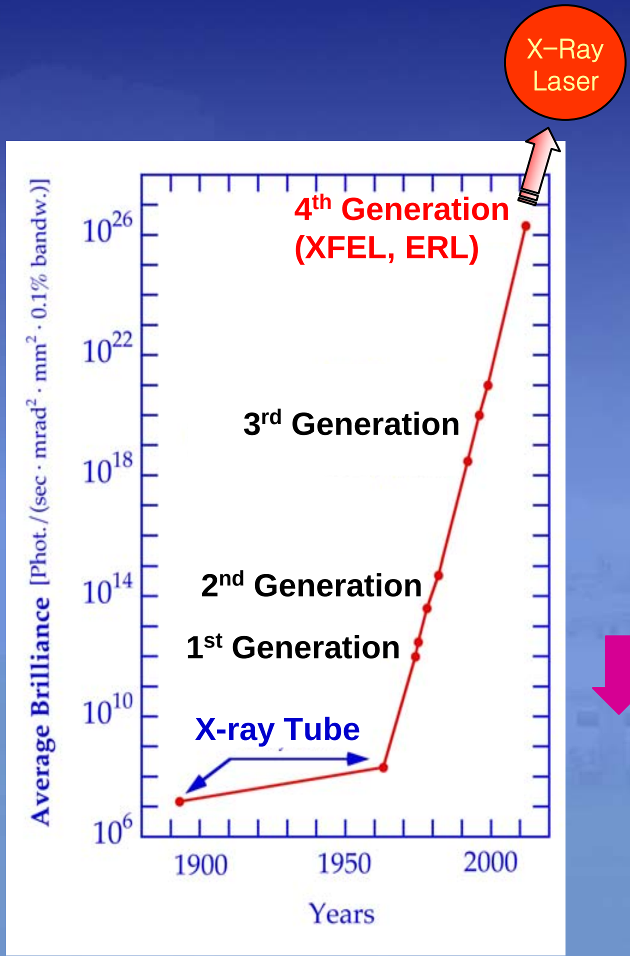


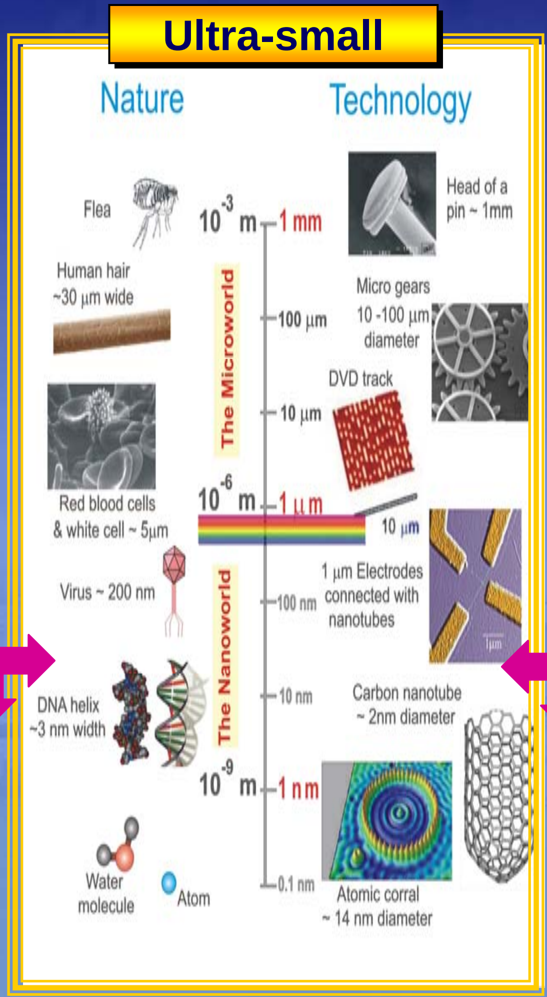
Average Brightness (photons / sec / mm² / mrad² / 0.1% bandpass)
10^30
10^28
10^26
10^24
10^22
10^20
10^18
10^16
10^14
10^12
10^10
10^8
10^6
10^4
10^2
Future Light Sources
XFEL-O
XFEL-SASE
ERLs
Next Generation
Undulators
3rd Generation
Bending Magnets
Sun
X Ray Tube
60-W Light Bulb
Candle
XFEL-SASE & XFEL-O
Log Peak Brilliance
35
30
25
Log Beam Brilliance
20
15
10
5
3rd generation
2nd generation
1st generation
X-ray tubes
Computer Storage Density
1900 '20 '40 '60 '80 2000 '20 '40
Year

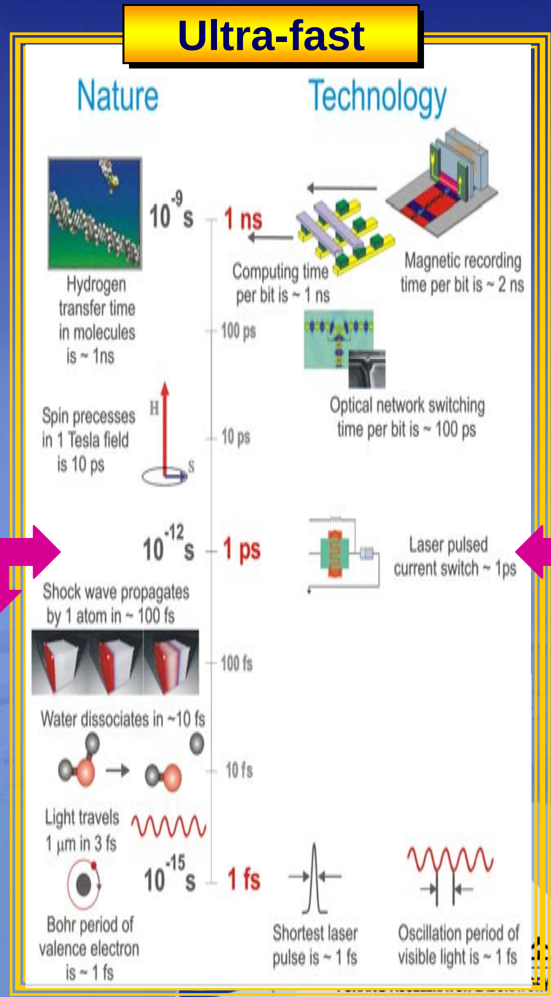
Applications of XFEL In Science

XFEL
ERL

- Coherent beam source
- Higher flux beam source
- Smaller size beam source
- Pulse beam source (~ fs)







Summary and Conclusions

- The development of third generation light source is still active and growing. There will be about 8 new ones operational before 2015.
- Intermediate energy light sources, such as Diamond, SOLEIL, ASP, Indus-2, ALBA, SSRF, CANDLE, NSLS-II, TPS, MAX-IV have been the focus of the recent development, the cost-effective feature makes them very suitable for meeting regional scientific needs of doing cutting-edge studies in various fields.
- Future development is very promising, not only the high energy physics machines will be converted to advanced light sources, like PRTRA-III and PEP-X, but also the ultimate storage ring light source is also very competitive.
- In the next few years, 4th generation facilities (XFEL) will be in operational, and one may expect unforeseen results. ERL and XFELO are other new approaches in competing with the 4th generation machines
- Users are very much diversified and expanding rapidly to other research areas

M. Ree's Group

1. Research Fields

http://www.postech.ac.kr/chem/mree

<Polymer Physics>
- Polymer chain conformation
- Structures and morphology
- Nanostructuring
- Electric, dielectric, optical, thermal, mechanical properties
- Sensor properties
- Surface, interfaces

<Polymer Synthesis>
- Functional polymers
- Structural polymers
- Polypeptides, DNA, RNA

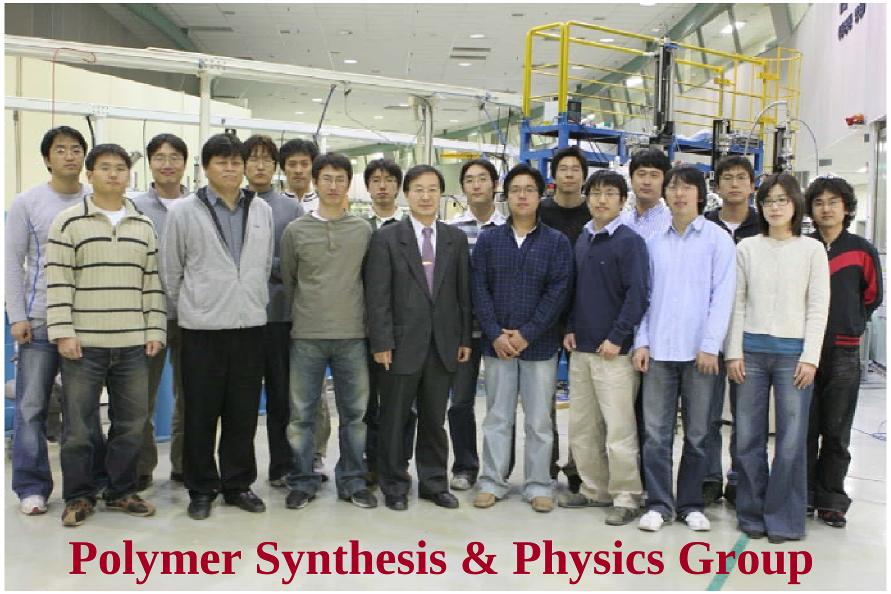
♦ Polymers for Microelectronics,
Displays, &
Sensors

♦ Polymers for Implants &
Biological Systems

♦ Proteins & Polynucleic acids (DNA, RNA)

2. Group Members (25)

1 Postdoctoral Fellow
15 Ph.D. candidates
1 Undergraduates
2 Technicians
2 Secretaries
4 Scientists (PLS: Coworkers)



Polymer Synthesis & Physics Group

Thank you very much for your attention !!!

포항가속기연구소
POHANG ACCELERATOR LABORATORY

3rd Generation SR Facilities (1)

3rd Generation?

Synchrotron light sources optimise the intensity of the light by incorporating long straight sections into the storage ring for 'insertion devices' such as undulator and wiggler magnets.

Facility	Location	Energy (GeV)	Operation Year (Status)	Beamline		
				BM	ID	TOTAL
ALS	USA	1.9	1993 (Operation)	27	16	44
ESRF	France	6.0	1993 (Operation)	13	36	49
NSRRC (TLS)	Taiwan	1.5	1993 (Operation)			26
ELETTRA	Italy	2.0/2.4	1994 (Operation)	8	15	23
PLS	Korea	2.5	1995 (Operation)	21	6	27
APS	USA	7.0	1996 (Operation)	21	42	63
SPring-8	Japan	8.0	1997 (Operation)	38	24	62
MAX-II	Sweden	1.5	1997 (Operation)	2	11	13
LNLS-II	Brazil	1.37	1997 (Operation)	11	1	12
Siberia-II	Russia	2.5	1999 (Operation)			
BESSY-II	Germany	1.7	1999 (Operation)	22	28	50

3rd Generation SR Facilities (2)

Facility	Location	Energy (GeV)	Circum. (m)	Operation Year (Status)	Beamline		
					BM	ID	TOTAL
NewSUBARU	Japan	1.5	118.7	2000 (Operation)	6	3	9
SLS	Switzerland	2.4-2.7	288	2001 (Operation)	6	9	15
ANKA	Germany	2.5	110.4	2002 (Operation)	1	12	13
CLS	Canada	2.9	170.88	2003 (Operation)	4	5	9
SPEAR-III	USA	3.0	234	2004 (Operation)	10	23	33
SAGA-LS	Japan	1.4	75.6	2005 (Operation)	4	0	4
AS	Australia	3.0	216	2007 (Operation)	8	1	9
Diamond	UK	3.0	561.6	2007 (Operation)	2	11	13
SOLEIL	France	2.75	354.1	2007 (Operation)	8	19	27
Indus-II	India	2.5	172.5	2007 (Operation)			
SSRF	China	3.5	432	2009 (Operation)	2	5	7

3rd Generation SR Facilities (3)

Facility	Location	Energy (GeV)	Circum. (m)	Operation Year (Status)	Beamline		
					BM	ID	TOTAL
PETRA-III	Germany	6.0	2304	2009 (Commissioning)			14
ALBA	Spain	3.0	268.8	Construction	2	3	5
SESAME	Jordan	2.5	133.12	Construction	3	3	6
CANDLE	Armenia	3.0	216	Construction	4	2	6
MAX-IV	Sweden	1.5/3.0	287.2	Construction			
NSLS-II	USA	3.0	780	Construction			
TPS	Taiwan	3.0	518.4	Construction			