6th AOFSRR School: Cheiron School 2012 (Sept. 24-Oct. 3, 2012)
Spring-8/RIKEN Harima, Hyogo, Japan



Overview of Synchrotron Radiation (SR)

Moonhor Ree

* Chemistry Department, Division of Advanced Materials Science & Polymer Research Institute Adviser for Science
* Pohang Accelerator Laboratory (PAL)

Pohang University of Science & Technology

Pohang 790-784, Korea

Tel: +82-54-279-2120, +82-(0)10-2080-2120 (mobile)

Fax: +82-54-279-3399

E-mail: ree@postech.edu

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

PAL 포항가속기연구소 POHANG ACCELERATOR LABORATORY

Outline

1. Introduction

- AOFSRR / Cheiron School
- History of SR
- SR

2. 1st-2nd Generation SR

3. 3rd Generation SR

- Current Status of 3rd Generation SR Facilities
- Applications in Science &Technology

4. 4th Generation SR

- Current Status of 4th Generation SR Facilities
- Applications in Science &Technology

5. Summary & Conclusions

AOFSRR Objectives

- To encourage regional collaboration in synchrotron radiation research and related subjects in Asia and Oceania.
- To promote advancement of synchrotron radiation research and related subjects in Asia and Oceania.
- To achieve the objective stated above, the AOFSRR shall hold a conference every year.
- The AOFSRR will also actively encourage any other activities that will promote synchrotron radiation research and related subjects in the region.

Specific Activities:

- Organize scientific collaboration meetings
- Exchange information of facilities and user groups
- Provide a framework for cooperative activities

AOFSRR Organization (2012)

Executive Committee

President : **Moonhor Ree (Korea)**

Vice president : **Hongjie Xu (China)**

Past president : **Keng Liang (Taiwan)**

Secretary-general : **Masaki Takata**

Secretary -Treasurer : **Richard Garrett**

Special Advisors to the President :

Osamu Shimomura (Japan)
Herbert Moser (German)
Sunil K. Sinha (USA)

Council

Member:

Australia (Keith A. Nugent ; AS)
China (Hongjie Xu ; SSRF)
India (P.D.Gupta ; INDUS)
Korea (Moo-hyun Cho ; PLS)
Japan (Junichiro Mizuki ; JSSRR)
Singapore (Mark Breese ; SSLS)
Taiwan (Shih-Lin Chang ; NSRRC)
Thailand (Sarawut Sujitjorn ; SLRI)

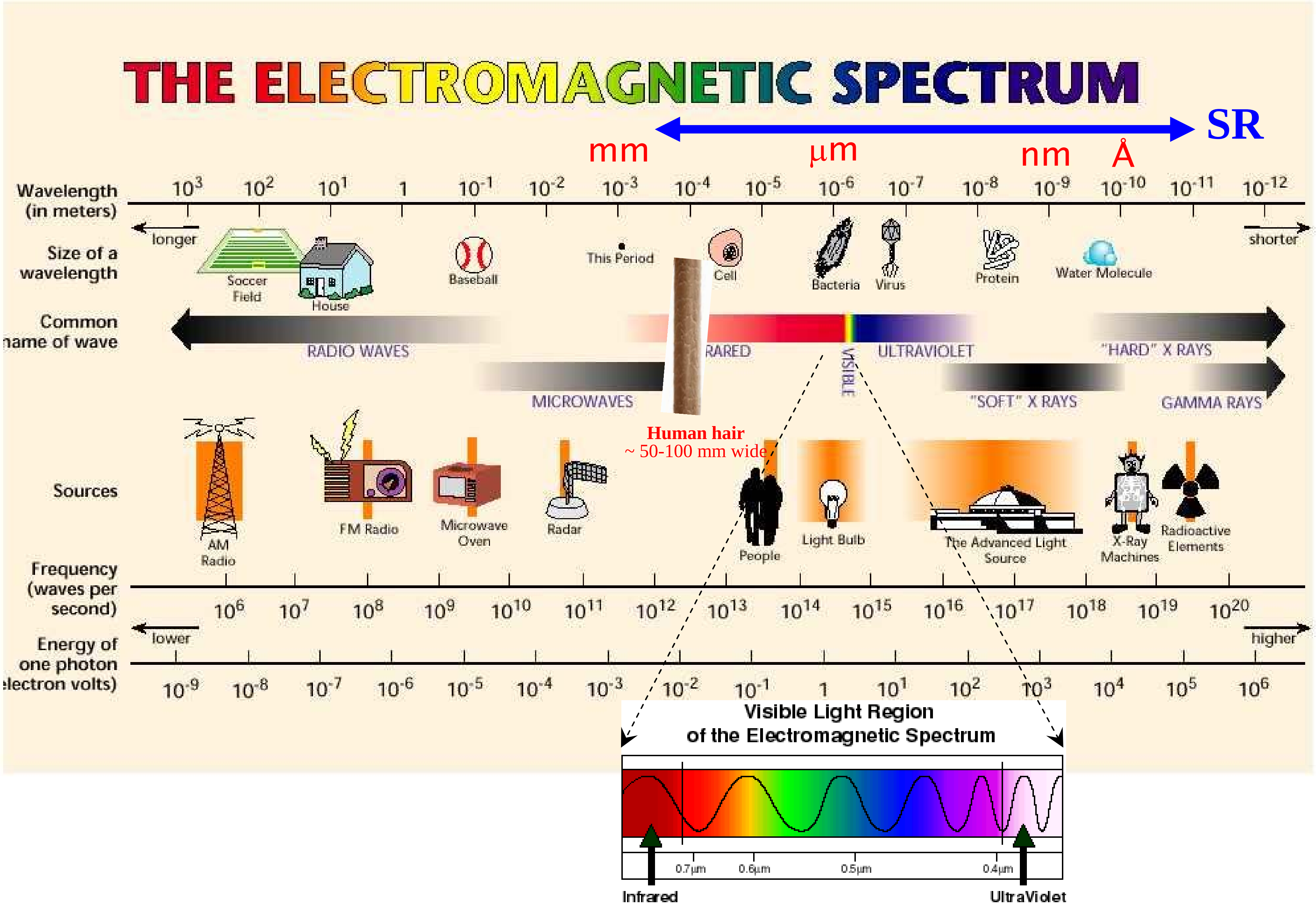
Associate Member:

Malaysia (Swee Ping Chia ; Univ. Malaya)
New Zealand (Richard Haverkamp ; Massey Univ.)
Vietnam (Tran Duc Thiep ;Vietnam Acad. Sci. & Tech.)

Indonesia (Suminar Pratapa ; Inst. Technol. Sepuluh Nov.) - new

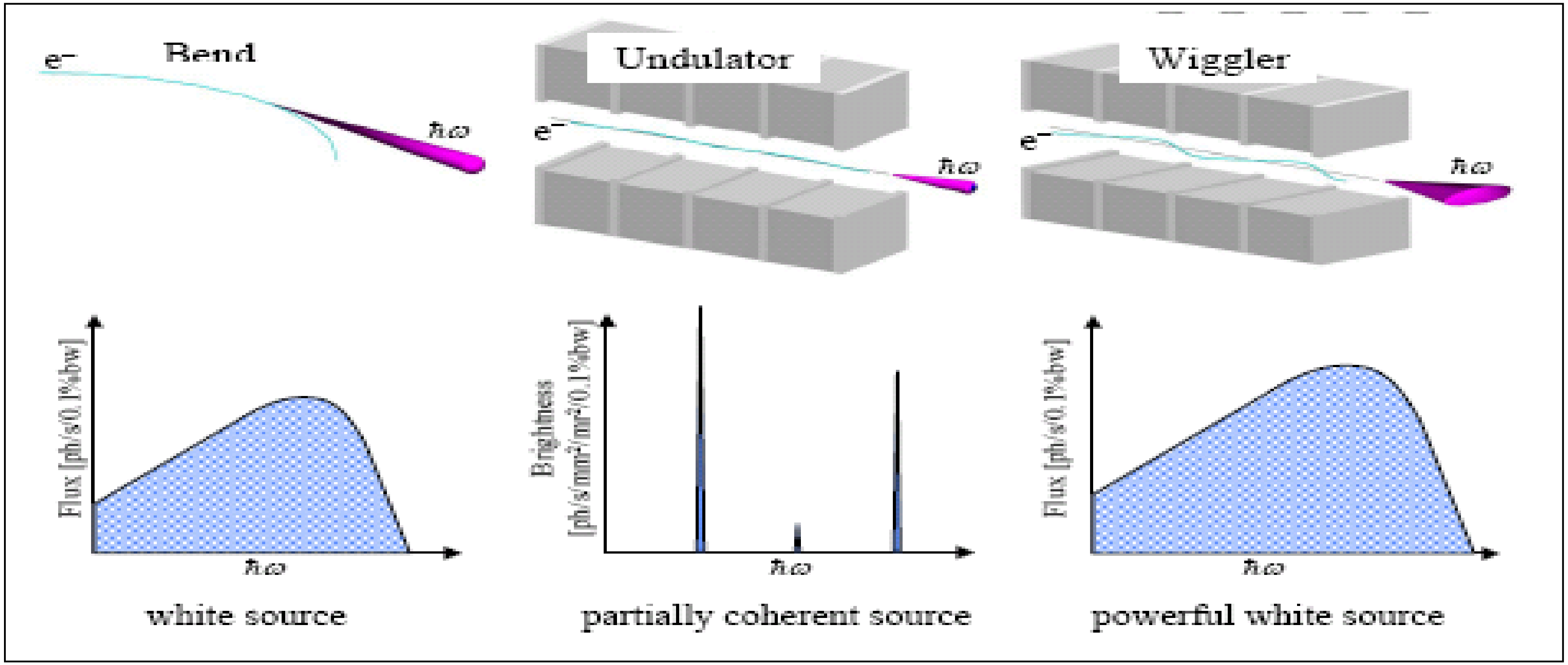
Guests
(permitted by the Council)

BEPC (1991)
2.2-2.5 GeV
NSRL (1991)
0.8 GeV
SSRF (2008)
3.5 GeV
INDUS I (1999)
0.45 GeV
INDUS II (2006)
2.5 GeV
SIAM (2004)
1.2 GeV
SSLS (2001)
0.7 GeV
PLS (1994)
3.0 GeV
PAL-XFEL(2014)
10.0 GeV
UVSOR (1983)
0.75 GeV
PF (1982)
2.5 GeV
SPring-8 (1997)
8.0 GeV
SACLA (2012)
8.0 GeV
TLS (1993)
1.5 GeV
TPS (2013)
3.0-3.3 GeV
AS (2006)
3.0 GeV
Synchrotron Facilities
in Asia/Oceania

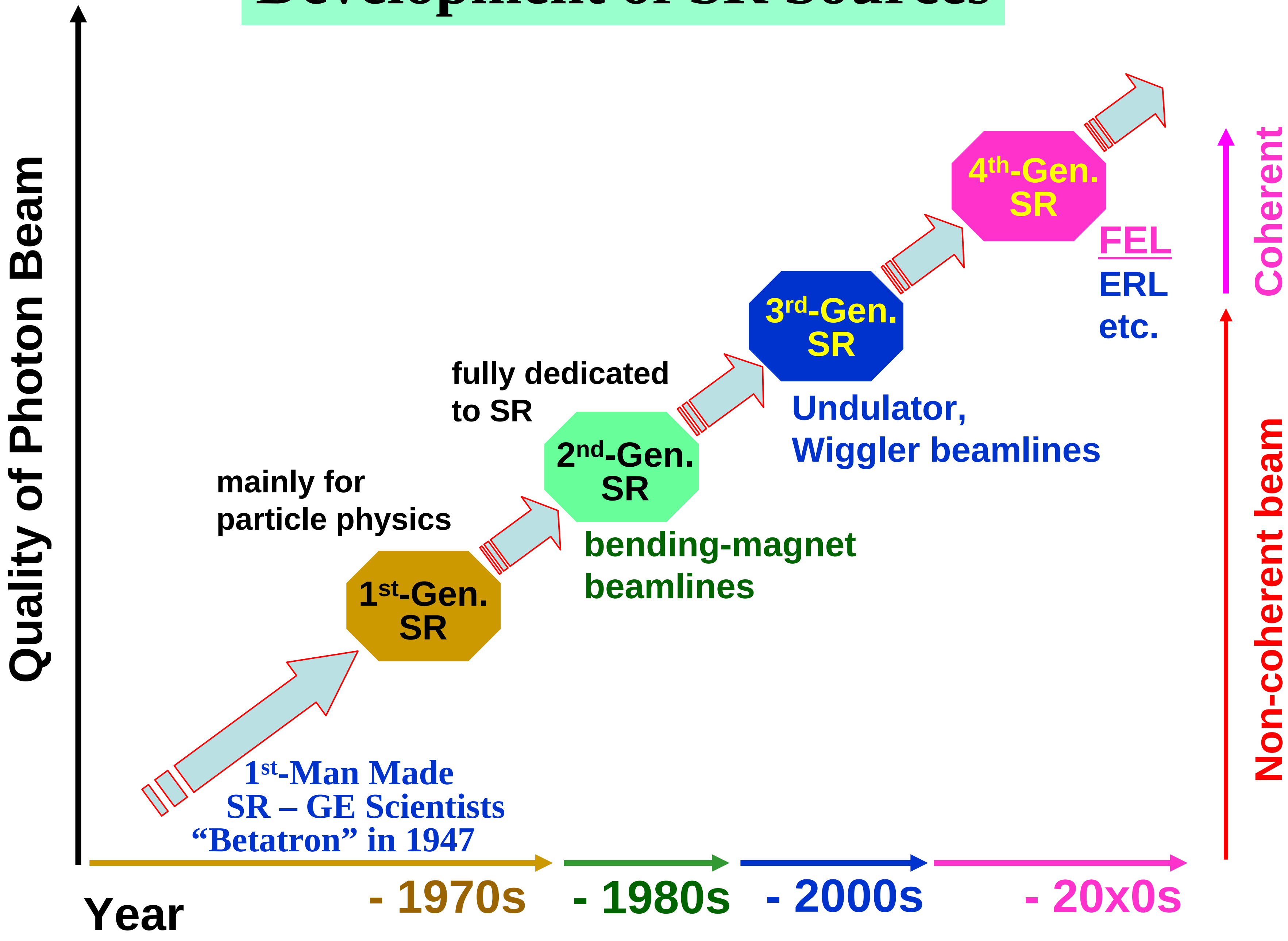

THE ELECTROMAGNETIC SPECTRUM
SR
mm
μm
nm
Å
Wavelength (in meters)
10^3 10^2 10^1 1 10^-1 10^-2 10^-3 10^-4 10^-5 10^-6 10^-7 10^-8 10^-9 10^-10 10^-11 10^-12
longer
shorter
Size of a wavelength
Soccer Field
House
Baseball
This Period
Cell
Bacteria
Virus
Protein
Water Molecule
Common name of wave
RADIO WAVES
RARED
VISIBLE
ULTRAVIOLET
"HARD" X RAYS
MICROWAVES
"SOFT" 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

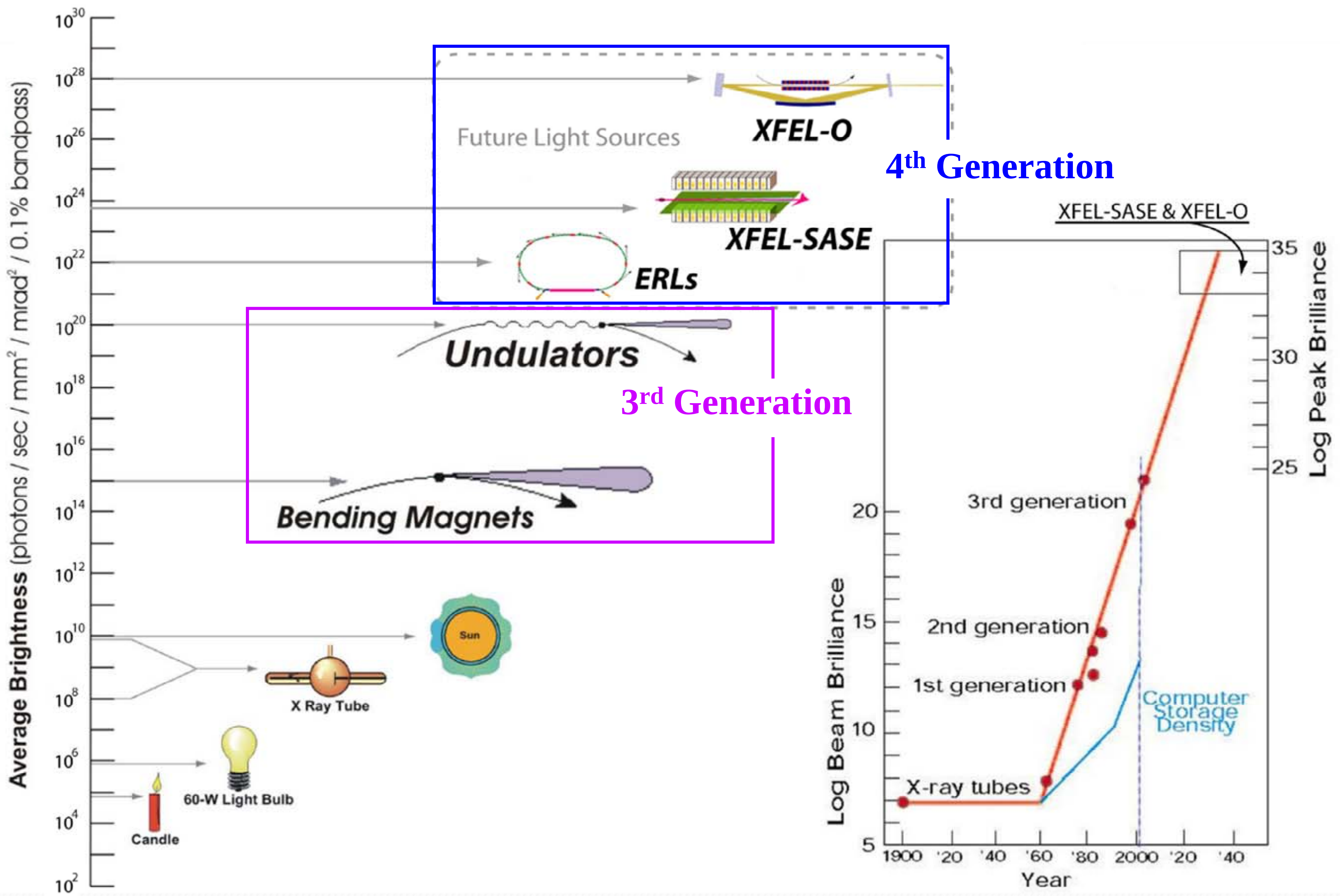
Synchrotron Radiation

- 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 in 1947.
- The curved trajectory can be created by bending magnet, wiggler and undulator magnets in accelerators.



Development of SR Sources





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
4th 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

How a Synchrotron Works

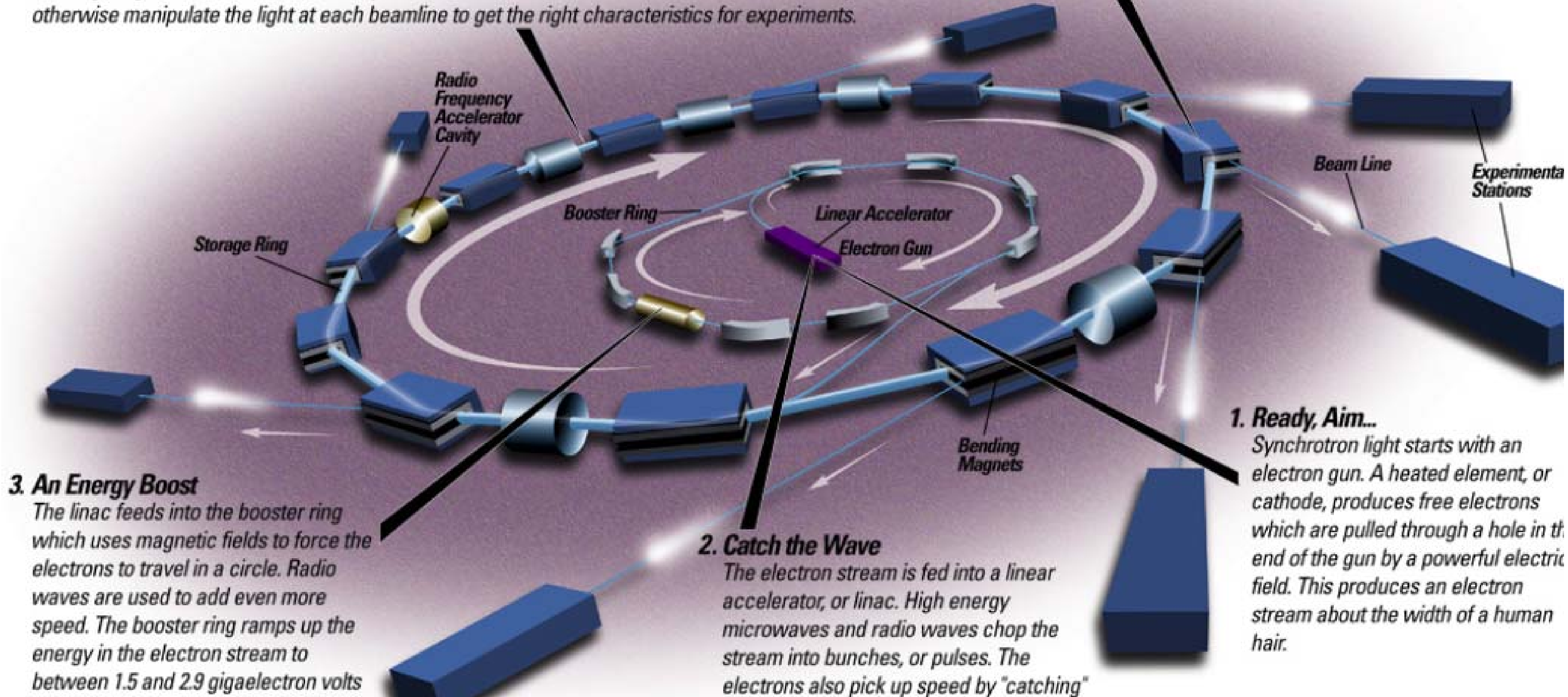
4. Storage Ring

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 electri 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.

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)

*** SR Users are more than 100,000 in the world.**

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

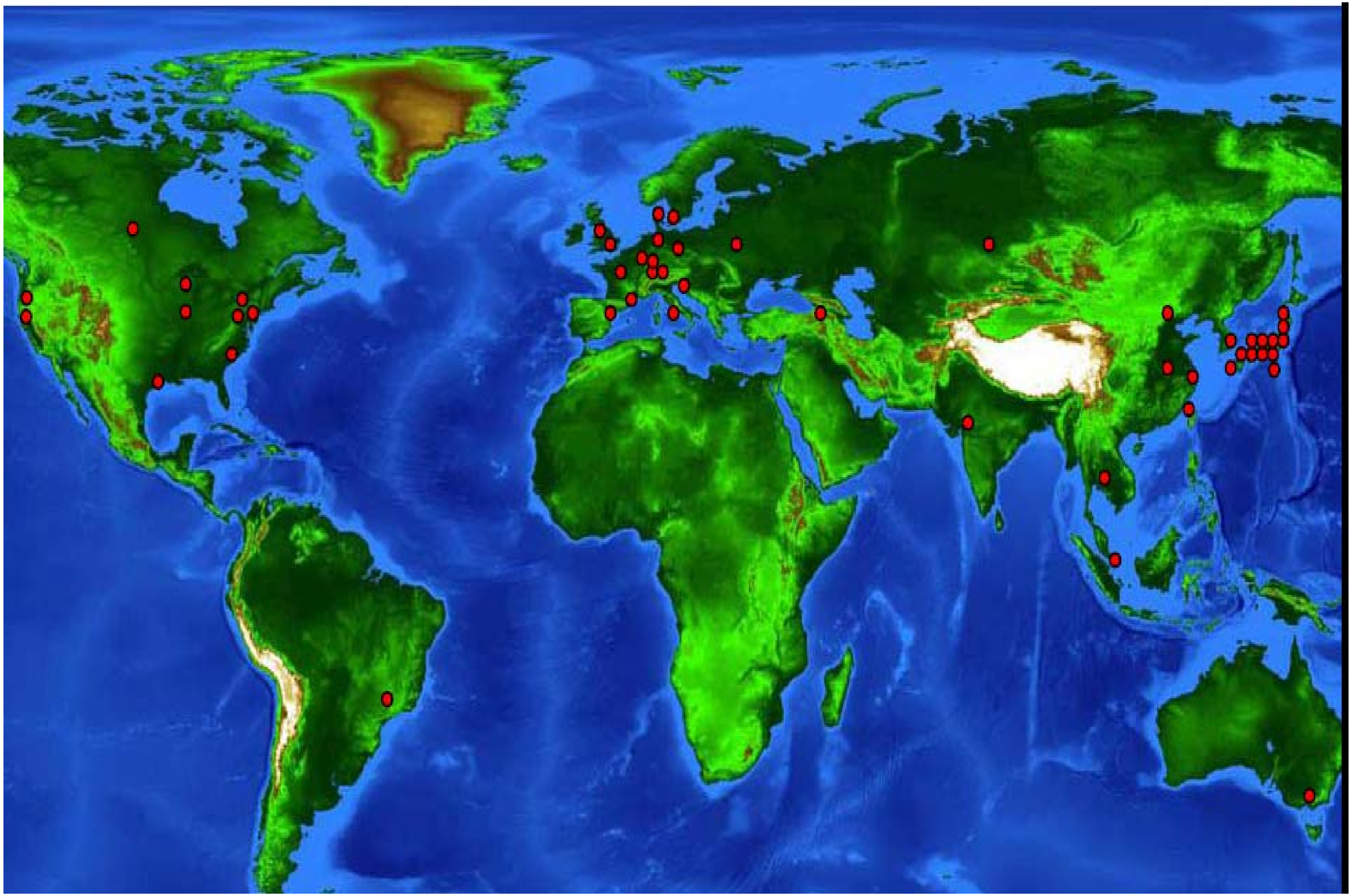
- Over the past 40 years, design and construction of dedicated SR facilities have been continuously carried out all over the world. Currently there are about 50 SR light sources in operation and about 23 of them are third generation light sources;

- Before 1970s, 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, undulators and Wigglers;
- 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.

- *Since the late 1990s, fourth generation light sources (so-called free electron lasers) have been started designing and construction.*
- *Since the laet 2000s, energy recovery linac (ERL) light sources have been started designing and construction.*

Synchrotron Radiation Facilities (in operation)

Asia-Oceania : 26 Europe : 25 America : 18



www.lightsources.org

3rd Generation Light Sources

- 3rd generation light sources, based on advanced undulators, Wigglers, 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 (6 Gev), APS (7 GeV), Spring-8 (8 GeV);

- Low energy ones (<2.5GeV): ALS, Elettra, TLS, BESSY-II, MAX-II, LNSL, … ;

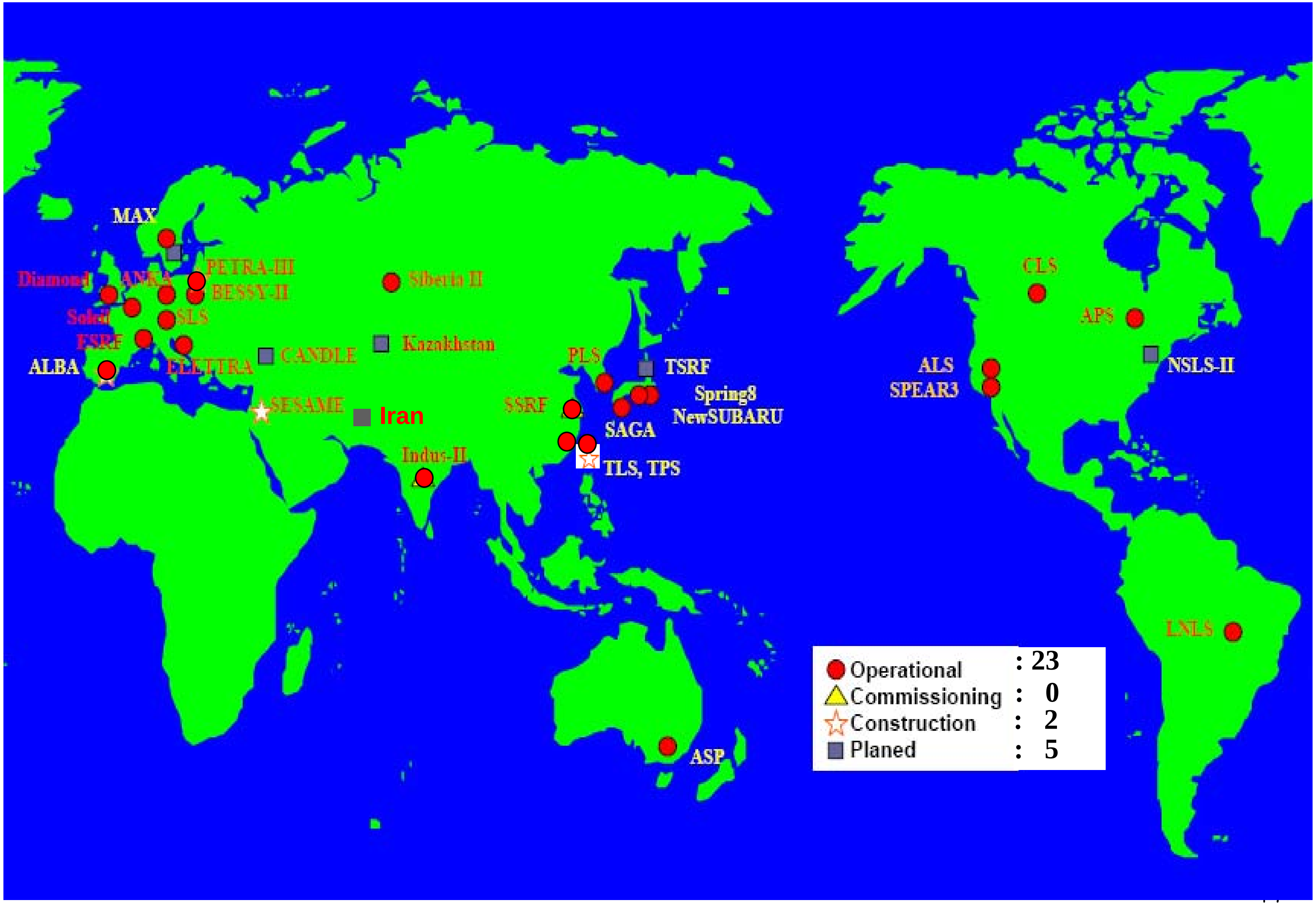
- Intermediate energy ones (2.5 ~ 4.0GeV): PLS/PLS-II, ANKA, SLS, CLS, SPEAR3, Diamond, SOLEIL, INDUS-II , ASP, SSRF, ALBA, NSLS-II, TPS, MAX-IV, … ;

- 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 in operation 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;

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 (in upgrading)	2.5 (3.0)	280.56	18.6 (5.8)	200 (400)	12×6.8m (+ 12x4.2m)	Operation (1995) (2011)
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)

New 3rd Generation Light Sources
in Operation, 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	Operaation
23. PETRA-III	6.0	2304	1.0	100	1×20m, 8×5m	Operation
24. ALBA	3.0	268.8	4.5	400	4×8m, 12×4.2m, 8×2.6m	Operation
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	Commissioning
29. MAX IV	3.0	287.2	0.8	500	12×4.6m	Construction
30. TSRF	TBD	TBD	TBD	TBD	TBD	Planned

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)

- **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.**

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

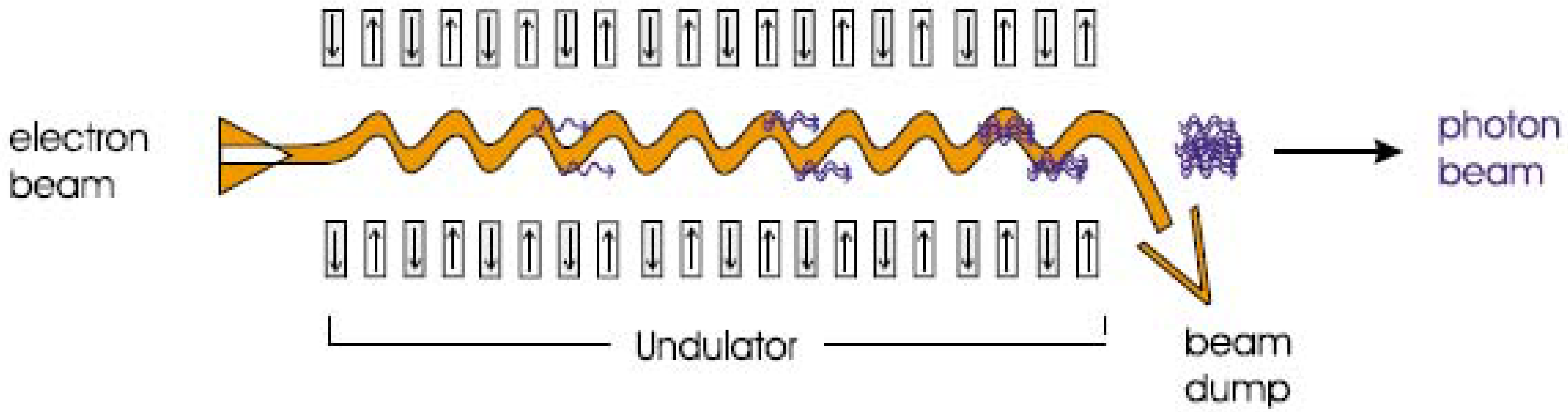
New Light Source

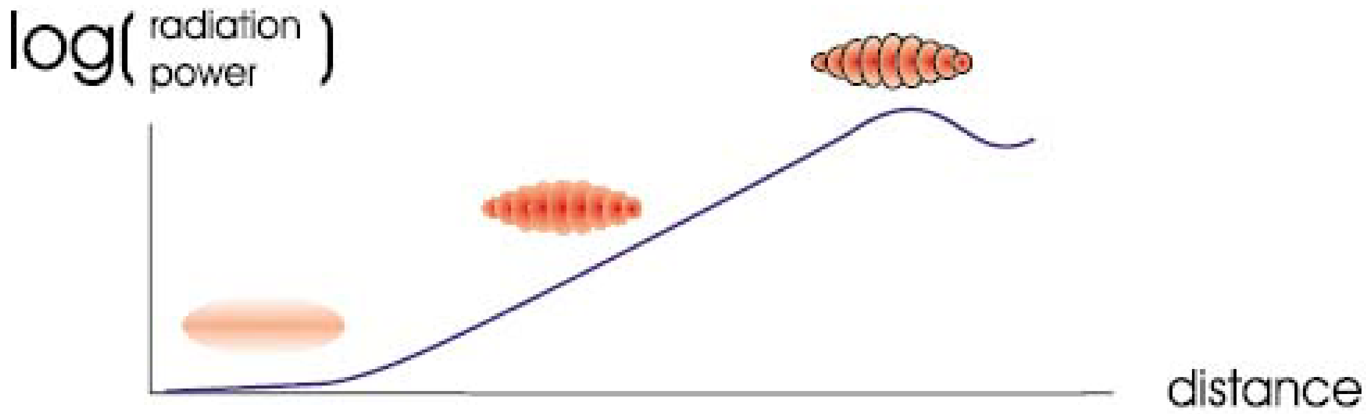
- X-Ray Free Electron Laser (XFEL)
- Energy Recovery Linear-Accelerator (ERL)

} 4th Generation SR

X-Ray Free Electron Laser (XFEL)

Self Amplification of Spontaneous Emission (SASE)

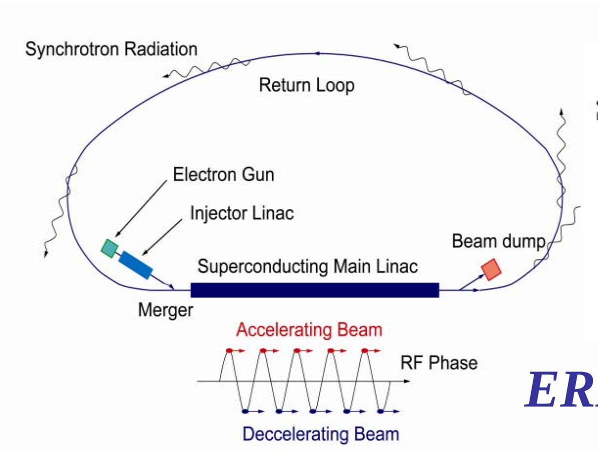




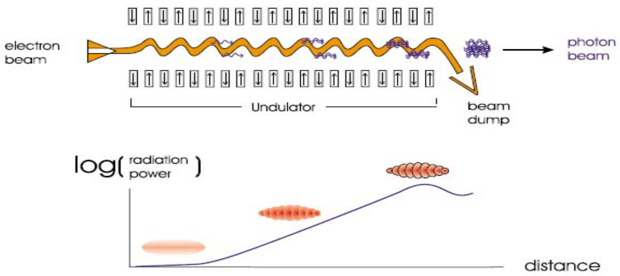
XFELs around the World

Project	Type	Location	Country	e-Beam (GeV)	Photon (nm)	Status
LEUTL	SASE	APS	USA	0.22	660-130	Since 2001
TTF I	SASE	DESY	Germany	0.3	125-85	Since 2002
SDL DUV-FEL	HGHG	SDL/NSLS	USA	0.145	400-100	Since 2002
FLASH (TTF)	SASE	DESY	Germany	1.0	12 - 6	Since 2006
SCSS Prototype	SASE	SPring-8	Japan	0.25	150-50	Since 2006
LCLS	SASE	SLAC	USA	14.5	0.15	in 2009
SACLA	SASE	SPring-8	Japan	8	0.1 (0.05)	in 2011
Euro XFEL	SASE	DESY	Germany	17.5	0.05	in 2014
PAL XFEL	SASE	Pohang	Korea	10	0.06	in 2014
PSI XFEL	SASE	PSI	Swiss	5.8	0.1	(in 2016)
SPARC	SASE	INFN Frascati	Italy	0.15	500	in 2007
FERMI	HGHG	Trieste	Italy	1.2	10	in 2011
DUV/Soft X-ray	HGHG	SINAP	China	0.8-1.3	>3	approved
Soft X-ray FEL	HGHG	BESSY	Germany	2.3	64 - 1.2	proposal
SPARX	HHG	INFN Frascati	Italy	1 - 2	1.5	proposal
4GLS	HGHG	Daresbury	GB	0.6	100 - 19	proposal
ARC-EN CIEL	HHG	Saclay	France	0.7	1	proposal

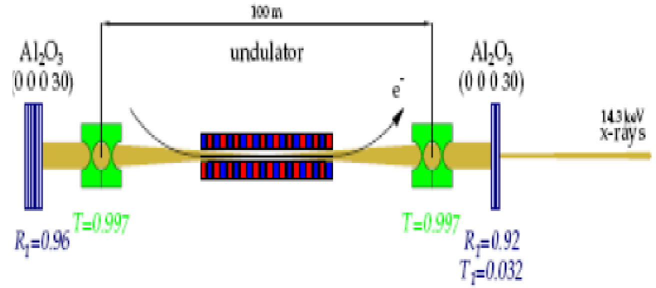
Functions of XFEL(SASE), XFEL-O & ERL



ERL



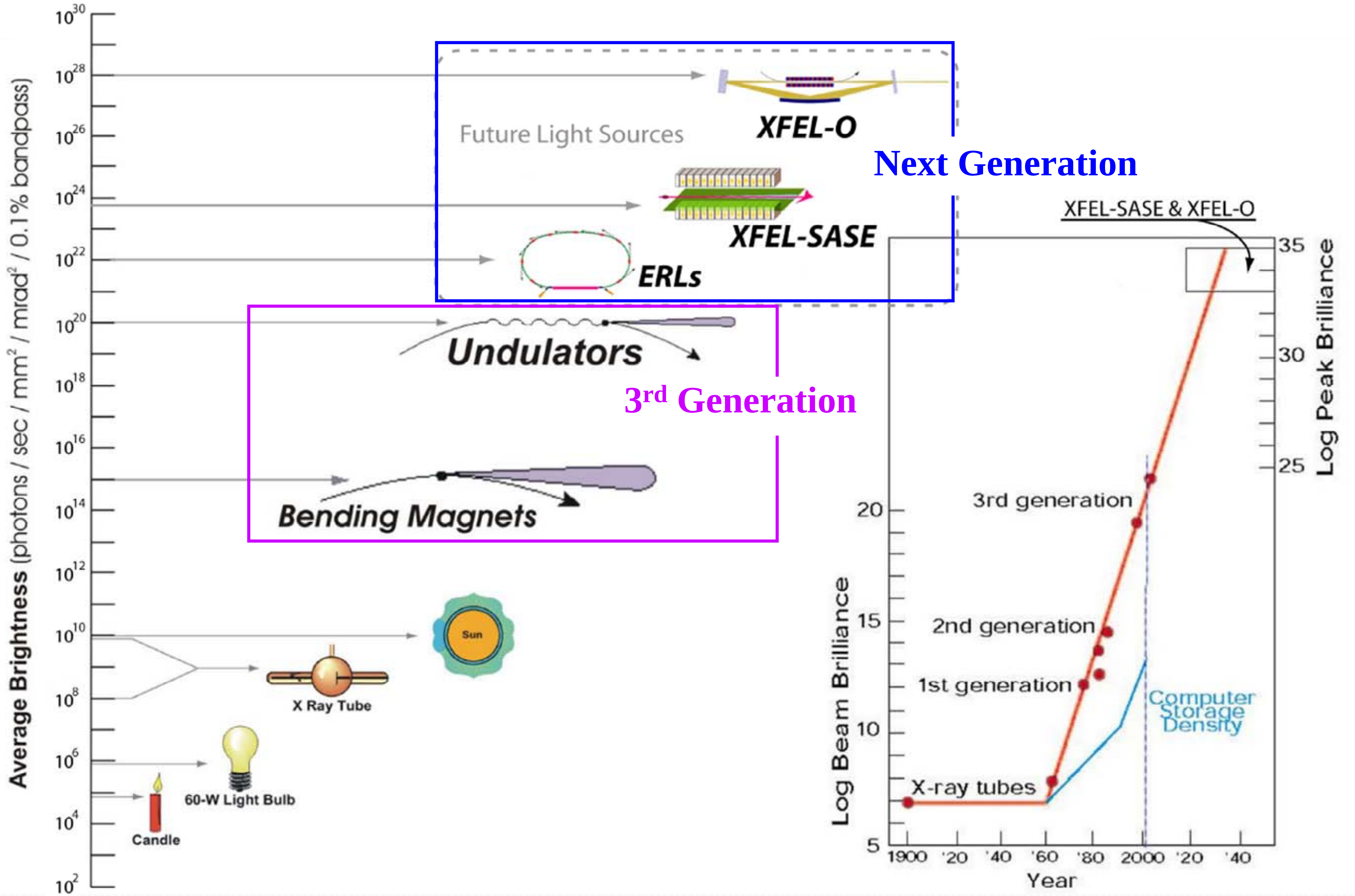
SASE-FEL



XFEL-O

SR	average brilliance	peak brilliance	repetition rate (Hz)	coherent fraction	bunch width(ps)	# of BLs	Remark
XFEL (SASE)	$\sim 10^{22\sim 24}$	$\sim 10^{33}$	100~10K	100%	0.1	few	One-shot measurement
XFEL-O (Option)	$\sim 10^{27}$	$\sim 10^{33}$	~1M	100%	1	few	Single mode FEL
ERL	$\sim 10^{23}$	$\sim 10^{26}$	1.3G	~20%	0.1~1	~30	Non-perturbed measurement
3rd-SR	$\sim 10^{20\sim 21}$	$\sim 10^{22}$	~500M	0.1%	10~100	~30	Non-perturbed measurement

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

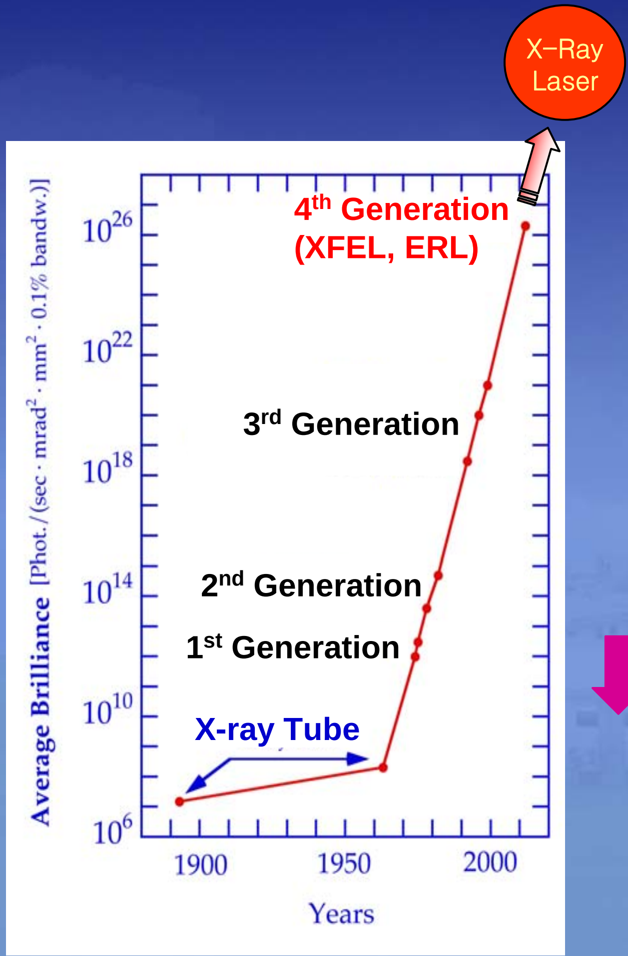


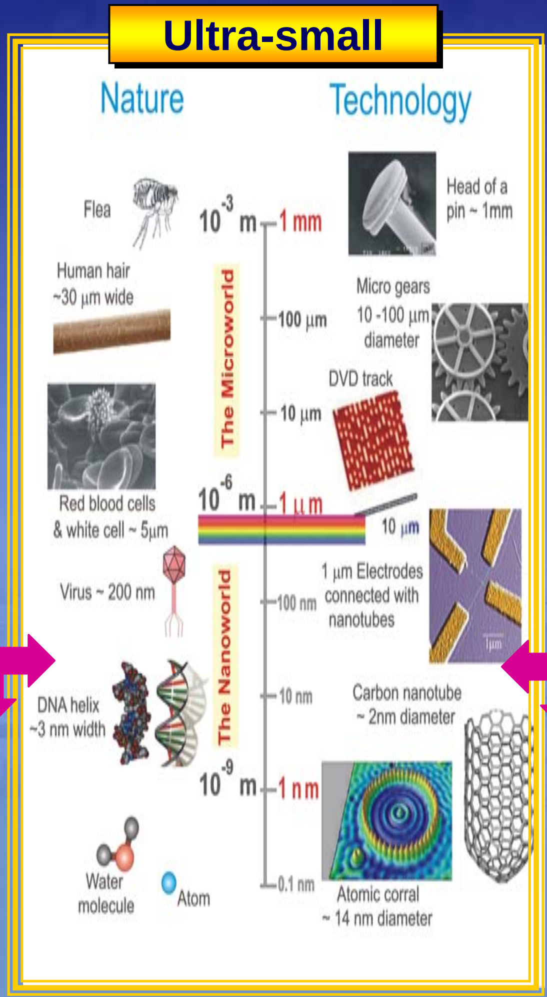
Average Brightness (photons / sec / mm² / mrad² / 0.1% bandpass)
Future Light Sources
XFEL-O
XFEL-SASE
ERLs
Next Generation
Undulators
3rd Generation
Bending Magnets
Sun
X Ray Tube
60-W Light Bulb
Candle
XFEL-SASE & XFEL-O
Log Peak Brilliance
Log Beam Brilliance
3rd generation
2nd generation
1st generation
X-ray tubes
Computer Storage Density
Year

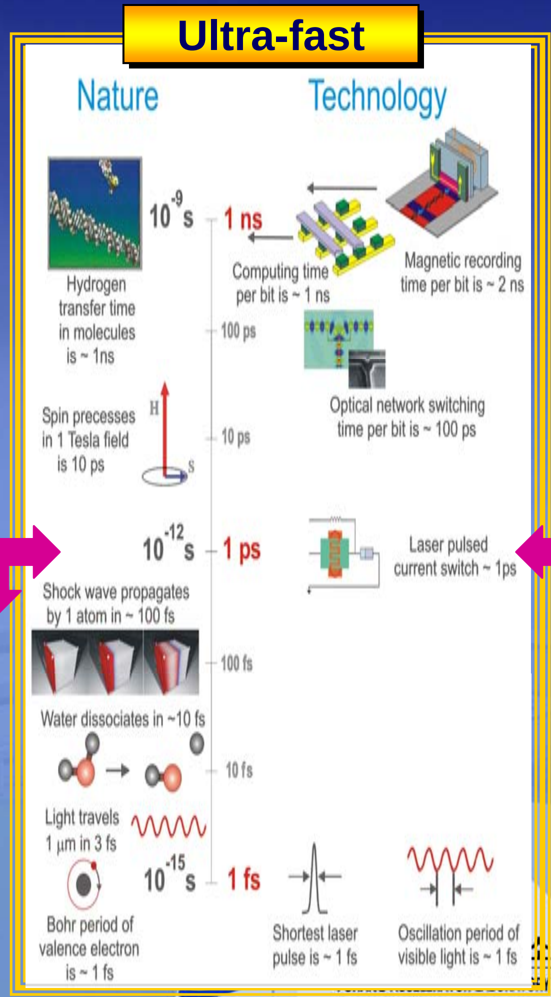
Applications of XFEL in Science

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.
- Two 4th generation facilities (XFEL) are in operation and more facilities are coming soon, and thus 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

SR Source is so essential for

your researches

in the highest quality!

M. Ree's Group (POSTECH)

1. Research Fields

<Polymer Physics>

- Nanostructures and Morphology
- 3D Single Molecule Structure
- Polymer Chain Conformation
- Surface, Interfaces
- Electric, dielectric, optical, thermal, mechanical properties
- Sensor properties

<Polymer Synthesis>

- Functional polymers
- Structural polymers
- Polypeptides, DNA, RNA

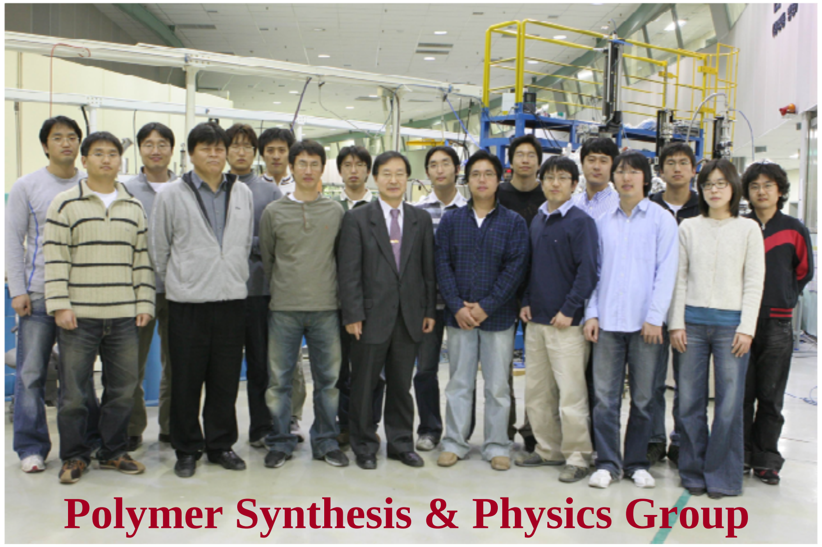
http://www.postech.ac.kr/chem/mree

Scattering / Reflectivity:
Synchrotron X-Ray, Neutron, Lasers

- ♦ Polymers for Microelectronics, Displays, & Sensors
- ♦ Polymers for Implants & Biological Systems
- ♦ Proteins & Polynucleic acids (DNA, RNA)

2. Group Members

16 Ph.D. candidates
2 Postdoctors
2 Technicians
4 Scientists (PLS: Coworkers)



Polymer Synthesis & Physics Group