Overview of Synchrotron Radiation (SR)

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RIKEN Harima Institute
MEXT, Japan
AOFSRR

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Prof. Osamu Shimomura (KEK, Japan)
Prof. Masaki Takata (RIKEN/Spring-8/U Tokyo, Japan)
Prof. Zhentang Zhao (SSRF, China)
Prof. Tetsuya Ishikawa (RIKEN/Spring-8, Japan)
Prof. Hiroshi Kawata (KEK, Japan)
Outline

1. Introduction
   - AOFSRR / Cheiron School
   - History of SR
   - SR

2. 1\textsuperscript{st}-2\textsuperscript{nd} Generation SR

3. 3\textsuperscript{rd} Generation SR
   - Current Status of 3\textsuperscript{rd} Generation SR Facilities
   - Applications in Science & Technology

4. 4\textsuperscript{th} Generation SR
   - Current Status of 4\textsuperscript{th} Generation SR Facilities
   - Applications in Science & Technology

5. Summary & Conclusions
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, 06-09/07/2010/Pohang, Korea
  6th, 24-28/10/2011/Bangkok, Thailand

- 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
  4th, 09-18/10/2010
  5th, 26/09-05/10/2011
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Swee Ping Chia (Univ. Malaya/Malaysia)
Tran Duc Thiep (Institute of Physics/Vietnam)
Asia-Oceania Forum for SR Research

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
SSL (2001)
0.7 GeV
PLS (1994)
2.5 GeV (-2010)
3.0 GeV (2011-
PAL-XFEL (2014)
10.0 GeV
UVSOR (1983)
0.75 GeV
PF (1982)
2.5 GeV
SR (1997)
8.0 GeV
Ritsumeiken (2002)
1.3 GeV
SAGA (2005)
1.2 GeV
SCSS (2010)
8.0 GeV
TLS (1993)
1.5 GeV
TPS (2013)
3.0-3.3 GeV
AS (2006)
3.0 GeV

M. Ree
July 6-9, 2010 @ Pohang
Cheiron School 2011

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Secretary: Masaki Takata (RIKEN/SPring-8, Japan)

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## Cheiron School 2011 - Program

<table>
<thead>
<tr>
<th>Time</th>
<th>Sep 26 Wed</th>
<th>Sep 27 Thurs</th>
<th>Sep 28 Fri</th>
<th>Sep 29 Sat</th>
<th>Oct 3 Mon</th>
<th>Oct 4 Tues</th>
<th>Oct 5 Wed</th>
</tr>
</thead>
<tbody>
<tr>
<td>8:00-10:00</td>
<td>Registration</td>
<td>Light Source 2</td>
<td>VUV &amp; SX Optics</td>
<td>Powder Diffraction</td>
<td>S. Kuyck (KUL)</td>
<td>Extreme Conditions</td>
<td>Advanced Experiments in Experiments with actinide ions (Fermilab)</td>
</tr>
<tr>
<td>8:00-10:00</td>
<td>Public Relations Center (Fellowship)</td>
<td>D. Allanhall (RSL)</td>
<td>D. Allanhall (RSL)</td>
<td>D. Allanhall (RSL)</td>
<td>Tett (Euratom)</td>
<td>Tett (Euratom)</td>
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<tr>
<td>10:00-10:30</td>
<td>Opening remarks</td>
<td>Coffee Break</td>
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<tr>
<td>10:30-11:00</td>
<td>Overview of SR BL-12 (PALUPS)</td>
<td>X-ray Baseline Design 1</td>
<td>X-ray Baseline Design 2</td>
<td>X-ray Baseline Design 3</td>
<td>X-ray Diffraction</td>
<td>S. Kuyck (KUL)</td>
<td>S. Kuyck (KUL)</td>
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<td>11:00-12:00</td>
<td>Lunch</td>
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<tr>
<td>12:00-14:00</td>
<td>Ring Accelerator Physics</td>
<td>H. Tanaka (RIKEN)</td>
<td>H. Tanaka (RIKEN)</td>
<td>H. Tanaka (RIKEN)</td>
<td>H. Tanaka (RIKEN)</td>
<td>H. Tanaka (RIKEN)</td>
<td>H. Tanaka (RIKEN)</td>
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<td>14:30-15:00</td>
<td>Light Source 1 (RIKEN)</td>
<td>Safety Education</td>
<td>XAFS</td>
<td>X-ray Microscopy</td>
<td>X-ray Microscopy</td>
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<td>15:00-15:30</td>
<td>Coffee Break</td>
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<td>Coffee Break</td>
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<tr>
<td>15:30-16:00</td>
<td>Site Visit</td>
<td>Meet the Experts</td>
<td>Meet the Experts</td>
<td>Meet the Experts</td>
<td>Meet the Experts</td>
<td>Meet the Experts</td>
<td>Meet the Experts</td>
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<tr>
<td>16:00-16:30</td>
<td>Welcome Reception</td>
<td>Dinner</td>
<td>Dinner</td>
<td>Dinner</td>
<td>Dinner</td>
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<td>Dinner</td>
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<tr>
<td>16:30-17:00</td>
<td>Welcome Reception at SPS</td>
<td>Dinner</td>
<td>Dinner</td>
<td>Dinner</td>
<td>Dinner</td>
<td>Dinner</td>
<td>Dinner</td>
</tr>
<tr>
<td>17:00-17:30</td>
<td>Dinner</td>
<td>Dinner</td>
<td>Dinner</td>
<td>Dinner</td>
<td>Dinner</td>
<td>Dinner</td>
<td>Dinner</td>
</tr>
<tr>
<td>17:30-18:00</td>
<td>Farewell Reception</td>
<td>Hokusai-kan</td>
<td>Hokusai-kan</td>
<td>Hokusai-kan</td>
<td>Hokusai-kan</td>
<td>Hokusai-kan</td>
<td>Hokusai-kan</td>
</tr>
</tbody>
</table>

* "SPECTRA" is a computer software developed at SPR to calculate surface properties of synchrotron radiation emitted from bending magnets, wigglers and undulators. This workshop is open for those who are interested and will be held only if the number of attendees is larger than 5."
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
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.
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.

- $e/m = 1.76 \times 10^8$ c/g
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."
The Supernova was observed by ancient Korean/Japanese/Chinese astronomers in the year 1054. The pulsar (a star that spins very fast) produces highly relativistic electrons which themselves produce synchrotron radiation (the bright compact emission) in the magnetic field of the Nebula (a cloud of dusts and gasses; a new star is produced from nebulae).

* Supernova is an exploding star. At least a supernova occurs per decade in our galaxy.
How a Synchrotron Works

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 the 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 99.99988 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.

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.

Source: University of Saskatchewan
Paradigm Media Group Inc.
Pohang Light Source

2.5 GeV Linac

2.5 GeV Storage Ring

Beamlines and Exp. Stations

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

<table>
<thead>
<tr>
<th>Beam energy (GeV)</th>
<th>2.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circumference(m)</td>
<td>280.56</td>
</tr>
<tr>
<td>Natural emittance (nm)</td>
<td>18.9</td>
</tr>
<tr>
<td>Rf (MHz)</td>
<td>500.082</td>
</tr>
<tr>
<td>Rf voltage (MV)</td>
<td>1.6</td>
</tr>
<tr>
<td>Tunes</td>
<td>14.28/8.18</td>
</tr>
<tr>
<td>Super-periods</td>
<td>12</td>
</tr>
</tbody>
</table>

30 B/L (9 IDs)
1 FEL (THz BL)
10 B/L (in plan)
41 (Total)
52 (in full capacity)

M. Ree
Cheiron School-2011
Shanghai Light Source

Electron Linac 150MeV

Booster 3.5GeV, C=180m

Storage Ring 3.5GeV, C=432m

Electron Linac 150MeV

M. Ree Cheiron School-2011
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 ($1/\gamma$);
- 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 22 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 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
Outline

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2. 1\textsuperscript{st}-2\textsuperscript{nd} Generation SR

3. 3\textsuperscript{rd} Generation SR
   - Current Status of 3\textsuperscript{rd} Generation SR Facilities
   - Applications in Science & Technology

4. 4\textsuperscript{th} Generation SR
   - Current Status of 4\textsuperscript{th} Generation SR Facilities
   - Applications in Science & Technology

5. Summary & Conclusions
### 1st Generation SR Facilities (1)

<table>
<thead>
<tr>
<th>Facility</th>
<th>Location</th>
<th>Energy (GeV)</th>
<th>Operation Year (Status)</th>
</tr>
</thead>
<tbody>
<tr>
<td>VEPP-2M</td>
<td>Russia</td>
<td>0.7</td>
<td>1965-1999 (Upgraded)</td>
</tr>
<tr>
<td>SPEAR-I(SSRL)</td>
<td>USA</td>
<td>3.0-3.5</td>
<td>1972-1992 (Upgraded)</td>
</tr>
<tr>
<td>DORIS(DESY)</td>
<td>Germany</td>
<td>3.7-5.2</td>
<td>1974-1993 (Upgraded)</td>
</tr>
<tr>
<td>SURF-II(NBS)</td>
<td>USA</td>
<td>0.28</td>
<td>1974-1997 (Upgraded)</td>
</tr>
<tr>
<td>Accum.Ring(KEK)</td>
<td>Japan</td>
<td>6.5</td>
<td>Partly Ded.</td>
</tr>
<tr>
<td>CESR(CHESS)</td>
<td>USA</td>
<td>5.5</td>
<td>1979-2002 (Upgraded)</td>
</tr>
<tr>
<td>VEPP-3(INP)</td>
<td>Russia</td>
<td>2.2</td>
<td>1979-1985 (Upgraded)</td>
</tr>
<tr>
<td>ELSA</td>
<td>Germany</td>
<td>1.5-3.5</td>
<td>1987 (Operation)</td>
</tr>
<tr>
<td>TRISTAN MR</td>
<td>Japan</td>
<td>6.0-30</td>
<td>1987-1995 (Shutdown)</td>
</tr>
<tr>
<td>BEPC(IHEP)</td>
<td>China</td>
<td>1.5-2.8</td>
<td>1989-2004 (Upgraded)</td>
</tr>
<tr>
<td>DCI(LURE)</td>
<td>France</td>
<td>1.8</td>
<td>Dedicated</td>
</tr>
</tbody>
</table>

1st Generation? Synchrotron light sources were basically beamlines built onto the existing facilities designed for particle physics studies.
### 1st Generation SR Facilities (2)

<table>
<thead>
<tr>
<th>Facility</th>
<th>Location</th>
<th>Energy (GeV)</th>
<th>Operation Year (Status)</th>
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</thead>
<tbody>
<tr>
<td>ASTRID</td>
<td>Denmark</td>
<td>0.6</td>
<td>1990 (Operation)</td>
</tr>
<tr>
<td>VEPP-4</td>
<td>Russia</td>
<td>5.0-7.0</td>
<td>1994 (Operation)</td>
</tr>
<tr>
<td>DAΦNE</td>
<td>Italy</td>
<td>0.51</td>
<td>1999 (Operation)</td>
</tr>
<tr>
<td>TSSR</td>
<td>Japan</td>
<td>1.5</td>
<td>Proposed</td>
</tr>
<tr>
<td>AmPS</td>
<td>Netherland</td>
<td>0.9</td>
<td>Planned use</td>
</tr>
<tr>
<td>EUTERPE</td>
<td>Netherland</td>
<td>0.4</td>
<td>Planned use</td>
</tr>
<tr>
<td>N-100</td>
<td>Russia</td>
<td>2.2</td>
<td>Dedicated</td>
</tr>
<tr>
<td>HP-2000</td>
<td>Russia</td>
<td>5.5</td>
<td>Partly Ded.</td>
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### 2nd Generation SR Facilities (1)

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

2nd Generation? Synchrotron light sources were dedicated to the production of synchrotron radiation and employed electron storage rings to harness the synchrotron light.

M. Ree Cheiron School-2011
## 2nd Generation SR Facilities (2)

<table>
<thead>
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<tbody>
<tr>
<td>TERAS</td>
<td>Japan</td>
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<td>Dedicated</td>
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<tr>
<td>Siberia-I</td>
<td>Russia</td>
<td>0.45</td>
<td>Dedicated</td>
</tr>
<tr>
<td>TNK</td>
<td>Russia</td>
<td>1.2-1.6</td>
<td>Dedicated</td>
</tr>
<tr>
<td>CAMD</td>
<td>USA</td>
<td>1.2</td>
<td>(Operation)</td>
</tr>
</tbody>
</table>
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
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, 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 in operation at DESY and the PEP-X proposal at SLAC.

M. Ree

Cheiron School-2011
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;
  - One more will be operational in the coming years, SESAME probably in 2013;
  - 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 in Operation (1)

<table>
<thead>
<tr>
<th>Light Source</th>
<th>Energy (GeV)</th>
<th>Circumference (m)</th>
<th>Emittance (nm.rad)</th>
<th>Current (mA)</th>
<th>Straight Section</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. ALS</td>
<td>1.9</td>
<td>196.8</td>
<td>6.3</td>
<td>400</td>
<td>12×6.7m</td>
<td>Operation (1993)</td>
</tr>
<tr>
<td>2. ESRF</td>
<td>6.0</td>
<td>844.4</td>
<td>3.7</td>
<td>200</td>
<td>32×6.3m</td>
<td>Operation (1993)</td>
</tr>
<tr>
<td>3. TLS</td>
<td>1.5</td>
<td>120</td>
<td>25</td>
<td>240</td>
<td>6×6m</td>
<td>Operation (1993)</td>
</tr>
<tr>
<td>4. ELETTRA</td>
<td>2.0/2.4</td>
<td>259</td>
<td>7</td>
<td>300</td>
<td>12×6.1m</td>
<td>Operation (1994)</td>
</tr>
<tr>
<td>5. PLS</td>
<td>2.5 (3.0)</td>
<td>280.56</td>
<td>18.6 (5.8)</td>
<td>200 (400)</td>
<td>12×6.8m (+ 12x4.2m)</td>
<td>Operation (1995) (2011)</td>
</tr>
<tr>
<td>(in upgrading)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6. APS</td>
<td>7.0</td>
<td>1104</td>
<td>3.0</td>
<td>100</td>
<td>40×6.7m</td>
<td>Operation (1996)</td>
</tr>
<tr>
<td>7. SPring-8</td>
<td>8.0</td>
<td>1436</td>
<td>2.8</td>
<td>100</td>
<td>44×6.6m, 4×30m</td>
<td>Operation (1997)</td>
</tr>
<tr>
<td>8. LNLS</td>
<td>1.37</td>
<td>93.2</td>
<td>70</td>
<td>250</td>
<td>6×3m</td>
<td>Operation (1997)</td>
</tr>
<tr>
<td>9. MAX-II</td>
<td>1.5</td>
<td>90</td>
<td>9.0</td>
<td>200</td>
<td>10×3.2m</td>
<td>Operation (1997)</td>
</tr>
<tr>
<td>10. BESSY-II</td>
<td>1.7</td>
<td>240</td>
<td>6.1</td>
<td>200</td>
<td>8×5.7m, 8×4.9m</td>
<td>Operation (1999)</td>
</tr>
<tr>
<td>11. Siberia-II</td>
<td>2.5</td>
<td>124</td>
<td>65</td>
<td>200</td>
<td>12×3m</td>
<td>Operation (1999)</td>
</tr>
<tr>
<td>12. NewSUBARU</td>
<td>1.5</td>
<td>118.7</td>
<td>38</td>
<td>500</td>
<td>2×14m, 4×4m</td>
<td>Operation (2000)</td>
</tr>
</tbody>
</table>
### 3rd Generation Light Sources in Operation (2)

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

<table>
<thead>
<tr>
<th>Light Source</th>
<th>Energy (GeV)</th>
<th>Circumference (m)</th>
<th>Emittance (nm.rad)</th>
<th>Current (mA)</th>
<th>Straight Section</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>22. Indus-2</td>
<td>2.5</td>
<td>172.5</td>
<td>58</td>
<td>300</td>
<td>8×4.5m</td>
<td>Commi.&amp;Opera.</td>
</tr>
<tr>
<td>23. PETRA-III</td>
<td>6.0</td>
<td>2304</td>
<td>1.0</td>
<td>100</td>
<td>1×20m, 8×5m</td>
<td>Construction (commissioning in 2010)</td>
</tr>
<tr>
<td>24. ALBA</td>
<td>3.0</td>
<td>268.8</td>
<td>4.5</td>
<td>400</td>
<td>4×8m, 12×4.2m, 8×2.6m</td>
<td>Construction</td>
</tr>
<tr>
<td>25. SESAME</td>
<td>2.5</td>
<td>133.12</td>
<td>26</td>
<td>400</td>
<td>8×4.44m, 8×2.38m</td>
<td>Construction</td>
</tr>
<tr>
<td>26. TPS</td>
<td>3.0</td>
<td>518.4</td>
<td>1.6</td>
<td>400</td>
<td>6×12m, 18×7m</td>
<td>Construction</td>
</tr>
<tr>
<td>27. CANDLE</td>
<td>3.0</td>
<td>216</td>
<td>8.4</td>
<td>350</td>
<td>16×4.8m</td>
<td>Planned</td>
</tr>
<tr>
<td>28. NSLS-II</td>
<td>3.0</td>
<td>792</td>
<td>2.1</td>
<td>500</td>
<td>15×9.3m, 15×6.6m</td>
<td>Planned</td>
</tr>
<tr>
<td>29. MAX IV</td>
<td>3.0</td>
<td>287.2</td>
<td>0.8</td>
<td>500</td>
<td>12×4.6m</td>
<td>Planned</td>
</tr>
<tr>
<td>30. TSRF</td>
<td>TBD</td>
<td>TBD</td>
<td>TBD</td>
<td>TBD</td>
<td>TBD</td>
<td>Planned</td>
</tr>
</tbody>
</table>
New 3\textsuperscript{rd} Generation Light Sources

Indus-2

PETRA-III

SESAME

ALBA

TPS

CANDLE

NSLS-II

MAX-IV
Third Generation Light Sources

- PLS (upgraded)

Emittance (nm.rad) vs. Energy (GeV) graph showing various light sources and their operational status:
- Operational
- Commissioning
- Construction
- Planned

M. Ree
Cheiron School-2011
Brilliance Improvement

![Diagram showing the progression from a candle to a synchrotron radiation source, with labels for 'Undulators', 'Bending Magnets', and a graph illustrating the increase in peak brilliance over time.]
Main Figures of Merit of 3\textsuperscript{rd} 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/mm²/mrad²/0.1%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 border 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)
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

- Materials (35%)
- Chemistry (22%)
- Mechanical Engineering (3%)
- Bio-Science (15%)
- Physics (10%)
- Iron Steel (4%)
- Surface Science (4%)
- Environmental Science (2%)

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

Users’ publications: ca. 900
Average Impact Factor: 3.8
• 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)**

Selected high-impact stats

<table>
<thead>
<tr>
<th>Publication</th>
<th>2004</th>
<th>2005</th>
<th>2006</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Cell</em></td>
<td>7</td>
<td>6</td>
<td>14</td>
</tr>
<tr>
<td><em>All Nature</em></td>
<td>32</td>
<td>37</td>
<td>37</td>
</tr>
<tr>
<td><em>PRL</em></td>
<td>21</td>
<td>27</td>
<td>37</td>
</tr>
<tr>
<td><em>Science</em></td>
<td>11</td>
<td>9</td>
<td>20</td>
</tr>
<tr>
<td><em>PNAS</em></td>
<td>33</td>
<td>44</td>
<td>43</td>
</tr>
</tbody>
</table>

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

3411 unique users in 2007

2006 Protein Data Bank deposits
Spectacular growth of structural biology

Advent of X-ray SR sources
ESRF, APS, SPring8, etc.
Outline

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   - Current Status of 4th Generation SR Facilities
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5. Summary & Conclusions
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

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

LCLS, Stanford, 2009
(First XFEL demonstration on April 10, 2009)

Beam Energy: 15 GeV
Facility Length: 2 km

SP8-XFEL, SPring-8, 2010

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

E-XFEL, Hamburg, DESY, 2014

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

- **Pohang PLS-II**
  - DBA, 3 GeV, 5.8nm.rad, 20 ID BLs

- **PAL-XFEL**
  - Linac Energy: 10 GeV
  - X-ray Wavelength: 0.06 nm
  - Project Period: 2011 ~ 2014
Energy Recovery Linac (ERL)

Synchrotron Radiation

Return Loop

Electron Gun

Injector Linac

Superconducting Main Linac

Merger

Beam dump

Accelerating Beam

RF Phase

Decelerating Beam
At the case of 8 keV photon energy

<table>
<thead>
<tr>
<th></th>
<th>PF-ERL undulator @ 5 GeV</th>
<th>SP ring-8 undulator @ 8 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Beam current</strong></td>
<td>100 mA</td>
<td>100 mA</td>
</tr>
<tr>
<td><strong>Undulator length</strong></td>
<td>30 m</td>
<td>5 m</td>
</tr>
<tr>
<td><strong>Source size (μm)</strong></td>
<td>horizontal: 37.8</td>
<td>18.2</td>
</tr>
<tr>
<td></td>
<td>vertical: 37.8</td>
<td>18.2</td>
</tr>
<tr>
<td><strong>Source div. (μrad)</strong></td>
<td>horizontal: 4.1</td>
<td>9.8</td>
</tr>
<tr>
<td></td>
<td>vertical: 4.1</td>
<td>9.8</td>
</tr>
<tr>
<td><strong>Beam size @ 50 m (μm)</strong></td>
<td>horizontal: 244</td>
<td>510</td>
</tr>
<tr>
<td></td>
<td>vertical: 244</td>
<td>510</td>
</tr>
<tr>
<td><strong>Average brilliance (ph/s/0.1%/mm²/m²)</strong></td>
<td>6.0 x 10²³</td>
<td>7.6 x 10²²</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.2 x 10²¹</td>
</tr>
<tr>
<td>% beam coherence</td>
<td>19</td>
<td>15</td>
</tr>
</tbody>
</table>

M. Ree

Cheiron School-2011
## Functions of XFEL (SASE), XFEL-O & ERL

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

(brilliance: photons/mm²/mrad²/0.1%/s @ 10 keV)
Applications of XFEL in Science

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

1. Introduction
   - AOFSRR / Cheiron School
   - History of SR
   - SR

2. 1\textsuperscript{st}-2\textsuperscript{nd} Generation SR

3. 3\textsuperscript{rd} Generation SR
   - Current Status of 3\textsuperscript{rd} Generation SR Facilities
   - Applications in Science & Technology

4. 4\textsuperscript{th} Generation SR
   - Current Status of 4\textsuperscript{th} Generation SR Facilities
   - Applications in Science & Technology

5. Summary & Conclusions
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.
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

2. Group Members

15 Ph.D. candidates
2 Postdoctoral researchers
2 Technicians
4 Scientists (PLS: Coworkers)

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)

Polymer Synthesis & Physics Group
Thank you very much for your attention !!!