A retrospect and prospect of the Photon Factory

Toshiaki Ohta
Birth of synchrotron radiation (1960s)

- Pioneering work was performed at NBS by Madden and Codling, using a small ring SURF (0.18 GeV) in 1961.

- Some were newly constructed for SR uses.
  - Tantalus-I (Wisconsin) 0.24 GeV in 1968
  - INS-SOR ring (Tanashi, Tokyo) 0.3 GeV in 1975
Hard X-ray Synchrotron Radiation sources (1970s)

- Conversion of High energy rings
  - SPEAR (SLAC) 2.2-4.5 GeV
  - 1973 Parasitic use
  - 1978 Dedicated to SR

- Construction of dedicated hard X-ray rings (1975)
  - Proposal 1 SRS 2 GeV (Daresbury, UK)
  - Proposal 2 NSLS 2.5 GeV (BNL, USA)
  - Proposal 3 PF 2.5 GeV (KEK, Japan)
Prof. Kazutake KOHRA  
(Univ. Tokyo, X-ray optics)

launched a campaign of constructing a high energy storage ring for SR as early as possible at society meetings and symposia since 1970.

Science Council of Japan recommended the government to implement a National Synchrotron Radiation Laboratory in Nov. 1974.
Photon Factory project as a subsidiary of KEK

Prof. Kohra

Prof. Nishikawa
User Community for the Photon Factory Project (〜1975)

Organizer: K. Kohra (X-ray optics, U.Tokyo)

K. Fuke (Accelerators, U. Tokyo)
H. Kuroda (Spectroscopy U.Tokyo)
H. Kamata (Spectroscopy, U.Tokyo)
I. Tanaka (Spectroscopy, TIT)
T. Sasaki (Spectroscopy, U. Tokyo)
Y. Iidaka (Crystallography, U. Tokyo)
S. Kikuta (X-ray Optics, U.Tokyo)
N. Kato (X-ray diffraction, Nagoya Univ.)
T. Mitsui (X-ray scattering, Osaka Univ.)
S. Namba (X-ray Lithography, Osaka Univ.)
S. Ebashi (Medicine, U.Tokyo)

PF Project Office
M. Ando
T. Ohta

Accelerators
I. Sato LINAC
M. Kihara Storage ring

Members: 300 in total.
Budget request for the Photon Factory Project in 1977

Total budget: 18.4 billion yen!

2.5 GeV storage ring

2.5 GeV LINAC

Office building for staff and users

Experimental hall

BL-11: VUV, soft X-ray (solid)
BL-12: VUV, soft X-rays (gases)
BL-10: Hard X-rays
BL-15: Hard X-rays
BL-14: Hard X-rays (Wiggler)
In 1978, a budget for preliminary investigation was approved.

In 1979, the full-scale budget was approved as a five years project and the construction started.
Linac Building under construction (1980)
Linac Building under construction (1981)

In Jan. 1982, 40 units were all assembled.

In Feb. 1982, electrons were accelerated up to 2.5 GeV
Storage Ring and Experimental Hall under construction
Experimental Hall under construction (1980-1981)
Expansion of the Experimental Hall

Half of SR beams could not be used.

“Number of potential users are almost 1000 and they must complain the shortage of beamlines in near future.”

“All right, we will approve the change of the plan if you bring the list of 1000 users next morning.”
Experimental Hall in 1982
On Feb. 11, 1982, the first electron beam was injected to the PF ring. Since then, the staffs of the light source group had been struggling to store the beam in the ring.
Finally, on March 11th, 1982, electron beam (6 mA, 2.5 GeV) was first stored in the PF storage ring.
First experiment in the Photon Factory
Laue Photos of Si and LiNbO$_3$ crystals (1982/3/11)

We could also get a real-time imaging of X-ray topography for crystal melting process.

TV and scientific magazines reported the news of PF
Synchrotron Radiation Facilities in the world in 1980’s

President of France, Mr. Mitterrand visited Photon Factory on April 17th, 1982.

Prime Minister of Japan, Mr. Suzuki visited Photon Factory on May 8th, 1982.
Synchrotron Radiation Facilities in Japan

“Synchrotron fever grips Japan!”
(Nature, 1986)
Experimental hall filled with beamlines

No. of Exp.Stations
Electrons are undulated with an array of permanent magnets.
SR is generated at each deflected point and interfered with each other.
Interference among these wide-band SRs generates an intense narrow-band radiation.

Wavelength

$$\lambda = \frac{\lambda_u}{2\gamma^2} \left(1 + \frac{K^2}{2}\right)$$

$$K = 93.4 \lambda_u [m] B [T]$$

Intensity

$$I \propto N^2$$

$N$: No. of poles

Energy width

$$\frac{\Delta \lambda}{\lambda} \propto \frac{1}{N}$$
Development of Undulators in the Photon Factory

A prototype of undulator (10 periods) installed in the SOR-Ring in 1981.

The first beam from the prototype of undulator in the SOR-Ring.

The first undulator (60 periods, $\lambda_u=6$ cm) installed in the PF-Ring in 1983.
Upgrade of PF 2.5 GeV Ring

1982  Emittance 400 nmrad (first beam)
1987  → 130 nmrad
1997  → 36 nmrad
~2005  Increase of straight sections
    7 → 13
SR from the PF-AR 6.5 GeV Ring
6.5 GeV Accumulation Ring for TRISTAN

\[ C = 384 \text{m}, \quad I = 60 \text{mA}, \quad \varepsilon = 294 \text{nmrad}, \quad \text{Single bunch} \]

Parasitic use started in 1986

dedicated in 1997

vacuum upgraded: 2002

lifetime → 15 hours

5 ID beamlines

1 multipole Wiggler

4 In-Vacuum Undulator

3 Bending magnets
Development of In-vacuum undulators (1990)

Shorter period length: $\lambda_u = 4\text{cm}$
Shorter magnet gap: 1~2cm
produce higher energy (14.4 keV)
higher intensity beam (N=90)

Courtesy of Prof. Yamamoto
Trend of the SR facilities in 1990s

"Second gen. Light Sources"
- Continuous electron motion
- "Bending trajectory "bending"
- "X-ray light bulb"
- "Bending magnet radiation"

"Third gen. Light Sources"
- Many straight sections (periodic magnets)
- Tightly controlled electron beam
- "Undulator" and "wiggler" radiation
- "Undulator" and "wiggler" radiation
- Partially coherent
- Tunable

For fulfillment of the undulator power, the emittance should be as low as possible.
Synchrotron Radiation Facilities in the world in 1990’s

Third generation medium size rings for soft X-ray were constructed one after another.
Three Large Scale Synchrotron Radiation Facilities

ESRF
6 GeV
844 m
1994～

APS
7 GeV
1104 m
1996～

Spring-8
8 GeV
1436 m
1997～

Synchrotron Radiation Facilities in the world in 1990’s
Restructuring of the organization in 1997

National Laboratory of High Energy Physics

→ High Energy Accelerator Research Organization

- Institute of Particles and Nuclear Physics

- Institute of Materials Structure Science
  - SR, Neutron, and Muon
  - Accelerator Laboratory

- Infrastructure Research Facility
PF biology group and their beamlines for structural biology contributed to the work of Ada Yonath, who won the Nobel Prize in 2009.
IMSS has several unique advanced quantum probes.

Condensed Matter Research Center (2006)

Synchrotron radiation (Photons)

Topological insulators
Multiferroics

IGZO (conductive ceramics)
Iron-based superconductors

Neutrons

Muons

Prof. Tokura (UT, Riken)

Prof. Hosono (TIT)

Slow positrons
Center for Integrative Quantum Beam Science (CIQuS)
Since 2020

**Cultivated Joint Usage**

Working together with co-users to examine the research content and guide them toward a multi-probe application system, from sample preparation to experiments, providing guidance, advice, and support at every step of the research process.

*Test run in FY2020*
*Research meetings: 14 cases*
*Trial experiments: 9 cases (25 days) at PF*

**Theme-driven Joint Research**

Setting up a grand challenge to contribute to the innovation, which should be solved through industry-academia-government cooperation and international collaboration.

**11 projects in 4 research areas**

**Human resource development**

Training new professional staff for cross-field use of quantum beams.

**CIQuS**

- **Staff**: Cooperation, Advice, Support
- **User**: Quantum beam joint program
- **Cooperation**: Cultivation

**Visualization of function expression sites in materials**

**Establishment of Foundation for multi-probe research**

**Solid-state physics towards new devices**

**History of natural objects**
Number of published papers
Number of Master and Doctor theses

- Doctor theses
- Master thesis
Achievements of the Photon Factory

1. Contribution to the scientific achievements, as revealed in many papers published by using PF.

2. Contribution to the education of graduate students as an inter-university research institute.

3. Cultivation of experts for SR accelerators and SR experiments, who have played an important role in construction of new SR facilities in Japan.

4. Contribution to the development of SR science. Typical one is undulators. Various kinds of undulators, especially in-vacuum undulators, have been developed, and played an essential role in medium size 4th-generation rings.
Prospect of the Photon Factory
World trend for Advanced SR facilities in 21 century

Large size brilliant light sources

Medium size high brilliant light sources (4th generation)

SLS(2.4 GeV) 2000 Switzerland

CLS(2.9 GeV) 2004 Canada

Soleil(2.7 GeV) 2007 France

Diamond(3 GeV) 2007 U.K.

ANST(3 GeV) 2007 Australia

SSRF(3.5 GeV) 2009 China
High Brilliant Synchrotron Light Sources in the world
Synchrotron Radiation Facilities in Japan

- **Spring-8**
  - 8 GeV, 1997

- **New SUBARU**
  - 1.5 GeV, 2000

- **SR center**
  - 0.7 GeV, 1996

- **HiSOR**
  - 0.7 GeV, 1998

- **UVSOR**
  - 0.75 GeV, 1983

- **Aichi**
  - 1.2 GeV, 2012

- **Photon Factory**
  - PF
  - 2.5 GeV, 1982

- **PF-AR**
  - 6.5 GeV, 1992

- **SLiT-J**
  - 3 GeV, 2024
Role-sharing of the SR facilities

<table>
<thead>
<tr>
<th>Advanced Facilities</th>
<th>Local facilities</th>
</tr>
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<tbody>
<tr>
<td>SPring-8</td>
<td>SR center</td>
</tr>
<tr>
<td>SACLA</td>
<td>New SUBARU</td>
</tr>
<tr>
<td>Photon Factory</td>
<td>Saga LS</td>
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<tr>
<td>UVSOR</td>
<td>Aichi SR</td>
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<tr>
<td>HiSOR</td>
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<tr>
<td>SLiT-J</td>
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Roles of the advanced Facilities

- Pursue cutting edge science & technology
- Aim at higher resolution in energy, space and time
- Find new phenomena
- Develop new methods for advanced analyses
- Contribute to Innovation of industries
The Photon Factory II project

Disadvantages

• XFEL facility, “SALCA” is running.
• The SLiT-J project has already started.
• SPring-8 II project is waiting for his turn in a queue.
• A new type of light source, other than the above facilities would be required.

Advantages

• Space and Infra-structure have been already prepared.
• There are many experts for construction of accelerators.
• IMSS is an unique institute, having SR, neutron and meson factories.

An innovative plan for the light source which convinces not only users, but also tax-payers.
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Thank you for your attention!