Partners: Then and now

How a small team came together to create a facility that continues to serve

HANAKI Hirofumi

"Partners" means the co-operative relations among the accelerator teams of the injector linac, Photon Factory, and SuperKEKB.
Notes

The original talk mainly presented an early history of Photon Factory’s storage ring and its injector linac.

This document is a revised version of the slides for the original talk. The errors in the slides are corrected and the contents spoken in the original talk are additionally written.

Figures without citation are provided by KEK personnel except for my own work. I deeply appreciate for their sincere supports and kindness.
KEK Site

KEK Image Archive  https://www.kek.jp/ja/imagearchive/12153/

1 km
1.7 km

Entrance

Tokyo

60 km

Symposium Site

KEK

Photon Factory and Injector Linac

PF-AR (6.5 GeV)
AR: Advanced Ring

PF-Ring (2.5 GeV)

e+ Injection

The word “ring” means synchrotron.

The word “linac” means linear accelerator.

The body of the linac is constructed underground.
The two rings, HER and LER, are in the same tunnel and collide electrons and positrons at a colliding point for studying high energy physics.
What is Photon Factory?

• A large facility providing very intense lights, especially x-rays, for scientific and industrial researches.
• The lights are emitted by electrons circulating in a ring accelerator.
• These light emissions are called synchrotron radiation.
Synchrotron Radiation

An electron running on a curved orbit emits synchrotron radiation lights with a power of $P_\gamma$.

$$P_\gamma \propto \frac{E^4}{\rho^2}$$

- Synchrotron radiation becomes dramatically intense when the beam energy is increased.
- Synchrotron radiation becomes weaker when the orbit radius becomes larger.

A 2.5-GeV electron circulating in PF-Ring looses 0.0004 GeV/turn by synchrotron radiation.
Why is synchrotron radiation necessary?

An experiment using synchrotron radiation lights at Photon Factory may require only 1/1000 or less of the time spent for the same experiment using an X-ray tube.

- Very intense radiation
- Higher photon energy
Present Photon Factory

Many experimental hutches occupy the large experimental hall. Experimental devices are in the hutches that shield X-rays.

The translucent yellow arrows express the directions of synchrotron radiations.
### Construction of Photon Factory

<table>
<thead>
<tr>
<th>Year</th>
<th>Month</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>1978</td>
<td>Apr.</td>
<td>Photon Factory was founded. The construction of the injector linac and ring started.</td>
</tr>
<tr>
<td>1982</td>
<td>Jan.</td>
<td>The linac and ring were completed.</td>
</tr>
<tr>
<td>1982</td>
<td>Mar.</td>
<td>2.5 GeV beams were stored in the ring.</td>
</tr>
<tr>
<td>1982</td>
<td>Apr.</td>
<td>French President, F. Mitterrand, visited PF.</td>
</tr>
<tr>
<td>1982</td>
<td>Jun.</td>
<td>SR experiments were commissioned.</td>
</tr>
</tbody>
</table>

*For memory of beam storage*

*President Mitterrand and Director General Nishikawa*

Before Photon Factory (1981)

The facilities commissioned for synchrotron radiation studies

- **NSLS** - 5.5 GeV
- **Tantalus** - 0.24 GeV
- **CHESS** - 5.5 GeV
- **SSRL** - 3 GeV
- **SURF II** - 0.25 GeV
- **NSLS-VUV** - 0.75 GeV
- **VEPP III** - 2.2 GeV
- **SOR-Ring** - 0.3 GeV
- **TERAS** - 0.6 GeV
- **DORIS III** - 5.6 GeV
- **ACO** - 0.54 GeV

**SRS** was a unique dedicated facility providing X-rays for SR studies.

**References**
Dawn of Synchrotron Radiation Science in Japan

SOR-Ring at Institute for Nuclear Study (Univ. of Tokyo)
World’s first storage ring designed for synchrotron radiation

1974  Machine completed
1976  Commissioned for SR studies
1997  Closed

Specification (1997)

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circumference</td>
<td>17.4 m</td>
</tr>
<tr>
<td>Beam energy</td>
<td>500 MeV</td>
</tr>
<tr>
<td>Beam current</td>
<td>500 mA max.</td>
</tr>
<tr>
<td>RF frequency</td>
<td>120.94 MHz</td>
</tr>
</tbody>
</table>
Photon Factory Ring

Design Principle*

• Feasible lattice design with high certainty employing the FODO lattice
• Spacious lattice capable of flexible upgrade
• Full energy injection (2.5 GeV)
  • PF and TRISTAN share the injector linac
• Straight sections for the future installations of insertion devices
  • Long straight section (5 m) : 2
  • Medium straight section (3.5 m) : 5
  • The introduction of the two long straight sections transformed the initially designed circular ring to an elliptical one.


## Comparison of Three X-ray SR Rings

<table>
<thead>
<tr>
<th>NSLS-X (USA)(^1)</th>
<th>PF (Japan)(^2)</th>
<th>SRS (UK)(^3,4)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Injector</strong></td>
<td><strong>Linac</strong> : 85 MeV</td>
<td><strong>Linac</strong> : 2.5 GeV</td>
</tr>
<tr>
<td>Linac : 750 MeV</td>
<td><strong>Booster</strong> : 750 MeV</td>
<td><strong>Linac</strong> : 12 MeV</td>
</tr>
<tr>
<td><strong>Beam energy</strong></td>
<td>2.5 GeV</td>
<td>2.5 GeV</td>
</tr>
<tr>
<td><strong>Mean radius</strong></td>
<td>27 m</td>
<td>29.8 m</td>
</tr>
<tr>
<td><strong>Beam ports</strong></td>
<td>BM : 30</td>
<td>BM : 23</td>
</tr>
<tr>
<td>BM: bending magnet</td>
<td>ID : 5</td>
<td>total 16</td>
</tr>
<tr>
<td>ID: insertion device</td>
<td>BM : 23</td>
<td>ID : 3</td>
</tr>
<tr>
<td><strong>Commissioned for SR studies</strong></td>
<td>1984</td>
<td>1982</td>
</tr>
<tr>
<td><strong>Decommissioned</strong></td>
<td>2014</td>
<td>In operation</td>
</tr>
</tbody>
</table>

\(^1\) The full energy injection enables frequent top-up injections to maintain the stored currents stable. This means that the users can obtain the synchrotron radiation with the stability in intensity and even in position.

\(^2\) The present straight sections are as follows: Long ID : 2 (5 m) \(^2\)

<table>
<thead>
<tr>
<th>Straight section</th>
<th>Length</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Long sections</td>
<td>8.9 m</td>
<td>2</td>
</tr>
<tr>
<td>Medium sections</td>
<td>5.4 m</td>
<td>5</td>
</tr>
<tr>
<td>Short section</td>
<td>1.5 m</td>
<td>4</td>
</tr>
</tbody>
</table>

The yellow terms are the advantages of PF-ring.

Insertion Device: Wiggler

Very strong magnetic fields bend an electron beam with a short orbit radius comparing to normal bending magnets. The synchrotron radiation from a wiggler therefore can be more intense. The electron orbit in this figure is vertically emphasized. The actual displacement of the orbit is about 5 mm, for example.
The running electrons undulate along the magnet arrays just like oscillation. The light emitted from each orbit bend overlaps and interferes with each other. During this process, an undulator forms the lights like a bullet holding the narrow directivity and narrow energy spreads of the photons. The actual horizontal amplitude of the orbit is about 5 µm or less.
The RF cavities compensate the radiation losses of the circulating electrons.

Research Activity Highlights in Early 10 years

Presenter's favorite choices

1. Stabilizing beam orbit variations by reduction of building thermal distortion due to sunshine (1990)

This research results made us to learn the importance of the ground and building structure of synchrotron radiation facility. Their researches had been often referred when new facilities were constructed.


This development enabled a 2 or 3-GeV storage ring to generate hard X-rays. Now medium-scale synchrotron radiation facilities that are equipped with in-vacuum undulators have been constructed and operated around the world.
Thermal distortion of PF-Ring Building

A hand-made hydrostatic leveling system was constructed to measure the displacement of the accelerator tunnel floor.


Simulated distortions of PF-Ring building due to sunshine. The distortions of the model are emphasized in this figure.

PF Activity Report 1988, Light Source Department title page and p.R-12
Thermal distortion of PF-Ring Building

Conclusion of examination
Elongation and shrinkage of the storage ring building roof due to sunshine.

Vertical displacements of ring tunnel floor

Daily beam motions

Countermeasure
Covering the roof with heat insulators

- Insulator 50 mm
- Concrete roof 150 mm
- Waterproof sheet

Vertical beam orbit drifts along the ring during 6 a.m. – 4 p.m. before and after the countermeasures.

In-Vacuum Undulator

The insertion device team developed an in-vacuum undulator that can narrow the magnet gap to a few mm at minimum to realize more intense magnetic fields.

One of the important technical issues is the control of the demagnetization of neodymium magnets caused by heating for degassing magnets. They solved this issue as follows:

All magnets are demagnetized slightly by the pre-baking before assembling magnet arrays. After this procedure, the demagnetization, which occurs in the degassing process of the whole undulator’s vacuum chamber, can be suppressed less than 0.1%.

In-Vacuum Undulator

Normal Undulator

In-vacuum undulators enable very short gap comparing to normal ones.

In-Vacuum Undulator

In-vacuum undulators generate higher energy X-rays comparing to normal ones.
Injector linac

Design Principle

• Feasible design with high certainty
• Design of the accelerating structures to reduce bunch break up instability of high current beam pulses
• High precision machining of waveguide components and accelerating structures to eliminate fine tune processes consuming costs and time
  • Fabrication of the accelerating structures by electroforming
• Accelerator control by a distributed processor network composed of minicomputers and microprocessors

These are explained in the following slides.
Accelerating Unit

Tune-free accelerating structure (cutaway)

30- or 46-MW Klystron (cutaway)

2-m Accelerating structure without tuning holes fabricated by **electroforming**

Cooling water channel

Microwave 2856 MHz

Standard structure

An accelerating structure fabricated by conventional brazing. Each cell has a tuning hole to adjust its resonant frequency.
Electroforming of Accelerating Structure Body

1. Fabricate disks and spacers by high-precision machining.
2. Combine the disks and spacers and press them to form the body of accelerating structure.
3. Dip the body in an electro-forming bath. Then wait for the growth of a thick copper coat on the body about 70 hrs.
4. Pull the body out of the electroforming bath.

Accelerator Control (1982–1993)

Design Principle
- Each device controller has a microprocessor mainly for data communication including data processing
- Considering autonomous operation capability of individual linac equipment
- Noise isolation of serial communication lines by optical fibers

Quantities of devices to be remote-controlled

<table>
<thead>
<tr>
<th>RF</th>
<th>Magnet PS</th>
<th>Ion Pump</th>
<th>Beam Monitor</th>
</tr>
</thead>
<tbody>
<tr>
<td>46</td>
<td>198</td>
<td>88</td>
<td>59</td>
</tr>
</tbody>
</table>

Network Operation Period

<table>
<thead>
<tr>
<th>LOOP-I</th>
<th>LOOP-II</th>
<th>LOOP-III</th>
</tr>
</thead>
</table>


* Microprocessor : Motorola’s MC6800 series
Accelerator Control

There was no good standard network like Ethernet at that time. Nevertheless, the linac control system, which was completed by a few scientists and technicians, was functioning and many devices could be tuned at a control desk. The network system, however, was not sufficiently reliable for automatic control requiring frequent data communication.
Upgrade of Injector Linac

Original linac for PF injection

1982 – 1984

In this figure, a set of a symbolic klystron and a symbolic accelerating structure expresses a real set (e.g. sector) of several klystrons, waveguides, accelerating structures, and beam transport magnets.

<table>
<thead>
<tr>
<th>Component</th>
<th>Numbers</th>
</tr>
</thead>
<tbody>
<tr>
<td>e⁻ energy</td>
<td>2.5 GeV</td>
</tr>
<tr>
<td>e⁺ energy</td>
<td>–</td>
</tr>
<tr>
<td>Acc. structure</td>
<td>162 units</td>
</tr>
<tr>
<td>Klystron</td>
<td>30 MW × 41</td>
</tr>
<tr>
<td>Electron gun</td>
<td>Thermionic gun</td>
</tr>
</tbody>
</table>

Components of Sector

- Sub-Booster*: 1
- Klystron: 8 max.
- Acc. Structure: 32 max.

* A sub-booster feeds RF powers to eight high-power klystrons to drive them.
Positrons were produced due to pair production, one of photon interactions with matter. Electron beam pulses of 200 MeV hit a tungsten target and generate bremsstrahlung radiations. The radiated photons interact with the target and consequently create positrons. The positron injector focuses and accelerates positrons up to 250 MeV.
Upgrade of Injector Linac

Injector Linac for PF & KEKB
1998 – 2010

The electron and positron energies were upgraded to 8 GeV and 3.5 GeV, respectively. The former positron linac was removed and new A, B and C sectors were constructed to increase the beam energy. A new positron injector was newly constructed. The RF power sources were also upgraded; 46-MW klystrons and RF pulse compressors called SLED, which double the accelerating voltages, were installed.
An RF-gun and a dumping ring were introduced to reduce the emittance of the electron and positron beams for the injection into SuperKEKB rings. The positron generator was moved to the upstream side and upgraded to increase the positron beam currents.
Beam Injections into 4 rings

One or two bunches of electron or positron are accelerated and injected into each ring in pulsed operation at 50 Hz or less.

Beam Injection (typical)

<table>
<thead>
<tr>
<th>Ring</th>
<th>Energy</th>
<th>Charge</th>
</tr>
</thead>
<tbody>
<tr>
<td>LHR</td>
<td>4 GeV</td>
<td>3 nC / bunch</td>
</tr>
<tr>
<td>HER</td>
<td>7 GeV</td>
<td>1.4 nC / bunch</td>
</tr>
<tr>
<td>PF-Ring</td>
<td>2.5 GeV</td>
<td>0.25 nC / bunch</td>
</tr>
<tr>
<td>PF-AR</td>
<td>6 GeV</td>
<td>0.3 nC / bunch</td>
</tr>
</tbody>
</table>

Real e⁻ & e⁺ storage

One e⁻ or e⁺ bunch is circulating in each ring in this simplified model. However, several or more bunches are stored in the real rings. The injected bunch runs into one of the stored bunches and the total charge of the stored bunch increases consequently.
4-Ring Simultaneous Top-Up Injection

Top-Up injection: Keeping a stored current constant by frequent beam injection

The top-up injections give great contributions to the improvement of the efficiency of every experiment.

The top-up injections into all the rings cannot be achieved only by increasing the injection rates. Many focusing magnets have to be switched within 20 ms, that is, this operation required major upgrade of the beam transport system.

2008 Top-Up injection to KEKB-HER/LER & PF-Ring
2018 Top-Up injection to PF-AR

Stored current stability before-and-after top-up injection into PF-ring

Photon Factory in Early Years

The injector linac division and light source division belonged to Photon Factory in early years.

Numbers of researchers and technicians

<table>
<thead>
<tr>
<th></th>
<th>1979</th>
<th>1982</th>
<th>1990</th>
</tr>
</thead>
<tbody>
<tr>
<td>Injector Linac Div.</td>
<td>6*</td>
<td>19</td>
<td>29</td>
</tr>
<tr>
<td>Light Source Div.</td>
<td>12</td>
<td>22</td>
<td>29</td>
</tr>
<tr>
<td>Instrumentation Div.</td>
<td>0</td>
<td>11</td>
<td>38</td>
</tr>
</tbody>
</table>

* A few researches of other institutes or universities were energetically supporting them.

Nostalgic days …
A welcome party for new members of Photon Factory, or an end-of-year party were held every year. These parties were very good opportunities to get together and to know each other beyond the divisions.
Pioneers

The first four directors greatly contributed the launch of Photon Factory.

Chief Director
Prof. Kohra

Injector Linac
Director
Prof. Tanaka

Light Source
Director
Prof. Huke

Instrumentation
Director
Prof. Sasaki
Thank you very much for your attention!