Construction Experience of LEPS and LEPS2 and X-ray Compton Scattering at SPring-8

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JASRI/SPring-8
Outline

- Brief Introduction of SPring-8
- LEPS and LEPS2 at SPring-8
- Backward Compton Scattering of Quasi-Monochromatic $\gamma$-ray Production using X-ray Undulator
  - Reflectivity Measurements of Single Crystal
  - Plan of Test Experiment for $\gamma$-ray Production
- Future Prospects of BCS facility at SPring-8
- Summary
Bird Eye’s View of SPring-8 Accelerator Complex
# Beam parameters of SPring-8 storage ring

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy [GeV]</td>
<td>8</td>
</tr>
<tr>
<td>Number of buckets</td>
<td>2436</td>
</tr>
<tr>
<td>Tunes (\nu_x / \nu_y)</td>
<td>41.14 / 19.34</td>
</tr>
<tr>
<td>Current [mA]:</td>
<td></td>
</tr>
<tr>
<td>single bunch</td>
<td>12</td>
</tr>
<tr>
<td>multi bunch</td>
<td>100</td>
</tr>
<tr>
<td>Bunch length ((\sigma)) [ps]</td>
<td>13</td>
</tr>
<tr>
<td>Horizontal emittance [(\text{nm} \cdot \text{rad})]</td>
<td>2.4 (^{51})</td>
</tr>
<tr>
<td>Vertical emittance [(\text{pm} \cdot \text{rad})]</td>
<td>4.8 (^{51})</td>
</tr>
<tr>
<td>Coupling [%]</td>
<td>0.2</td>
</tr>
<tr>
<td>RF voltage [MV]</td>
<td>16</td>
</tr>
<tr>
<td>Momentum acceptance [%]</td>
<td>(~3)</td>
</tr>
<tr>
<td>Beam size ((\sigma_x / \sigma_y)) (^{51}) [(\mu\text{m})]</td>
<td></td>
</tr>
<tr>
<td>Long ID section</td>
<td>333 / 7</td>
</tr>
<tr>
<td>ID section</td>
<td>316 / 5</td>
</tr>
<tr>
<td>BM1 section</td>
<td>94 / 12</td>
</tr>
<tr>
<td>BM2 section</td>
<td>100 / 12</td>
</tr>
<tr>
<td>Beam divergence ((\sigma_x^2 / \sigma_y^2)) (^{51}) [(\mu\text{rad})]</td>
<td></td>
</tr>
<tr>
<td>Long ID section</td>
<td>8 / 0.7</td>
</tr>
<tr>
<td>ID section</td>
<td>9 / 1.0</td>
</tr>
<tr>
<td>BM1 section</td>
<td>58 / 0.5</td>
</tr>
<tr>
<td>BM2 section</td>
<td>68 / 0.5</td>
</tr>
<tr>
<td>Operational chromaticities ((\xi_x / \xi_y))</td>
<td>(+2/+2^{52})</td>
</tr>
<tr>
<td>Lifetime [hr]:</td>
<td></td>
</tr>
<tr>
<td>100mA (multi bunch)</td>
<td>(~200)</td>
</tr>
<tr>
<td>1mA (single bunch)</td>
<td>(~20)</td>
</tr>
<tr>
<td>Horizontal dispersion [m]:</td>
<td></td>
</tr>
<tr>
<td>Long ID section</td>
<td>0.153</td>
</tr>
<tr>
<td>ID section</td>
<td>0.146</td>
</tr>
<tr>
<td>BM1 section</td>
<td>0.039</td>
</tr>
<tr>
<td>BM2 section</td>
<td>0.059</td>
</tr>
<tr>
<td>Fast orbit stability (0.1 – 200Hz) [(\mu\text{m})]:</td>
<td></td>
</tr>
<tr>
<td>horizontal (rms)</td>
<td>(~4)</td>
</tr>
<tr>
<td>vertical (rms)</td>
<td>(~1)</td>
</tr>
</tbody>
</table>

\(^{51}\) Assuming 0.2% coupling

\(^{52}\) With bunch-by-bunch feedback
Operational 56 beamlines, Under Construction: 1 beamline
MeV Photons Production by BCS using FIR laser at BL38B2

- Output power of FIR laser is 890mW at wavelength of 119 μm
- Counting rate: 7.6±0.11 cps (>3MeV)

Simulation Result by EGS4

Production rate of Gamma-ray at the interaction point

1.3×10³ photons/sec
BL33LEP (LEP : Laser Electron Photon) at SPring-8

- First Proposal of LEPS beamline submitted to SPring-8 in 1996.
- Construction of LEPS started in 1998.
  - Laser injection System was constructed in 1998.
  - Experimental hatch was completed in March 1999.

8 GeV electron
\[ \Delta E/E = 10^{-3} \]
100 mA

SPring-8 SR ring
\[ \lambda_L = 350 \text{ nm} \]

Electron tagging
1.5 GeV < \( E_\gamma \) < 2.4 GeV
\[ \Delta E_\gamma = 15 \text{ MeV} \]

\( E_\gamma^{\text{max}} = 2.4 \text{ GeV} \)
\( N_\gamma = 1 \times 10^7 \gamma/\text{s} \)
Original BL33B2 beamline is planed as a bending source beamline (blue line) for synchrotron radiation experiments.

Interaction length between laser photon and stored electron in the bending magnet is very short.

BL33LEP beamline was shifted (red line). (Interaction region is in arc-section)

Bending magnet was turned 180 degrees.

Vacuum chambers were replaced newly designed chambers. (Bending chamber, Crotch chamber including Crotch absorber, and Straight chamber)

**LEPS Beamline Construction**

**BL33LEP**

**Interaction region**

**BL33B2 line**
Interaction Region in the arc section for LEPS

v-kicker

h-kicker
γ-photons Extraction Port

γ-ray

extraction port

Laser
2.4 GeV 8 GeV

- LEP (BL33LEP) experiments started in 1999.

First LEPS Beam Observation in 1999

- Linear Polarization: 95% at 2.4 GeV
- Assumed 100% laser beam polarization

Polarization of LEP Beam

Linear Polarization

Electron Energy = 8 GeV

2.4 GeV 8 GeV

counts

10^9

10^8

10^7

10^6

10^5

10^4

10^3

10^2

10^1

10^0

counts

photon energy (GeV)
Influence on beam lifetime by $\gamma$-ray production

- Beam lifetime of stored electron beam decreases by $\gamma$-ray production

![Graph showing the effect of $\gamma$-ray production on beam lifetime]

- Effect of $\gamma$-ray production

![Graph showing SR DCCT Current (mA) and LEP intensity (estimated from Tagger)]
The Top-up Operation started since May 2004.

- **Merits of top-up operation**
  - Improving average brilliance
  - Stabilizing thermal condition at beamline components
  - **Improving measurement precision** by stable source intensity
  - *(For LEPS) No limit for Production Rate of LEPS beam*
From LEPS to LEPS2

- LEPS2 proposal was submitted to SPring-8 in March 2010 and Approved in June 2010.
- One-order higher intense GeV photons compared with LEPS
- Multi-laser injection system was development
- Utilization of 30-m long straight section (LSS)
- Some components of storage ring were replaced

30 m long straight section completed in 2000
BL31LEP constructed at 30 m long straight section of SPring-8

8 GeV electron

Backward Compton Scattering
Recoil electron (Tagging)

Laser

γ-ray beam
$E_{\gamma\text{max}} = 2.4$ GeV

Parallel γ-ray beam
γ-ray beam dose not spread

Electron beam size and divergence

<table>
<thead>
<tr>
<th></th>
<th>BL33LEP</th>
<th>LSS</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\langle \sigma_x' \rangle$ [μrad]</td>
<td>58</td>
<td>8</td>
</tr>
<tr>
<td>$\langle \sigma_y' \rangle$ [μrad]</td>
<td>1.8</td>
<td>0.7</td>
</tr>
<tr>
<td>$\langle \sigma_x \rangle$ [mm]</td>
<td>0.34</td>
<td>0.337</td>
</tr>
<tr>
<td>$\langle \sigma_y \rangle$ [mm]</td>
<td>12</td>
<td>7</td>
</tr>
</tbody>
</table>

Beam divergence of γ-ray ~ 64μrad

Four lasers simultaneously will be injected
Test $\gamma$-ray production started in Jan. 27th, 2013.

Energy spectrum measured with a large BGO crystal (300 mm thick, 80 mm$\phi$)

**First $\gamma$-ray beam**

- $E_{\gamma} < 0.65$ GeV is cut off by a collimator.
- Laser Compton back-scattering beam @ $I_e = 0.1$ mA
- Bremsstrahlung beam @ $I_e = 10$ mA

**Photon beam profile**

- Large BGO crystal $\phi 8$ cm x L 30 cm with 3 inch PMT
- Charge Veto Counter
From our experience of construction of LEPS and LEPS2,

**User Group of BCS Photons**

**Accelerator Group**

**Collaboration is very IMPORTANT** between user group of BCS photons and accelerator group.

**Accelerator peoples contribution:**

- Modification of Storage ring components (magnets and vacuum system)
- Orbit stability
- Orbit correction
- Top-up operation
Quasi-Monochromatic Very High GeV Photons Production by Backward Compton Scattering

Schematic diagram of BCS

\[ k_2 = k_1 \frac{1 + \beta \cos \theta_1}{1 + \beta \cos \theta_2 + \frac{k_1}{E_e} (1 - \cos \chi)} \]  \hspace{1cm} (1)

In case of head-on collision, maximum energy of scattered Photon :

\[ k_{2\text{max}} = \frac{k_1 (1 + \beta)}{1 + \beta + \frac{2k_1}{E_e}} \approx \frac{4k_1 E_e^2}{(m_e c^2)^2 + 4k_1 E_e} \]  \hspace{1cm} (2)

When \( k_1 \) is 10 keV, \( E_e = 8 \text{ GeV} \hspace{1cm} k_{2\text{max}} \sim 8 \text{ GeV} \)

(photon energy of \( \gamma \)-ray is almost equal to electron energy).
Spectrum Shape (Milburn, 1963)

\[
\frac{1}{\sigma_0} \frac{d\sigma}{d(k_2/E_e)} = \frac{3}{16\lambda} \left[ \frac{\lambda^2(1-x)^2}{1 + \lambda(1-x)} + 2(1 + x^2) + O[x^n] \right]
\]  

(3)

\(\sigma_0\) : Thomson scattering cross-section,
\(\lambda = \frac{2\gamma k_1}{m_e c^2}\), \(x = \cos \theta_0\) \((\theta_0\) : photon scattering angle)

For low \(k_1\) (e. g. laser light, \(E_1 = 3.49\) eV),
the second term of Eq. (3) is dominant.
\(\gamma\)-ray spectrum is the parabolic shape
with wide photon energy range.

For high \(k_1\) (e. g. undulator, \(E_1 > 100\) eV),
the first term is dominant and
\(\gamma\)-ray spectrum damps in the low energy region.

For very high \(k_1\) (e. g. hard X-ray undulator, \(E_1 > 5\)keV),
higher-order term \(x^n\) \((n > 2)\) of Eq. (3) becomes important.
\(\gamma\)-ray spectrum uprises steeply near the maximum BCS gamma-ray of \(k_{2\text{max}}\).
Motivation

• BCS using laser (infrared to ultra-violet) established with successful results, but extension of the maximum photon energy of $\gamma$-ray opens new fields of the photo production experiments of nuclear and particle physics

  LEP(BL33LEP) and LEP2(BL31LEP) at SPring-8

• Quasi-monochromatic $\gamma$-ray

  No tagging system ($\gamma$-ray intensity and energy are measured)

• In SR facility, many high power X-ray undulators. Very attractive to use as incident photon source for BCS

  Photon energy close to the kinematic limit

• Single crystal with high-reflectivity at normal-incidence (K-J. Kim et al.)

  X-ray photon reflected back by a single crystal

• SPring-8-II is now proposed with 6 GeV electron beam energy

  $\gamma$-ray photon energy will be half
Calculated $\gamma$-ray distribution as a parameter of incident photon energy

Electron energy = 8 GeV

Calculated by Schin Daté
10keV incident X-ray and Produced $\gamma$–ray in kinematic limit
Reflectivity measurement of single crystal

Ion Chambers

Al absorber (T ~ 0.2)

3-Axis Goniometer

Single Crystal
X-ray

Al absorber (T ~ 0.2)

Incident X-ray Intensity: \( S_0 (\Delta E_{\text{mono}}/E_{\text{mono}} = 1.4 \times 10^{-4}) \)

\[
\frac{I}{I_0} = C \cdot \frac{S_0 \cdot T + S_0 \cdot T \cdot R \cdot \Delta E_{\text{crystal}}}{S_0 + S_0 \cdot T^2 \cdot R \cdot \Delta E_{\text{crystal}}/\Delta E_{\text{mono}}} \approx C \cdot T \left( 1 + R \cdot \frac{\Delta E_{\text{crystal}}}{\Delta E_{\text{mono}}} \right)
\]

\[
\frac{I}{I_0}_{R \neq 0} = C \cdot T \left( 1 + R \cdot \frac{\Delta E_{\text{crystal}}}{\Delta E_{\text{mono}}} \right)
\]

and

\[
\frac{I}{I_0}_{R = 0} = C \cdot T
\]

Reflectivity \((R)\)
\((\Delta E_{\text{crystal}} \sim 10 \sim 100 \text{meV})\)

Reflectivity is estimated by measurement of \((I/I_0)_{R \neq 0}\) and \((I/I_0)_{R = 0}\). (Assumed \(\Delta E_{\text{mono}}\) and \(\Delta E_{\text{crystal}}\))

Single Crystal (Bragg Mirror)
Diamond (333) Bragg Reflection at normal-incidence

\[ \frac{I}{I_0} \] at 9.033 keV

\[ R = 0.63 \]

\[ (\frac{I}{I_0})_{R=0} = 0.163 \]

\[ (\frac{I}{I_0})_{R=0} = 0.1583 \]

where \( \Delta E_{\text{mono}} = 1.26 \text{ eV} \) and \( \Delta E_{\text{crystal}} = 60 \text{ meV} \).
Diamond (5 5 5)  
Photon Energy [keV]  
15.05 keV  

Diamond(555) $R \approx 0.61$  

Si (5 5 5)  
Photon Energy [keV]  
9.883 keV  

Si (555) $R \approx 0.31$
Expected $\gamma$-ray yield

Calculated Flux from ID of BL05SS

Reflected number of photons by Diamond Bragg Mirror :

$$N_{ph} = 7.96 \times 10^{11} \text{ [phs/sec]}$$

$$N_\gamma \approx 10^2 \text{ [phs/sec]}$$
Plan of Test Experiment for \(\gamma\)-ray Production

Schematic Drawing of \(\gamma\)-ray Production System

Multipole Wiggler
76mm \(\times\) 51 periods
\(K_{\text{max}} = 5.8\)
Photon Energy = 5 ~ 30keV
Optics Hatch of BL05SS at SPring-8

Mirror Chamber including Diamond mirror mounting system with cooling device on 4-Axis Goniometer and Focusing System

Detector for produced BCS $\gamma$-ray
Ultra High Intense Monochromatic 6GeV Photons can be produced by the BCS between XFEL Photons and Ultra Low Emittance 6 GeV electron beam of SPring-8-II.
Summary

• LEPS and LEPS2 are successfully advances.
• For the construction of BCS beamline, the collaboration is very important between User Group of BCS photons and Accelerator Group.
• We proposed BCS using X-ray undulator radiation and Bragg reflection of single crystal to produce quasi-monochromatic GeV $\gamma$-ray.
• Reflectivity measurement of silicon and diamond single crystal has been done.
• Experimental setup of $\gamma$-ray production by X-ray BCS using a single crystal (diamond) is now under preparation.

Thank you for your attention