Diamond Based Fast Luminosity Monitoring for SuperKEKB

*LumiBelle2 Project*

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LAL-Orsay

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P. Cornebise, D. El Khechen (PhD student 2012-2016), Y. Peinaud, C. Rimbault

**Collaborators**
- Belle II: Sadaharu Uehara + Belle II / BEAST team
- SuperKEKB: Yoshihiro Funakoshi, Kenichi Kanazawa, Mika Masuzawa, Yukiyoshi Ohnishi, Yusuke Suetsugu, Makoto Tobiyama, Alan Fisher (SLAC), Uli Wienands (ANL)
Exploring the luminosity frontier with SuperKEKB

KEKB
\[2 \times 10^{34}/\text{cm}^2/\text{s}\]

SuperKEKB
\[8 \times 10^{35}/\text{cm}^2/\text{s}\]

Future e+e− circular colliders use “nanobeam” collision scheme
⇒ was tried for 1st time at SuperKEKB in 2018
SuperKEKB / Belle-II & “Machine-Detector Interface”

- Control beam induced backgrounds
- Luminosity monitoring & tuning

   - single beam commissioning, vacuum scrubbing
   - no luminosity (no final focus), no detector
   - colliding beam commissioning, no vertex detector
3) Phase 3: ~ February 2019...
   - towards full luminosity for physics running

\[ \beta_y = 300 \, \mu m \quad d \sim 300 \, \mu m \]

\[ d = \frac{\sigma_x^*}{\phi} \]

\[ \phi = 83 \, \text{mrad} \]

\[ \sigma_x = 5-6 \, \text{mm} \]

\[ \sigma_y^* = 10-12 \, \mu m \]

\[ d = \frac{\sigma_y^*}{\beta_y} \]

\[ \beta_y = 300 \, \mu m \]

\[ d \sim 300 \, \mu m \]

→ mitigates hour-glass (and beam-beam) effects

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### Parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>KEKB</th>
<th>SuperKEKB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy ( E_b )</td>
<td>3.5</td>
<td>4</td>
</tr>
<tr>
<td>Half crossing angle ( \varphi )</td>
<td>11</td>
<td>41.5</td>
</tr>
<tr>
<td># of Bunches ( N )</td>
<td>1584</td>
<td>2500</td>
</tr>
<tr>
<td>Horizontal emittance ( \varepsilon_x )</td>
<td>18</td>
<td>3.2</td>
</tr>
<tr>
<td>Emittance ratio ( \kappa )</td>
<td>0.88</td>
<td>0.27</td>
</tr>
<tr>
<td>Beta functions at IP ( \beta_x / \beta_y )</td>
<td>1200/5.9</td>
<td>32/0.27</td>
</tr>
<tr>
<td>Beam currents ( I_b )</td>
<td>1.64</td>
<td>3.6</td>
</tr>
<tr>
<td>Beam-beam param. ( \xi_y )</td>
<td>0.129</td>
<td>0.088</td>
</tr>
<tr>
<td>Bunch Length ( \sigma_z )</td>
<td>6.0</td>
<td>6.0</td>
</tr>
<tr>
<td>Horizontal Beam Size ( \sigma_x^* )</td>
<td>150</td>
<td>10</td>
</tr>
<tr>
<td>Vertical Beam Size ( \sigma_y^* )</td>
<td>0.94</td>
<td>0.048</td>
</tr>
<tr>
<td>Luminosity ( L )</td>
<td>( 2.1 \times 10^{34} )</td>
<td>( 8 \times 10^{35} )</td>
</tr>
</tbody>
</table>

units

- GeV
- mrad
- nm
- %
- mm
- A
- \( \sigma \) mm
- \( \mu m \)
- \( \mu m \)
- \( \text{cm}^2 \text{s}^{-1} \)

→ Luminosity × 40
Luminosity

Fast & slow variations at IP require feedback corrections

- **Beam-beam deflection** for fast vertical motion
  \[ \Delta y \text{ at IP} = \sim 5\text{nm} \sim 1/10\sigma_y^* \]
  \[ \Delta y \text{ at BPM} = \sim 1.3 \mu\text{m} \]
  Vertical vibration \sim 25-100 \text{ Hz}
  Sampling (BPMs) \sim 32 \text{ kHz}

- **Luminosity feedback** by “dithering” for slower horizontal motion

  Horizontal motion \sim \text{ few Hz}
  Modulation freq. \( f_0 \) \sim 79 \text{ Hz}
  Sampling (lumi. meas.) \sim 1 \text{ kHz}
  - minimize \( f_0 \) output component
  - dithering \( \times \) lumi. signal \( \rightarrow \) phase

Cf. WEXBA04 by Yoshihiro Funakoshi, Wednesday, 11:20 am

\[
L(t) = \frac{f_{rev} N_1 N_2}{4\pi \sigma_x \sigma_y} e^{-\left(\frac{[q + psin(2\pi ft)]^2}{4}\right)}
\]
Radiative Bhabha at vanishing scattering angle

$$\sigma \sim 250 \text{ m barn} \ (E_\gamma > 1\% \ E_{\text{beam}})$$

Correction for cross section due to finite beam size

Relative measurements

- $10^{-2}$ in 1 ms over all bunches ("dithering")
- $10^{-2}$ in $\sim 1$ s for each 2500 bunch $\rightarrow 4\text{ns}$
- Dynamic range $\rightarrow 10^{32} \sim 10^{36} \text{ cm}^{-2}\text{s}^{-1}$
- Non luminosity scaling contamination $< 1\%$
  (e.g. beam gas bremsstrahlung and Touschek losses)

Y. Funakoshi (KEK), background workshop, Feb. 2012
Two complementary techniques

**LumiBelle2**

- Diamond sensors
- $4 \times 4 \times 0.5/0.14 \, mm^3$ single crystal CVD diamond sensors
- Fast charge/current amplifiers
- Digital electronics

**ZDLM (Zero Degree Luminosity Monitor)**

- Cherenkov and scintillator detectors + PMT
- $15 \times 15 \times 64 \, mm^3$ LGSO non-organic scintillator and ES-crystal (quartz)
- Analog electronics

Count photons and recoiling electrons or positrons from the radiative Bhabha process at vanishing scattering angles

$\sigma \sim 250 \, mbarn \ (E_{\gamma} > 1\% \ E_{\text{beam}})$
LER side

- **Signal**: Bhabha positrons
- **Background**: Bremsstrahlung and Touschek positrons
- **Platform**: 11 m after IP
- **3 sensors aligned**
- **Window + radiator**
HER side

- Signal: Bhabha photons
- Background: Bremsstrahlung photons, Touschek electrons
- Platform: 30.5-30.8 m after IP
- 3 sensors: up & down, (side)
DAQ and online signal processing

\[ \text{TIL: if } S[(i - 1) \times 2 + 1] - S[(i - 1) \times 2 + 3] > \text{threshold:} \]

\[ \text{TIL } += S[(i - 1) \times 2 + 1] - S[(i - 1) \times 2 + 3] \]

\[ \text{RAWSUM: if } S(j) > \text{threshold:} \]

\[ \text{Rawsum } += S(j) \]

No trigger + Synchronization to RF \-----> Continuous monitoring, averaging at 1 kHz

TIL and RAWSUM are different ways of calculating the luminosity from the measured signal
Single beam background

**Coulomb**
- Proportional to vacuum pressure and beam current
- Important globally but negligible for luminosity monitoring _dominant for LumiBelle2_

**Bremsstrahlung**
- Proportional to vacuum pressure and beam current
- Largest source of background in phase 2
- Photons measured at HER side
- Positrons measured at LER side

**Touschek**
- Proportional to square of beam current
- Inversely proportional to beam size

**Luminosity signal**

**Radiative Bhabha process**
- Scattered @ IP
- Proportional to luminosity
- Large cross-section
Background study (1)

- Background measurement:
  - Bremsstrahlung $\propto I^*P$
  - Touschek $\propto I^2/\left(\sigma_x\sigma_y\sigma_z\right) \propto I \times P$

Dominant

Beam current

Pressure

TIL_A

TIL_C

Beam gas desorption

Pressure is proportional to current

Background signal is proportional to product of beam current and pressure
Background study (2)

• Comparison with simulation

Scattering position of lost particles

Total pressures at 1000, 10000 A*hrs, I = 3.6 A

• Total indicates sum of H₂, CO, CO₂, and CH₄ partial pressures
• Asymmetric because of synchrotron radiation

Simulated vacuum profile @ IP
Jason CARTER (ANL) & Marton ADY (CERN)

\[ Z_{\text{eff}} = 4.5 \]

Simulated results about 20% larger than measurement

Simulated results about 10% larger than measurement
First collision – April 26, 2018
Control room display of recent luminosity run (June 16, 2018)

Normalization of LumiBelle2 w.r.t. ECL LOM absolute luminosity (channel / configuration dependent + can evolve in time... is monitored)

<table>
<thead>
<tr>
<th></th>
<th>LER 1&lt;sup&gt;st&lt;/sup&gt;</th>
<th>LER 2&lt;sup&gt;nd&lt;/sup&gt;</th>
<th>HER 1&lt;sup&gt;st&lt;/sup&gt;</th>
<th>HER 2&lt;sup&gt;nd&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(25 ± 8)×10&lt;sup&gt;2&lt;/sup&gt;</td>
<td>(4 ± 1)×10&lt;sup&gt;2&lt;/sup&gt;</td>
<td>(13 ± 4)</td>
<td>1.2 ± 0.4</td>
</tr>
</tbody>
</table>
LumiBelle2 LER compared to ZDLM and ECL LOM
Offline check of LumiBelle2 channel correlations

<table>
<thead>
<tr>
<th></th>
<th>CH1</th>
<th>CH2</th>
<th>CH3</th>
<th>CH4</th>
</tr>
</thead>
<tbody>
<tr>
<td>CH1</td>
<td>1</td>
<td>0.9092</td>
<td>0.9624</td>
<td>0.9019</td>
</tr>
<tr>
<td>CH2</td>
<td>0.9092</td>
<td>1</td>
<td>0.8888</td>
<td>0.9975</td>
</tr>
<tr>
<td>CH3</td>
<td>0.9624</td>
<td>0.8888</td>
<td>1</td>
<td>0.8822</td>
</tr>
<tr>
<td>CH4</td>
<td>0.9019</td>
<td>0.9975</td>
<td>0.8822</td>
<td>1</td>
</tr>
</tbody>
</table>
**Application:** input to *dithering feedback* to maintain collisions horizontally

LER: \[ d = p \cdot \sin(2\pi f t) \]

Offset: \( q \)

HER

Luminosity monitoring signal @ 1kHz

ZDLM LumiBelle2

Luminosity offset ZDLM LumiBelle2

Closed orbit IP bump (correction @ 1 Hz)

Orbit offset @ IP calculation (size and sign)

Lock-in amplifier

Yoshihiro Funakoshi’s talk 26 September Parallel Session Tu-2a, 11:20 am
Application: Luminosity fitting w.r.t. IP beam tuning parameters

- Example: vertical offset scan to estimate average of $e^+$ and $e^-$ $\sigma_y$ at IP
  - Offset scans usually range from $\Delta y = -14\mu m$ to $\Delta y = +14\mu m$
  - $\sigma_y$ estimated from 4 LumiBelle2 luminosity monitors
  - Bias from beam-beam induced blow-up for high current and/or small $\beta^*$
    - Can help to probe the beam-beam blow-up and benchmark the beam-beam simulations

\[ L = \exp \left( -\frac{\Delta y^2}{2\Sigma_y^2} \right) \]

\[ \Sigma_y^2 = \sigma_{1,y}^2 + \sigma_{2,y}^2 \approx 2\sigma_y^2 \]
Evolution in $\sigma_y^*$ in May

- $\sigma_y^*$ is obtained for each monitor and averaged
- The errors combine statistical and systematic measurement uncertainties
- Already some bias from the beam-beam blow-up?
Sensitive luminosity monitor important to correct optical aberrations in vertical IP beam size*

→ must do at very low intensity to avoid confusion from beam-beam blow-up

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* Yukiyoshi Ohnishi’s opening plenary talk on Monday 24/9
SNR and optimum offset from vertical beam offset scan

- $L_{\text{ECL-LOM}} = 1.3 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$
- measured SNR $\sim 65$ (simulation $\rightarrow 42$)
- optimum collision offset $\sim 0.19 \text{ \mu m}$
- $\Sigma_y \sim 0.51 \text{ \mu m}$
Application: bunch-by-bunch luminosity monitoring

- $L_{ECL-LOM} = 1.6 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$ (end of Phase 2)

- $N_{bunch} = 395$

- bunch separation = 32 ns (nominally $\rightarrow$ 4 ns)

- RMS bunch luminosity spread = 9.3 %

- RMS bunch current product spread = 8.7 %

- integrated lumi. precision @ 1 kHz = 2.35%

- bunch-by-bunch Lumi precision @ 1 Hz = 1.5%
Conclusion and prospects

• **LumiBelle2 operated satisfactorily during Phase 2**
  - reasonable agreement with simulation for single beam backgrounds
  - provides useful online luminosity information for SKB machine tuning (e.g. IP beam size tuning)
  - 1st test as input to horizontal IP orbit dithering feedback → Cf. Y. Funakoshi’s talk on Wednesday
  - application: evaluate mean $\sigma_y$ of beams at IP → “Van der Meer” scans @ LHC
  - bunch-by-bunch luminosities

• **Future evolution of LumiBelle2**
  - increase HER signal rates → have identified and will use better location for Phase 3
  - faster charge amplifiers & lower noise current amplifiers
  - long term DAQ solution, possibly with a few more channels
  - shielding / protection to mitigate activation on LER side under study
  - ability to easily vary signal acceptance to keep few % precision @ 1 kHz over $10^{32} - 10^{36}$ cm$^{-2}$s$^{-1}$
    → important to limit accumulated radiation dose
  - more remote operation, with less human resources and less presence at KEK
    → one of LAL Belle II group service tasks

• **Application to future high energy colliders**
  - start by evaluating basic specifications and methods
Backup slides
LumiBelle2 precision/dose and luminosity

HER:
- Initially low precision
- Low dose

LER:
- High precision
- High dose

- Need both HER and LER to cover full range of SKB luminosities;
- HER precision can be improved with larger diamonds;
- LER can be moved to receive a lower dose;
- Recent study shows % level precision enough for horizontal IP orbit feedback with dithering technique

<table>
<thead>
<tr>
<th>Phase</th>
<th>Luminosity (cm(^2) s(^{-1}))</th>
<th>( \Delta L/L ) HER/LER (%)</th>
<th>Dose HER/LER (Mgy/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>( 1 \times 10^{33} )</td>
<td>28.9 / 2</td>
<td>2e-7 / 2e-4</td>
</tr>
<tr>
<td>2.2</td>
<td>( 1 \times 10^{34} )</td>
<td>20.7 / 0.6</td>
<td>1.5e-6 / 1.5e-3</td>
</tr>
<tr>
<td>2.3</td>
<td>( 2 \times 10^{34} )</td>
<td>15.1 / 0.4</td>
<td>3e-6 / 3e-3</td>
</tr>
<tr>
<td>2.4</td>
<td>( 4 \times 10^{34} )</td>
<td>10.5 / 0.3</td>
<td>6e-6 / 6e-3</td>
</tr>
<tr>
<td>3</td>
<td>( 8 \times 10^{35} )</td>
<td>3.1 / 0.07</td>
<td>1.2e-4 / 0.12</td>
</tr>
</tbody>
</table>