Radiation monitoring with diamond sensors for the Belle-II vertex detector

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Outline

- The SuperKEKB collider
- The Belle II detector
- The Radiation monitoring system
- Diamond sensors
- Calibrations and characterization
- First commissioning of SuperKEKB

introduction

why

how

results

(An example)
Belle II at SuperKEKB

- Doubled beam currents
- Reduced beam spot size

$L_{\text{peak}}$: $8 \times 10^{35}$ cm$^{-2}$s$^{-1}$ (40 x KEKB)
$L_{\text{int}}$: 50 ab$^{-1}$ by 2025 (50 x KEKB)
Radiation monitoring system

Large radiation doses expected

in 10 years:

15/18 Mrad on pixels
10 Mrad on the silicon vertex detector

need to monitor radiation occurring in the inner silicon detector

Requirements:

Radiation monitoring

- sufficiently accurate measurement of instantaneous and integrated dose

Deliver beam abort signal

- large increase in backgrounds
  - “fast” abort trigger system

- lesser increase in backgrounds
  - “slow” abort trigger system

use 20 single crystal diamond sensors
Why diamond sensors?

- Response time for fastest beam abort trigger: 10 µs
- Response time for slow beam abort trigger: >10 s
- Precision on instantaneous dose rate:
  - 50.0 mrad/s for fast abort
  - 5.0 mrad/s for slow abort

requirements

1- Strong resistance to radiation and temperature
2- No need for darkness, pn junction or cooling
3- Ultrafast charge collection due to high drift velocity

- wide band gap (5.5 eV)
- high displacement energy (42 eV)
- extreme thermal conductivity (2000 W m\(^{-1}\) K\(^{-1}\))
- high mobility for holes (1200 cm\(^2\) V\(^{-1}\)s\(^{-1}\)) and electrons (1800 cm\(^2\) V\(^{-1}\)s\(^{-1}\))

work as an ionization chamber

Volume:
(4.5 x 4.5 x 0.5) mm\(^3\)
Tests and calibrations

- the metallised diamond crystal is first glued on the printed circuit support

- the upper electrode is wire bonded

(0) Preliminary test: dark I-V characteristic:

Dark currents below the pA range at typical O(100V) operation voltage

• stability with time

• uniformity

• charge collection efficiency

• conversion from current to dose rate
**I-V with \( \beta^{90}\text{Sr} \) source**

I-V characteristic (just an example)

- **Sensor A**
- **Sensor B**

2 single crystal CVD diamonds with metalization (Ti + Pt + Au)

source-sensor distance fixed at 2mm

Different behaviour observed for each diamond sensor

- Hysteresis loop in some sensors
- Deep levels act as centres to capture or emit carriers during the charging or discharging process
Stability

Check stability as diamonds will record dose for years

same diamond with different polarity

HV = +100V at back

HV = -100V at back

≈10% uncertainty in response at +100V

<1% uncertainty in response at -100V

We will choose this polarity
stability is reached after a transient presumably due to traps in the crystal

Asymptotic state: both shallow and deep levels completely filled

Shockley-Hall-Read theory for impurity levels as trapping centres.

Two different types of traps:
• shallow traps
• deep traps

\[ \tau_s \sim 100 \text{ s} \]
\[ \tau_d \sim 9000 \text{ s} \]
Dependence on $\beta$ source distance

Response as a function of the distance between the source and the sensor depends on HV bias

- photoconductive gain due to ohmic contact between electrodes and diamond $\rightarrow$ charge injected from the electrode

Current-to-dose conversion requires knowledge of the photoconductive gain

Use FLUKA to compare with measurement and infer the gain for each diamond
Comparison with FLUKA

- measured current (at 100V)
- fluka current

current decreases approximately with the inverse square of the distance

agreement with simulation

measured current > simulated current

photoconductive gain (at 100V)

photoconductive gain

\[ \text{Ratio} = \frac{I_{\text{meas}}}{I_{\text{FLUKA}}} \]
TCT with Alpha source

(TCT = Transient Current Technique) α source: 241-Am, 55kBq

square pulse → check of the uniformity of the electric field in the diamond bulk

pulse area constant from -90V up to -400V → Fully efficient from -90V (CCE ~ 100%)

the width of the signal is the drift time of charge carrier
it decreases consistently with the bias applied
Commissioning schedule

**Phase I**
(no Belle II detector)

- 2016
  - 1 2 3 4 5 6 7 8 9 10 11 12
  - 4 diamonds installed on the beam pipe
- Concluded!

**Phase II**
(BELLE II detector without VXD)
- First collisions
- 2017
  - 1 2 3 4 5 6 7 8 9 10 11 12
  - 8 diamonds will be installed
- 2018
  - 1 2 3 4 5 6 7 8 9 10 11 12
  - (full BELLE II detector)

**Phase III**
- 2018
  - 1 2 3 4 5 6 7 8 9 10 11 12
  - 20 diamonds will be installed
Phase I SuperKEKB commissioning

Four diamonds installed on the pipe for beam-radiation measurement

- first test and calibration of diamonds sensors in realistic conditions to prove proper operations and check precision for fast and slow aborts
- first measurement of beam-induced background in SuperKEKB to provide valuable feedback for validating background simulations

An example

integrated doses
Summary

• 40x increase in superKEKB luminosity
  ➔ High instantaneous/integrated radiation doses for the inner silicon detector

• use 20 single crystal diamond sensors to monitor radiation.
  Complete characterization:
  ➔ • dark current
  ➔ • stability with time
  ➔ • uniformity
  ➔ • charge collection efficiency
  ➔ • photoconductive gain
  ➔ • conversion from current to dose rate

• 4 sensors and electronics prototypes installed in the first SuperKEKB commissioning phase.
  - Measurements of all primary beam backgrounds and integrated dose measurement

• First test and calibration on diamond and readout electronics done. Precision (0.5 nA on the shortest 10μs time scale) OK for reliable fast and slow aborts for phase 2/3

  Development of beam abort in next commissioning phase (02-2018 → 07-2018)
## Radiation Monitoring with Diamond Sensors for the Belle-II Vertex Detector

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of radiation sensors</td>
<td>20</td>
</tr>
<tr>
<td>diamond sensor size</td>
<td>5 mm×5 mm×500μm</td>
</tr>
<tr>
<td>maximum coax. cable length from sensor to electronics</td>
<td>3 + 40 m</td>
</tr>
<tr>
<td>sensor current/dose rate conversion factor</td>
<td>1 ÷ 10 nA/(mrad/s)</td>
</tr>
<tr>
<td>sensor current measurement sensitivity</td>
<td>0.01 nA</td>
</tr>
<tr>
<td>sensor current measurement range</td>
<td>1 ÷ 10 mA</td>
</tr>
<tr>
<td>normal frequency of current sampling</td>
<td>100 kHz</td>
</tr>
<tr>
<td>depth of buffer memory for specific events (aborts etc)</td>
<td>600 ms</td>
</tr>
<tr>
<td>normal frequency of data recording on slow control DAQ</td>
<td>1 ÷ 10 Hz</td>
</tr>
<tr>
<td>response time of fastest (hardware) beam abort trigger</td>
<td>10 μs</td>
</tr>
<tr>
<td>response time of slow (software) beam abort trigger</td>
<td>&gt; 10 s</td>
</tr>
<tr>
<td>instantaneous dose rate sensitivity</td>
<td>1.0 mrad/s</td>
</tr>
<tr>
<td>integrated dose overall relative uncertainty</td>
<td>5%</td>
</tr>
</tbody>
</table>

for typical diamond sensors (fast aborts):

| current measurement, precision (time scale 1 ms)        | 10 nA                |
| response time                                          | up to 10 μs          |
| current range                                           | 0 ÷ 5 mA             |

for typical diamond sensors (slow aborts):

| current measurement, precision (time scale 1 s)         | < 1 nA               |
| response time                                          | > 1 ÷ 100 s          |
| current range                                           | 0 ÷ 15 μA            |
Diamond sensor response

~1.6nA
~2.8nA
~0.18nA
~0.18nA

**HER beam current**

**LER beam current**
First signals

Currents vs time

Zoom on beam loss spike

Start filling

LIN. scale

LOG. scale

Top-off every 4 min.
Background Studies

Current scan

Beam - gas scattering

Touschek scattering

Diamond current vs inverse beam size: Linear fit, intercept → extrapolation to pure beam-gas contribution
Beam abort thresholds (1/2)

Preliminary study from diamond sensors

Diamonds: Abort Buffer Memories

- diamond current will be sampled and digitized at 100kHz
- several levels of running averages are computed providing an effective digital filter

Present configuration of revolving Abort Buffer Memories to be improved with really “running sums”

![Diagram of memory configurations](image)
Beam abort thresholds (2/2)

Buffer memories: snapshot example

Example of snapshot of Buffer Memories (Mem1 to Mem4) for Dia3 = BW_0 in stable beam conditions, with average $I(BW_0) = 1.5 \text{ nA}$

Noise decreases with increased averaging, from about $0.47 \text{ nA}$ to $< 0.04 \text{ nA}$

OK both for fast ($10 \mu s$) and slow ($> 1 \text{ s}$) beam aborts with appropriate thresholds

- **BW_0 Mem1**: 100000 entries, 1 s history, $\sigma = 0.47 \text{ nA}$
  - -1 nA to 3 nA

- **BW_0 Mem2**: 1000 entries, 1 s history, $\sigma = 0.18 \text{ nA}$
  - 0 nA to 3 nA

- **BW_0 Mem3**: 1000 entries, 50 s history, $\sigma = 0.047 \text{ nA}$
  - 0 nA to 3 nA

- **BW_0 Mem4**: 100 entries, 100 s history, $\sigma = 0.034 \text{ nA}$
  - 0 nA to 3 nA
FLUKA

simplified geometry:

- source
- diamond
- Al screen
- deposited energy

photoconductive gain \( = \frac{I_{\text{meas}}}{I_{\text{FLUKA}}} \)

assuming:
- deposited energy equal in simulation and measurement
- \( CCE_{\text{FLUKA}} = 1 \), \( CCE_{\text{meas}} = 1 \)
- no photoconductive gain in simulation

TIPP2017, 23-05-2017
Radiation Monitoring with Diamond Sensors for the Belle-II Vertex Detector
IV characteristic

Current [ nA ]

Voltage [ V ]

-400 -200 0 200 400

-2 -1.5 -1 -0.5 0 0.5 1 1.5 2

DC13
DC14
DC15
DC16

Radiation Monitoring with Diamond Sensors for the Belle-II Vertex Detector
Photoconductive gain

Gain factor vs distance source-sensor [mm]

- 100 V
- 200 V
- 300 V
Charge Collection Efficiency

Example: DM5, CCE ≈ 100%

Landau Most Probable Value (MPV) vs HV → Charge Collection Efficiency

\[
CCE = \frac{Q_{raccolta}}{Q_{generata}} = \frac{v_{dr}}{d} \left( 1 - e^{-\frac{d}{v_{dr}\tau}} \right), \quad \text{con} \quad v_{dr} = \mu \frac{V}{d}
\]
Reference: With $\beta^{90}$Sr source at 18 mm distance -> FLUKA vs measurement
We measure currents -> we need a conversion factor from current to dose

**FLUKA**

- **RE** (Released Energy) = 3.25 GeV/s
- Assuming:
  - $CCE_{FLUKA} = 1$
  - $E_{e-h} = 13$ eV

\[
\text{Dose} = \frac{\text{RE} \times 1.6 \times 10^{-19}}{M} = 1.47 \text{ mrad/s}
\]

\[
\frac{(\text{Dose/I})}{0.04 \text{ nA}} = \frac{37 \text{ mrad/s}}{\text{nA}}
\]

\[
\begin{aligned}
\text{predicted current} & \quad I_{FLUKA} = \frac{\text{RE}_{FLUKA} \times q_e}{E_{e-h}} \\
\text{generated charge} & \quad CCE_{FLUKA} \times (G_{PC})_{FLUKA} = 40 \text{ pA}
\end{aligned}
\]
Current-dose calibration factor (2/2)

We measure currents -> we need a conversion factor from current to dose

Measurements

Photoconductive gain = $I_m/I_{FLUKA}$

<table>
<thead>
<tr>
<th>(pA)</th>
<th>@-100V</th>
<th>@+100 V</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fluka*</td>
<td>-40</td>
<td>+40</td>
</tr>
<tr>
<td>DM4</td>
<td>-850</td>
<td>+660</td>
</tr>
<tr>
<td>DM5</td>
<td>-460</td>
<td>+180</td>
</tr>
<tr>
<td>DC3</td>
<td>-230</td>
<td>+340</td>
</tr>
<tr>
<td>DM7*</td>
<td>-130</td>
<td>+340</td>
</tr>
</tbody>
</table>

$G_{PC-} = \begin{bmatrix} 21.25 \\ 11.5 \\ 5.75 \\ 3.25 \end{bmatrix}$

$G_{PC+} = \begin{bmatrix} 16.5 \\ 4.5 \\ 8.5 \\ 8.5 \end{bmatrix}$

$Im = \text{generated charge}$

$CCE_{exp} \cdot G_{PC,exp}$

assumption: equal to generated charge FLUKA

Dose (mrad/s) = $\frac{I_m \text{ (nA)} \cdot 37 \text{ mrad/s/nA}}{G_{PC}}$

Systematics

- Source distance -> 11%
- Diamond Active Volume -> 10%
- Source activity -> 7%
- Electronics Offset drift ~ 2%
- HV effects order 1%
- Priming/pumping effects (initial stability) < 10%
  (long term < 1%)
- FLUKA simulation -> 1%
I-V with $\beta^{90}$Sr source (d=18mm)

DC3

DM4

DM5

DM7
# BEAST sensors

<table>
<thead>
<tr>
<th>System</th>
<th>Detectors installed</th>
<th>Measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td>&quot;CLAWS&quot; scintillator</td>
<td>8</td>
<td>injection backgrounds</td>
</tr>
<tr>
<td>Diamonds</td>
<td>4</td>
<td>ionization dose</td>
</tr>
<tr>
<td>BGO</td>
<td>8</td>
<td>luminosity</td>
</tr>
<tr>
<td>Crystals</td>
<td>6 CsI(Tl) 6 CsI 6 LYSO</td>
<td>EM energy spectrum</td>
</tr>
<tr>
<td>He-3 tubes</td>
<td>4</td>
<td>thermal neutron flux</td>
</tr>
<tr>
<td>Micro-TPCs</td>
<td>2</td>
<td>fast neutron</td>
</tr>
<tr>
<td>PIN diodes</td>
<td>64</td>
<td>neutral vs charged radiation dose</td>
</tr>
</tbody>
</table>