Earthquakes frequently occur in Japan. Even though countermeasures are thoroughly considered and well executed, earthquakes still impact facilities and experimental devices. The large relative displacements induced by an earthquake can damage beam pipe bellows and interfere with sub-detectors by causing the tolerance between them to disappear. So, we installed acceleration sensors on the Belle II detector and mounted gap sensors on the QCSs to measure the relative displacements. Response spectrum analyses (RSAs) of the Belle II detector were conducted to evaluate the impact of earthquakes. We then compared the measurements to the RSA results, which led to an idea for a countermeasure.

**INTRODUCTION**

The purpose of this study was to understand the cause of a power shutdown of the superconducting quadrupole magnets (QCSs) at the interaction region of the Belle II detector, which is located at the SuperKEKB accelerator complex at KEK (High Energy Accelerator Research Organization) in Tsukuba, Japan. [1, 2]. The power shutdown first occurred on March 20, 2021 during an earthquake with an intensity of 3.5 as per the Japan Meteorological Agency (JMA) scale. At the interaction region of the Belle II detector, there is also a superconducting detector solenoid (that can produce a magnetic field of 1.5 T) and superconducting compensation solenoids that cancel the detector solenoid field at the QCS. The size of the Belle II detector is 8 × 8 × 10 m (length, width, and height, respectively) and its total weight is 1400 tons. [3]. The power shutdown of the QCSs was expected to be caused by disturbed magnetic fields in the solenoids, as the earthquake-induced voltage in the compensation solenoids exceeded the pre-set threshold (i.e., the QCS quench was triggered).

Response spectrum analyses (RSA) were also carried out for a 3D model of the Belle II detector to estimate the displacements in the detector via simulation. The RSA results showed that the Belle II detector can be shaken by up to a few mm by an earthquake with an intensity of 4 [4].

Because of the precision required by the detector and accelerator design, these displacements and interferences were taken seriously. In addition, if the displacement reached beyond the acceptable tolerance, it would be possible for damage to the beam pipe bellows connected to the QCSs to occur, and interference between the sub-detectors could also occur if the gaps between them disappeared.

**MEASUREMENT SYSTEM**

Two acceleration sensors were mounted on both the top of the Belle II detector (Belle II-top) and the underground floor 16 m below it (GL-16m), as shown in Fig. 1.

One sensor was a piezo-type tri-axial acceleration sensor (Acc-1), and its precision was 0.05 gal. The other was a servo-type high-precision acceleration sensor (Acc-2) with 10^-6 gal precision. These four sensors measured the seismic acceleration in three directions.

The displacements were measured with the high-precision sensor (Acc-2) which has 1.7×10^-4 mm integration error to obtain the cumulative sum (integration) of the acceleration histories, which were processed using a high-pass filter with a cut-off frequency of 0.5 Hz to remove the DC offset and trend.

**VERIFICATION OF THE CAUSE OF THE POWER SHUTDOWN**

The cause of the QCS power shutdown was verified using the gap sensors, which were attached to the forward (FWD) QCS-R cryostat and backward (BWD) QCS-L cryostat.

<table>
<thead>
<tr>
<th>Date</th>
<th>Intensity (I)</th>
<th>FWD (mm)</th>
<th>BWD (mm)</th>
<th>Difference (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>May 3</td>
<td>1.3</td>
<td>0.0359</td>
<td>0.0364</td>
<td>0.0005</td>
</tr>
<tr>
<td>May 5</td>
<td>2.4</td>
<td>0.099</td>
<td>0.104</td>
<td>0.0053</td>
</tr>
<tr>
<td>May 9</td>
<td>1.0</td>
<td>0.0371</td>
<td>0.0353</td>
<td>0.0017</td>
</tr>
<tr>
<td>May 22</td>
<td>2.4</td>
<td>0.091</td>
<td>0.083</td>
<td>0.0084</td>
</tr>
</tbody>
</table>

The precision of the gap sensors was 0.6 μm, and they measured the gaps between the QCS cryostats and the inner...
wall of the central drift chamber (CDC) in the lateral (NS) and vertical (UD) directions (i.e., in the plane perpendicular to the beam axis). Table 1 lists the maximum gap displacements for the earthquakes occurred in May, 2022. The difference between the maximum gap displacements at the two QCSs were very small compared to the individual displacements. Therefore, the gap displacements must have originated from the CDC (i.e., the Belle II detector). The QCSs were unlikely to be the cause, and thus the Belle II detector was the most likely cause. In the next section, the gap displacements calculated by the RSA based on the 3D model of the Belle II detector are compared to the measurements.

**VERIFICATION OF THE RSA RESULTS**

**Ground Motion at the Underground Level**

After the installation of the acceleration sensors, RSA calculations were also carried out on the Belle II detector 3D model (Belle II-top) using the ANSYS software package, with the ground motion of the GL-16m as the input ground motion.

Table 2 shows the comparison between the RSA calculations and the measurements for this case.

Table 2: Maximum displacements recorded by the measurements (“Meas.”) which were the averages of the values measured at the QCSs, and the RSA results assuming the ground motion at the GL-16m.

<table>
<thead>
<tr>
<th>Date in 2022</th>
<th>Intensity (I)</th>
<th>RSA mm</th>
<th>Meas. mm</th>
<th>Difference mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>May 29</td>
<td>2.5</td>
<td>0.16</td>
<td>0.17</td>
<td>-0.01</td>
</tr>
<tr>
<td>Sep. 30</td>
<td>2.1</td>
<td>0.10</td>
<td>0.10</td>
<td>0.00</td>
</tr>
<tr>
<td>Nov. 9</td>
<td>2.8</td>
<td>0.17</td>
<td>0.20</td>
<td>-0.03</td>
</tr>
<tr>
<td>Nov. 14</td>
<td>2.3</td>
<td>0.17</td>
<td>0.19</td>
<td>-0.02</td>
</tr>
</tbody>
</table>

For the underground data, the RSA calculations were in good agreement with the measurements. The comparison between RSA the calculations and the measurements in the NS direction for the earthquake that occurred on November 9, 2022 is shown in Fig. 2.

**MEASUREMENT OF THE SEISMIC CHARACTERISTICS ON THE FLOOR OF THE BELLE II DETECTOR.**

As already mentioned, the Belle II detector rests on a floor 16 m below the ground level. Accordingly, the seismic characteristics measured on that floor were compared to those measured on the ground level.

The acceleration histories measured for both the ground level (GL) and the underground level (GL-16m) are shown in the plots in the left column of Fig. 3. Seismic waves generally become increasingly damped as measurements are taken further underground. However, the response spectra in the horizontal (NS and EW) directions indicate that they were almost the same for frequencies below 2 Hz.
MEASUREMENT OF THE RELATIVE DISPLACEMENT BETWEEN THE BELLE II DETECTOR AND THE FLOOR

The relative displacement between the Belle II detector (Belle II-top) and the underground level (GL-16m) was measured with high-precision acceleration sensors at the start of a long shutdown period for the SuperKEKB accelerator (i.e., at the end of June 2022), during which the detector solenoid was not excited.

![Image](image1.png)

Figure 4: Horizontal displacement measured for the earthquake that occurred on November 9th, 2022

Figure 4 shows typical measurements of the displacement histories for Belle II-top (blue lines) and GL-16m (green lines) in the horizontal directions for the earthquake that occurred on November 9, 2022, which had an intensity of 2.8. The differences between the displacements are shown as the relative displacements (red lines). In the lateral (NS) direction (perpendicular to the beam axis), the displacements at both Belle II-top and GL-16m seem to be in the same phase, as the relative displacements were smaller than the individual displacements. However, in the longitudinal (EW) direction (along the beam axis), the relative phase angle between the Belle II-top and GL-16m displacements reached up to 180 degrees.

![Image](image2.png)

Figure 5: Power spectrum densities (PSDs) of the relative displacements in the NS and EW directions for the earthquake that occurred on November 9, 2022

The maximum relative displacements in the NS and EW directions were 0.2 mm and 1.5 mm, respectively. To examine this phase behaviour in detail, a fast Fourier transform (FFT) was performed. Fig. 5 shows the power spectrum densities (PSDs) of the relative displacements in the NS and EW directions, as determined by the FFT analysis. In the NS direction (blue line), no prominent resonant peak was observed. However, there was an obvious resonant peak at 3.5 Hz in the EW direction (red line), which corresponds to the first mode of the resonant frequency of the Belle II detector. This 3.5 Hz resonance has also been observed for other earthquakes.

CONCLUSION

In this study, the cause of earthquake-induced QCS quench triggers in the Belle II detector was experimentally investigated using gap sensors and high-precision acceleration sensors. The cause of the QCS power shutdown was discovered to be due to the movement of the Belle II detector, and not the QCSs themselves. The RSA results of the Belle II detector model were in good agreement with the ground motion measured at the underground level (GL-16m). For the earthquake characteristics, we found that the acceleration response spectra at the ground and GL-16m levels were almost the same for frequencies below 2 Hz. This is an important factor to consider in the design of soft or large structures, even those constructed underground as their natural frequencies are low, to minimize earthquake damage. The displacements at Belle II-top and GL-16m were measured with high-precision acceleration sensors.

We will continue these investigations into the effects of earthquakes on the Belle II detector. In future work, we will develop additional countermeasure ideas to further protect the detector from strong earthquakes.

ACKNOWLEDGEMENT

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REFERENCES


