

Cryostat Motion of the SuperKEKB Final Focus Magnets During Earthquakes

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Abstract

The final-focus superconducting magnet system (QCS) of the SuperKEKB interaction region is housed in large cryostats installed on both sides of the interaction point (IP). Each cryostat is supported from one side in a cantilever configuration, while its IP-side end is not mechanically fixed. The position of each cryostat relative to the Belle II detector is continuously monitored by capacitive gap sensors. These sensors have recorded the response of the cryostats to numerous earthquakes with different magnitudes, hypocentral locations, and depths. In this study, cryostat motion during several representative earthquakes is compared. The measurements clearly resolve the transient vibration of the cryostats during seismic events. An $M5.0$ local earthquake produced a peak displacement exceeding $200\text{ }\mu\text{m}$, approximately consistent with a simple magnitude-amplitude scaling from a smaller earthquake with a similar source location and depth. In contrast, a long-period earthquake produced a smaller peak displacement but a substantially longer-lasting response. For the events studied, the cryostats generally returned close to their pre-earthquake positions after the excitation. These observations provide information on the mechanical response and stability of the interaction-region superconducting magnet system and demonstrate the usefulness of continuous position monitoring for future high-luminosity colliders.

INTRODUCTION

The SuperKEKB interaction region contains superconducting final-focus quadrupole magnets located very close to the IP [1]. These magnets are installed inside the QCS cryostats on the left and right sides of the Belle II detector. Unlike conventional accelerator magnets mounted individually on the tunnel floor, the QCS magnets form part of a mechanically complex system involving the cryostats, detector solenoid, compensation solenoids, and their support structures.

An important feature of the QCS mechanical configuration is that each cryostat is supported from one side through a movable base, forming a cantilever structure, as shown in Fig. 1 [3]. The end of the cryostat nearest the IP is not directly supported. Consequently, the positions of the final-focus magnets can be affected by deformation of the support and cryostat structures as well as by motion of the surrounding floor.

Several sources of motion have been observed during the construction and operation of SuperKEKB. For example, installation of the approximately 1300-t Belle II detector caused measurable subsidence of the beam-line floor near the IP. Electromagnetic forces also affect the cryostat position: its final position is determined partly by the balance of forces associated with the Belle II detector solenoid and the QCS compensation solenoid. A QCS solenoid quench

can disturb this balance and produce cryostat motion of several hundred micrometers.

In addition to these effects, earthquakes provide transient mechanical excitation of the entire interaction-region system. At SuperKEKB, even very small earthquakes in the region, including those that are not perceptible to people, can trigger a beam abort. Because Japan experiences frequent seismic activity, the continuously recorded monitoring data provide an opportunity to investigate the response of a large superconducting final-focus system under a variety of seismic conditions. This paper presents examples of cryostat motion observed during earthquakes and discusses the characteristics of the measured response.

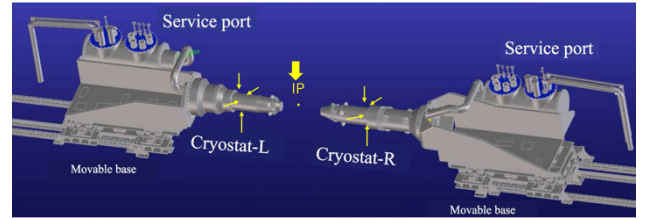


Figure 1: SuperKEKB interaction region showing the L- and R-side QCS cryostats and their cantilever supports. Gap-sensor locations are indicated by yellow arrows.

CRYOSTAT POSITION MONITORING

Four capacitive gap sensors are installed on each of the left- and right-side cryostats. They measure the distance between the cryostat and the Belle II detector, thereby providing a continuous measurement of the relative cryostat position with respect to Belle II rather than an absolute position in the accelerator coordinate system. This distinction is important when interpreting the earthquake data: the signals represent the relative mechanical response between the cryostat and the detector structure.

The sensors are sampled at high frequency and therefore provide a sensitive probe of transient cryostat motion. The earthquake measurements presented here were recorded at a sampling frequency of 256 Hz. The same monitoring system has shown that the cryostat position varies over several time scales. Daily variations correlated with outside air temperature have been observed, together with longer-term floor and cryostat motion [2]. Earthquake-induced motion therefore occurs on top of these slower environmental and operational variations. The relatively short duration and characteristic oscillatory waveform of seismic events, however, allow them to be clearly identified in the gap-sensor data.

OBSERVED RESPONSE TO EARTH-QUAKES

A number of earthquakes were recorded during the 2025–2026 SuperKEKB operating period. Relatively small events produced cryostat motions ranging from a few to several tens of micrometers, whereas larger events produced motions exceeding $100\mu\text{m}$.

Response to a Local Earthquake

Figure 2 shows a representative gap-sensor signal recorded during an earthquake. The characteristic response consists of a rapid increase in vibration amplitude following the arrival of the seismic disturbance, followed by gradual decay. Similar responses are observed by all four sensors, although the amplitudes differ because of the sensor locations and their sensitivity to different components of the relative motion.

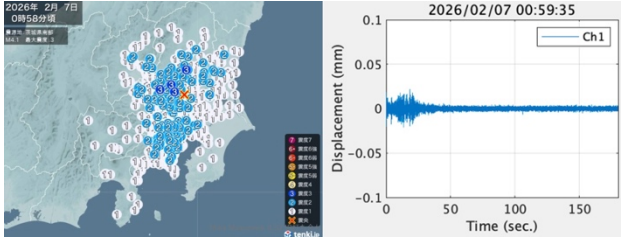


Figure 2: Example of a gap-sensor signal recorded during an earthquake. The numbers on the map indicate the seismic intensity on the Japan Meteorological Agency (JMA) seismic intensity scale [4], and the cross marks the epicenter.

A particularly clear example was recorded on 1 April 2026. The earthquake had a magnitude of approximately $M5.0$ and a depth of about 50 km. The gap sensors recorded a peak displacement slightly exceeding $200\mu\text{m}$ as shown in Fig.3. The waveforms show a strong initial excitation followed by damped motion over several tens of seconds. The response was substantially larger than that observed during the $M4.1$ earthquake on 7 February 2026.

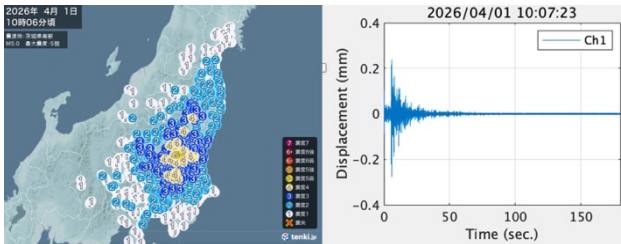


Figure 3: Gap-sensor signal recorded during the $M = 5.0$ earthquake on 1 April 2026. The map shows the JMA seismic intensity distribution and the epicenter (cross).

The amplitude observed during the April 1 earthquake can be compared with that of the February 7 event using the magnitude relation of the form [5]

$$M = \log_{10} A + B(\Delta, h), \quad (1)$$

where A is the amplitude measured at the observation point and $B(\Delta, h)$ represents corrections associated with epicentral distance Δ and hypocentral depth h . The two earthquakes had similar epicentral locations and hypocentral depths. If the difference in the correction term is neglected as a first approximation, the measured amplitude of approximately $25\mu\text{m}$ for the $M = 4.1$ February 7 earthquake gives

$$A_{M=5.0} \simeq 25 \times 10^{(5.0-4.1)} \simeq 200\mu\text{m} \quad (2)$$

This simple estimate is in good agreement with the approximately $200\mu\text{m}$ amplitude measured during the April 1 earthquake. The agreement suggests that, for these two events with similar source locations and depths, the observed cryostat motion is approximately consistent with the expected magnitude-amplitude scaling. However, the cryostat response also depends on epicentral distance, hypocentral depth, propagation path, local ground response, and the frequency content of the seismic motion. The agreement between these two events should therefore not be interpreted as a general prediction of cryostat displacement from earthquake magnitude alone.

Response to a Long-Period Earthquake

A distinctly different response was observed during the long-period earthquake off the Sanriku coast on 20 April 2026. Although the seismic intensity at KEK was similar to that of the April 1 event, the characteristics of the measured cryostat motion were markedly different. The peak displacement was approximately $50\mu\text{m}$ as shown in Fig.4, considerably smaller than the approximately $200\mu\text{m}$ observed on April 1. In contrast, the oscillation exhibited a longer characteristic period, as shown in the expanded view in Fig. 5, and persisted for a substantially longer time. Vibration was still detected several minutes after the initial trigger. These observations indicate that the cryostat response cannot be characterized by earthquake magnitude or local seismic intensity alone; the frequency content and duration of the seismic excitation are also important.

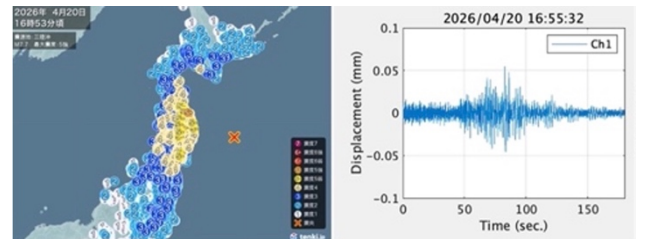


Figure 4: Gap-sensor response to the long-period earthquake off the Sanriku coast on 20 April 2026. The map shows the JMA seismic intensity distribution and the epicenter (cross).

Despite the differences in amplitude, period, and duration among the events examined, the transient motion

generally decays and the cryostat returns close to its pre-earthquake position. This behavior suggests a predominantly elastic response of the cryostat/support system to the seismic excitation observed so far. Small residual changes, however, must be distinguished from the normal slow motion of the interaction region, since long-term drift and seasonal floor-level variations are independently observed. HLS measurements, for example, have shown seasonal floor-level variations exceeding 1 mm in the straight sections around the IP [2].

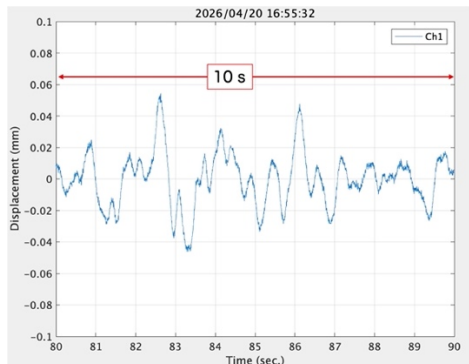


Figure 5: Expanded view of the gap-sensor response to the long-period earthquake off the Sanriku coast on 20 April 2026, showing the longer-period component of the cryostat motion.

DISCUSSION

The measurements illustrate an important feature of the SuperKEKB interaction region: alignment is not simply a static condition established during installation. The QCS cryostats form part of a mechanically active system whose position can change in response to environmental conditions, electromagnetic forces, equipment events such as quenches, long-term floor motion, and earthquakes.

The comparison of the April 1 and April 20 events further illustrates the importance of the characteristics of the seismic excitation. Although similar seismic intensities were reported at KEK, the cryostat responses differed substantially in amplitude, characteristic period, and duration. This indicates that peak displacement alone is insufficient to characterize the mechanical response of the interaction-region system. The frequency spectrum and duration of the excitation should also be considered.

For earthquake studies, the high-rate gap-sensor data are particularly valuable because they directly measure the relative response of the installed cryostat-detector system rather than relying solely on external seismic measurements. Correlation with ground-motion measurements at KEK would allow the response of the cryostat/support structure to be separated more quantitatively from the seismic excitation itself.

The present observations also indicate that both transient amplitude and residual displacement should be considered when evaluating mechanical stability. A relatively large transient displacement may have little lasting effect if the system returns reproducibly to its pre-earthquake position. Conversely, even a much smaller residual displacement

could be important for a final-focus magnet whose alignment directly affects the collision optics.

These observations may therefore be relevant to the design of future collider interaction regions. Continuous relative-position monitoring can provide information not only during initial installation and alignment but also throughout machine operation, allowing mechanical changes associated with earthquakes and other external disturbances to be identified.

SUMMARY

The SuperKEKB QCS cryostats are continuously monitored by capacitive gap sensors that measure their positions relative to the Belle II detector. The monitoring system has recorded numerous earthquakes and clearly resolves the transient vibration of the cryostats during seismic excitation. An $M5.0$ earthquake recorded on 1 April 2026 produced a peak displacement slightly exceeding $200\text{ }\mu\text{m}$. A simple comparison with an $M4.1$ earthquake originating from a similar region and at a similar depth gives an expected amplitude of approximately $200\text{ }\mu\text{m}$, in good agreement with the observed value. Although this comparison is based on only two events, it suggests that the measured response is approximately consistent with the expected magnitude-amplitude scaling under similar source conditions. In contrast, the long-period earthquake off the Sanriku coast on 20 April 2026 produced a smaller peak displacement of approximately $50\text{ }\mu\text{m}$ but a longer-period and substantially longer-lasting response. The comparison demonstrates that earthquake magnitude or local seismic intensity alone is insufficient to characterize the cryostat response; the frequency content and duration of the seismic excitation are also important. For the earthquakes examined so far, the cryostat motion generally decays toward the pre-earthquake position, consistent with a predominantly elastic response of the cryostat/support system.

Continuous monitoring of this type provides useful information for maintaining the alignment and mechanical stability of superconducting final-focus systems and may also be valuable for the interaction regions of future high-luminosity colliders.

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