FULL REALIGNMENT OF THE EUROPEAN SYNCHROTRON RADIATION FACILITY STORAGE RING

D. Martin†, G. Chamblas, G. Gatta, C. Gonzalez Torres
European Synchrotron Radiation Facility, Grenoble, France

Abstract

The Extremely Brilliant Source (EBS) Storage Ring at the European Synchrotron Radiation Facility (ESRF) was installed in 2019 and commissioned in 2020. Over the following six years, ground movements and differential displacement at floor slab joints progressively degraded the alignment between neighbouring girders. The first full realignment of the storage ring took place during the 2025–26 winter shutdown, following preliminary tests in summer 2025. The campaign achieved a standard deviation of approximately 25 µm in both horizontal and vertical directions relative to a smooth curve for the girders actually adjusted. Including all girders, the corresponding values were 31 µm horizontally and 27 µm vertically, improving on the alignment achieved in 2019. However, continuing floor movements rapidly degraded these results, and subsequent partial realignments failed to restore the overall alignment quality. The campaign demonstrated both the effectiveness and the practical limitations of the existing procedures, particularly the time required for horizontal realignment. The results highlight the need for more efficient adjustment methods and a better understanding of the alignment quality that can be maintained over time.

INTRODUCTION

The Extremely Brilliant Source (EBS) Storage Ring (SR) upgrade of the European Synchrotron Radiation Facility (ESRF) was installed in 2019 and commissioned in 2020. Its performance relies on the precise positioning of the SR magnets, with particularly stringent alignment requirements for the combined-function magnets, high-gradient quadrupoles, and sextupoles. Maintaining this alignment is therefore essential: as the magnets move away from their optimal positions, machine performance degrades.

No global realignment of the SR was carried out between its installation and 2025. During these six years, well-characterised ground movements at the ESRF site gradually displaced the magnets and degraded the overall alignment. By 2025, the accumulated movement was sufficient to require a global realignment of the storage ring. The procedure was first validated on four of the 32 SR cells during the summer 2025 shutdown, before the complete storage ring was realigned during the 2025–26 winter shutdown.

The campaign restored the SR alignment and, at the same time, provided a direct measure of what can realistically be achieved on the installed machine with the equipment, materials, and techniques currently available at the ESRF. This paper traces the degradation of the SR alignment back to the observed ground movements and presents the results of the 2025–26 realignment campaign. These results show that regular realignment will remain necessary as site movements continue, but also that the present approach has reached its practical limits. Achieving better alignment will require a different strategy.

BACKGROUND

EBS Alignment Requirements

The EBS alignment requirements are summarised in Table 1. The most stringent apply to the high-gradient quadrupoles, combined-function magnets, and sextupoles, with permissible alignment errors of 50–70 µm in the horizontal and vertical directions perpendicular to the beam. The requirements are expressed at one standard deviation, with a maximum permissible error of 2.5 standard deviations. [1]

Table 1: Key magnet alignment requirements

Magnet family	**Δx [µm]**	**Δy [µm]**	**Δz [µm]**
Dipole	1000	>100	>100
HGQ, CFD	500	60	60
MGQ	500	100	85
Sextupole	500	70	50
Octupole	500	100	100

HGQ – high gradient quadrupole
CFD – combined function dipole
MGQ – medium gradient quadrupole

The EBS could not, however, simply be installed at its theoretical position. A key constraint during installation was to avoid realigning the existing beamlines. The new machine therefore had to reproduce the source points and straight-section directions of the old machine. Doing this ensured the beamlines remained untouched, but tied the position of the new machine to the old machine.

The alignment requirements make no distinction between magnets on the same girder and magnets on separate girders. In practice, this distinction is important. Measurements in 2022 showed that magnets remain stable on their girders, while relative movement between adjacent girders dominates the degradation of the SR alignment. For example, movements at the storage-ring slab joints are an important contributor to the relative displacements.

* † martin@esrf.fr

EBS installation and operation 2019 to 2026

The EBS SR consists of 32 cells. In each cell, the magnets are installed on four girders, G1 to G4, with the DQ2 magnet supported between G2 and G3; a separate girder assembly is installed in the injection straight section. Magnet fiducialisation and girder assembly took place in two dedicated laboratories. Following fiducialisation, the magnets were aligned on the girders, then opened to install and align the vacuum chambers before being reassembled and measured. This measurement established the initial alignment quality of each completed girder assembly. The measurements were repeated at key stages during installation and subsequently during operation to determine whether transport, interventions or time had affected the relative positions of the magnets. The completed girders were transported to and from offsite storage before installation in the SR tunnel. Following installation, connection of the services and vacuum-chamber bakeout, the machine was measured again and finally smoothed for commissioning in 2019. Smoothing minimises relative alignment errors between magnets on adjacent girders while allowing the machine to follow a slowly varying trajectory around the ring. It therefore prioritises local magnet-to-magnet alignment over deviations from the nominal absolute position of the SR. The complete installation and alignment process is described in [2].

The existing SR floor presented an additional constraint. By 2018, its elevation varied by approximately ±25 mm around the ring. Most of this variation was already present when the floor was constructed in 1990, reflecting the civil engineering practices of the time for a structure extending over several hundred metres. The floor had also undergone gradual deformation due to site movements, contributing approximately ±5 mm to the overall height variation between 1990 and 2018. The ±25 mm therefore describes the geometry of the floor in 2018, rather than the magnitude of its movement since construction. By comparison, Fig. 4 shows the accumulated vertical movements between 2010 and 2026, ranging from approximately −3 to +2 mm. The SR was regularly realigned to its reference position between 1995 and 2009; subsequent alignment interventions were limited to smoothing.

Local floor height variations of up to 10 mm presented an additional difficulty when installing the girder support plates. These plates were levelled and glued to the floor, but local irregularities sometimes produced gaps exceeding the maximum permitted glue thickness of 7 mm. Shims were subsequently installed on the glued plates to bring the girder pedestals to their required heights, positioning the vertical adjustment jacks close to the midpoint of their stroke and preserving adjustment range in both directions. Each girder incorporates four adjustment jacks for vertical alignment. This four-point support is hyperstatic: differential movement between the supports can therefore introduce stresses into the girder as well as changing its position.

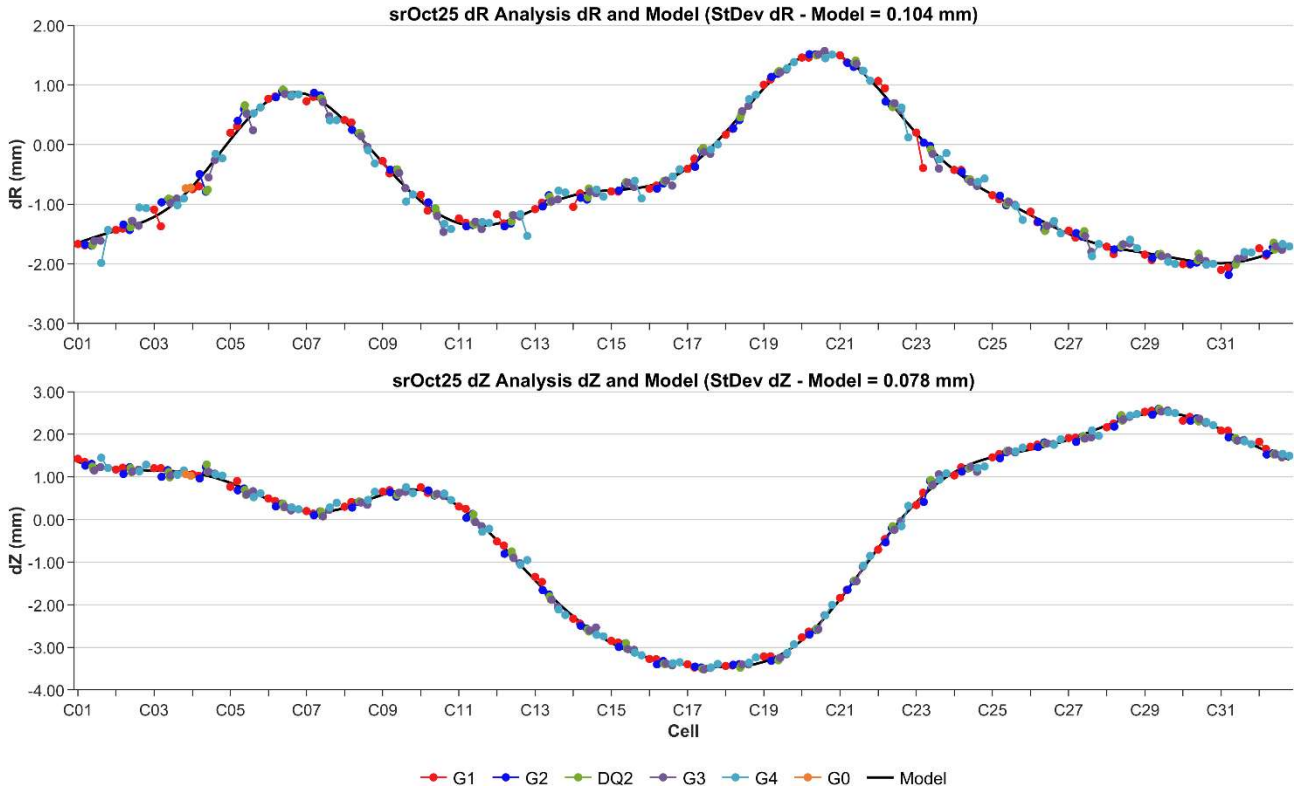


Figure 1: Absolute alignment of the machine in October 2025 before realignment. Note this is for information, the absolute alignment was not changed. This alignment is the result of long term site deformation.

ESRF Site Movement Signatures

Ground and slab movements at the ESRF result from a combination of geological, thermal and hydrological processes acting over timescales ranging from days to years. Their effects range from slow, large-scale deformation of the site (Figures 1 and 2) to more rapid and localised movements of individual slabs. The principal observed effects can be grouped into slow site movements, thermally induced slab bending, and hydrologically driven movements associated with river levels, dam operations and groundwater variations.

Slow Site Movements

Slow site movements reflect the geology and geomorphology of the Grenoble basin. Long-term levelling and InSAR measurements show spatially variable subsidence across the basin, attributed primarily to compaction of its thick sedimentary deposits [3]. ESRF levelling measurements show a gradual vertical tilt across the site, while the SR exhibits a long-term horizontal elongation along the valley and river axes (Figures 1 to 4). These movements develop over periods of years and produce smooth, large-scale deformation of the site and machine.

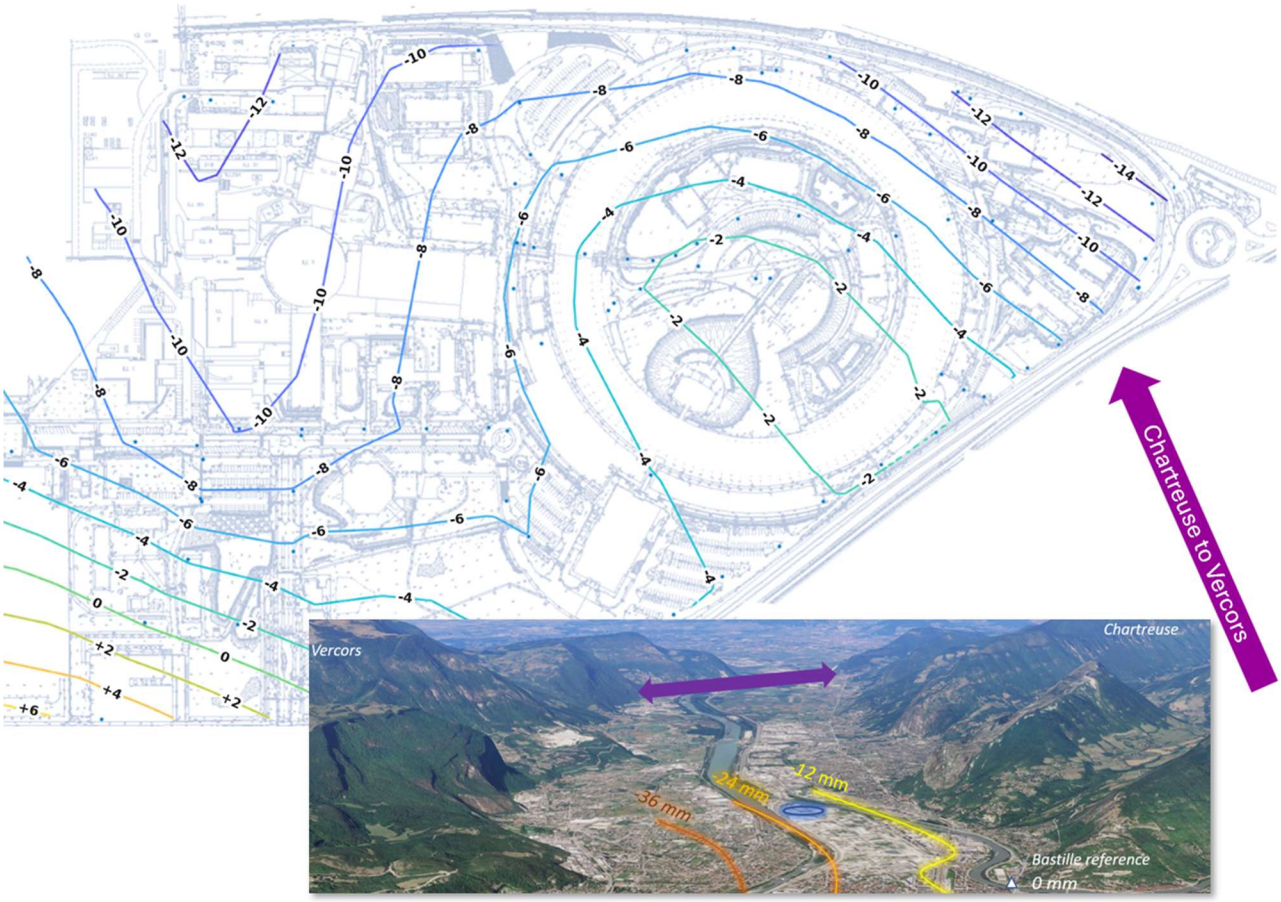


Figure 2: Vertical deformation of the ESRF site over the 10-year period 2015 to 2025. Note all contours are in mm.

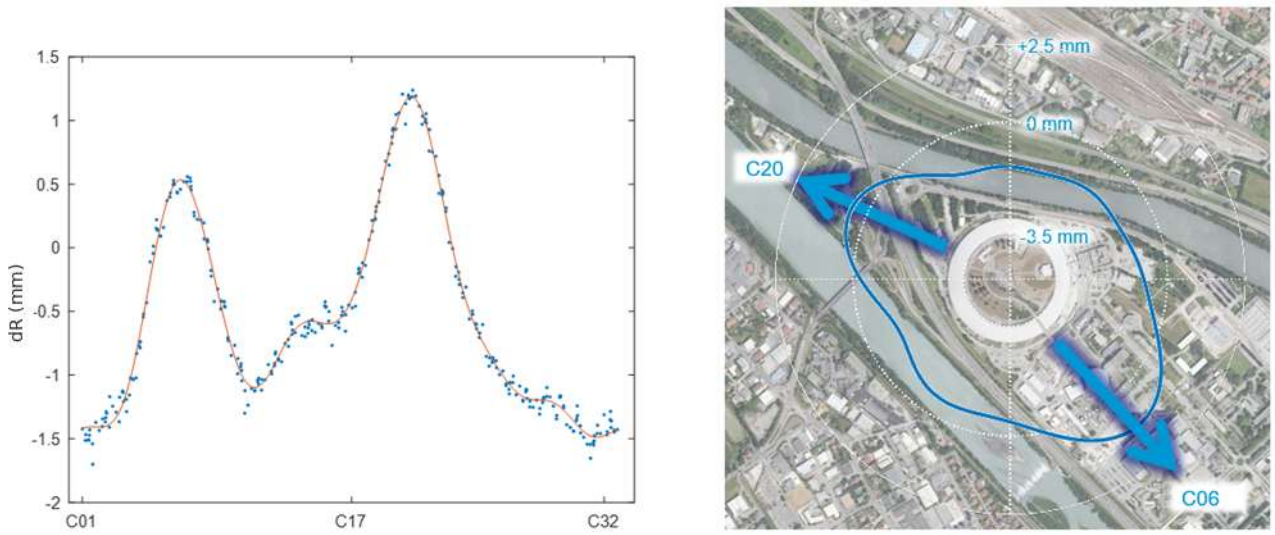


Figure 3: Horizontal deformation of the ESRF site along the Drac and Isere rivers axes.

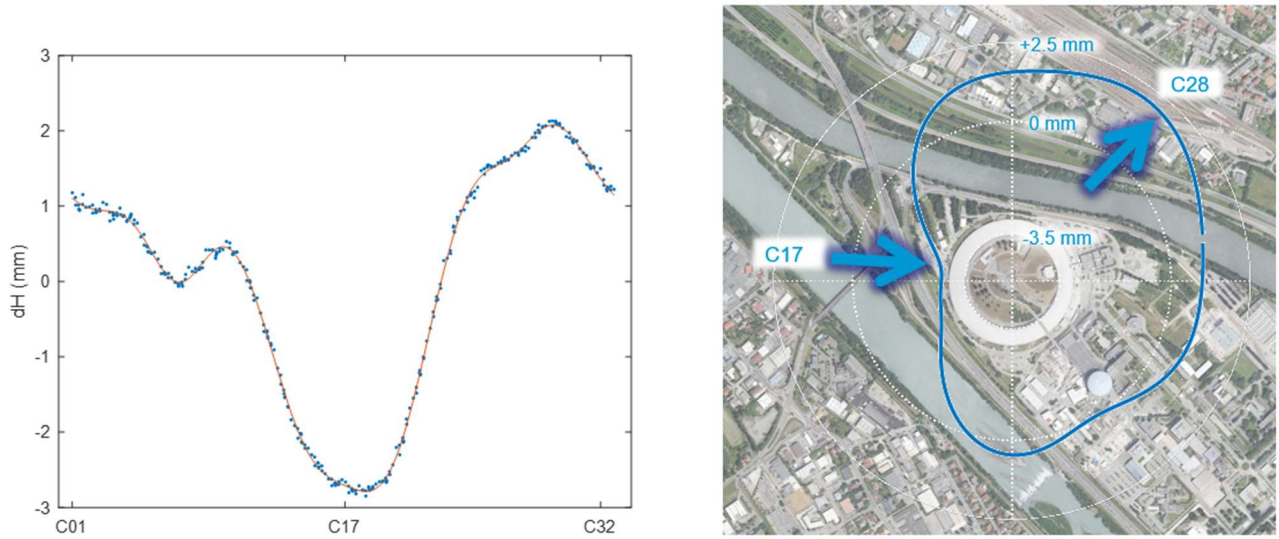


Figure 4: Vertical deformation of the ESRF site showing tilting across the valley.

Slab Bending

Slab bending results from variations in the temperature gradient through the concrete slab. These variations generate thermal stresses within the slab, causing it to bend. Within an individual slab the resulting deformation is relatively smooth, but this continuity is broken at the joints between adjacent slabs. Differential bending across a joint can therefore produce significant relative vertical movement (Figures 5 to 7). This movement is transferred to the magnets through the girders and their supports, which are fixed to the floor, creating discontinuities in the relative magnet alignment and a corresponding perturbation of the beam. The magnitude and rate of the movement depend on changes in the thermal gradient. Diurnal variations in tunnel temperature and annual variations in the ground temperature beneath the slab produce distinct short- and long-term responses [4, 5].

The resulting movements occur over very different timescales. Diurnal variations are typically small, producing relative movements of the order of 10 µm. Seasonal variations develop gradually over several months but can have much larger effects. More rapid movements can occur when thermal conditions change substantially over a period of days. During the 2025–26 winter shutdown, for example, the mean external air temperature fell from approximately 4.8 °C on 23 December to −3.6 °C on 5 January. This exceptional 8.4 °C decrease, combined with changes in the tunnel thermal conditions, altered the temperature gradient through the slab. Vertical movements of the order of 100 µm were subsequently measured at the exits of the G2 girders, producing substantial relative displacements across the DQ2 supports between G2 and G3.

Other Events — Flood and Hydrological Effects

Dam flushing produces a clearly observed hydrological response of the site. The operation is carried out during periods of heavy rainfall or runoff, when the dam is opened

to flush accumulated alluvial sediment from the riverbed. A flushing event typically lasts two to five days and produces a rapid, smooth deformation of the site. The deformation largely reverses once the event ends, although a small residual displacement remains, consistent with the removal of sediment from the riverbed. In both spatial extent and timescale, dam flushing therefore represents an intermediate response between the slow, large-scale site deformation and the rapid, local movements associated with slab bending and other local events.

Groundwater variations may also contribute to site movement. Previous measurement campaigns using piezometers at several locations across the ESRF site indicated that groundwater levels may vary non-linearly across the site. A piezometer near the centre of the site is currently monitored and records groundwater-level variations associated with dam-flushing events. An ongoing project will equip up to ten existing piezometers with real-time sensors and long-term data logging, allowing the spatial and temporal evolution of groundwater levels to be characterised more systematically. Groundwater variations are believed to influence both the SR and the beamlines, particularly those closest to the rivers, although their contribution to the observed movements cannot yet be quantified reliably.

Flood events can produce much more localised effects. In November 2023, the Isère reached a flow of approximately 1050 m³/s. During this event, a rapid local vertical displacement of the G4 girder exit was observed on the ID18 straight section in real time by the hydrostatic levelling system (HLS). Subsequent survey measurements confirmed displacements in all three directions: dR and dZ perpendicular to the beam, and dL along the beam. Similar events have been observed elsewhere around the SR, both before and since. Their precise mechanism has not been established, although changes in hydrological loading may contribute to the accumulation or release of stresses within the slabs.

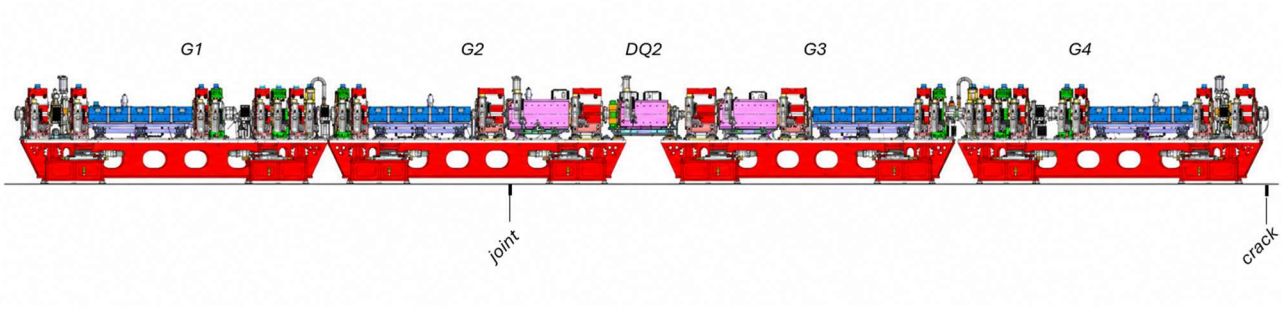


Figure 5: Distribution of the EBS girders in the tunnel ESRF SR tunnel.

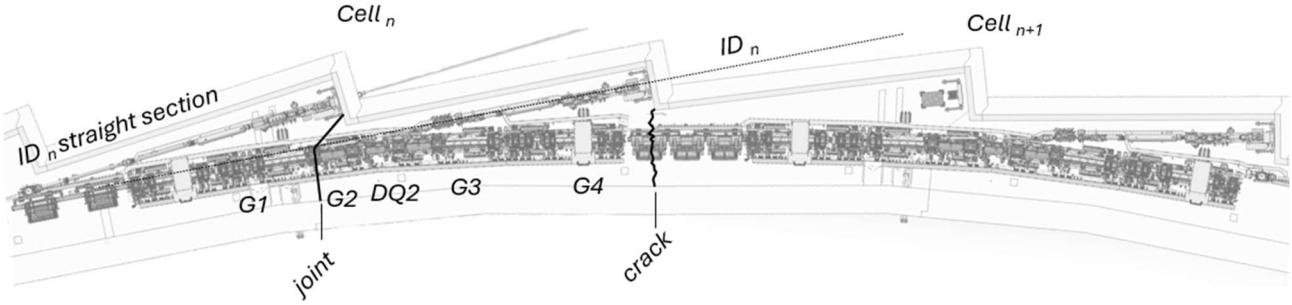


Figure 6: The EBS girders in the tunnels showing the positions of the slab construction joint and the crack.

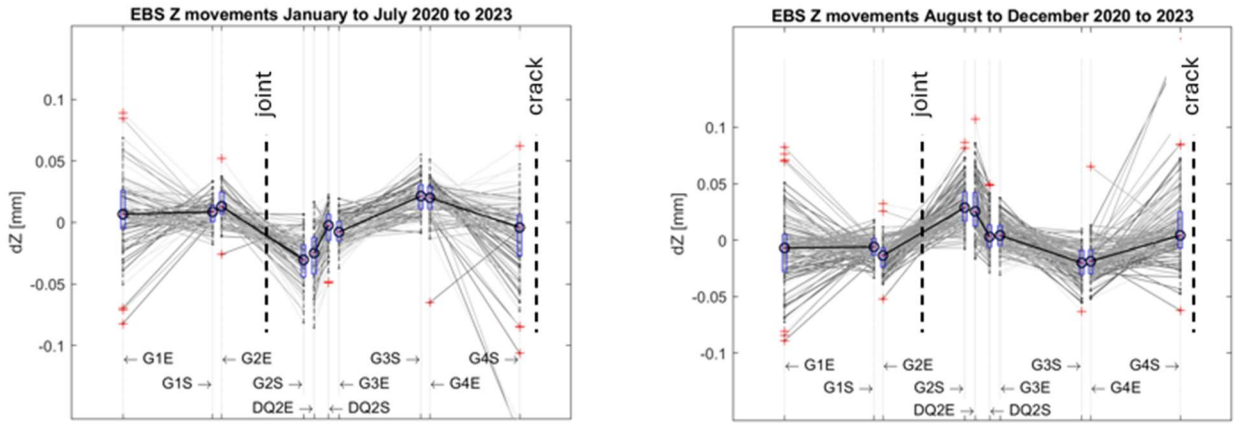


Figure 7: Impact of slab bending on EBS January to July and August to December over a 3 year period.

Site Movement Impacts on the SR Alignment

The impact of site movement on the SR depends strongly on its spatial wavelength. Short-wavelength alignment errors have a much greater effect on the beam than smooth, long-wavelength deformation. Beam-dynamics calculations illustrate the scale of this difference: at a wavelength of $L/128$, approximately 6 m, an alignment-error amplitude of 30 µm produces a residual orbit distortion of approximately 30 µm. At a wavelength of $L/2$, approximately 422 m, an error amplitude of about 7 mm is required to produce the same residual orbit distortion. [6] The SR is therefore much more sensitive to local relative displacements than to smooth deformation extending over a large part of the ring.

This distinction is important when interpreting the ESRF site movements. The long-term horizontal elongation and vertical tilt have displaced parts of the machine by several millimetres since its installation, but these movements occur over long spatial wavelengths and therefore have a relatively small effect on the beam. In contrast, differential movement at slab joints occurs over much shorter distances and changes the relative alignment of neighbouring girders. Even when the absolute displacement is small, these local movements can therefore have a much greater impact on the machine.

Measurements made on all 129 SR girders in 2022 showed that the magnets had not moved significantly with respect to one another on their respective girders since girder assembly in 2019. The uncertainty was of the order of 15 µm, close to that of laser tracker measurements. SR alignment degradation therefore occurs between girders rather than between magnets on the same girder. Relative horizontal and vertical movements between adjacent girders can introduce significant discontinuities between neighbouring magnet supports. The movements described above, including slab bending and rapid local events, consequently affect the machine much more strongly than larger but smoother deformation of the site.

No global realignment of the SR was carried out between its final alignment in 2019 and 2025. During this period, the cumulative effect of site and slab movements progressively degraded the relative alignment of the girders and the overall smoothing of the machine. By 2025, this degradation required a full realignment of the SR.

SR REALIGNMENT

A full realignment of the SR required the adjustment of nearly all the girders using the jacks integrated into each girder. These jacks had not been used since 2019, and the adjustment procedure had never been applied to the complete installed machine in a single campaign. Before committing to a full SR realignment, the procedure needed to be tested under operational conditions and the time and resources required for the complete campaign established. The realignment strategy was also designed to minimise interference with other sensitive machine systems and processes.

Summer 2025 Tests

Cells 18 to 21 were successfully realigned during the summer 2025 shutdown, with individual girder movements constrained to less than ±0.12 mm. The tests validated the adjustment procedure and confirmed its suitability for application to the complete SR during the 2025–26 winter shutdown

Winter Shutdown 2025-26 Realignment Campaign

Following the successful summer tests, a full SR realignment was undertaken during the 2025–26 winter shutdown. Unlike the summer tests, no general constraint was imposed on the magnitude of the girder movements. The objective was to restore the smoothing of the machine by reducing the relative alignment errors between adjacent girders to zero as far as practicable.

Several restrictions were nevertheless imposed to protect sensitive systems. No twist corrections were made because these require opposite vertical movements of diagonally opposed jacks and could affect the vacuum bellows. At the request of the Operations Group, C03G4, C04G0 and C04G1 in the injection region were not moved. The DQ2

magnets were also excluded from direct adjustment. Each DQ2 is fixed at the exit of G2 and rests freely on the entrance of G3, and was therefore allowed to follow the relative movement of the two girders in both (R) and (Z) rather than being aligned independently.

The campaign was organised as an iterative sequence of measurement, calculation and adjustment. Vertical corrections were performed first, using the October 2025 survey as the reference. Although a complete vertical realignment can be carried out in approximately 30 minutes, two hours were allocated to this first full-machine adjustment as a precaution. Several thousand individual jack movements were made during the campaign. Since a commanded jack movement does not necessarily produce the exact required displacement, individual adjustments often required more than one iteration to converge towards zero relative alignment error.

The initial vertical realignment was followed by a full SR survey using four teams working in parallel. This is the same survey configuration that has been used since the installation of the EBS, providing a consistent measurement of the SR alignment over time. The survey measures the entry and exit of G1, G2, DQ2, G3 and G4 in each of the 32 cells, together with the G0 injection girder, giving a total of 322 measured points around the SR. Even with four teams working in parallel, a complete survey requires 6–8 hours. The measurement procedure is described in detail in [2]. The results were processed to calculate the horizontal corrections, which were applied by two alignment teams over one day. A second full SR survey was then required to control the results and calculate the remaining corrections, followed by further vertical adjustment before the Christmas break.

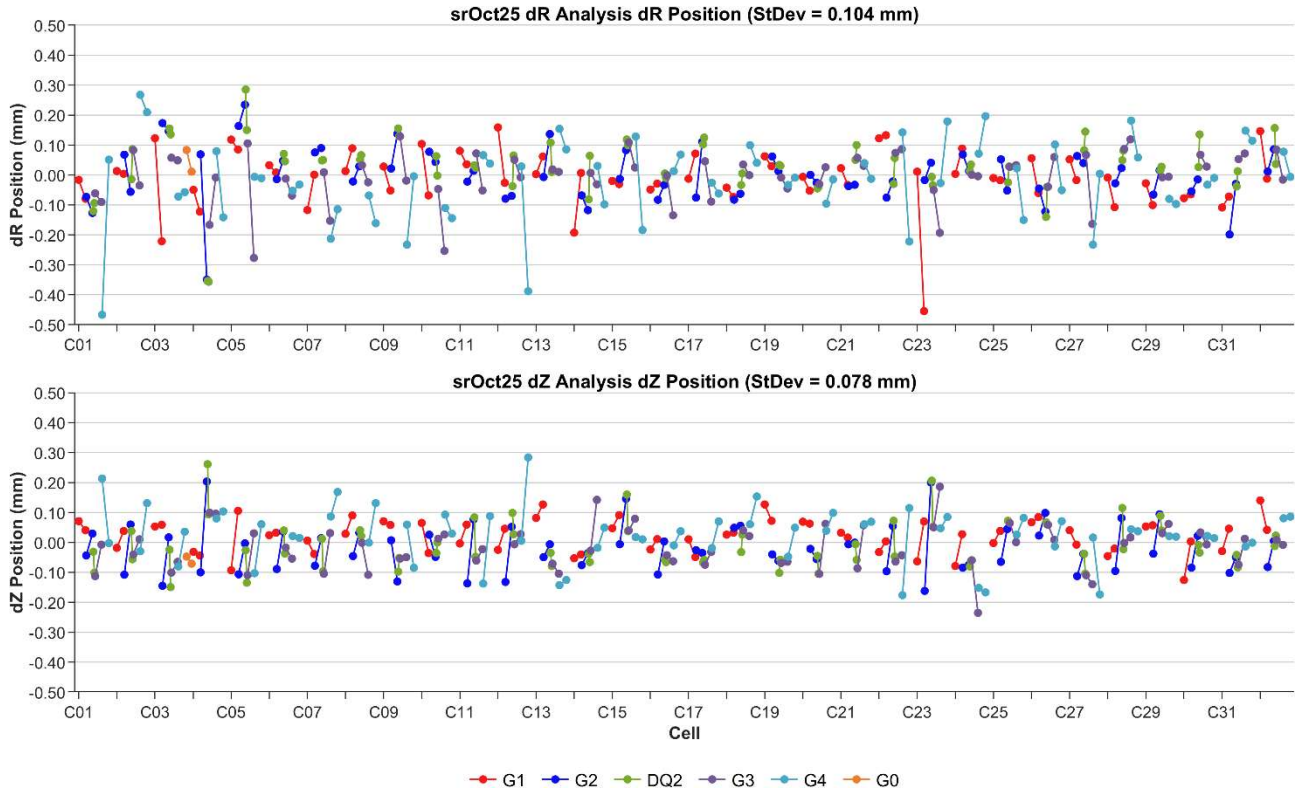


Figure 8: On the top graph dR measured in October 2025 used for the initial December alignment pass. On the bottom graph dZ measured in October 2025 and used for the initial realignment in December 2025

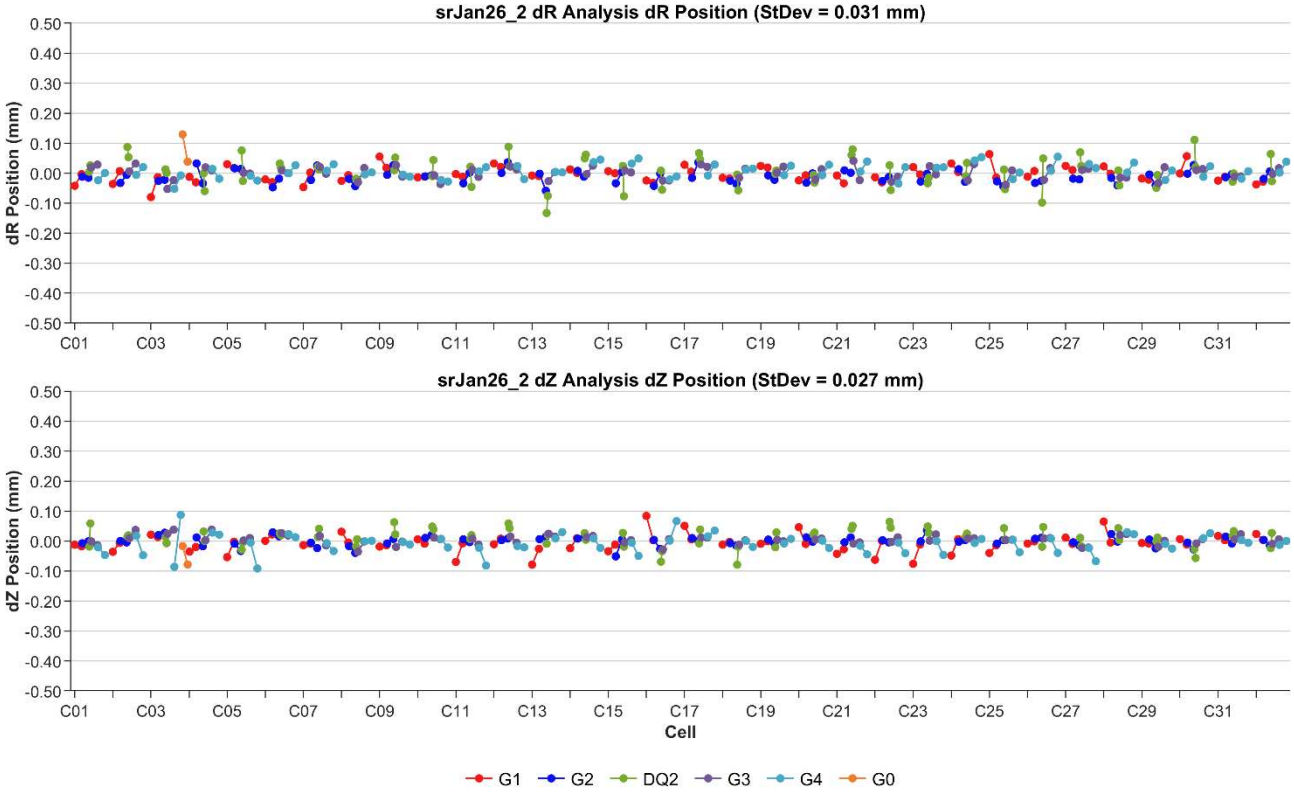


Figure 9: On the top graph dR measured in January 2026 immediately after completing the realignment. On the bottom graph dZ measured in January 2026 immediately after completing the realignment.

When work resumed after the two-week Christmas break, the vertical alignment had changed substantially (Figure 10). The HLS showed significant movement, particularly at the G2 girder exits, and the vertical realignment was therefore repeated using the HLS measurements. This movement coincided with the exceptional 8.4 °C decrease in external air temperature and simultaneous decrease in the tunnel temperature, resulting change in the thermal gradient through the slab.

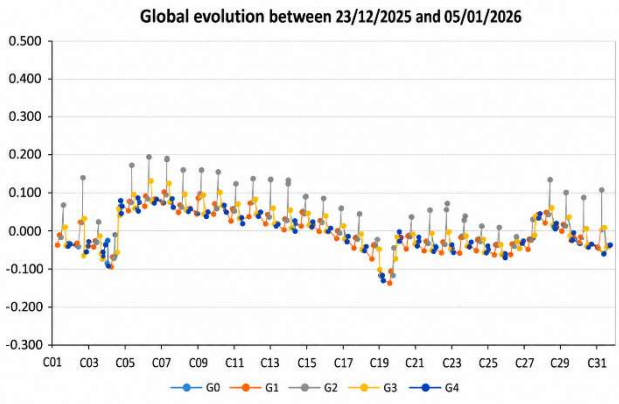


Figure 10: Evolution of the SR alignment over the Christmas period 2025-26 as observed by the HLS.

The subsequent adjustments followed the same iterative process. Each horizontal adjustment requires a complete SR survey, calculation of the required corrections, manual adjustment of the girders, a second complete SR survey, and calculation of the residual errors. This exposes a fundamental difference between the horizontal and vertical procedures. With the HLS and encoders, the complete vertical alignment can be measured, corrected and controlled in approximately 30 minutes. In the horizontal direction, even with four survey teams and two alignment teams working in parallel, a complete measurement–realignment–control cycle takes approximately three days.

Results and Aftermath of the Realignment Campaign

The full realignment produced very good results. Immediately after the final iteration in January 2026, the smoothing error standard deviations were 31 µm in (R) and 27 µm in (Z) when all magnets were included (Figures 8 and 9 and Table 2). Excluding C03G4, C04G0, C04G1 and the DQ2 magnets, which had not been directly adjusted, the standard deviation of the errors was approximately 24 µm in both directions. This was better than the alignment achieved for commissioning in November 2019, when the corresponding values were 39 µm in (R) and 36 µm in (Z).

The improvement was also reflected in machine performance. Before realignment, the alignment errors standard deviations were approximately 102 µm horizontally and 78 µm vertically; after realignment both were reduced to approximately 40 µm. Following machine tuning, the horizontal emittance decreased from 180 to 143 pm, the vertical emittance from 7 pm to below 1 pm, and the fitted horizontal and vertical beta beating to approximately 0.5%.

The Touschek lifetime at 200 mA increased from 24 to 30 h (Table 3).

The alignment did not, however, remain at this level. The smoothing error standard deviations increased from 31 µm in (R) and 27 µm in (Z) in January to 54 µm and 60 µm respectively by March. Following a partial realignment in May, they were 56 µm in (R) and 67 µm in (Z), increasing further to 68 µm and 71 µm by July. The partial realignment therefore corrected the selected region but had little effect on the alignment quality of the complete ring.

Table 2: Evolution of SR smoothing errors during the 2025–26 realignment campaign.

Survey / realignment stage	dR [mm]	dZ [mm]
November 2019	0.039	0.036
July 2025, partial realignment	0.106	0.084
First iteration, 22 Dec. 2025	0.040	0.040
Second iteration, 5 Jan. 2026	0.037	0.034
Final iteration, 7 Jan. 2026	0.031	0.027
Final iteration, adjusted magnets only*	0.024	0.024

** Excluding C03G4, C04G0, C04G1 and the DQ2 magnets, which were not directly adjusted.*

Table 3: Storage ring beam performance before and after machine tuning following the 2025–26 realignment.

Parameter	Initial	After tuning
Overall ring COD	H: 63 µm V: 57 µm	H: 49 µm V: 52 µm
Emittance	H: 180 pm V: 7 pm	H: 143 pm V: <1 pm
β-beating (fitted)	H: 5% V: 12.9%	H: 0.5% V: 0.5%
Peak dispersion	H: 10 mm V: 5 mm	H: 3 mm V: 3 mm
Touschek lifetime*	24 h	30 h

** At 200 mA, with vertical emittance ε_y = 10 pm. H and V denote horizontal and vertical directions, respectively.*

This rapid deterioration is consistent with the continuing movements observed around the SR. In particular, vertical movement continued at the slab joints during the weeks immediately following the winter campaign. Further local events were subsequently observed, including a rapid movement in the ID23 straight section in February 2026 and another event in September. Such events occur at different locations and cannot presently be predicted in either time or position (Table 4).

Table 4: Evolution of SR smoothing errors following the January 2026 realignment.

Survey	dR [µm]	ΔdR [µm]	dZ [µm]	ΔdZ [µm]
Jan. 2026*	31 (24)	—	27 (24)	—
Mar. 2026	54	23	60	33
May 2026†	56	2	67	7
Jul. 2026	68	12	71	4

** Values in brackets exclude C03G4, C04G0, C04G1 and the DQ2 magnets, which were not directly adjusted during the full realignment.*

† Following partial realignment of cells C21–C25.

CONSIDERATIONS FOR FUTURE SR REALIGNMENT

The 2025–26 campaign demonstrated that the current realignment procedure can restore the SR to a very high alignment quality. However, this quality deteriorates rapidly as a result of continuing floor movements, particularly at the slab joints, and external events affecting the site. These movements are unavoidable with the existing floor and geographical setting. Maintaining good alignment therefore requires much more frequent corrections than have been carried out in the past.

The principal obstacle to frequent realignment is the horizontal adjustment procedure. Each iteration requires a complete SR survey, calculation of the corrections, manual adjustment of the girders, and a second survey and calculation to determine the residual errors. Even with four survey teams and two alignment teams, a complete cycle takes approximately three days. During these three days, virtually all other activities in the SR tunnel must be suspended, including vacuum-chamber bakeout, installation of equipment such as insertion devices, and civil and electrical works. The procedure also places a considerable burden on the Survey and Alignment Group. Frequent full horizontal realignment is therefore impractical with the present procedure.

Reducing the time required for horizontal realignment would require a fundamental change in the procedure. Automatic horizontal movers, combined with a high-precision measurement system such as a Wire Positioning System (WPS) or a three-dimensional Frequency Scanning Interferometry (FSI) system, could measure, adjust and control the horizontal alignment in real time. This would eliminate manual adjustment and repeated full SR surveys during realignment. Horizontal corrections could then take just a few minutes, in parallel with vertical corrections using the existing adjustment jacks and HLS. Implementing such a system would, however, require considerable investment in

equipment, installation and development, together with substantial engineering resources.

Automation would reduce the time required for realignment, but it would not prevent the movements that cause alignment degradation. The ESRF cannot escape the influence of its geographical setting, including the rivers, groundwater and long-term site movements. Rebuilding the SR floor could reduce or eliminate local movements at the slab joints, but would require a major intervention.

This raises a more fundamental question about the alignment quality that can realistically be achieved and maintained. Better measurement and adjustment systems can reduce alignment errors, but continuing movements impose practical limits on the quality that can be maintained over time. These limits depend on the magnitude, spatial distribution and rate of the movements, as well as the frequency of realignment. Beyond a certain point, further improvements in adjustment precision or frequency may offer little lasting benefit. Establishing these limits deserves further investigation.

CONCLUSION

The 2025–26 campaign restored the ESRF Storage Ring alignment to a quality better than that achieved during commissioning in 2019. The campaign also confirmed that the existing procedures can realign the complete SR, but horizontal adjustments remain time-consuming and labour-intensive.

The improvement was short-lived. Continuing site movements, particularly differential movements at the slab joints, increased the relative alignment errors between neighbouring girders and degraded the overall smoothing of the SR (Table 4). Subsequent partial realignments provided local corrections but did not significantly improve the overall alignment of the SR, demonstrating that they are not a satisfactory alternative to complete realignment. Maintaining good alignment will therefore require more frequent full-machine corrections. Automatic horizontal adjustment combined with real-time measurement could greatly reduce the time required, but would demand substantial investment.

The campaign demonstrates that achieving good alignment and maintaining it are fundamentally different challenges. More precise measurement and faster adjustment can improve alignment quality, but their benefits diminish if the supporting structure continues to move. Future alignment strategies must therefore consider not only how accurately and frequently the SR can be realigned, but also how long that alignment can be maintained. Determining the practical limits of this approach is essential before committing to increasingly sophisticated and costly alignment systems.

REFERENCES

[1] D. Martin and G. Gatta, “Towards an Expression of Uncertainty in Accelerator Alignment,” Proceedings of the 17th International Workshop on Accelerator Alignment (IWAA 2024), SLAC National Accelerator Laboratory, Menlo Park, CA, USA, 2024.

[2] G. Gatta, C. Gonzalez-Torres and D. Martin, “The Measurement of the ESRF Storage Ring,” Proceedings of the 17th International Workshop on Accelerator Alignment (IWAA 2024), SLAC National Accelerator Laboratory, Menlo Park, CA, USA, 2024.

[3] V. Schindelholz, A. Cheaib, E. Maufroy, C. Cornou, and E. Pathier, “Using soil-compaction rates by the European Ground Motion Service (PS-InSAR) to estimate, at high spatial resolution, the site conditions of the Grenoble basin (French Alps) for its response to earthquakes,” EGUsphere, preprint, 2026. doi:10.5194/egusphere-2026-5011

[4] D. Martin, “Experimental validation of the ESRF upgrade program experimental hall prototype slab,” in Proc. International Workshop on Accelerator Alignment (IWAA 2012), Batavia, IL, USA, Sep. 2012.

[5] D. Martin, “Stability studies of high-quality concrete slab floors at the ESRF,” presented at the 16th International Workshop on Accelerator Alignment (IWAA 2022), CERN, Geneva, Switzerland, Oct.–Nov. 2022.

[6] S. Liuzzo, “Error tolerances, girder errors and long-range errors from a beam dynamics point of view,” presented at the European Workshop on Accelerator Alignment (EWAA 2023), Grenoble, France, 27 Jun. 2023.