

SURVEY ACTIVITIES IN KEK -OVERCOMING THE GREAT EAST JAPAN EARTHQUAKE-

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Abstract

The KEK injector linac has played a pivotal role in Japanese high-energy physics and synchrotron radiation science since its commissioning in 1982. Over the past four decades, the linac has continuously evolved to serve multiple target storage rings, currently injecting both electron and positron beams into four independent rings: the Photon Factory (PF), Photon Factory Advanced Ring (PF-AR), and the Low Energy Ring (LER) and High Energy Ring (HER) of SuperKEKB. Unlike many major accelerator facilities worldwide, KEK does not maintain a centralized, dedicated alignment group; instead, survey and alignment tasks are performed by personnel primarily responsible for vacuum or magnet subsystems.

This paper provides a comprehensive review of the survey activities and alignment strategy for the KEK injector linac. Particular emphasis is placed on the emergency response and rapid recovery following the 2011 Great East Japan Earthquake, which caused severe displacement and structural damage throughout the facility. Through systematic survey procedures using combination of a laser-based fiducial straight-line system, laser trackers, dial gauges, level measurements, and wire position sensors, beam injection to the PF was successfully resumed just two months after the earthquake. Furthermore, we discuss the present alignment status, including a residual 0.13 mrad relative slope between linac sectors, and outline future plans for advanced alignment techniques, such as Structured Laser Beam (SLB) systems, alongside upcoming facility upgrades.

INTRODUCTION

The High Energy Accelerator Research Organization (KEK), located in Tsukuba, Ibaraki, Japan, hosts a complex network of particle accelerators dedicated to elementary particle physics, nuclear physics, and materials science. The primary accelerator complex at the Tsukuba campus spans a 1.7 km by 1.0 km area and houses several world-leading facilities, including the PF, PF-AR, and the SuperKEKB collider complex.

At the core of the Tsukuba campus operations is the electron and positron injector linac. First commissioned in 1982 to inject 2.5 GeV electron into the PF storage ring, the linac has undergone major structural and performance upgrades to meet the demanding requirements of successive flagship projects, including TRISTAN, KEKB, and currently SuperKEKB. Today, the linac simultaneously delivers high-quality electron and positron beams to four distinct user storage rings.

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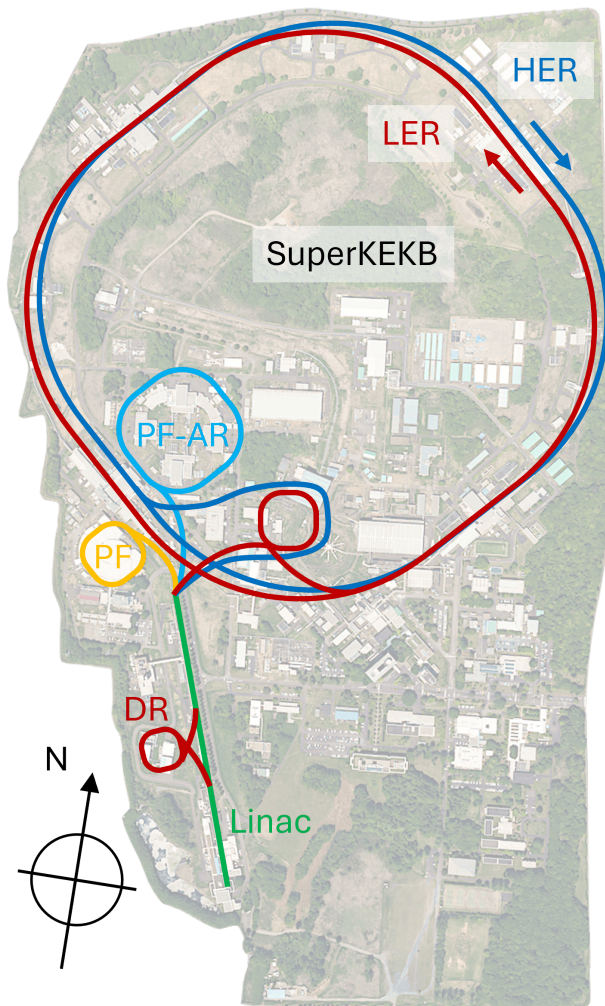


Figure 1: Present accelerator configuration at KEK Tsukuba campus.

This paper traces the technological evolution of the injector linac, documents the severe disruption and emergency recovery operations following the Great East Japan Earthquake of March 11, 2011, examines current alignment characteristics, and discusses future alignment strategies.

EVOLUTION OF THE INJECTOR LINAC AND ALIGNMENT METHODS

Historical Evolution and Configuration Changes

The layout and component installation of the injector linac have undergone four major evolutionary phases over the past 40 years:

1. Original PF injection linac (1982 – 1984):

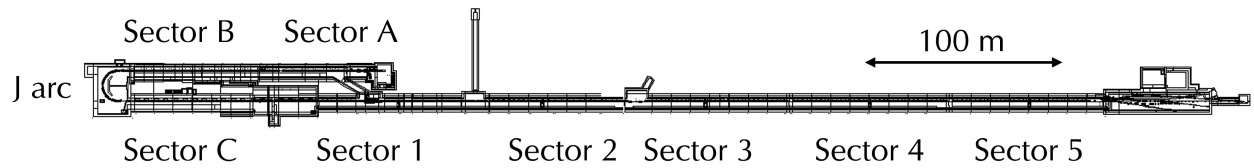


Figure 2: Current configuration of the KEK injector linac

Designed as a straight 2.5 GeV electron injector linac consisting 162 accelerating structures powered by 41 klystrons (30 MW each). electron generation relied on a single thermionic gun at the upstream end.

2. TRISTAN injector phase (1984 – 1995):

Sectors A and B were added to the injector, and a thermionic gun and positron converter were integrated in that area as the Sector P to supply positron to TRISTAN and its Accumulation Ring (AR). Both electron and positron were accelerated up to 2.5 GeV using 177 accelerating structures and 47 klystrons. Positrons were also routinely injected into the PF ring between 1998 and 1995.

3. KEKB upgrade phase (1998 – 2010):

RF pulse compressors (SLAC Energy Doubler; SLED) were installed to meet the requirements of the KEKB collider (8.0 GeV e^- HER and 3.5 GeV e^+ LER), increasing the total number of klystrons to 57 (46 MW peak power) and accelerating structures to 220. The beamline layout was expanded to include J-arc, Sectors A through C, and Sectors 1 through 5. In 2009, during construction of SuperKEKB, one thermionic electron gun was relocated from Sector C to Sector 3 to allow independent injection into the PF while isolating construction zones.

4. SuperKEKB era (present):

A new RF photo-cathode gun for low-emittance electron generation, a flux concentrator for positron production, and a 1.1 GeV Damping Ring (DR) for reducing positron emittance were introduced and commissioned in order to achieve the high beam currents and low emittances demanded by SuperKEKB (7.0 GeV e^- HER and 4.0 GeV e^+ LER) as shown in Fig. 1. The linac presently comprises 226 accelerating structures driven by 60 klystrons across a total path length exceeding 600 meters (Fig. 2).

Transition of Metrology Tools

The surveying equipment used along the injector linac has evolved in response to changing facility requirements. During the design phase of the injector linac, the laser-based fiducial straight-line system employed by SLAC [1] was adopted [2]. This system enabled the precision alignment of accelerating structure units [3], while the alignment of individual quadrupole and bending magnets relied primarily on conventional optical instruments such as automatic levels and precision theodolites.

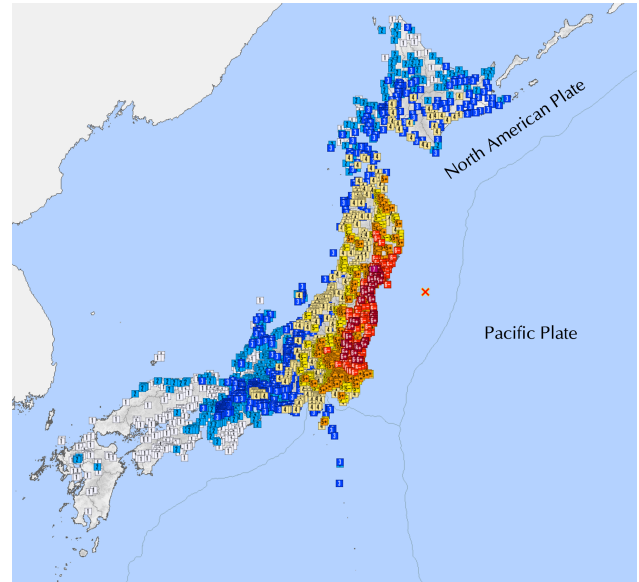


Figure 3: Seismic intensity distribution of the Great East Japan Earthquake that occurred at 14:46 JST on March 11, 2011 (created using the JMA database). The red X marks the epicenter at a depth of 24 km below sea level.

During the construction of KEKB, the light source for the laser-based fiducial straight-line system was briefly switched from the conventional large He-Ne gas laser to a compact diode-pumped solid-state Nd:YAG laser [4]; however, it was subsequently reverted to He-Ne laser, accompanied by improvements to the optical system [5].

Although trials involving laser trackers began in 2009, their full-scale implementation did not occur until 2011, following the earthquake.

Subsequently, in 2020, network surveying, utilizing laser trackers and digital levels, combined with weighted network analysis was fully implemented and deployed across the injector linac, achieving rapid 3D spatial and high precision measurement over the extensive length of the beamline [6].

THE GREAT EAST JAPAN EARTHQUAKE AND EMERGENCY RECOVERY

Earthquake Impact and Damage Overview

On March 11, 2011, at 14:46 JST, a magnitude 9.0 earthquake, which is the most powerful recorded in Japan's history, struck off the Pacific coast of Sanriku as shown in Fig. 3. At the KEK campus, situated approximately 400 km

Table 1: Evolution of Accelerator Configurations at the KEK Tsukuba Campus

Historical phase	Target rings & beam energy [GeV]	Key equipment / Survey tools
1982 (Original)	PF: 2.5 (e^-)	Thermionic gun / Laser-based fiducial line, automatic level, theodolite
1984 (TRISTAN)	PF: 2.5 (e^+ & e^-), TRISTAN (AR / MR): 2.5 (e^+ & e^-)	e^+ converter (250 MeV) / Laser-based fiducial line, automatic level, theodolite
1998 (KEKB)	PF: 2.5 (e^-), PF-AR: 6.5 (e^-), HER: 8 (e^-), LER: 3.5 (e^+)	SLED / Laser-based fiducial line, automatic level, theodolite
Present (SuperKEKB)	PF: 2.5 (e^-), PF-AR: 6.5 (e^-), HER: 7 (e^-), LER: 4 (e^+)	RF-gun, Damping Ring (1.1 GeV) / Laser tracker, digital level

southwest of the epicenter, the observed seismic intensity reached 6⁻ on the Japanese Meteorological Agency (JMA) scale. Coincidentally, at the exact moment the earthquake struck, linac technical personnel were attending an hands-on training lecture on laser tracker operation given by KEB alignment experts.

The violent ground motion caused extensive physical damage throughout the injector linac underground tunnel as shown in Fig. 4:

- Mechanical displacements: Heavy quadrupole magnets detached from their mounts or shifted significantly.
- Vacuum system breach: Severe mechanical stress tore bellows and flanged joints, exposing major sections of the high vacuum chamber to atmospheric air.
- Support structure deformation: Girder structures supporting the accelerating cells experienced shear deformation, tilting, and spatial displacement.
- Facility infrastructure damage: Water leakage from concrete expansion joints flooded sections of the tunnel floor, and compressed air lines were ruptured.

Recovery Strategy and Two-Month Timeline

Because the scheduled restart of user operation for the PF was imminent, KEK management prioritized the emergency restoration of the downstream linac sections (Sectors 3, 4, and 5) required for 2.5 GeV electron injection into the PF, while deferring full restoration of the upstream sectors (Sectors A, B, C, 1, and 2). An aggressive, highly coordinated emergency recovery schedule was executed as listed in Table 2. Through non-stop efforts, beam injection into the PF ring successfully resumed on May 16, 2011, exactly two months after the catastrophic earthquake. The alignment restoration in Sectors 3 to 5 proceeded in three distinct phases:

1. Coarse positioning: Initial rough position checks were conducted using traditional plumb bobs and steel scales to establish baseline continuity across damaged joint sections.
2. Precision spatial mapping: Laser trackers mapped the absolute positions of target fiducials on accelerating structures and quadrupole magnets relative to reference network monuments.
3. Fine adjustment: Mechanical adjustments for girders



Figure 4: Damage to the injector linac tunnel caused by the earthquake. Quadrupole magnets fell from its support stand (*upper*), and groundwater gushed out at an expansion joint (*lower*). A pond is located adjacent to the west side of the injector linac, serving as the source of the groundwater.

and rolling corrections for accelerating structures were conducted using precision fix level referring the result of the tracker survey.

CURRENT ALIGNMENT STATUS

Residual Slope between Linac Sectors

In 2020, the author moved from the large-scale synchrotron radiation facility SPring-8 to KEK and applied

Table 2: Emergency recovery work carried out at the injector linac immediately after the earthquake occurred

Date (2011)	Task / Recovery Activity	Sectors
Mar 14 – Mar 17	Initial safety inspection & structural damage survey	All
Mar 14 – Mar 31	Vacuum chamber repair & leak hunting	3, 4, 5
Mar 31 – Apr 02	Preliminary manual offset measurement (plumb/scale)	3, 4, 5
Apr 04 – Apr 19	Precision 3D laser tracker survey (structures/magnets)	3, 4, 5
Apr 08	Restoration of main compressed air supply system	Site
Apr 22 – Apr 23	Horizontal realignment of girders using dial gauges	4, 5
Apr 25 – Apr 26	Roll angle corrections using precision fix levels	3, 4, 5
Apr 27	Final girder alignment, WPS survey, vacuum seal check	3, 4, 5
Apr 28	High-power RF conditioning (klystron aging)	3, 4, 5
May 10	Beam commissioning initiation	3, 4, 5
May 16	Successful beam injection to PF	PF

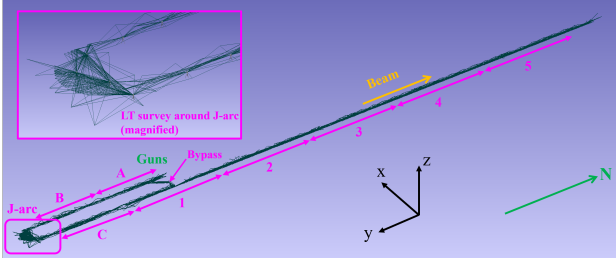


Figure 5: Schematic view of the network survey using the laser tracker.

network surveying, utilizing laser trackers and digital levels, along with weighted network analysis [7] to the injector linac as shown in Fig. 5. Using a laser tracker (Leica AT500), a network survey is conducted across 63 instrument stations to measure nearly 600 electromagnets and approximately 380 reference points installed in the injector linac. Additionally, for 22 of the electromagnets, a leveling network survey is performed using a digital level (Trimble DiNi0.3) across 21 instrument stations, employing a round-trip measurement method. The aforementioned network survey has been conducted annually since 2020 during the summer accelerator shutdown period.

The results revealed that the beamlines in Sectors A and B were not parallel to those extending from Sector C through Sector 5, there was a relative slope of approximately 0.13 mrad between them as shown in Fig. 6.

Operational Decision and Mitigation

While it would be possible to eliminate this 0.13 mrad deflection by comprehensively realigning the accelerator components and physically re-anchoring the tunnel floor, doing so would require a prolonged shutdown lasting several months. Under standard multi-ring injection operations, beam steering magnets and orbit feedback systems can reliably correct this deflection; therefore, we decided to maintain the current geometric configuration in order to prioritize beam uptime for SuperKEKB physics experiments and PF user program.

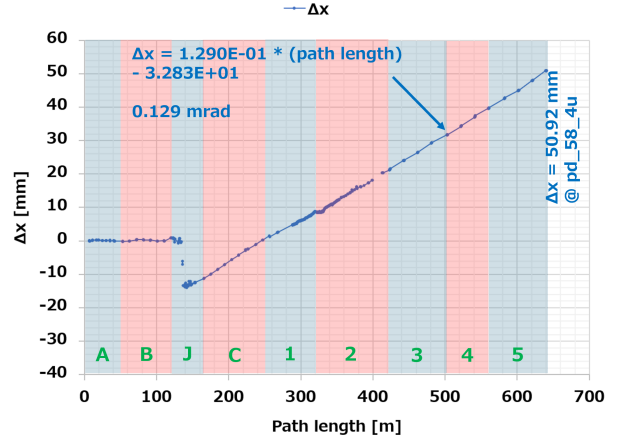


Figure 6: Difference (Δx) between the measured horizontal coordinates (x) of the injector linac (surveyed in 2021) and the design coordinates. The relative slopes for Sectors A and B versus Sectors C through 5 are estimated to be 0.13 mrad.

FUTURE PERSPECTIVES AND UPGRADES

Linac and Storage Ring Upgrades

Several major facility upgrades are currently planned or under evaluation at KEK as follows:

PF upgrade: Conceptual upgrade are discussing to construct an independent superconducting injector linac, support combined single/multi-bunch injection schemes, and potentially integrate a Free Electron Laser (FEL) light source.

SuperKEKB Long Shutdown 2 (LS2): Comprehensive upgrades during LS2 will involve redesigning the Interaction Region (IR), strengthening focus superconducting magnets (QCS), and upgrading detector readout systems in order to achieve the target peak luminosity of $6 \times 10^{35} \text{ cm}^{-2} \text{ s}^{-1}$.

Next-generation Alignment Technology: Structured Lase Beam

KEK is preparing to re-establish an automated continuous laser-based fiducial line system to maintain strict sub-millimeter trajectory tolerances over long distances in ad-

dition to constant manual tracker surveys. Our group has established a collaboration with CERN and is exploring the implementation of Structured Laser Beam (SLB) technology. By irradiating a laser beam—which exhibits characteristics similar to a Bessel beam and resists diffraction—along the beamline and monitoring its center position using an image sensor equipped with appropriate radiation shielding, it becomes possible to monitor the position of the acceleration unit in real time, thereby significantly improving long-term operational stability.

CONCLUSION

The KEK injector linac has successfully adapted over four decades to meet changing physics priorities, evolving from a 2.5 GeV electron injector into a versatile multi-beam source powering four storage rings. Despite lacking a dedicated alignment division, KEK’s technical staffs and researchers demonstrated remarkable responsiveness following the 2011 Great East Japan Earthquake; through disciplined precision survey and re-alignment, they restored beam injection to the PF in just two month.

While a minor 0.13 mrad relative slope remains along the linac beamline today, it is effectively managed via orbit control systems. Moving forward, the introduction of laser-

based alignment using SLB technology will enable KEK’s accelerator complex to stably deliver ultra-high-emittance and high current beams for decades to come.

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