Alignment of SuperKEKB Main Ring Magnet System Our experiences

Mika Masuzawa (KEK)

mini-workshop on FCC-ee optics tuning and alignment
May12, 2022

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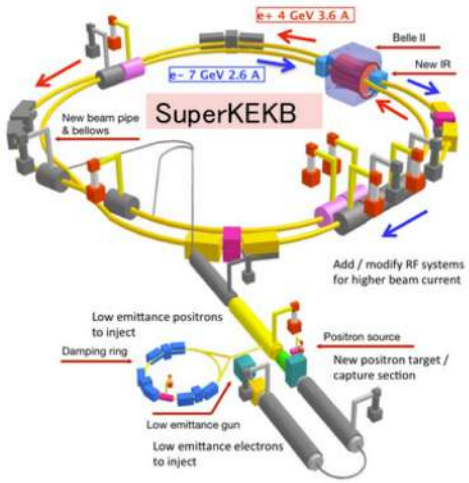
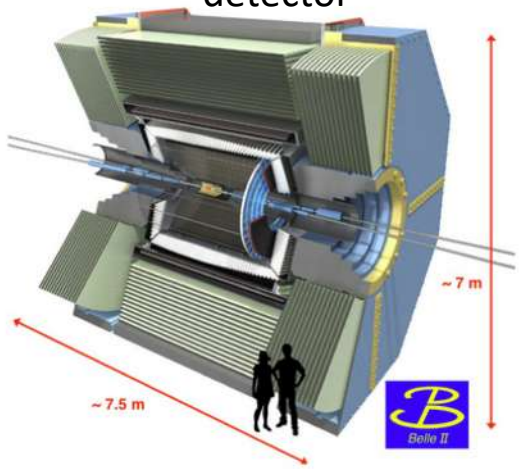
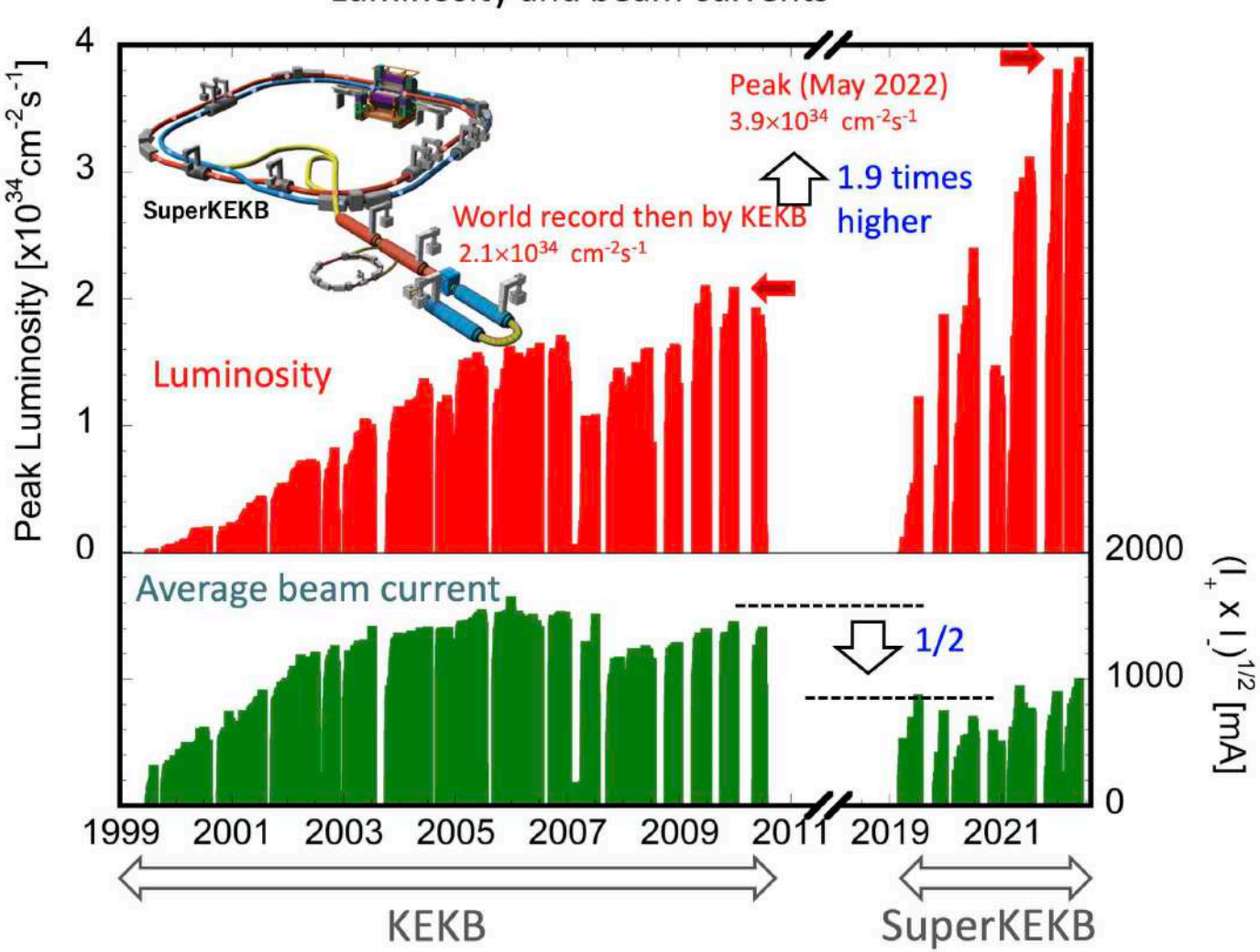
- Introduction
  - SuperKEKB



Belle II detector



SuperKEKB is an energy-saving machine
Thanks to “nano-beam” scheme



SuperKEKB : luminosity frontier machine

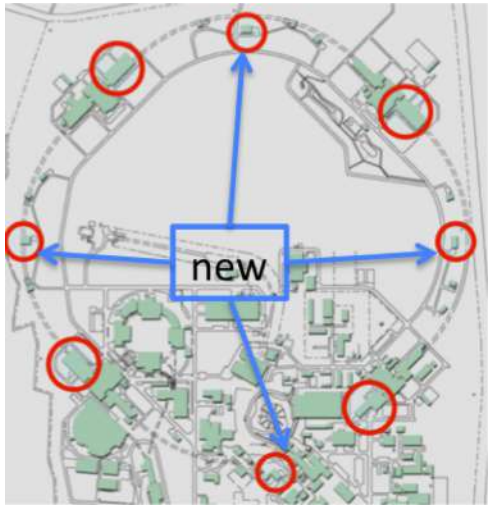
Double ring

High Energy Ring (HER) : electorn
Low Energy Ring (LER): positron

3km circumference, 11m below GL
On soft soil called “Kanto loam” soil
MR tunnel, originally built or TRISTAN, inherited to KEKB and now to SuperKEKB (3 generations)

- Challenges
  - Tight schedule, everyone wants to do lots of things at the same time.
  - Tunnel keeps moving.
  - KEKB alignment network was destroyed by the earthquake in 2011.

Tight schedule, everyone wants to do lots of things at the same time



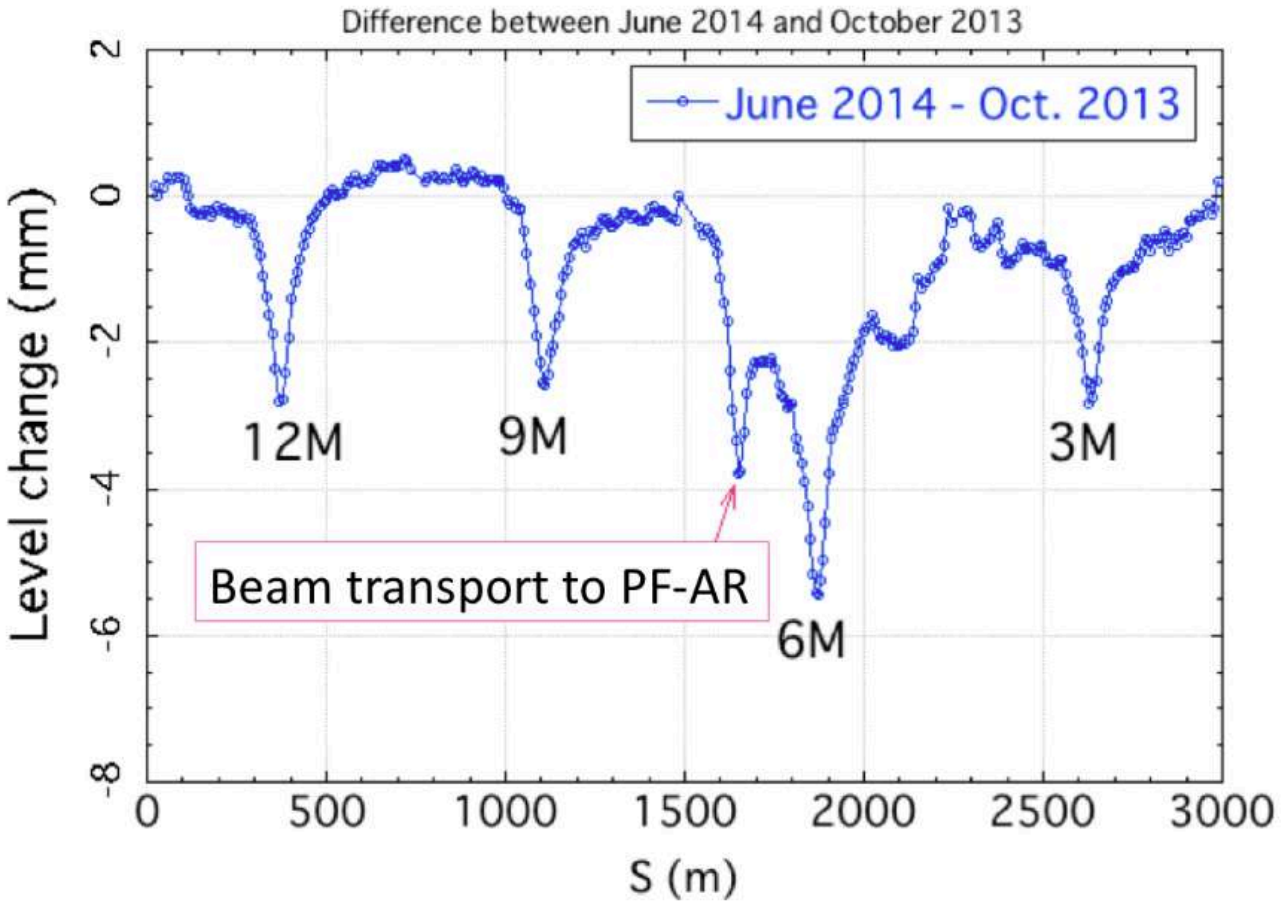
KEKB➔SuperKEKB
More magnets & power supplies
New utility buildings were built.

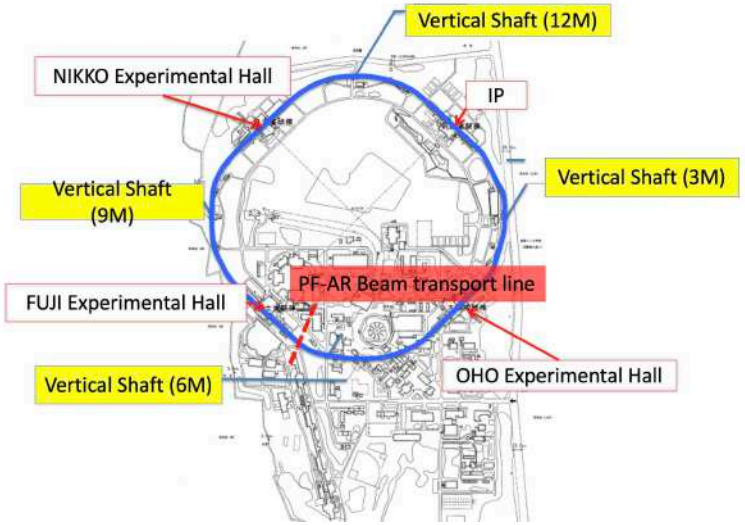
Excavation of the vertical shafts, right above the tunnel.
Rich ground water…

While we were surveying the monuments.

Tunnel kept moving

- We had to wait until the last minute before carrying out 2nd round alignment because
  - Effect of the construction of new facility buildings along the tunnel was large.
  - Tunnel temperature was not stable at all (varied more than 10 degrees)





Tunnel kept moving

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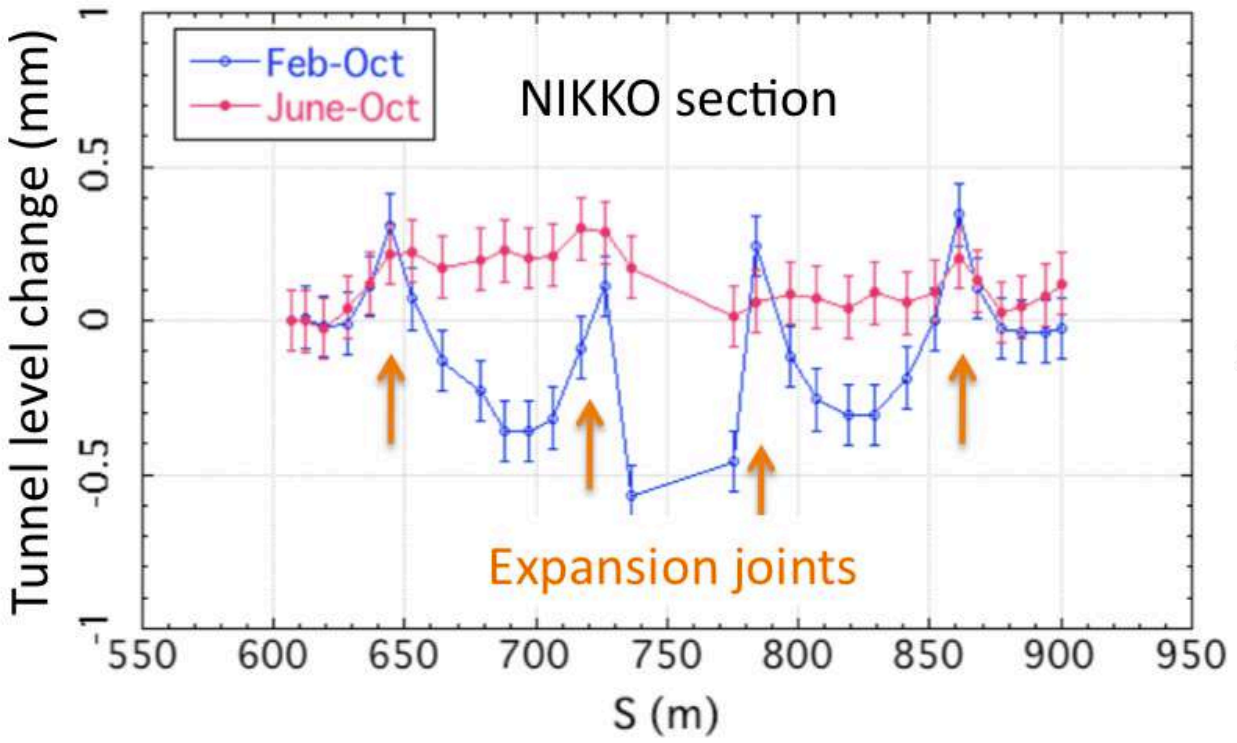
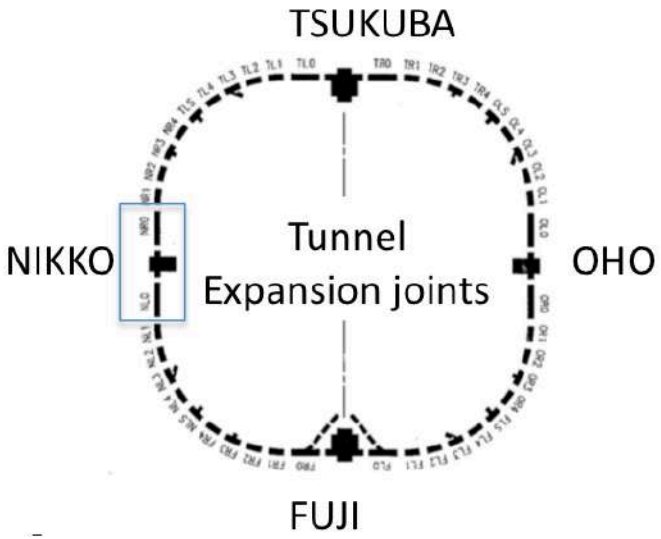
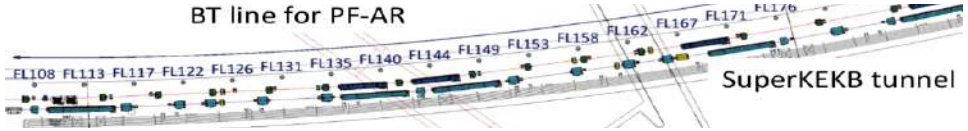




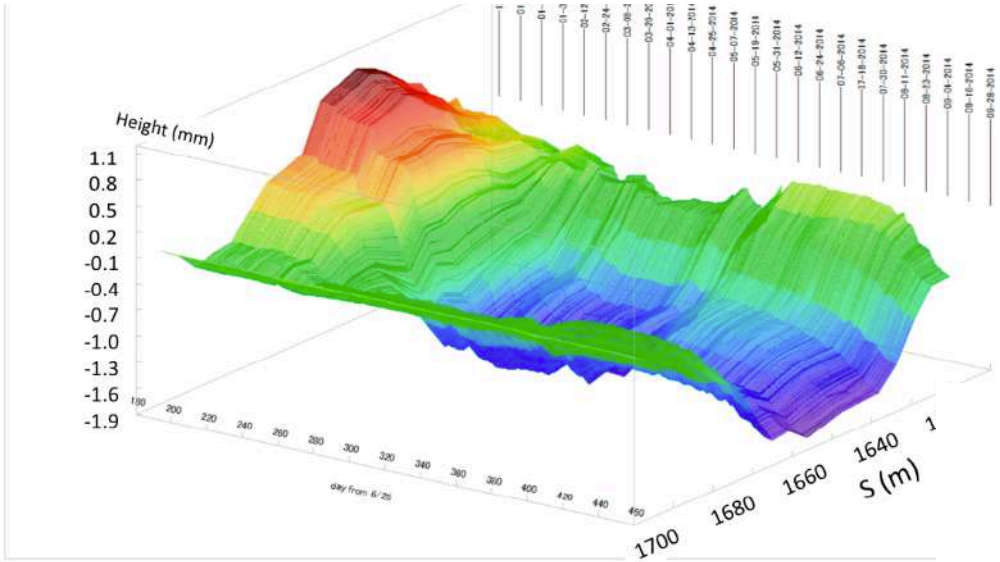
No AC in the tunnel (electricity saving)

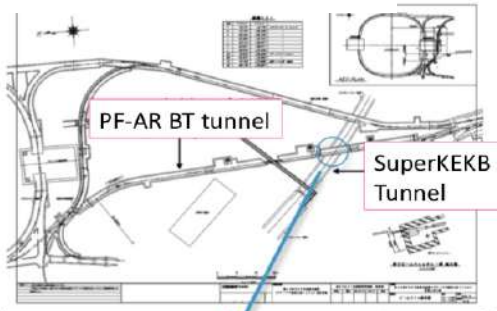
As large as 0.5 mm level change is seem at the expansion joint between summer and winter.

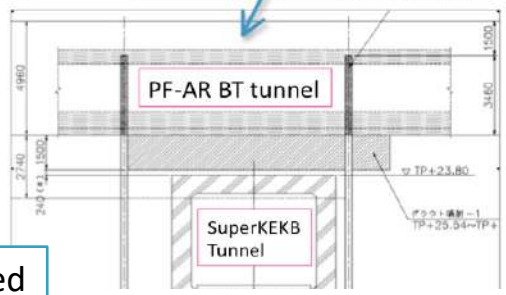
Tunnel kept moving



Effect of the new BT line to PF-AR monitored by HLS (BINP)

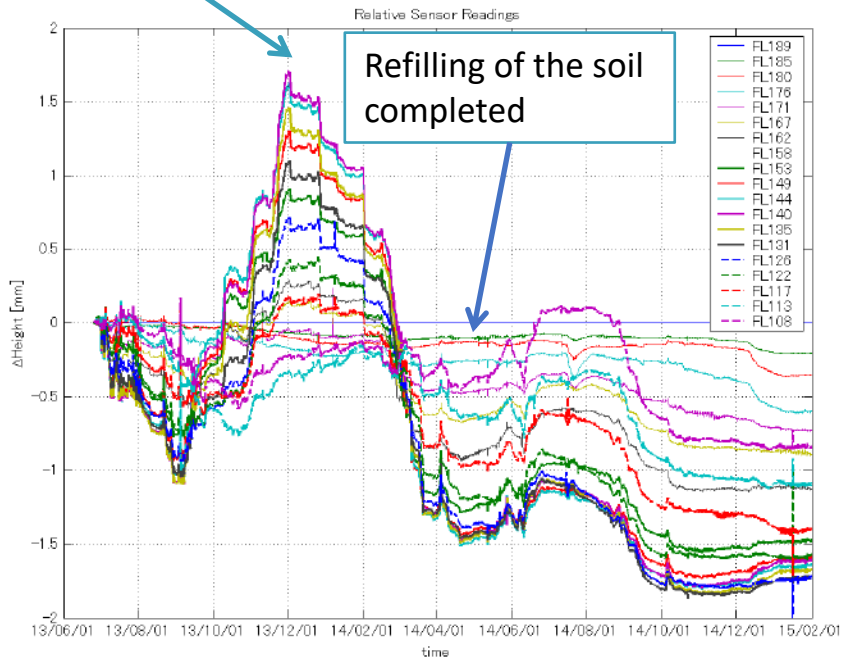




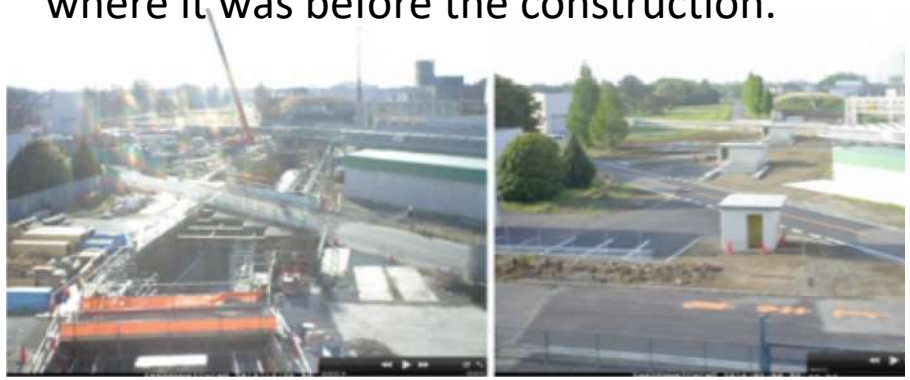


Excavation finished

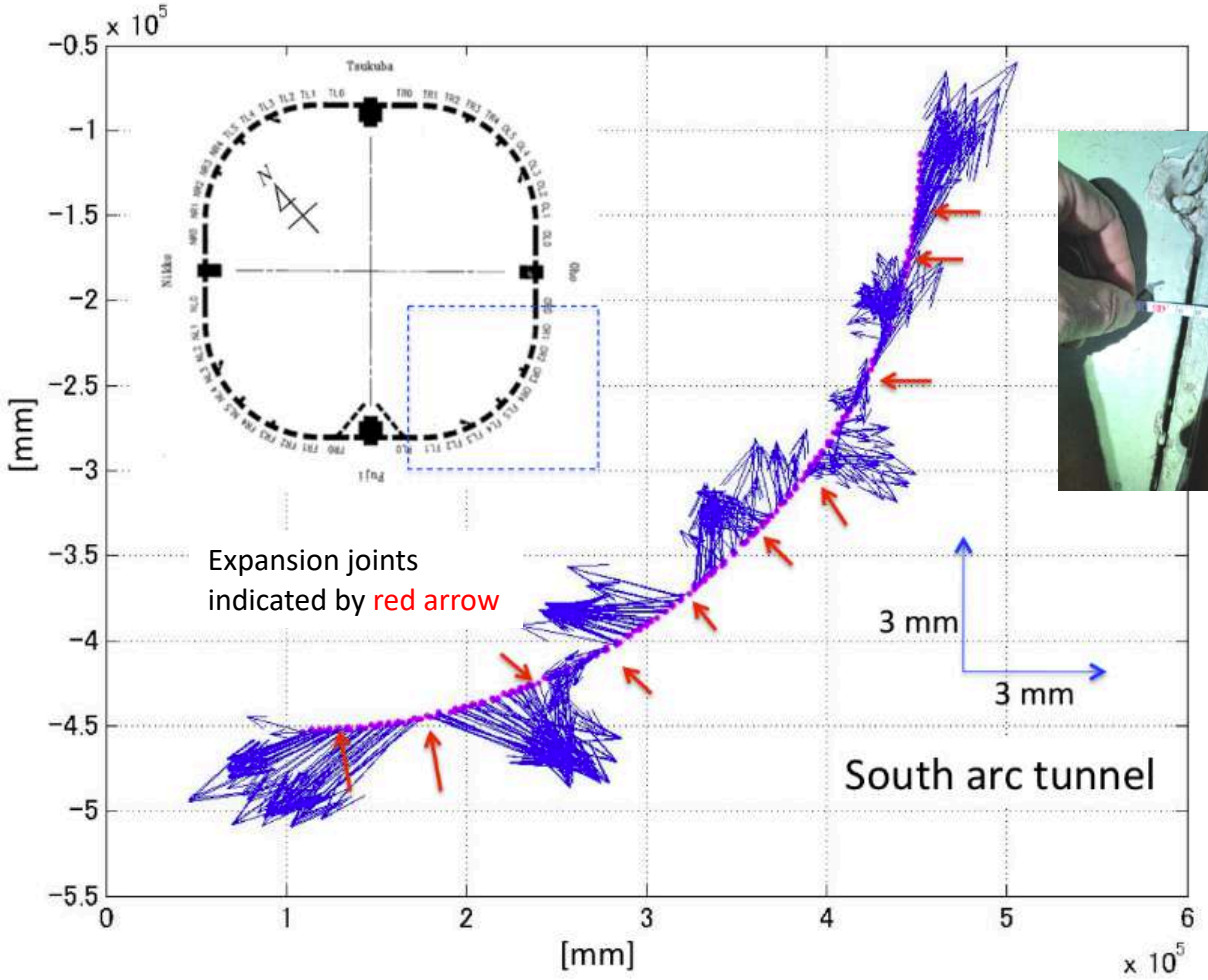
Refilling of the soil completed



The tunnel level does not seem to go back to where it was before the construction.



KEKB alignment network was destroyed by the earthquake in 2011



- Strategy
  - 2nd round survey in the summer 2015, the last minute to be in time for Phase I commissioning
  - Smoothing, based on the network analysis
  - Prioritize issues

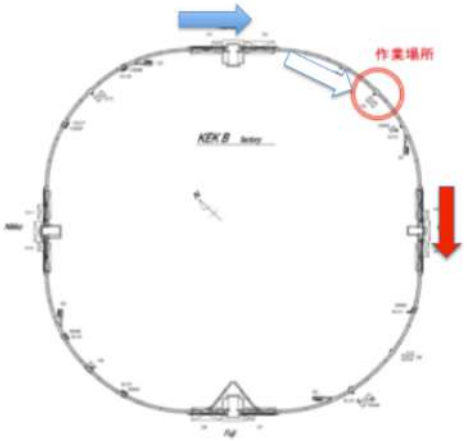
2nd round survey campaign in the summer

June and July 2015

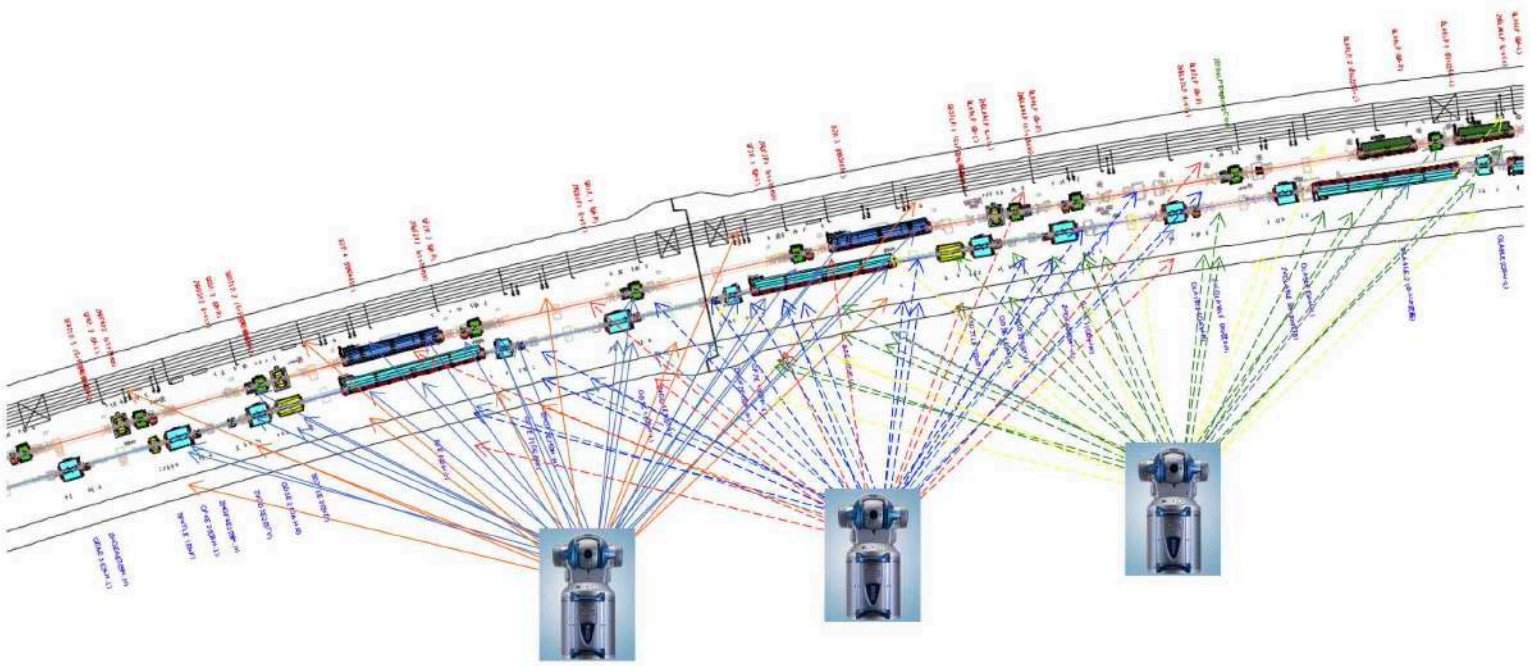
Survey was carried out by 3 teams.
Calibration of the laser trackers was done carefully.

Special attention was paid to systematic errors, as even very small systematic errors can result in a large error at the end over hundreds of measurement sets.

(long) distance being compared with TS30

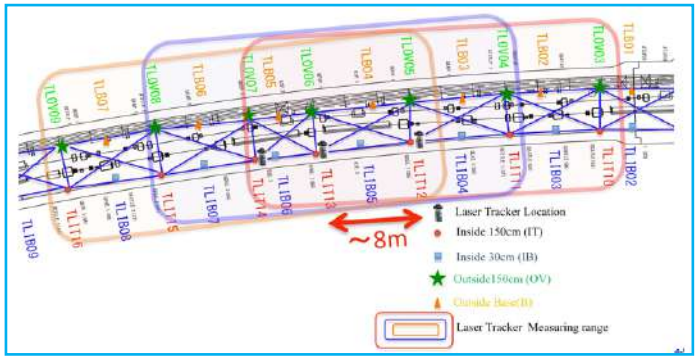


New geodetic network



The surveying network is constructed as successive unit rectangles

- ~8 m in length and ~2 m in width.
- ~32 m long area (4 unit rectangles) was covered by one tracker setup (station)



Constraints on the working area/time

- Alignment can not coexist with power supply test
- PS test can not coexist with water flow check
- none can coexist with RF high power test
- civil engineering can not coexist with survey/alignment…

→Schedule management was a critical issue

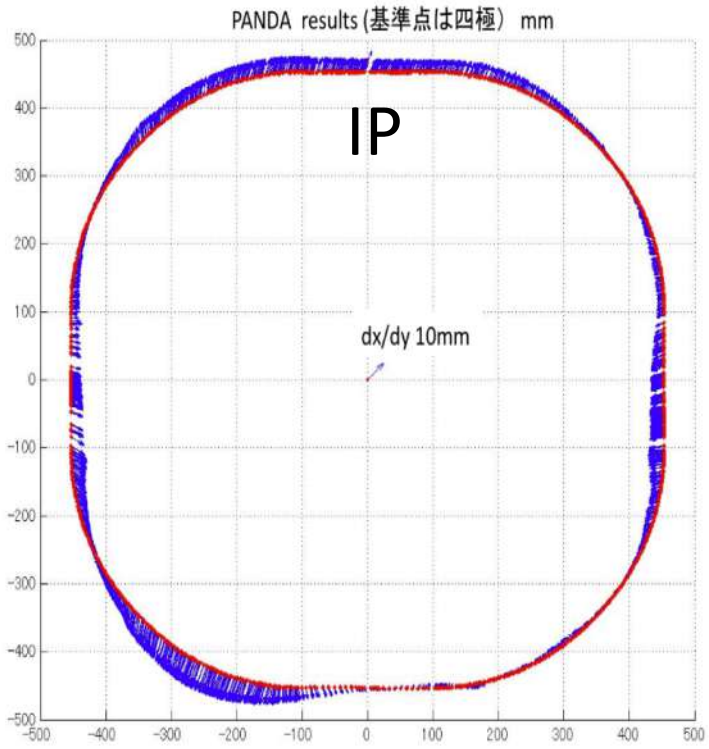
# of points to be surveyed
More than 1200 network control points in the tunnel
More than 4000 reference points for the magnets
→More than 5000 points to be surveyed and analyzed

→More than 400 LT settings, with overlaps

- We got hundreds of data points every day from 3 teams, which were analyzed and cross-checked by 3 people independently everyday.

- If we found something funny, we requested the survey team to go back before they moved a long distance down the tunnel.

Survey Data and analysis results



The north and west parts expands to the outside as large as 10 mm. This probably happened when the TRISTAN monuments were first built.

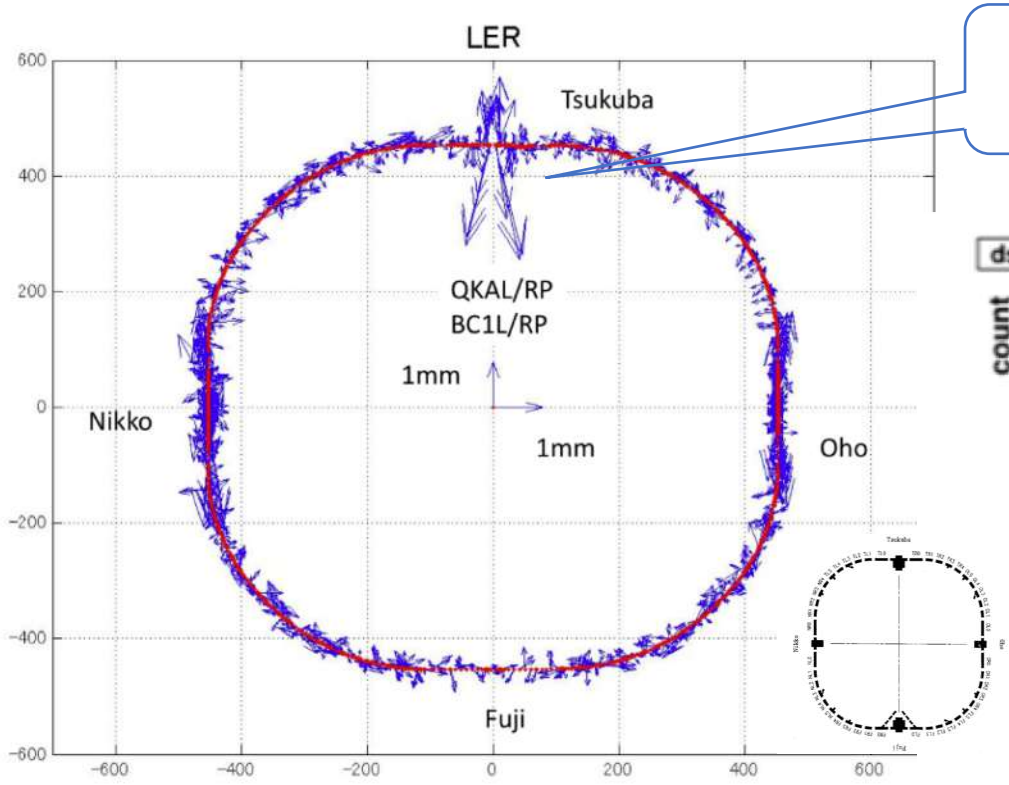
Does this matter?
➔No. Deformation of low order does not matter.

Constraints:
The rings have to close.
➔Smooth periodic curves will do.

Our choice was Fourier series (n=60). We tried FS with n=30 but the # of magnets to be adjusted increased, the amount of the adjustment became larger…
(of course we can do it but it would have affected other accelerator components such as vacuum chamber and rf…)

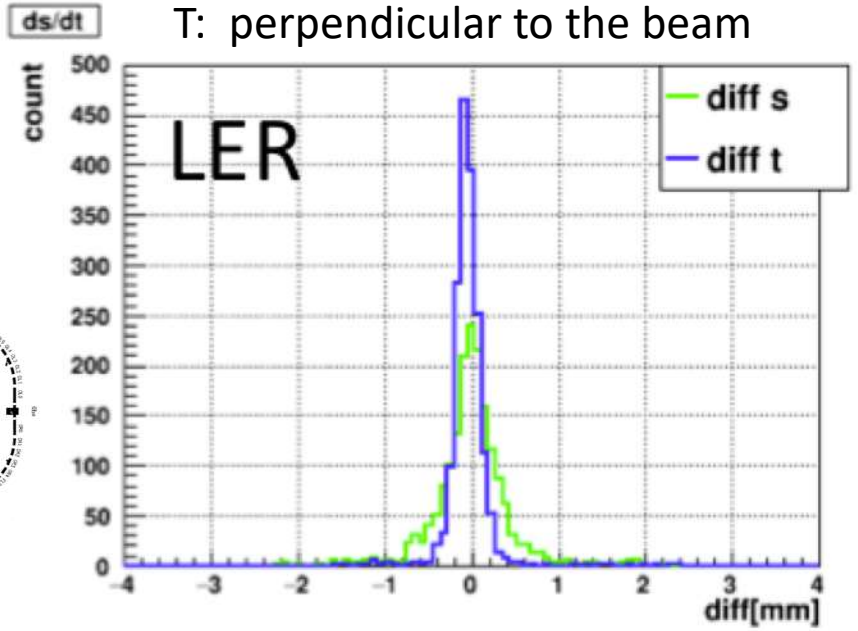
Survey Data and analysis results

Deviation from a smooth curve



We used the old lattice (oops)

S: Beam direction
T: perpendicular to the beam

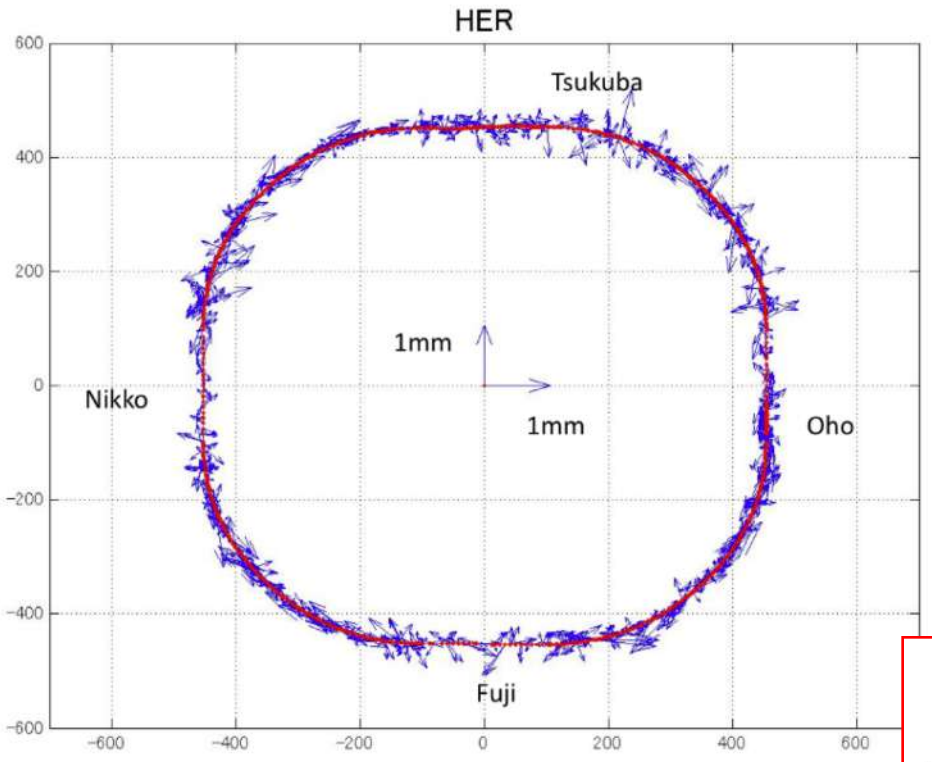


The spread in “s (beam direction)” is larger.
This is due to the expansion joints.

The temperature was NOT controlled during the SuperKEKB construction.
The temp. differ between when we did the 1st rough alignment and the 2nd survey.

Survey Data and analysis results

Deviation from smooth curves (we call it the “Adachi Curve”)



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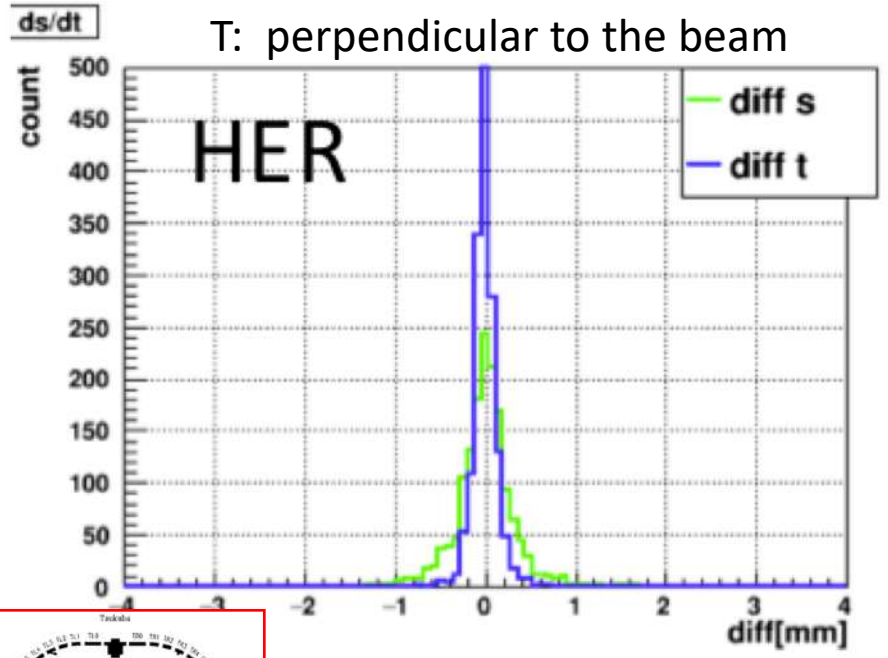
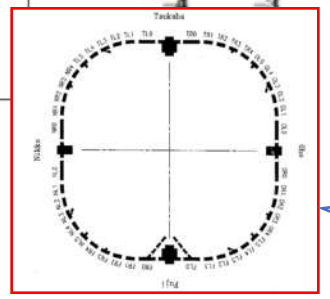




Expansion joints to absorb the thermal expansion & contraction.

The spread in “s (beam direction)” is larger.
This is due to the expansion joints.

The temperature was NOT controlled during the SuperKEKB construction.
The temp. differs between when we did the 1st rough alignment and the 2nd survey.

Alignment strategy

Discussion with the optics group, prioritize issues for "good-enough" for Phase I

Time (schedule), man power (cost) ,impact to the other groups, against machine performance (good enough for Phase I) was discussed with the Optics G.

	Tolerance (Δt)	Tolerance (Δs)
Dipole	0.4mm	0.8mm
Wiggler	0.4mm	0.8mm
Quadrupole	0.2mm	0.4mm
Sextupole	0.2mm	0.4mm
LER Dipole(3 ref. pts)	0.4mm	0.8mm

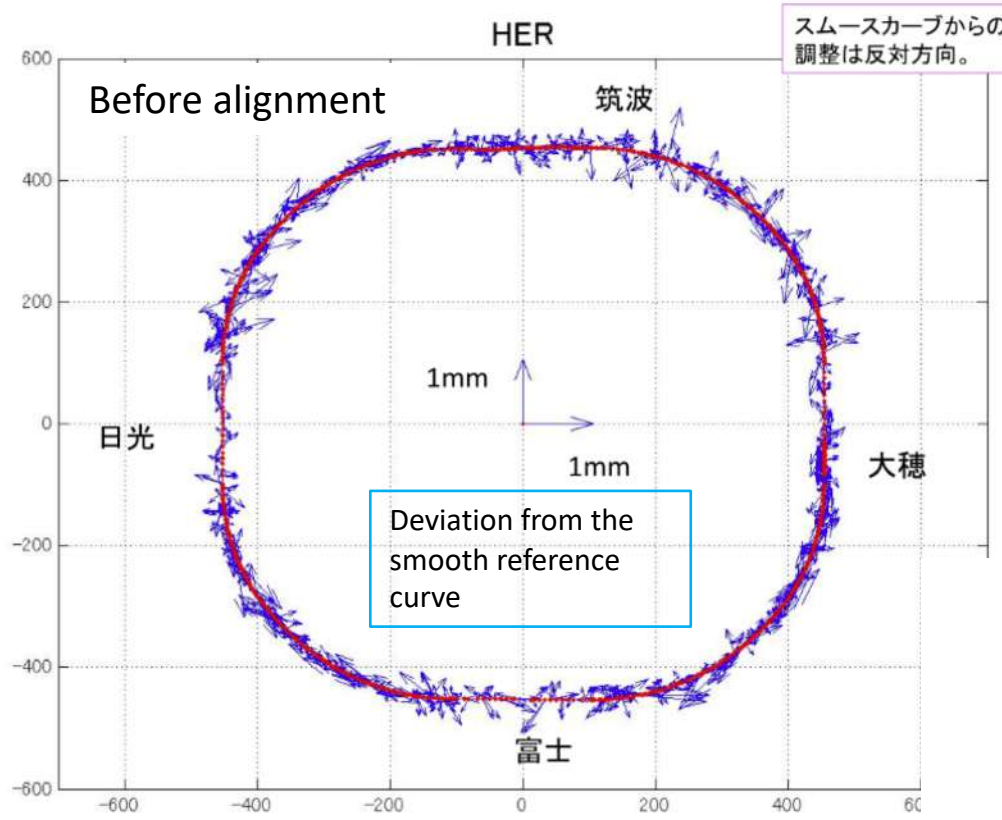
Tough work in the tight space.

Obviously not here.

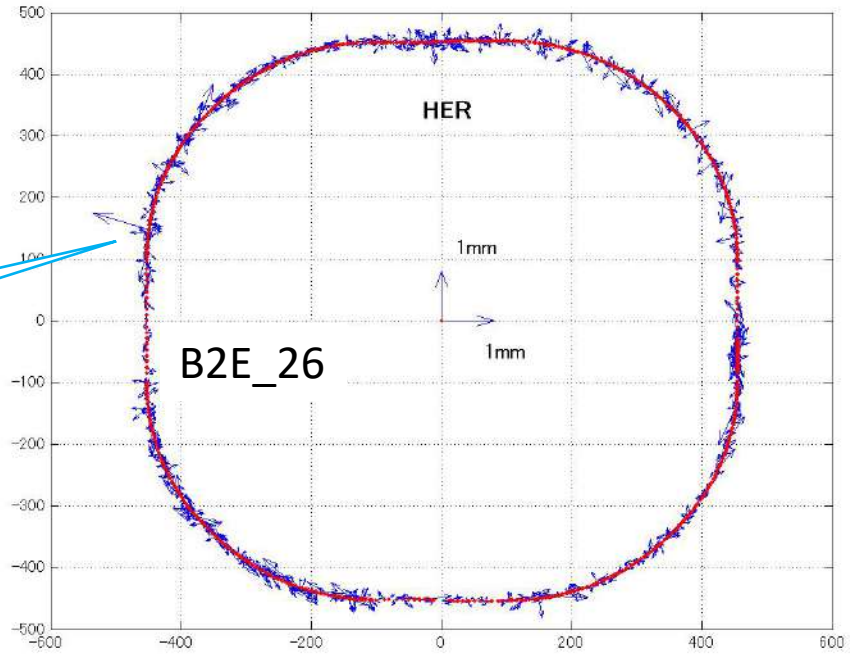
I'm jealous!

Alignment strategy

Alignment was carried out by two teams, followed by a survey team dedicated to checking the alignment.



Found a misalignment, which was fixed right away.

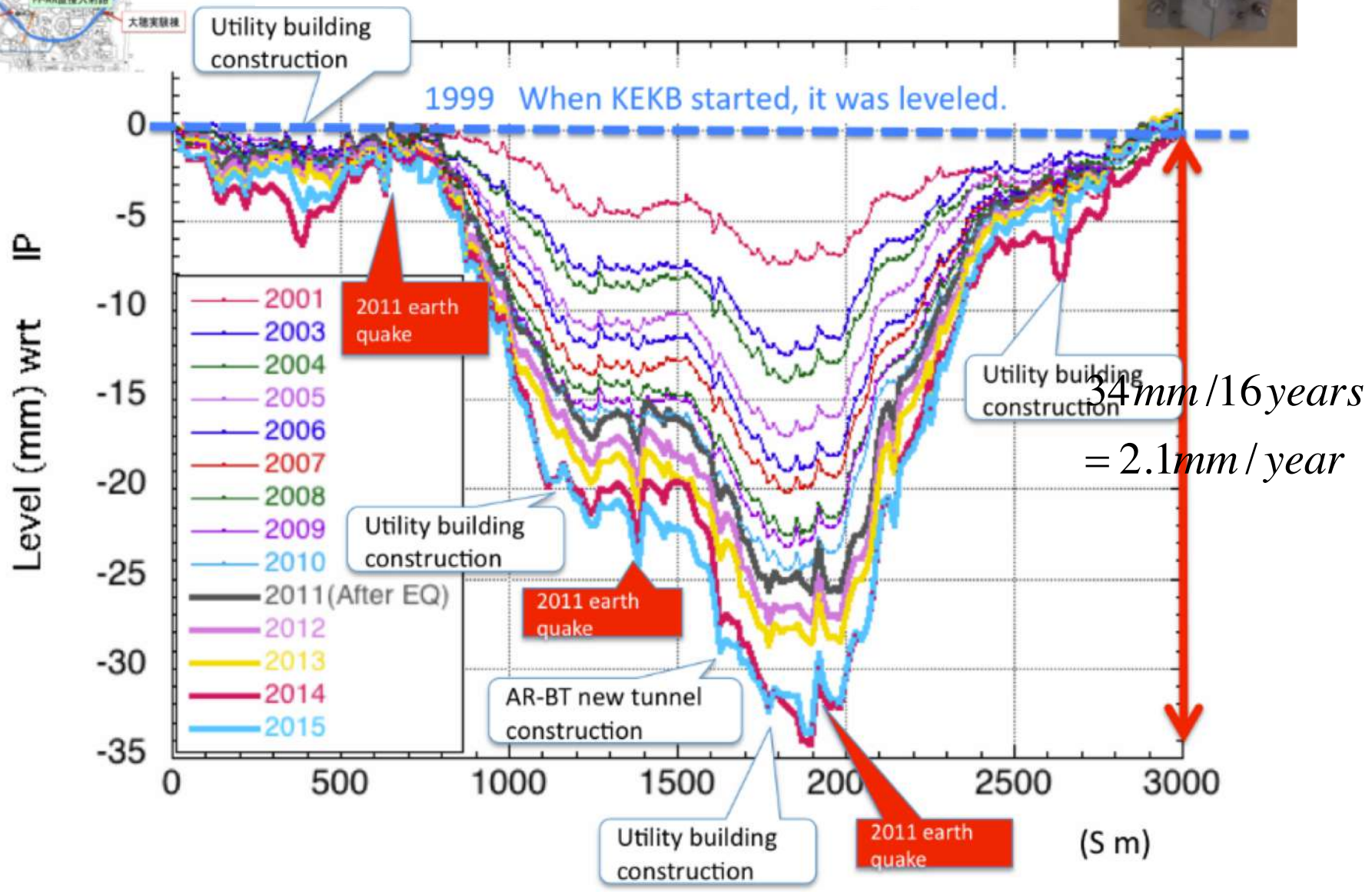


After alignment

- Results
  - Phase I, without IR
    - Vertical
    - Horizontal
      - Circumference estimate for setting the RF frequency
      - Difference between HER/LER for collision
  - Phase II (IR with FF superconducting magnet system)

Vertical

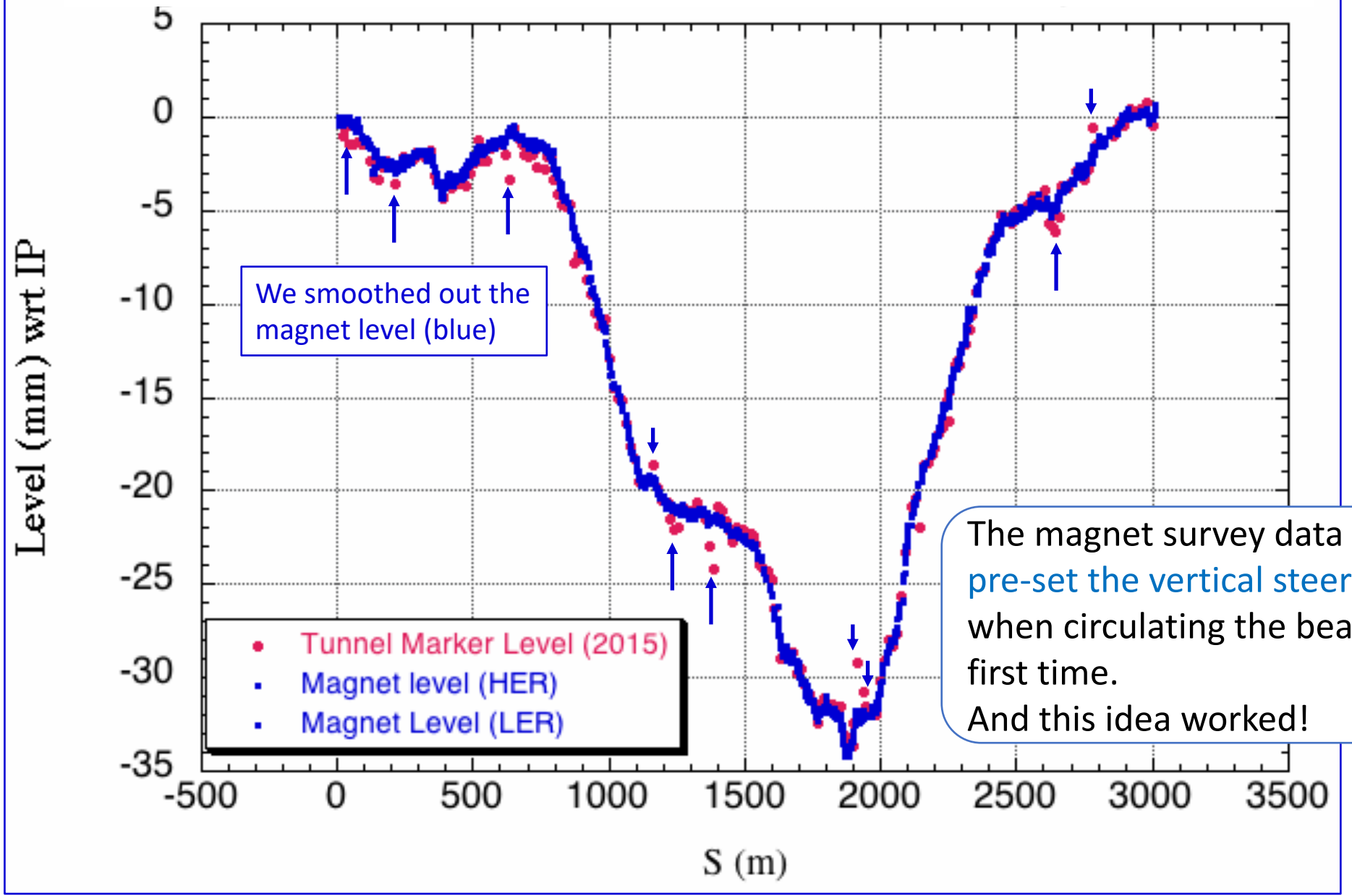
Tunnel sinking continued



$$34mm/16years = 2.1mm/year$$

Vertical

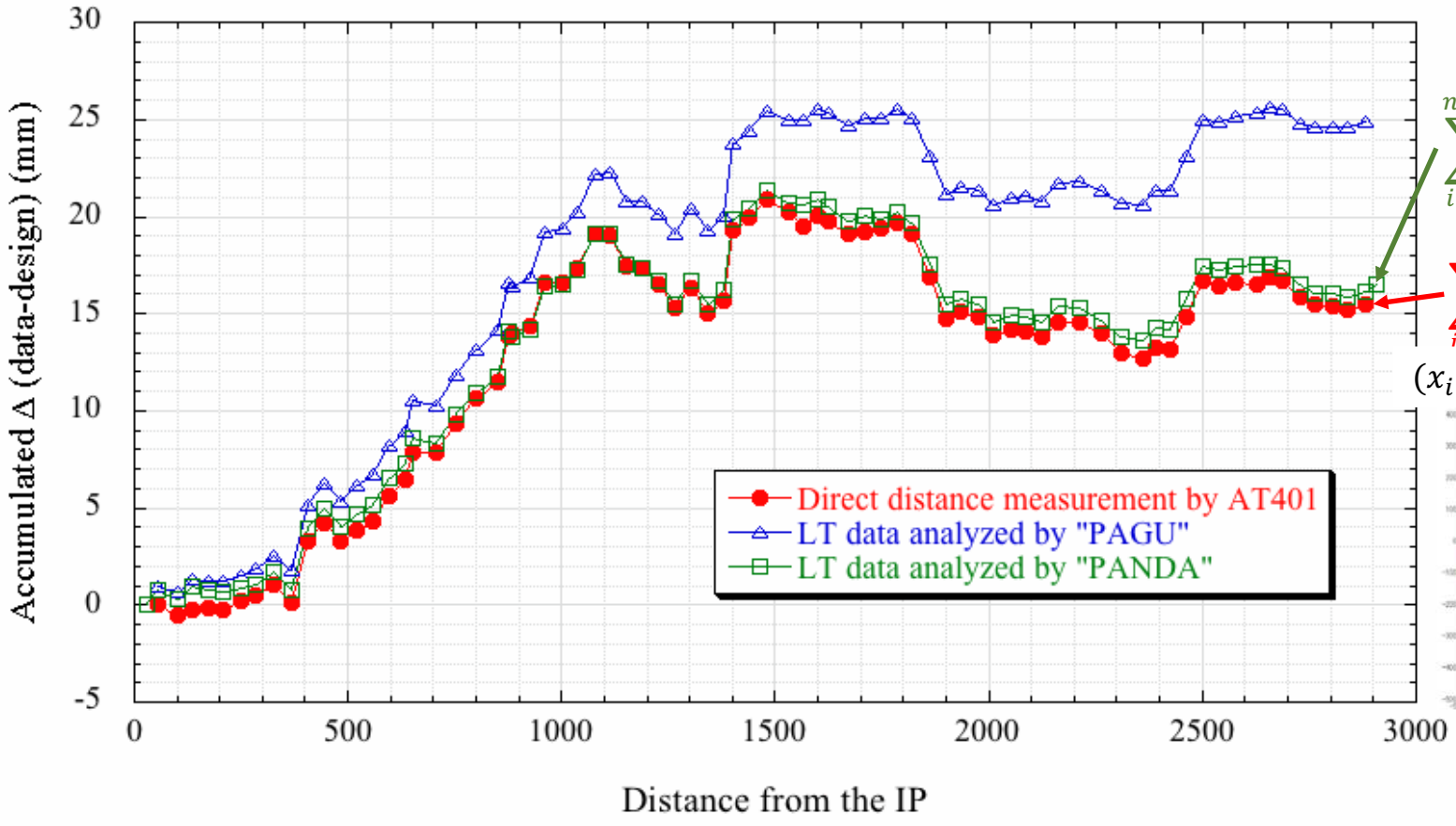
We aligned the magnets, not to use the tunnel level monument but smoothed them out locally



The magnet survey data were used to pre-set the vertical steering magnets when circulating the beam for the first time.
And this idea worked!

Horizontal

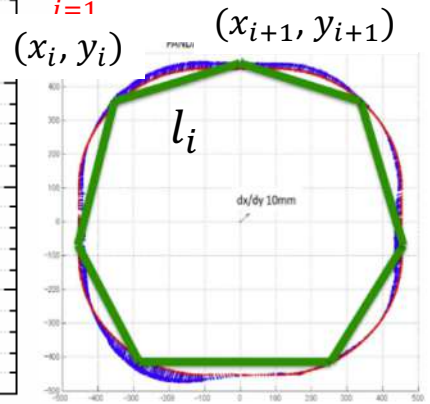
Circumference estimate



How we evaluated systematic error

$$\sum_{i=1}^{n-1}\sqrt{(x_{i+1}-x_i)^2+(y_{i+1}-y_i)^2}$$

$$\sum_{i=1}^{n} l_i$$



Each magnet position(x,y) is obtained from LT survey and network analysis.
We can calculate the sum of each side of a n-polygon.

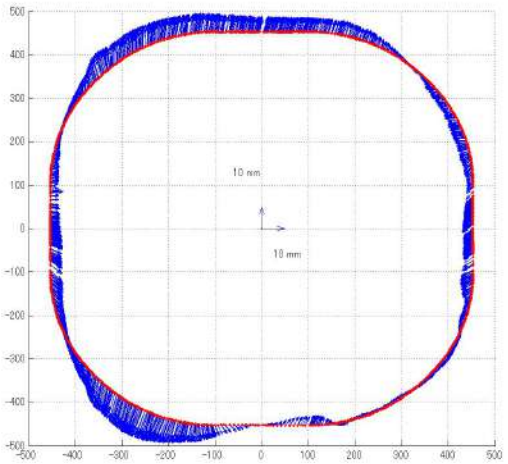
The sum is compared with the direct distance measurement using other instrument

Our best guess from the survey and analysis was that the circumference is about 16.4 mm longer than the SuperKEKB design. This information was used when injecting the LER beam to the ring on Feb.9, 2016 and the beam said Yes!

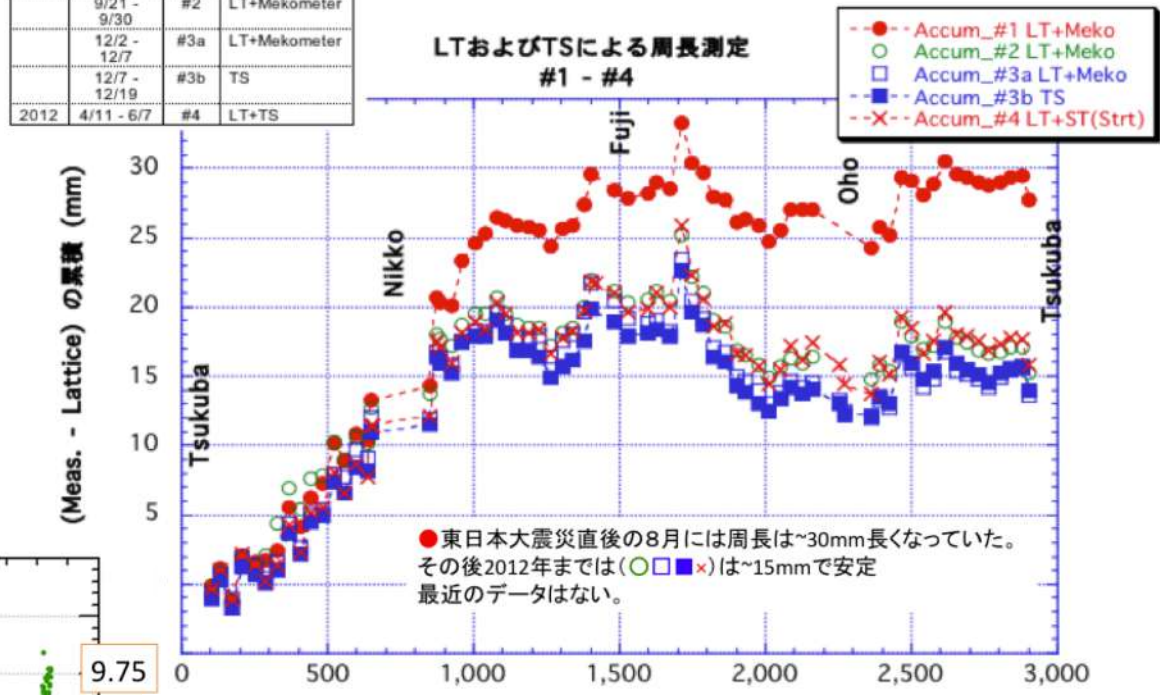
Horizontal

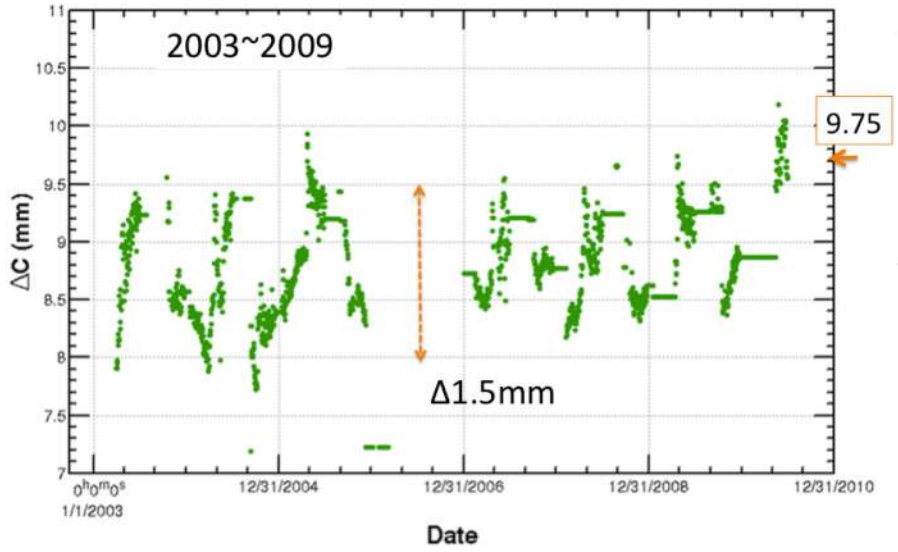
Our rings look like this

(Our rings have been always larger than the design)



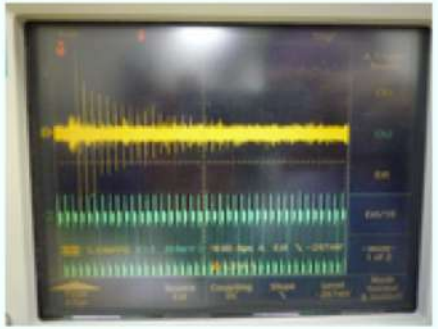
2011	7/28 - 8/24	#1	LT+Mekometer
	9/21 - 9/30	#2	LT+Mekometer
	12/2 - 12/7	#3a	LT+Mekometer
	12/7 - 12/19	#3b	TS
2012	4/11 - 6/7	#4	LT+TS



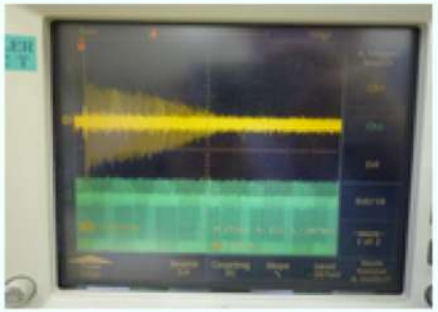


Our rings were the largest right after the Great East Japan Earthquake in 2011. They started shrinking but not back to the level of KEKB.

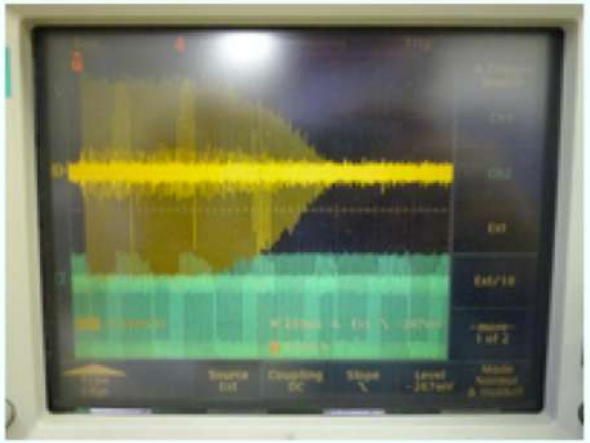
18:35:14 20ターン目が見えた



19:53:52 ZHQF4P24 調整
100ターン



20:03:44 ZVQDWNP1調整
130ターン



Beam circulation in the LER was confirmed

Difference between LER and HER

LER was commissioned first, then HER.

RF said that the difference between two rings in circumference is ONLY 0.2 mm (with some luck!).

When repeating the same type of measurements many many times, say ~a few 100 times, pay special attention to any systematic errors of the instruments, analysis program and so on.


SuperKEKB (Phase-1)
アライメント終了
2015.10.14
御用

The last days of KEKB

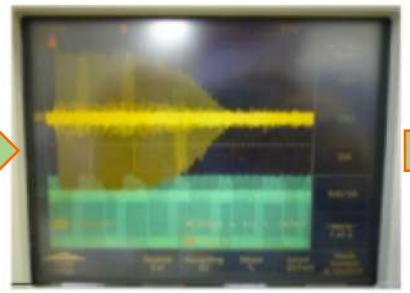
Dismantling of the KEKB magnet

Magnets cables removed

SuperKEKB Beam line

Magnets being installed

SuperKEKB layout

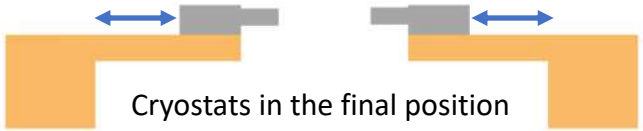


KEKB Review 2016

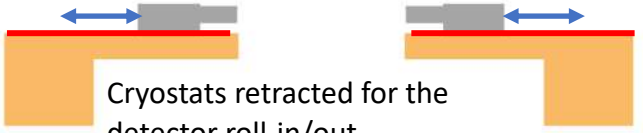
A big milestone for us 2/9/2016

- Results
  - Phase I, without IR
    - Vertical
    - Horizontal
      - Circumference estimate for setting the RF frequency
      - Difference between HER/LER for collision
  - Phase II (IR with FF superconducting magnet system)
    - Installation of the final focus superconducting magnet system “QCS” during the 2016 summer shutdown

The IR floor is leveled nicely by “self-leveling” method, prior to QCS installation



Cryostats in the final position
Alignment was done with
this configuration



Cryostats retracted for the
detector roll-in/out

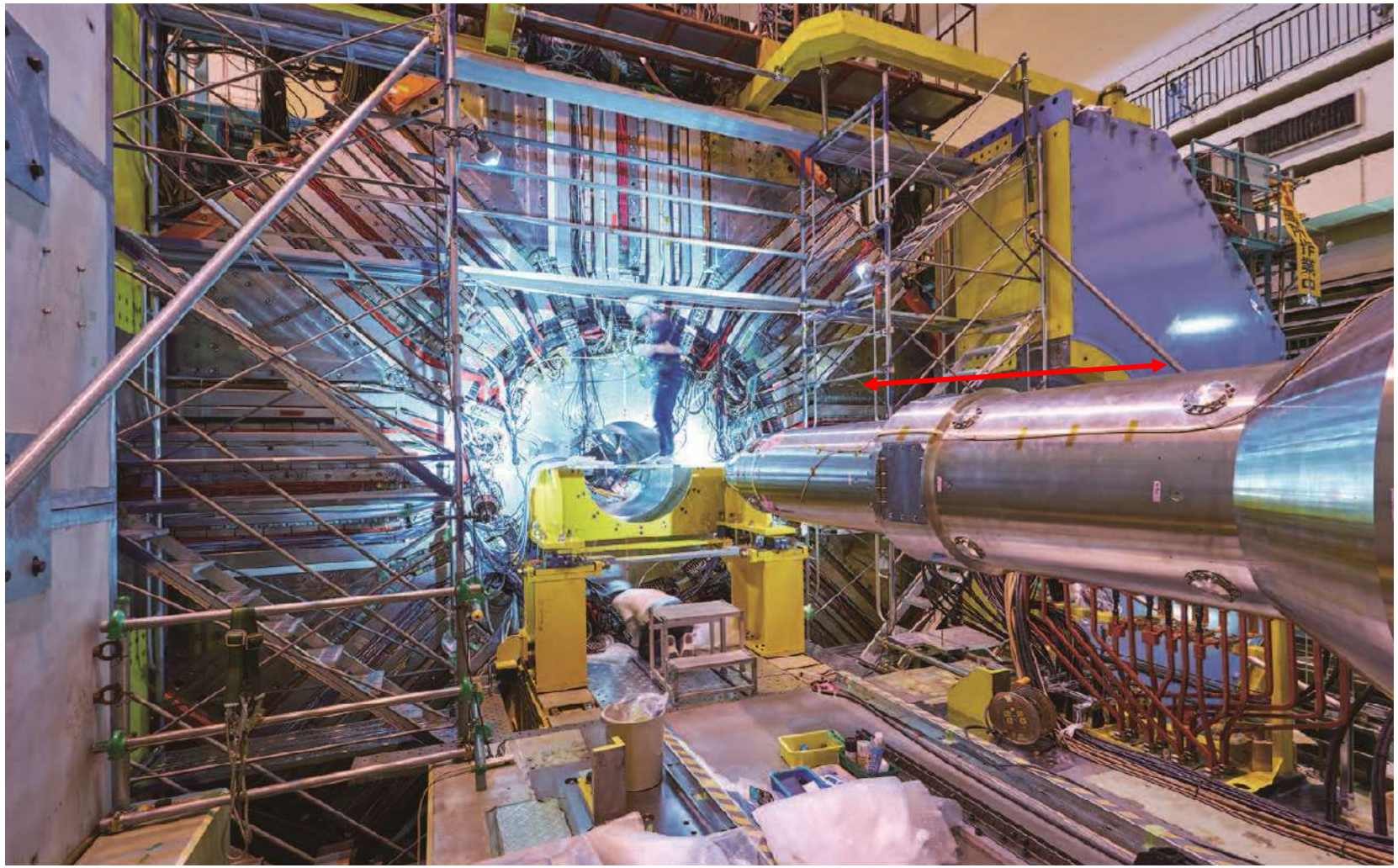
Self-leveling concrete (floor levelling compound)

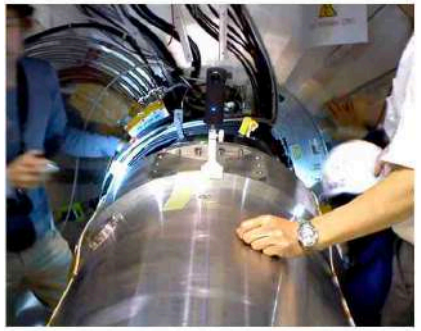
- polymer-modified cement
- high flow
- used to create a flat and smooth surface
- Compressive strength similar to or higher than traditional concrete

Floor surface has to be smooth

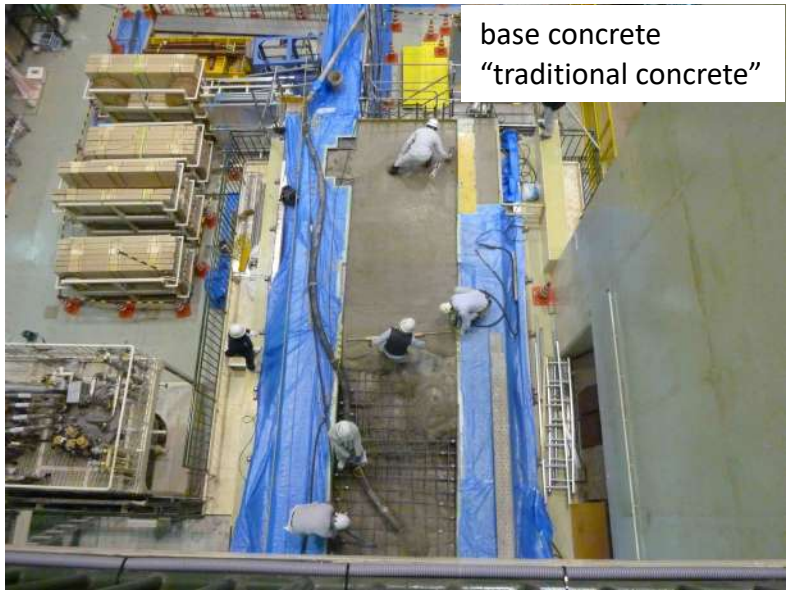
Cryostat can not wobble while being pushed in/being retracted
→smooth floor (and the rail) necessary

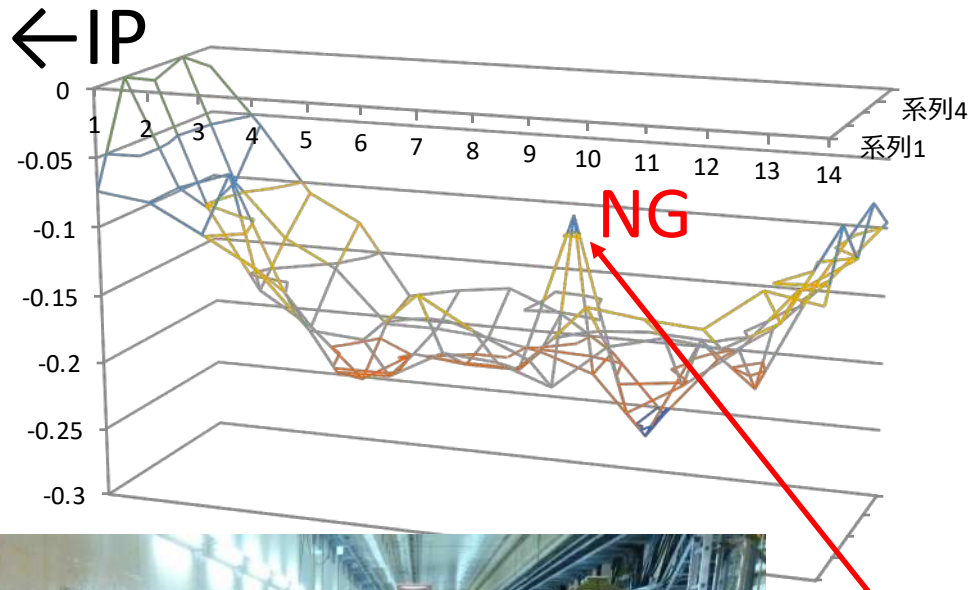
- Very tight space between the detector and the cryostats
- and that tight space is full of cables



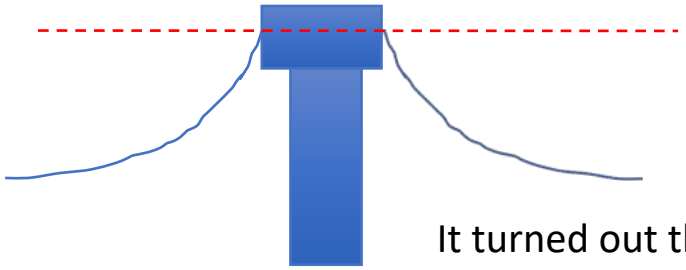


Self-leveling concrete





Flatness of the surface was surveyed with a Laser tracker.

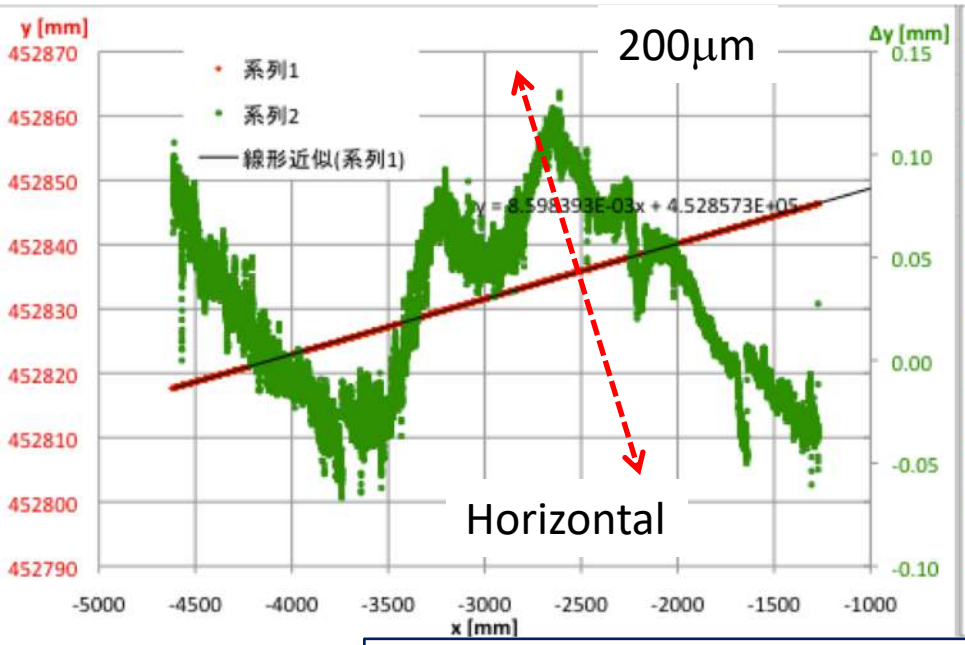


It turned out that a bolt was sticking out from the base concrete.

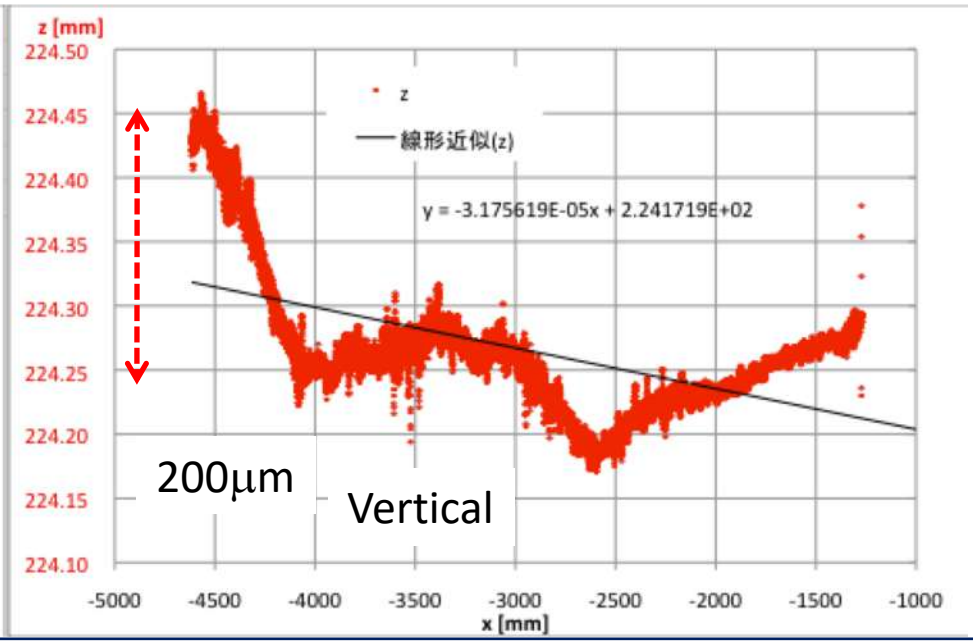
Cryostat can not wobble while being pushed in/being retracted
→smooth floor (and the rail) necessary

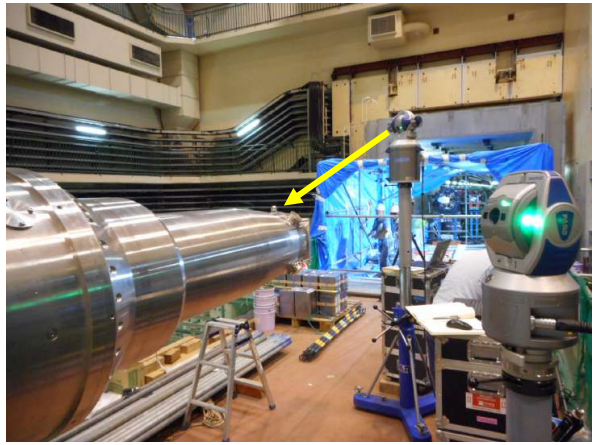
- Very tight space between the detector and the cryostats
- and that tight space is full of cables

The cryostat motion follows the rails



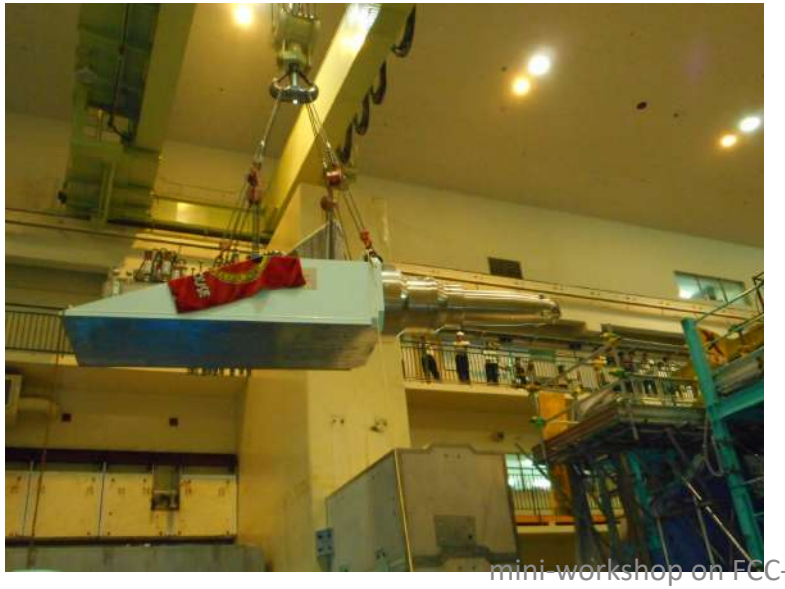
The cryostat motion follows the floor



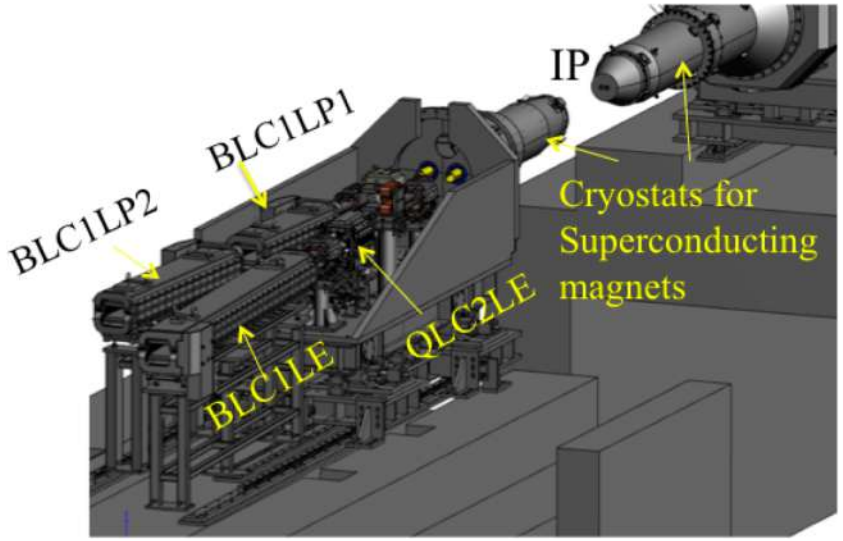


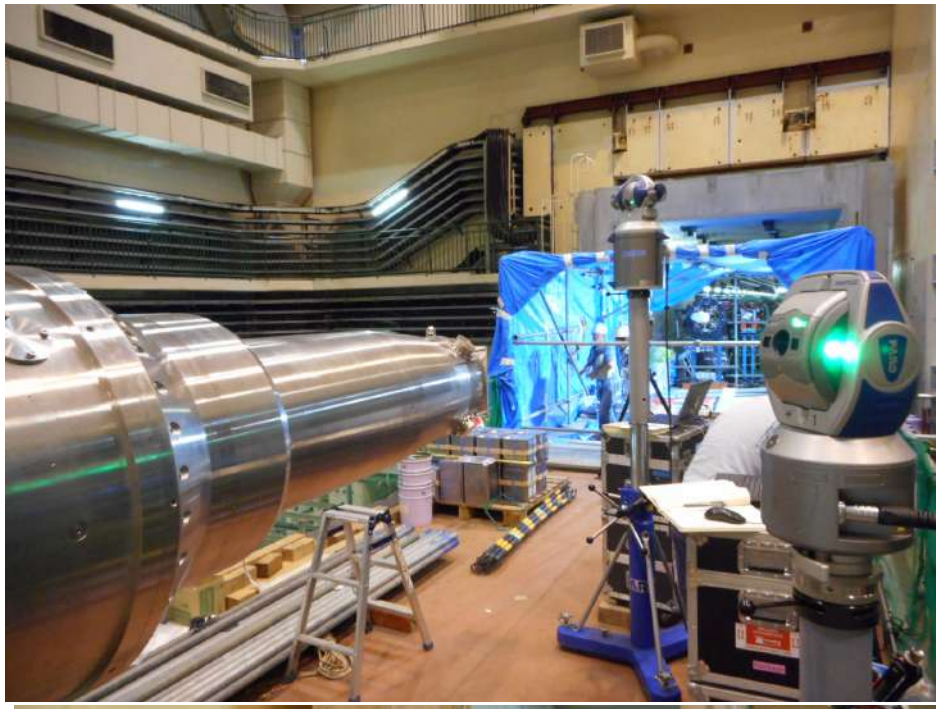
- We repeated the push in/retract 5 times, the position of the cryostat was monitored by a Laser tracker while moving for about 4m along the rails.
- Good reproducibility
- Wobbling in horizontal/vertical within the tolerances

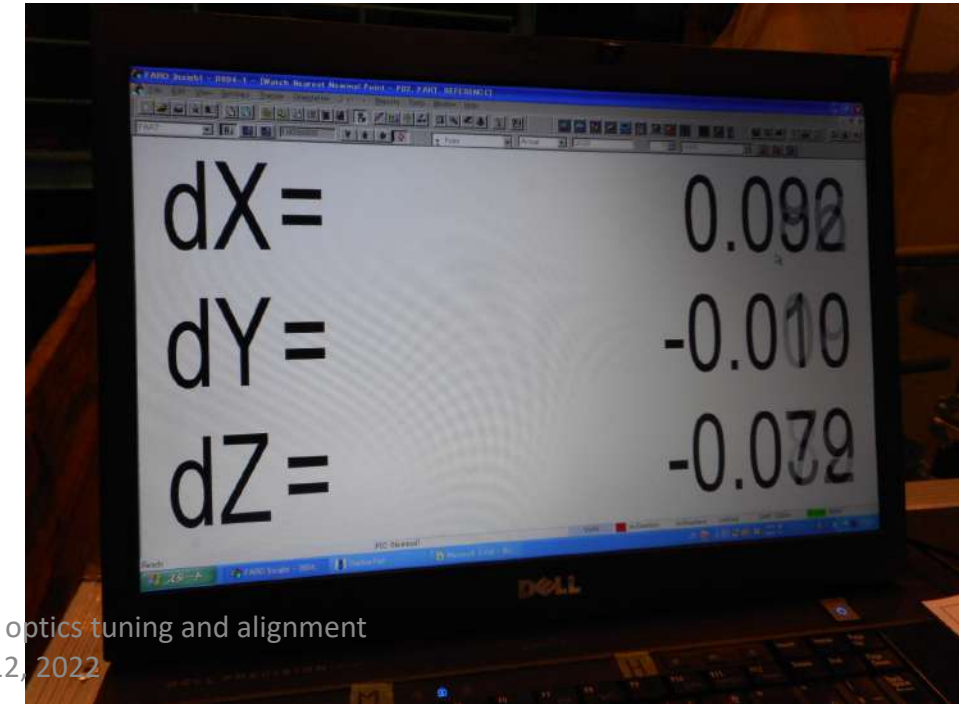
QCSL cryostat installation Aug. 2016



Alignment


IP
BLC1LP1
BLC1LP2
Cryostats for
Superconducting
magnets
QLC2LE
BLC1LE

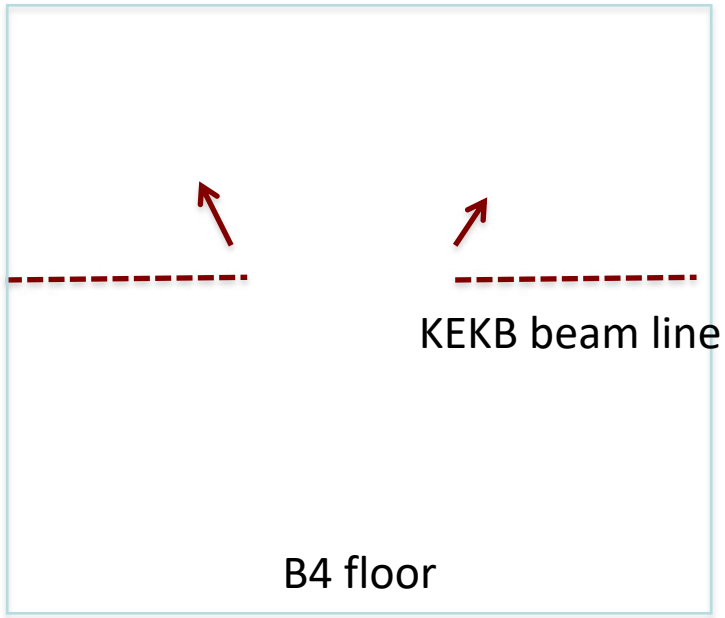



dX=
0.092
dY=
-0.010
dZ=
-0.079

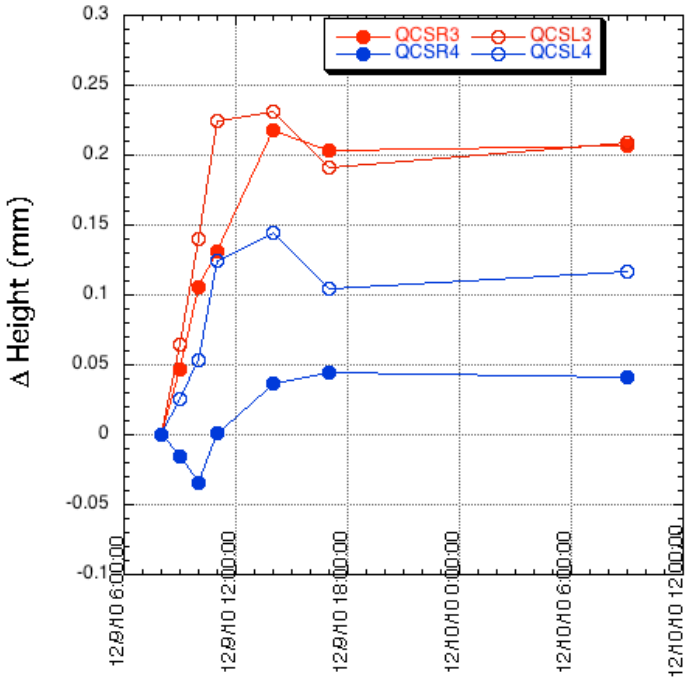
Beam line & floor motion during Belle roll-out analyzed.

Beam line & floor motion should be taken into account when evaluating the alignment tolerances (or/and the specs for QC correction coils) for SuperKEKB QC's along with the cryostat motion due to the electro-magnetic force when the detector solenoid/QC's being ramped up.

KEKB QCS alignment was done before Belle rolled in.



KEKB beam line opens up like a drawbridge
when the detector moves away from the beam line.
→Within the tolerance

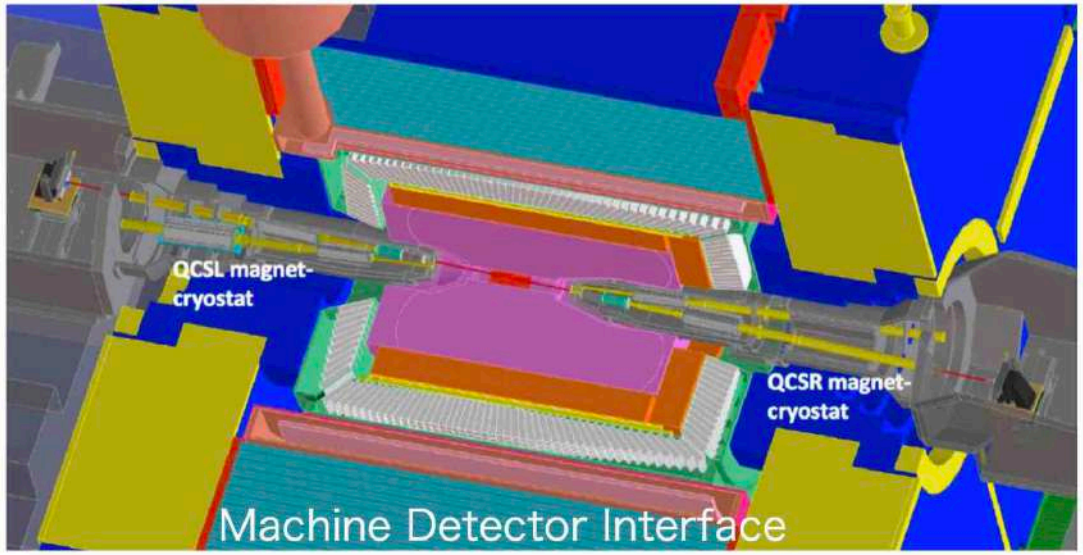


~ +0.2 mm

Bad design

- Vibration issues
  - KEK measurements
  - & Monitoring system by LAPP

Vibration monitoring system by LAPP



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Vibration and luminosity frequency analysis of the SuperKEKB collider

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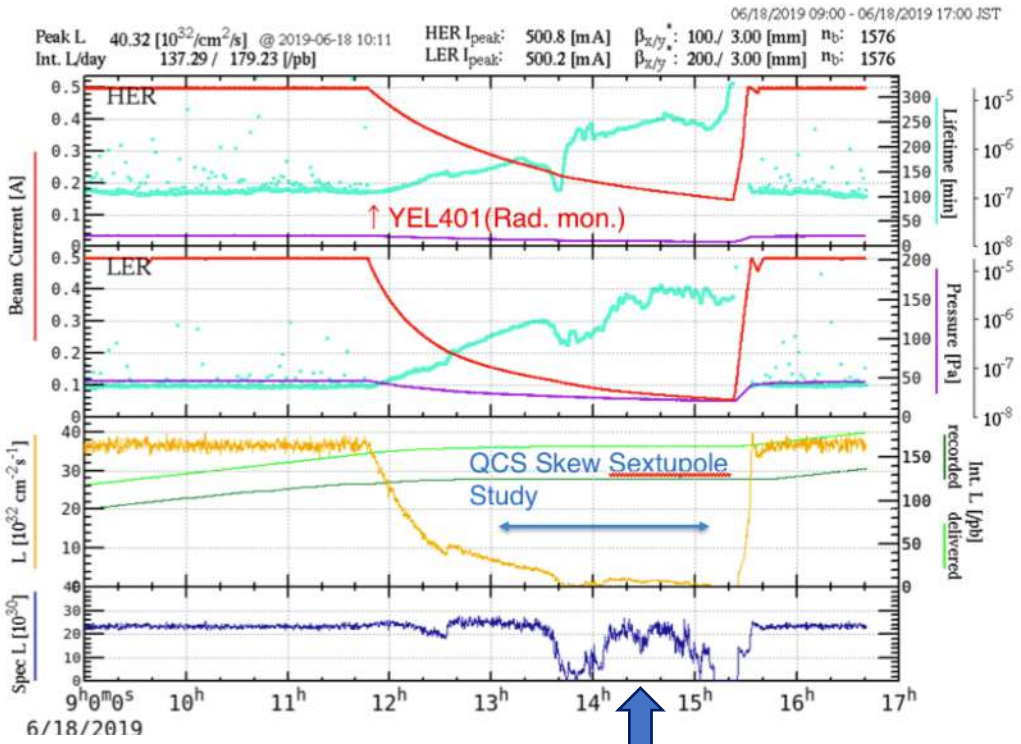
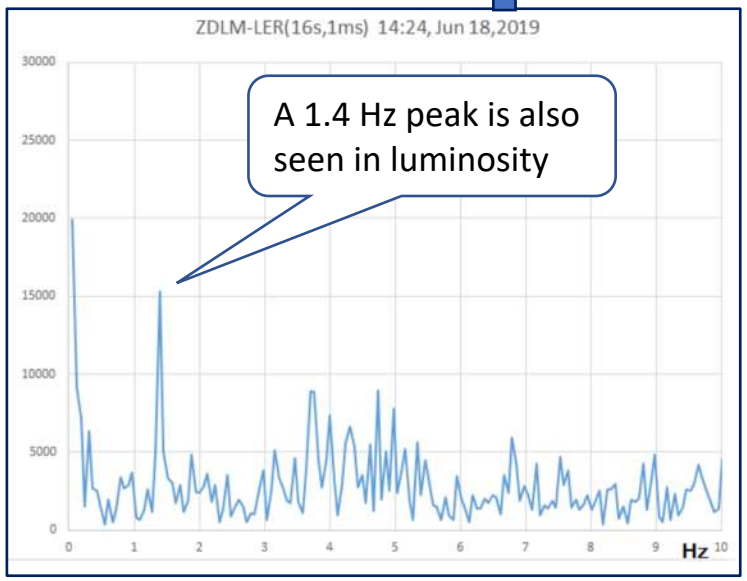
The LAPP Vibration Monitoring system detects

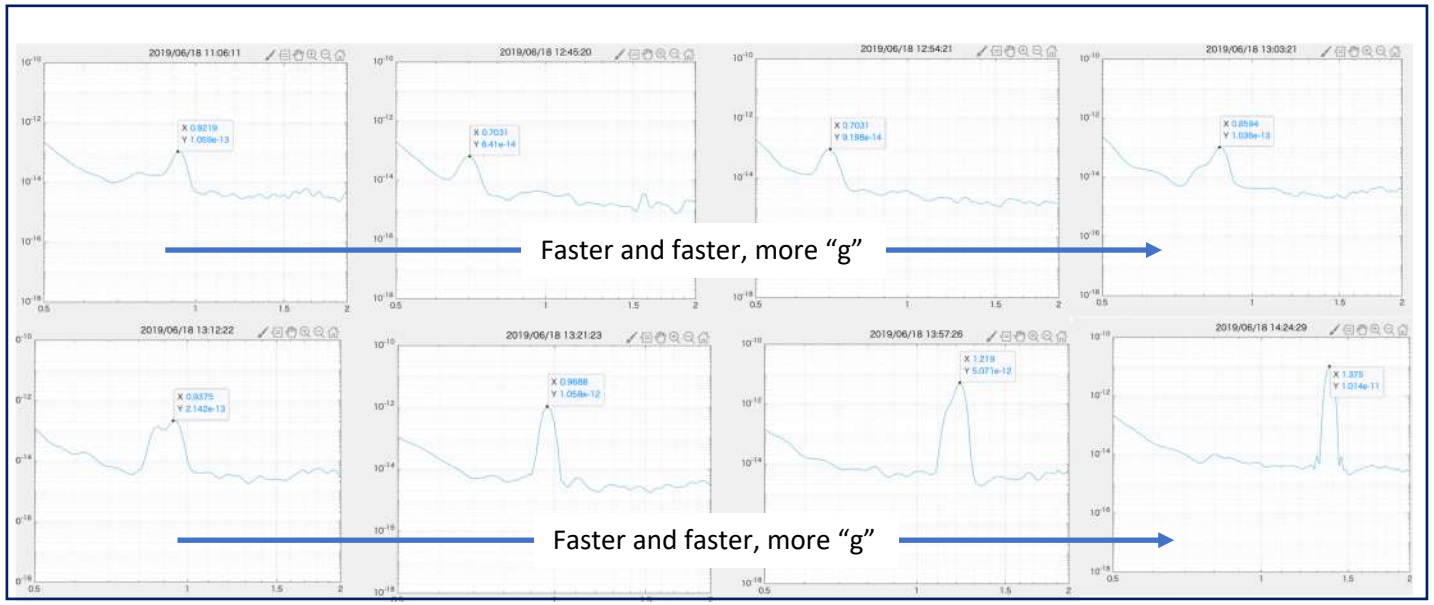
- Cryostat motion
- Ground motion
- earthquakes
- People's activities, such as traffic
- Comparison between luminosity and cryostat vibration, for example, can also be made → with the increase of the luminosity, the effects of vibrations may increase.

The data can be useful for the future modification and upgrade of the interaction region and the QCS system.

KEK vibration measurements







B-BLOCK B9
Large-scale Geotechnical Dynamic Centrifuge

https://www.youtube.com/watch?v=b-kNqO-ohwA

Centrifugal force

$$a = r\omega^2 \quad r = 6.6\ m$$

$$f = \frac{1}{2\pi} sqrt\left(\frac{a}{r}\right)$$

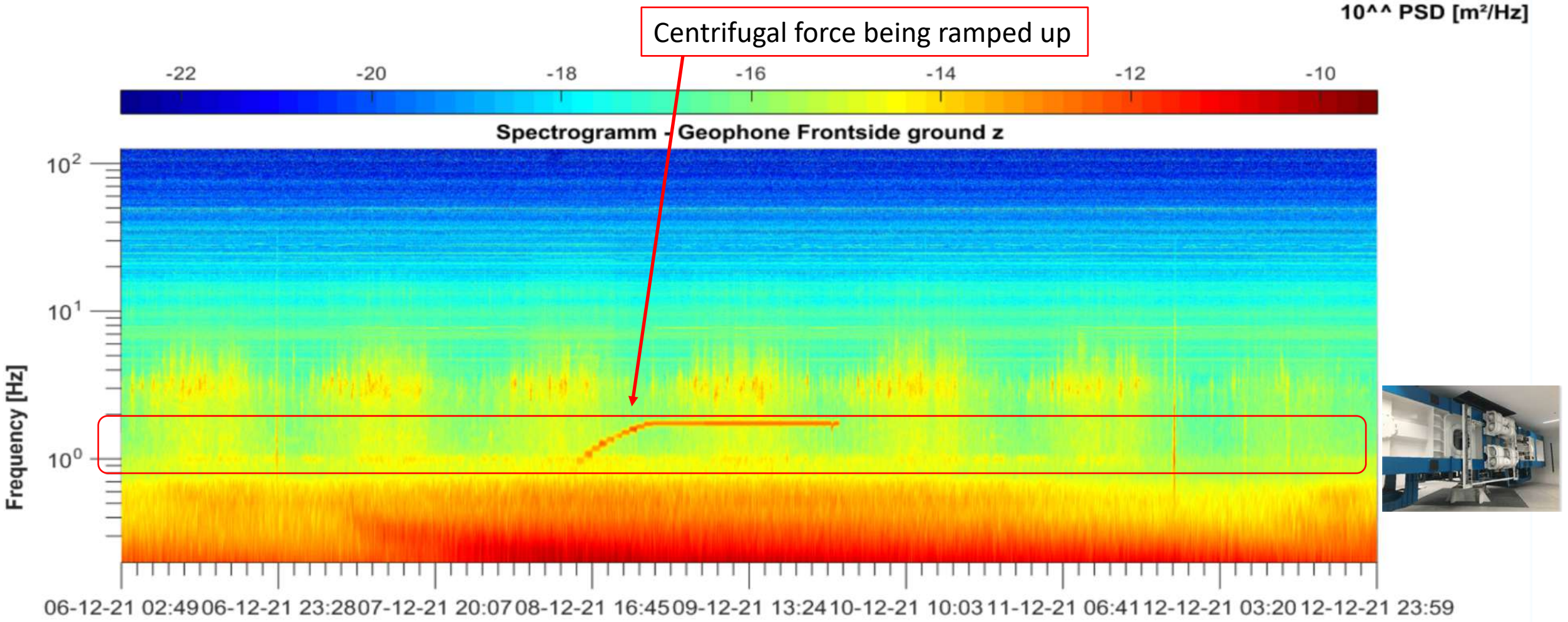
a was $50g$ on June 18 experiment by Civil Engineering Research Institute

$\rightarrow f = 1.371\ Hz$!

【仕　様】	
有効回転半径	6.6m
最大遠心加速度	100G
最大積載容量	400t・G
最大加振加速度	50G
最大加振容量	50t・G
最大速度	150cm/s
最大変位	±10mm
加振周波数	10～300Hz

Civil Engineering Research Institute

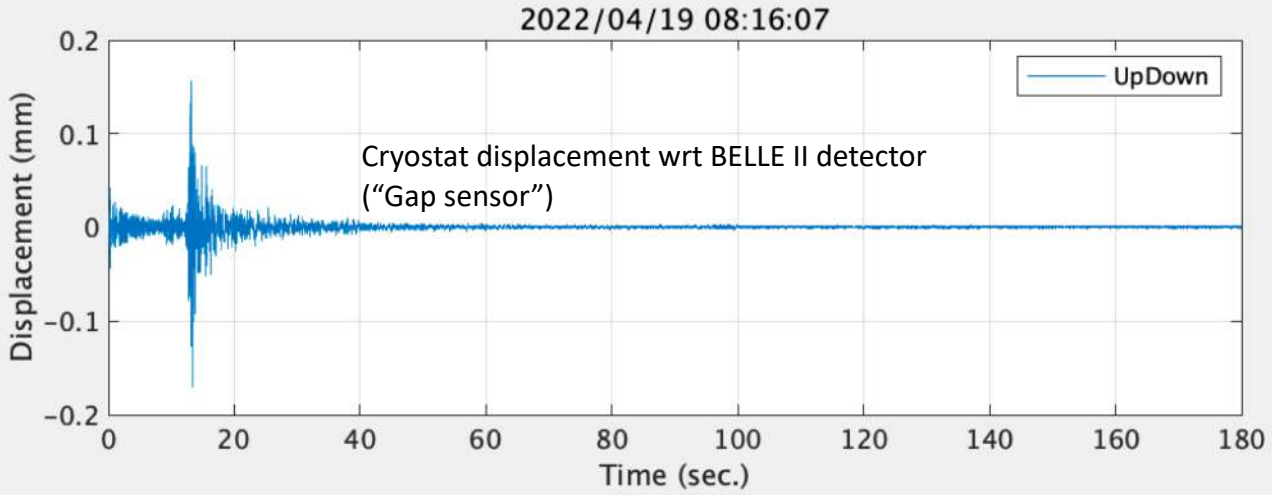
Civil Engineering Research Institute experiment also seen by the LAPP geophones (example, Dec.6 2021~Dec.13, 2021)



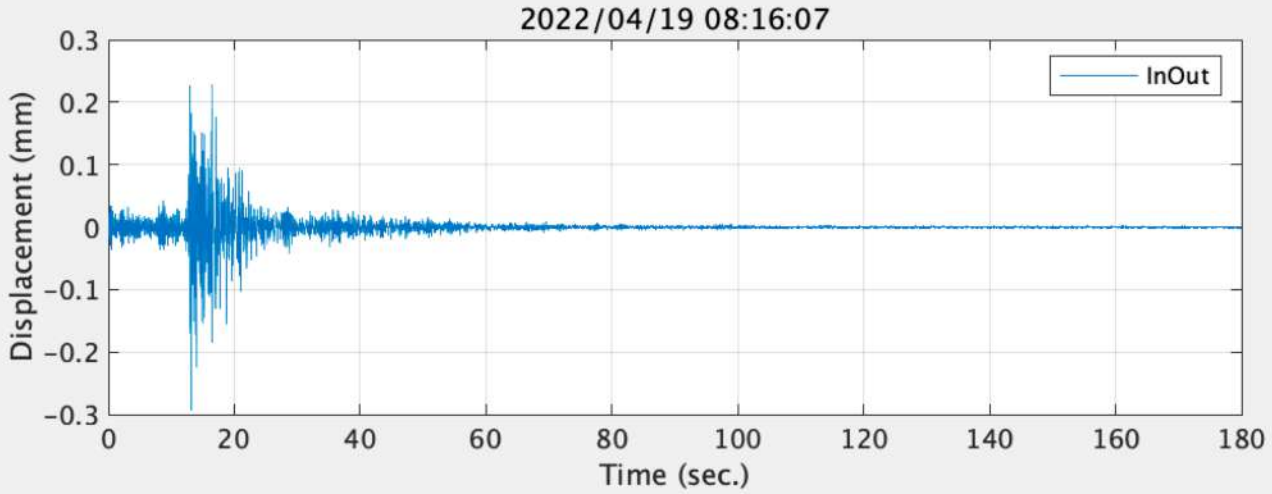
SuperKEKB loses beams when EQ happens

08:16:17 LER Beam Abort (948.8mA) Gate Open 中

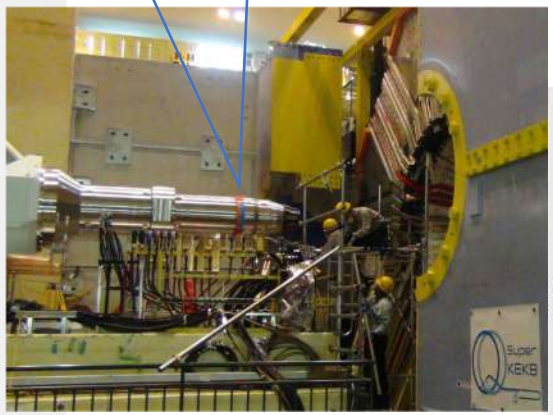
HER Beam Abort (758.2mA) Gate Open 中

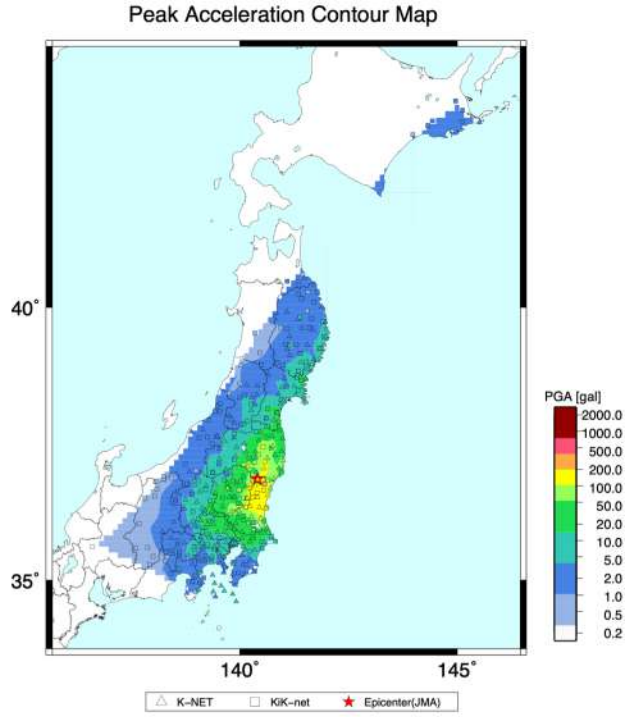


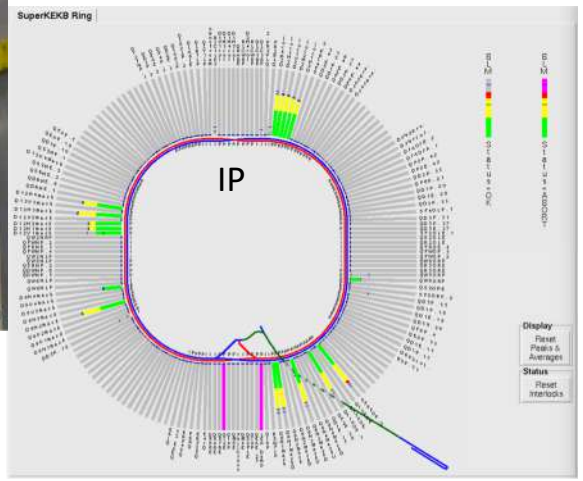
Cryostat displacement wrt BELLE II detector
("Gap sensor")



Cryostat vibrates in the detector, which sometimes triggers a quench, because $\frac{d\phi}{dt}$ generated due to the coil motion in the detector solenoidal field gives a false quench signal.







- Summary

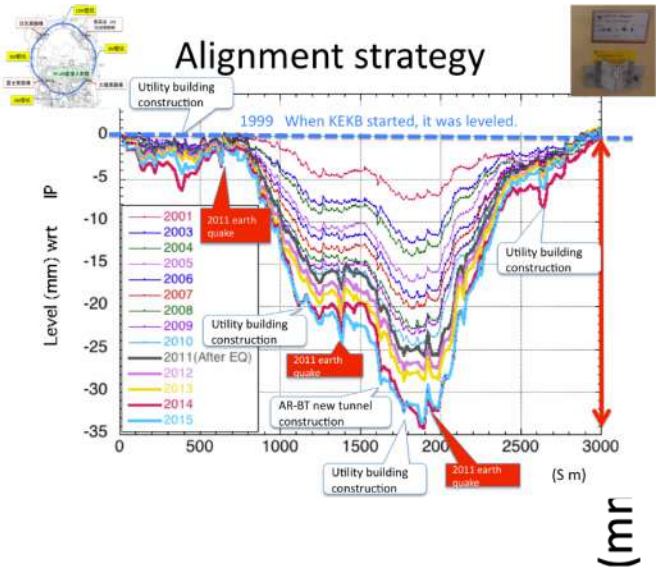
Summary

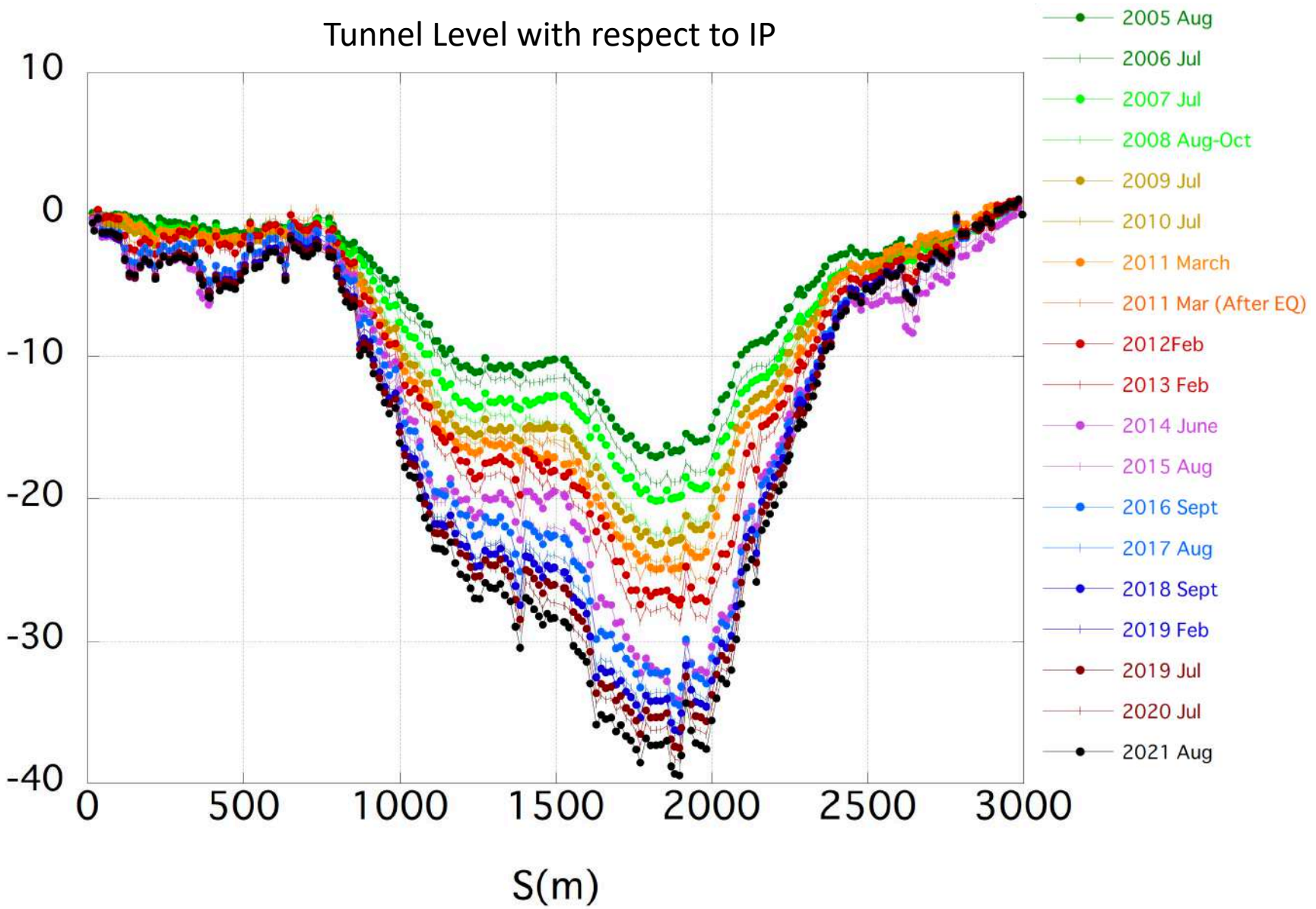
- The prediction for the circumference agreed with the actual circumference within 1 ppm accuracy and the difference in the circumference in both rings was found to be a couple of hundred microns.
- The level data were used to pre-set the vertical steering magnets when we first injected the beam to the main ring.
  - Both contributed to a smooth start-up of the SuperKEKB main ring.

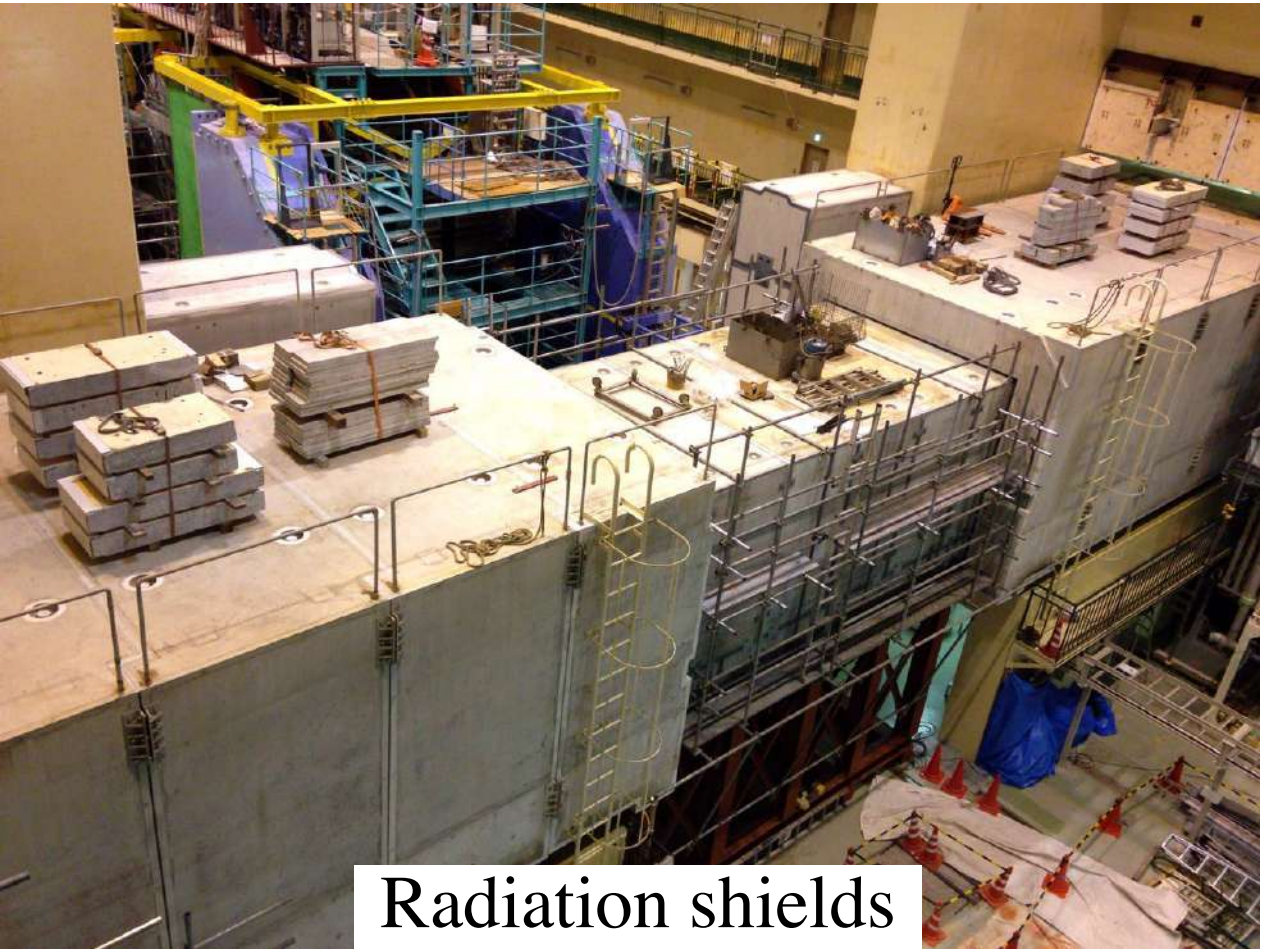
- We did not use a state-of-the-art instrument, method but we did good enough job given the amount of resources.

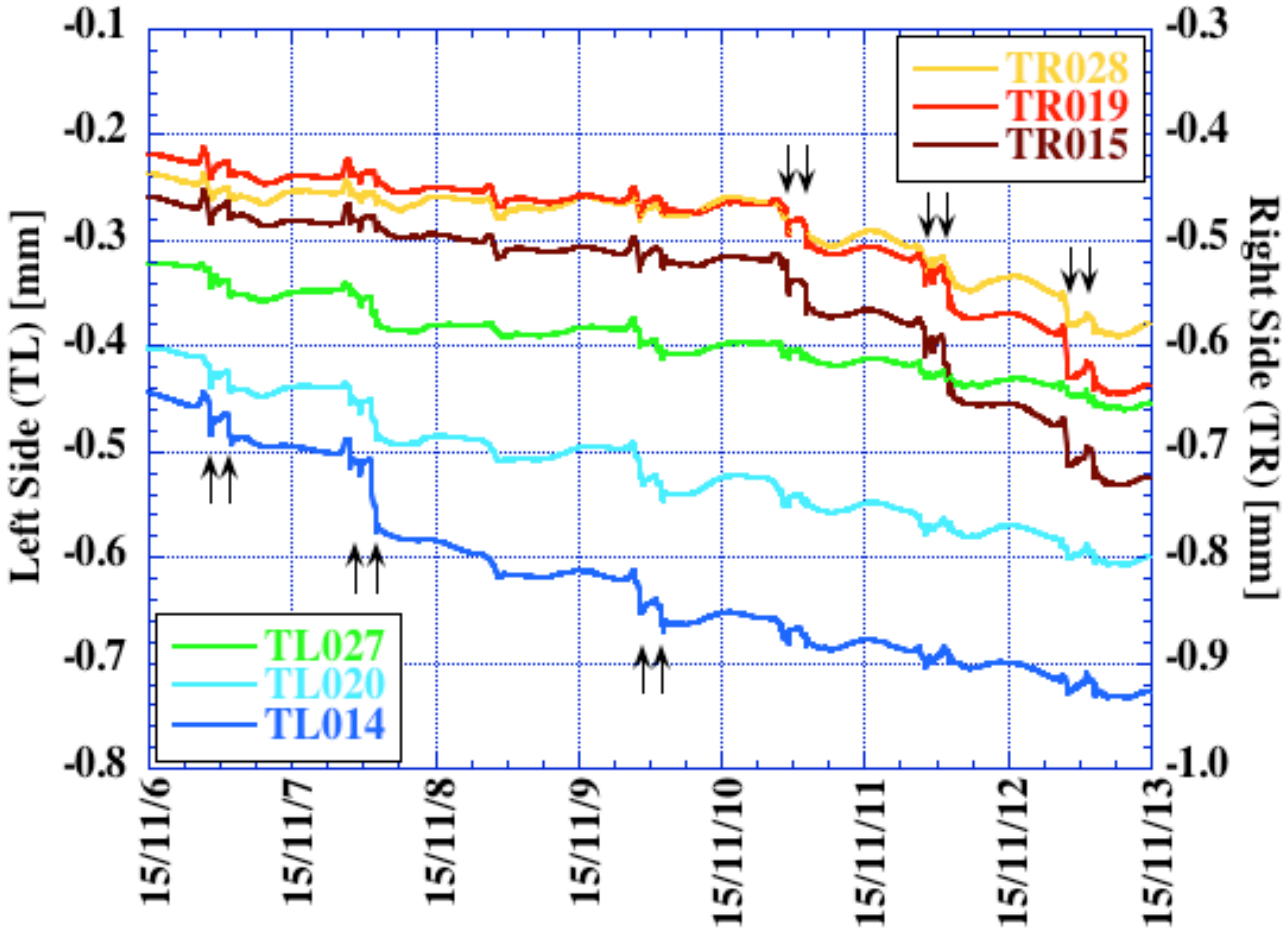
- The tunnel keeps sinking.
- Vibration may become an issue for the future with lowering β_y^*
  - Collaboration with LAPP on vibration measurements/monitoring.

A new beam transport line (BT) to another accelerator complex (PF-AR) was also being built just a few meters above the SuperKEKB tunnel. The construction of the facility buildings started in 2013, just as we started building the new survey network for SuperKEKB. The construction work includes excavation of vertical shafts very close to the tunnel. The excavation sites and the new BT line to PF-AR are indicated in Fig. 2. This heavy construction work made the establishment of the new survey network and alignment work very difficult.

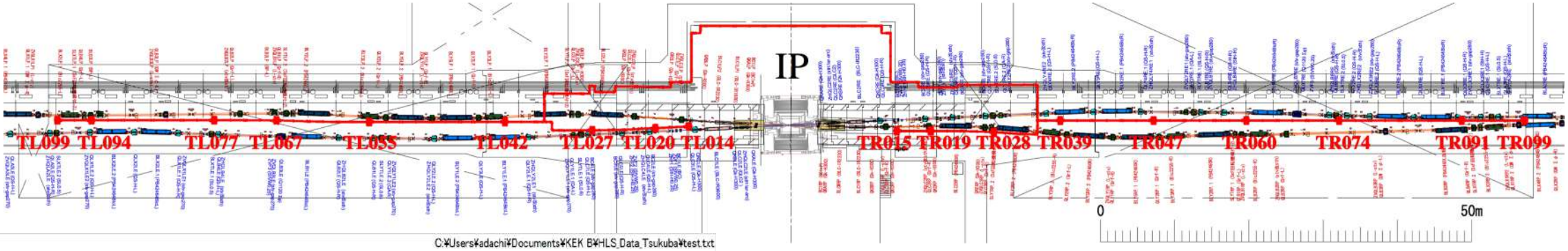


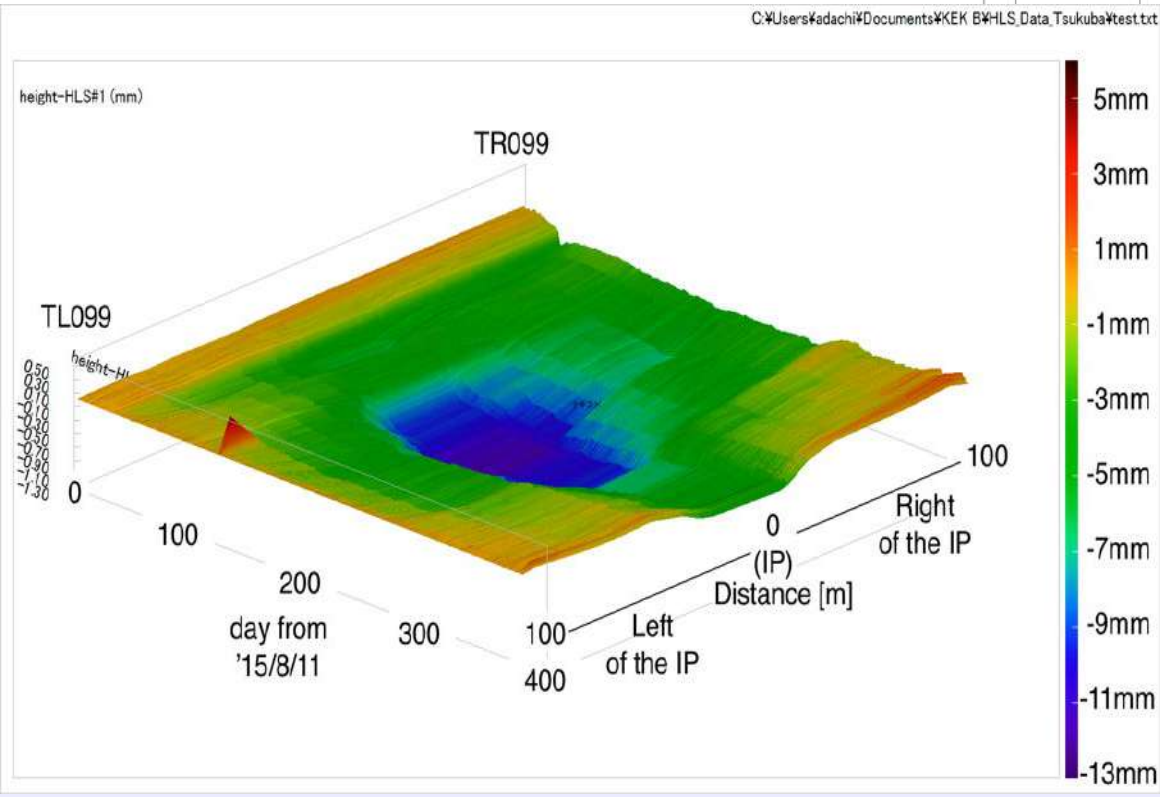






The both side of the IP sections are covered by radiation shields. Each section weighs about 60 tons. The floor levels during the radiation shield installation are shown. Two shields were installed per day. The sensors near the IP presented the largest variation of approximately 200 µm.





Tunnel level changes.(3D)

We got BINP type HLS from
SLAC, DESY
(we bought some, of course)

But they are being damaged by radiation…
We can not make these kind of plot any more.

Radiation seems to be stronger than KEKB
especially near the collimator