

A Numerical alignment error estimation for the SPring-8-II

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Introduction

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One of targets of the SPring-8 storage ring upgrade plan (SPring-8-II) :

Ultra-low emittance ring: $2.4 \text{ nm}\cdot\text{rad} \rightarrow 0.15 \text{ nm}\cdot\text{rad}$ (natural)

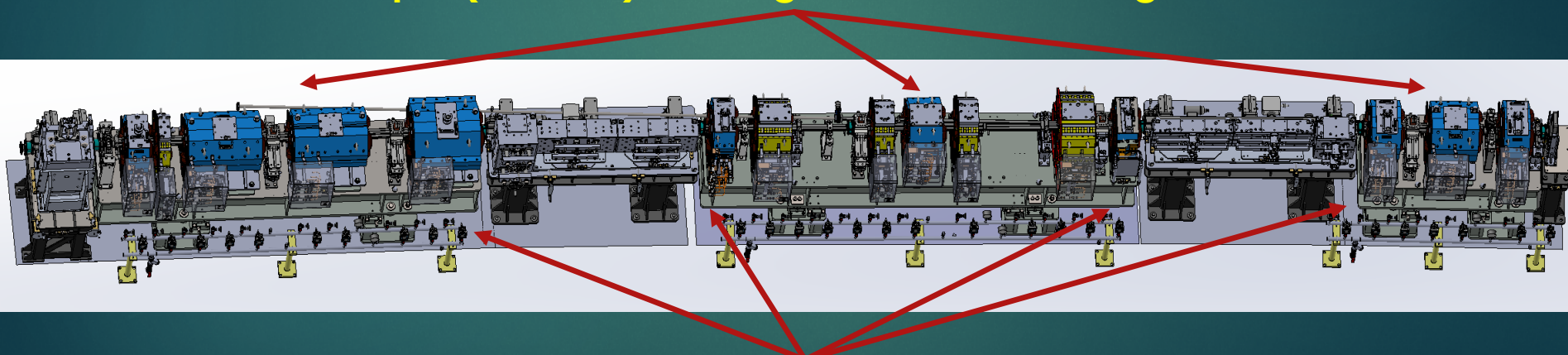
SPring-8-II storage ring : 44 normal cells + 4 straight sections, $\sim 1.5 \text{ km}$ long
Magnets for 1 normal cell :

6 common girders w/ multipole & correction magnets

5 permanent bending magnets

Allowable alignment errors in horizontal/vertical planes (peak-to-peak):

$\pm 30 \mu\text{m}$ (desired) for magnets on common girders



$\pm 90 \mu\text{m}$ for each neighboring 2 common girders

Introduction

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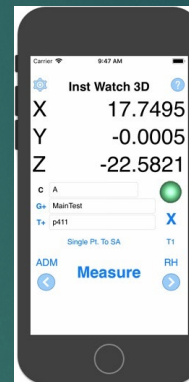
Goals of this study are to answer following 3 questions;

1. Do our conventional methods of alignment and survey satisfy allowable alignment errors?

Alignment :
Pushing bolts + HEX wrenches
monitoring coordinates by a laser tracker
in real time

Survey :

Leica AT-402 laser tracker
for horizontal



Trimble DiNi0.3
for vertical



2. Do we need additional observation points?

Quadrupole magnets at both ends of common girders (12 pts / cell)
Monuments on the tunnel wall (2 or 4 pts / cell)

3. Do we need the realignment? If yes, how often?

Alignment error estimations for accelerator components

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Observations of accelerator components' coordinates A_{obs} :

$$A_{obs} = A_{des} + \Delta A_{top} + \Delta A_{env} \pm \sigma_{meas} \quad (1)$$

A_{des} : designed coordinates
 ΔA_{top} : topographical effects
 ΔA_{env} : environmental effects
 σ_{meas} : measurement errors

Both ΔA_{top} & ΔA_{env} are assumed as 0, in this error estimation.

Error ellipse : often used for alignment or survey to help one's visual understanding.
Absolute error ellipse : individual observation
Relative error ellipse : relation between 2 observations

Alignment errors for neighboring 2 common girders are estimated w/ relative error ellipses by Microsoft Visual Basic (Excel!) based network analysis code[†].

[†] : S. Matsui *et al.*, Proc. 12th Annual Meeting of PASJ, Tsuruga, Aug. 5-7 (2015), pp. 140-145

Alignment error estimations for accelerator components

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Calculation conditions:

~1.5 km long ring:

44 normal cells + 4 straight sections.

Observation points:

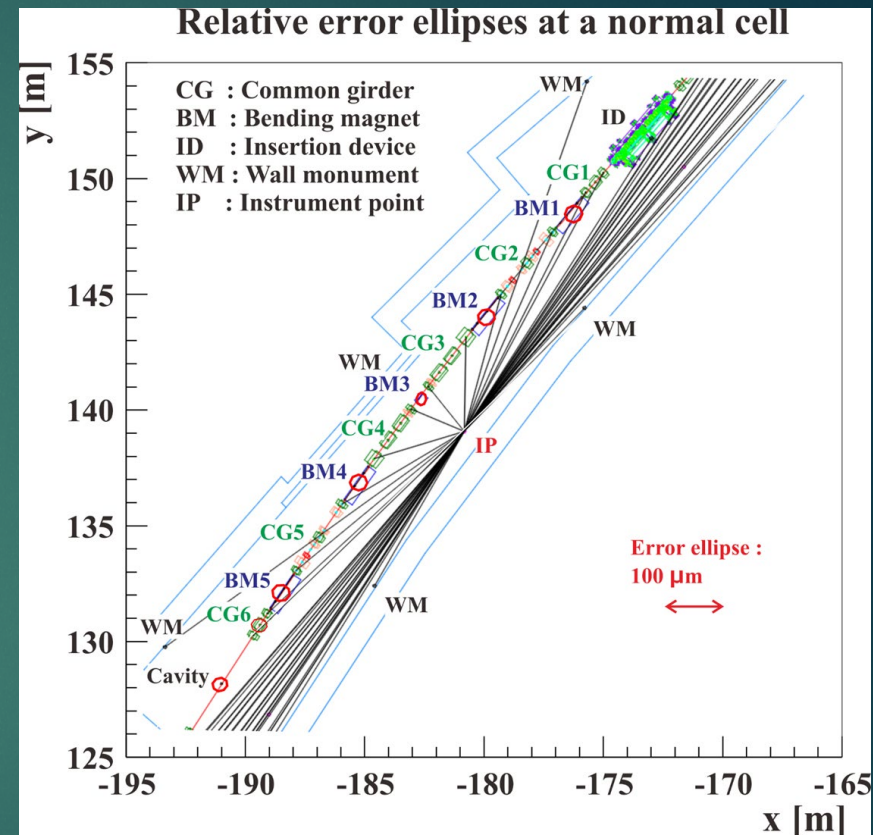
- 1) quadrupoles at both ends of common girders (526 pts)
- 2) IDs (51 pts)
- 3) monuments on the tunnel wall (204 pts)

Conventional survey method adopted:

Leica AT-402 L.T. for horizontal (781 pts)
Trimble DiNi0.3 for vertical (48 pts on center of each cell)

Assumed errors (based on our survey results):

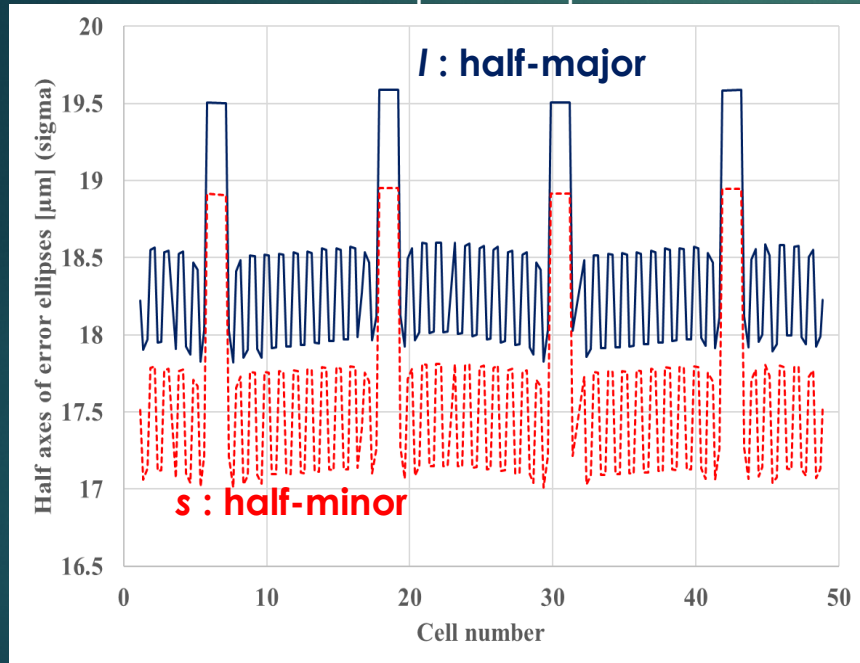
- 1) angle : 0.57 arcsec
- 2) distance : $\pm 7.6 \mu\text{m} + 2.5 \mu\text{m/m}$



Alignment error estimations for accelerator components

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In case of 4 wall points per 1 cell:



$$l_{ave} = 18 \mu\text{m}, s_{ave} = 17 \mu\text{m}$$

Ave. alignment error in horizontal:
 $\sqrt{18^2 + 17^2} \cong 25 \mu\text{m}$
(at most $28 \mu\text{m}$ for straight sections)

For vertical, $26 \mu\text{m}$ (σ) is estimated by our survey results.

Required : $\pm 90 \mu\text{m}$ (peak-to-peak)
 $\leftrightarrow 90/(2\sqrt{2}) \cong 32 \mu\text{m}$

No explicit changes in the alignment error between 2 or 4 wall points.

Our conventional alignment methods also works fine.
Details were already explained in previous Kimura's talk.

Alignment error estimations for accelerator components

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Goals of this study are to answer following 3 questions;

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- 3. Do we need the realignment? If yes, how often?

Necessity of realignment

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Alignment errors confirmed to be satisfied the allowable errors while their installation.

After installation, we have to pay attention to all magnets coordinates (especially for magnets at both ends of common girders) to see how they change.

The major source of the change is considered to be ΔA_{top} in;

$$A_{obs} = A_{des} + \Delta A_{top} + \Delta A_{env} \pm \sigma_{meas} \quad (1)$$

Considerable contents of ΔA_{top} :

- Earth tides

- Activity of the geologic fault characterized by earthquakes

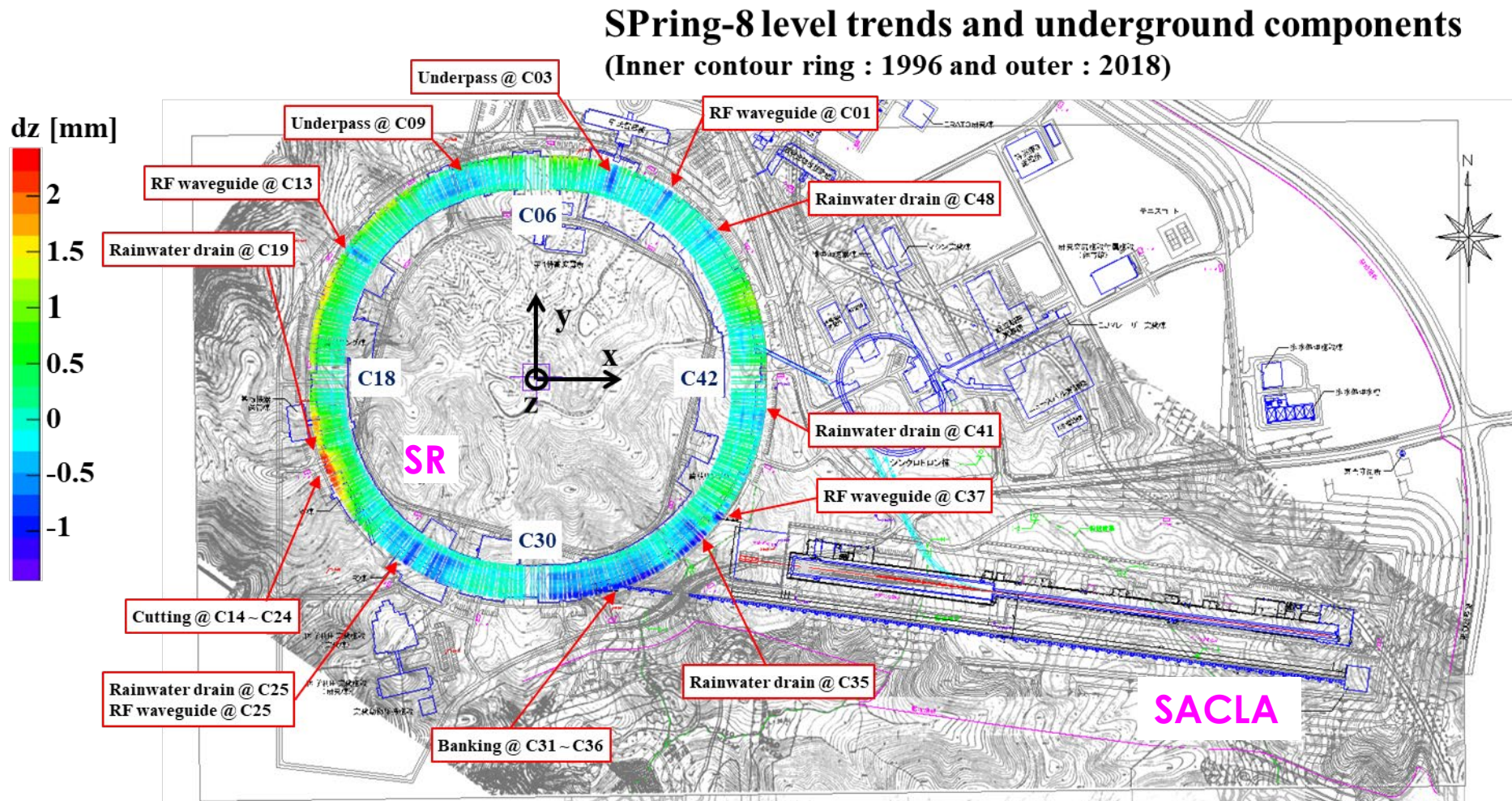
- Day/Night or seasonal changes of temperature and pressure

Here, some kind of isolated temperature changes by FCUs etc. in the accelerator tunnel is assumed and still treated as 0 for ΔA_{env} .

Necessity of realignment

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Example: trends of ground level changes over ~20 years survey...



Thus expected coordinate variations for SPring-8-II are calculated by SPring-8 survey data. Then trends of residuals (expected VS designed) for each neighboring 2 girders are compared.

Necessity of realignment

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First, ground deformation growth rate $a(s_j)$ for j -th point $A_i(s_j)$ of **SPring-8** is calculated by the MLS method w/ **a linear approximation**:

$$\Delta A_i^2(s_j) = \sum_i \{A_i(s_j) - A'_i(s_j)\}^2 \quad (9)$$

$$A'_i(s_j) = a(s_j)i + b(s_j) \quad (10)$$

A, A' : observed or optimized x, y and z .
 s : coordinate on the designed beam orbit.
 originated @ the most upstream quadrupole in Cell 1.
 i : 1~22, passed year since 1996.
 j : 1~271, observation point number.
 b : offsets.

Next, the deformation growth rate $a(s_k)$ of k -th ($k = 1 \sim 781$) **SPring-8-II** point:

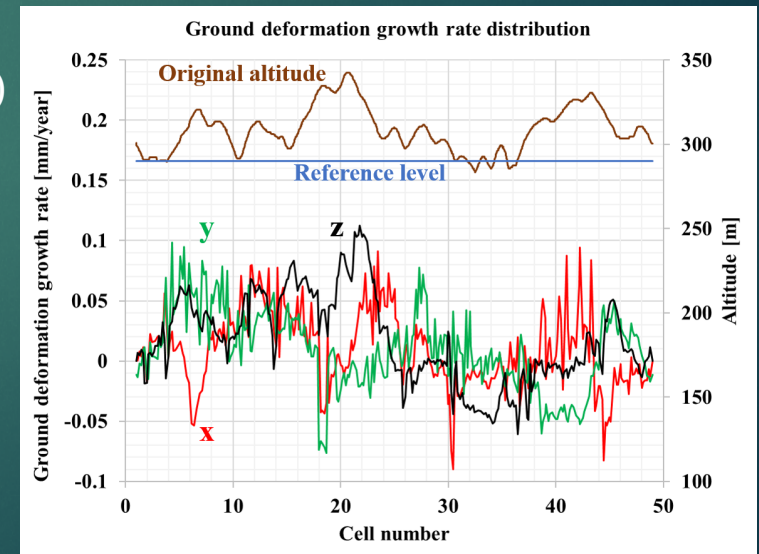
$$a(s_k) = \frac{a(s_j) - a(s_{j-1})}{s_j - s_{j-1}} (s_k - s_{j-1}) + a(s_{j-1}) \quad (11)$$

Offset $b(s_k)$ is designed coordinate $A_0(s_k)$.

Finally, expected k -th coordinates after l -year later from the installation:

$$A_l(s_k) = a(s_k)l + A_0(s_k) \quad (12)$$

$$\Leftrightarrow dA_l(s_k) = A_l(s_k) - A_0(s_k) = a(s_k)l \quad (13)$$



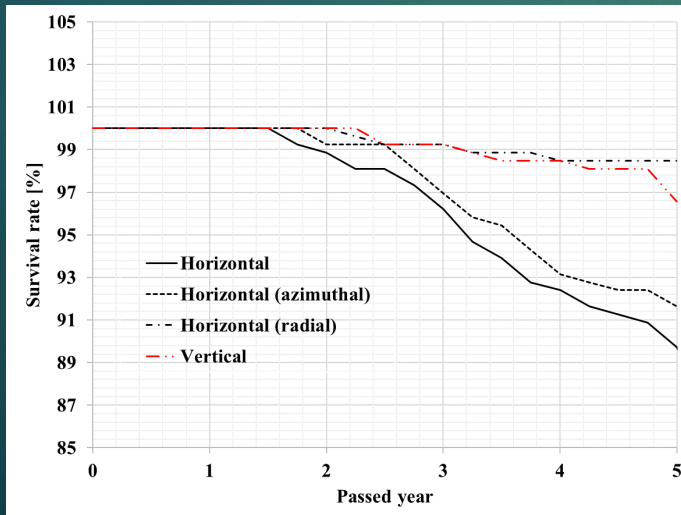
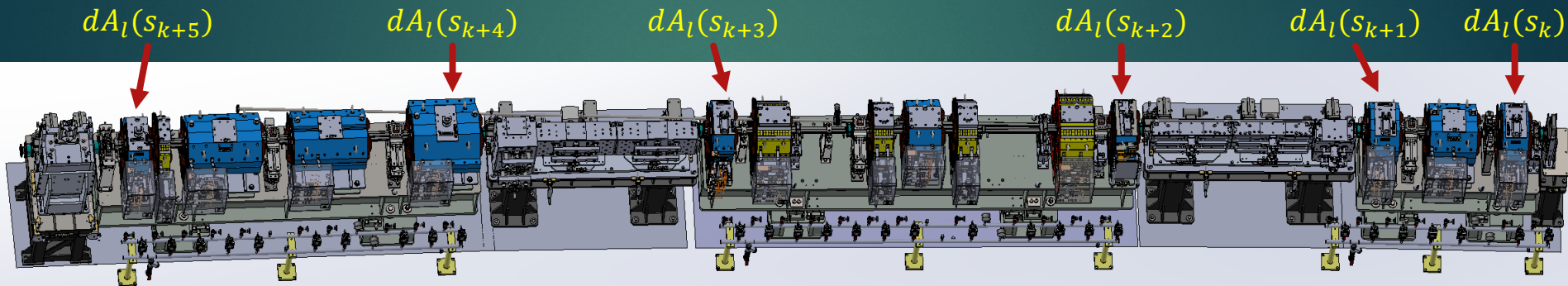
Necessity of realignment

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Residual (expected VS designed) for each neighboring 2 common girders can be separately defined in horizontal / vertical:

$$\Delta R_{hol}(l) = \sqrt{\{dx_l(s_k) - dx_l(s_{k-1})\}^2 + \{dy_l(s_k) - dy_l(s_{k-1})\}^2} \quad (14)$$

$$\Delta R_{ver}(l) = |dz_l(s_k) - dz_l(s_{k-1})| \quad (15)$$



Survival rates of girder combinations (total 263) beneath the allowable alignment error; $\pm 90 \mu\text{m}$.

Realignment is required for both horizontal & vertical within ~2 years.

Horizontal direction needs to be discussed dividing into azimuthal / radial components. Much more strict tolerance is required for the radial direction comparing to azimuthal one.

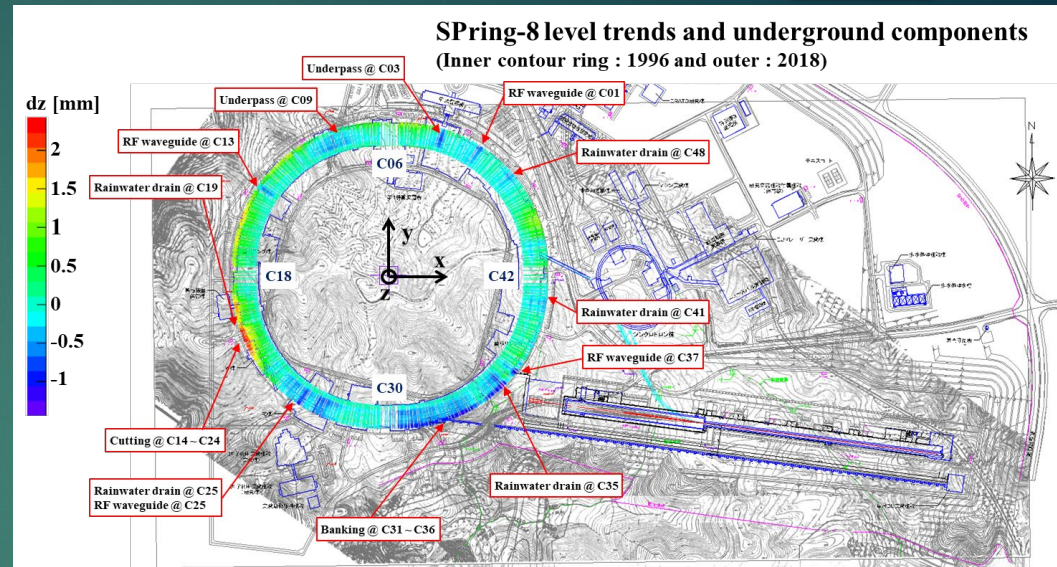
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Interpretation of the ground elevation w/ ATL-law approach

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As discussed above, ~20 years of rich survey data sets for the SPring-8 storage ring indicate -1.5 ~ 2.5 mm of ground elevation changes.



Again, sources of the ground motion:

- Earth tides

- Activity of the geologic fault

- Day/Night or seasonal changes of temperature and pressure

- And stochastic diffusive motion; random-walk or Brownian motion

In accelerator physics, B. A. Baklakov *et al.* firstly proposed ATL-law to describe the ground elevation differences $\langle dz^2 \rangle$ between 2 points separated by L over time interval T w/ a coefficient of the earth's crust characteristic A : $\langle dz^2 \rangle \approx ATL$. Then, V. D. Shiltsev intensively investigated A for various accelerator facilities.

Interpretation of the ground elevation w/ *ATL*-law approach

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Elevation change $dz(s)$ in time interval T ($T = 1, \dots, 22$)
at the designed beam orbit coordinate s & the year t of surveyed:

$$dz(s) = z(t + T, s) - z(t, s) \quad (16)$$

Now, the variance of elevation changes for distance L between 2 points:

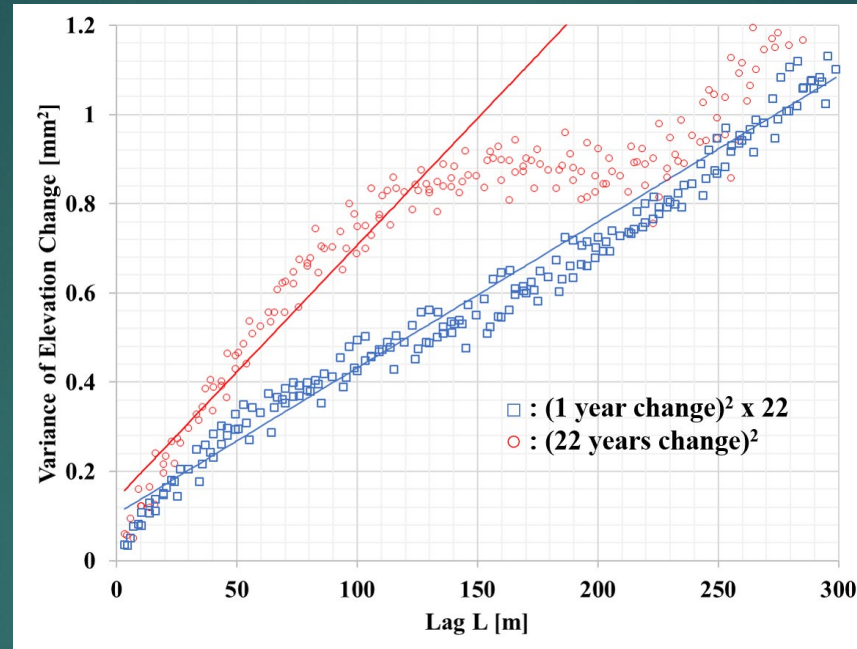
$$\langle dz^2(T, L) \rangle = \frac{1}{M} \sum_M \frac{1}{N} \sum_N \{dz(T, s + L) - dz(T, s)\}^2 \quad (17)$$

M : pairs of the time interval T

N : pairs of points of circumference distanced by L

Interpretation of the ground elevation w/ ATL-law approach

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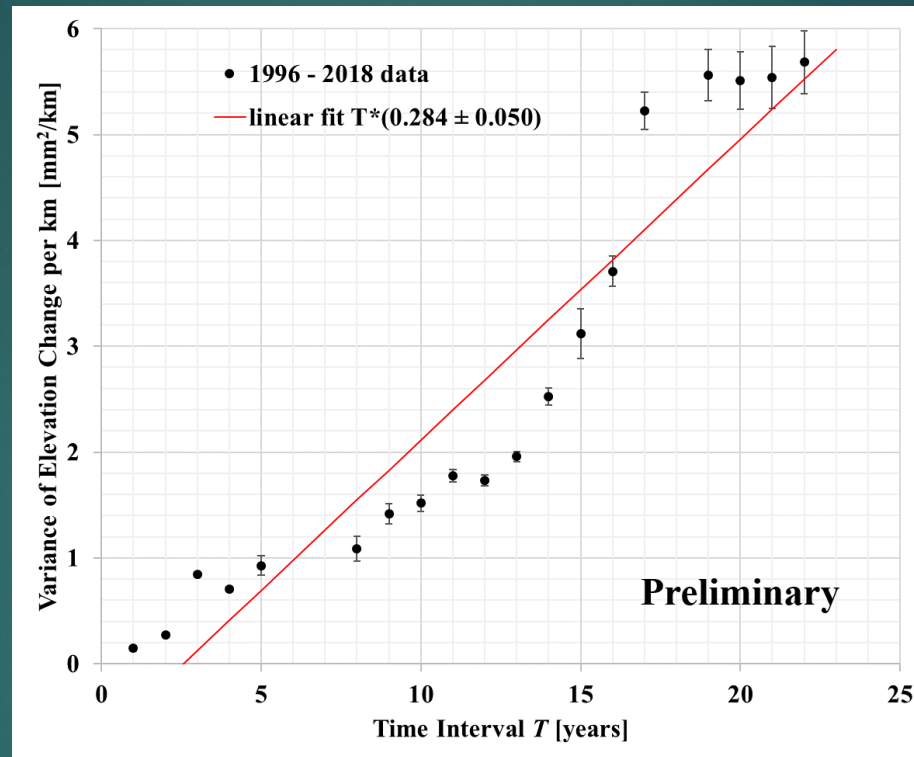
Gradient change is considered to be systematic, i.e., not-random changes, such as continuous lift up or damping at ground construction areas.

Such systematic changes should be excluded from data & further investigations are under go.

Gradients of the variance of elevation changes for each time interval are evaluated by fitting up to $L \sim 150$ m.

Interpretation of the ground elevation w/ *ATL*-law approach

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Evaluated coefficient of the ground crust characteristic @ SPring-8:
 $A_{\text{SPring-8}} = (9.0 \pm 1.5) \times 10^{-6} \mu\text{m}^2/\text{s}/\text{m}$ (Preliminary)

Interpretation of the ground elevation w/ ATL-law approach

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Courtesy of V. Shitsev

Tevatron Collider data		$A, [10^{-6} (\mu\text{m}^2/\text{s})/\text{m}]$	Time	Scale
“Tie-rods” (V)	L, T	4.9 ± 0.1	1–6 yr	6.3 km
20 HLS system	L, T	2.2 ± 1.2	1 week	600 m
Beam orbit (V)	T	2.6 ± 0.3	15 h	6.3 km
(H)	T	1.8 ± 0.2	15 h	6.3 km
Beam orbit drifts in other accelerators				
HERA- e (V)	T	4 ± 2	25 d	6.3 km
HERA- p (V)	T	8 ± 4	5 d	6.3 km
TRISTAN (V)	T	27 ± 7	2 d	3.0 km
Circmf. KEKB	T	27 ± 3	4 months	3.0 km
LEP (V)	T	10.9 ± 6.8	18 h	26.7 km
LEP (V)	T	39 ± 23	3.3 h	26.7 km
(H)	T	32 ± 19	3.3 h	26.7 km
SPS (V)	T	6.3 ± 3.0	2 hr	6.9 km
Accelerator alignment/survey data analysis				
CERN LEP (V)	L, T	6.8–9.0	6, 9 months	26.7 km
		3 ± 0.6	6 yr	26.7 km
CERN SPS (V)	L, T	14 ± 5	3–12 yr	6.9 km
Ground motion studies data				
PFO (CA, USA)	T	0.7	5 yr	732 m
SLAC Linac (V)	T	1.4 ± 0.2	0.5 hr	3 km
Esashi (Japan)	T	0.3–0.5	15 yr	50 m
Sazare (Japan)	T	0.01–0.12	6 weeks	48 m
KEKB tunnel	T	40	4 d	42 m
FNAL PW7	T	6.4 ± 3.6	3 months	180 m
FNAL MINOS	L, T	0.18	1 month	90 m
Aurora mine	L, T	0.6 ± 0.3	2 weeks	210 m

$$A_{SPring-8} = (9.0 \pm 1.5) \times 10^{-6} \mu\text{m}^2/\text{s}/\text{m}$$

1.

Alignment errors for neighboring 2 common girders designed as the SPring-8-II configuration is calculated and confirmed to satisfy required allowable errors via a 2D network analysis.

Conventional alignment and survey methods are assumed for the analysis. Numbers and orientation of observation points on the tunnel wall are still under optimizing to improve errors.

2.

Necessity of realignment of the SPring-8-II components are discussed based on the existing SPring-8 survey data measured over ~20 years. Realignment will be required within at most 2 years.

3.

Variance of elevation changes for the SPring-8 are discussed applying the empirical *ATL*-law with rich statistics. The coefficient to characterize the earth's crust is also estimated. Further investigation for systematic effects is in progress.