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Straightness evaluation for the 206-m-long part of the KEK electron/positron linac using inclinometers

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Target

Evaluate aligning straightness of linear particle accelerators (Linacs) for distance of several 100 m with accuracy of better than 1 mm

Contents

1. Introduction
   - •Straightness evaluation using an inclinometer

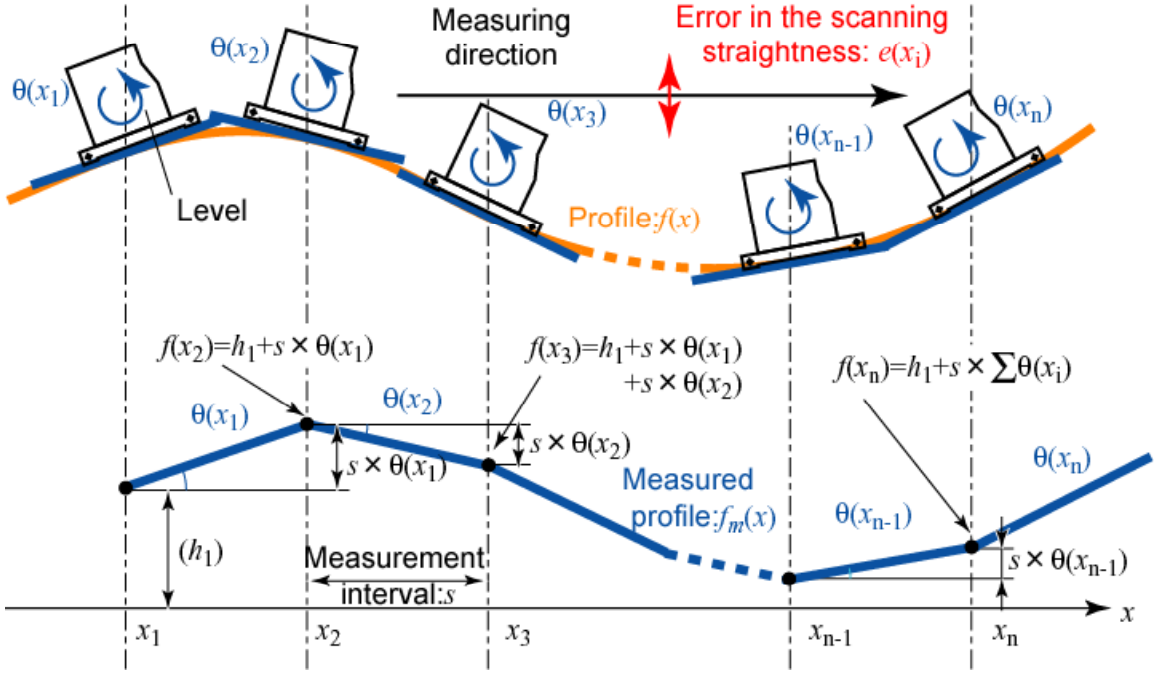
2. Demonstration
   - 71-m-long (single accelerator sector) straightness evaluation with a straight bar
   - 206-m-long (multi accelerator sectors) straightness evaluation with a straight bar and offset bars

3. Conclusion

Straightness evaluation using an inclinometer

Not affected by transferring locus (= error in the scanning straightness)

⇒ Advantageous for long distance evaluation



Straightness:

$$f(x_n) = h_1 + s \times \sum_{i=1}^{n-1} \theta(x_i)$$

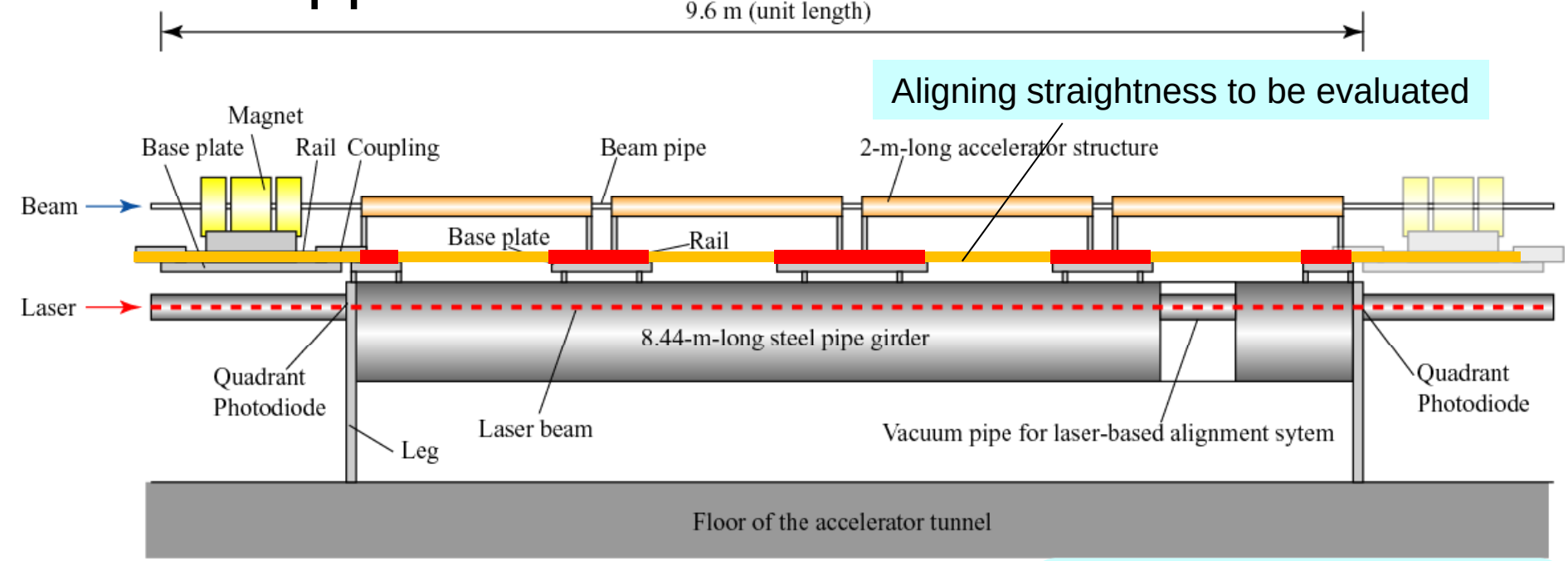
h_1:Arbitrary straightness of the start point,
s_i: Sampling interval, (s_i=s)
$\theta(x_i)$: Measured tangential angle,
n: Number of measurements

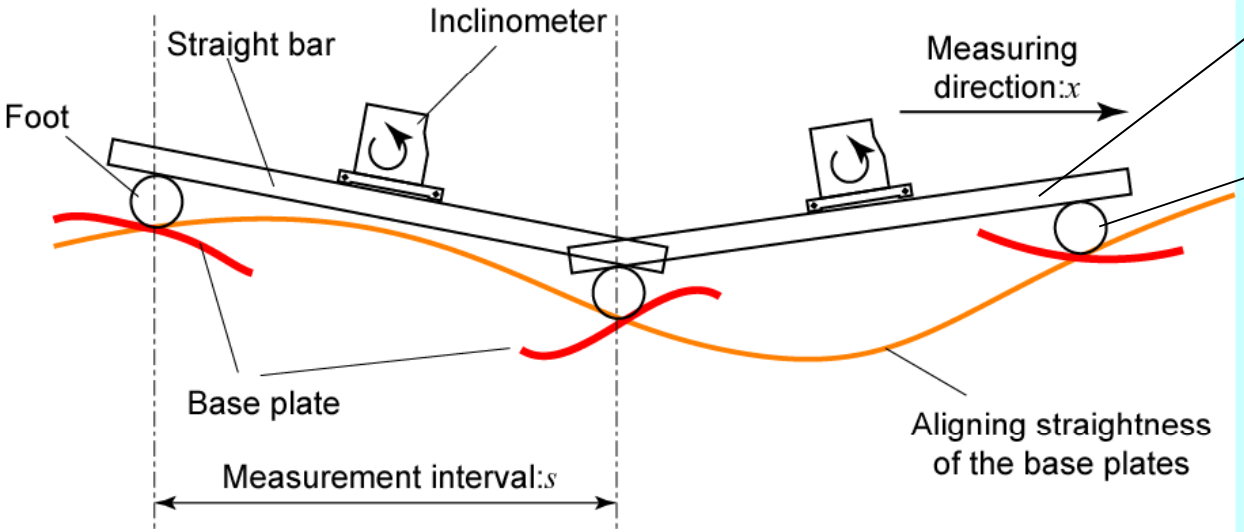
Error propagated to the straightness: $\sigma_f = \sqrt{\sigma_s^2 \cdot \sum_{i=1}^{n} \{\theta(x_i)\}^2 + \sigma_\theta^2 \cdot \sum_{i=1}^{n} s_i^2}$

$\approx \sqrt{s \cdot l} \cdot \sigma_\theta$ (In case $\theta(x_i) \fallingdotseq 0$ ⇒quasi-straight object)

σ_s: Error in the sampling interval: s_i,
σ_θ: Error in the measured tangential angle,
l: Measurement distance, (l=$s\times n$)

Application to the KEK e^-/e^+ Linac





Straight bar
⇒Ensures continuity of aligning straightness

Contact foot
⇒Reduces affect of plate shape and roughness

- Spatial low pass filter
- Reduce affects of positioning error in evaluation

Gravity referenced precise electric inclinometer (Talyvel 4)

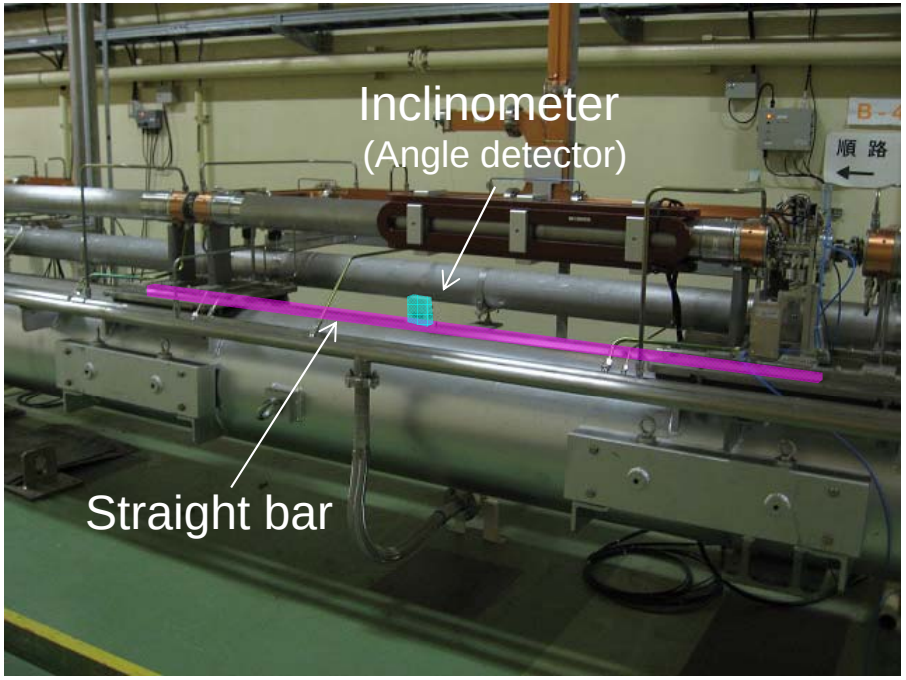
Angle detector

Controller

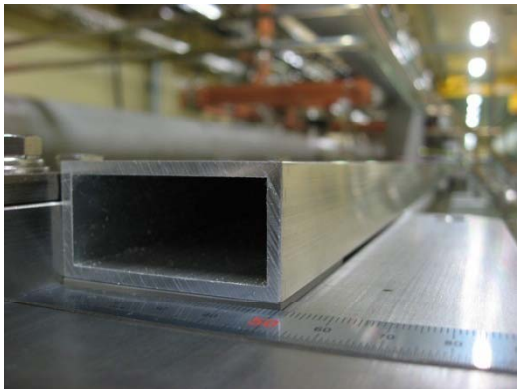
- Range: ±3 mrad (±600 sec),
- Resolution: 0.5 μrad (0.1 sec),
- Accuracy: 0.2 sec±3%-definition

【 Acknowledgement 】
Authors thank Yukinori Kobayashi and members of the Accelerator Division 7 in Accelerator Laboratory in KEK and Masahiro Katoh of Institute of Molecular Science for providing us Talyvel 4.

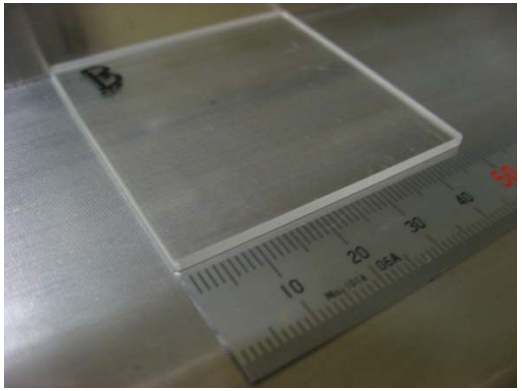
Straightness evaluation for the KEK e^-/e^+ Linac using an inclinometer and a straight bar



Straight bar made of 3-mm-tick Al rectangular pipe (1990~2306-mm-long, 50-mm-wide, and 25-mm-high)



Cross-section of the straight bar

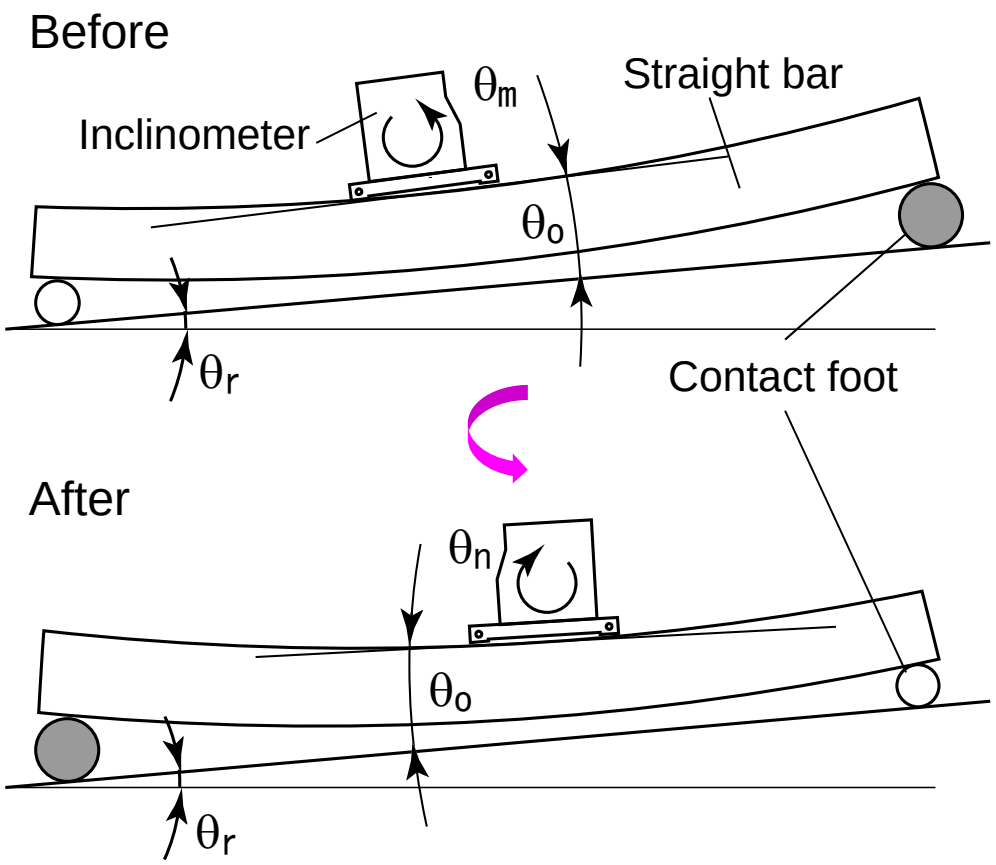


Foot made of 2-mm-tick glass plate (=optical parallel- λ = 633 nm) with area of 50 × 50 mm

Reversal measurement

Eliminate offset of the angle measurement system

(= Inclinometer + Straight bar + Pair of contact feet)



Offset of the system: θ_o caused by

Offset of the inclinometer,

Shape error of the bar

(including the height difference between the pair of the contact feet),

Deformation of the bar

can be eliminated by

$$\theta_r = (\theta_m - \theta_n)/2$$

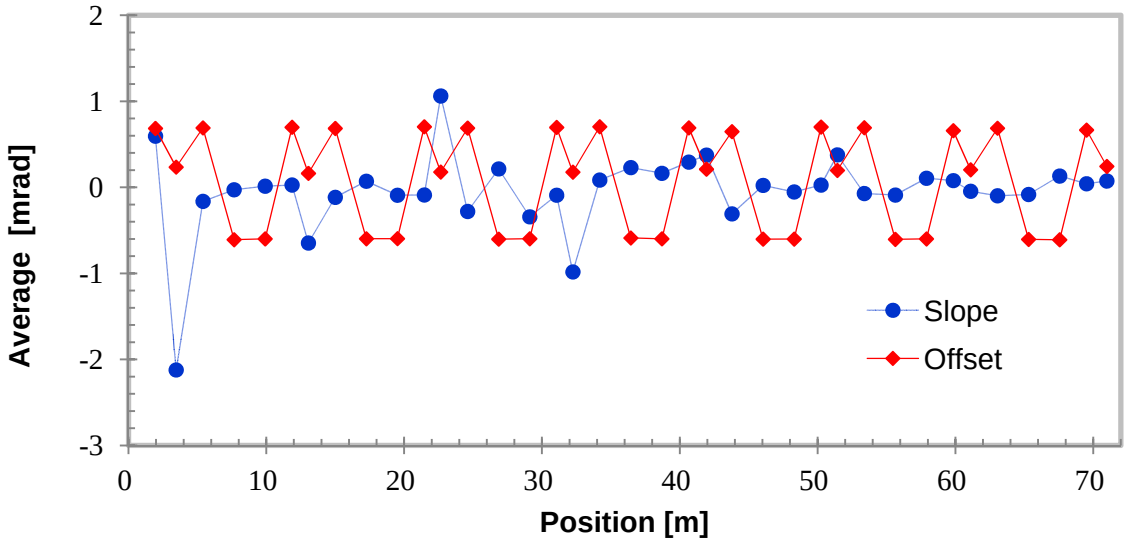
θ_r, :Angle to be measured,

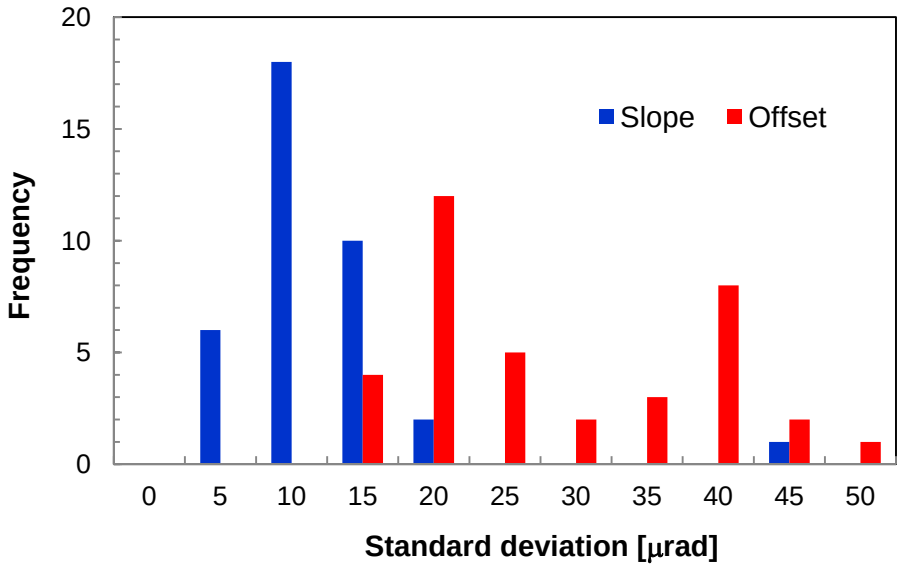
θ_o :Offset of the system,

$\theta_m = \theta_r + \theta_0$:Measurement before reverse,

$\theta_n = -\theta_r + \theta_0$:Measurement after reverse

Effect of the reversal measurements





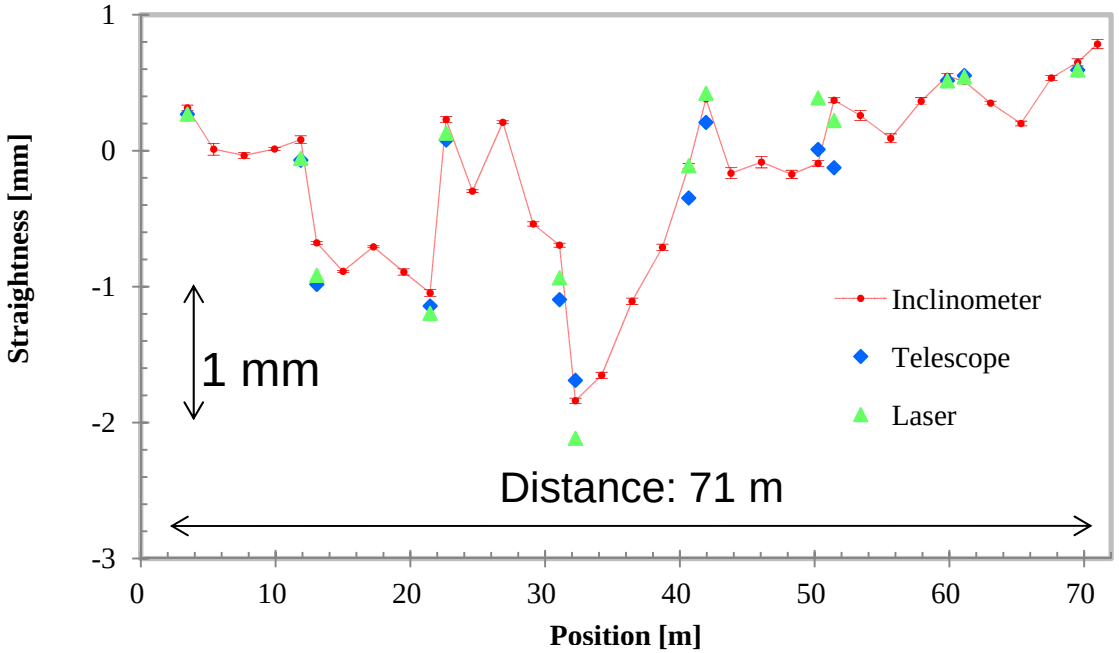
The offset angles: θ_0
is comparable to
the slope angles: θ_r .

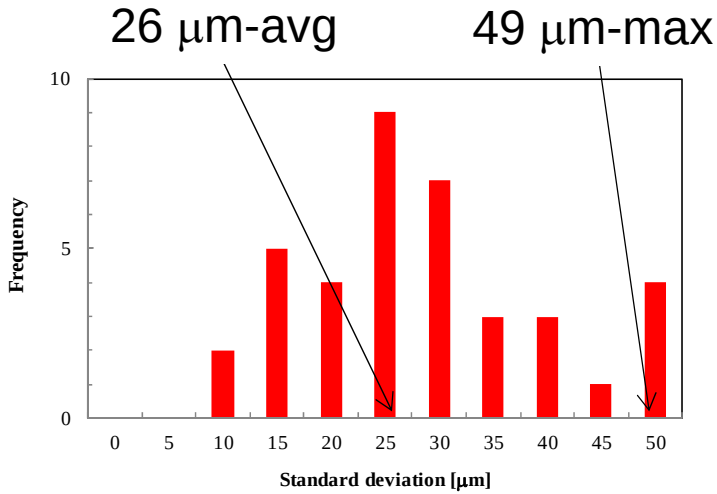
Offsets must be eliminated

Standard deviations of the slope angles
are smaller than those of the offset angles

Fluctuations of the offset angles (⇒drift) are also reduced.

Evaluation results for the 71-m-long part of the sector C





Histogram of the standard deviations for each position

Comparison between the other methods,

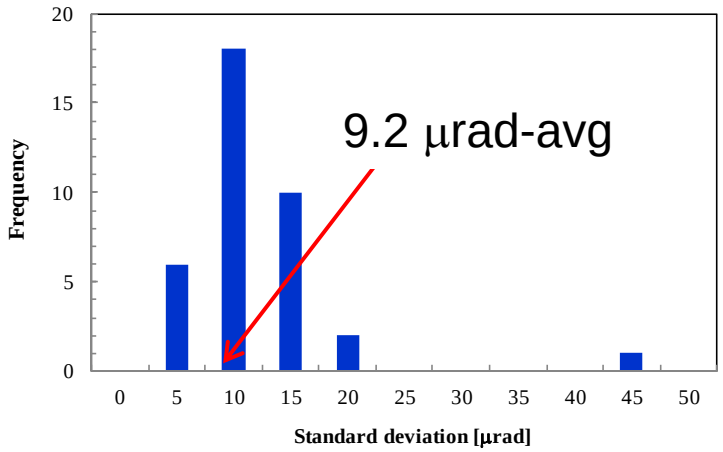
"Laser" stands for the results by our laser alignment system

- Agreed with the two results within sub-mm.
- Straightness can be evaluated with standard deviations of 26 μm-avg, and 49 μm-max.

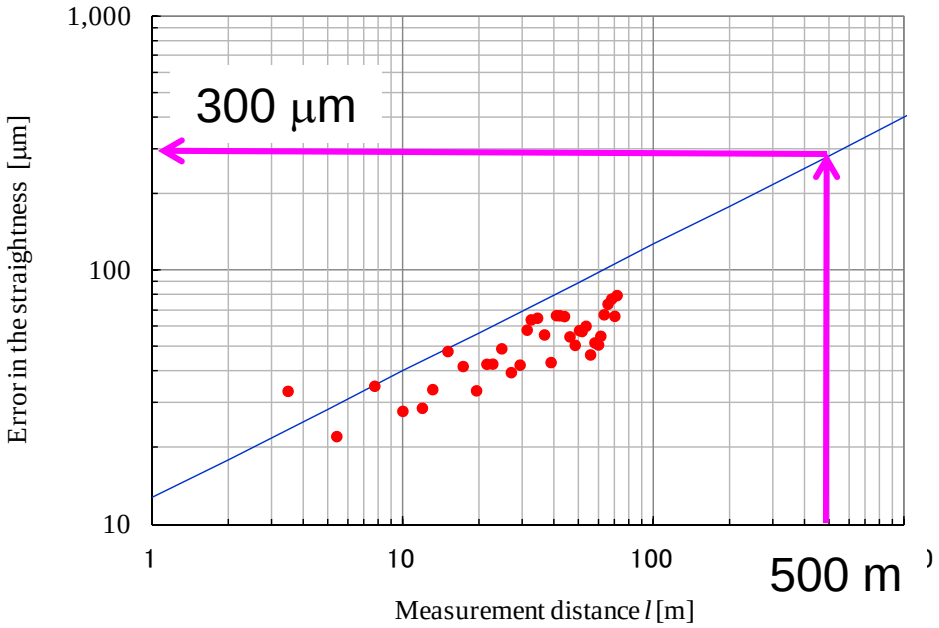
*The earth curvature was compensated considering the earth as a sphere with a radius of 6371 km for the result by the inclinometer.

Error estimation

- 0.6 mm-2σ for 500 m ⇒Can be adopted for evaluating the KEK linac



Histogram of the standard deviations for the derived slope angles



Error propagated to the straightness -experimental and estimated value.

Error propagated to the straightness:

$$\sigma_f = \sqrt{s \cdot l} \cdot \sigma_\theta$$

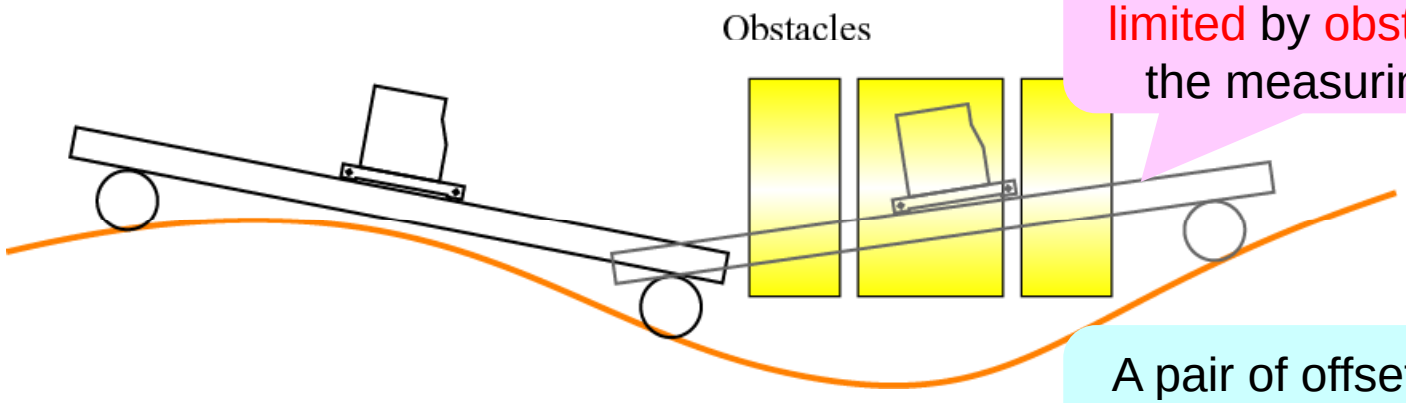
l: Measurement distance,
s: Sampling interval ⇒ 1.9 m-avg,
σ_θ: Error in the obtained angle
⇒ 9.2 μrad-avg

- The experimental value agrees well with the estimated one.

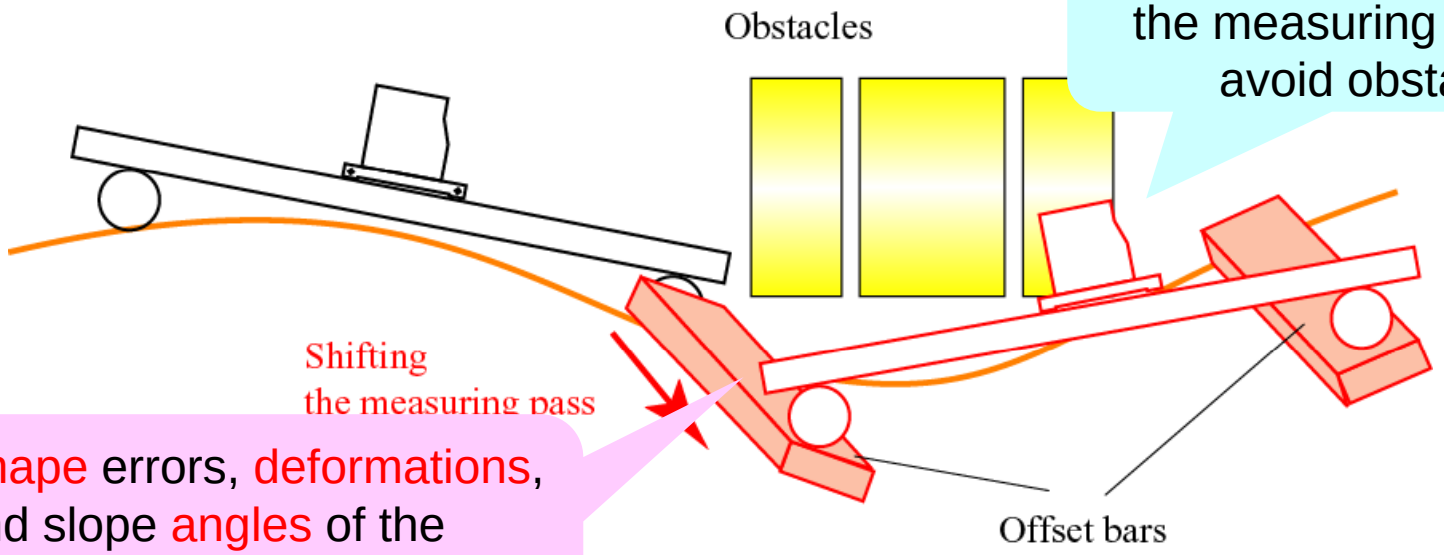
The estimated value is reliable.

Offset bars for avoiding obstacles on the measuring pass

Evaluation distance is limited by obstacles on the measuring path

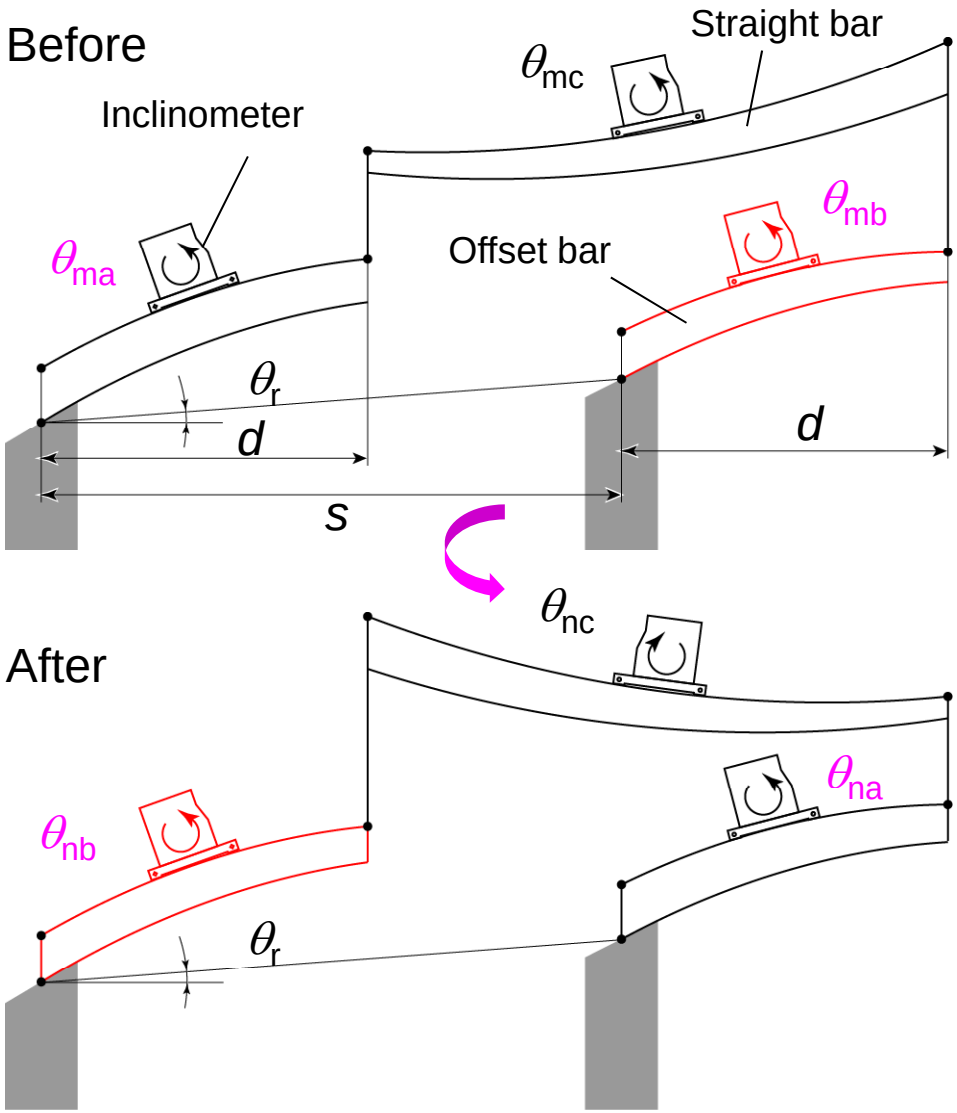


A pair of offset bars shifts the measuring path and avoid obstacles



Shape errors, deformations, and slope angles of the offset bars will affect the measurements

Reversal measurement considering slope angles of the offset bars



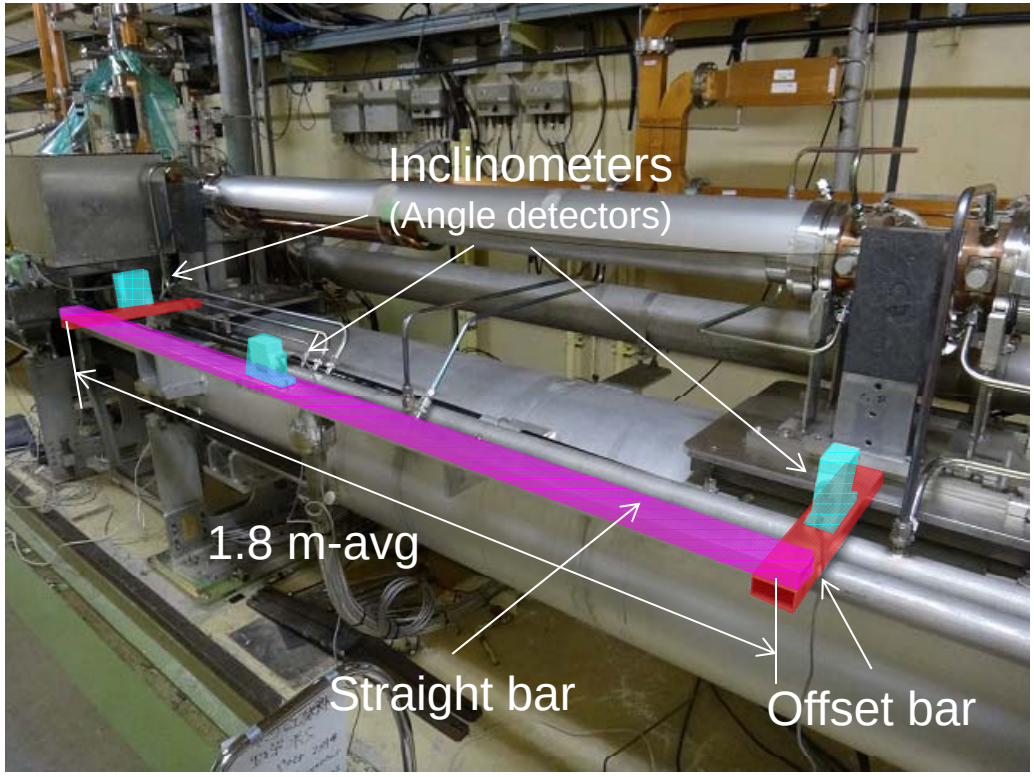
Offset of the system caused by
Offsets of the inclinometers,
Shape errors of the bars,
Deformations and slopes of the bars

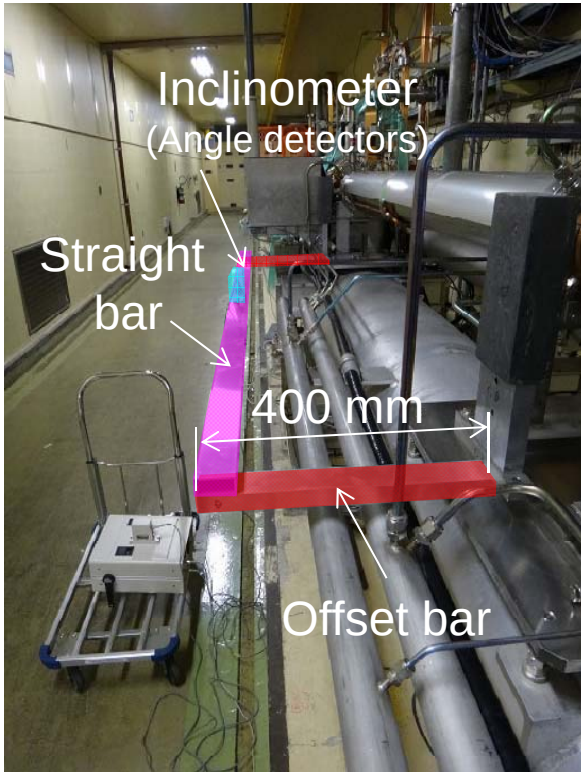
can be eliminated by

$$\theta_r = \frac{\theta_{mc} - \theta_{nc}}{2} - \frac{d\{(\theta_{mb} - \theta_{ma}) + (\theta_{na} - \theta_{nb})\}}{2s}$$

θ_t: Slope angle (angle to be measured),
θ_{ma}, θ_{mb}, θ_{mc}: Measurements before reverse,
θ_{na}, θ_{nb}, θ_{nc}: Measurement after reverse,
d: Length of the offset bars,
s: Length of the straight bar

Straightness evaluation for the KEK e^-/e^+ Linac using a pair of offset bars





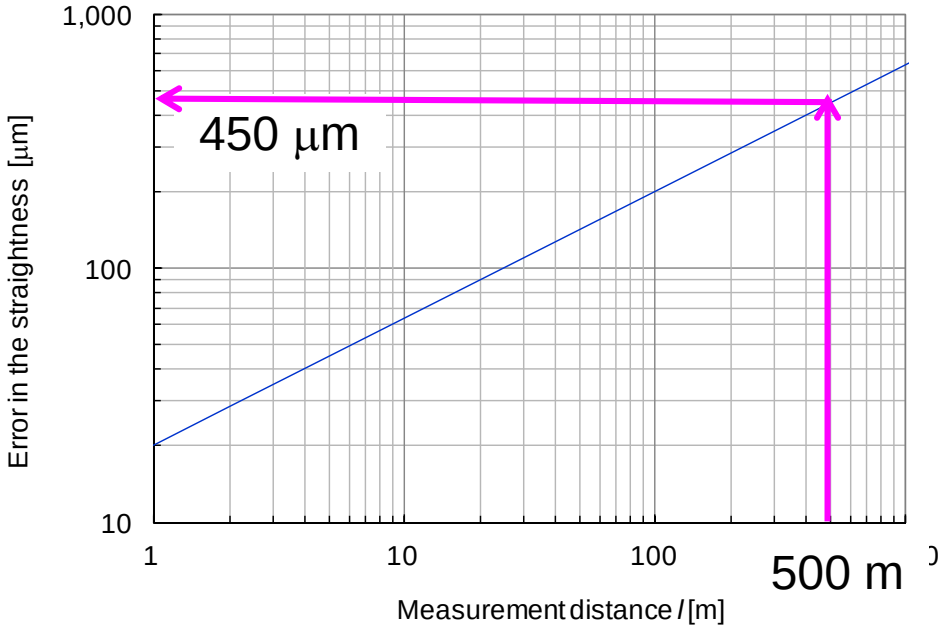
Deviation of the derived slope angle and Error estimation

- 0.9 mm-2σ for 500 m ⇒Can be adopted for evaluating the KEK linac

Error propagated to the straightness:

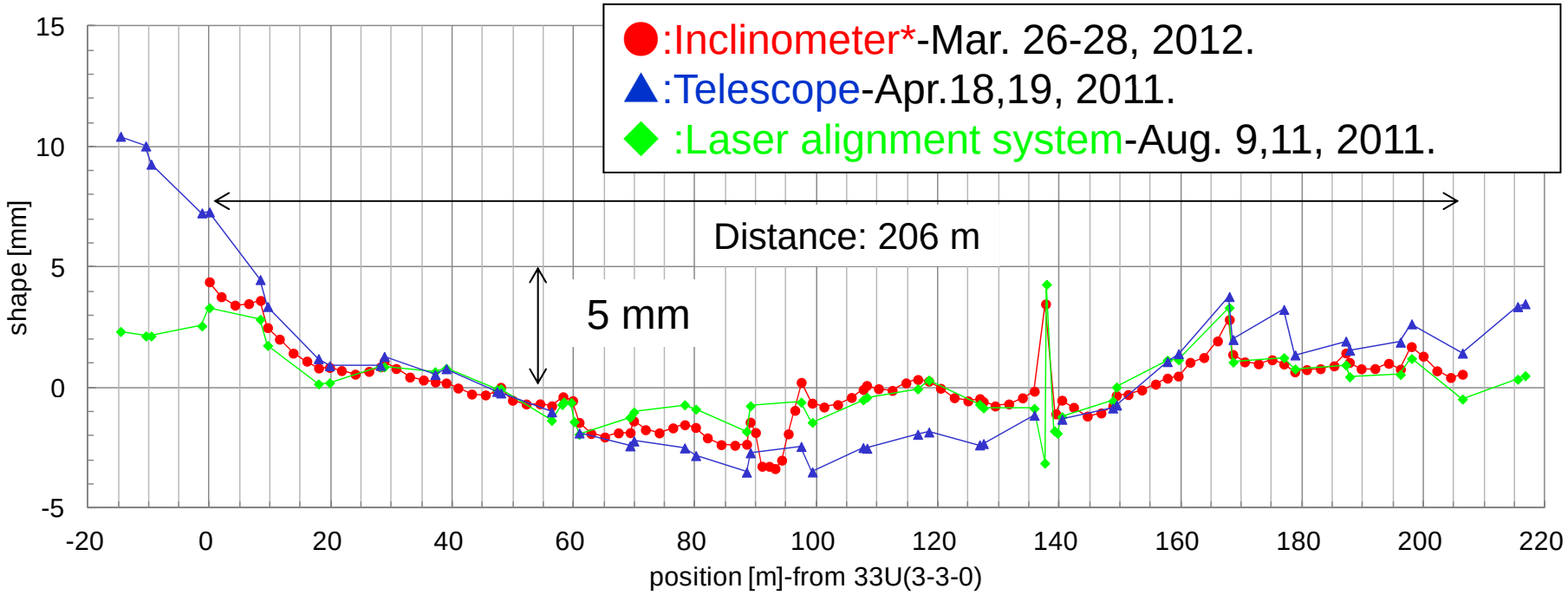
$$\sigma_f = \sqrt{s \cdot l} \cdot \sigma_\theta$$

l: Measurement distance,
s: Sampling interval ⇒ 1.8 m-avg,
σ_θ: Error in the obtained angle
⇒ 15 μrad for single measurement point



Error propagated to the straightness -estimated value.

Straightness evaluation for the 206-m-long part of the KEK e^-/e^+ linac



- Similar trend.
- Partly agreed within sub-mm range.

Fairly reliable with each other

*The earth curvature was compensated considering the earth as a sphere with a radius of 6371 km.

Conclusion

1. Reversal measurement is effective for eliminating offset and reducing drift of the angle measurement system.

2. Obstacles on the measuring path can be avoided by pair of offset bars. It can extend evaluation distance of the system.

3. By considering slope angles of the offset bars, affects of the shape errors, deformations, and slopes of the offset bars can be eliminated.

4. 206-m-long straightness evaluation of the KEK e^-/e^+ Linac was demonstrated with standard deviation of 15 μrad for the derived slope angles.

5. It is applicable for evaluating the whole 500-m-long KEK e^-/e^+ Linac with 2σ of better than 1 mm.

Issues

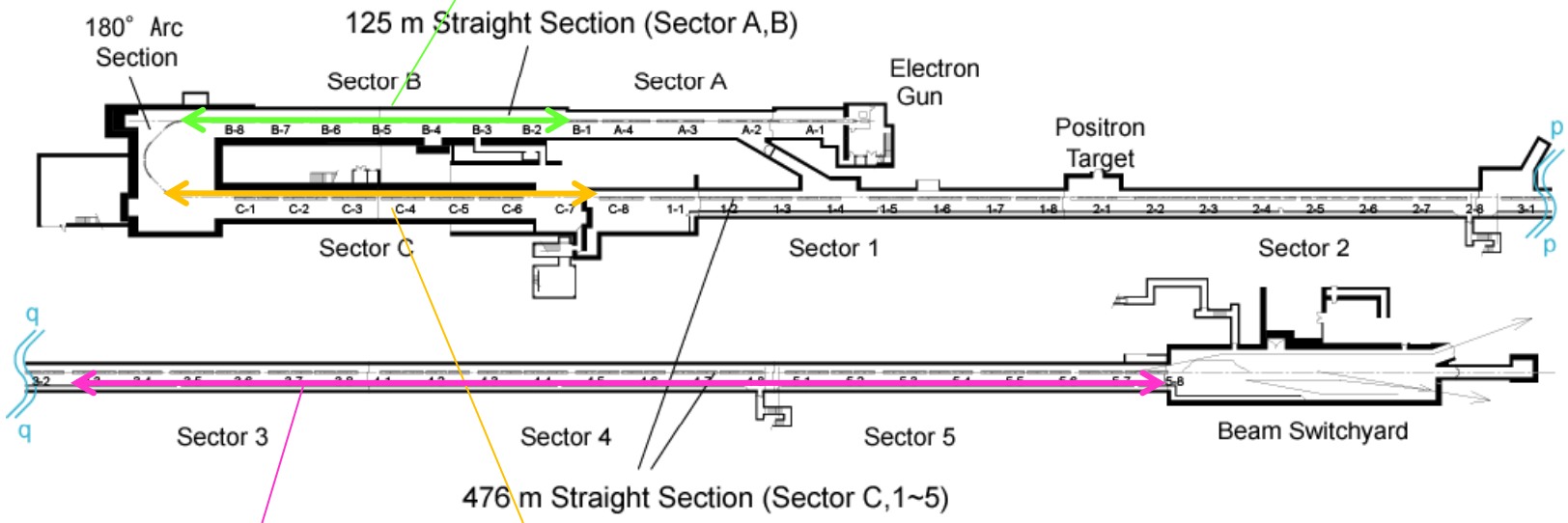
1. Demonstrate longer (500 m or longer) straightness measurement

2. Estimate/evaluate the system's performance precisely for longer measurement distance.

3. Consider/realize horizontal straightness evaluation method
   (Straightness in the horizontal plane)

Straightness measurement using inclinometers adopted for the KEK e^-/e^+ linac

69-m-long part of the Sector B, (Aug. 25-28, 2009)



71-m-long part of the Sector C, (Mar. 29-31, 2010)

206-m-long part for the longer straight section (Mar. 26-8, 2012)