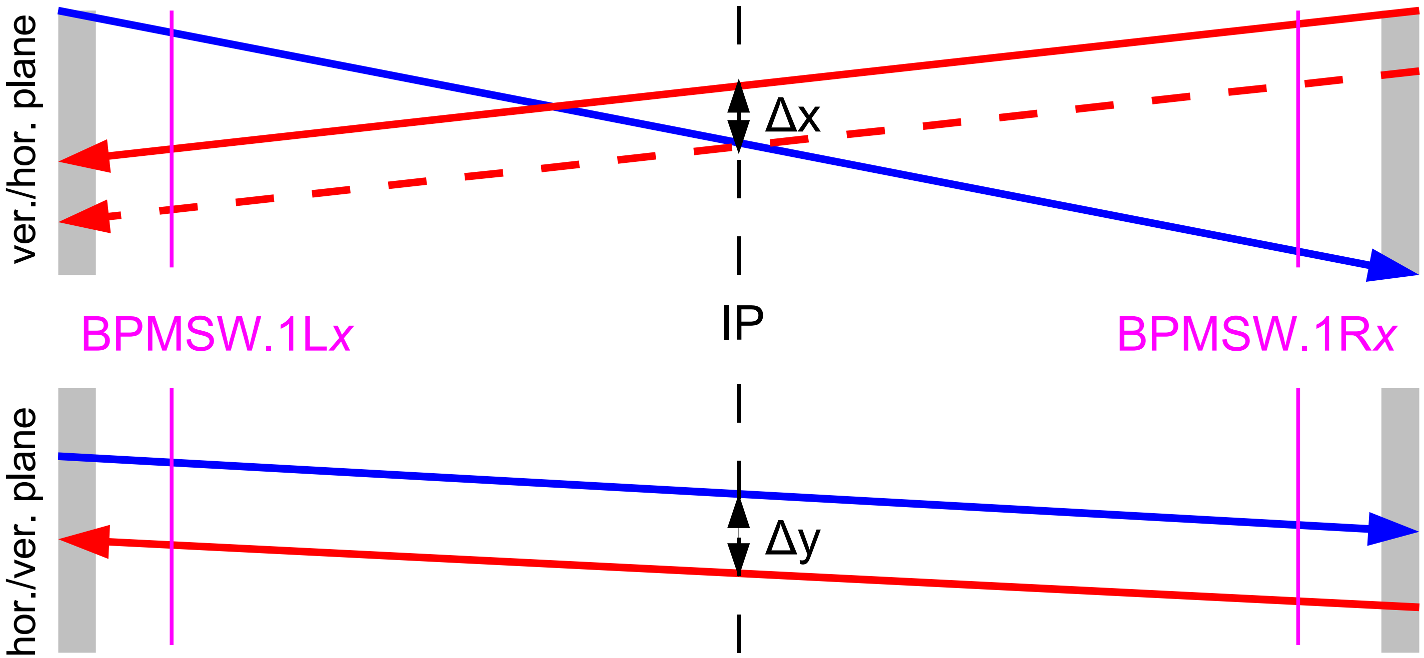
An accelerator perspective on:

LHC Interaction Point Stability
or
“How well do we know the beam line”

Ralph J. Steinhagen

$$L = L_0 \cdot e^{-\frac{1}{4}\left[\left(\frac{\Delta x}{\sigma_x}\right)^2 + \left(\frac{\Delta y}{\sigma_y}\right)^2\right]} \cdot F_{crossing} \cdot F_{hour\ glass} \cdot \ldots$$

- Effective beam overlap:

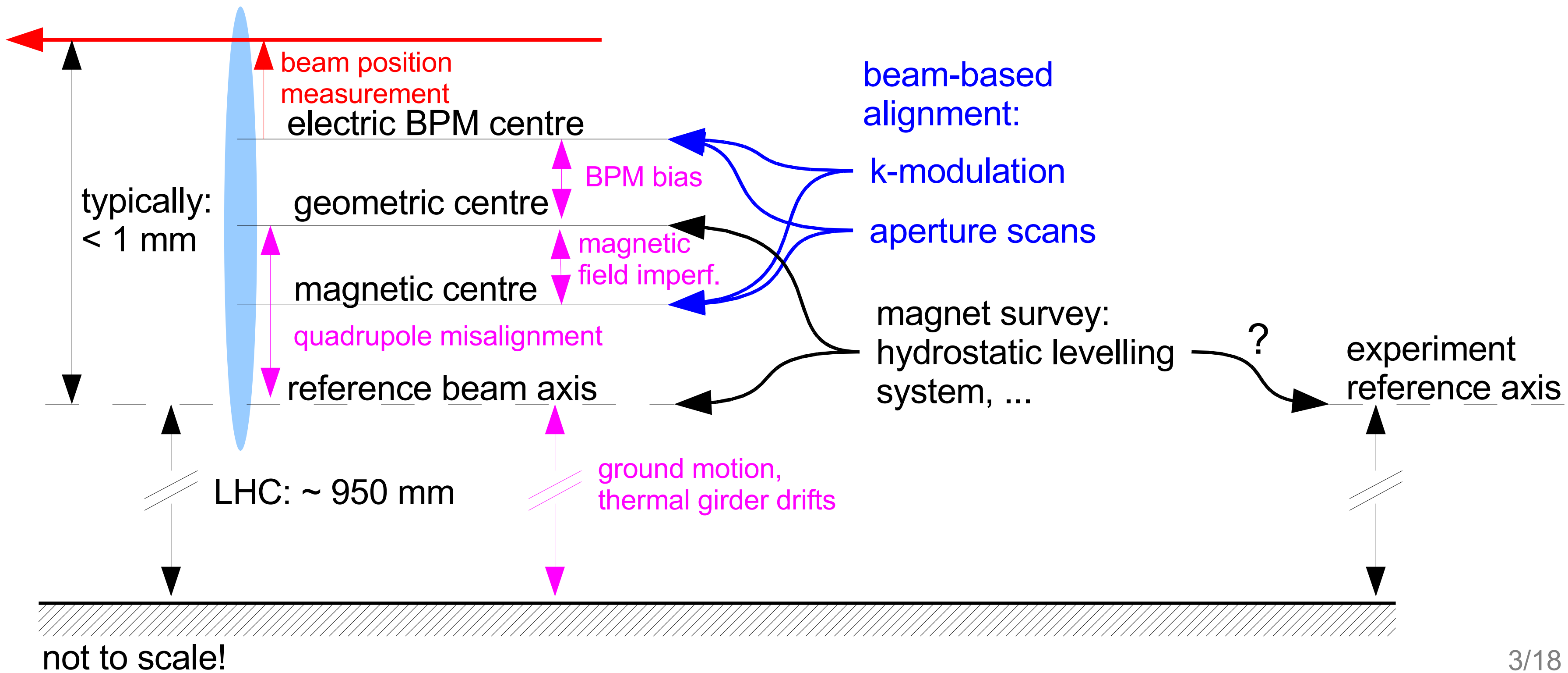


Δx/Δy [σ]	L/L_0 [%]
0	100
0.5	≈ 94
1	≈ 79
2	≈ 37
3	≈ 11
4	≈ 2

- geometric optics: beam overlap at IP ↔ beam position stability at BPMSW
  – nominal: $\sigma^* \approx 15$ µm, e.g. 1σ overlap at IP → 15 µm stability at BPMSW
- N.B. nom. crossing angle "guarantees" one plane overlap (long. shift « 20 µm)

Alignment Reference System Definition

- Beam stability analysis depends on the choice of reference system:
  - beam position measurements (different for B1 & B2!)
  - magnetic quadrupole centre (minimising feed-down effects)
  - geometric quadrupole centre (maintaining aperture constraints)
  - external reference
- Some definitions:

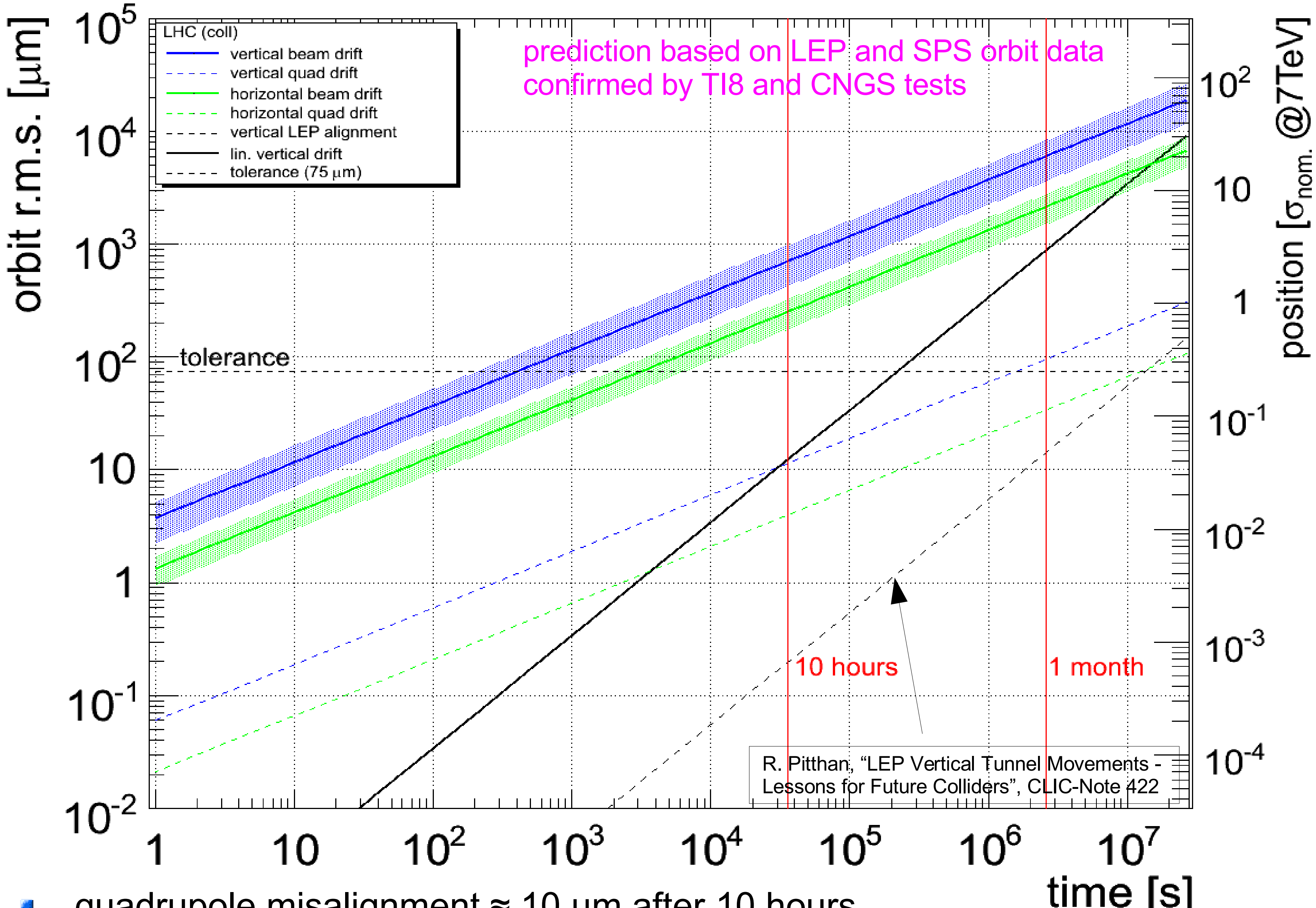


Some “known” static uncertainties

- Beam Position Measurement:
  - electrical BPM bias: 100 µm r.m.s.
  - electrical BPM centre w.r.t. geometric quad. centre: 200 µm r.m.s.
    - after aperture scan: < 50-100 µm r.m.s.
  - electrical BPM centre w.r.t. geometric quad. centre: 200 µm r.m.s.
    - after k-modulation: < 50 (5?) µm

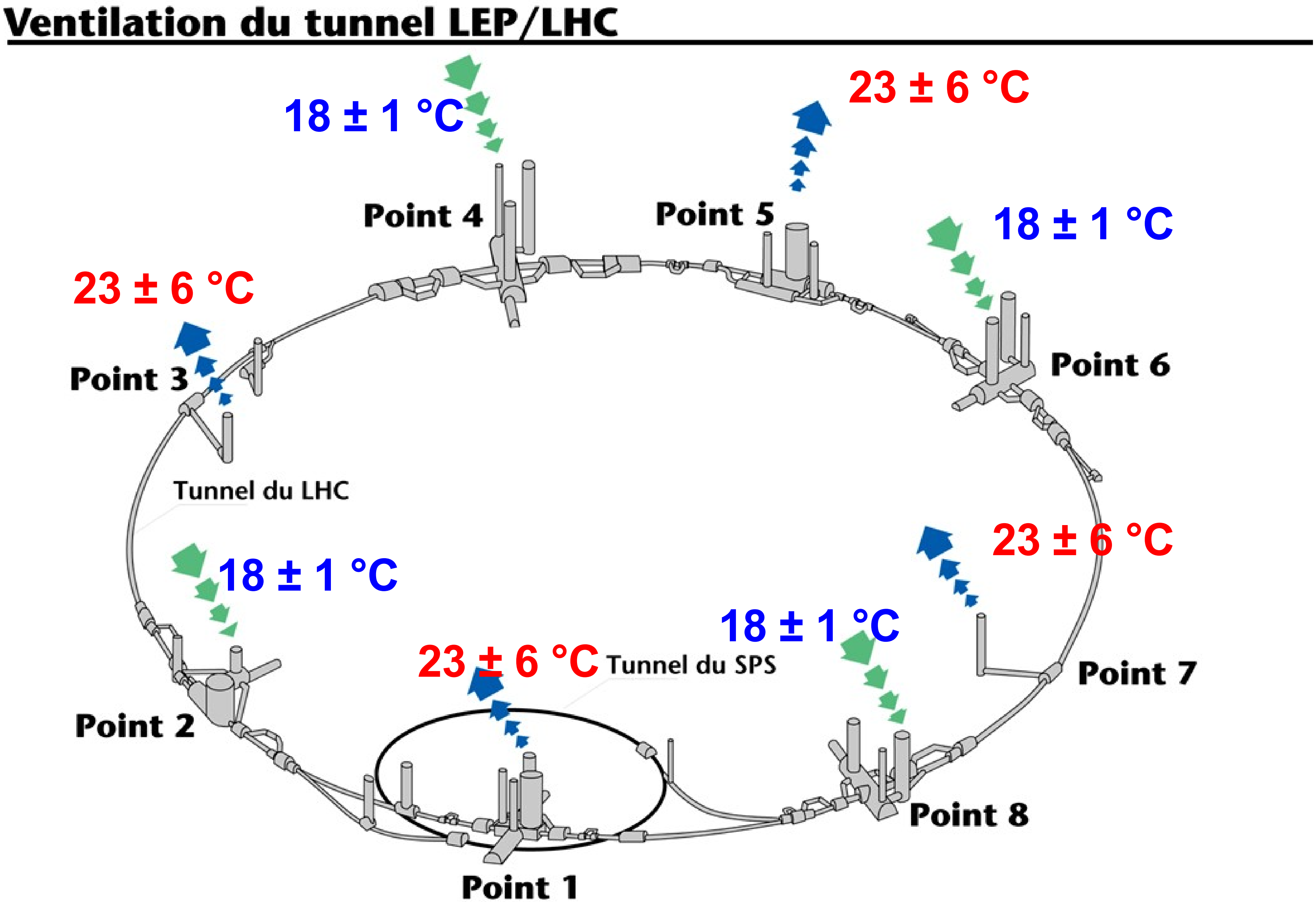
- Survey group targets for magnet alignment:
  - 0.2 mm r.m.s. globally
  - 0.1 mm r.m.s. as an average over 10 neighbouring magnets
  - N.B. Orbit FB: working assumption: 0.5 mm r.m.s.
  - Watch out: CLIC-Note-422, CERN-THESIS-2001-010
    → final focus stability might be determined by systematic drifts

Micron Stability of the Triplet Installation in the Presence of Ground Motion and Thermal Drifts



- quadrupole misalignment ≈ 10 μm after 10 hours
  → closed orbit drifts (coll. optics) ≈ 1-3 σ

Thermal Expansion of Girders



Thermal Expansion of Girders

- Mechanism: Orbit feedback intrinsically aligns with respect to the BPMs that are either attached to the quadrupoles or have similar girders
- Thermal expansion, steel $\alpha_{steel} \approx 10\text{-}17 \cdot 10^{-6}\,K^{-1}$ (BS:970, DIN18800):

$$\Delta x = x_0 \cdot \alpha \cdot \Delta T$$

- Systematic shift of beam reference system with respect to non-moving external reference (e.g. potentially collimators):
  - Cryo-Magnets: $x_0 \geq (340 \pm 20)$ mm → $\Delta x \approx 3.4$ - 5.8 μm/°C
  - Warm equipment: $x_0 \approx 950$ mm → $\Delta x \approx 9.5 – 16$ μm/°C
- The inlet temperature is stabilised to about ±1°C
  - temperature changes shouldn't pose a problem for even IRs

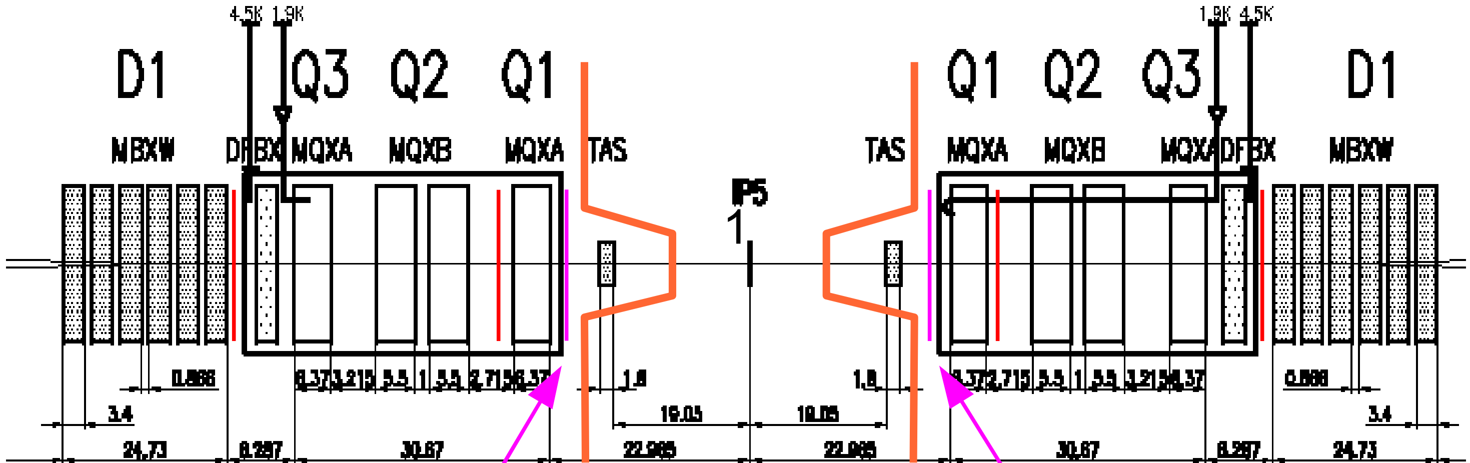
Thermal Expansion of Girders - Experimental Insertions

- Left-Right temperature gradient:

tunnel air: $T_1 \approx 23 \pm 6$ °C

cavern: $T_3 \approx 23 \pm 6$ °C (?)

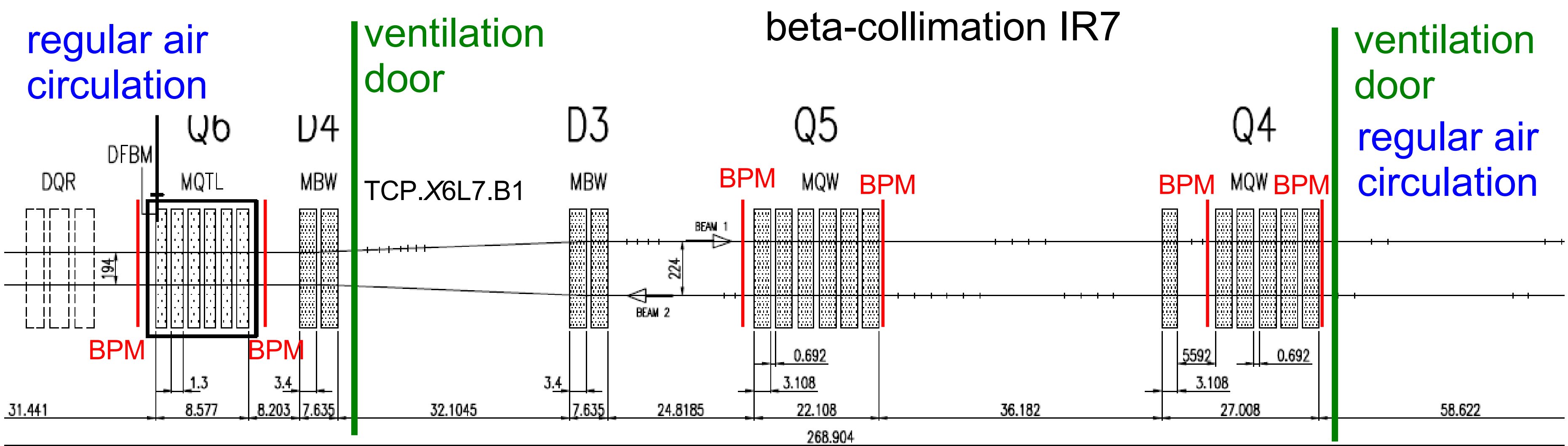
tunnel right: $T_2 \approx 23 \pm 6$ °C



- $T_1 \neq T_2 \neq T_3$
  - powering of arc equipment (CODs, ...) → dyn. heat-load asymmetry
  - IR4 (RF, BI) → IP5 ← IR6 (beam extraction)
- Working assumption: $\Delta T = |T_2 - T_1| \approx \pm 1...2$ °C → $\Delta x_{thermal} \approx 16\text{-}32$ µm

Thermal Expansion of Girders - Cleaning Insertions

- However, temperature variations in odd IRs might be larger due to different thermal loads in neighbouring arcs.
- Special case: Collimation in IR7



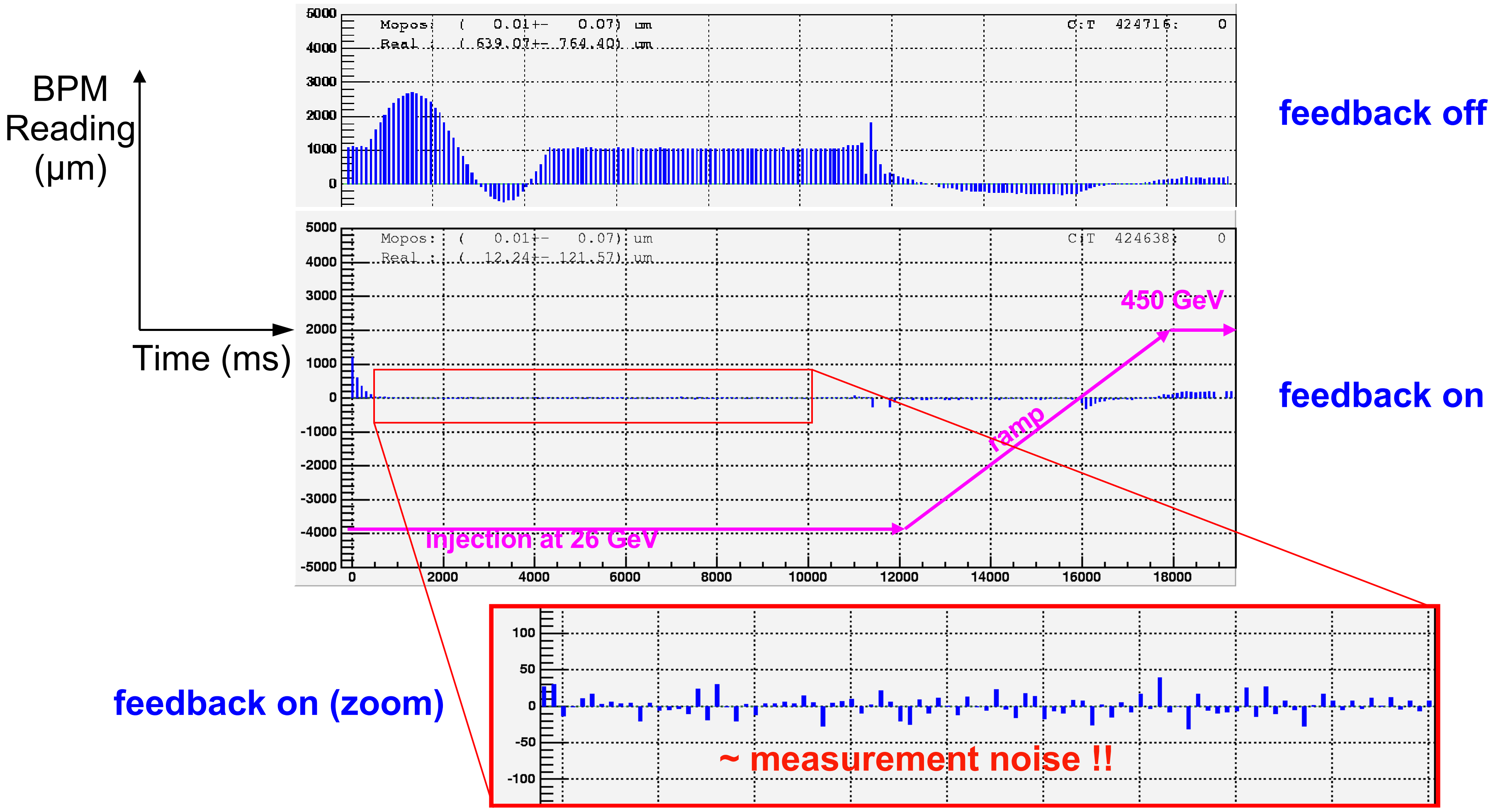
- Closed air circulation in IR7: T estimate as high as 35°C
- Already $\Delta T = \pm 2°C \rightarrow \Delta x \approx \pm 20$ µm, Collimation: ± 50 µm might be tolerable
  (TOTEM 10 µm requirements – a midnight summer dream?)
- CNGS/Ti8: Estimates where ≈ 10°C off (measured 25°C vs. estimated 35°C)
- Wait for LHC commissioning with beam and real temperature experience

Summary

- *Mike: "How well do you (we) know the beamline at the interaction point?"*
  - without beam-based alignment: Δx ≈ 300-600 μm r.m.s.
    - for details: LHC Collimation WG Meeting #79
  - with beam-based alignment: Δx ≈ 5 μm r.m.s.
    - after k-modulation, Lumi-scans (my "guess")
- *Mike: "Will it change within a run or to the next run/fill?"* - Yes
  - stability without orbit feedback but "perfect" feed-forward of last cycle Δx ≈ 300 – 600 μm r.m.s.
    - for details: LHC Collimation WG Meeting #79
  - stability with orbit feedback:
    - w.r.t. geometric cold quad. centre: Δx ≈ 5-7 μm r.m.s.
      - assumes nominal FB operation
    - w.r.t. geometric warm quad. centre: Δx ≈ 20-30 μm r.m.s.
      - limited by thermal gradients
    - w.r.t. ext. reference (e.g. CMS detector): Δx ≈ 30-50 μm r.m.s.
      - limited by ground motion and thermal drifts
  - Numbers assume perfect fill-to-fill beam parameters reproducibility
  - does not include long-term BPM stability: → I will verify this issue!

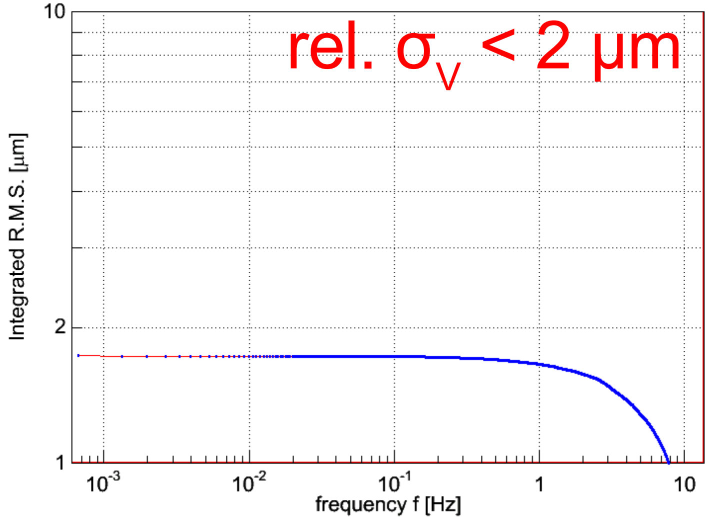
Reserve Slides

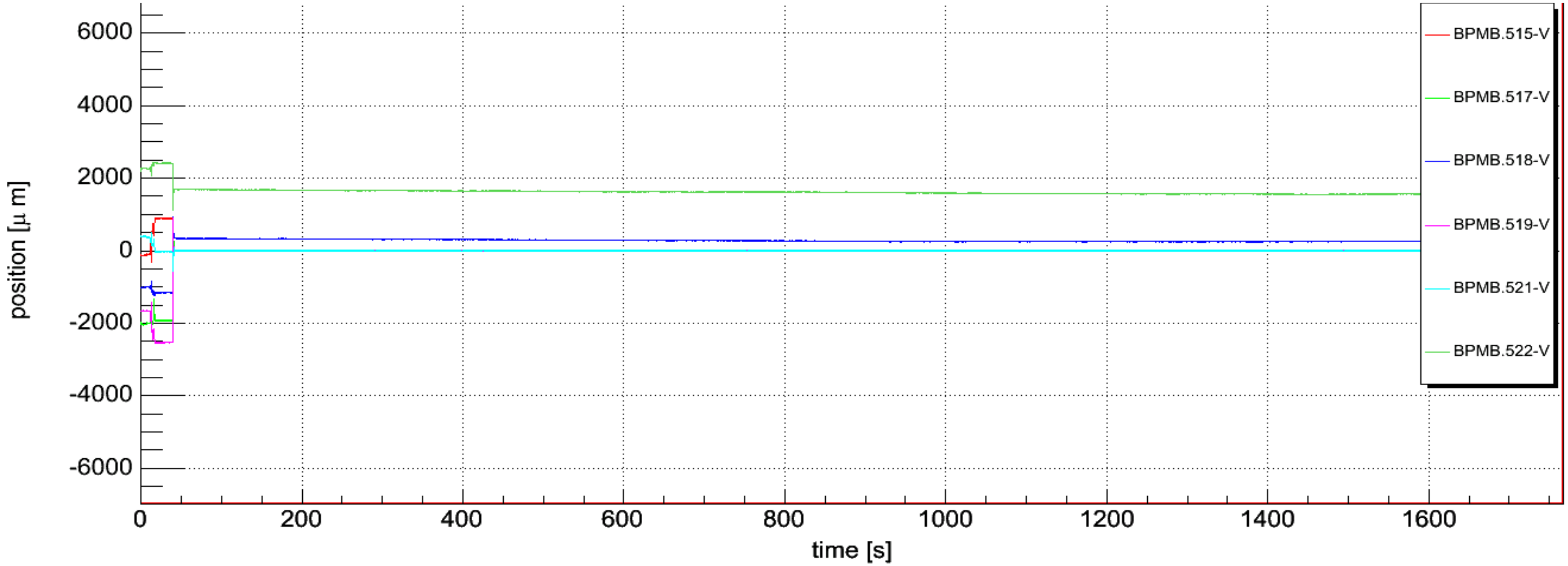
LHC Orbit Feedback Test at the SPS I/II



LHC Orbit Feedback Test at the SPS II/II

- Stabilisation "record" in the SPS
  - 270 GeV coasting (proton) beam, 72 nom bunches, $\beta_v \approx 100$ m
  - rivals modern light sources
  - magnitudes better than required
- Target: maintain same longterm stability
  - thermal drifts, dependence on beam parameter, ..

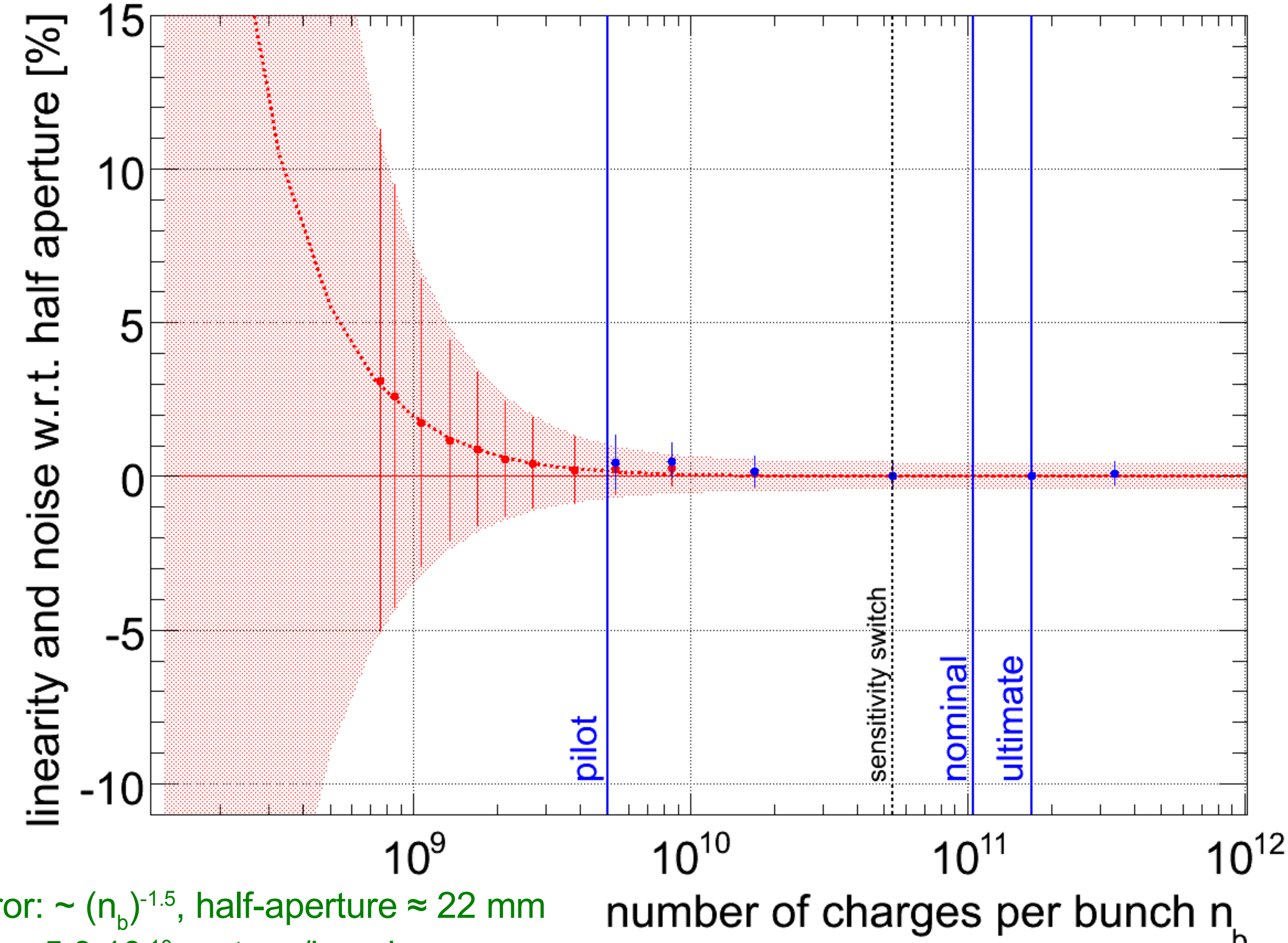




From threading the first pilot to 43x43 bunches

- 43x43 operation: max. intensity $4 \cdot 10^{10}$ protons/bunch

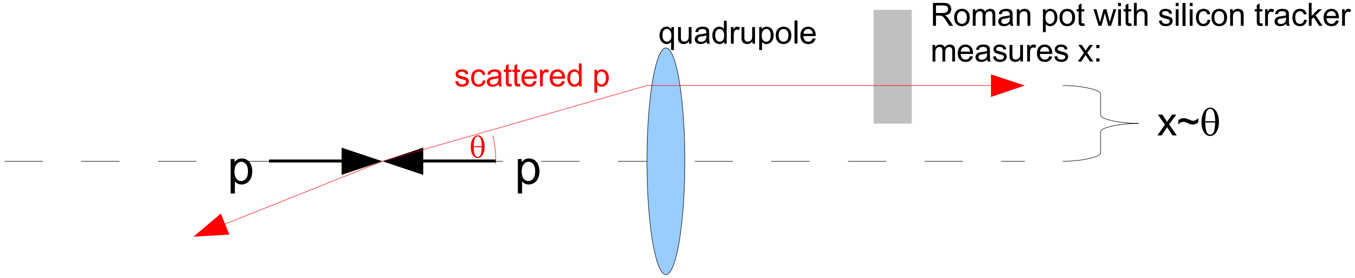
→ No gain-switching: BPMs will always operate at 'high' sensitivity



noise/error: ~ $(n_b)^{-1.5}$, half-aperture ≈ 22 mm
switch at: ~$5.3 \cdot 10^{-10}$ protons/bunch

p Luminosity using Optical Theorem

- Special parallel to point focusing machine optic ($\beta_0 \approx 1600$ m)



  - Roman Pots move close to the beam halo (~ 10σ) and measure dN/dt down to:

$$t_{min} = (p\,\theta_{min})^2 \sim \frac{p^2}{\beta_0 \beta_d} \cdot x_{min}^2$$

  - Requires good knowledge on
    - Beta-functions β_0 at IP and β_d at detector
    - Beam momentum p
    - minimum distance of roman pot x_{min} w.r.t. beam centre

  - Desired: $\Delta L/L \approx 1\% \rightarrow \Delta t/t \approx 1\% \rightarrow \Delta\theta/\theta \approx \Delta x/x \approx 5\cdot 10^{-3}$
    - → absolute beam position stability at roman pot (x_{min}~ 1mm) < 5 μm!!
    - Understanding of systematics and alignment play an important role