Monitoring of CMS Tracker Mechanical Stability with Laser Alignment System

Forum on Tracker Mechanics
Hamburg 30 June 2014

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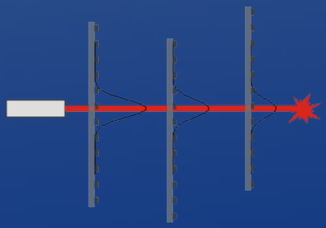
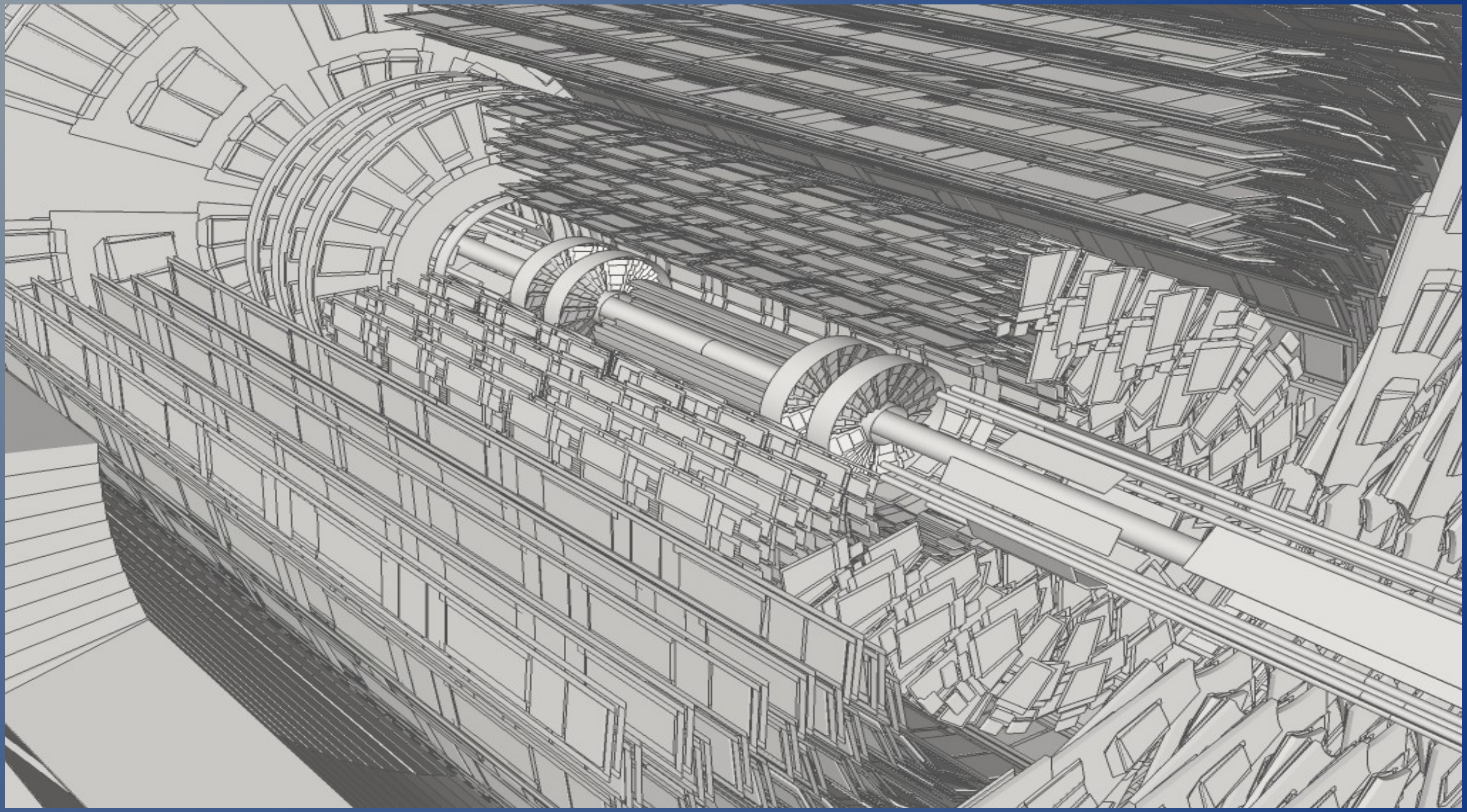


Contents

- Description of the System
- Precision of the measurements
- CMS Tracker long term stability
- Movements during Tracker cooling
- Comparison with track alignment
- LAS experience and lessons

CMS Tracker



- CMS Silicon Strip Tracker: more than 15000 silicon modules and a total active detector area of about 200 m^2
- Modules are organized in large subdetectors: TOB (6 cylindrical layers), TIB (4 layers), TID (3 discs per side), TEC (9 discs per side)

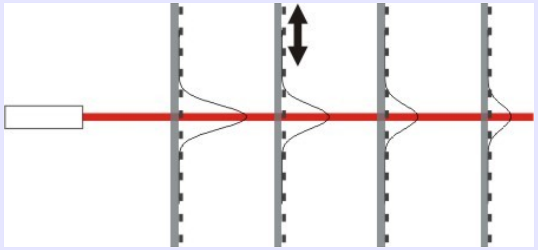
LAS Goals

- Monitoring of the Tracker subdetectors stability: required accuracy: 10 µm/µrad
- Reconstruction of subdetectors relative geometry: required accuracy 100 µm/µrad

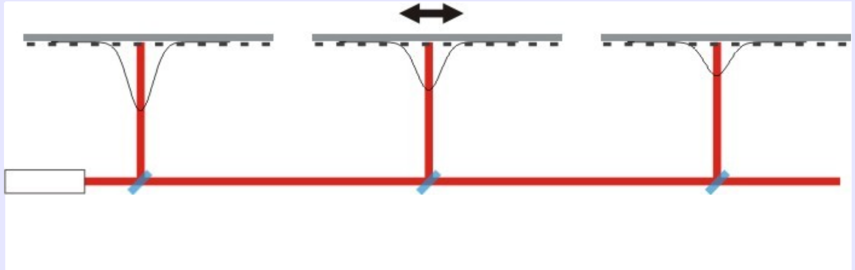
LAS Working Principle

- Use the Tracker silicon strip modules to detect the beams
- Send several laser beams through the Tracker
- From changes of the measured laser spots infer movements of the Tracker subdetectors
- Light absorption in Si : 10 cm^{-1} at λ = 1080 nm and T = 300 K (transmission ~80%)

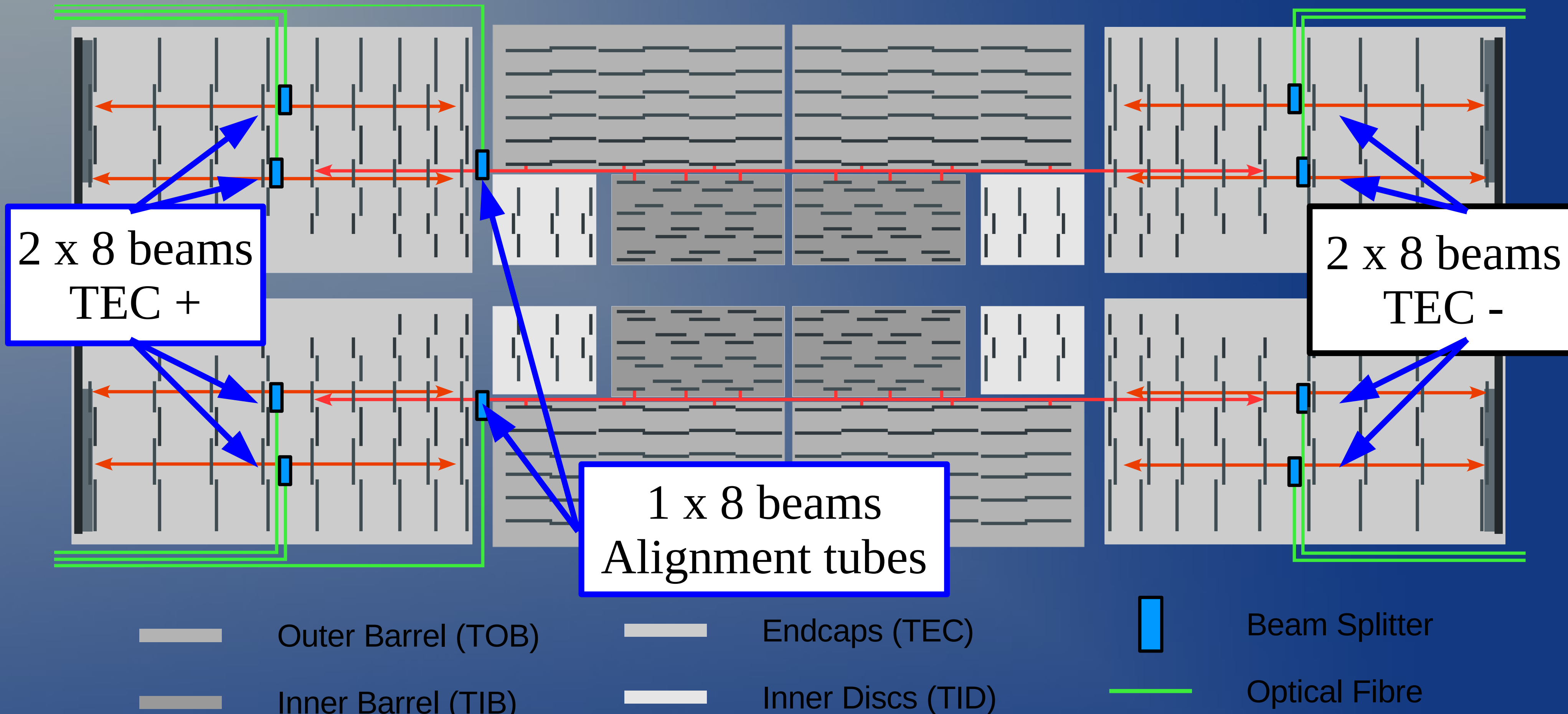
Variant 1 (endcap alignment): Beam passes through several layers of sensors (Silicon is semitransparent to infrared light)



Variant 2 (subdetector alignment): Beam is split and sent to several sensors (Mirrors have to be mounted on a rigid structure)



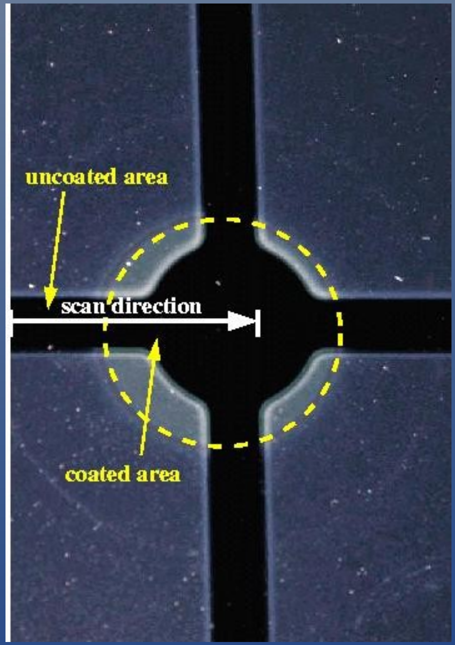
LAS Overview



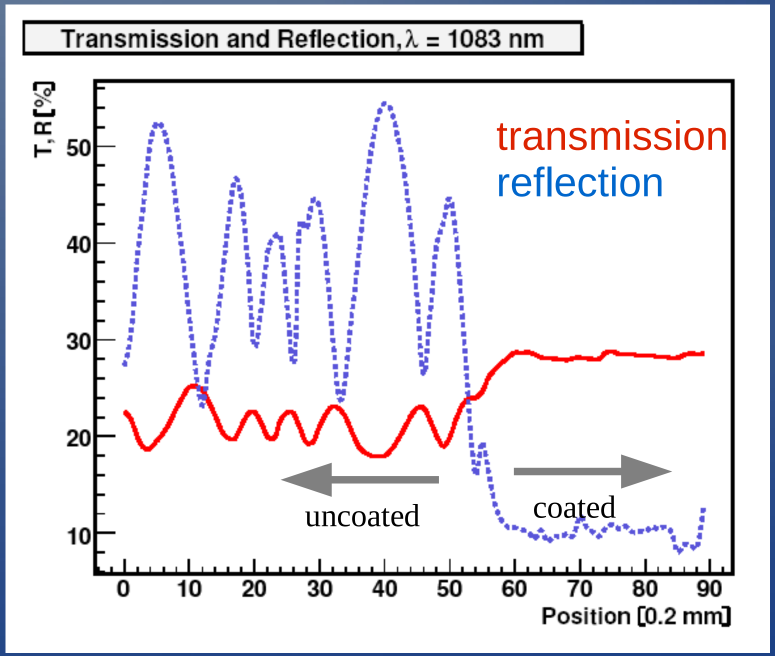
- 32 laser beams in each Endcap, 8 laser beams for Barrel/Endcap alignment
- 434 Modules out of 17.000 are hit by laser beams
- The design goal was to reach an alignment precision of 10 μm for relative measurements

Endcap Alignment Sensors

- Silicon sensors polished on both sides
- Hole in backplane metallization
- Antireflective coating on backside
- No antireflective coating on strips due to effects on interstrip capacitance



Sensor Backplane

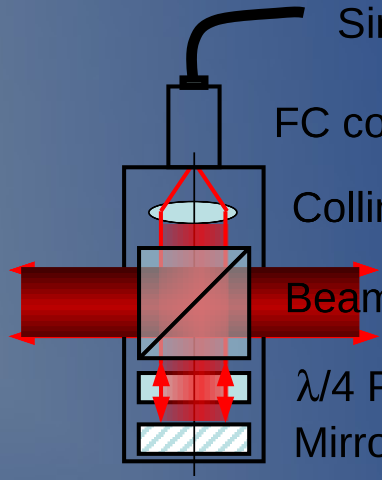


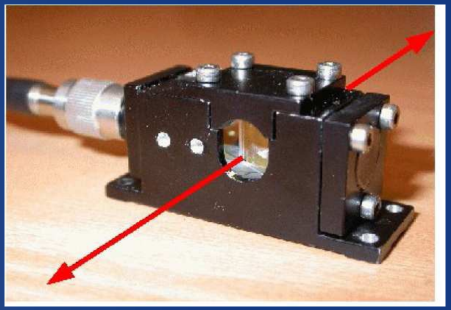
AR coating

- Tranmission improves
- Reduced multiple reflections
  -> Reduced interference
  -> reduced distortion of profiles

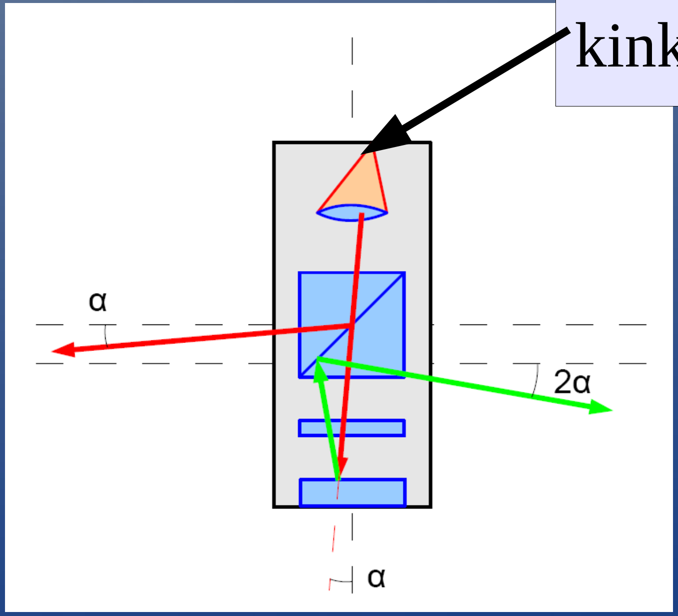
Beam Splitters

The beam splitters generate a pair of back-to-back beams:



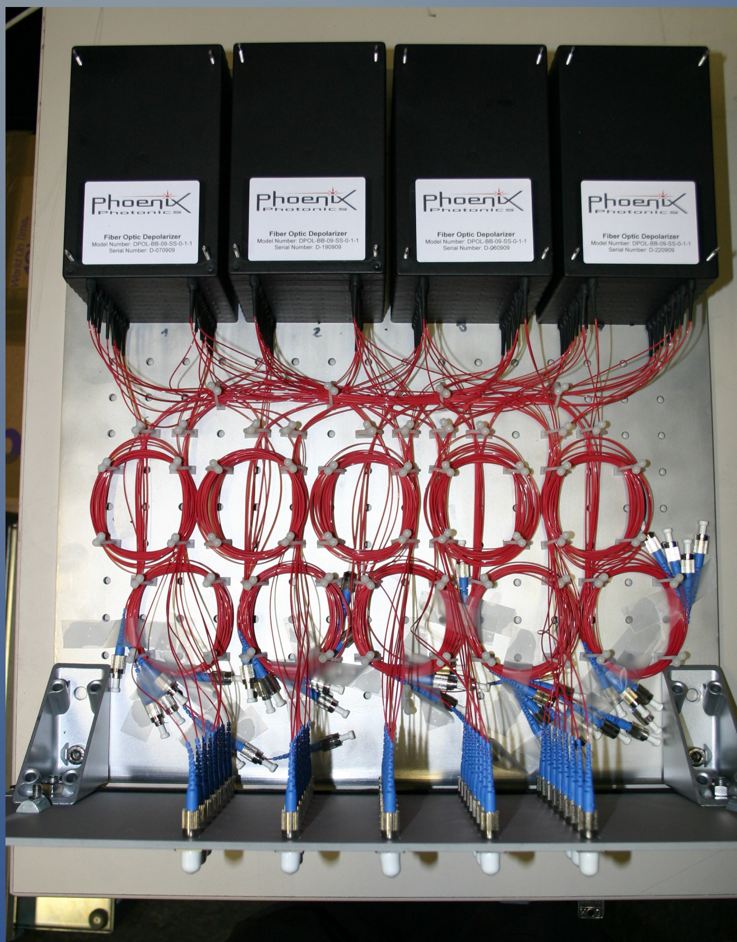


misaligned fibres lead to a kink between the beams



- All beam splitters have been calibrated in the lab for collinearity with the final fibre connected.
- This data is used to correct the absolute LAS measurements.
- Relative measurements are not affected

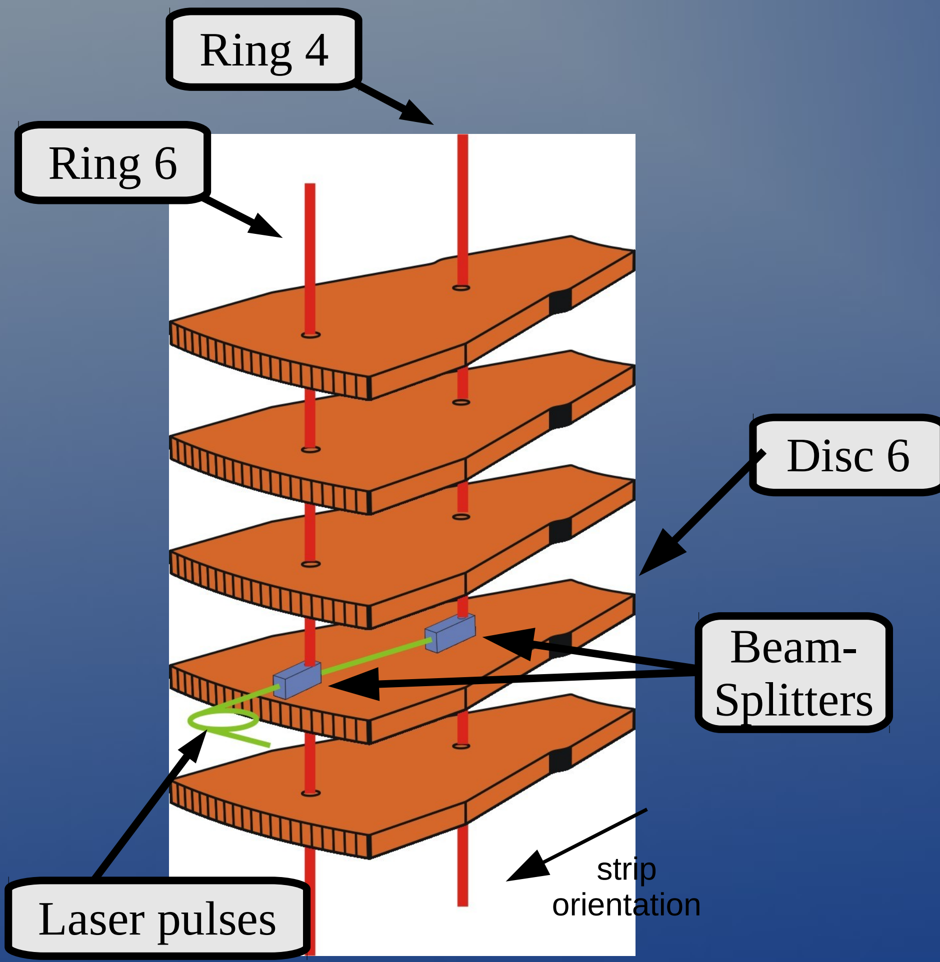
Depolarizers

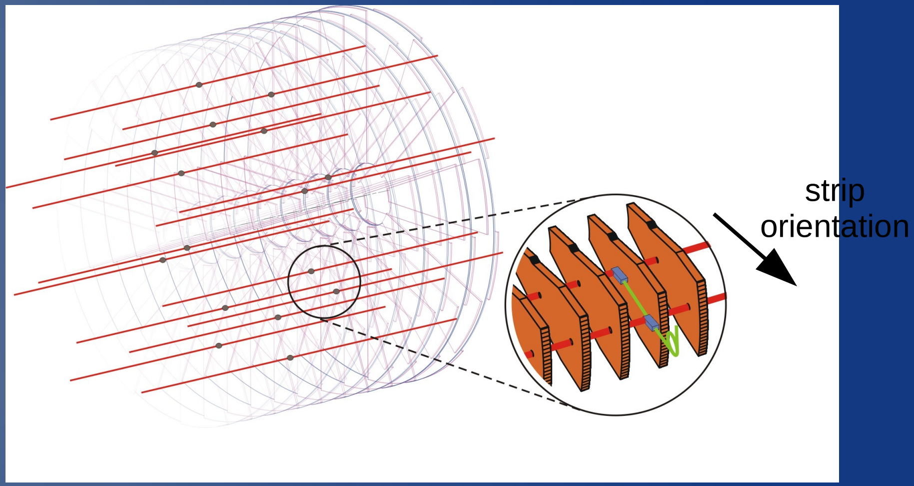


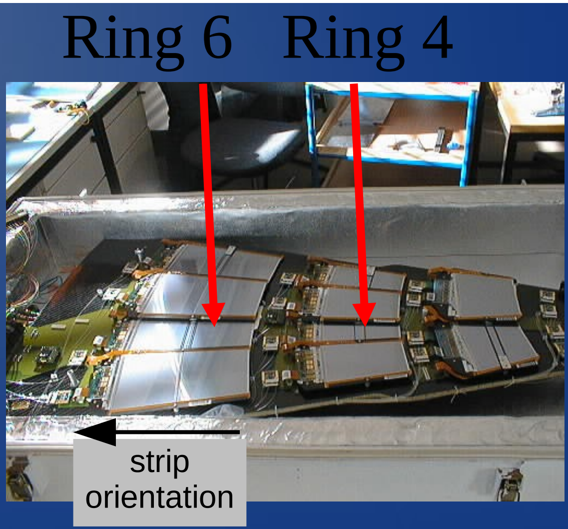
- Beam Splitters require unpolarized light to get equal splitting
- Laser diodes produce polarized light
- Fiber Depolarizers in the Laser Room ensure good splitting
- Intalled end of 2010 to improve quality of the signals

Internal Endcap Beams

- 2 x 8 beams in each Endcap (ring 4 and 6)

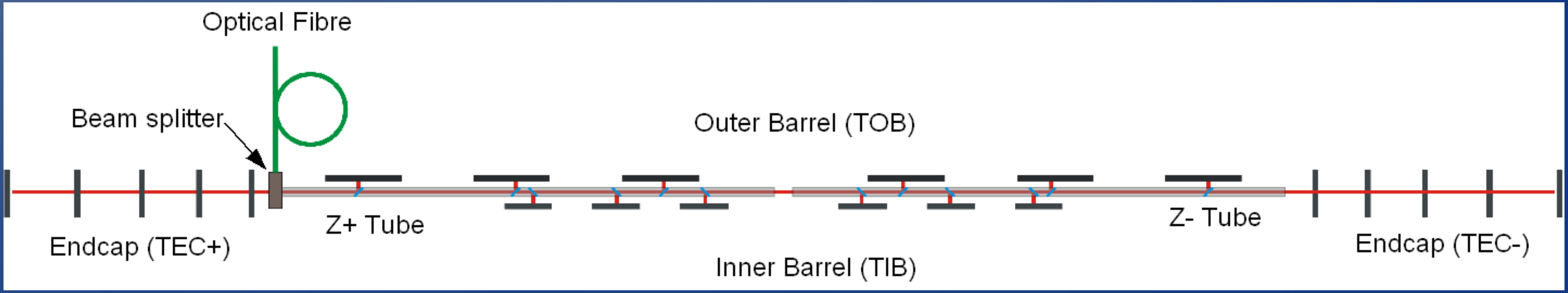






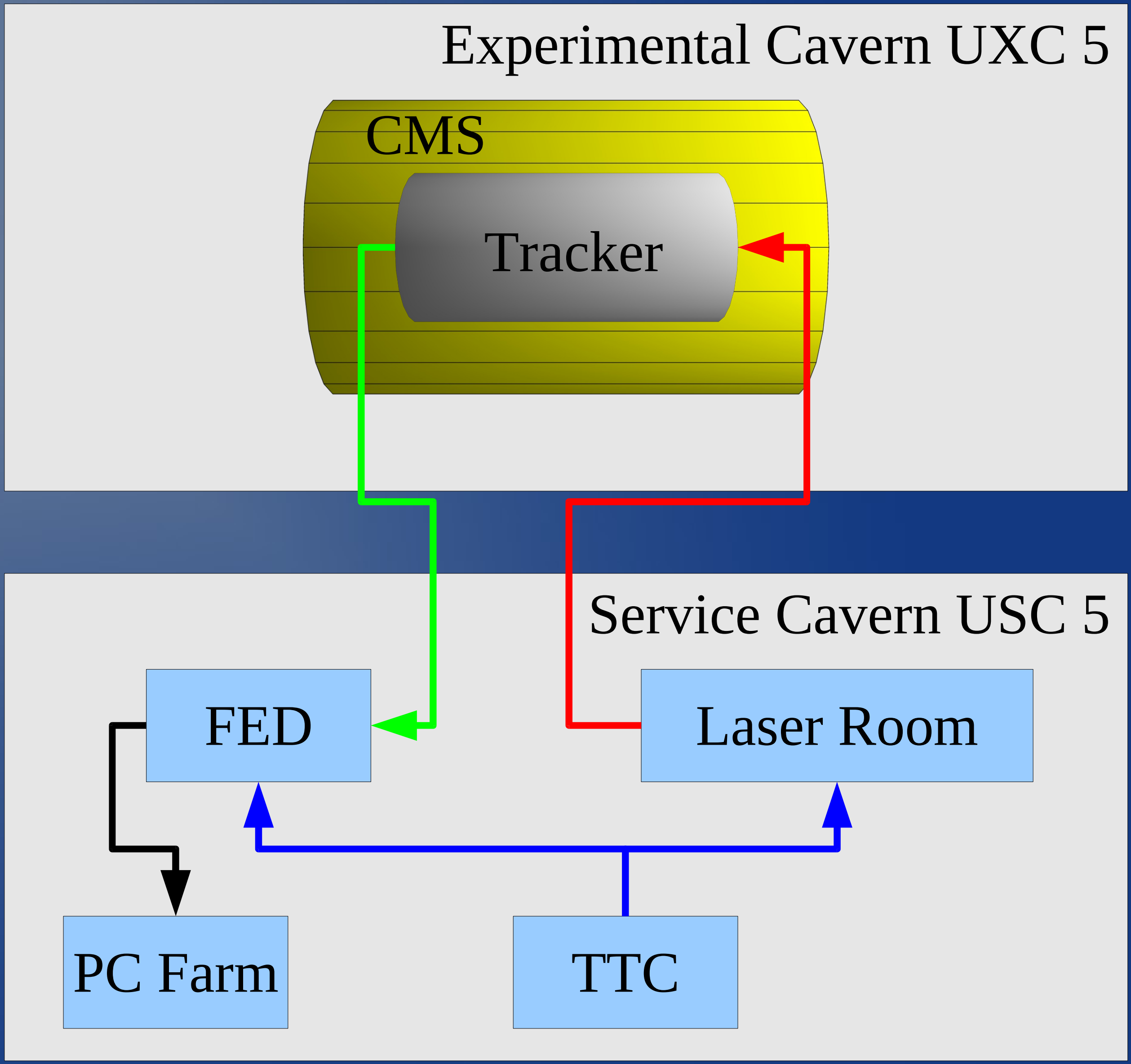
Alignment Tubes

- Beamsplitters mounted on one end of Al tube (reduce thermal gradients)
- 6 semitransparent mirrors per tube (3 for Inner Barrel, 3 for Outer Barrel)
- Glass plates with single-sided AR-coating (5% reflection per mirror)
- The tubes are kinematically mounted on the TOB inner tube

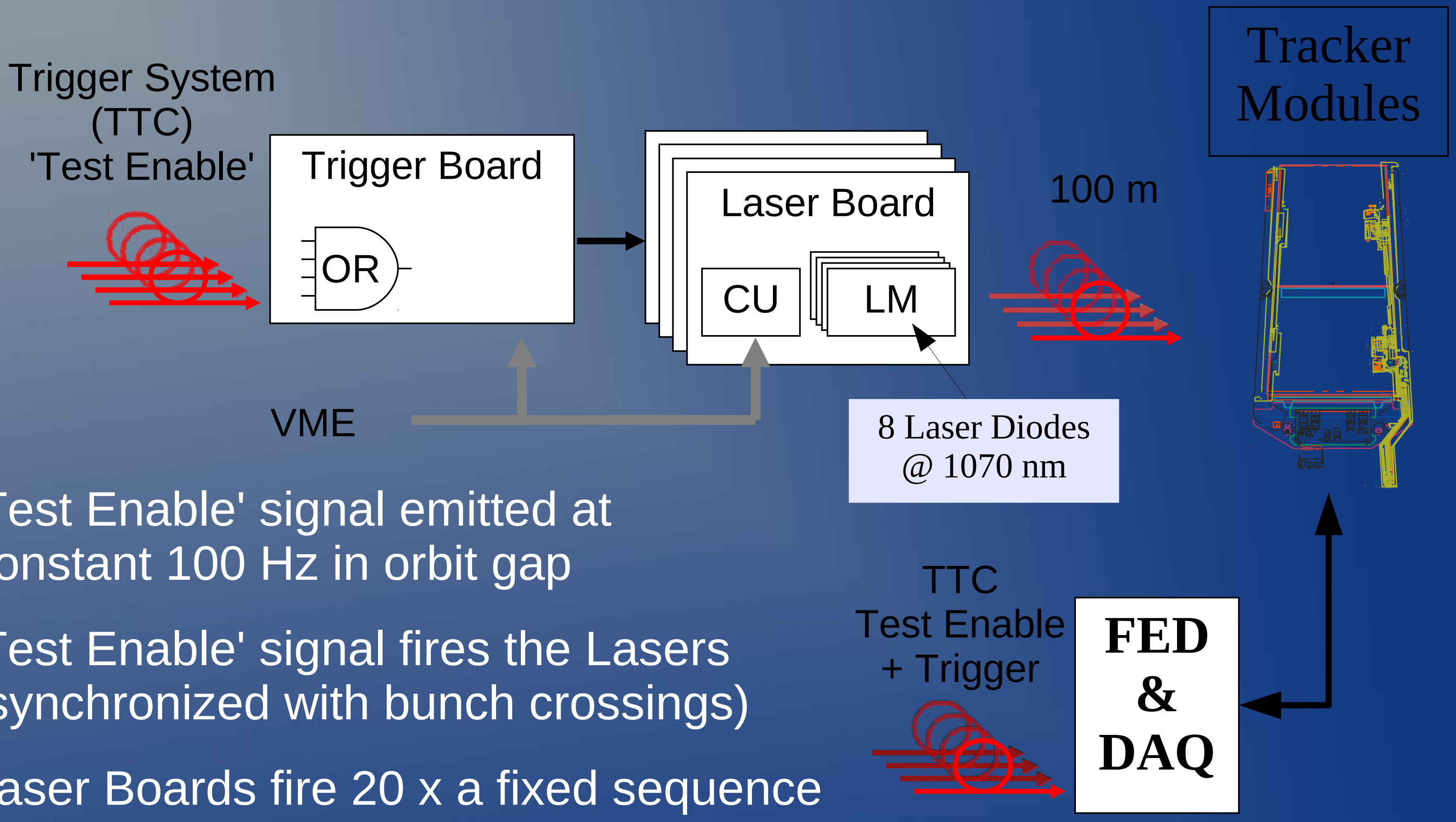


Laser Pulse Generation

- Laser Sources in service cavern
- Trigger System (TTC) fires Lasers
- Front End Driver (FED) treats laser events as physics events
- PC Farm recognizes laser events and sends them to calibration stream

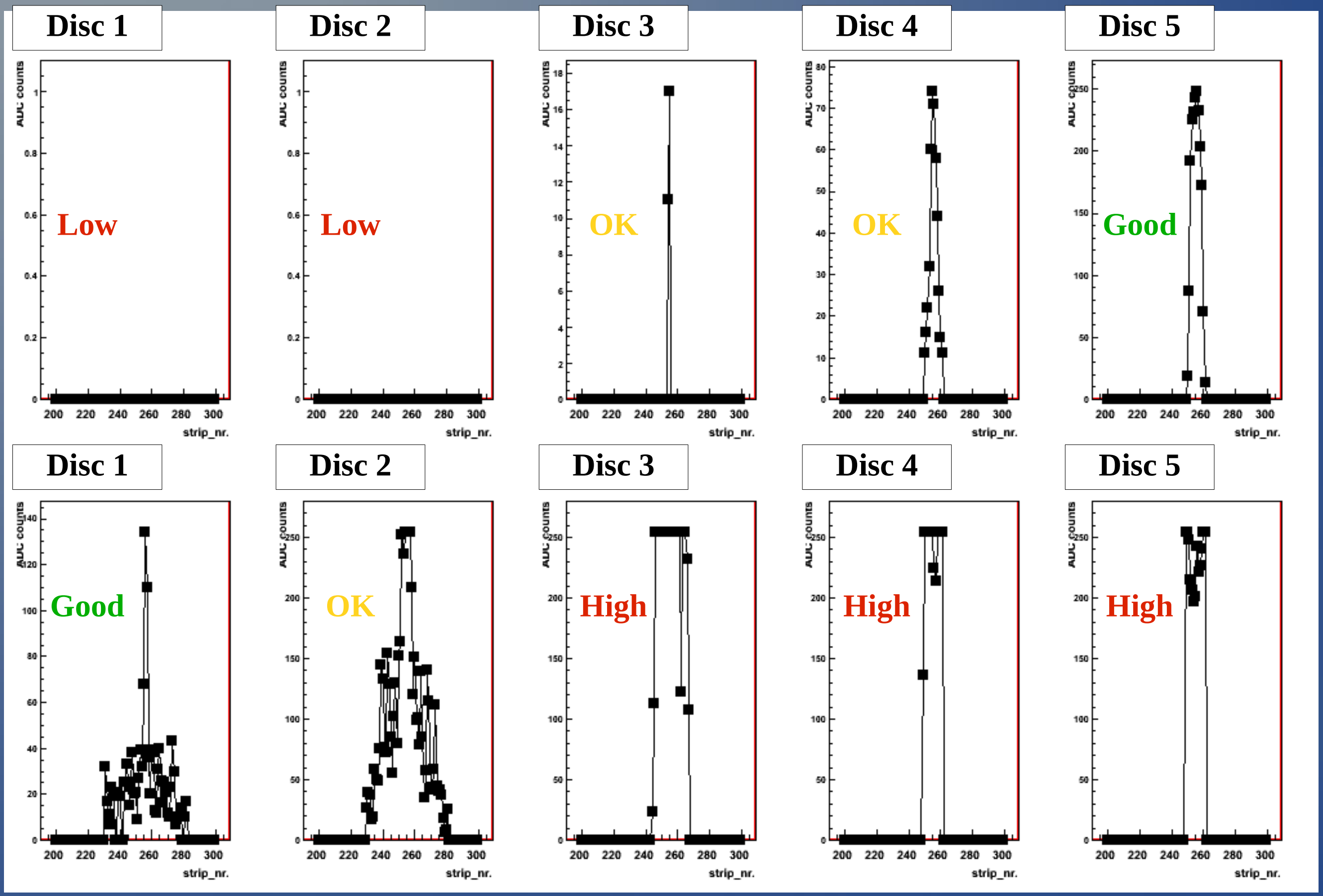


Laser Pulse Generation



- 'Test Enable' signal emitted at constant 100 Hz in orbit gap
- 'Test Enable' signal fires the Lasers (synchronized with bunch crossings)
- Laser Boards fire 20 x a fixed sequence of 100 pulses
  (2000 pulses = one snapshot)
- Intensities and delays are varied to achieve good signal on every module

Reaching different TEC Layers



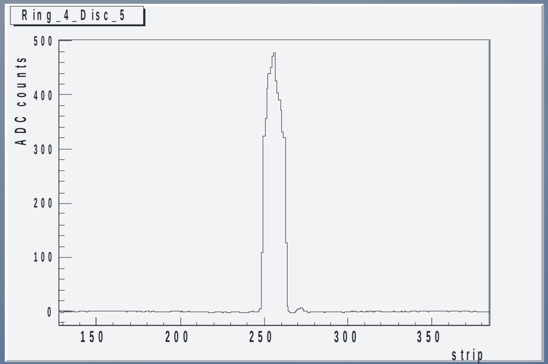
Low intensity:
Disc 1,2 no signal
Disc 5 good

High Intensity:
Disc 1 good
Disc 2-5 satureted

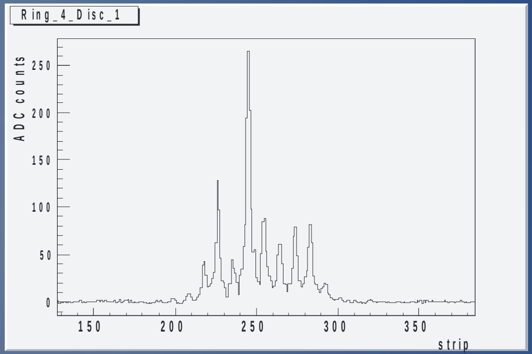
- The laser intensity is adapted event by event to reach different layers for optimal signal quality
- Max. 5 layers => 5 different intensities

Laser Profiles

Example: TEC- Ring4



Laser beam profile
next to the beam splitter



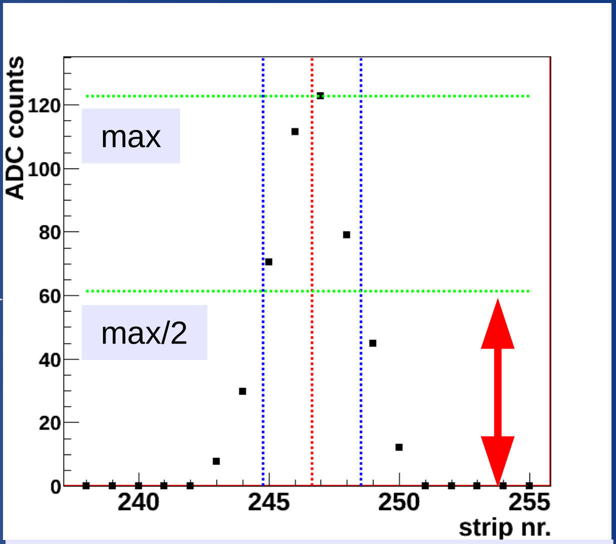
Laser beam profile
after 4 layers of sensors

Every profile is an average of 200 triggers

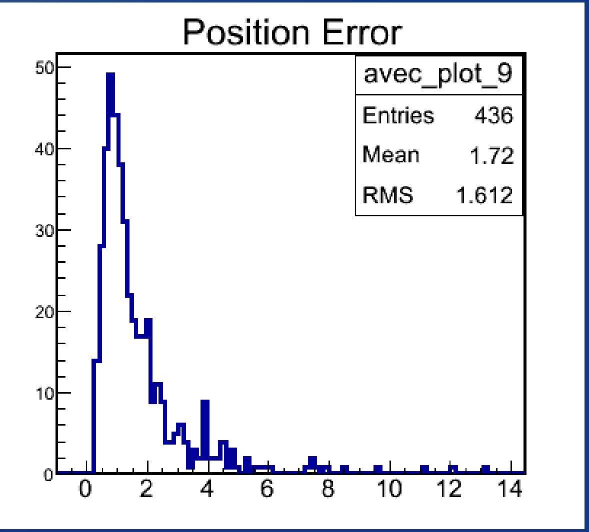
- Central part of beam 4-20 strips wide
- All laser spots lie within range (+- 5mm around nom. pos.)
- TEC profiles display diffraction patterns (strips act as grating)
- 10 modules out of 434 do not have data (6 x TIB, 4 x TEC)
- 16 modules out of 434 are masked because of bad quality profiles (either too little signal or noisy in position determination)

Laser Spot Positions

- Profiles are not perfect gaussians
  Non-perfect optical elements
  Diffraction when passing several layers
  Some signals are close to the saturation
- Algorithm computes position from the slopes:
  Position is taken in between 50% of maximum
- Position Calculation:
  - Integrate all good profiles for each module
  - Apply edge algorithm to get position
- Position Error Estimation
  - Get RMS of strips used for position calculation
  - Propagate errors to position
  - This neglects intensity fluctuations of the laser profiles
  - Mean Error around 2μm



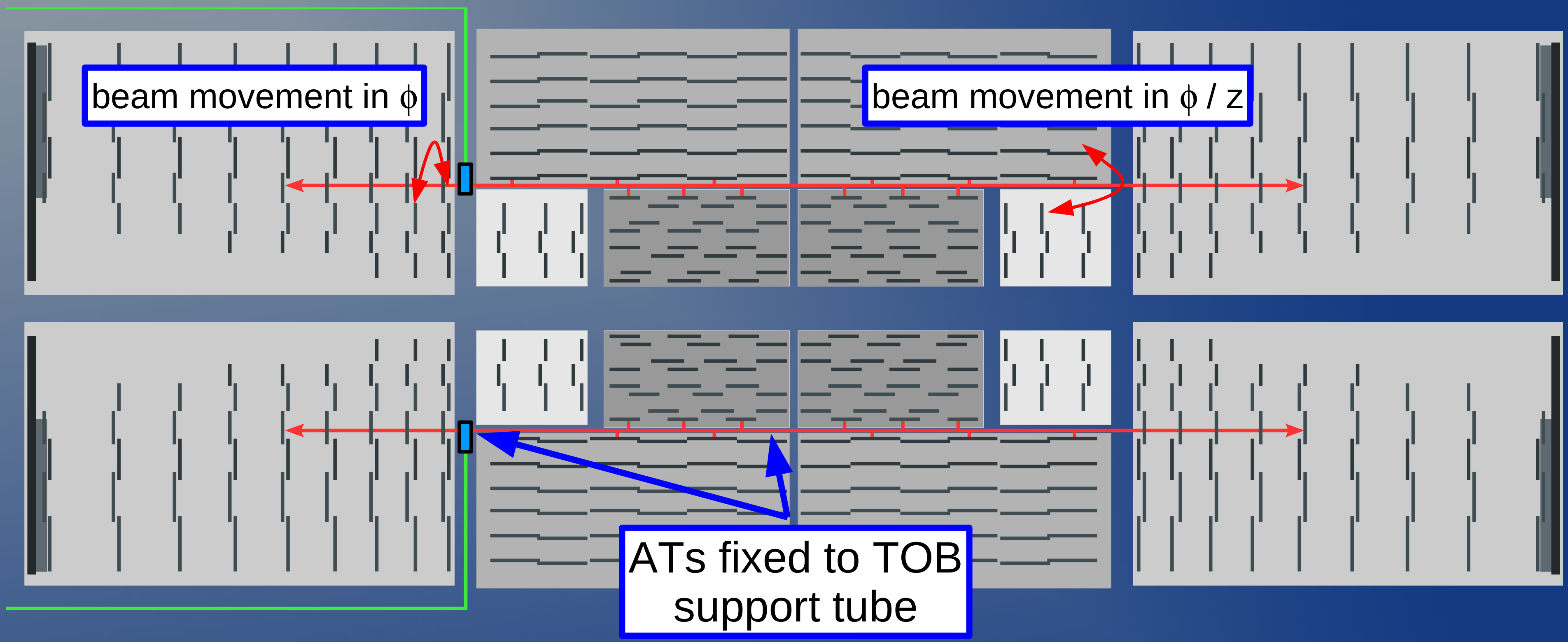
Take position between half height of profile



Parameter Reconstruction

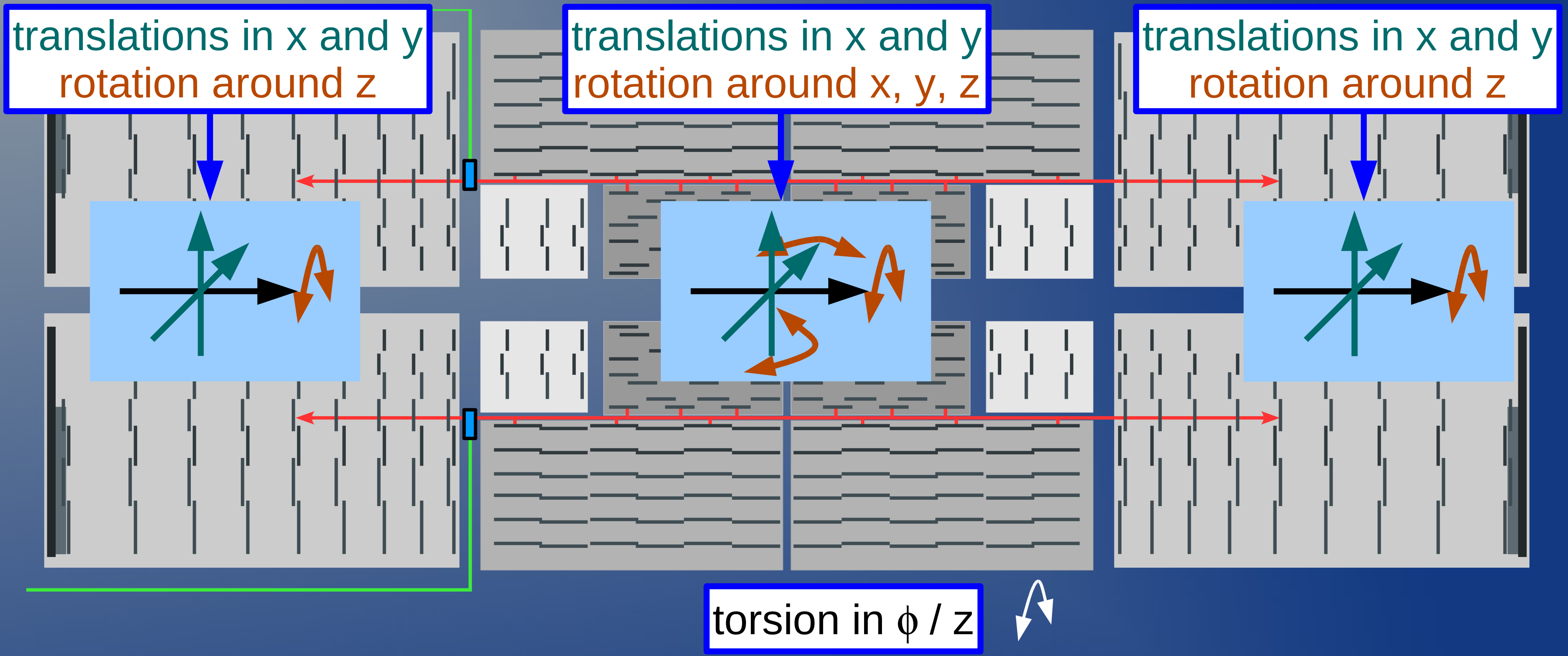
- Describe movements of Tracker structure with linear parameters
- Perform χ^2 minimization with all measured laser spot positions
- The minimization is done with a matrix inversion in ROOT
- Errors on parameters are obtained from covariance matrix
- Depending on the fit type we have:
  between 80 and 430 measurements
  between 21 and 140 fit parameters

Parameters for laser beams



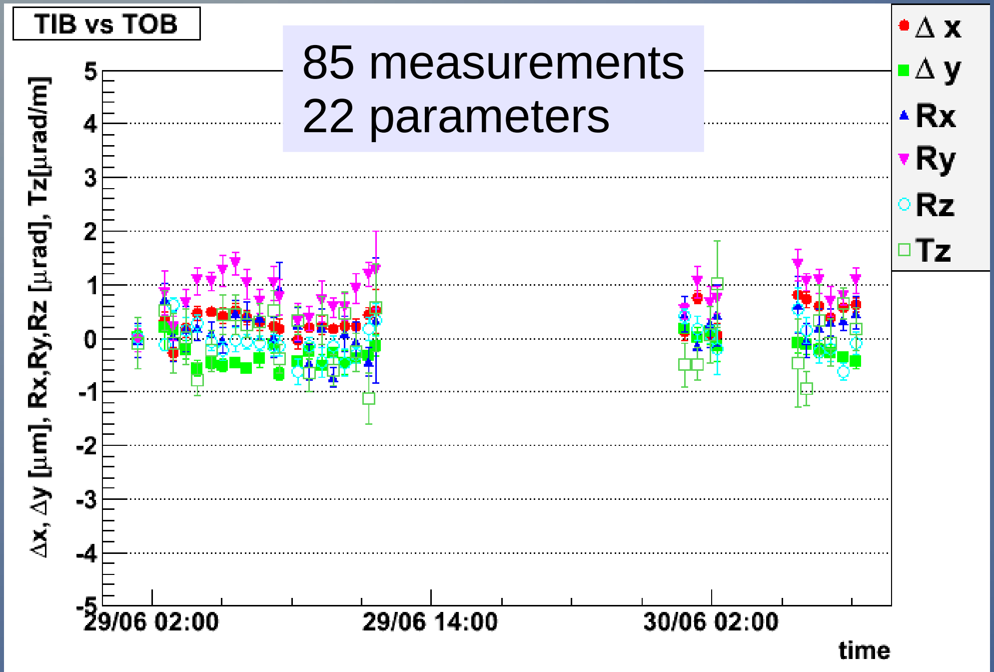
- TOB is used as reference frame
- The alignment tubes are fixed kinematically inside the TOB Inner Tube
- Laser beams are allowed to move: 2 parameters per beam (offset and slope)
- Beam deviations are straight lines

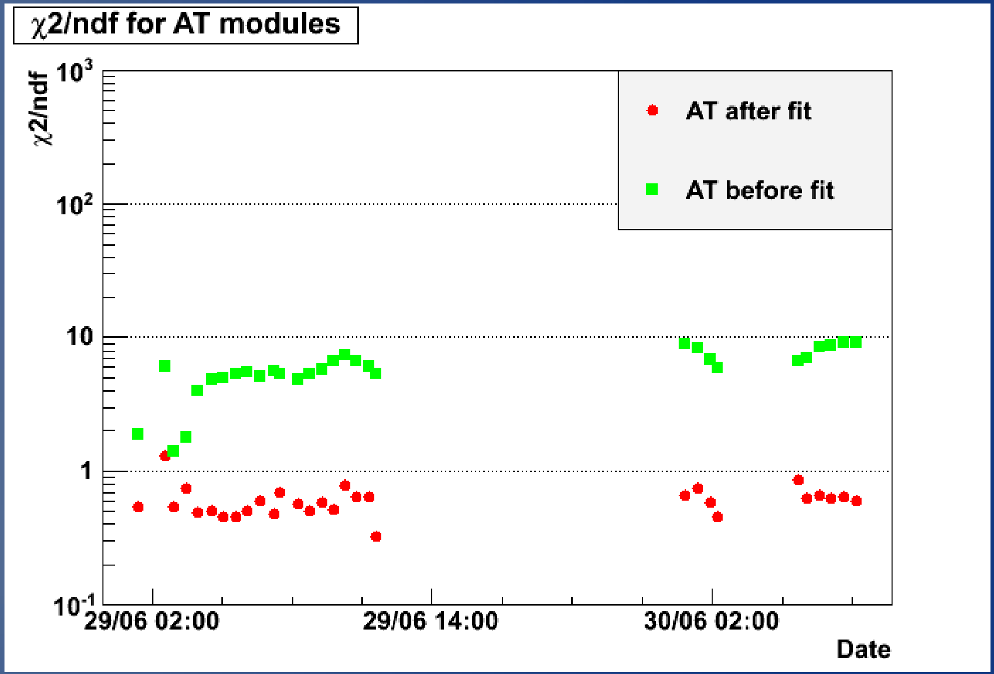
Parameters for subdetectors



- LAS is not sensitive to displacements in z-direction
- 5 TIB parameters (2 Translations: Dx, Dy, 3 Rotations: Rx, Ry, Rz)
- 2 x 3 TEC parameters (2 Translations: Dx, Dy, 1 Rotation: Rz)
  Smaller lever arm for rotations around x and y

Short Term measurement

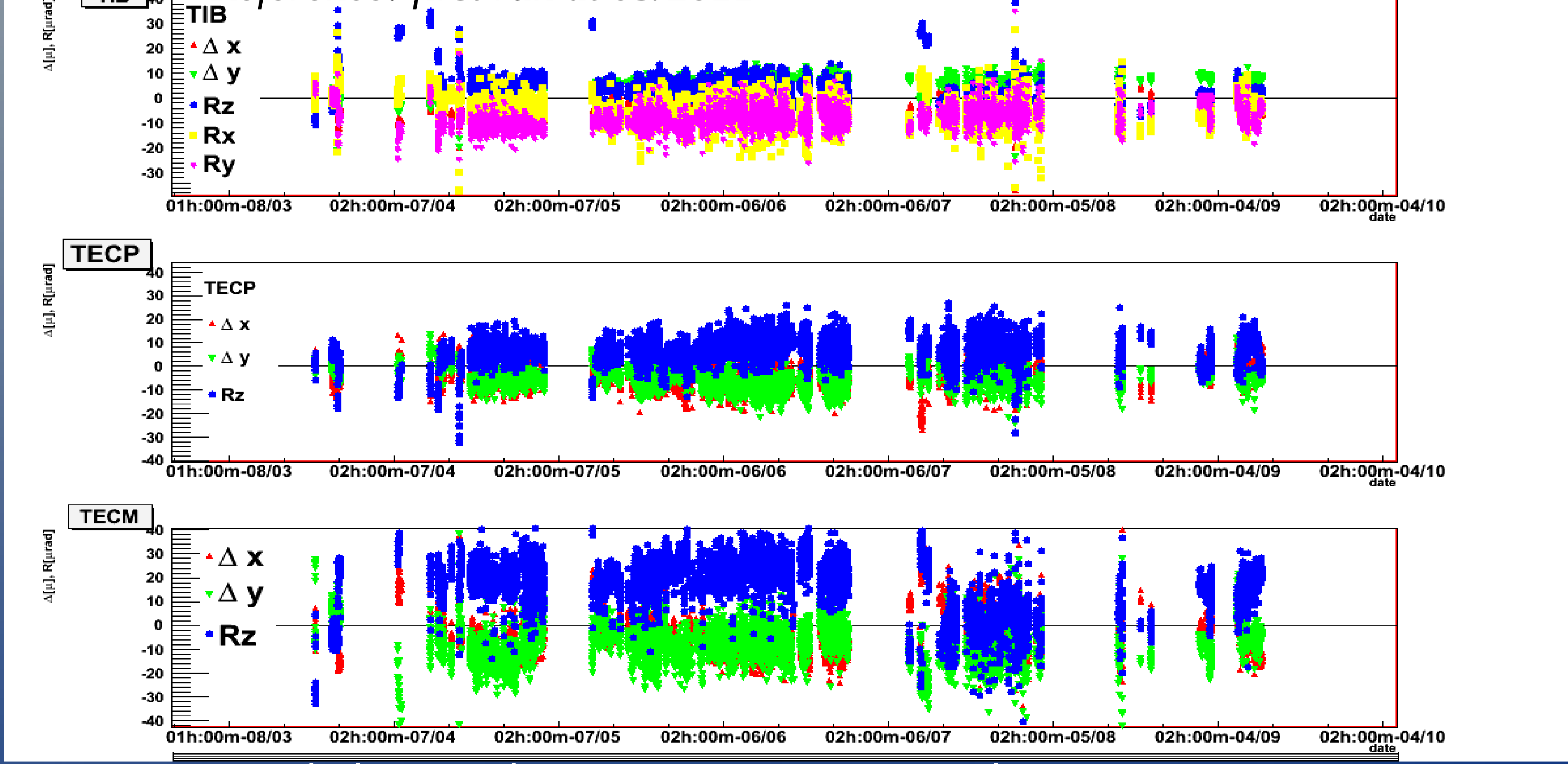




- On a time scale of days-weeks, the precision is limited by the strip noise
- The precision with which the laser spots are measured ranges from 0.5 μm to 10 μm
- This translates to errors in the alignment parameters in the range of
  0.7 - 1 μm for translations
  1.0 – 2.5 μrad for rotations
- The above plot averages over several measurements => smaller error bars

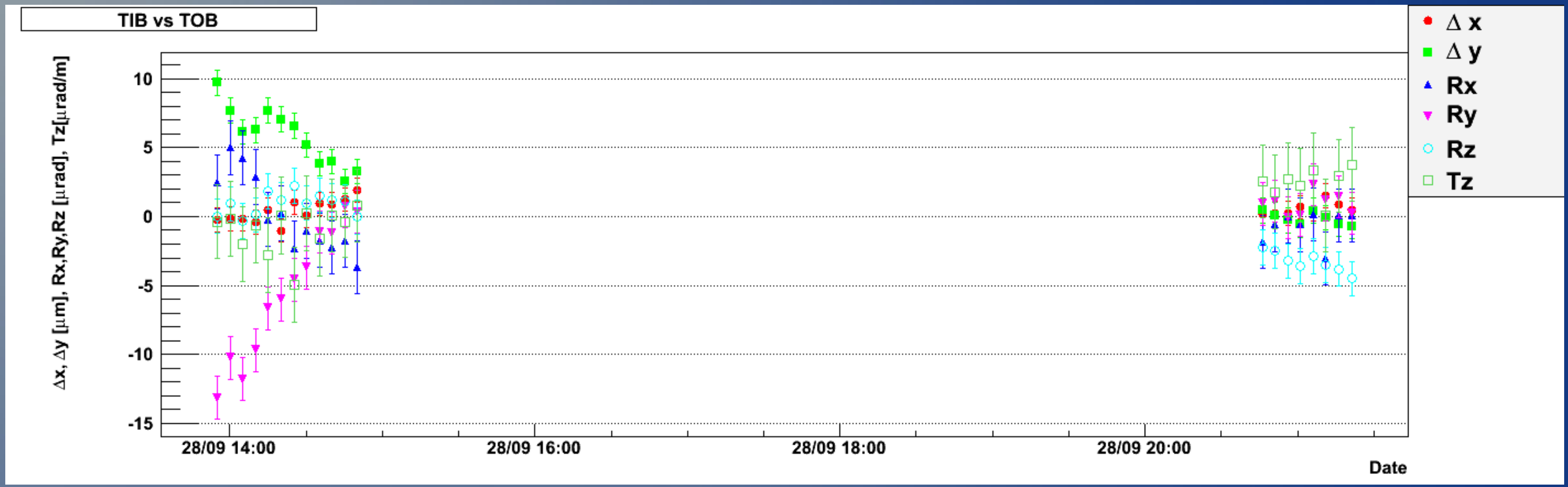
Long Term Tracker Stability 2011 Results

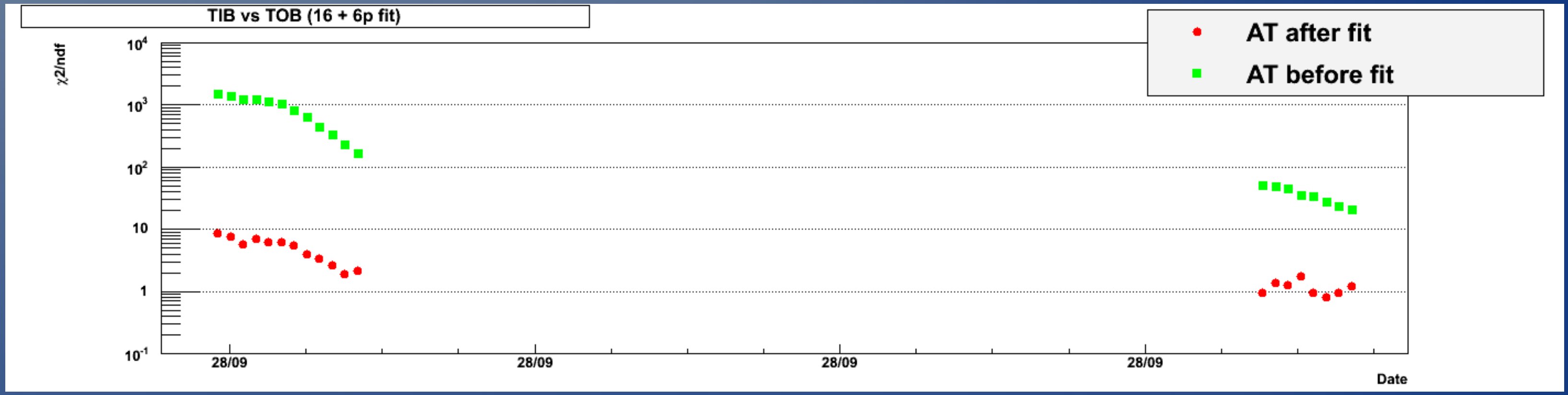
Reference: first run at 03/2011



- Compressed plot: 1 point averages over several measurements
- Long term stability of TIB wrt TOB is within 10 μm / μrad
- Long term stability of TEC+/TEC- wrt TOB is within 20-30 μm / μrad

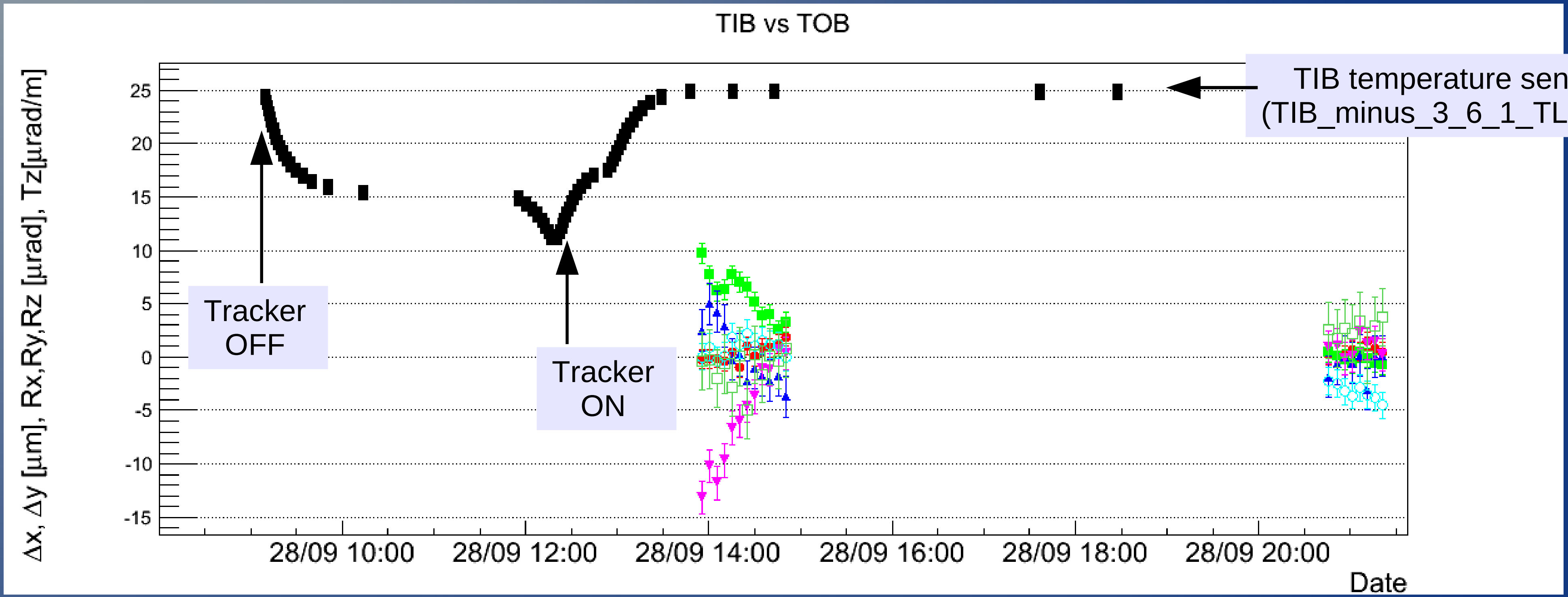
Short Term Movements





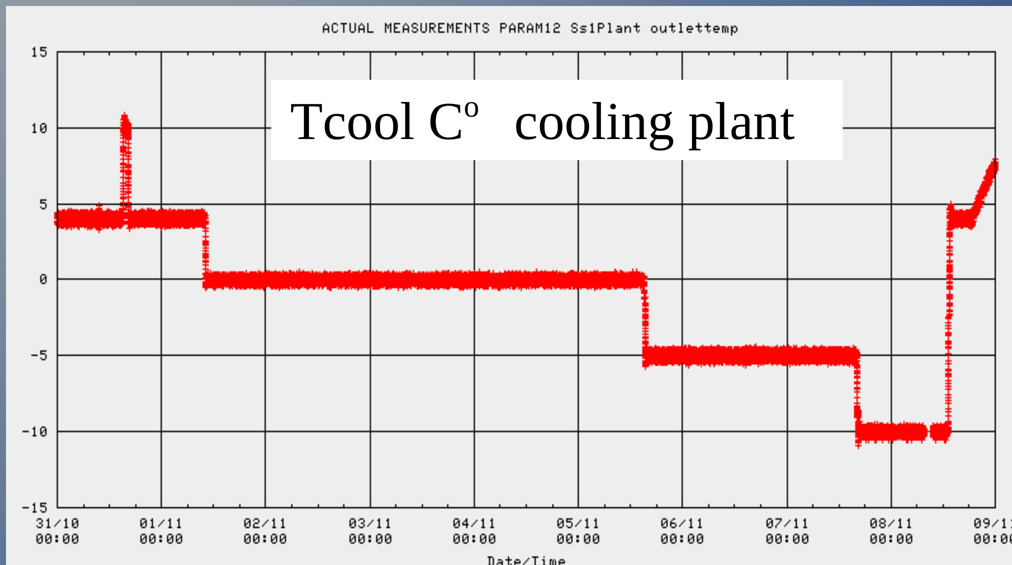
- On a short term we sometimes observe significant changes of the alignment parameters
- These changes are correlated with temperature changes of the Tracker

Short Term Movements and Temperature

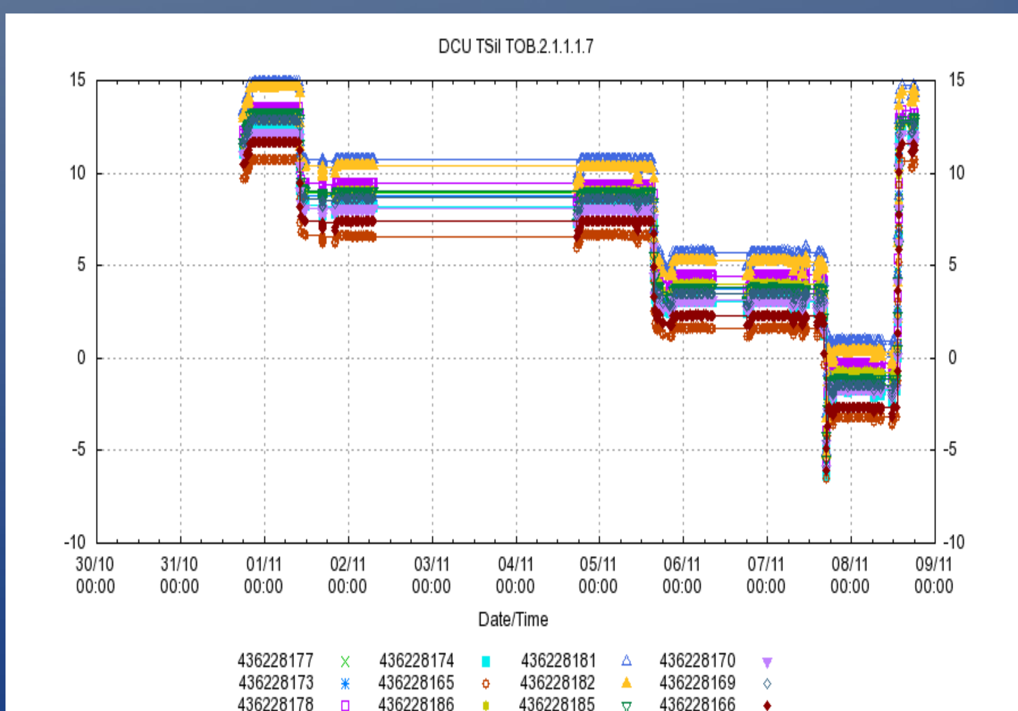


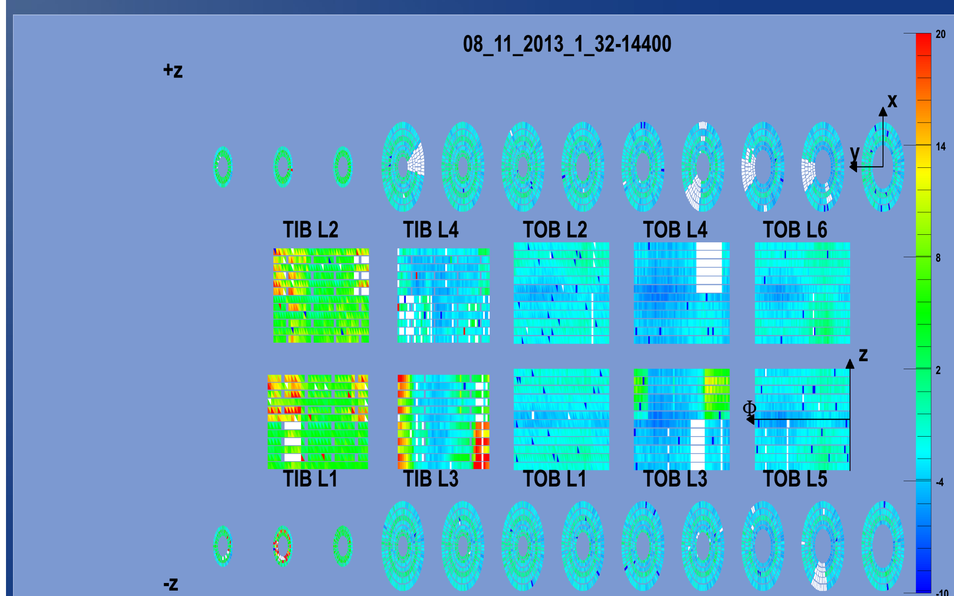
- The movements are correlated with temperature changes of the Tracker
- This is non-standard operation of the Tracker
  Normally the Tracker is in thermal equilibrium for many hours, before data taking starts

Cool-down Test Nov 2013

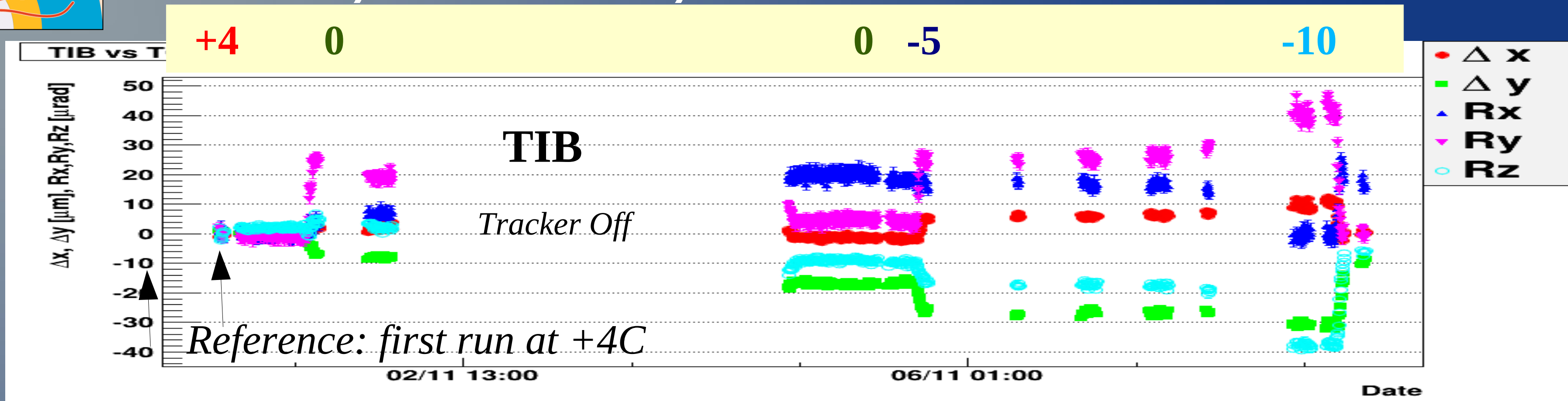


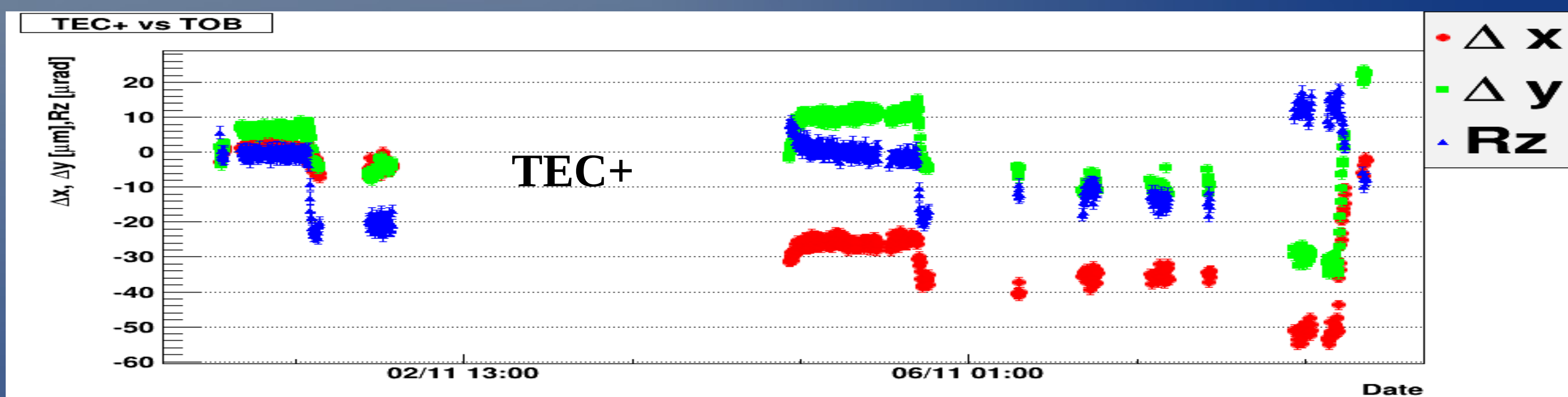
- First CMS Tracker cool-down to -10 C
- > 100h LAS data taking
- > 50h cosmics data

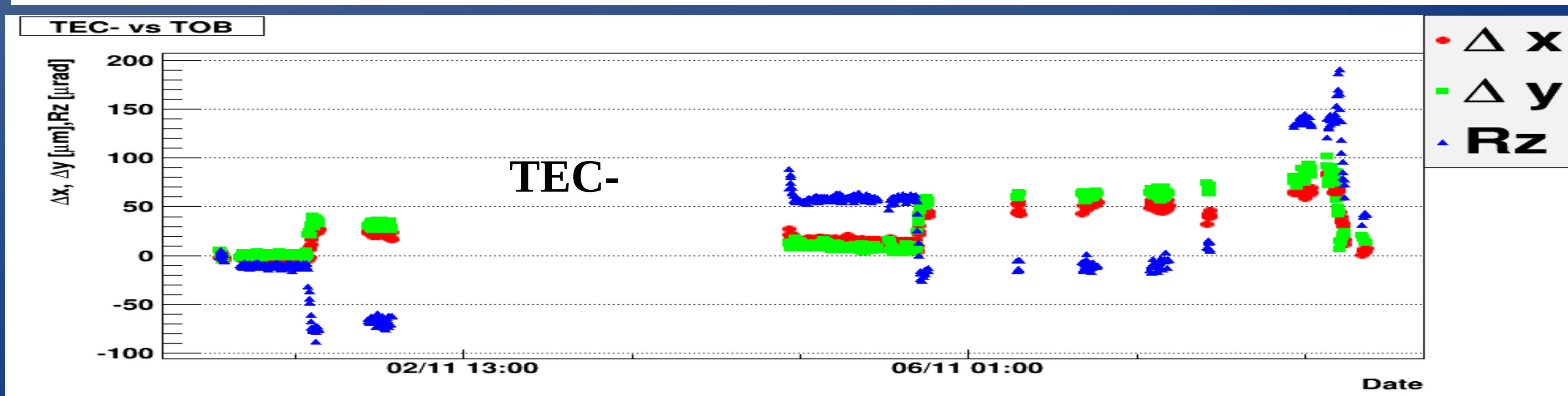




TIB, TEC+, TEC- wrt TOB

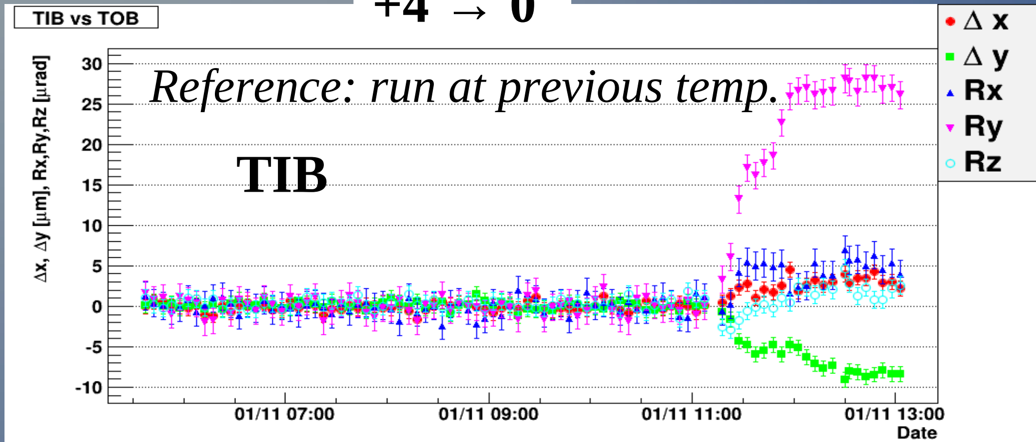




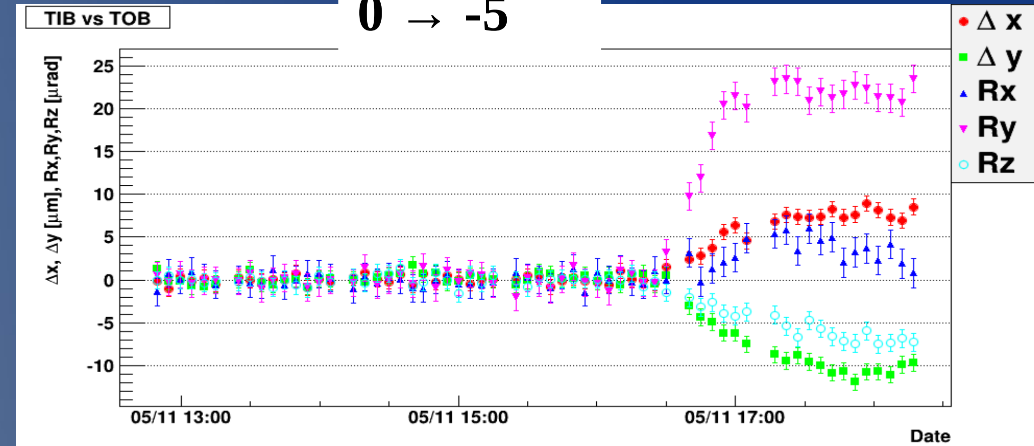


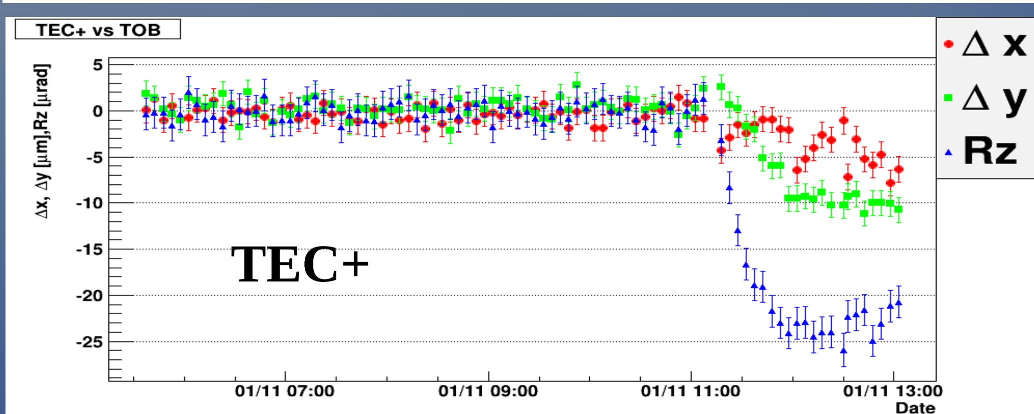
Cool-down Patterns

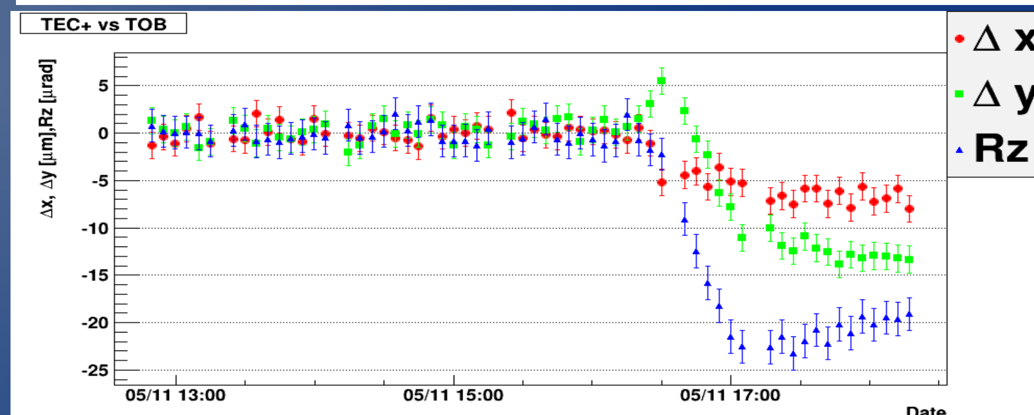
+4 → 0

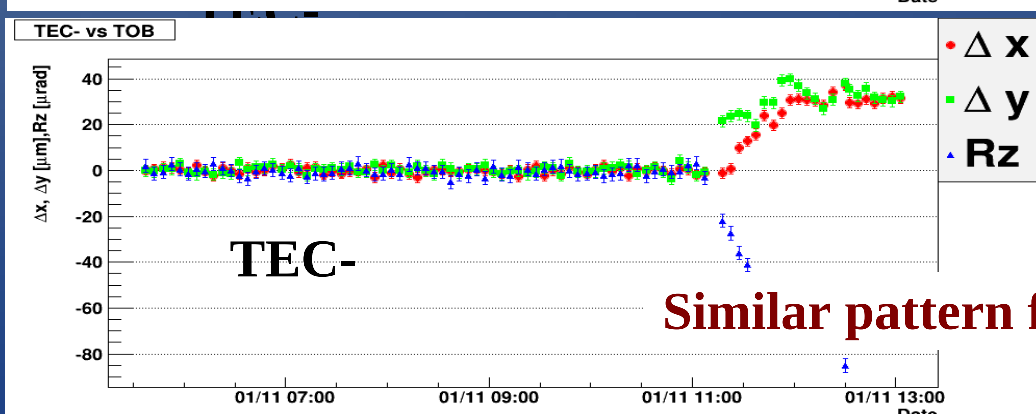


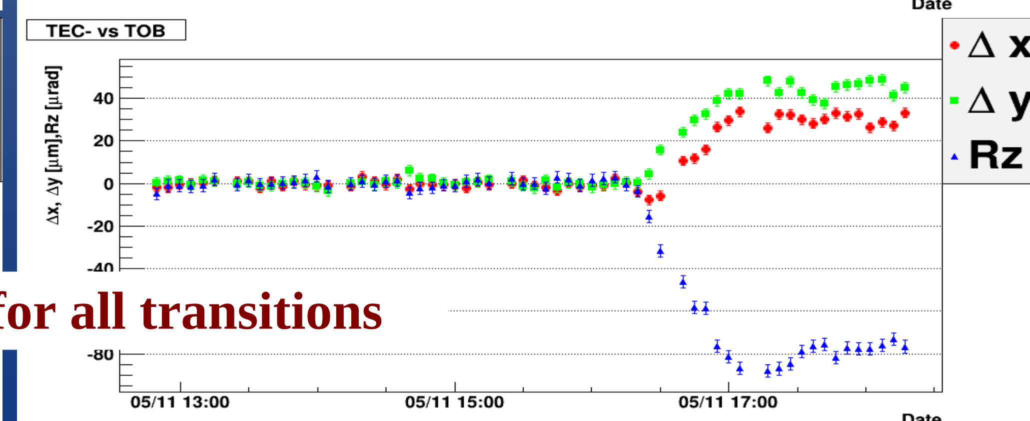
0 → -5





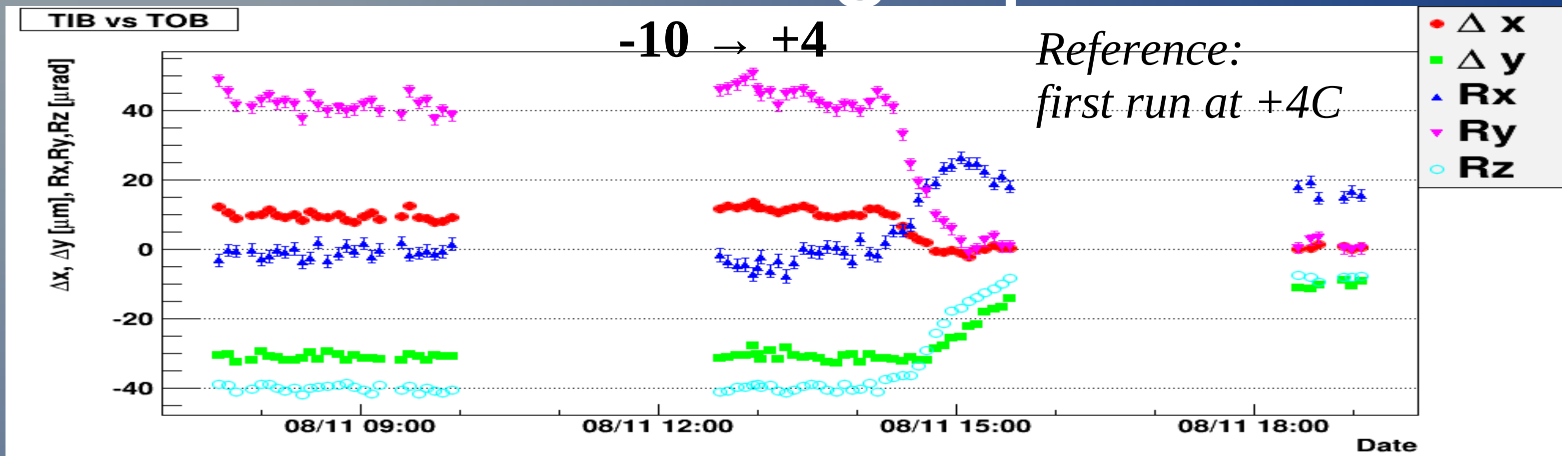


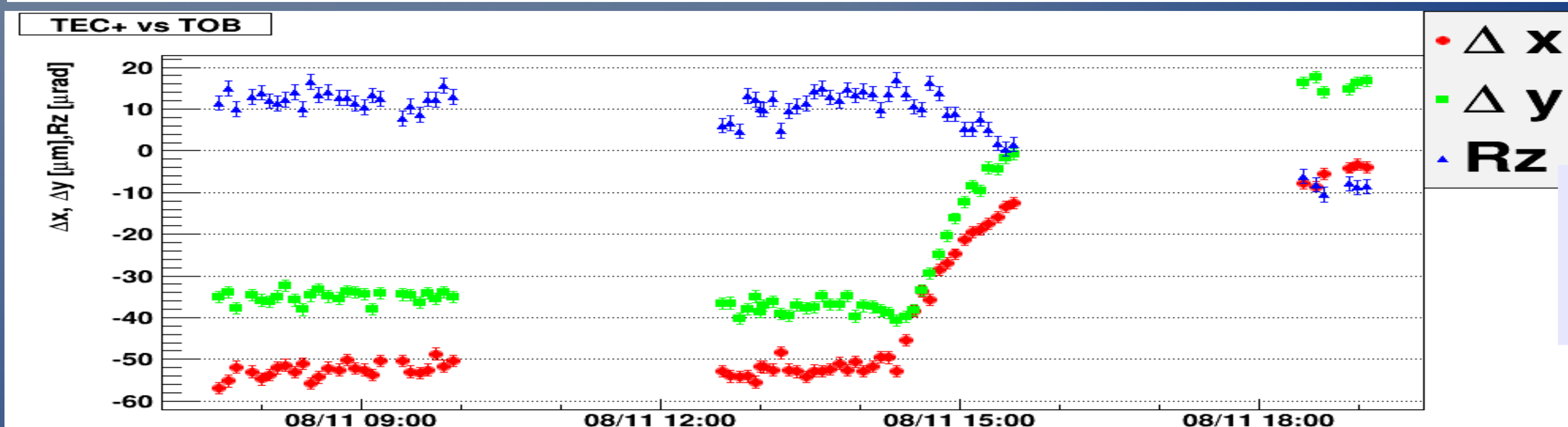


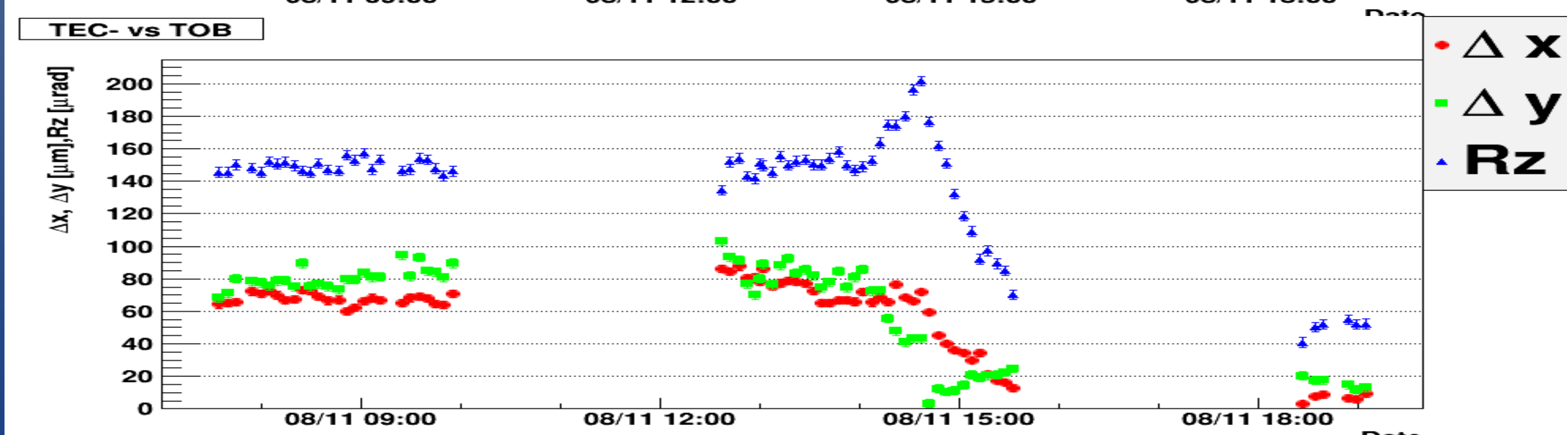


Similar pattern for all transitions

Warming-up Patterns

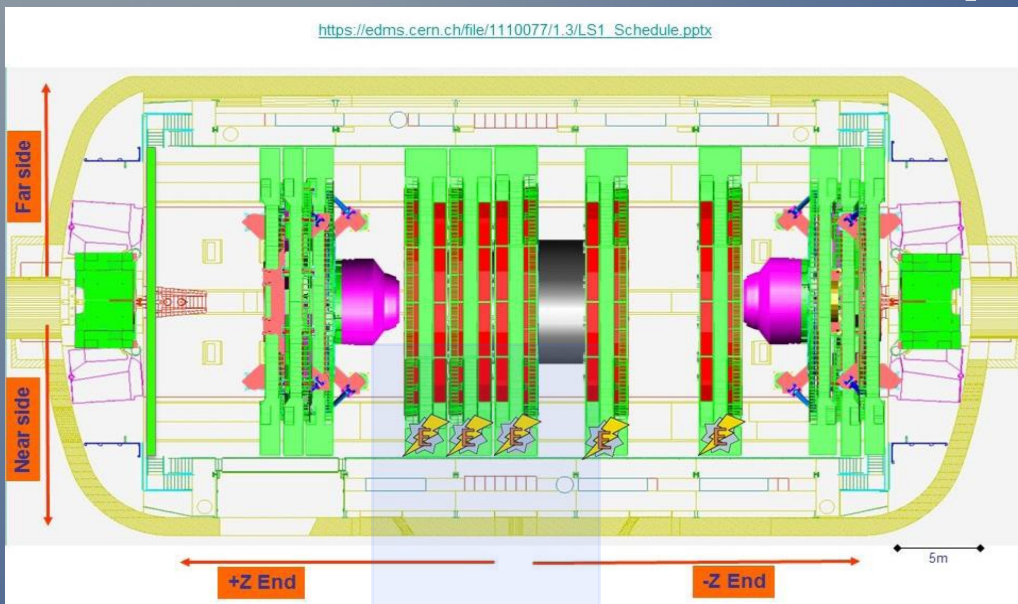


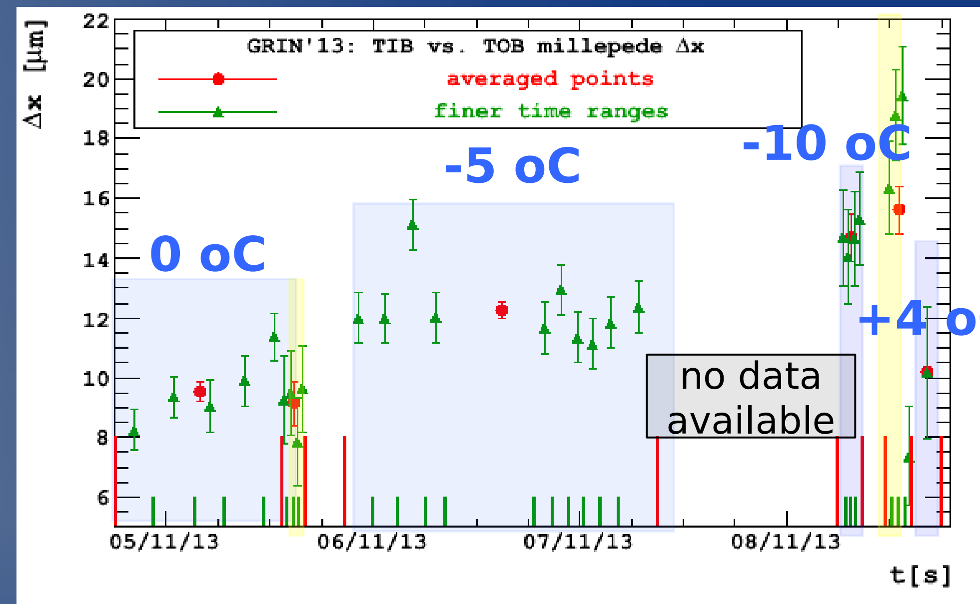




All the parameters are back to initial values within 10 μm/μrad

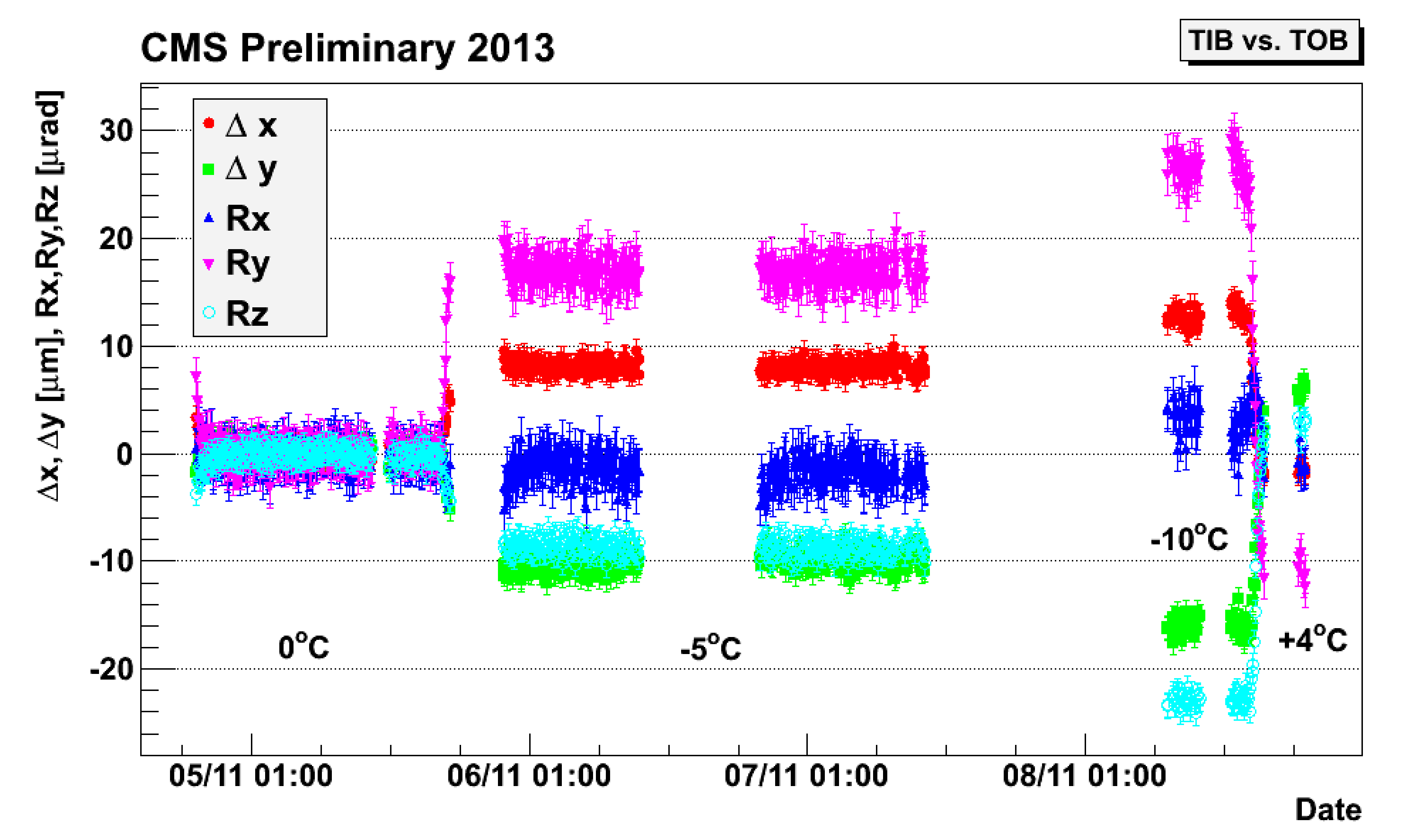
CMS Acceptance and Millipede



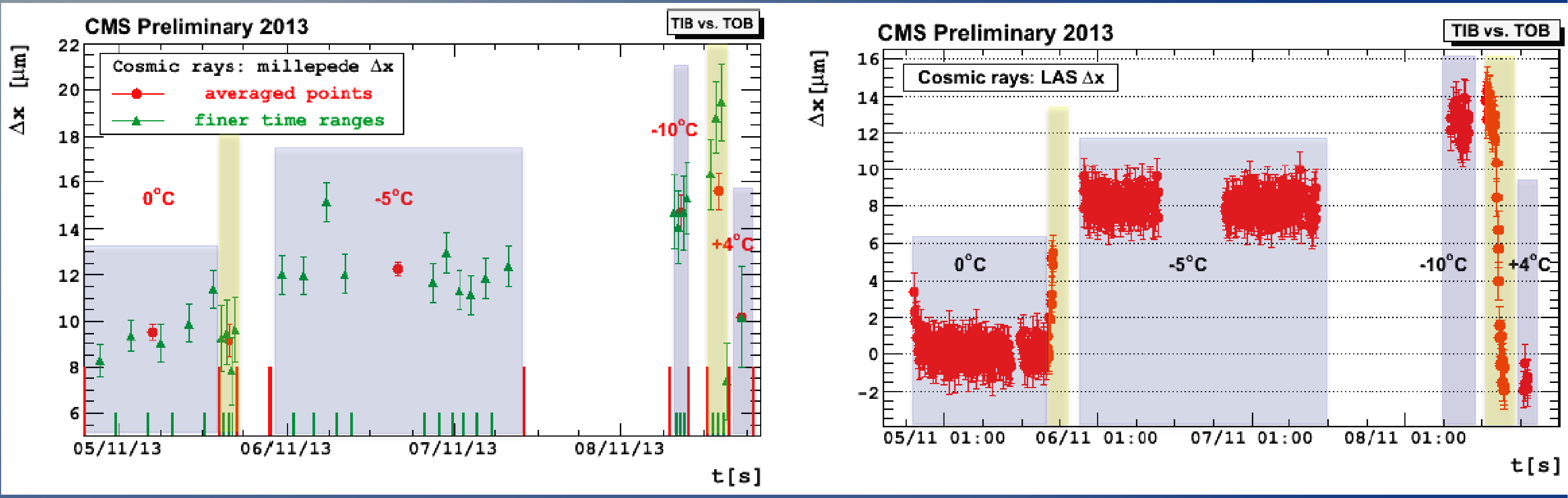


- Cosmics statistics is very limited at higher ($\eta > 1$) rapidity → only TIB vs TOB
- Tracker alignment modes adjusted in Millipede to cope with the LAS model: only Δx, Δy, Rx, Ry and Rz are considered, TIB and TOB are rigid cylinders, TOB is fixed and TIB can move
- In red – results for larger time intervals (averaged measurements), in green – results for finer time intervals
- Blue time intervals - recorded with constant temperature, yellow - during temperature transition

LAS: TIB vs TOB

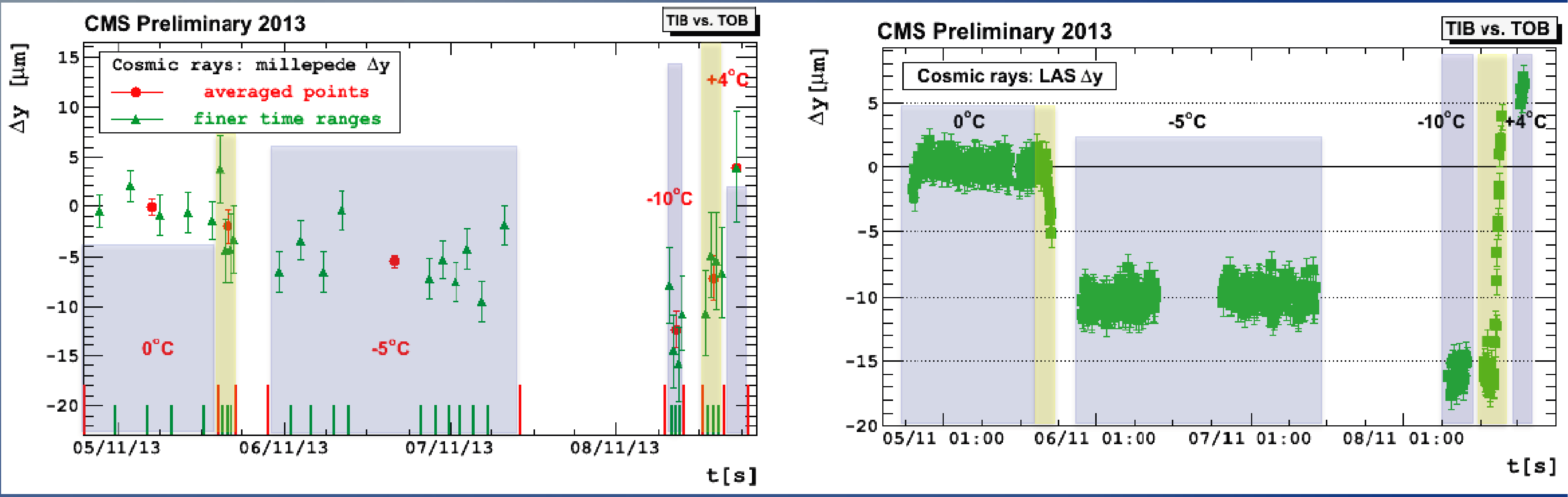


Comparison with Track Alignment: TIB Dx



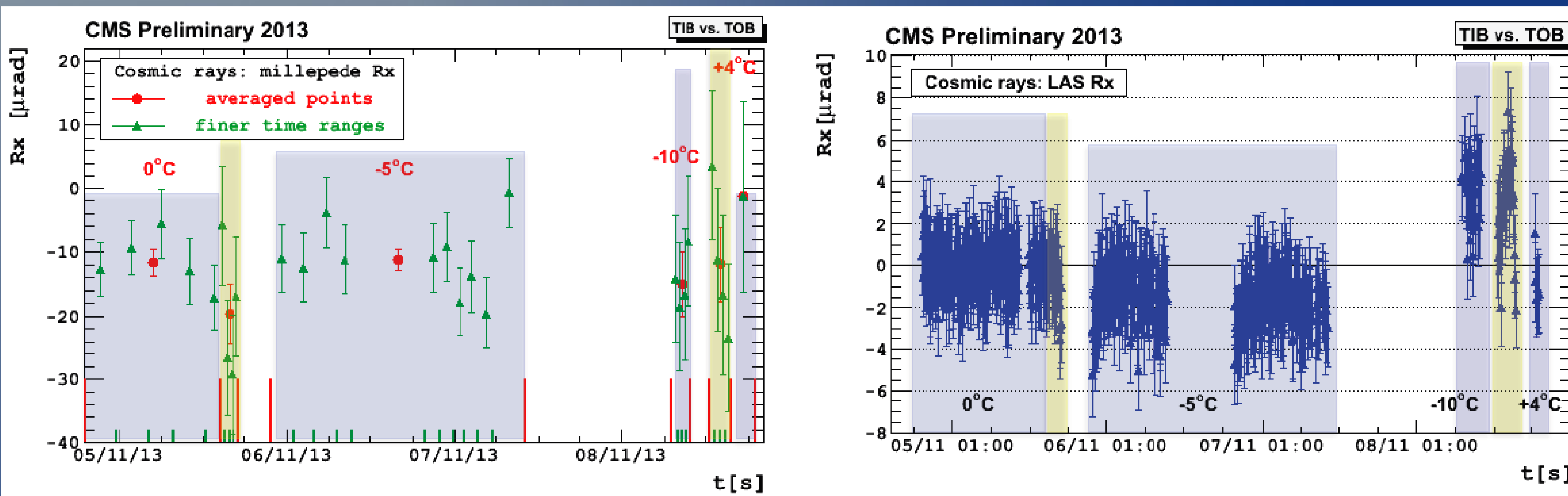
- TIB alignment parameter Δx with Millepede (left) and with LAS (right) when TOB is considered a fix rigid body
- relative movements to the observed position in Δx at 0◦C measured with Millepede are strongly correlated with the ones measured with LAS

Comparison with Track Alignment: TIB Dy



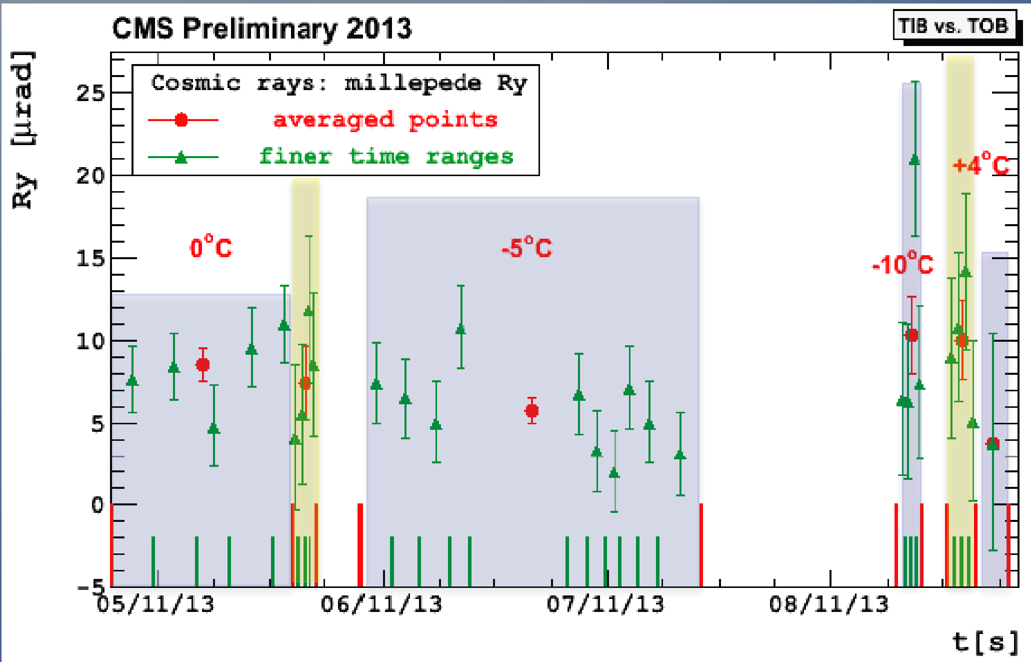
- TIB alignment parameter Δy with Millepede (left) and with LAS (right) when TOB is considered a fix rigid body
- relative movements to the observed position in Δy at 0◦C measured with Millepede are strongly correlated with the ones measured with LAS

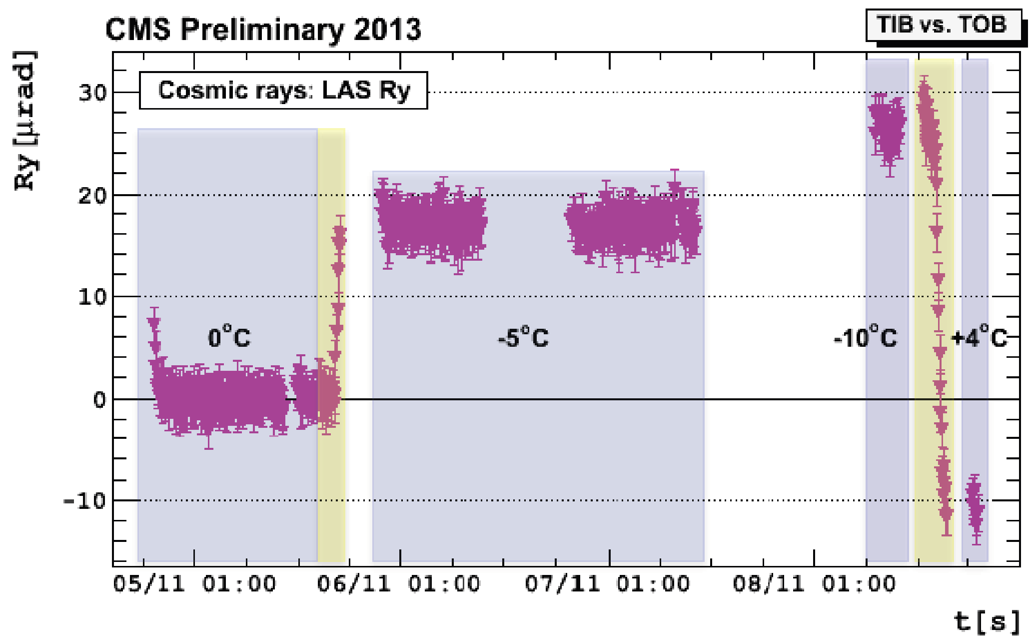
Comparison with Track Alignment: TIB Rx



- TIB alignment parameter Rx with Millepede (left) and with LAS (right) when TOB is considered a fix rigid body
- Millipede measurements of Rx shows weak sensitivity due to the mostly vertical orientation of cosmic particles

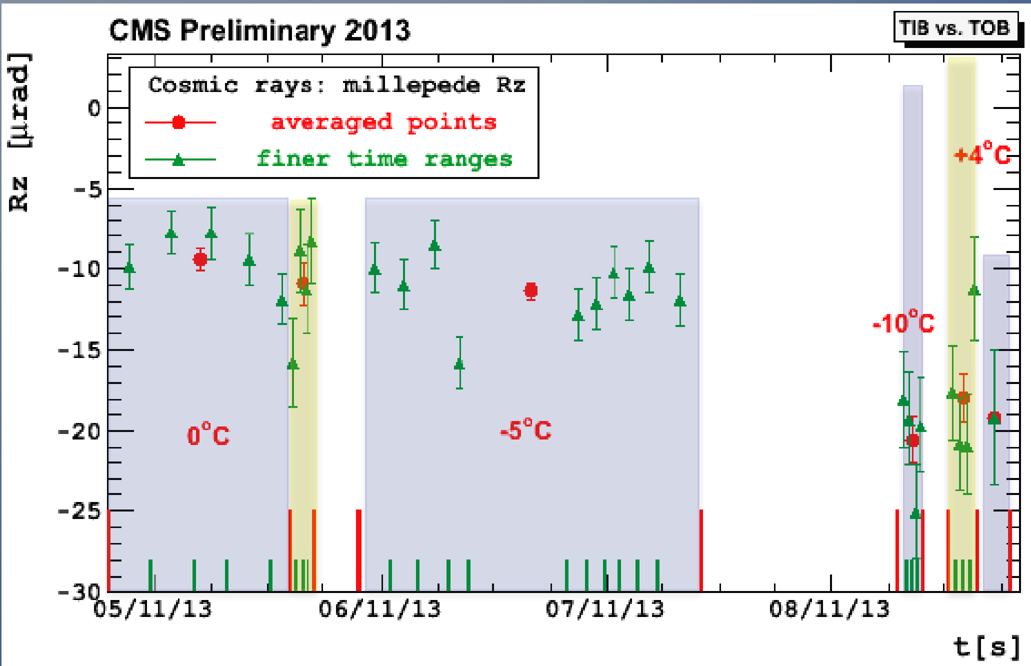
Comparison with Track Alignment: TIB Ry

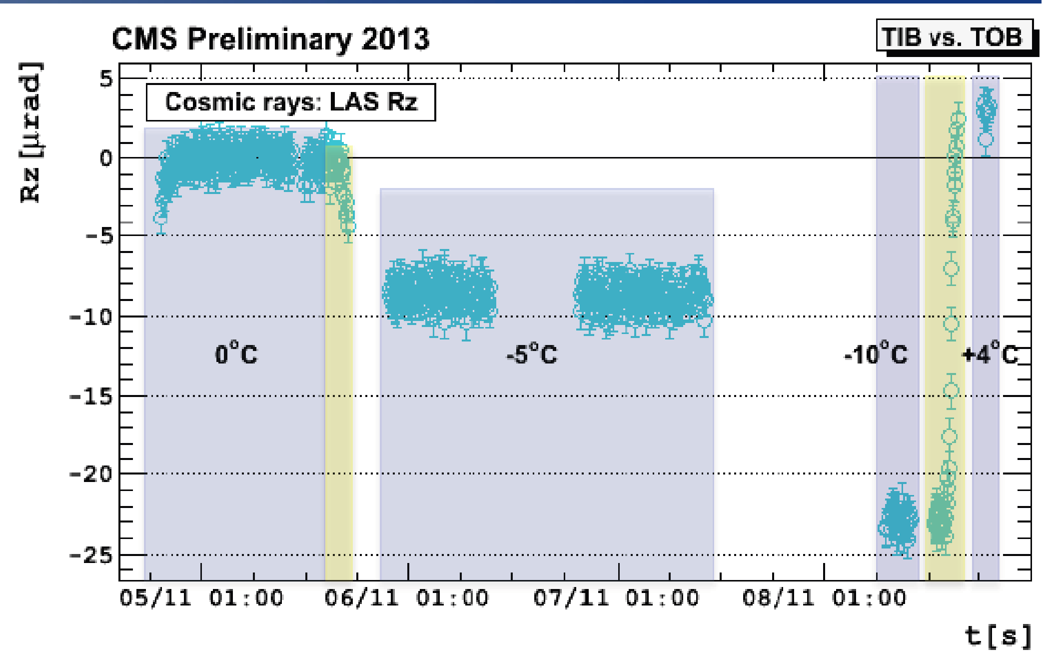




- TIB alignment parameter Ry with Millepede (left) and with LAS (right) when TOB is considered a fix rigid body
- Millipede measurements of Ry shows weak sensitivity due to the limited z spread of cosmic particles

Comparison with Track Alignment: TIB Rz





- TIB alignment parameter Rz with Millepede (left) and with LAS (right) when TOB is considered a fix rigid body
- Rz relative movements to the observed position at 0◦C measured Millepede are correlated with the ones measured with LAS

Summary on Tracker Stability

- Stability of TIB wrt TOB is within 10 μm/μrad, TEC+/TEC- wrt TOB is within 20-30 μm/μrad (2011 results)
- There are short term (~ one hour) movements of the Tracker subdetectors by several tens μm/μrad which are linked to temperature changes inside the Tracker after voltage was on
- During the cooling test in Nov 2013, when the Tracker was for the first time cooled down to -10 ^{0}C:
- TIB wrt TOB movements correlated with the temperature steps were observed. The range of the movements: +-30 μm/μrad. No hysteresis effect: after the tracker temperature was back to the initial value the TIB wrt TOB position was also back
- TEC wrt TOB movements of larger amplitudes were detected. Also without hysteresis.
- LAS results for the TIB wrt TOB movements were confirmed by procedure of alignment with cosmic tracks

LAS Experience
Pros

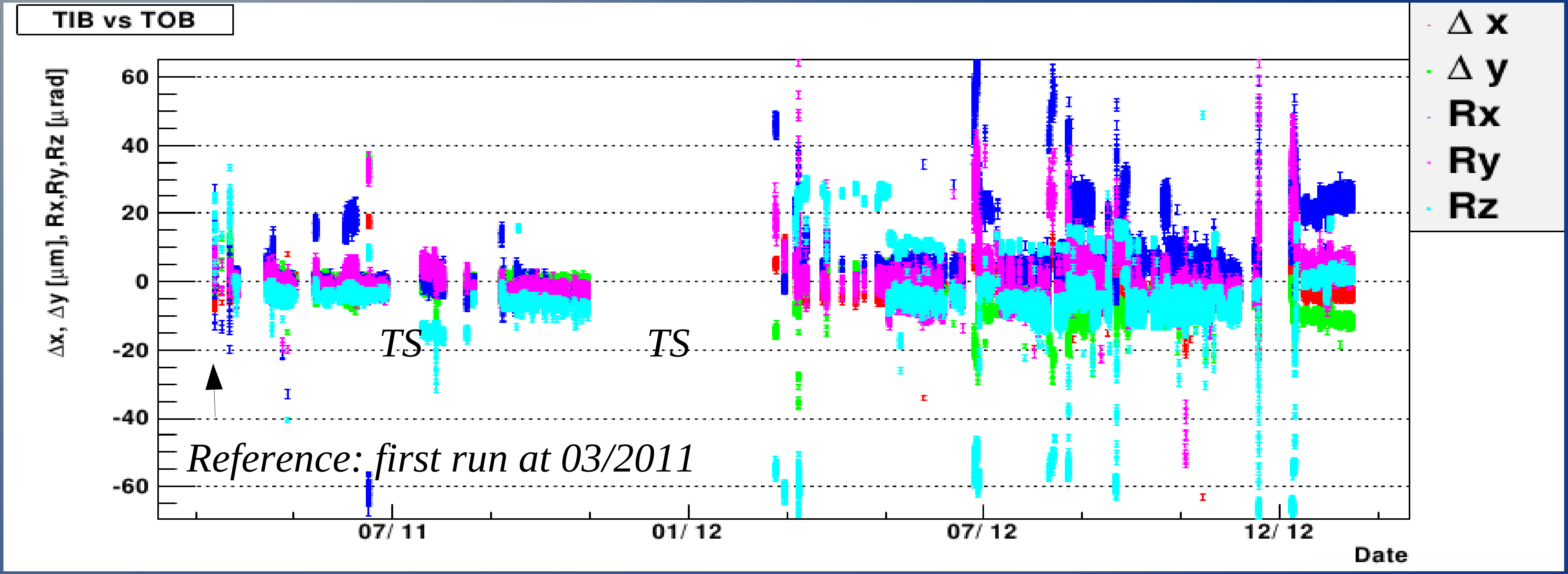
- *Direct measurements*: no transfer from system fiducial points to position of Si-modules
- *Multi-point*: each laser beam covers a long distance of the Tracker
- *Straightness monitor*: relevant for momentum reconstruction
- *Radiation hard*: no radiation sensitive elements inside TK volume
- *Reliable*: no lost beams, few lost modules (3 at TIB, 4 at TECs)
- *Fast*: one snapshot of 2000 triggers takes 20 sec

LAS Experience
Contras

- *Limited number of lines of sights*: no monitoring of Pixels, TIDs, TOB and TIB internally
- *Special treatment of Si-modules*: AR coating, hole in back-side metallization
- *Profile distortions*: absorption and diffraction. Requires spot reconstruction algorithm applicable to different signal shapes
- *Laser beam movements*: beams change direction and offset, but not straightness. Additional degrees of freedom at a small cost of resolution.
- *No dedicated DAQ*: impossible to commission independently (before!) of the rest of the Tk, no monitoring if Tk is off
- *No in-situ calibration*: impossible to verify reconstructed geometrical parameters by comparison with known movements

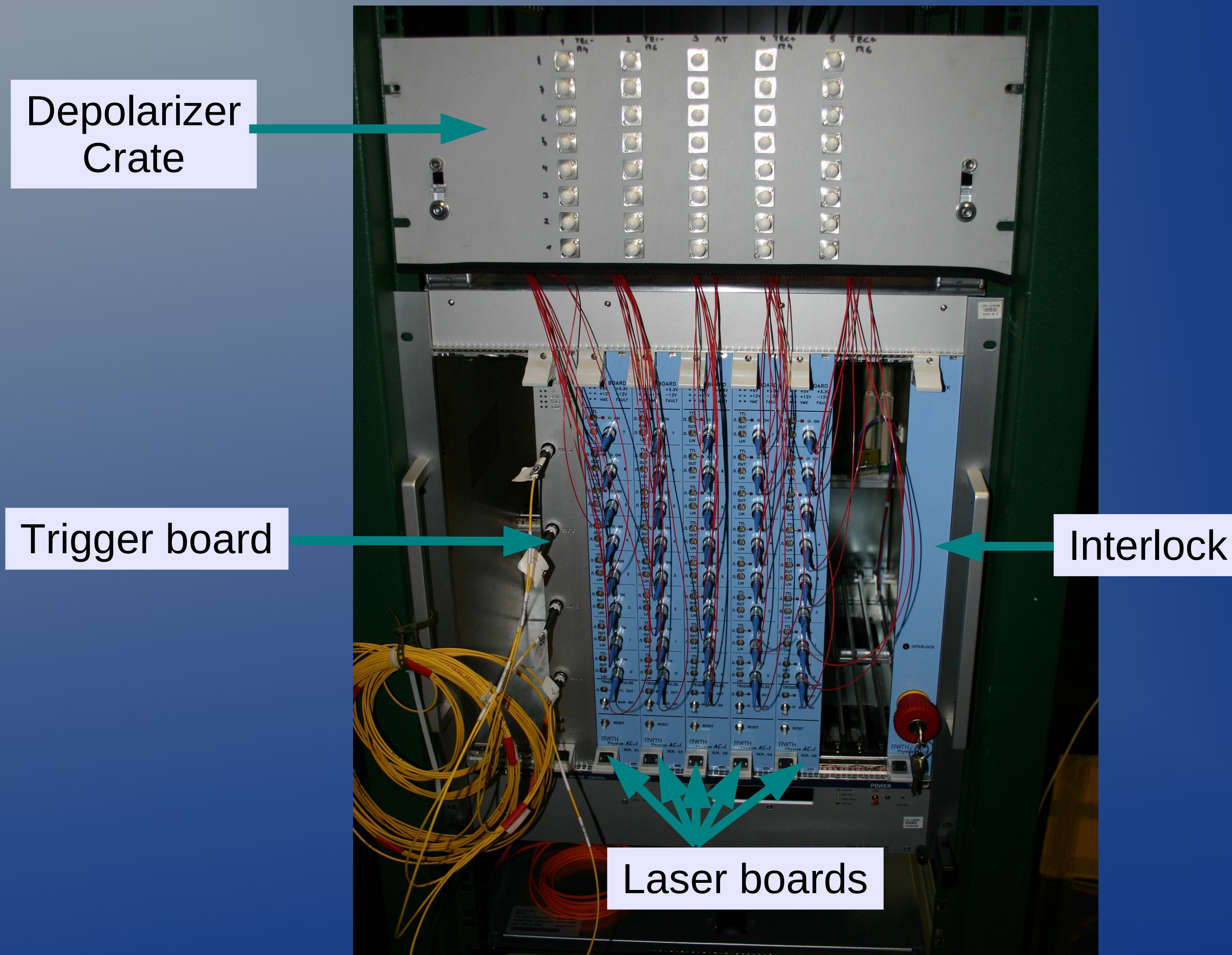
Back Up

Long Term Tracker Stability TIB wrt TOB in Run 1

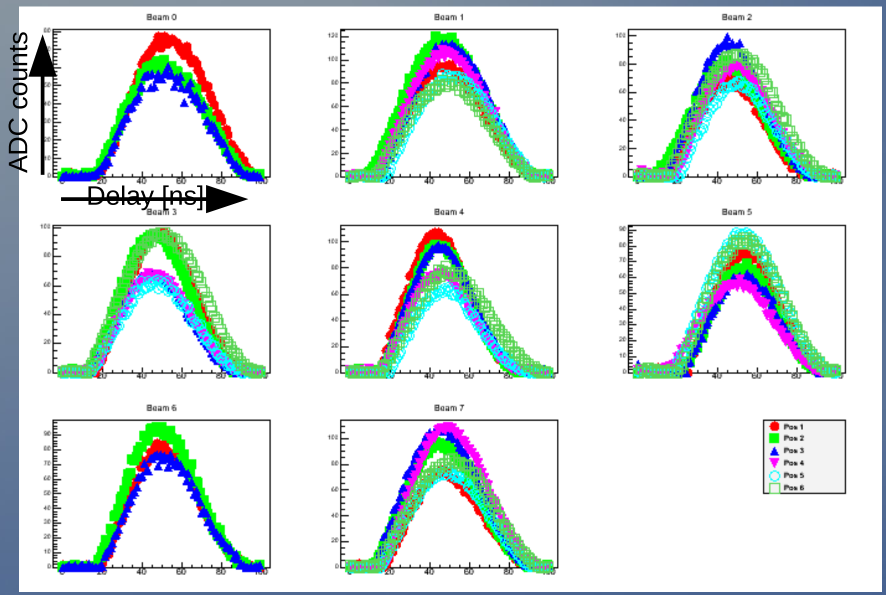


- Data points were taken during physics runs in steps of 5 min.
- Compressed plot: 1 point averages over several measurements
- Long term stability of the alignment parameters are within 10 µm / µrad
- Short term variations are connected with technical stops

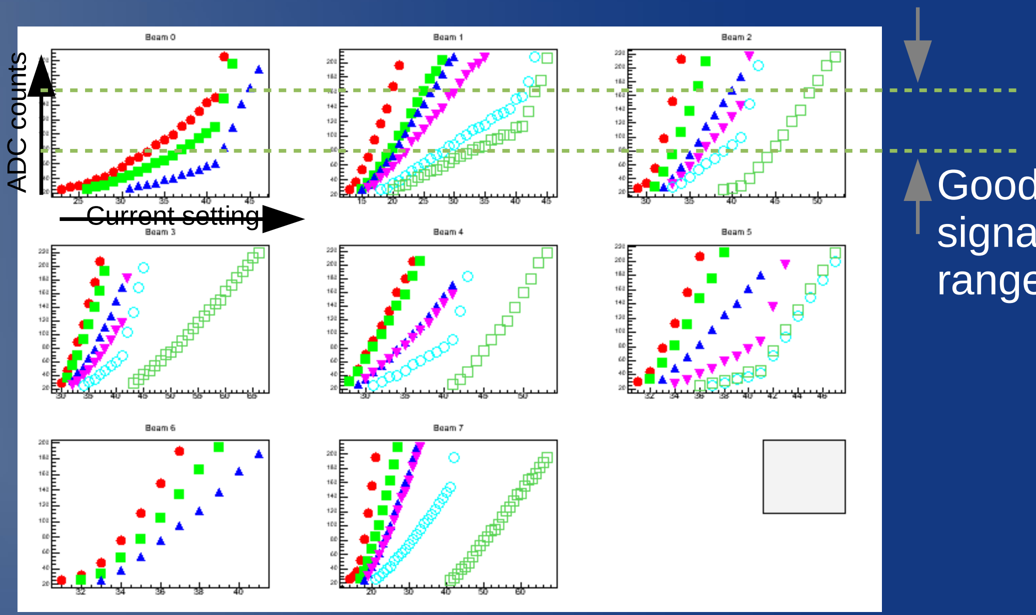
Laser Rack



Calibration of Laser Diodes Delays and Intensities



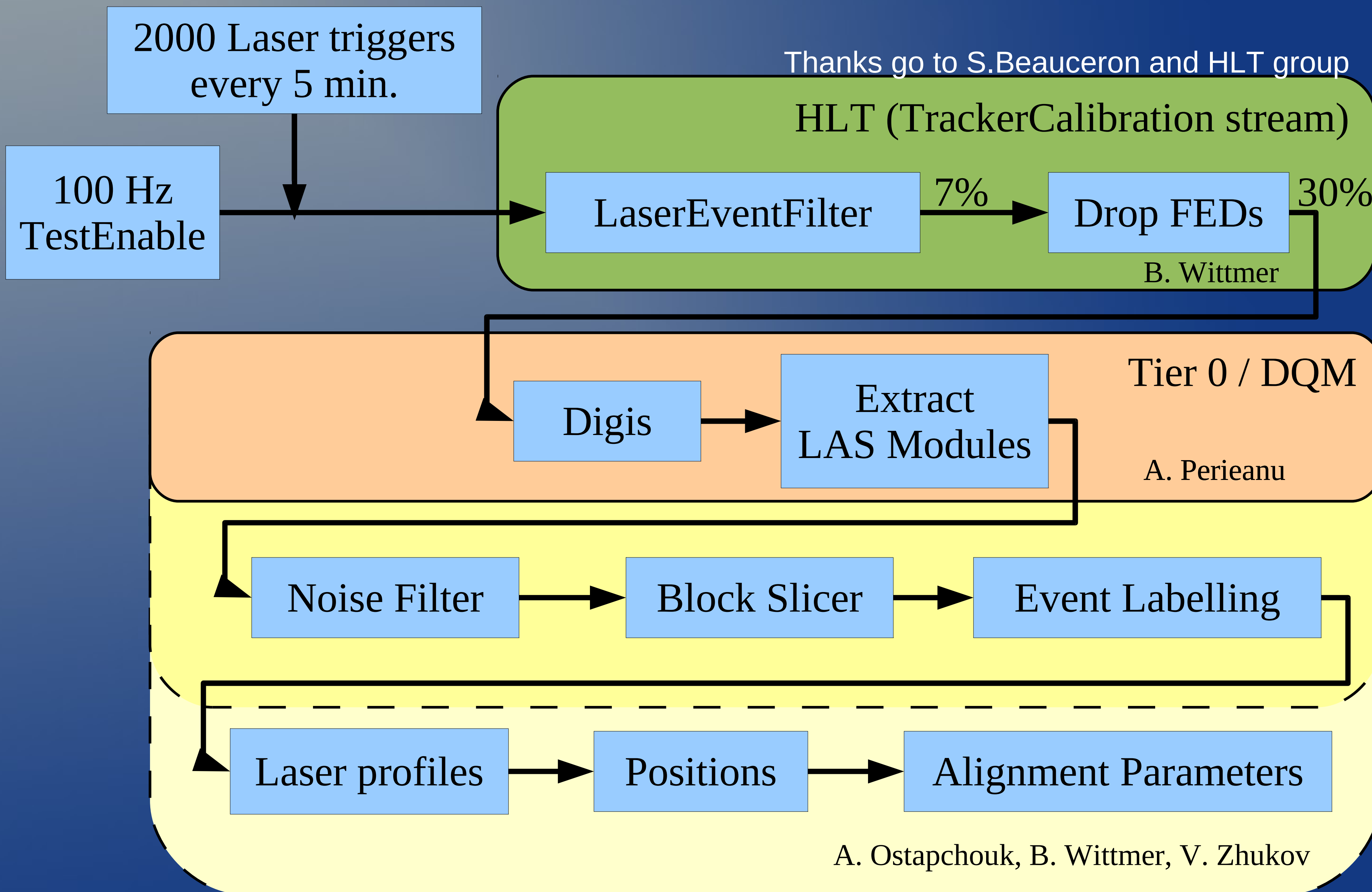
TIB fine delay



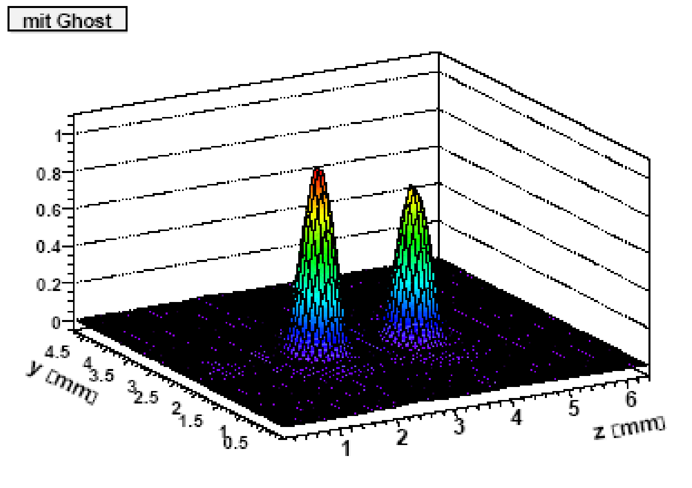
TIB intensity

- Coarse delay scan determines bunch crossing for Laser Trigger
- Fine delay scan aligns all modules in time
  - 100 steps of 1 ns
  - Repeated for every setting in intensity scan
- Intensity scan goes across 67 settings for the Diode current

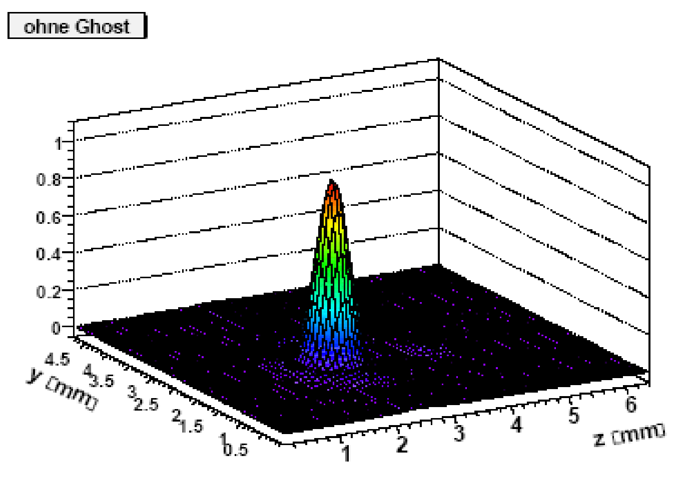
Tracker Laser Event Data



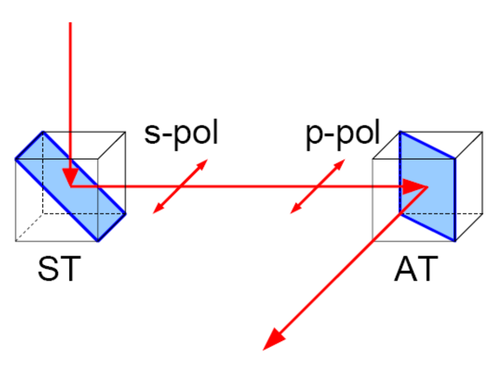
Polarization in Alignment Tubes

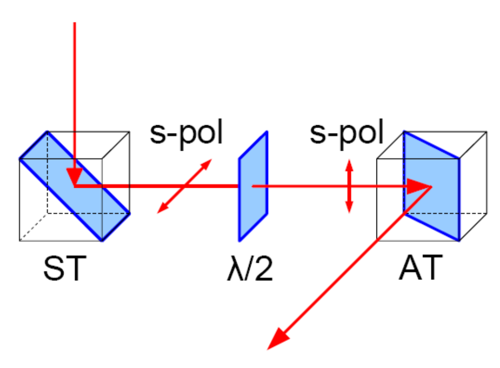


(a) Strahlprofil mit Ghost



(b) Strahlprofil ohne Ghost





- Reflection in beam splitter and AT mirrors depends on polarization
- Polarization mismatch generates 'ghosts'
- Cured with λ/2 plate