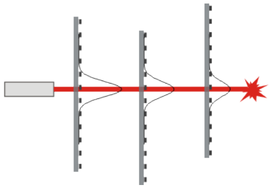
Laser Alignment System of the CMS Tracker



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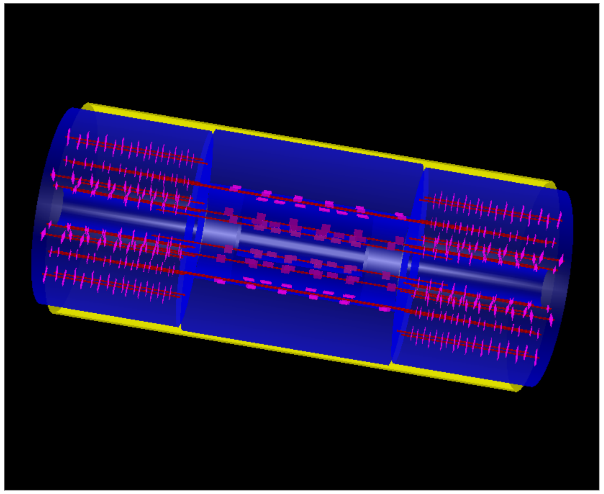


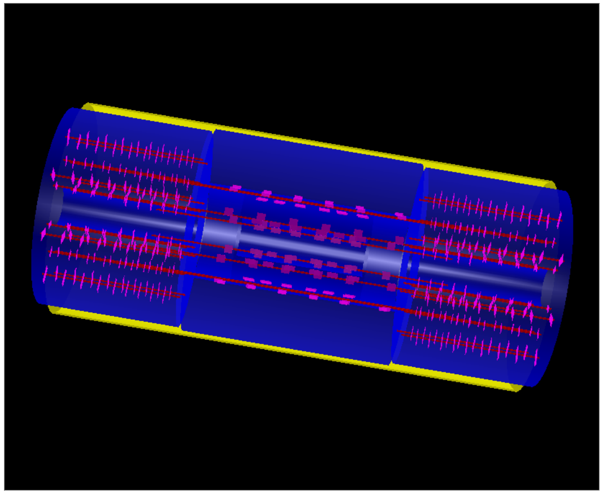
Outline

- Goals and Concepts
- Layout, Components, Parameters
  - Mechanics, Electronics
  - Alignment Parameters
- Results
  - Absolute reconstruction
  - Stability monitoring
- Evaluation of the system
  - Positive features
  - Negative ones
  - Possible alternatives
- Conclusions

Purpose of Tracker Laser Alignment System

- Deformations of Tracker could be possible due to temperature, humidity or B-field
- Monitor alignment of mechanical structure
  - Align endcap discs with respect to each other
  - Align Inner/Outer Barrel and Endcaps with respect to each other
- Monitor changes in alignment < 20 μm
- Precision of absolute alignment < 100 μm
  - Ensures stable pattern recognition

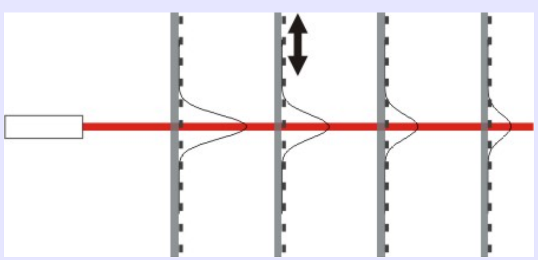
Working Principle and Layout



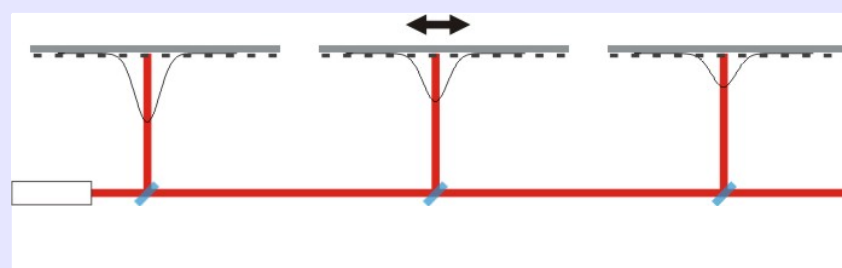
Working Principle

- Use the Tracker microstrip sensors to detect the beams
- Send several laser beams through the Tracker
- From changes of the measured laser spots infer movements of the modules
- Light absorption in Si : 10 cm^{-1} at λ = 1080 nm and T = 300 K

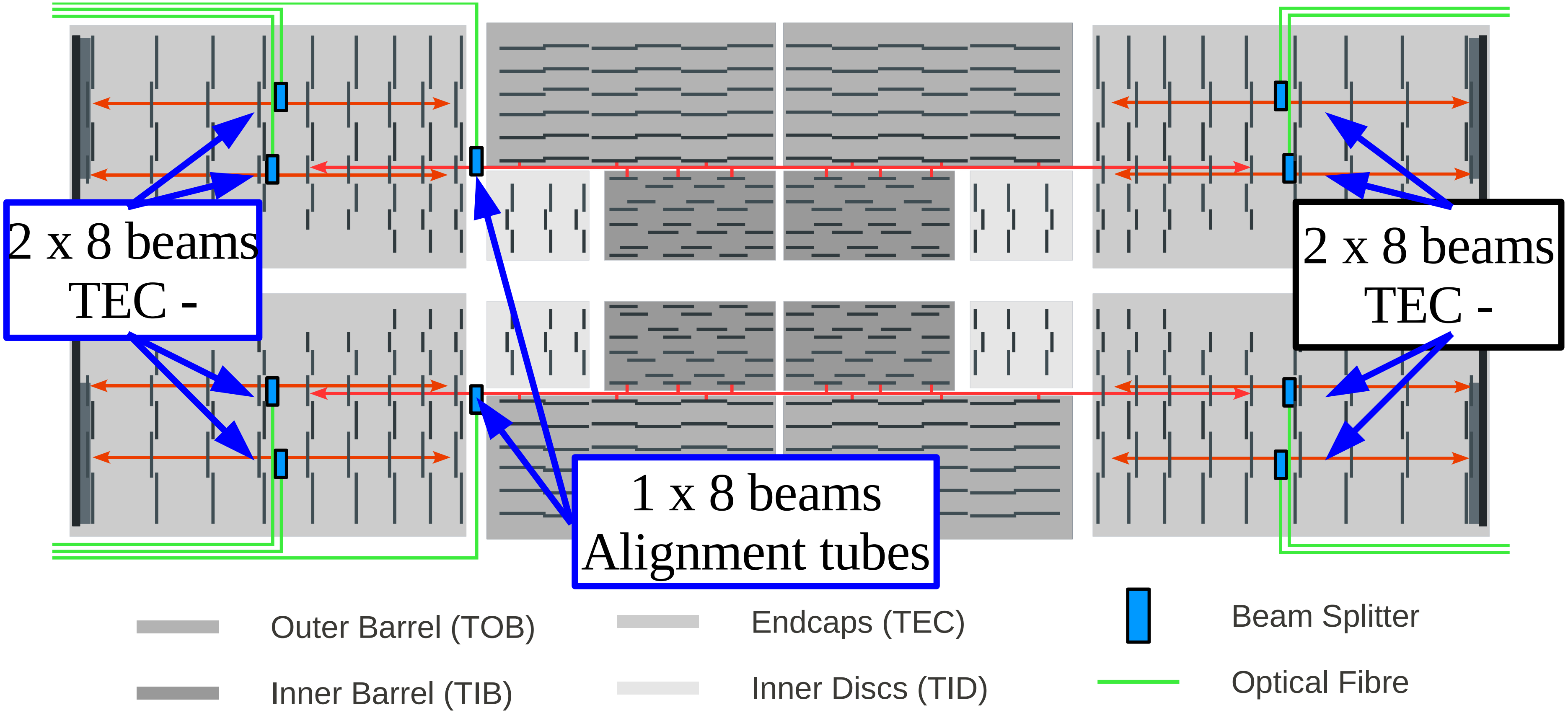
Variant 1 (endcap alignment): Beam passes through several layers of sensors (Silicon is semitransparent to infrared light)



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



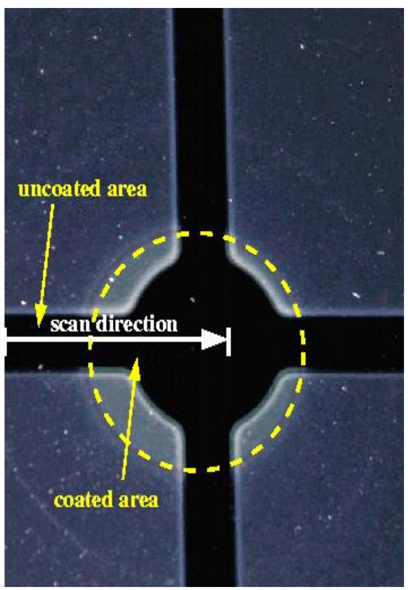
Overview



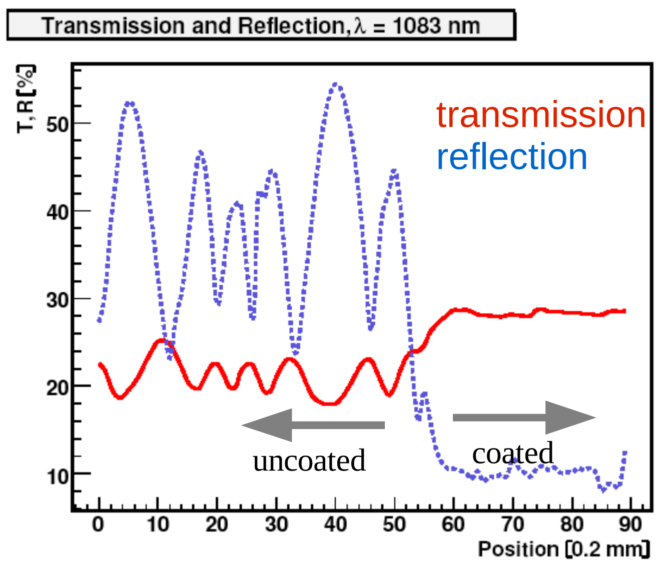
- 32 laser beams in each Endcap, 8 laser beams for Barrel/Endcap alignment
- 434 Modules out of 15.000 are hit by laser beams

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

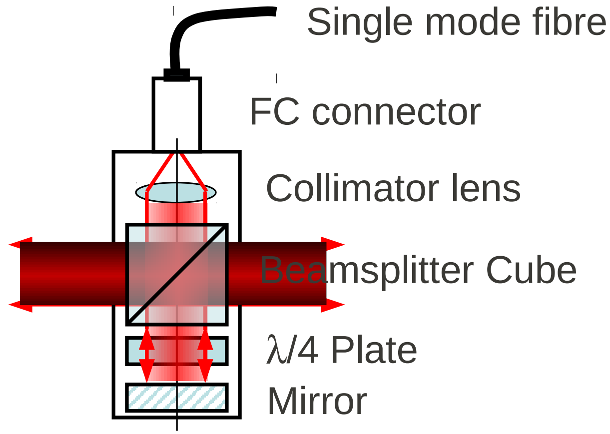


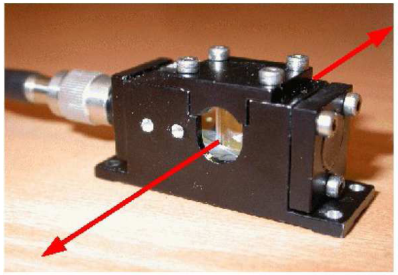
<u>AR coating</u>

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

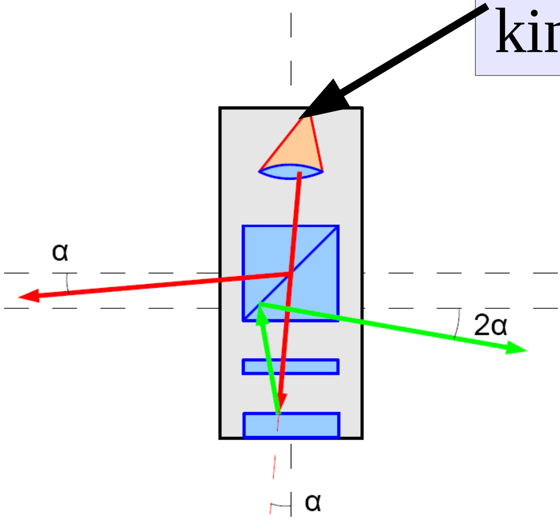
Beam Splitters

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





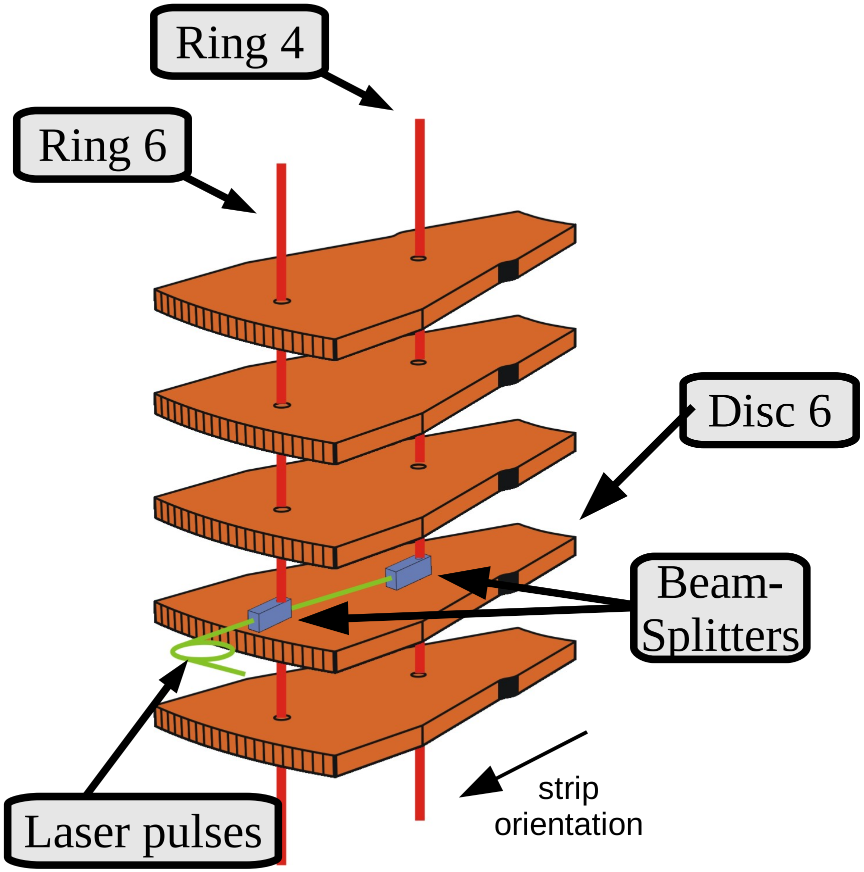
misaligned fibres lead to a kink between the beams

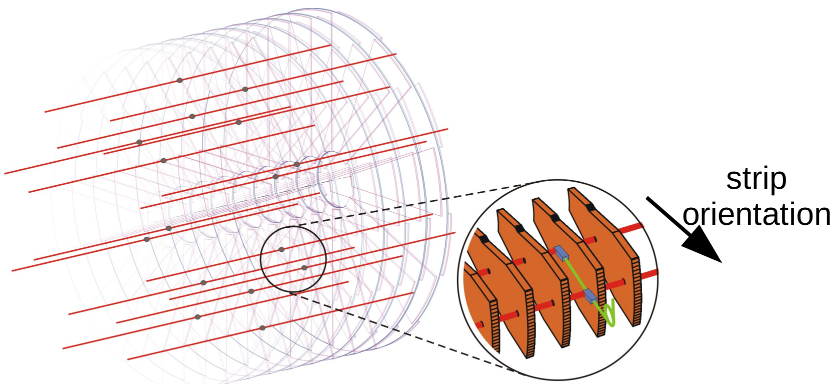


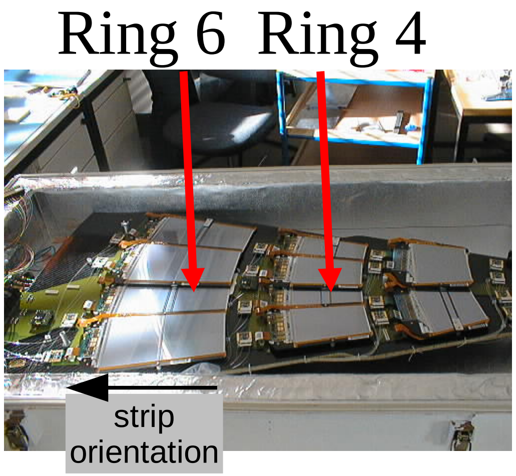
- All beam splitters have been calibrated in the lab for collinearity with the final fibre connected.
- This data is used to correct the absolute LAS measurements.

Internal Endcap Beams

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

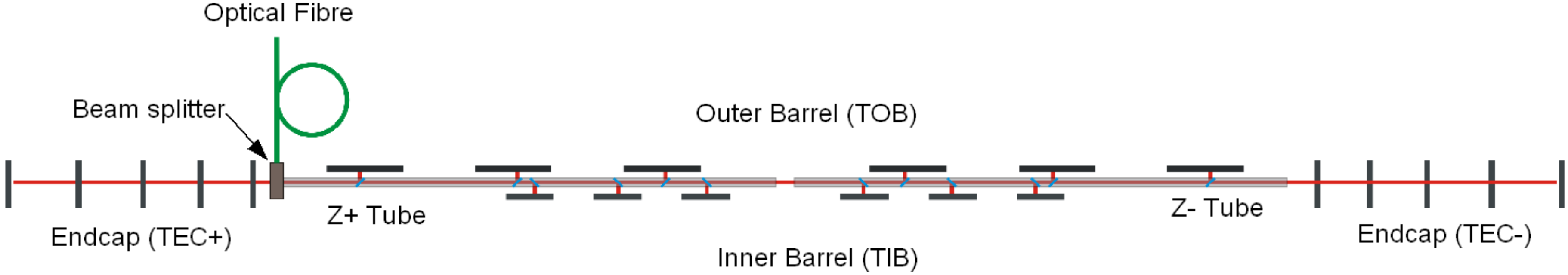






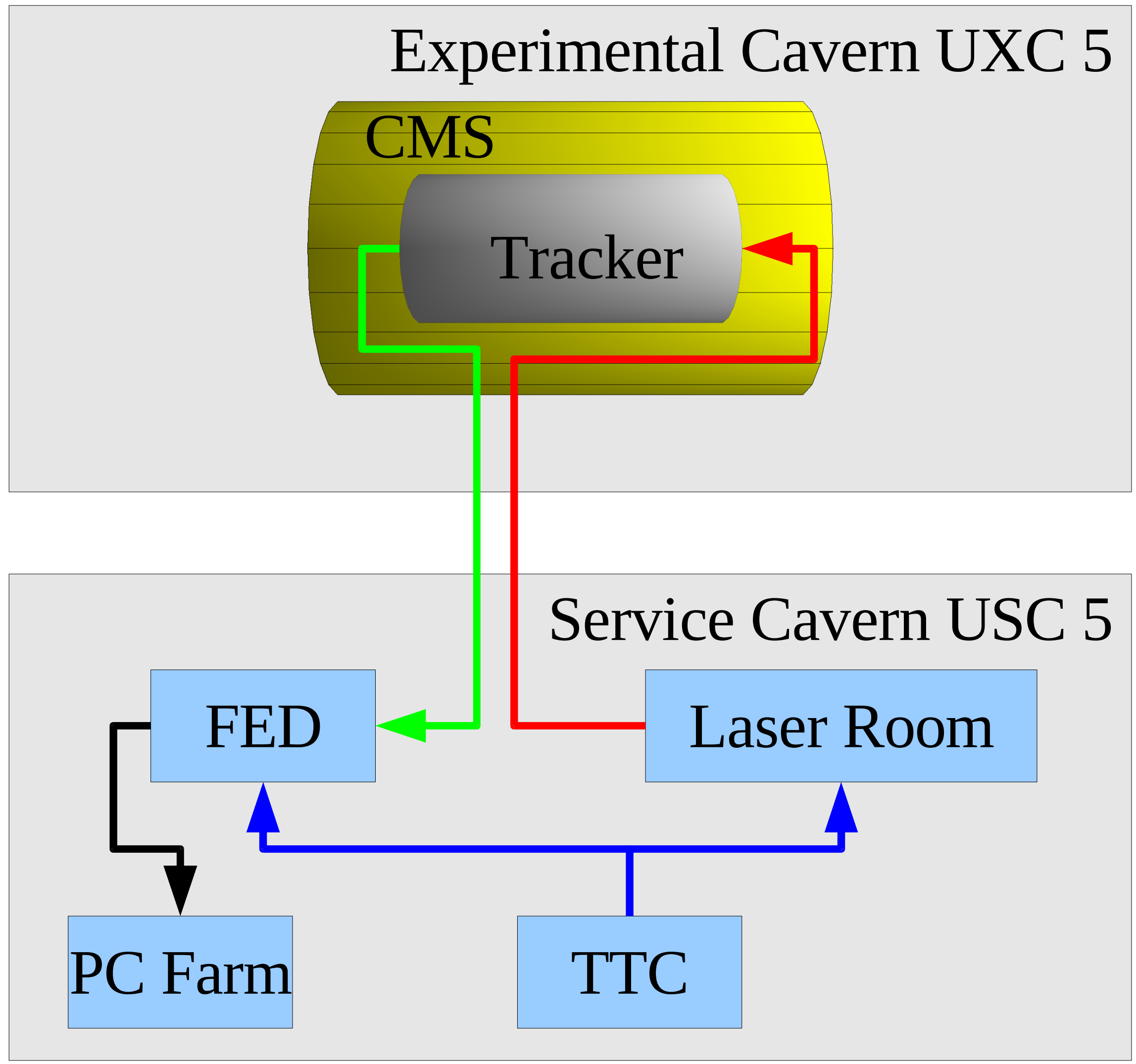
Alignment Tubes

- 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)
- Collinearity of beamsplitters and complanarity of AT beams have been calibrated in lab
- This data is used to correct the absolute LAS

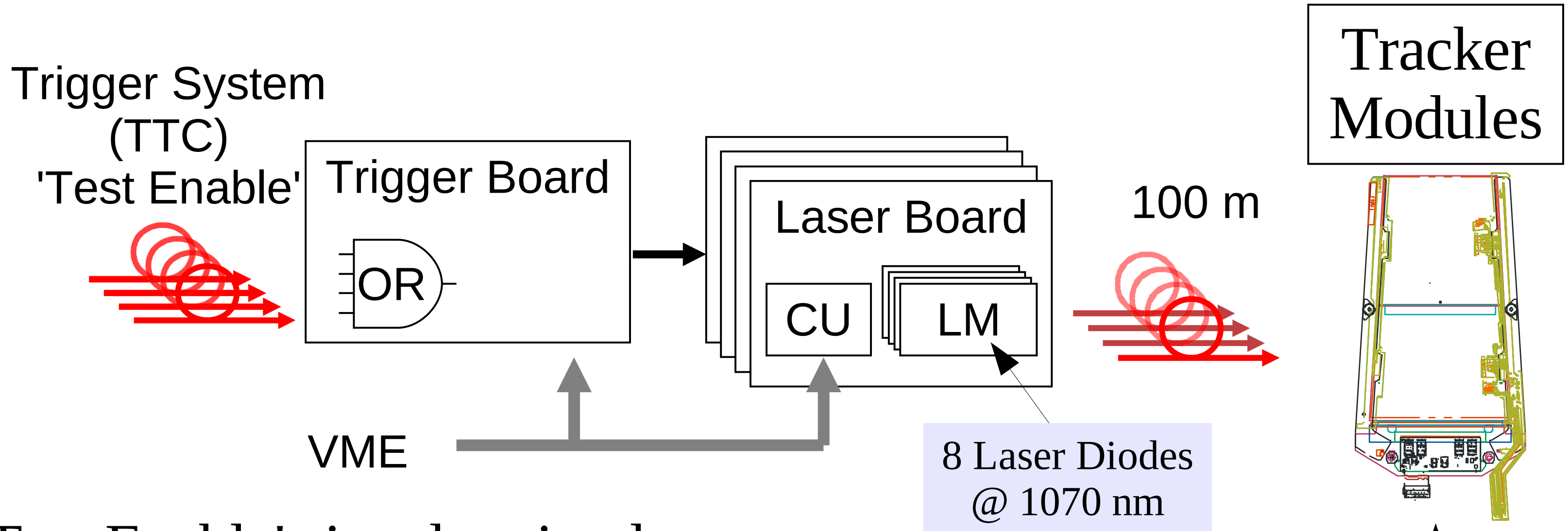


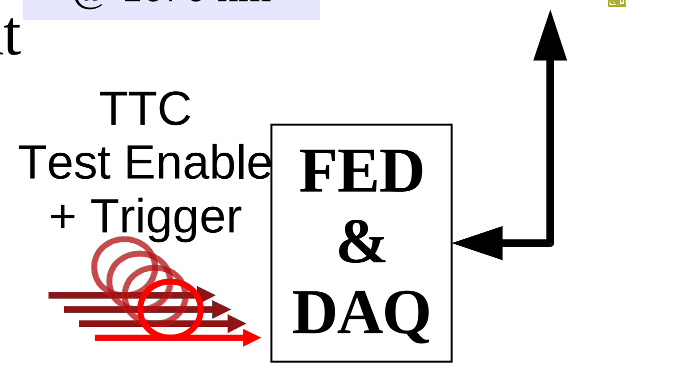
Laser Pulse Generation

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



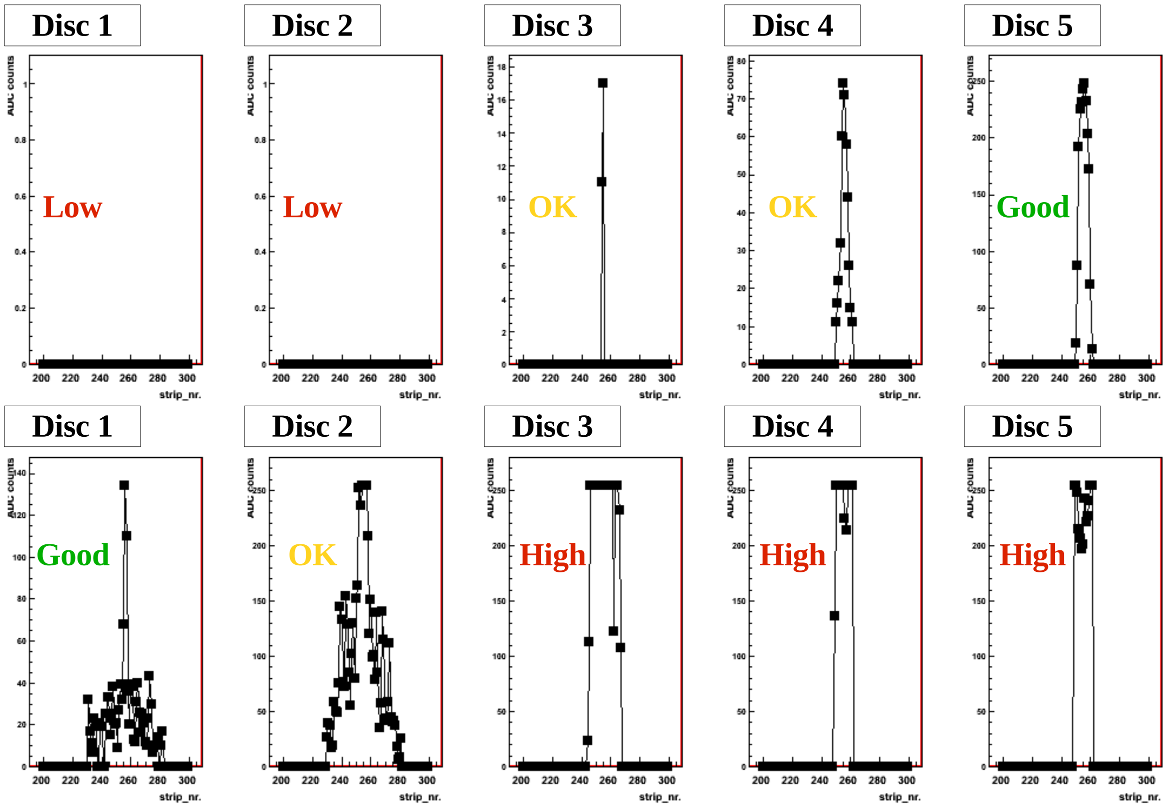
Laser Pulse Generation





- 'Test Enable' signal emitted at constant 100 Hz
- 'Test Enable' signal fires the Lasers (synchronized with bunch crossings)
- Laser Boards stop firing after a fixed number of triggers (0-3200)

Reaching different TEC Layers

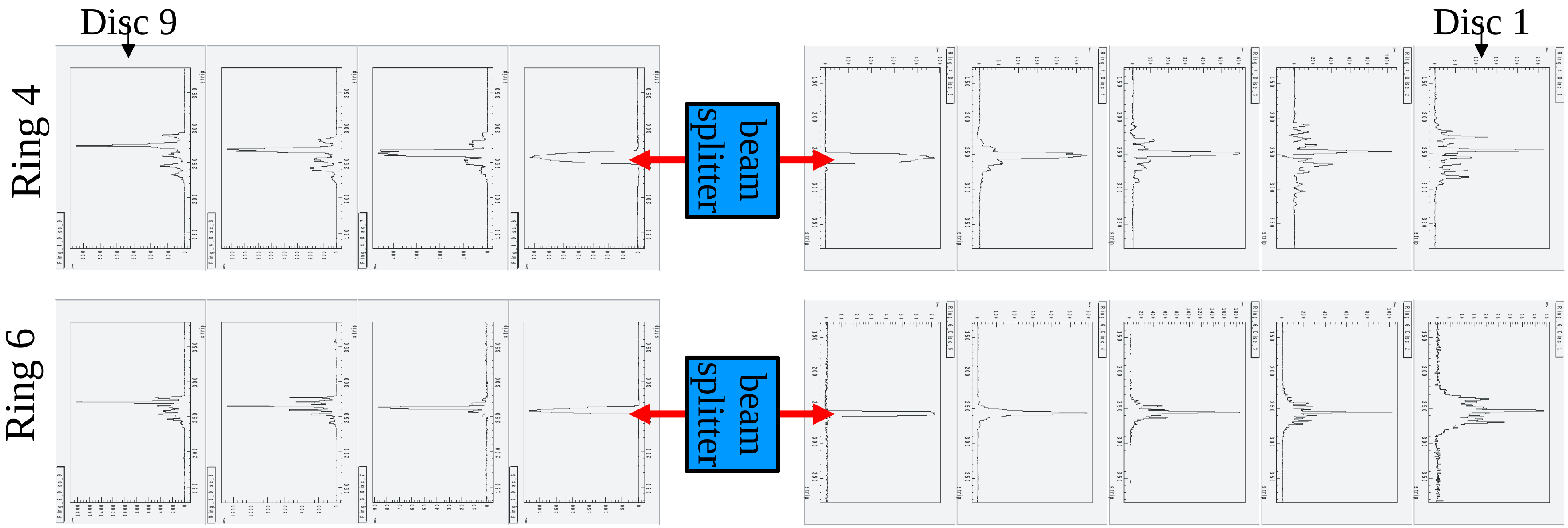


Low intensity:
Disc 1,2 no signal
Disc 5 good

High Intensity:
Disc 1 good
Disc 2-5 satureted

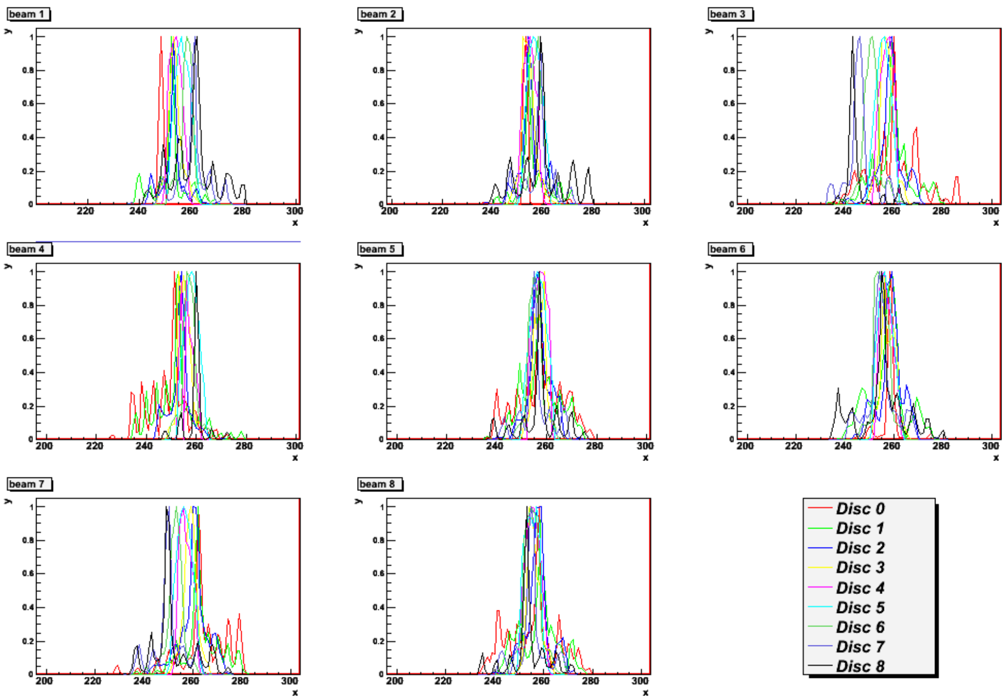
- The laser intensity is adapted event by event to reach different layers for optimal signal quality
- Max. 5 layers => 5 different intensities

Endcap Beam Profiles

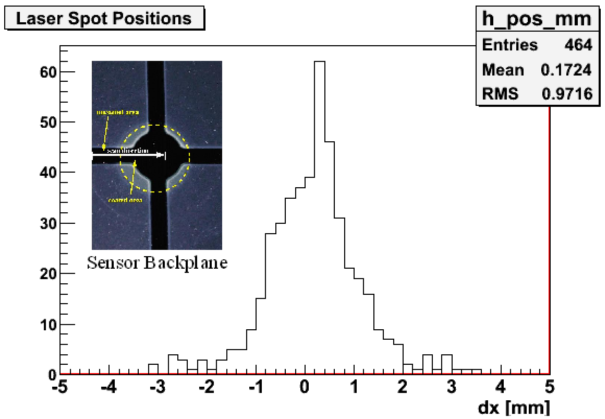


- Intensity adapted for each disc (20% transmission per layer)
- 200 Events per intensity to increase S/N
- Baseline correction was performed

Commissioned profiles



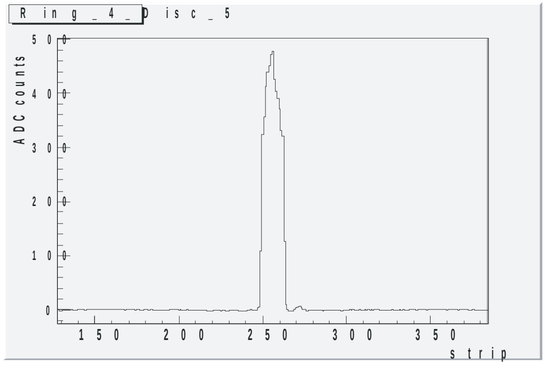
Endcap profiles (TEC- Ring 4)



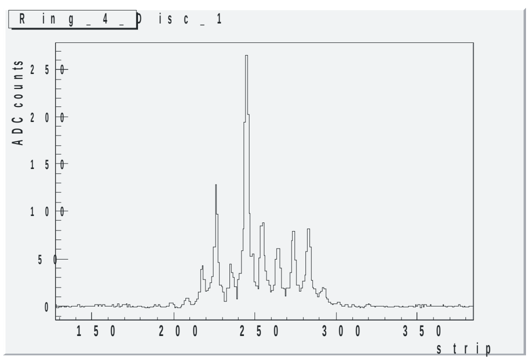
Positions within dynamic range

- Good signal on almost all modules
  - 6 Endcap modules that were not read out are missing
  - 5 Endcap modules (TEC+) show profiles with bad shapes
- All measured profiles are within the dynamic range

Non-Gaussian Profiles



Laser beam profile
next to the beam splitter



Laser beam profile
after 4 layers of sensors

Distortion of Beam Profiles due to

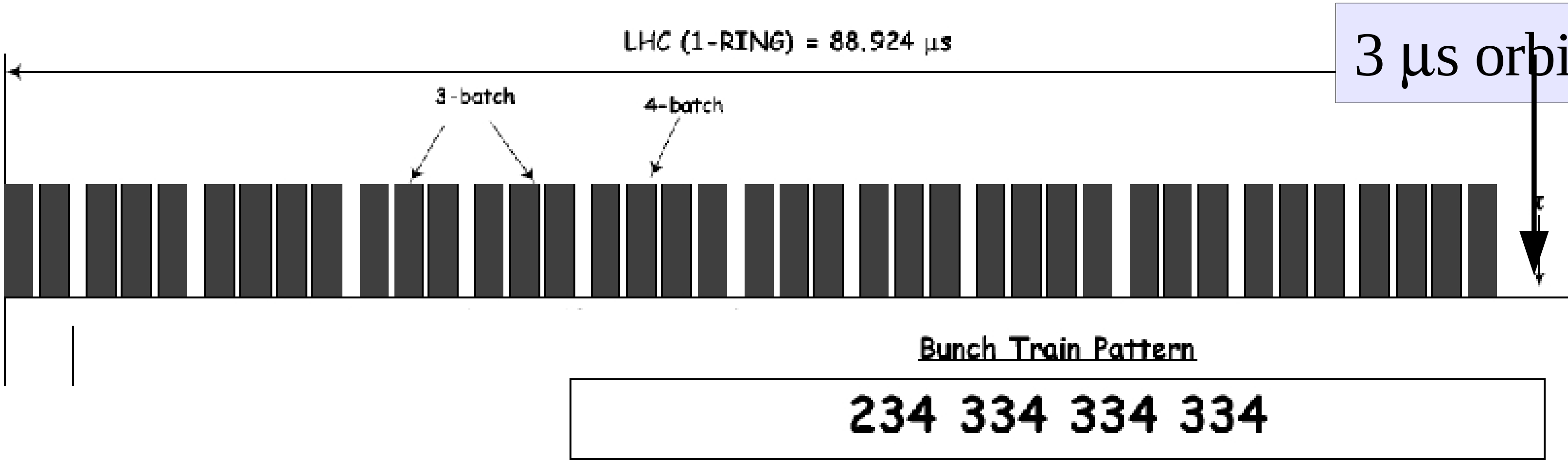
- Non-perfect beam optics (depends on distance to beam splitter)
  -> asymmetric non-Gaussian profiles
- Baseline distortion due to large charge
  -> asymmetric profiles
- Diffraction at microstrips (depends on amount of layers passed and strip pitch)
  -> side maxima
- Interference inside silicon bulk due to multiple reflections
  -> asymmetric non-Gaussian profiles

Limits position measuring accuracy
to 20-30 µm

Modes of Operation

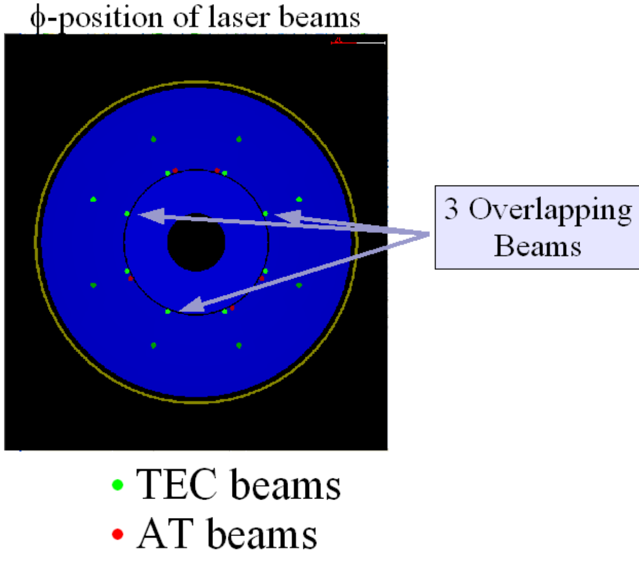
- Dedicated Alignment Runs
  - Run with local or global DAQ
  - No zero suppression
  - All tracker parameters optimized for LAS
- Laser Alignment during Physics Runs
  - 'Test Enable' signal arrives in orbit gap (3μs)
  - Zero suppressed mode
  - Tracker parameters optimized for particles

3 μs orbit gap



Required Triggers

- 5 different intensities for Endcap layers
- Alternate operation of AT/TEC beams due to beam overlap
- 200 events per module to reduce noise (very conservative choice)
- 5 x 2 x 200 = 2.000 events
- This is called a 'snapshot' and allows to compute the alignment constants
- 100 Hz 'Test Enable' Trigger rate
- 'Snapshots' are taken regularly to monitor Tracker alignment
(every 5 min.)

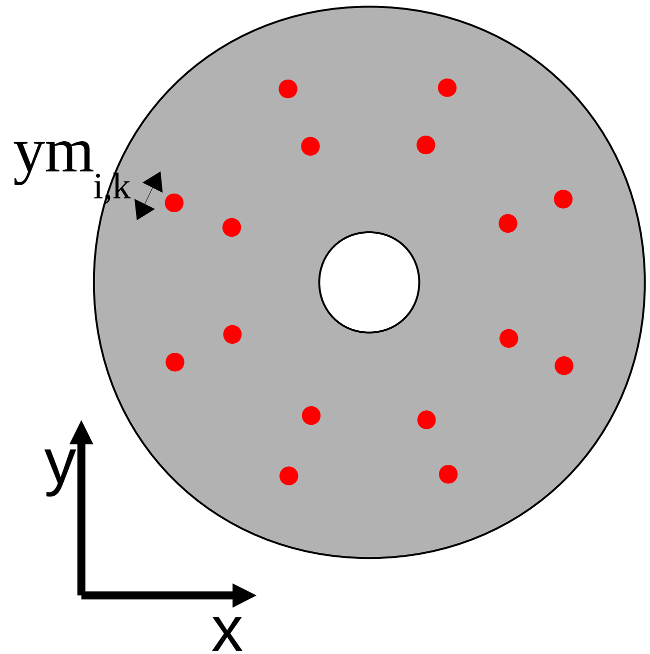


Laser Alignment Output

- Data Quality Monitoring
  - Quality of LAS data
  - Quick feedback on Tracker stability
- Generation of Tracker Geometry correction
  - LAS standalone alignment
  - Can be applied online on top of existing alignment
- Input to combined Alignment
  - Combine Laser Alignment Data with track-based alignment, stability, weak modes

Internal Endcap Alignment

- 2 x 8 Beams
  (index i, position θ, radius R_0)
- 9 Discs (index k, position z)
- Consider translations in x and y and rotations ϕ (around z)
- Beams are straight, but can move (2 visible dof: θ_{Ai}, θ_{Bi})



Positions of laser spots as function of alignment parameters:

$$ym_{i,k} := \left(-\Delta\Phi_k\right)R_0 + \sin\left(\theta_i\right)\Delta x_k + \left(-\cos\left(\theta_i\right)\right)\Delta y_k + \left(-\left(\frac{z_k}{L} - 1\right)\right)\Delta\theta_{Ai}R_0 + \frac{-z_k}{L}\Delta\theta_{Bi}R_0$$

Collective movements of discs cannot be distinguished from collective movements of beams!

TEC Alignment Parameters

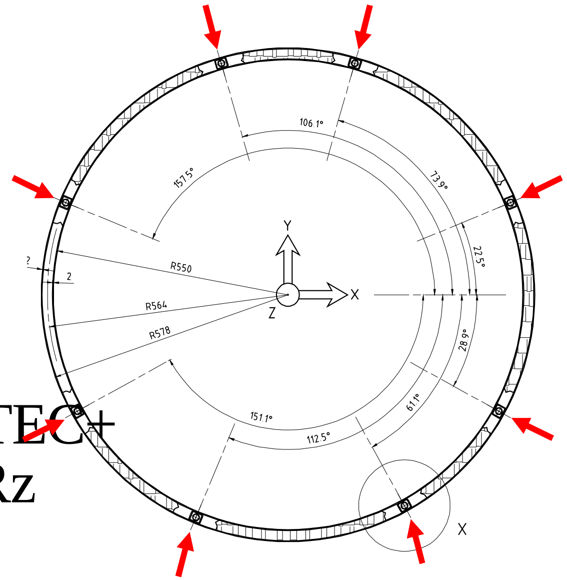
- $\Delta\varphi_k$: Individual disc rotation around z-axis.
- Δx_k: Individual x-displacement of each disc.
- Δy_k: Individual y-displacement of each disc.
- $\Delta\theta_{ai}$: Individual beam displacement in φ on disc 1.
- $\Delta\theta_{bi}$: Individual beam displacement in φ between disc 1 and disc 9.
- $\Delta\varphi_0$: Rotation of all discs with respect to the beams.
- Δx_0: Displacement in x of all discs with respect to the beams.
- Δy_0: Displacement in y of all discs with respect to the beams.
- $\Delta\varphi_t$: Collective torsion of discs with respect to the beams.
- Δx_t: Collective shearing in x-direction of discs with respect to the beams.
- Δy_t: Collective shearing in y-direction of discs with respect to the beams.

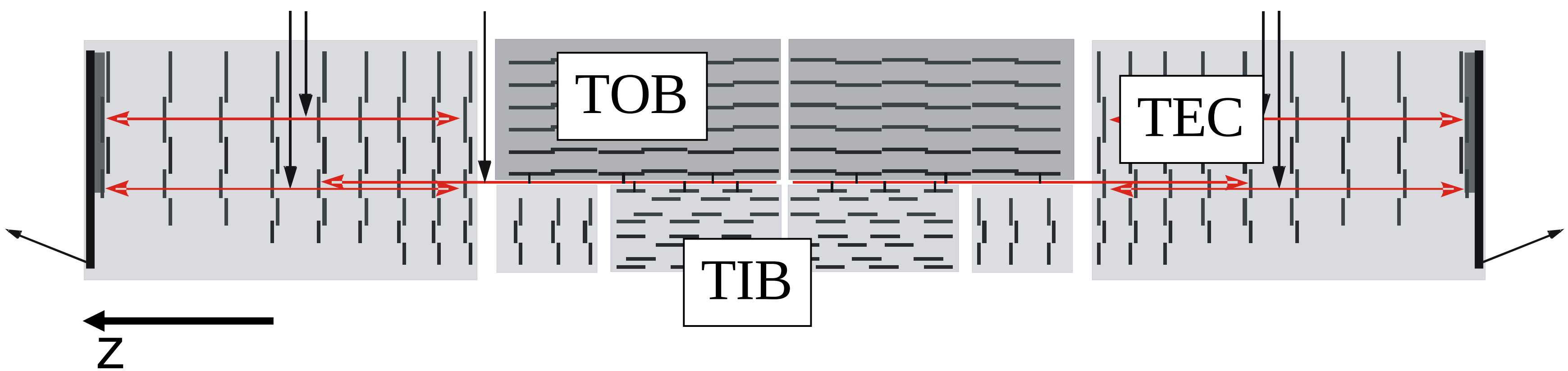
Only Δx_k, Δy_k, $\Delta\phi_k$ are relevant.

Global parameters Δ_0, Δ_t resolved with alignment tube beams

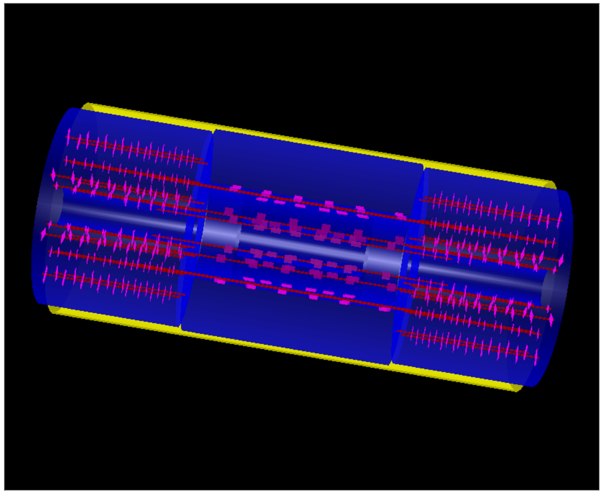
Barrel / Endcap Alignment

- 8 Alignment tubes
- 2 x 6 spots per tube on Inner and Outer Barrel modules
- 5 layers per tube in each Endcap at ring 4
- Beams straight but can move (2 DoF)
- TIB wrt TOB, 5 parameters: Dx,Dy,Rx,Ry,Rz. TEC+ and TEC- wrt TOB, 3 parameters each: Dx,Dy,Rz
- 176 measurements and 31 degrees of freedom

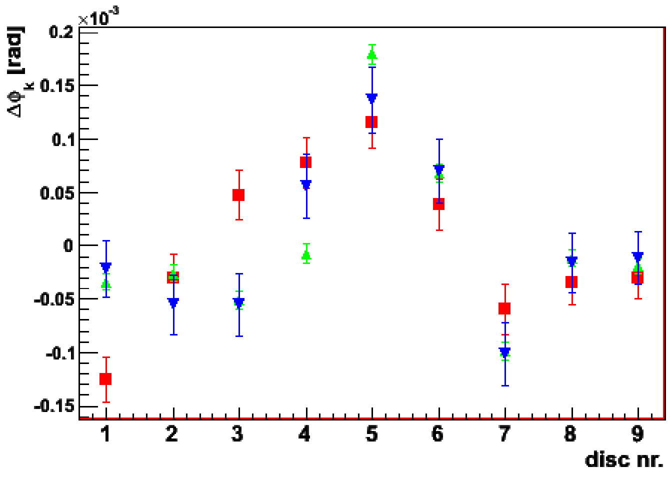


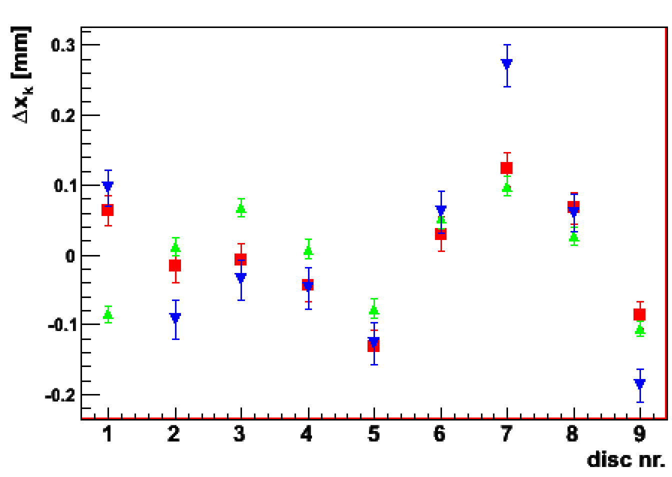


Results

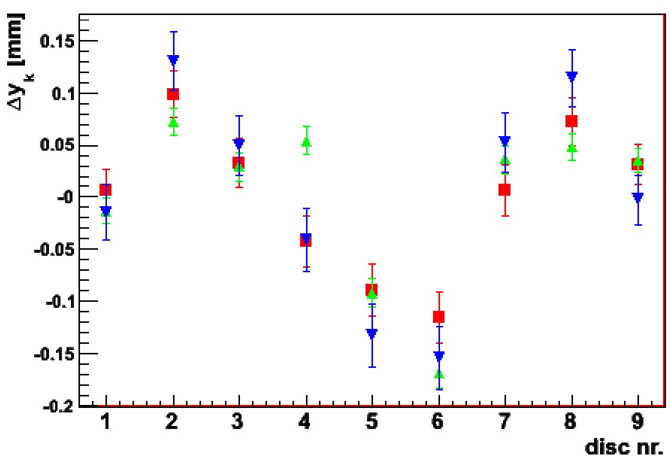


Measurements during integration





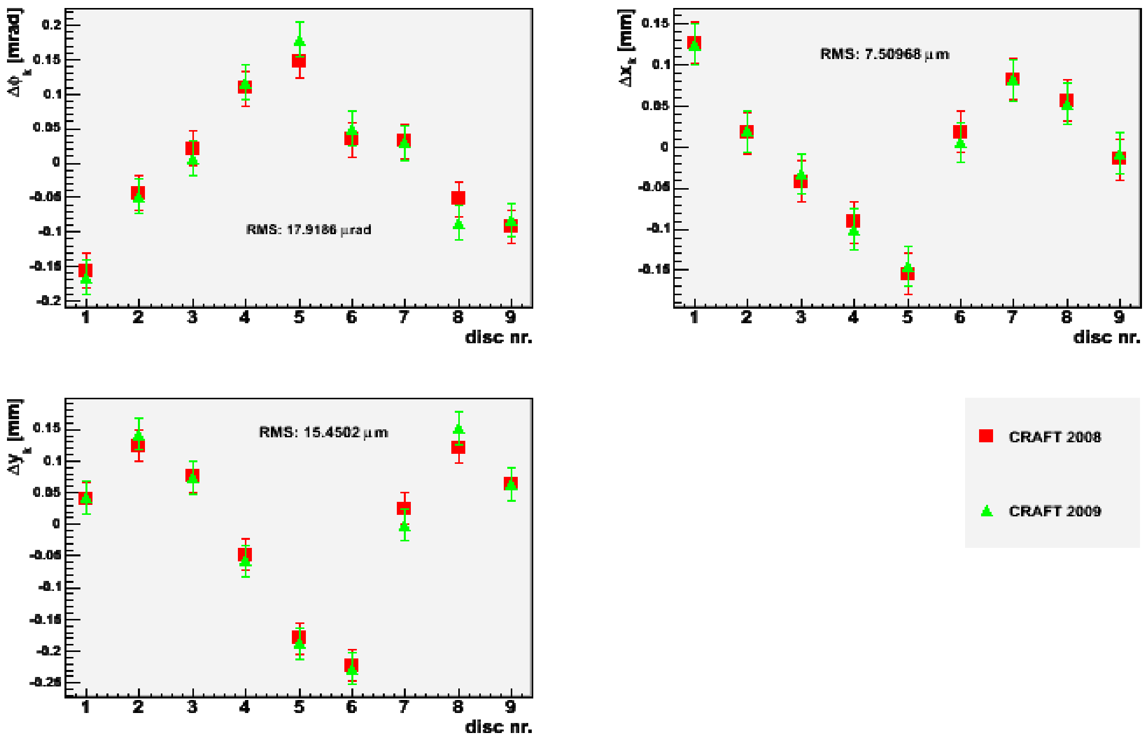
Absolute alignment !



- Precision for alignment parameters:
  - LAS: 20 µm / 30 µrad
  - Survey: 15 µm / 9 µrad
  - Cosmics: 30 µm / 30 µrad

Comparison with/without B-field

PRELIMINARY TEC+ RESULTS



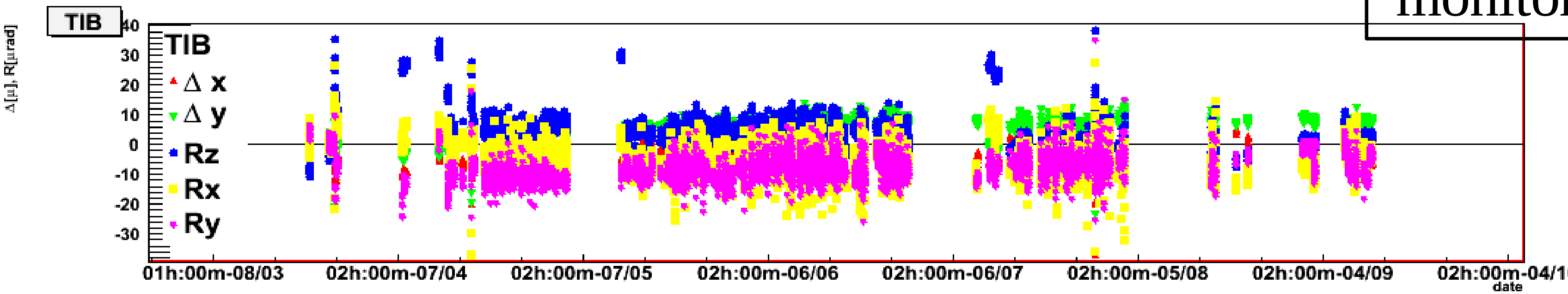
- CRAFT 2008
  - B = 0T
  - Peak mode
- CRAFT 2009
  - B = 3.8T
  - Deconvolution

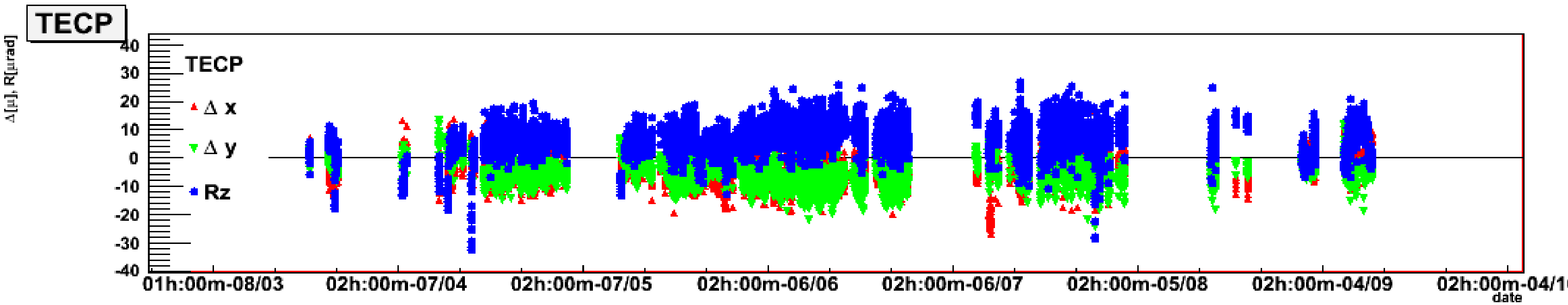
- Alignment parameters reproduced within 18 μrad / 15 μm
- Consistent with measurement precision ≈ 30 μm and no movement

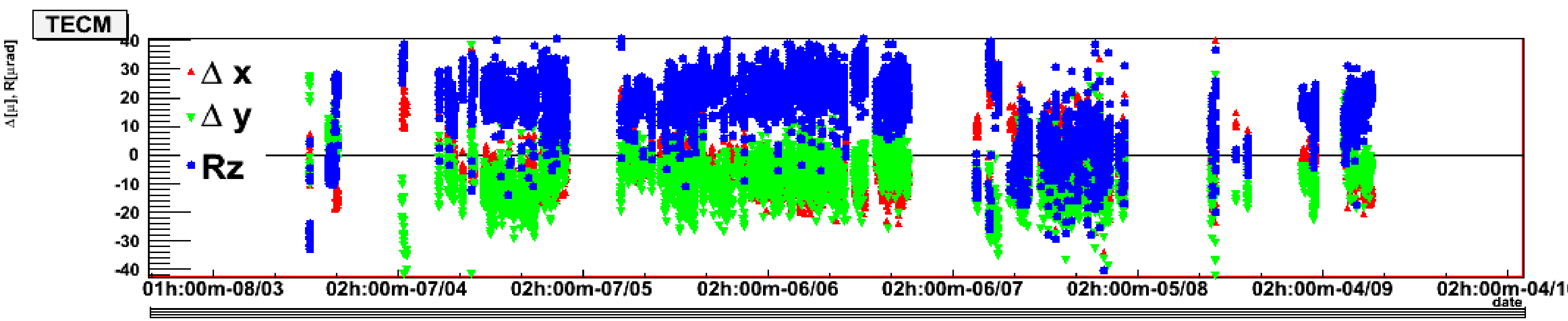
LAS stability 2011

TIB, TEC's global alignment parameters stability relative to reference run *161439*

Relative monitoring !

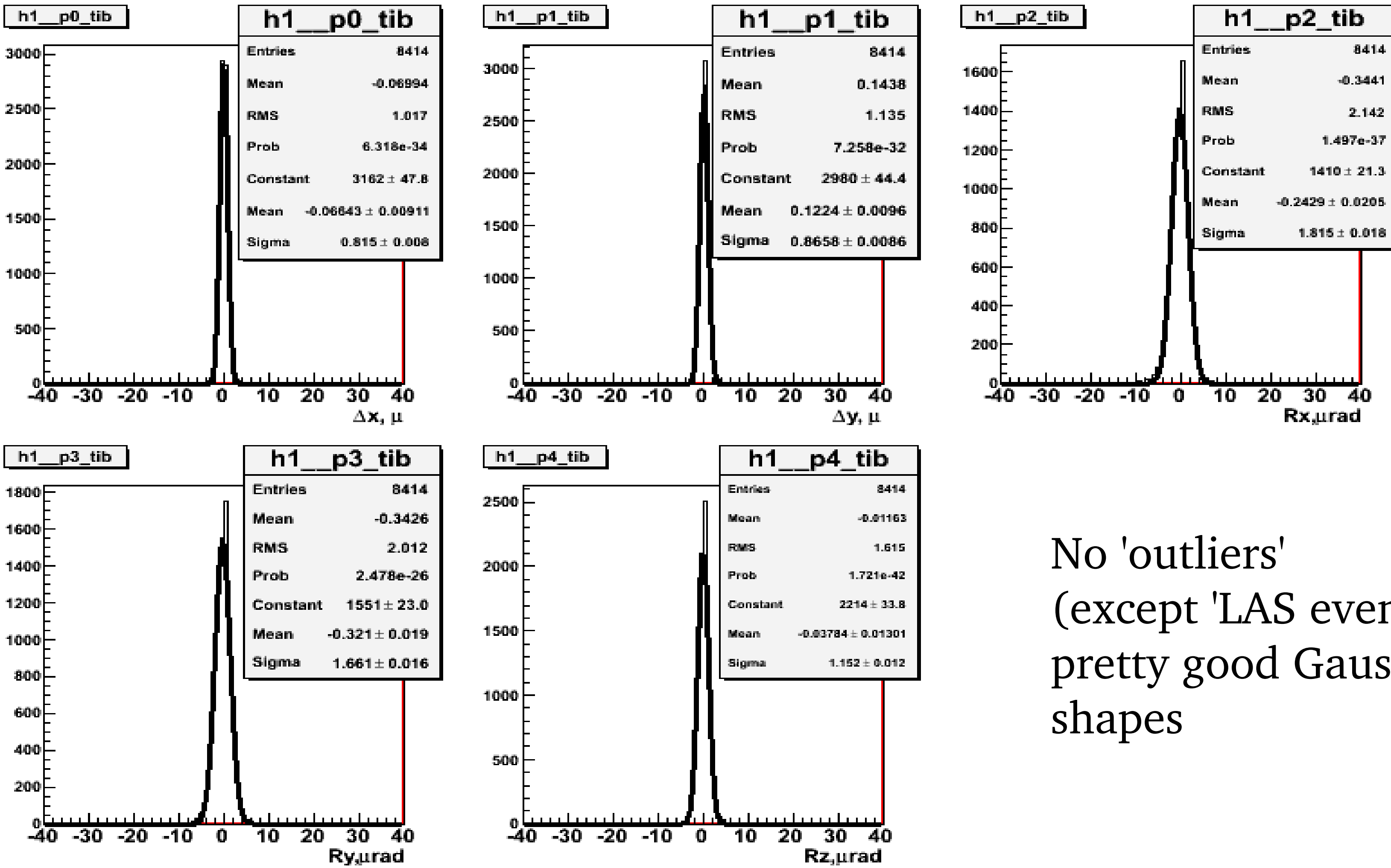






Alignment parameters distributions

Example: TIB parameters(within run)



No 'outliers'
(except 'LAS events')
pretty good Gaussian
shapes

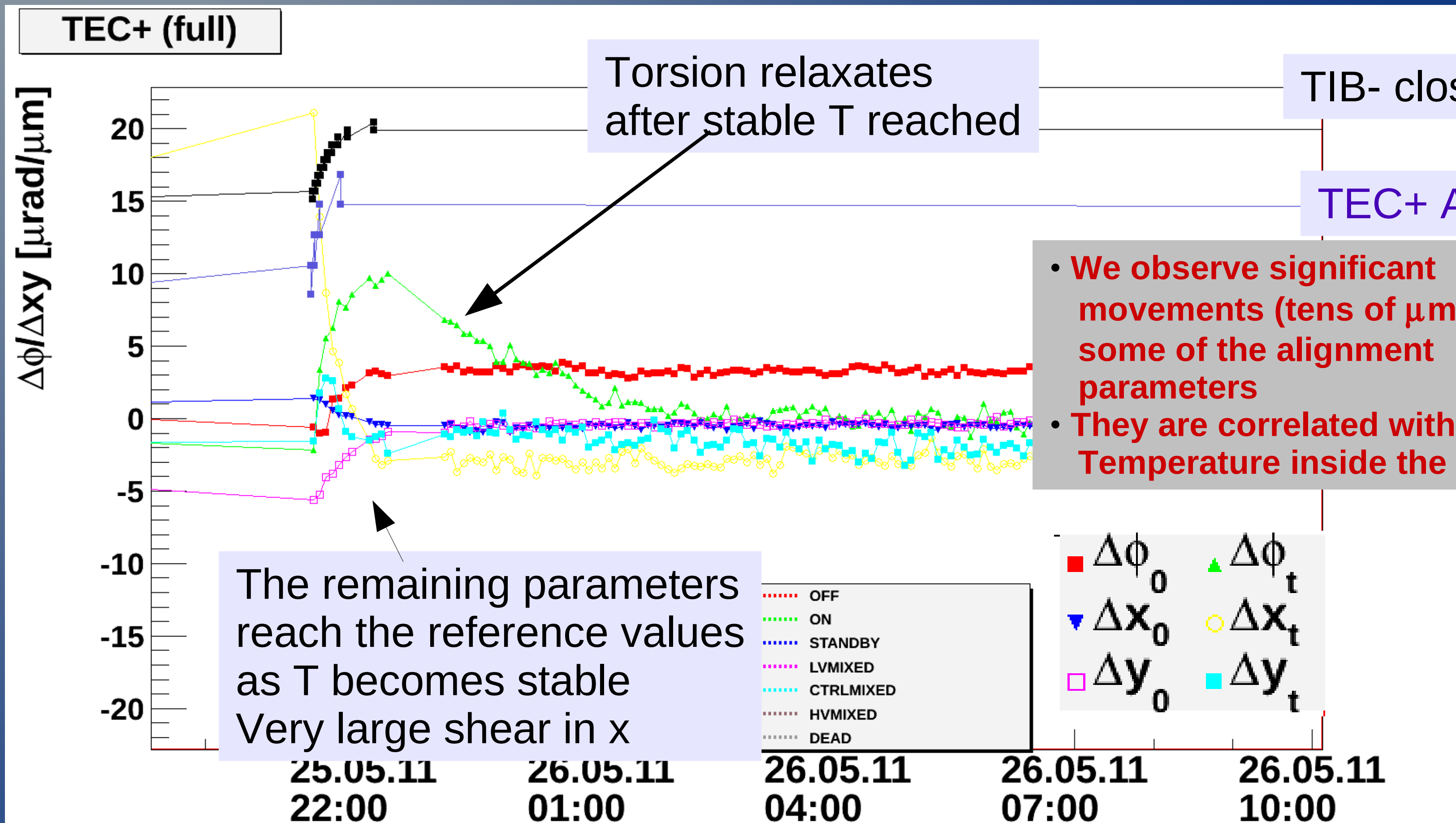
LAS monitoring resolution

Two resolutions: within the run (timescale < 10 h) and run to run(time scale > 1 month).

	σDx	σDx	σRx	σRy	σRz
TIB	0.8/ 2.4	0.9 /2.2	1.8/ 3.3	1.7/ 3.4	1.2/ 2.7
TEC+	2.4/ 4.2	2.3/ 3.8	-	-	3.0/ 4.8
TEC-	4.5 /5.8	6.2/ 7.4	-	-	7.4/ 8.4

- TIB, TEC+ mean resolution 1-3 μm/rad within the run, and 2-5 μm/rad between runs
- TEC- is slightly worse: 4-7 μm/rad and 6-8 μm/rad respectively

Example of 2011 measurement



- **We observe significant movements (tens of μm) in some of the alignment parameters**
- **They are correlated with the Temperature inside the Tracker**

Happens very rarely (non-standard operation of Tk)
Difficult to get independent confirmation. Time scale is very fast for track-based alignment, work in progress.

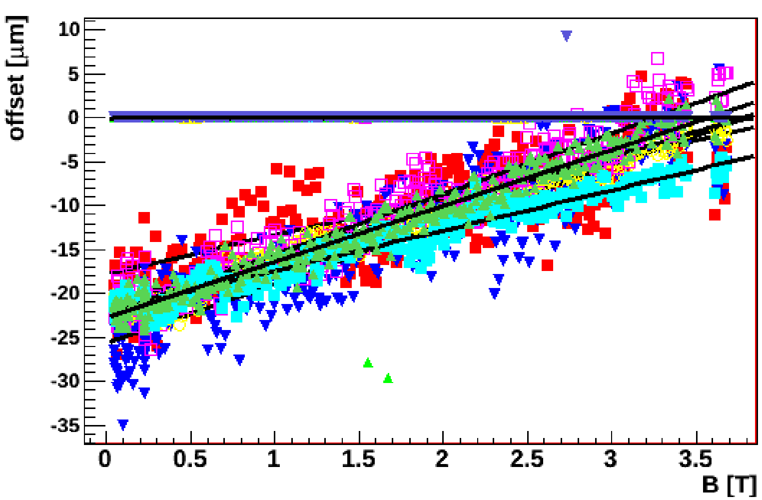
LAS Evaluation
Positive Features

- *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 (only one AT beam has bad signal shapes on TEC+ side, probably due to an obstacle at Margerita region), few lost modules (3 at TIB, 4 at TECs)
- *Fast*: one snapshot of 2000 triggers takes 20 sec, can be easily reduced to just 2 sec

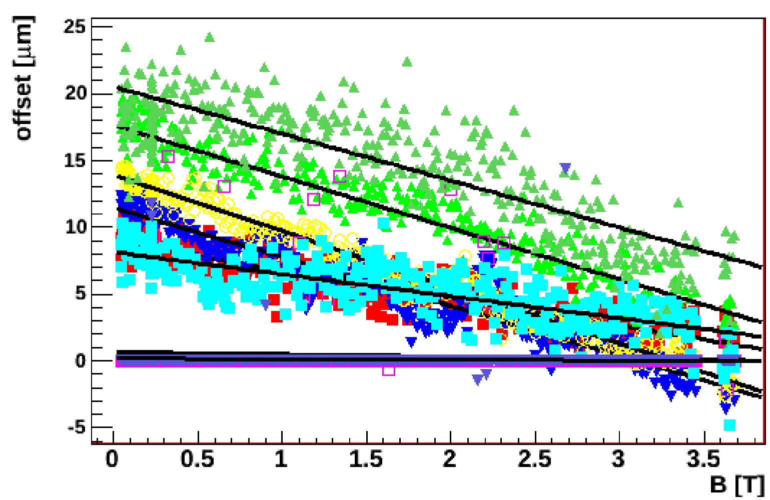
LAS Evaluation
Positive side effects

- *Lorentz angle mesurement*: In the barrel detectors the laser signals shift as B-field changes, just like signals from particles.
- *Sensor ageing*: The laser signals could be used to evaluate the ageing of the Si-Sensors (depletion depth, mobility of charge carriers)

Lorentz shift TOB modules



Lorentz shift TIB modules



LAS Evaluation Difficulties

- *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
- *Non-standard Laser Diodes:* Selection of wavelength and power
- *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

LAS Evaluation
Possible Alternatives

- *RASNIK*: 3-points straightness monitor, based on CCD camera and illuminated chess-board mask. Used in ATLAS Muon.
  - Pro: dedicated DAQ, stability, high resolution
  - Contra: CCD in high rad environment, bulky, transfer from fiducial points to Si-modules, 3-point (should be nested)
- *ALMY*: multy-points straightness monitor, based on amorphous Si-sensors and laser beams. Used in CMS Muon.
  - Pro: dedicated DAQ, high resolution
  - Contra: bulky, sensor and front-end electronics in high rad environment, laser beam instability, transfer from fiducial points to Si-modules

LAS Evaluation
Possible Alternatives

- *FSI*: distance measurements, based on Frequency Scan Interferometry. Used in ATLAS Tracker.
  - Pro: dedicated DAQ, high resolution, stability, many lines of sights
  - Contra: transfer from fiducial points to Si-modules
  - Viable alternative to LAS

LAS Evaluation Conclusions

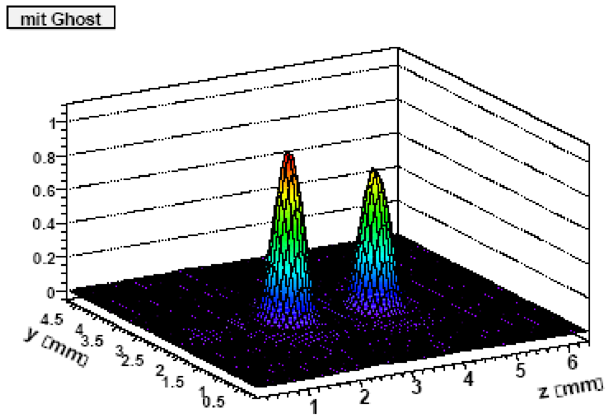
- *LAS Goals*
  - Absolute geometry reconstruction with 100 μm precision by LAS for pattern recognition at the initial stage of LHC was not an issue, because during 2009 data taking with cosmics this task was fulfilled with much better precision by alignment with tracks.
  - Monitoring of the Tracker stability was reached at a level < 10 μm precision, which exceed the primary goal of 20 μm

LAS Evaluation Conclusions

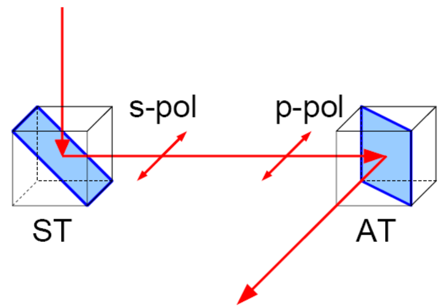
- *LAS Evaluation*
  - The system shows an ability to monitor stability of large Tracker structures with an adequate precision.
  - Limited number of lines of sights makes impossible to monitor such important subdetectors as Pixels, TIDs, TOB and TIB internal stability.
  - Absence of a dedicated alignment DAQ does not allow to commission the system before the initial phase of the Tracker running, when the information provided by LAS is most needed. Needs to be addressed in a better way next time.
  - Alignment system based on FSI principles may be a viable alternative to LAS

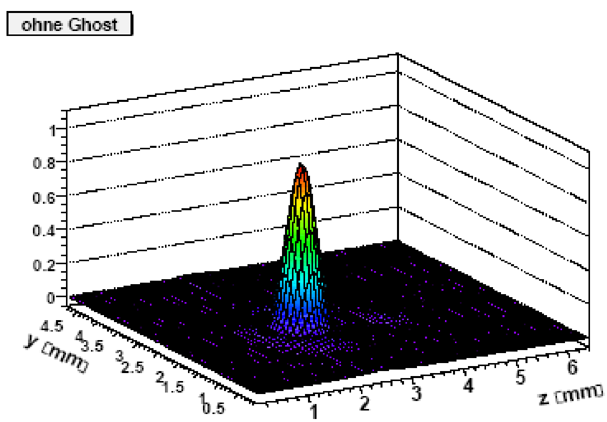
Backup

Polarization in Alignment Tubes

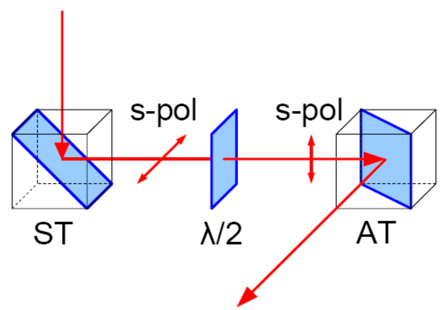


(a) Strahlprofil mit Ghost





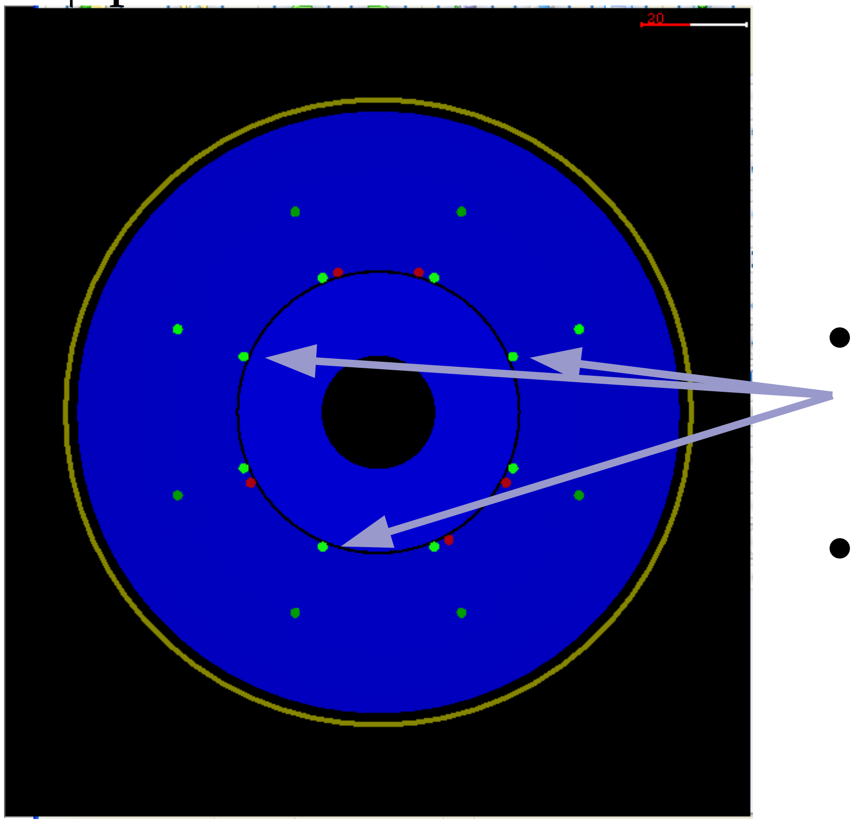
(b) Strahlprofil ohne Ghost



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

Beam Ovelap

ϕ-position of laser beams



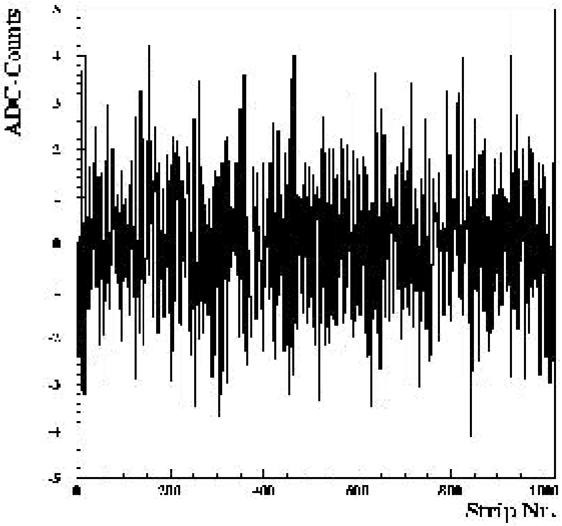
- TEC beams
- AT beams

- 3 AT beams overlap with TEC beams
- They have to be operated alternately

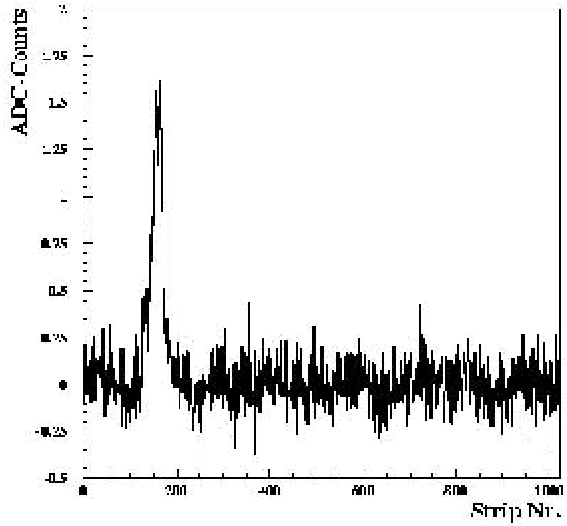
Reducing Noise

- Summing up events improves S/N
- Limitation in zero suppressed mode

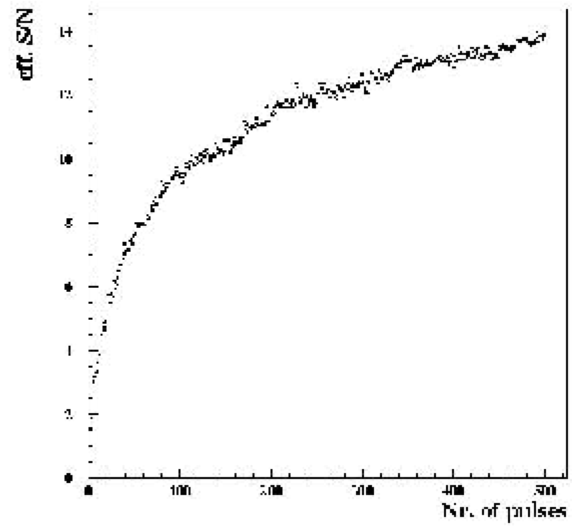
Extreme example (S/N < 1) :



single event (S/N<1)



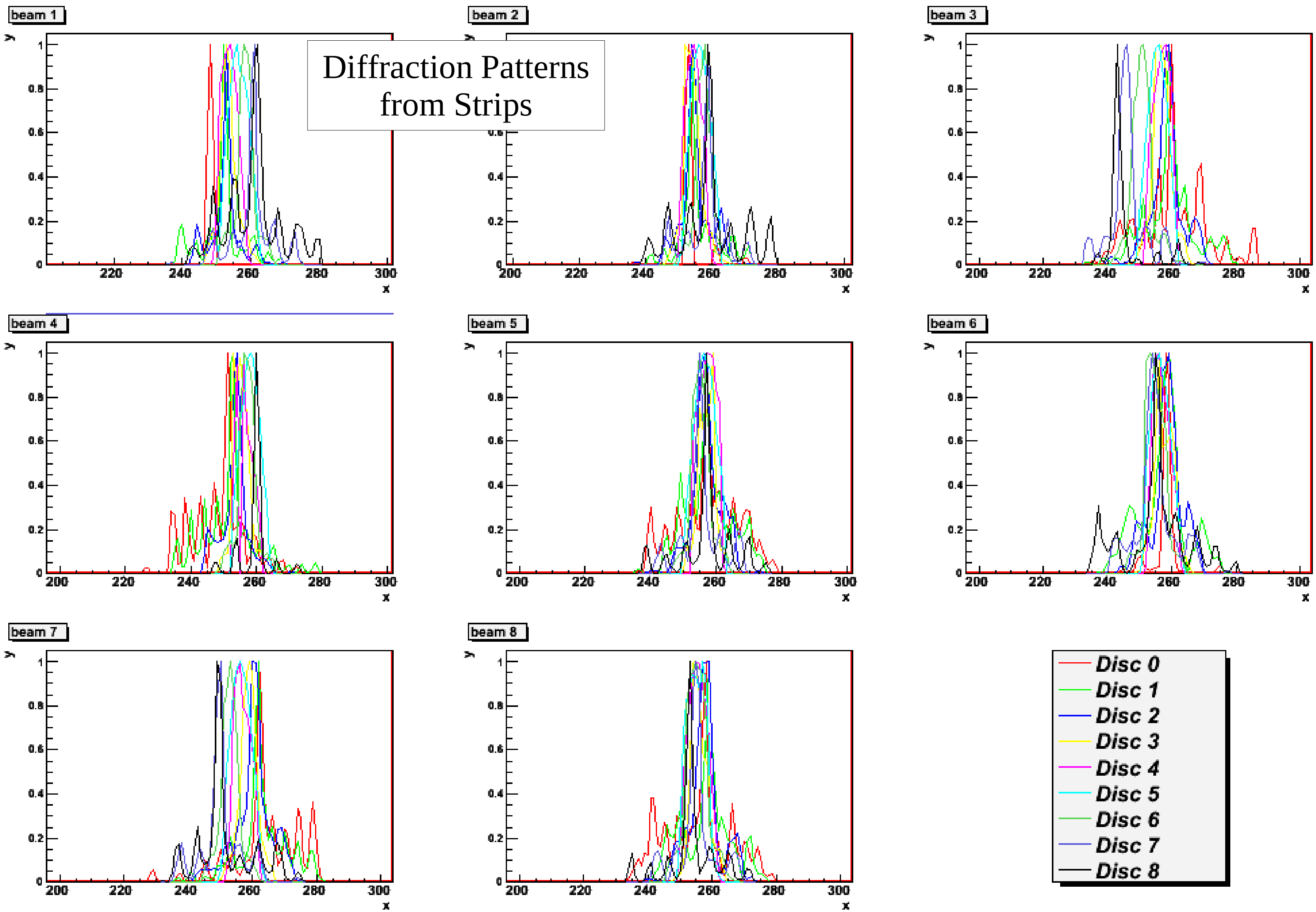
500 events averaged



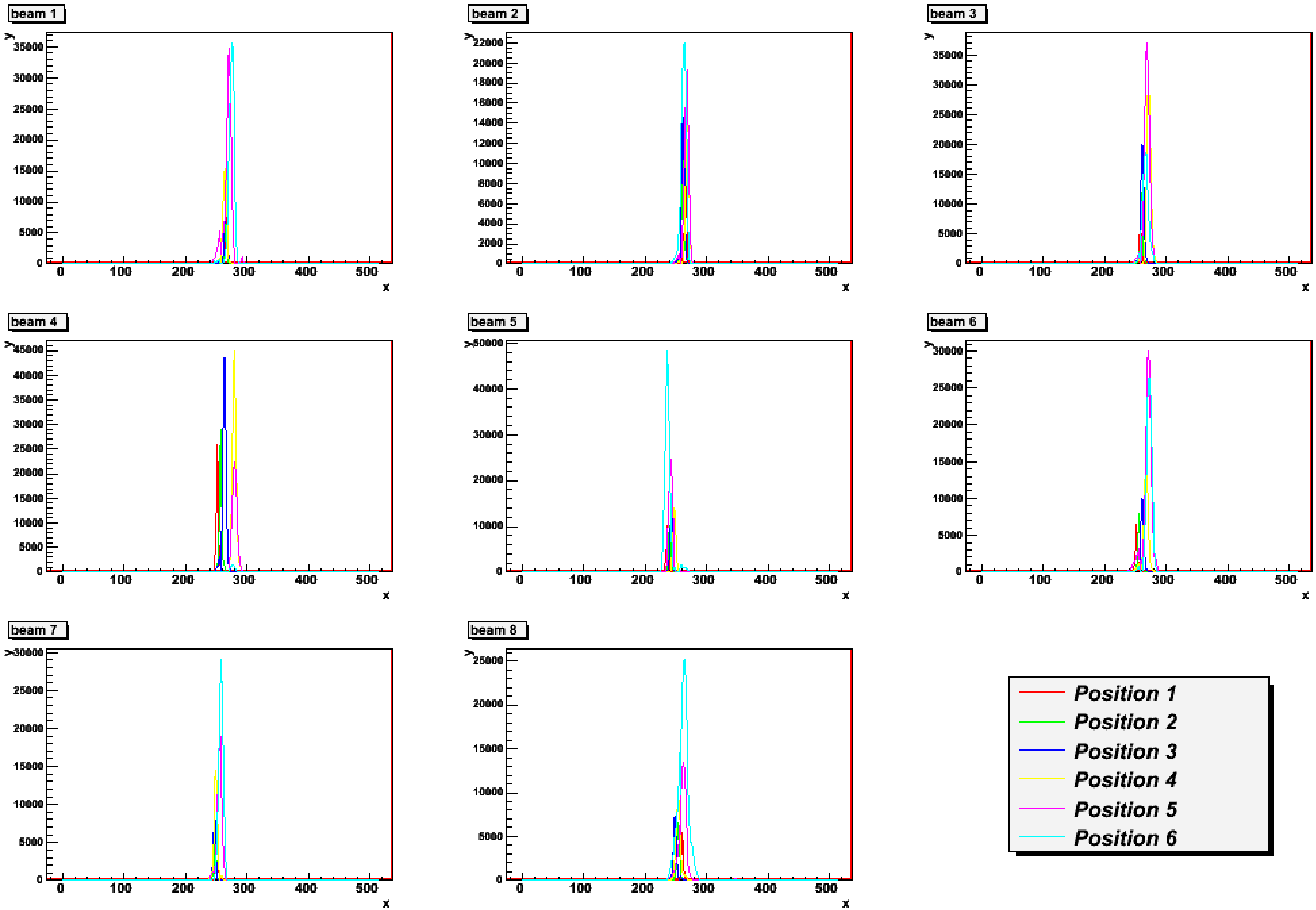
effective S/N

Profiles for Endcap (Ring 4)

Diffraction Patterns from Strips

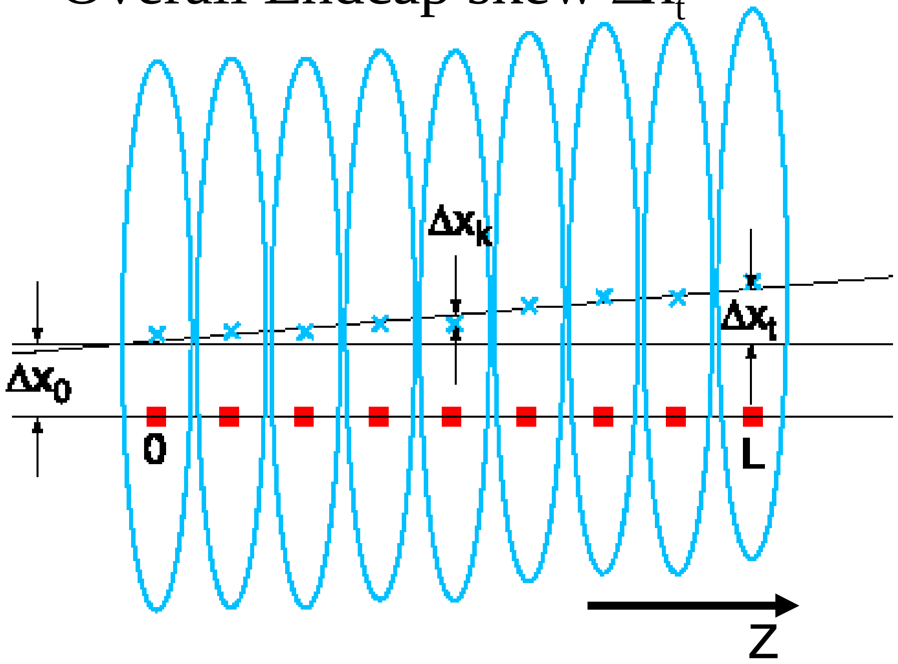


Laser Profiles for Inner Barrel



Endcap Alignment Coordinates

- Separate collective movements from individual disc movements
- Overall Endcap movement Δx_0
- Overall Endcap skew Δx_t



$$\sum_k \Delta x_k = 0$$

$$\sum_k z_k \Delta x_k = 0$$

k = 1..9