Alignment of high resolution pixel tracking telescopes

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DEPFET Active Pixel Detector

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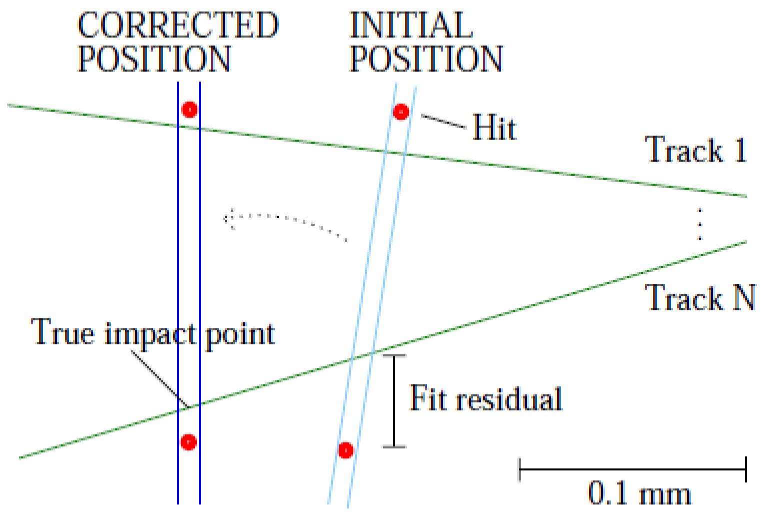
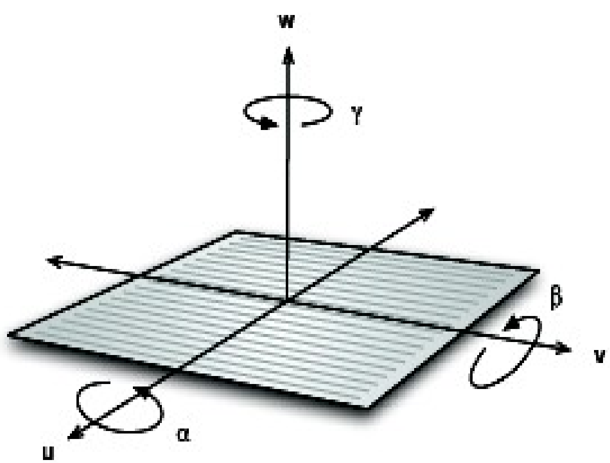
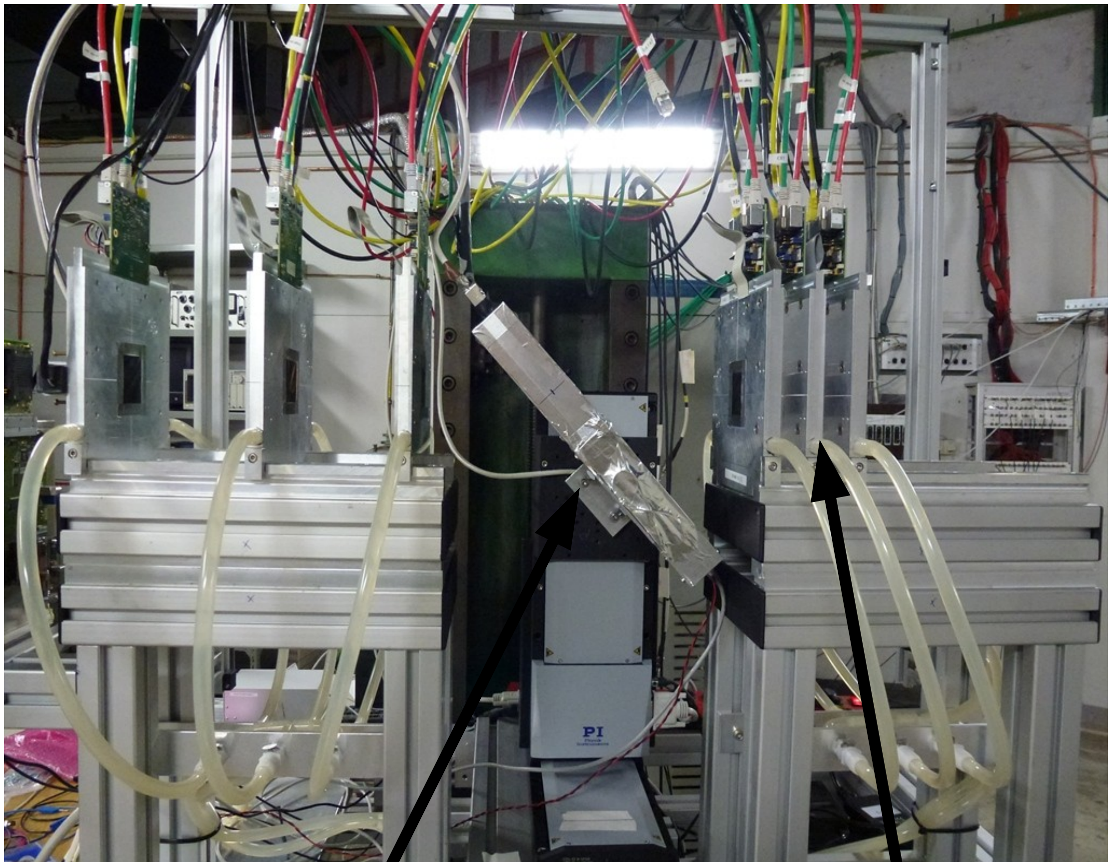
Pixel Sensor Alignment





- Very precise measurement of intersection coord. in sensor plane (~1um).
- Imprecise mechanical survey measurements of sensor positions in 3D space:
  - Small sensor not directly accessible (hidden in boxes).
  - Need to measure 3 shifts and 3 tilts per sensor.
- Misalignment of sensors produces errors whenever
  - Transform hit from local (u,v) to global (x,y,z) coordinates
  - Propagate track parameters to local sensor frame.
    - Predicted u, v coordinates
    - Predicted slopes du/dw and dv/dw
- Solution: Minimize hit residual wrt to
  - Sensor movements in space → (alignment parameters)
  - And track parameters

EUDET Telescope @ DESY & CERN

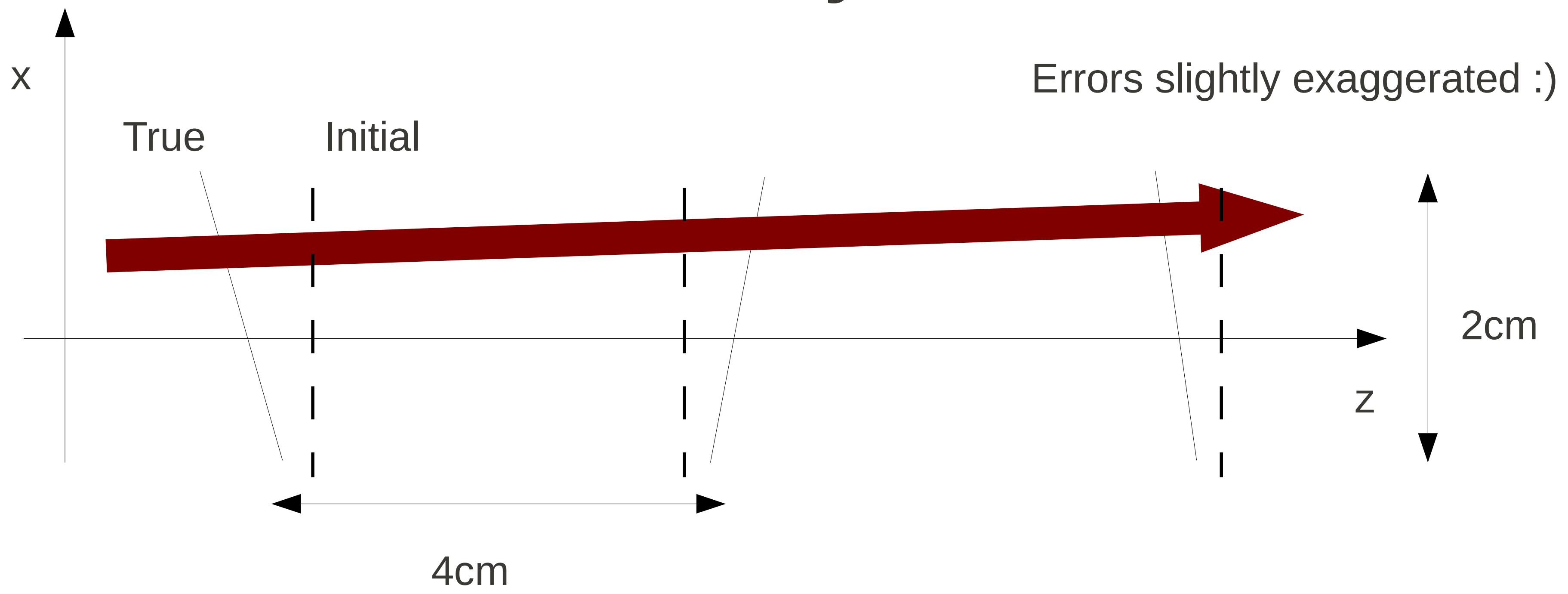


DUT module
- independent mounting
-> imprecise shifts/tilts

Mimosa26 pixel module
- good mechnical support
- tracks with ~90° incidence

- Error in sensor positions and rotations should be small relative to
  - Track parameter errors
  - Sensor measurmenr errors
- It means for the Mimosa26 sensors in EUDET telescope:
  - Error X/Y < 1um (sensitive!!)
  - Error RotZ << 1mrad (sensitive!!)
- Sensitivity for rotX, rotY und Z depends on beam properties. In the DESY case: :
  - Beam spot size: 1cm
  - Beam divergenz: 1mrad
  - → error Z << 1mm (DESY)
  - → error rotX/Y ~ 1mrad (DESY)

How does reality look like?



- EUDET telescope @ DESY (M26 sensors)
  - Errors in Z ~ 1-5mm
  - Errors in X/Y ~100um
  - Errors RotX/Y/Z ~ 20 mrad
  - Beam energies 1-6GeV

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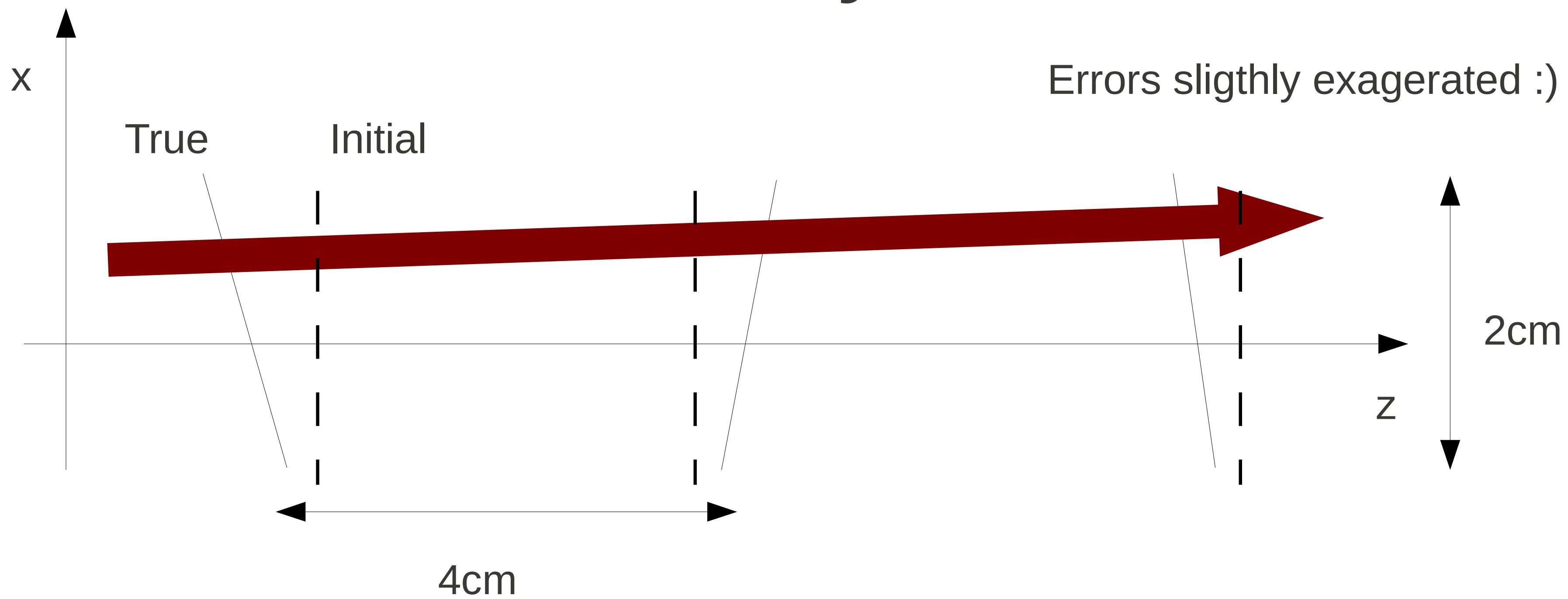
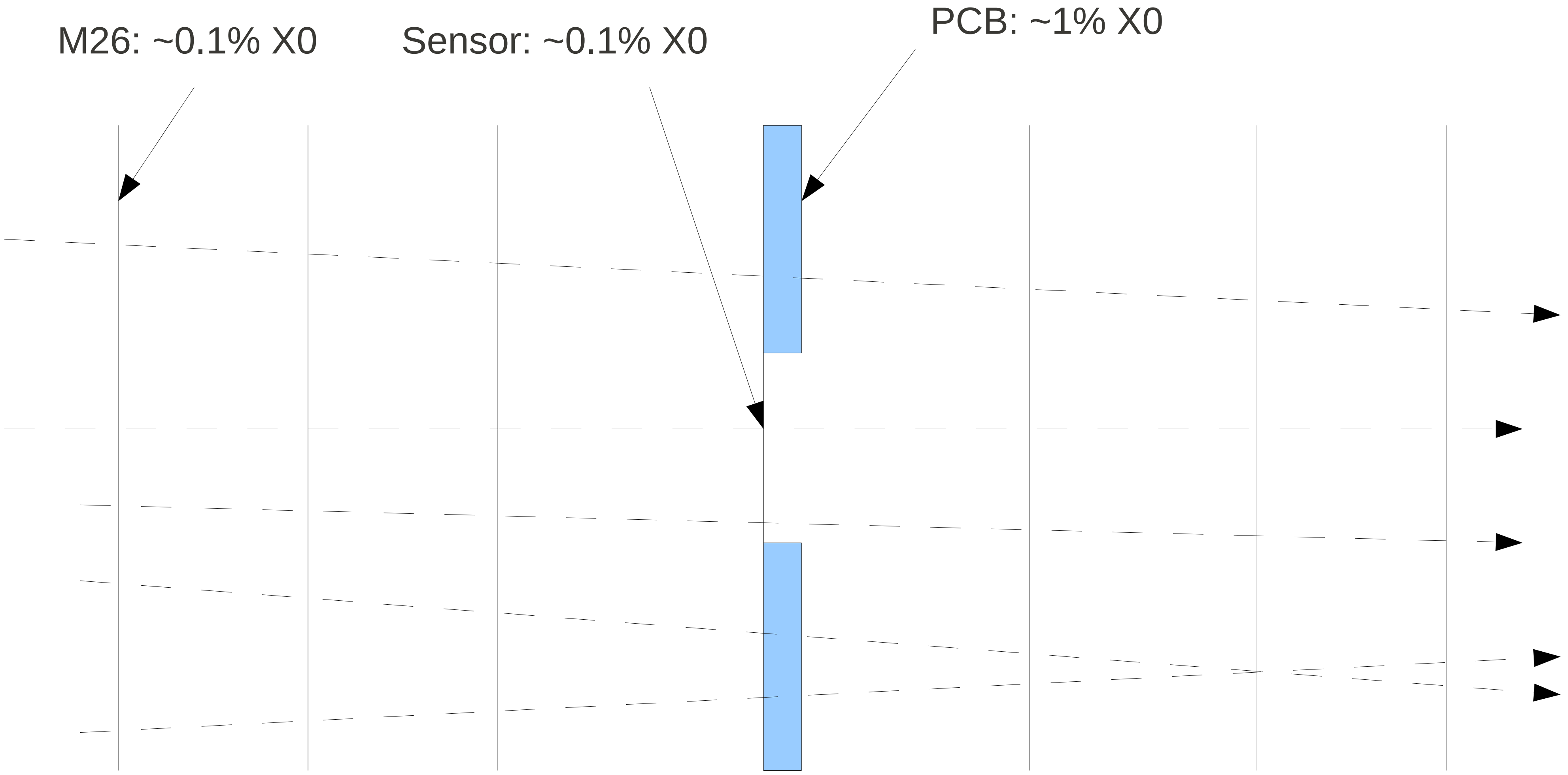


- A good alignment needs corrections in all 3 shifts and 3 tilts
- But not all corrections are equally important
  - X/Y/rotZ → then Z → than rotX und rotY
- Alignment Fitter und TrackFinder/TrackSelection should be iterated:
  - TrackFinder requires alignment of at least X/Y to find any tracks at all.
  - Quality indicators (chi2 etc.) will be biased unless at least X/Y and rotZ are aligned
- Minimize material budget of the DUT sensors as much as possible, good model of material budget needed.

Alignment Strategy

- There are several valid choices for the actual alignment algorithm in a test beam scenario
  - Tried several methods: Kalman Alignment Algorithmus, MillePedeII, Globale Alignment.
    - Hardly any difference in number of iterations or chi2 distributions.
  - Some aspects are important:
    - Track model must take into account multipe scattering (Kalman Filter or Brocken Lines model)
    - Fitter needs accurate information about the material budget of Mimosas modules AND the DUT's → Framework issue!!
    - Some Boot Strapping is needed to get some tracks in a badly aligned sensor at all.
    - Framework needs infrastucture to iterate the complete cycle of track finding and alignment fitter until convergence.
    - Framework needs tools to validate the alignment solution (check plots and alignment simulations)

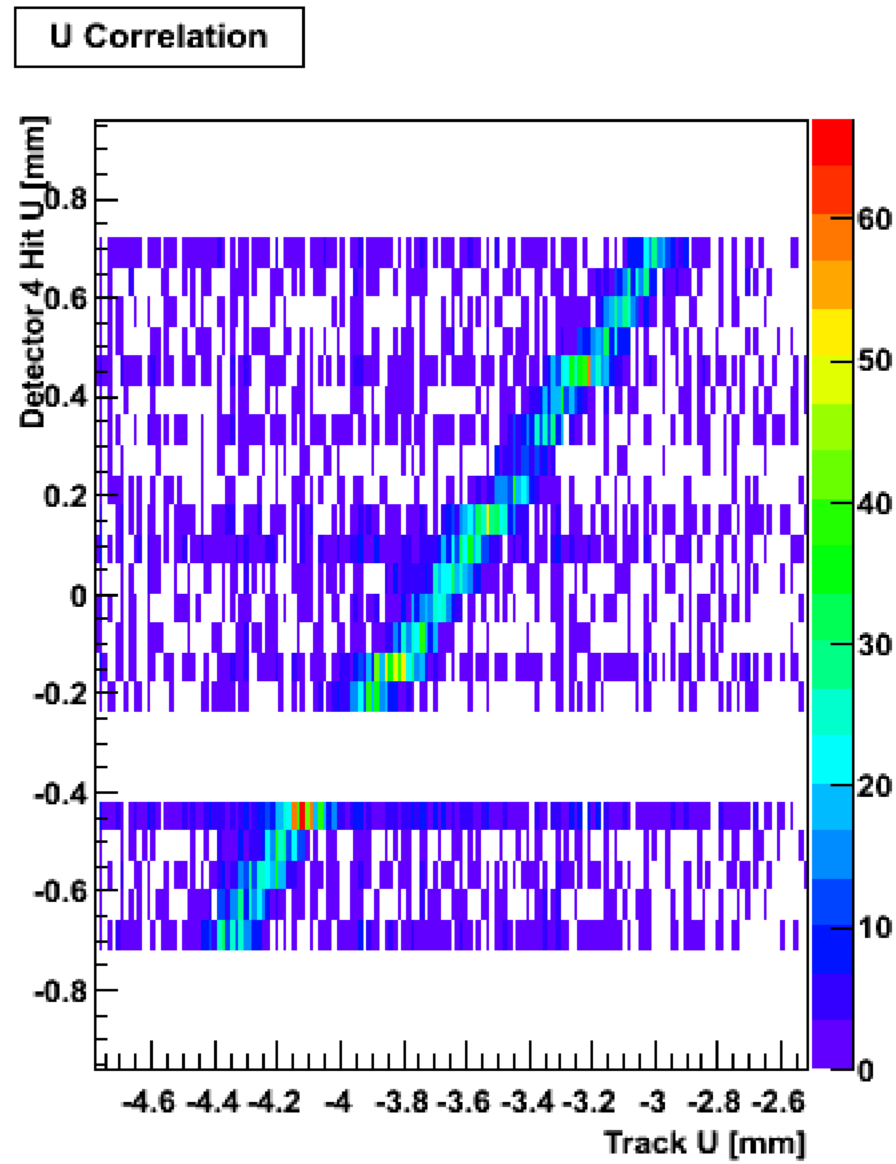
DUT Material Budget (DEPFET)



Telescope tracks may see large variations of DUT material budget.
→ Need position resolved material map in sensor plane (u,v).

Alignment – Boot Strapping

- A) **Pre- Alignment with Hits:** Correct X/Y shifts of sensors
  - Form track candidate from hits on first sensor and extrapolate parallel to z axis.
  - Shift U/V residuals to zero mean value on all othe sensors.
- B) **Pre-Tracking:** Pre- alignment allows to form a first sample of tracks
  - Seed tracks from two hits, add other hits along the track seed.
  - Require hits on all sensors → this minimizes fake tracks
  - Cut on distance between hit seed track, typically ~200um
  - No cuts on trach χ^2 (not even close to a true χ^2)
- BUT: Efficiency of track finding is low, in particular if DUT(s) very thick and/or rotZ is very off. And still many fakes.



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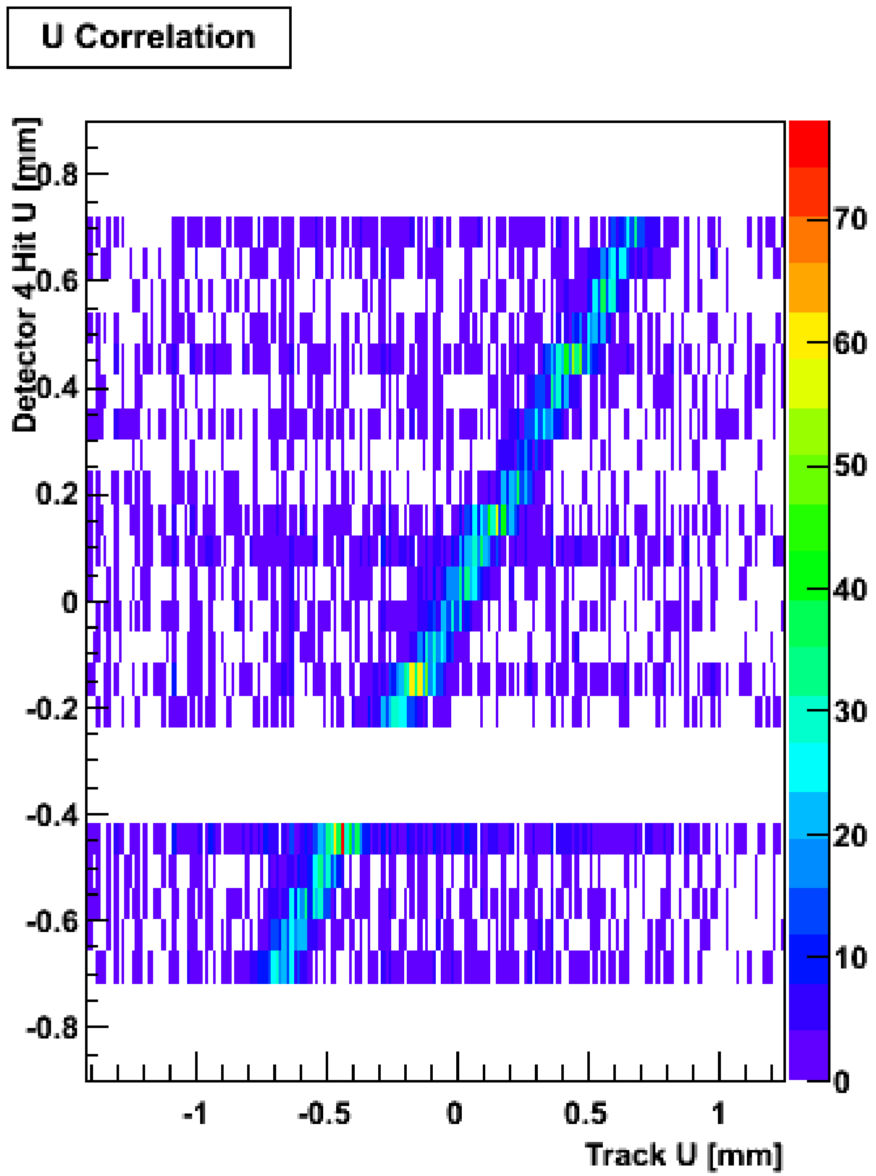


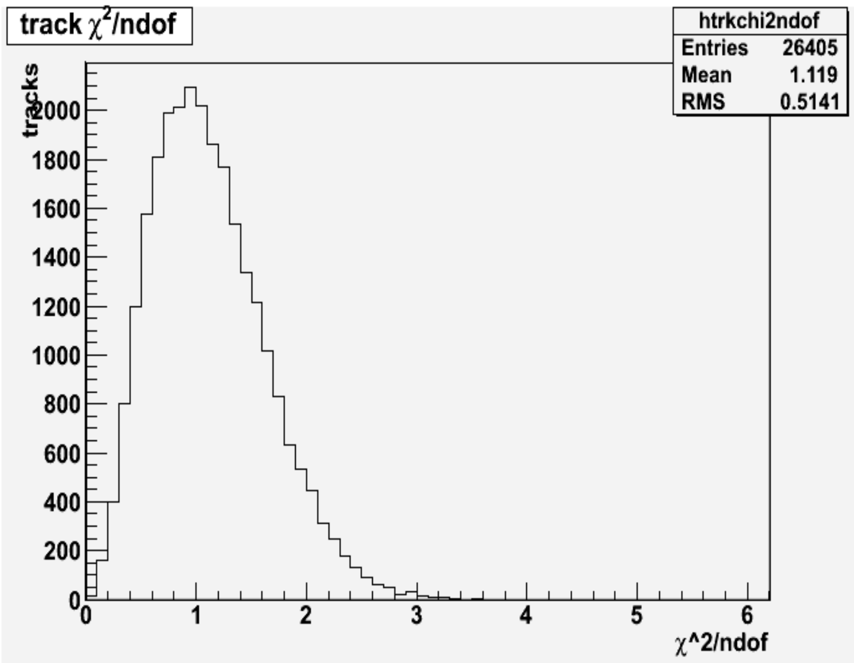
Alignment – with tracks

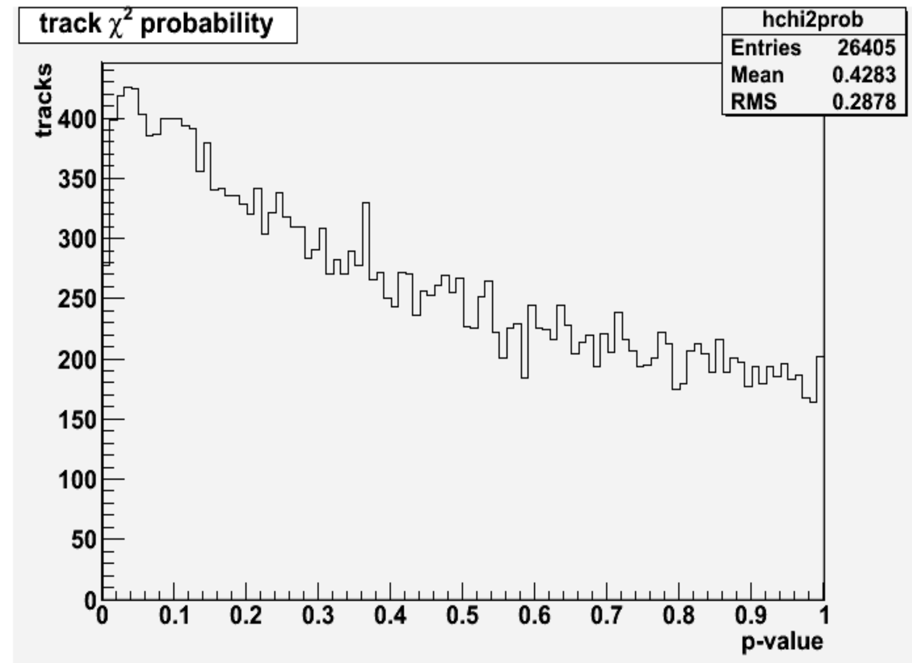
- C) **Alignment with Tracks:** First alignment run should be constrained to 'robust' degrees of freedom
  - Fit X,Y, rotZ
  - but fix Z, rotX, rotY
  - also fix first/last sensor
- D) **TrackFinder:** Repeat track finder step with stronger cuts on χ^2 and outlier rejection (for example based on Chi2Increments).
  - Better alignment increases track finding efficiency and sensitivity of outlier rejection ($\rightarrow$ cleaner track sample).
- E) Repeat alignment fit with more degrees of freedom per sensor:
  - Still fix first/last sensor
  - Do not forget to validate alignment solution!!

Validation of Alignment

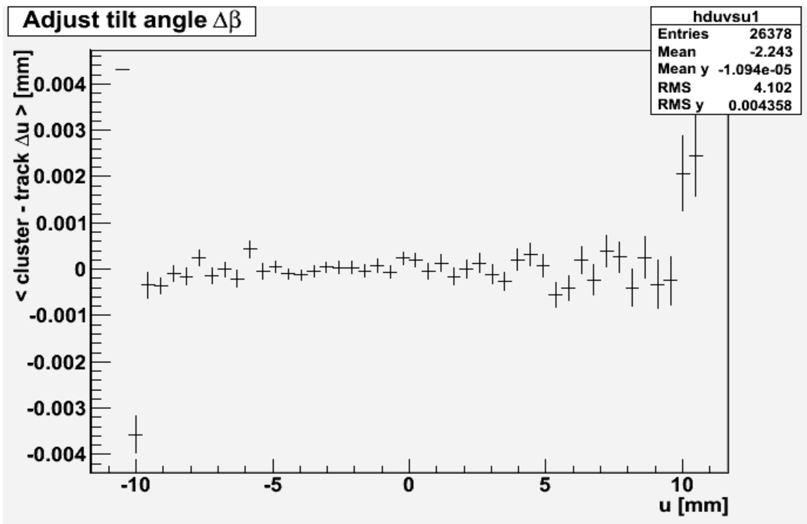
- Alignment corrections (dx,dy,dz,dα,dβ,dγ) must
  - converge → repeat fit and check it!!
  - stay within limits from mechanical survey
    - No stretching of setup (Z), or shearing (X/Y)
- Check mean residuals are zero, independent of track intersection (U,V) and track incidence slopes (dU/dW, dV/dW).
- Check track quality in aligned sensor
  - χ^2/ndof has mean of 1 and rms of 0.5
  - Flat p-value distribution

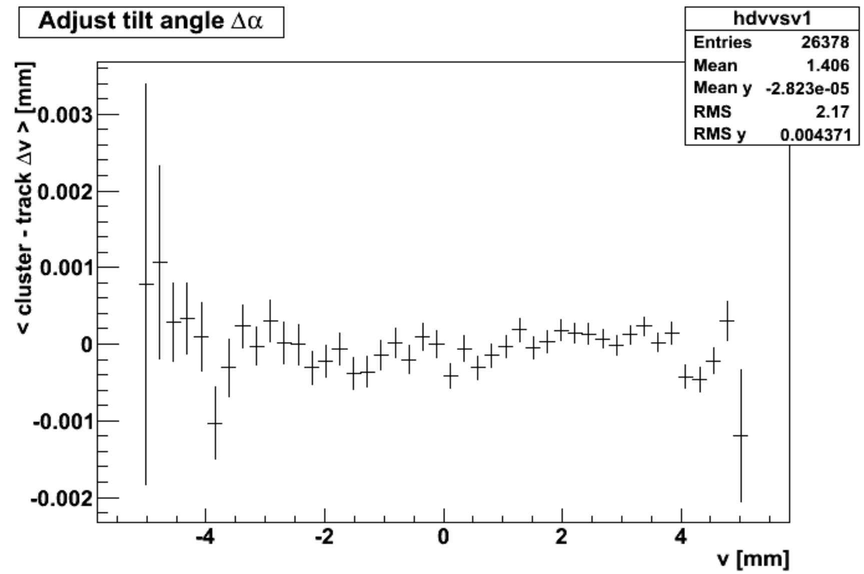
Validation Plots ...

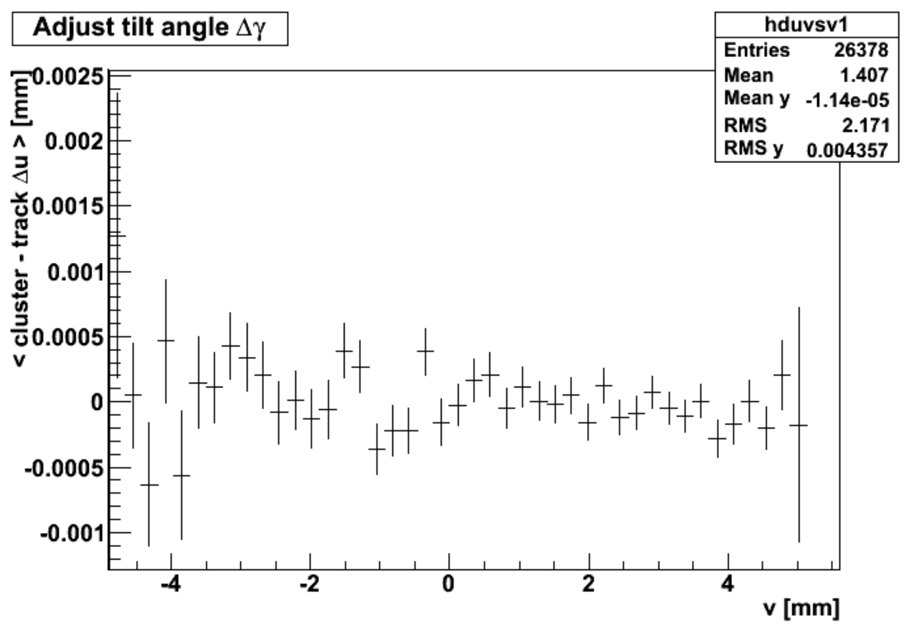




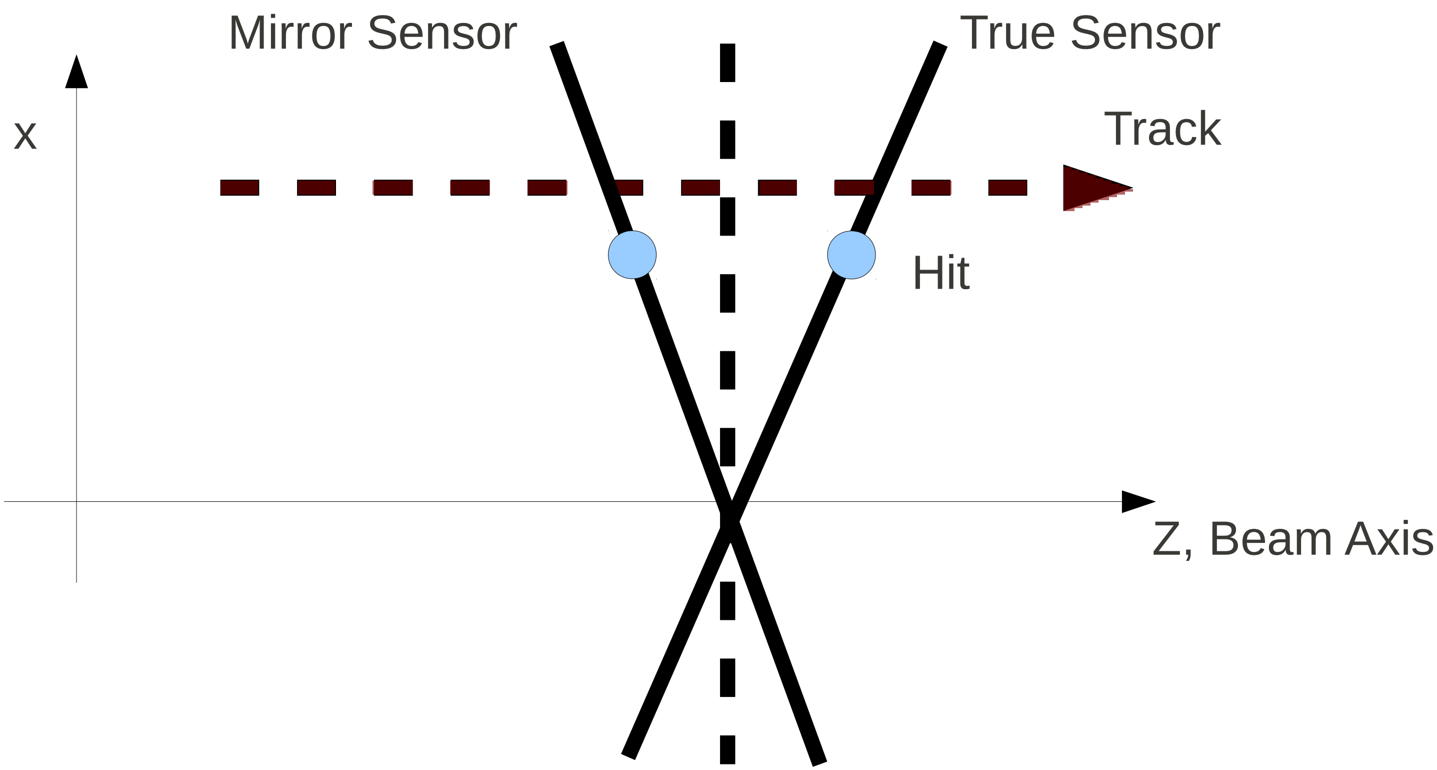
Validation plots ...







Correction of rotations with tracks



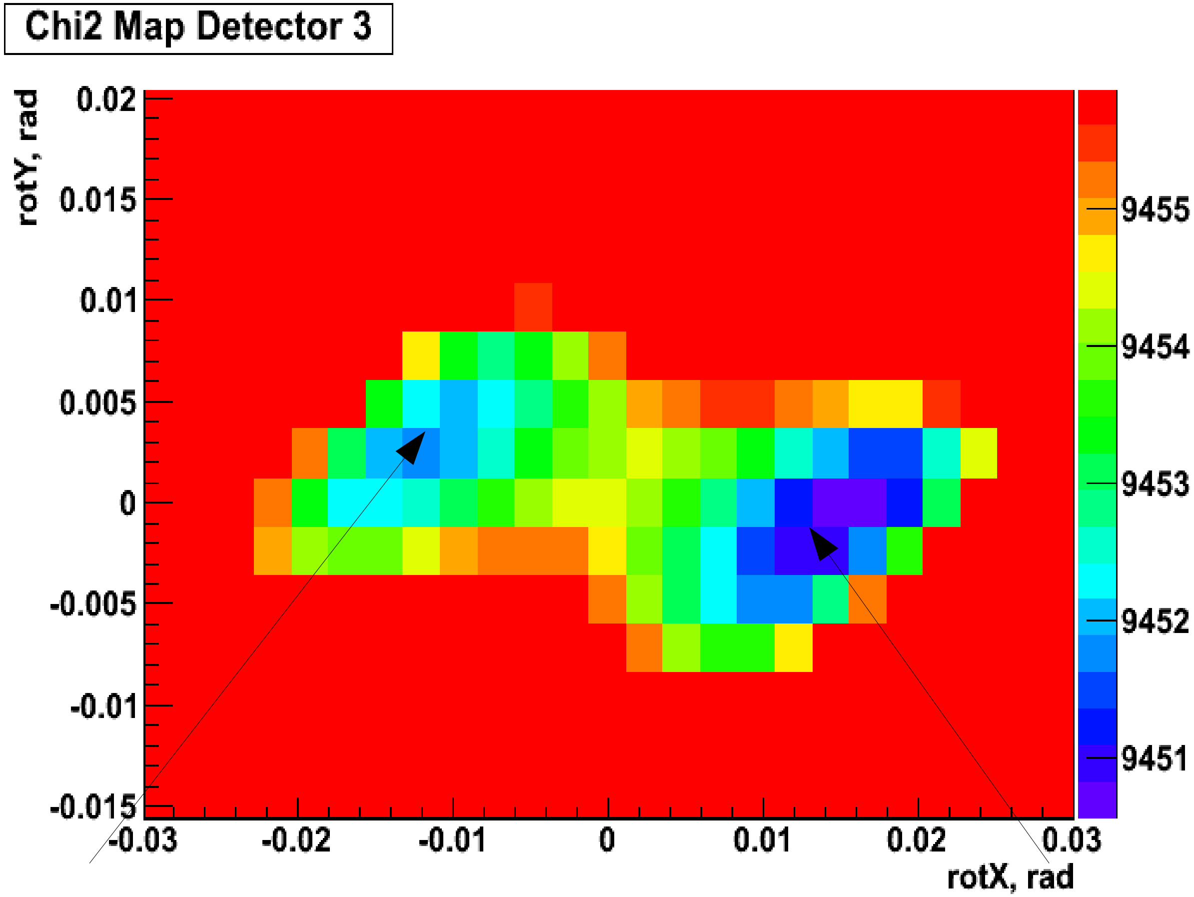
:- If all tracks go exactly parallel beam axis, there exist mirror solutions for sensor tilts in track based alignment. (Nonlinear model)

:- If beam divergence is small (~1mrad), a linearized fitter will sometimes Converge into a local minima, mirror solution.

:- Choosing the wrong sign produces alignment errors on the same scale as the initial misalignment.

Simulation of the DESY Setup

Each bin represents sensor rotations of one M26 module. Color scale
Is sum of smoothed chi2 values of 5000 tracks.



Local minimum

True solution

Conclusions

- Precise alignment of the EUDET telescope at low beam energy is a challenge:
  - But: It can open the door to high resolution studies at DESY beam lines
- Ingredients for a successful alignment:
  - Limit total material budget of all DUT sensors (~1% X0)
  - Accurate model of material budget of DUT in gear file
  - Minimize Z distances of sensors, and try to measure Z positions with precision better 5mm.
  - Check sensors are not strongly tilted (>20mrad) relative to the telescope table
  - Check beam spot does not move from sensor to sensor. Check correlation bands.
- Iterative alignment with multiple cycles of TrackFinder and AlignmentFitter needed.
- Validation of alignment: Automatic production of alignment check plots on run-by-run level.

Thanks